SPRINGER
REFERENCE

Joseph N. Pelton
Editor

Scott Madry *Associate Editor*

Handbook of Small Satellites

Technology, Design, Manufacture, Applications, Economics and Regulation

INTERNATIONAL ASSOCIATION for the ADVANCEMENT of SPACE SAFETY

INTERNATIONAL SPACE UNIVERSITY

Springer

Handbook of Small Satellites

Joseph N. Pelton
Editor

Scott Madry
Associate Editor

Handbook of Small Satellites

Technology, Design, Manufacture, Applications, Economics and Regulation

With 476 Figures and 92 Tables

Springer

Editor
Joseph N. Pelton
Executive Board
International Association for the
Advancement of Space Safety
Arlington, VA, USA

International Space University (ISU)
Strasbourg, France

Associate Editor
Scott Madry
The University of North Carolina at Chapel Hill
Chapel Hill, NC, USA

ISBN 978-3-030-36307-9 ISBN 978-3-030-36308-6 (eBook)
ISBN 978-3-030-36309-3 (print and electronic bundle)
https://doi.org/10.1007/978-3-030-36308-6

© Springer Nature Switzerland AG 2020
All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

The Space Industry as of 2020 continues to be one of the most rapidly growing sectors in the global economy with nearly half a trillion dollars in various activities related to telecommunications, remote sensing and Earth observation, meteorology and climate change monitoring, space navigation, space exploration and experimentation, national defense, as well as a range of brand new space activities. These innovative applications include on-orbit services, RF Geolocation, data analytics, electronic-tracking antenna system in space and on the ground, commercial inter-satellite linkages and data relay, artificial identification systems (AIS), Internet of Things (IoT) services provided by space systems, re-usable launch vehicles, and more. The world of space today has expanded significantly beyond the activities carried out by national and regional space agencies and military and defense-related space agencies. Some market studies have suggested that commercial space activities are now three times larger than governmental and defense-related activities. The so-called "NewSpace" and "Space 2.0" activities have, in large part, been responsible for the rapid growth and expansion of the global space industrial and services activities. Nevertheless, "New Space" systems and small satellite-related industries will be adversely impacted by the Corona-virus along with the rest of the global economy for the next few years.

One of the factors that has driven this new growth is the new small satellite revolution in the space industry. Tens of thousands of small satellites have been proposed to be deployed in constellations – largely in low Earth orbit and largely between 700 km and 1500 km altitudes. These new initiatives to deploy small satellite constellations on a very large scale have, in part, driven new demands for new types of space systems and technology. In particular, it has helped fuel expanded space markets for such new capabilities as highly cost-efficient reusable launch vehicle or highly versatile new phased array antenna systems with electronic-pointing capabilities to support new broadband networking and communications to LEO constellations.

This new *Handbook on Small Satellites* is an important and comprehensive reference source for all aspects of the amazingly fast-growing field of small satellites. It covers everything from the small femtosats (or chipsats) that are below 100 g in mass to picosats (100 g to 1 kg), nanosats (1–10 kg) (which also covers cubesats), microsats (10–100 kg), and even mini-satellites that can be as large as 1000 kg although some limit these to 500 kg or 600 kg of mass. It covers the latest information about chipsats, pocketqubes, and cubesats for experiments and technology demonstrations but also examines the latest innovations related to commercial small satellites for a new range of space applications. In short, it covers every aspect of the small satellite world. Thus there are articles that discuss launch vehicles, facilitators for launch arrangements, and licensing and regulatory issues and concerns, such as end of life de-orbit and orbital debris challenges. It also addresses financing, new applications, and every aspect of small satellite design and technological engineering. The *Handbook of Satellite Applications* that preceded this *Handbook of Small Satellites* provided a broad and useful overview, but this new resource provides within its 82 chapters a wealth of specific information about every aspect of this important new field of space development.

Noted experts around the world from Africa, Asia, Australasia, Europe, North, and South America – over seventy in number – have contributed to this remarkable publication. Many of these contributors have ties to the International Space University and are, or have been, on its faculty or were at one time students of this global university that is devoted to understanding the cosmos as well as every aspect of space applications. I salute this remarkable new reference handbook and especially Dr. Joseph Pelton, who was the first Chairman of the Board and first Dean of the International Space University, plus all of its authors from around the globe.

President, International Space University
Strasbourg, France

Juan de Dalmau

Preface

Why a Handbook on Small Satellites

There are many excellent books and articles now available on all aspects of small satellites. This is a field that has exploded in activity and global interest in the past decade. There are a wide range of individual sources about the technology, others on the applications and services, and yet others about the economics, launch arrangements, policy and regulation, and social and political consequences. Yet there has not previously been a comprehensive and interdisciplinary source of information that collects all of this information together in a holistic way – until now. This *Handbook of Small Satellites* seeks to provide a complete overview of all aspects of the small satellite field.

Thus leading experts from around the world have been recruited to provide in one reference source the latest and state-of-the-art information about small satellites – from the smallest Femtosat to the largest and most sophisticated small satellites that are being deployed in so-called "mega-LEO" satellite constellations. Thus this handbook provides information about the historical development of "smallsats" as well as an explanation of the various types of "smallsats" that are being developed and launched today. It also provides latest information on the space and ground systems technology, the applications and services, and the economic, policy, regulatory, legal, business, and social aspects of this burgeoning field of space activity.

This book seeks to provides information from the perspective of all those interested in space satellites. It thus seeks to provide useful information for the student experimenter and for those undertaking smallsat projects for civilian space agencies and military and defense agencies. It also provides useful information suitable for so-called "NewSpace" business enterprises engaged in small satellite-related businesses as well as the political and legal officials that provide the regulatory oversight for small satellite systems. This includes information about the efficient allocation and oversight of the frequency spectrum needed for these systems to operate effectively.

This *Handbook on Small Satellites* addresses key issues such as orbital space debris, end of life removal of small satellites from orbit, new ways to design and build satellites, frequency spectrum coordination, as well as innovative ways to address the problems of jamming and interference. It even addresses new approaches to the efficient use of space resources and satellites such as placing hosted payloads on larger satellites. It addresses the new opportunities for achieving cost-efficient “space-like” services from high altitude platform systems (HAPS).

It is the hope of all the contributors to this reference work and the scores of participants from around the world that this handbook will be helpful. In particular it is hoped that the many chapters that follow, plus the many references to books and articles found in endnotes, can serve as a useful guide to the design, manufacture, deployment, use, oversight, and business developments needed for the future success of “small satellites” enterprises around the world. The burgeoning number of smallsat systems and launches represent a powerful element in the growth of “NewSpace” or “Space 2.0” ventures. These new space businesses have sprung up around the world. They are now giving new impetus to a rapidly expanding space industry. In time these space enterprises will expand to become a “trillion dollar” industry. These new space industries will help sustain a growing world economy. In short, “smallsats” will touch everyone. They will aid enterprises that range from ecology to banking, from fishing to mining, from airline travel to health care and education.

This is not to say that “smallsats” will replace large satellites. Large and powerful high throughput satellite, for instance, are currently best positioned to provide broadcast television services to small low-cost satellite dishes. Other satellites services, such as for Precise Navigation and Timing (PNT) services and those providing precise radar imaging with active sensing systems, will also require sophisticated satellites with relatively high power levels as well. The technical, operational, and economic reasons for making the “right” decisions on satellite size and architecture will be explained in later parts of this Handbook. Instead of small satellites being a “replacement” to large and powerful satellites, we will see a sort of co-existence of all types of satellites from tiny and small to medium and large-scale. Even so, innovations in one area may very well be shared and transferred. The case of Canada’s new three satellite Radarsat constellation is perhaps an excellent case in point.

Scope and Structure of this Handbook

This *Handbook of Small Satellites* seeks to provide a comprehensive overview of the small satellite field. It thus addresses the history of small satellites and provides insight into the technology and its evolution over time both in terms of the spacecraft, the tracking, telemetry and command aspects of its operation, as well as the corresponding changes to the ground segment for users of this technology that represents a critical part of the evolutionary path of the feasibility and economics of small satellites. Key new features such as hosted payloads, high altitude platform systems, active debris removal, on-orbit servicing, ground systems with electronic tracking capabilities, and more will be addressed as well.

After the technological and operational aspects are presented, the next part will address key aspects of small satellite design, engineering, and manufacture. This will also address business-related concerns such as contracting, resiliency and sparing philosophy, and protection of intellectual property rights.

The next part addresses the great complexity of applications and services and the many different types of small satellites that can be deployed to meet the needs associated with the increasingly diverse range of services as well as the many types of organizations and units that are now pursuing the active deployment and use of small satellites. This even includes the use of small satellites by defense agencies and military ministries.

The final major element of the handbook addresses the economic, legal, and regulatory issues and constraints that are concerned with the increasingly complex field of small satellites.

This is followed by a conclusion part that assesses all of the current trends; major technical, economic, social, and regulatory issues that are pending; and how this relates to the small satellite revolution and Space 2.0 industries. This synoptic final analysis provides a coherent overview of the field of small satellites around the world. It also provides the key trends in the area of small satellites and its ups and downs to broader world goals and objectives such as the United Nations 17 Sustainable Development Goals (see Fig. 1) and the work of the Davos World Economic Forum.

There are also series of "reference articles" in Part 14 that provide information on small satellite projects, companies, and launchers as well as information related to regulatory actions and policies and finally a glossary of terms. In light of the transitory nature of developments in this fast moving field, an effort is made to provide website addresses with current URLs so that the status of projects can be

Fig. 1 New capabilities offered by Smallsats Can Benefit Developing Nations and the UN Sustainable Development Goals. (Graphic Courtesy of the United Nations)

obtained from the official site for small satellite projects. Collectively this handbook should provide comprehensive information about every aspect of the fast moving world of small satellites.

Joseph N. Pelton
Editor

Acknowledgments

This *Handbook on Small Satellites* has taken some time to evolve from concept to reality. Maury Solomon of Springer Nature, with whom I have collaborated for many years on perhaps a dozen books, first proposed the idea of this handbook. I responded that it was too early to do such a large reference book and there was not enough technical content to justify a multi-volume project at the time.

But the growing technological advances, the expanding educational and experimental uses, and the burgeoning commercial use of various types of small satellites all suggested that the rationale for such a book continued to mature. Maury Solomon wisely suggested that this was an area that is growing in scope. She envisioned a handbook that spanned satellite and launcher technology, systems design, expanding applications, experimentation, economics, regulation, markets, and especially commercial innovation. Ms. Solomon presented a strong case that this was a project that called for an interdisciplinary approach.

Over time, the reasons for a handbook on small satellites thus grew. In 2017 my colleague Prof. Scott Madry and I began teaching a course on small satellites at the University of Cape Town. Then, in the following year, I provided editorial oversight in the writing of a new book on small satellites that grew out of the course. In this way, I finally was convinced that such a handbook on small satellites was truly an unmet need.

I thus want to give special credit to Maury Solomon, now retired from Springer Nature, as the first advocate of this project. I also want to warmly thank her successor, Hannah Kaufmann, who has seamlessly and very helpfully supported making this new handbook a reality.

And then there is also the production team at Springer. These professionals have tirelessly toiled for months on end to make this very complex and exhaustive handbook a reality. Saskia Ellis, in particular, has spent many intensive months editing and formatting the scores of articles that kept pouring in from around the world. This included sorting out copyright issues and clarifying ambiguous text. Her help has truly been invaluable. Likewise, Barbara Wolf provided wonderful support when we needed permissions from publishers to use previously published materials. Enormous credit must go to the entire Springer team that has helped every step of the way.

In all, there are over 70 authors from around the world that have provided enormous support to this effort. Their dedication to the growth, development, and success of the many dimensions of the small satellite world is amazing. These authors quickly recognized that this handbook could help contribute to the success of the small satellite phenomena – commercially, experimentally, and educationally. Thus I want to thank all of the contributors who have shared their knowledge and contributed their time and efforts to make this handbook a success. In particular, Dr. Peter Martinez, in his roles in creating the small satellite course at the University of Cape Town and as Director of the Secure World Foundation, provided support and encouragement in a number of ways.

Finally, I wish to thank my close friend and secret weapon in getting this huge handbook to press, Dr. Scott Madry. His efforts in drafting articles, co-authoring articles with me, and helping with editing did yeoman work essential to completing this very comprehensive work. I would also like to thank the sponsors of the handbook, the International Space University and the International Association for the Advancement of Space Safety (IAASS). And in particular, Juan de Dalmau, President of the International Space University (ISU), and Tommaso Sgobba, Executive Director of the International Association for the Advancement of Space Safety (IAASS), for their support.

In all, more than a hundred people helped make this handbook a success and I wish to thank them all for their generous and high-quality work in preparing their various chapters. I wish to express to them all my heart-felt and profound appreciation.

Joseph N. Pelton
Editor

The Handbook Sponsors

The *Handbook of Small Satellites* was undertaken with the sponsorship of two organizations. Although these two organizations have somewhat different missions, they are both generally dedicated to the study and understanding of outer space and to research and educational programs that contribute to this end. They are both dedicated to the peaceful uses of outer space and a better understanding of the cosmos, in terms of its physics, its commercial potential and applications, and improved safety in space.

The International Space University (ISU) seeks to develop the future leaders of the world space community by providing interdisciplinary educational programs to students and space professionals in an international, intercultural environment. The ISU also serves as a neutral international forum for the exchange of knowledge and ideas on challenging issues related to space and space applications. ISU programs impart critical skills essential to future space initiatives in the public and private sectors while they also promote international understanding and cooperation; foster an interactive global network of students, teachers, and alumni; encourage the innovative development of space for peaceful purposes; and seek to improve life on Earth and advance humanity into space. It offers a Master of Space Studies in its home campus in Strasbourg, France, a Space Studies Program that is hosted at sites around the world, a Southern Hemisphere Space Studies Program, an annual Symposium, books and articles published by its worldwide faculty, and a wide range of other programs.

The International Association for the Advancement of Space Safety (IAASS) was formed with the mission to create an international space safety culture. Its specific goals are: to advance the science and application of space safety; to improve the communication, dissemination of knowledge, and cooperation between interested groups and individuals; to improve understanding and awareness of the space safety discipline; to promote and improve the development of space safety professionals and standards; and to advocate the establishment of safety laws, rules, and self-regulatory bodies at national, international, and industrial level for the civil/commercial use of space. It accomplishes these goals through academic and training programs, the publishing of books, the *Space Safety Magazine* and the *Journal of Space Safety Engineering*, as well as conferences, workshops, and other space safety related programs.

A number of members of these two international institutions supported the research, writing, and production of this handbook.

Contents

Volume 1

Volume 2

About the Editors

Dr. Joseph N. Pelton is an award-winning author and editor of some 50 books and over 300 articles in the field of telecommunications and networking, space systems, future technologies, and urban planning. His book *Global Talk* won a Pulitzer Prize nomination and won the Eugene Emme Literature Award of the International Association of Astronautics. In July 2013, he received the British Interplanetary Society International Award known as "The Arthur" in honor of Arthur C. Clarke. Dr. Pelton also received the Arthur C. Clarke Foundation's Lifetime Achievement award in 2001 and the IAASS "da Vinci Award" for lifetime achievement. Most recently he won the Guardian Award of the Lifeboat Foundation, which was previously won by Bill Gates, Elon Musk, and Warren Buffet.

Dr. Pelton is the Founding President of the Society of Satellite Professionals International, the Founder and former Executive Director of the Arthur C. Clarke Foundation, and played a key role in the founding of the International Space University. He announced the formation of the Clarke Foundation at the White House in 1983 while he was acting as the Managing Director of the National Committee for World Communications Year – A US Presidential Appointment. He played a role in the formation of the Arthur C. Clarke Center on the Human Imagination at the University of California-San Diego in 2012 as well as a new STEM education exhibit at the National Electronics Museum that opened in September 2018. He also currently serves as Director of Research for Planetary Defense LLC. His degrees are from the University of Tulsa (B.S.), New York University (M.A.), and Georgetown University (Ph.D.) His most recent books include: *Preparing for the Next Cyber Revolution*, *Space 2.0: Revolutionary Advances* *in the Space Industry*, *The New Gold Rush: The Riches of Space Beckon*, *Smart Cities for Today and Tomorrow*, *Digital Defense*, and *The Farthest Shore: An 21st Century Guide to Space* (*2nd Edition*). He is currently assisting the Hudson Foundation with a re-examination of global space policy. His web page is: www.josephpelton.com. He resides in Arlington, Virginia.

Dr. Scott Madry is a Research Associate Professor of Archaeology at the University of North Carolina at Chapel Hill. He also serves as the President of Informatics International, Inc. Dr. Madry lectures all over the world on the applications of space technology for remote sensing and Earth observation, including its many use for disaster response and recovery and natural and cultural resource management. He is a proponent of open source software and has presented over 150 short courses around the world on the use of free and open source geomatics tools.

Dr. Madry is a well-published author in the field of space applications and geomatics, having published 6 books and over 75 papers and articles. His books include: *Space Systems for Disaster Warning Response and Recovery*; *Global Navigation Satellite Systems and Their Applications*; the *Handbook for Satellite Applications* (*1st and 2nd editions*); *Innovative Design, Manufacturing, and Testing of Small Satellites*; and *Disruptive Space Technologies and Innovations: The Next Chapter*. He has conducted archaeological field research in Burgundy France for over 30 years, has been a three-time Fulbright Scholar, and was twice awarded the President's Volunteer Service Award for his work with the American Red Cross and the URISA GISCorps.

Contributing Authors

Guglielmo S. Aglietti Professor Aglietti is Director of the Space Institute at the University of Auckland in New Zealand where he is also a Professor of Space Engineering. He was previously associated with Surrey Space Technology Ltd and played a key role in the development of small satellite project known as Clean Space that has demonstrated the feasibility of a number of techniques associated with active removal of space debris from Earth's orbit.

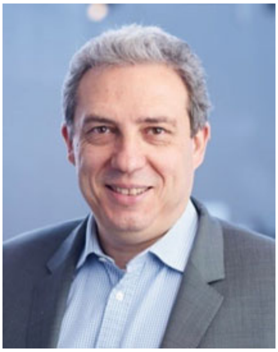
Audrey L. Allison is Vice President of Global Spectrum Management at The Boeing Company in Arlington, Virginia, USA, where she is responsible for radiofrequency spectrum acquisition, compliance, and policy support for Boeing technology, products, services, operations, and customers. Allison is Boeing's lead representative at the International Telecommunication Union (ITU) in Geneva, Switzerland. She is Vice-Chair of the Satellite Industry Association and a Board Member of the United States ITU Association.

Allison also serves as Adjunct Faculty to the International Space University in Strasbourg, France, and Visiting Lecturer to McGill University Institute of Air and Space Law in Montreal. She is the author of The ITU and Managing Satellite Orbital and Spectrum Resources in the 21st Century, Springer, 2014.

Previously, Allison was an Attorney-Advisor to the Satellite Division of the Federal Communications Commission's International Bureau, Counsel in the Office of General Counsel at Iridium LLC, and a Consultant to the

Department of Defense in international spectrum regulatory issues.

Allison earned an M.B.A., *cum laude,* from the International Space University; a Master of International Law from Georgetown University in Washington, DC; a *Juris Doctor* from Catholic University of America's Institute for Communications Law Studies in Washington, DC; and a Bachelor of Arts from the Pennsylvania State University in University Park, Pennsylvania.



Dr. Tony Azzarelli, Eng, M.B.A., M.Sc., CEng, FIET, FRSA, is responsible for several ventures as CEO and Founder of Azzurra Telecom Ltd and Company Director and Co-founder of ACCESS SPACE Alliance Ltd. He is also the CTO at AB5 Consulting and Vice President of Spectrum Licensing Affairs at OneWeb.

Tony has more than 25 years' experience in the telecommunication sector, with senior leadership appointments at Access Space Alliance, Azzurra Telecom, AB5 Consulting, OneWeb, Ofcom UK, Inmarsat, The Boeing Company, the European Space Agency, and ICO Global Communications. He holds a Doctor's degree in Electronics, a Master's degree in Business Administration, and a Postgraduate Certificate from the ISU Summer Session 1993. Tony is a Chartered Engineer, a Fellow of the Institute of Engineering and Technology, and a Fellow of the Royal Society of Arts.

Morgan Bailey is the Head of Communications at Rocket Lab. In this role she leads the company's marketing, communications, community engagement, and government relations strategies across the USA and New Zealand markets. Having worked with Rocket Lab since the unveiling of the Electron orbital launch vehicle program in 2014, Morgan has deep knowledge of the launch industry and the ever-evolving needs of small satellite operators.

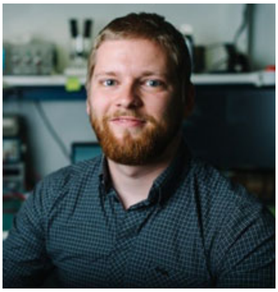
Prior to joining Rocket Lab, Morgan carried out corporate communications work in Australia and New Zealand for Hawaiian Airlines, AIG, Bank of New Zealand, Progressive Enterprises, and more.

Dr. Christoph Beischl holds a Ph.D. in Space Policy and Law from the University of London and is currently a Research Fellow at the London Institute of Space Policy and Law. His main research areas include (i) space policies and regulations in the Asian region, (ii) intergovernmental space cooperation, as well as (iii) political and legal considerations that need to be addressed to ensure the stable use of outer space, for example, concerning the deployment of small satellite mega-constellations, on-orbit servicing, and active debris removal. Christoph graduated with a Magister Artium in Political Science (Major), Law and Modern and Contemporary History (Minors) from the University of Munich focusing, among others, on politics in the East Asian region and political ideology. He is an active member of the Space Generation Advisory Council for many years.

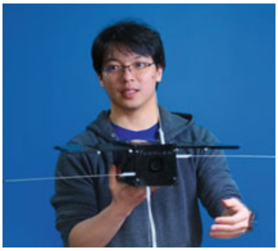
Pierre Bousquet has served as a Senior Expert on Planetology, Exploration and Microgravity in the Scientific project Directorate at CNES in Toulouse, France, since 2017. He is the Project Manager of the French contribution to Bepi Colombo (European mission to Mercury). He is also in charge of several design studies based on small probes for deep space exploration.

Pierre is a Technical Advisor to the French delegation for PB-HME (ESA's Program Board on Human Missions and Exploration). He is a senior member of French Association of Aeronautics and Astronautics (AAAF). Pierre is a corresponding member of the International Academy of Astronautics (IAA). He is also a member of the Space Exploration committee of the International Astronautic Federation (IAF) and member of the UN-mandated "Space Missions Planning Advisory Group" (SMPAG) on the threat represented by near-Earth objects. Pierre has more than 50 publications in international conferences and journals. He has served as an Occasional Lecturer at French engineering schools ISAE, EUROSAE, and EMAC.

Dr. Vitali Braun ESA/ESOC, Space Debris Engineer. Vitali Braun joined ESA's Space Debris Office as an Engineer in 2015. He is supporting operational collision avoidance activities for ESA and third party missions, re-entry predictions, and risk assessments. He is responsible for the maintenance of ESA's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model and the Debris Risk Assessment and Mitigation Analysis (DRAMA) tool suite. From 2010 to 2015, he was working as Research Associate at the Technische Universität Braunschweig , performing debris risk analyses, software development, but also supporting university courses on orbital mechanics and supervising students. Since 2016, he holds a Doctor of Engineering (Dr.-Ing.) from the Technische Universität Braunschweig, Germany.



Jeroen Cappaert is the Co-Founder and Chief Technology Officer at Spire. His main mission is to ensure the future technology developments needed to deliver what the businesses require. Jeroen has a background in electronics engineering and aerospace engineering. He carried out his previous work and research, which includes high-enthalpy flow simulation, computational mechanics and fluid dynamics, spacecraft avionics and payload design, and low-thrust astrodynamics, at NASA Ames, the Von Karman Institute for Fluid Dynamics, and the International Space University. Jeroen Cappaert's education includes an M.Sc. in Space Studies from the International Space University, a Master's thesis on Uncertainty quantification for hypersonic flow simulation from Von Karman Institute for Fluid Dynamics, an M.Sc. in Mechanical Engineering (cum Laude), and B.Sc. in Mechanical Engineering (with a minor in Electrical Engineering) from KU Leuven.



Wen Cheng Chong serves as Chief Technology Officer for Kepler Communications. With a knack for tackling complex challenges, Wen has led the team to launch the first Ku-band commercial LEO spacecraft ever, carrying that project from napkin to orbit in 12 months. Wen personally manages all aspects of Kepler's technical undertakings, including its ground systems, user terminals, space operations, and software.

Adriana Elysa Alimandro Corrêa holds a Master in Electronics and Automation Engineering (2013) and a B.S. degree in Physics (2011) from the University of Brasília. She joined the Brazilian Space Agency in 2013. Her past experience includes an aerospace training (2012) at Yuzhnoe State Design Office, Ukraine; a professor (2015–2016) position at the Federal District University Center; and a nanosatellite assembly training at ISRO, India (2019).

Bill Cowley graduated from the University of Adelaide with Science and Engineering degrees. After working for Telstra and the Australian Defence MInistry for several years, he moved to the University of South Australia in 1985 and joined the Institute for Telecommunications Research. He was director of ITR for a 4-year period. In September 2015, Bill retired from his UniSA position of Professor of Communication Signal Processing and is currently an Adjunct Professor at UniSA. He's also an Adjunct Faculty Member of the International Space University. His interests include communications signal processing for RF and optical communications.

Dr. Eric Dahlstrom background is in physics, astronomy, and space engineering. He has worked as a contractor on NASA projects for many years. This has included a significant amount of work on the design of the International Space Station (ISS). For the last 8 years he has been a consultant to support space startup companies in Silicon Valley. For many years he has taught at and been involved with International Space University (ISU) and is currently on its faculty. Over the years he has taught in 10 countries for the International Space University. Further, he has also been strongly involved with the Singularity University, located on the NASA Ames Campus in Mountain View, California. The latest in new space technologies and applications has meant that the barriers to developing new commercial space activities have been lowered. This has allowed for space systems in places like New Zealand. He is currently in New Zealand seeking to develop new space systems and ventures under a Edmund Hillary Grant.

Dr. Kenneth Davidian has worked for the FAA's Office of Commercial Space Transportation (AST) in Washington, DC since 2008 and is currently the AST Director of Research and Program Manager for the FAA Center of Excellence for Commercial Space Transportation. Dr. Davidian serves as a member of the Ohio State University Aerospace Engineering External Advisory Board, Editor-in-Chief of the New Space journal, Chair of the IAF Entrepreneurial & Investment Committee, and Vice Chair of the IAF Space Economy Committee. Dr. Davidian is a corresponding member of the International Academy of Astronautics and an Adviser to the Space Generation Advisory Committee's Commercial Space Project Group. Prior to FAA AST, Dr. Davidian worked for the NASA Lewis Research Center, International Space University, Paragon Space Development Corporation, X PRIZE Foundation, and NASA Headquarters. Dr. Davidian received his B.S. degree in Aeronautical and Astronautical Engineering from the Ohio State University in 1983 and an M.S. degree in Mechanical Engineering from Case Western Reserve University in 1987. He attended the International Space University Summer Session Program in 1989. Dr. Davidian received his Ph.D. in Business Administration from the University of Cape Town, Graduate School of Business, in 2018. His thesis focuses on innovation management and understanding the processes of emerging and evolving markets.

Dr. Kiruthika Devaraj is Director of EE/RF at Planet Labs Inc. where she leads the electrical engineering and RF/communication groups to design and manufacture the avionics, power, and communications systems for Planet's satellites. Planet builds and operates the world's largest constellation of remote sensing satellites to image the Earth on a daily basis and make change visible, accessible, and actionable. A recent notable project includes the architecture and development of Planet's high speed downlink radio and antenna that achieved 1.7 Gbps data throughput from a 3U form-factor CubeSat. Prior to Planet, Kiruthika was a Postdoctoral Research Fellow at the Kavli Institute of Particle Astrophysics and Cosmology (KIPAC) at Stanford University where she built microwave and millimeter-wave instruments to study star formation processes. One of the instruments she built, Argus, a 16-pixel W-band focal plane array, is commissioned at the Green Bank Telescope. She has an M.S. and Ph.D. in Electrical Engineering from the Georgia Institute of Technology. At Georgia Tech, she worked on the NASA mission Juno, building a laboratory analog of Jupiter's atmosphere and studying the microwave properties of gases in the Jovian atmosphere.

David Draper NASA Deputy Chief Scientist Dr. David Draper is an Earth and planetary scientist with 28 years of professional experience in studying the Earth, Moon, planets, and Solar System. These scientific studies explored frontier questions regarding characteristics, processes, and events of and on Earth, the Moon, and Mars. His scientific specialty is in experimental simulations at high temperatures and pressures, using basaltic magmas as probes of the processes occurring within planetary interiors. His prior experience includes leading the Astromaterials Research Office at NASA Johnson Space Center in Houston, Texas, and he has also led teams proposing competed robotic missions of planetary exploration.

Joseph D. Fargnoli is the cofounder of the New York Space Alliance and Managing Director of an associated New York based investing group. He is passionate about working with a range of early stage New Space companies bringing New York's financial, legal, marketing, technical, and manufacturing capacity to help realize the potential in moon shot opportunities.

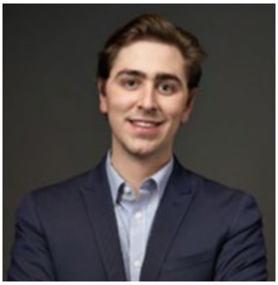
Joseph's areas of technical expertise are in the design and development of telecommunication and remote sensing systems particularly with regards to the exploitation of SAR, hyperspectral and multispectral phenomenology, and in the integration with imagery and other forms of information from multiple modalities and sources. In particular, Joseph has expertise in the development of informatics solutions incorporating remote sensing image science with modern analytic architectures and cloud based IT infrastructure. His career background includes Northrop Grumman Electronic Sensors and Systems group working on Civil and National

Electro-Optical as well as SAR system and Kodak/ITT/Exelis/Harris with focus on National and Commercial systems. He also served as a Technical Fellow within the NRO. After forming the RITRE Corporation, efforts were merged into driving the strategy and business case for the formation of the THIEA Systems Group.

Dr. David Finkleman is Chief Engineer at Sky Sentry LLC. He is also affiliated with the International Standards Organization (ISO). He is a leading authority on civil, commercial, and military space with special expertise in small satellite systems and technology and space traffic management and space situational awareness. He has degrees from Virginia Tech and MIT where he earned Master of Science and his Ph.D. Dr. Finkleman is a retired Colonel from the US Air Force where he served as a member of the Senior Executive Service. He has served as Director of Studies and Analysis and Senior Scientist at North American Aerospace Defense Command and U.S. Space Command, Peterson Air Force Base, Colorado. He also served as Associate Professor of Aeronautics at the U.S. Air Force Academy and was Project Officer for elements of the Airborne Laser Laboratory at Kirtland Air Force Base, NM. Dr. Finkleman also served with the Navy Directed Energy Weapons Program as a civilian. He also played a key role in the creation and initial operation of the Space Data Association. He has numerous publications in the field of space and systems.

Steven Freeland is Professor of International Law at Western Sydney University, Australia, where he teaches both postgraduate and undergraduate students and supervises Ph.D. students in the fields of International Criminal Law, Commercial Aspects of Space Law, Public International Law, and Human Rights Law. He is a Visiting Professor at the University of Vienna; a Permanent Visiting Professor of the iCourts Centre of Excellence for International Courts, Denmark; a Member of Faculty of the London Institute of Space Policy and Law; and was a Marie Curie Fellow in 2013–2014. He has been an Expert Assessor of Research Proposals in Australia, Canada, the Netherlands, South Africa, and Hong Kong and has taught courses at universities in over 20 countries. Among other appointments, he is a Director of the Paris-based International Institute of Space Law and a member of the Space Law Committee of the London-based International Law Association. He sits on the Editorial Board of a number of international journals, including the *Australian International Law Journal*, the Canada-based *Annals of Air and Space Law*, the Germany-based *German Journal of Air and Space Law*, the China-based *Space Law Review*, and the London-based *ROOM Space Journal*. He has authored approximately 300 publications on various aspects of International Law and has presented over 800 commentaries.

Helen Grant recently retired as the Associate Chief Scientist for Programs and Projects in the NASA Office of the Chief Scientist. She has extensive experience as a Project Manager and Systems Engineer for human space flight projects as well as developing systems and technology for scientific research. Before coming to the Office of the Chief Scientist, Ms. Grant managed the NASA organization responsible for performing independent assessments of major NASA programs and projects and improving NASA cost and schedule analysis policy and practice.



Michael Grasso is a leader in the Strategy and Corporate Development team at Blue Origin. Michael supports Blue Origin on corporate strategy, corporate development, sales, and marketing activities. Previously Michael served as an Economic Advisor for Space at the Luxembourg Ministry of the Economy. In this capacity, Michael supported the Luxembourg Government's commercial space strategy and space investment policy. He led the development of the public-private partnership to establish Luxembourg's space focused venture investment fund. Michael also worked at the Avascent Group where he supported commercial and government space clients.

Dr. James L. Green currently serves as Chief Scientist for NASA, an appointment he has held since May 2018. He received his Ph.D. in Space Physics from the University of Iowa in 1979 and has worked at NASA's Marshall Space Flight Center and Goddard Space Flight Center before becoming the Director of the Planetary Science Division at NASA Headquarter in 2006. He has written over 110 scientific articles in refereed journals involving various aspects of the Earth's and Jupiter's magnetospheres and over 50 technical articles on various aspects of data systems and computer networks. In 1988 he received the Arthur S. Flemming award given for outstanding individual performance in the federal government and was awarded Japan's Kotani Prize in 1996 in recognition of his international science data management activities.

Rob Harvey is the Director of Onboard Software at Planet, Inc. He and his team are responsible for developing and maintaining the avionics flight software for over 100 active satellites, including Planet's fleet of Doves, Superdoves and Skysat satellites, as well as developing new systems for future satellite platforms. The flight software team also supports ongoing satellite manufacturing efforts, post-launch satellite commissioning, on-orbit anomaly analysis, as well as ground tooling efforts. Prior to Planet, Robert worked in various embedded software roles in consumer electronics, including building out GPS/GSM telematics products and handheld GPS devices. For many years prior to that, Robert was involved in GPS receiver design, notably being involved in some of the first integrations of GPS into mobile phones for E911 services. Robert has an M.Sc. in Geomatics Engineering from the University of Calgary where he worked on GPS-based precision pointing devices. He has a B.Sc. in Engineering Physics from Queen's University in Kingston, Ontario, Canada.

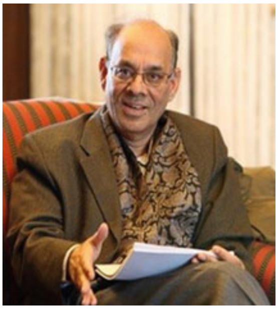
Yvon Henri has over 35 years' experience in the satellite communications field and has worked on space policy and regulatory affairs in both the public and private sectors as well as in intergovernmental organizations at France Telecom (Paris, France), INTELSAT (Washington, DC, USA), and the Radiocommunication

Bureau of the International Telecommunication Union (ITU) in Geneva (Switzerland) where he was Chief of the Space Services Department (SSD) up to June 2017. Throughout his professional career, Mr. Henri has always strived to initiate, develop, and promote policies to enhance the opportunities afforded by the telecommunication/ICT sector, in particular for the global harmonization of space and terrestrial applications, with particular focus on the adaptation of space services to the constantly evolving world.

Mr. Henri has been elected member of the Radio Regulations Board (RRB) at the last ITU Plenipotentiary Conference in Dubai (29 October–16 November 2018)) and is also Chief Regulatory Advisor at OneWeb.

Dr. Henry R. Hertzfeld is the Director of the Space Policy Institute and a Research Professor at the Elliott School of International Affairs, George Washington University. He is also an Adjunct Professor of Law at GW and teaches the Space Law course. He is an expert in the legal, economic, and policy issues of space and advanced technological development. Dr. Hertzfeld has served as a Senior Economist and Policy Analyst at both NASA and the National Science Foundation and is a consultant to both US and international agencies and organizations. He is author of many articles on the legal and economic issues concerning space and technology. Dr. Hertzfeld is a member of the Bar in Pennsylvania and the District of Columbia.

Theresa Hitchens has recently joined *Space Defense* as a Senior Analyst and Lead Reporter. She has spent the past two decades working as a strategic space and defense-related researcher, writer, and opinion-leader on space and cyber security, multilateral governance, NATO, arms control, and international security issues. She is leaving her post as Senior Research Associate at the University of Maryland's Center for International and Security Studies. Before this, she was appointed by the Secretary General of the United Nations to serve in Geneva, Switzerland, as director of the U.N. Institute for Disarmament Research (UNIDIR). She held that post for 6 years. Prior to that she was a reporter on space and defense news for Defense News and the Inside Washington newsletters.



Dr. Ram Jakhu is a faculty member and the former Director of the Institute of Air and Space Law and is on the Faculty of Law, McGill University, in Montreal, Canada. He teaches and conducts research in international space law, law of space applications, law of space commercialization, space security, national regulation of space activities, and public international law. In addition to his extensive academic experience of over 30 years in the field of international and national Space Law and Policy, he has consulted to several private and governmental entities and helped draft national laws and regulations in various countries. Currently, he is the Project Director of an international research project for drafting McGill Manual on International Law Applicable to Military Uses of Outer Space (MILAMOS). He is Managing Editor of the Space Regulations Library Series and Member of the Editorial Boards of the *Annals of Air and Space Law* and the *German Journal of Air and Space Law*.

Prof. Jakhu initiated and managed a comprehensive international and interdisciplinary study related to global space governance, the final report of which has been published as *Global Space Governance: An International Study* (Springer, 2017). He served as Director of the McGill Institute of Air and Space Law; Faculty Member and Director of the Master of Space Studies Program of the International Space University, Strasbourg, France; and Member of the World Economic Forum's Global Agenda Council on Space Security. He has taught Space Law and Policy in several countries. He has made presentations to the United Nations Committee of Peaceful Uses of Outer Space in Vienna and at the United Nations Headquarters in New York.

In 2016, Prof. Jakhu received the "Leonardo da Vinci Life-Long Achievement Award" from the International Association for the Advancement of Space Safety and in 2007 the "Distinguished Service Award" from International Institute of Space Law for significant contribution to the development of space law. He holds Doctor of Civil Law (Dean's Honors List) and Master of Law (LL.M.) degrees from McGill University, Canada, as well as LL.

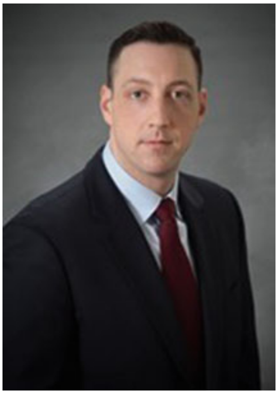
M., LL.B., and B.A. degrees from Panjab University, India.

Martin Jarrold is Vice President International Programme Development, Global VSAT Forum. He has worked for the Global VSAT Forum (GVF) since June 2001. His particular responsibilities include outreach to the member organizations of GVF and the further development of the profile of the association within the satellite communications industry and across the global telecommunications policy and regulatory community. This extends to the development and delivery of programs focused on extending the understanding of, and promoting the use of, satellite-based communications in various key end-user vertical markets.

Mr. Jarrold is a frequent contributor to various telecommunications and other industry publications. In addition, he regularly chairs and contributes to a wide variety of telecommunications conferences, symposia, and workshops around the world, including working with the International Telecommunication Union.

Mr. Jarrold has participated in various European Space Agency programs, leading the GVF contributions to projects on “Two-Way Satellite Communications” and on “Standards Preparation for SOTM Terminals.” A new collaboration with ESA on antenna testing using quadcopter drones is currently underway.

Previously, Mr. Jarrold was Commissioning Editor and Head of Research for *Space Business International* magazine. His earlier career was predominantly in teaching and writing. He holds an honors degree in History and Politics and is based at the headquarters of GVF in London.



Chris Johnson is the Space Law Advisor for Secure World Foundation and has 9 years of professional experience in international space law and policy. He has authored and co-authored publications on international space law, national space legislation, international cooperation in space, human-robotic cooperative space exploration, and on the societal benefits of space technology for Africa.

Prior to joining SWF, Mr. Johnson worked as an attorney in New York City and entered the space field in 2010 as an intern at the United Nations Office for Outer Space Affairs (OOSA) in Vienna, Austria, during the 53rd Committee on the Peaceful Uses of Outer Space. He has also served as an intern in the Office of International and Interagency Relations (OIIR) at NASA Headquarters in Washington, DC and as a legal stagiaire in the International Law and EU Legal Affairs division at the European Space Agency's Legal Department at ESA Headquarters in Paris, France. As a member of the Space Generation Advisory Council (SGAC), Mr. Johnson co-founded the Space Law and Policy Project Group in 2012.

Mr. Johnson serves as a Professor of Law (Adjunct) at the Georgetown University Law Center in Washington, DC, where he co-teaches the spring Space Law Seminar. He is also Adjunct Faculty at the International Space University (ISU) in Strasbourg, France, the Legal Advisor for the Moon Village Association (MVA), and a Core Expert and Rule Drafter in the Manual on International Law Applicable to Military Activities in Outer Space (MILAMOS) project.

Dr. Sanat Kaul serves as the Chairman and Managing Director of Delhi Tourism & Transportation Development Corporation Limited. Dr. Kaul has been the Representative of India on the Council of International Civil Aviation Organization in Montreal, Canada. He has held several important positions throughout his career including Joint Secretary of Ministry of Civil Aviation, Commissioner of Sales Tax Department, Government of NCT of Delhi, and Secretary – Delhi Finance Commission. Dr. Kaul has been an Independent Non-Executive Director of Noida Toll Bridge Company Limited since April 2008. He served as Director of Delhi Tourism

& Transportation Development Corporation Limited. He is now retired from the Indian Administrative Services. Dr. Kaul holds a Ph.D. in Economics from the University of London and a Master's Degree from London School of Economics. He has specialized in Aerospace Law from the Institute of Air & Space Law, McGill University, Montreal, Canada.

Vatsala Khetawat obtained her undergraduate degree (MEng) in aerospace engineering from the University of Sheffield in the United Kingdom. Concurrent to this program, she trained and successfully obtained her European JAA SEP Private Pilot Licence (PPL). After completing her undergraduate studies she participated in a professional development program called the Southern Hemisphere Summer Space Program (SHSSP) of the International Space University in Adelaide, Australia, in 2013, followed by an internship at the Avionics Department at the Indian Space Research Organization (ISRO). She continued her studies at the International Space University to obtain her Master of Science (M.Sc.) in Space Studies. She then worked at NASA Ames Research Center in California for 1 year under and a special ISU Internship program. Most recently she graduated with her Master of Technology Management from UC Santa Barbara in California. In addition to her academic and work experiences, she has also travelled to 29 countries, which gave her the opportunity to experience cultures and understand people's perspective. For the Handbook of Small Satellites she has worked with Professor Pelton to research small satellite constellations.

Christoffel Kotze established a small technology strategic advisory company in 2012 after a successful corporate career spanning two decades. This company specializes in providing assistance to digital transformation projects within organizations, with a special interest in the use of technology resources to support sustainable development. Current research interests include space technology and new approaches to digital transformation and solutions to the "digital divide." His academic background includes a Bachelor of Commerce Honors (Information Systems) – University of Cape Town, Bachelor of Science (Physiology & Microbiology) – University of Pretoria, Diploma in DataMetrics (Computer Science) – University of South Africa, and a number of strategy focused executive management courses at the Graduate School of Business from the University of Cape Town. He hold an M.Phil. (Space Science) degree from the University of Cape Town. He is ISACA Certified in the Governance of Enterprise IT.

Chris Kunstadter is Global Head of Space at AXA XL, a leading provider of space insurance. He is actively involved in all aspects of AXA XL's space activity, including technical, financial, and actuarial analysis, policy construction, claims handling, industry outreach, and business development.

Chris is a recognized leader in global space risk management issues. For over three decades, he has worked closely with satellite operators and manufacturers, launch providers, government agencies, and others to enhance industry understanding of space risk management and responsible space activity.

Chris is a member of the FAA's Commercial Space Transportation Advisory Committee (COMSTAC) and Chair of COMSTAC's Legal and Regulatory Working Group. He serves on the Executive Committee of the International Union of Aerospace Insurers (IUAI) and is a Charter Member of the Consortium for Execution of Rendezvous and Servicing (CONFERS).

Chris joined XL in 2006, after 23 years at USAIG, where he was Executive Vice President in charge of the Aerospace and IT departments.

Chris received a B.A. degree in Literature and an M.S. degree in Engineering from the University of California. He holds a Commercial Pilot license with Instrument and Multi-Engine ratings and is a Certified Flight Instructor. Chris is an avid musician and serves on the boards of several music-oriented not-for-profit organizations.

Shane Laverty is the Technical Writer at Kepler Communications. Shane chiefly supports the management of Kepler's domestic and international regulatory affairs, working to consolidate and communicate its technical endeavors and sharpen its written image.

Dr. Rene Laufer is Associate Research Professor of Space Sciences at Baylor University, Texas, as well as honorary Associate Professor at the University of Cape Town's Space Lab. He co-chairs the International Academy of Astronautics' small satellite committee and is actively involved in several small satellite related conferences and international working groups and co-authored book chapters, journal papers, study reports, and conference contributions in the same field. Dr. Laufer has formerly worked at German Aerospace Center (DLR) and the University of Stuttgart, Germany, in the area of planetary exploration and small satellites and teaches regularly on various space engineering, space exploration, and space science topics in four continents.

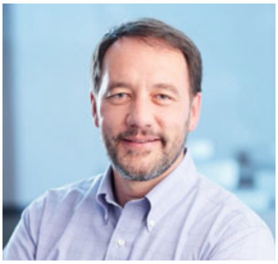
Dr. Rodrigo Leonardi holds a Ph.D. in Astrophysics (2006) from Brazilian Institute for Space Research (INPE) and a B.S. degree (1999) in Mathematics from the University of Brasília. He joined the Brazilian Space Agency in 2017 and nowadays coordinates a portfolio of initiatives to promote space-related science and technology. His past experience includes a Postdoctoral Research Fellow (2007–2009) position at the University of California, a Scientist position at the European Space Agency (2009–2015), and an Advisor position at CGEE, a think tank center for strategic studies, where he conducted prospective studies for the Brazilian space sector. He has coauthored 158 papers in peer-reviewed scientific journals.

Vanessa Lewis is a Communication Systems Modeling Engineer at Kepler Communications. Vanessa models Kepler's satellite network to ensure it complies with regulatory standards, and she assists with spectrum coordination between Kepler and other operators.

Matt Ligon has been involved in the design of space system electronics for the last 12 years. In 2012 he joined Planet Labs (then Cosmogia) as an early stage employee. He has been a key contributor in the development of the Planet Labs satellite systems in the areas of system design and planning, RF hardware design, and antenna design. In 2014, he co-founded Bitbeam to develop radio hardware for the fledgling cubesat industry. Matt returned to Planet in 2015 where he continues to work on radio system development. In 2019, Planet's "SuperDove" 3U satellite system achieved 1.7Gbps downlink throughput, a smallsat record that has yet to be surpassed by a flight proven system. Prior to Planet, Matt worked at Aerojet Rocketdyne developing instrumentation electronics for the J2-X rocket engine. Matt has a B.S. in Electrical Engineering from UCLA and M.S. in Electrical Engineering from USC.

Timothy J. Logue is the Senior Director of Sales and Business Development at Thales Alenia Space, having joined Thales's Washington, DC office in 2009. Mr. Logue has been involved in the satellite and telecom industries for more than 35 years, beginning as a policy analyst with the Communications Satellite Corporation. He has worked for satellite manufacturing companies for the last 13 years after 20 years as a consultant with law firms.

Mr. Logue has also been active in professional organizations, especially the Pacific Telecommunication Council since the 1980s. He attended his first PTC conference in 1981. Most recently he served as Co-chairman and Chairman of the PTC's Advisory Council and then was elected to the Board of Governors in 2013 and again in 2016. He is currently also the Treasurer of The Arthur C. Clarke Foundation, and has held leadership positions with the Space and Satellite Professionals International (formerly the Society of Satellite Professionals International).



Dr. Timothy Maclay is the Director of Mission Systems Engineering for OneWeb. His unit is focused on the network's space system architecture and provides technical and policy support to OneWeb's regulatory activities. Prior to joining OneWeb, Dr. Maclay was the VP of Systems Engineering at Orbcomm, where he spent nearly 20 years in various leadership roles in low-Earth-orbit (LEO) satellite constellation design and operations. He began his career with Kaman Sciences working in the area of space safety research after earning a Ph.D. in Aerospace Engineering Sciences from the University of Colorado in the fields of astrodynamics, debris environment modeling, and hypervelocity impact physics.

Dr. Maclay has served on orbital debris technical committees for the National Research Council, NASA's Engineering Safety Center, the AIAA, and the IAA. He has also served on the board of the Hypervelocity Impact Society. He has chaired a number of conferences and sessions associated with orbital debris and has presented and published extensively on related topics.

Dr. Amit K. Maitra is the U.N. Ambassadors for Refugees-Africa. He is the Founder and Chairman of the Foundation for Emerging Solutions. He has served for many years as a strategist and consultant to NASA, the U.S. Air Force, and the U.S. Department of Defense. He served as an advisor to NASA with regard to international technology transfer arrangements with regard to NASA Space Station Freedom. He has also over the years served as an advisor and consultant to the World Bank, Korean Information Technology, Japanese Aerospace Industry Association, IBM, RCA, and others on infrastructure development projects, including on various satellite communications systems. Dr. Maitra is widely published and has written a number of books on spectrum allocation policies, satellite communications development, the Internet, and information systems.

He has a Ph.D. from the Weatherhead School of Management from the Case Western Reserve University and a M.P.A.-M.A. from the University of Minnesota. He has been a visiting scholar at the Wharton School of Business at the University of Pennyslvania. He received his B.S. in engineering from the University of Calcutta where he graduated Summa cum Laude.

Peter Martinez is the Executive Director of the Secure World Foundation. He has extensive experience in space policy formulation, space regulation, and space diplomacy. He also has extensive experience in capacity building in space science and technology and in workforce development.

Prior to joining the Secure World Foundation, Dr. Martinez held the post of Professor of Space Studies at the University of Cape Town. Before this he acquired 15 years of executive level management experience and associated general management skills gained in the research and development environment of the South African Astronomical Observatory, a National Facility under the South African National Research Foundation, where he served as Acting Director for two extended terms and for shorter periods on numerous other occasions. From 2010 to 2015 he was the Chairman of the South African Council for Space Affairs, the national regulatory authority for space activities in South Africa. From February 2011 to June 2018, he served as the Chairman of the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) Scientific and Technical Subcommittee's Working Group on the Long-Term Sustainability of Outer Space Activities. From 2012 to 2013 he was South Africa's representative on the United Nations Group of Government Experts on transparency and confidence building measures for space activities. He is a member of the International Academy of Astronautics, the International Institute of Space Law, and a Fellow of the Royal Astronomical Society. He has authored or co-authored over 200 publications on topics in astronomy, space research, space law, and space policy.

Attila Matas, satellite Orbit/Spectrum consultant in the field of GSO and non-GSO satellites, is a retired head of the Space Publications and Registration (SPR) Division in the ITU Radiocommunication Bureau – Space Services department. During his 24 years career within the ITU (1993–2017), first as Satellite Engineer responsible for the Space Master International Frequency Register and later as Head of SPR division, he was directly responsible for the processing and publication of GSO and non-GSO space systems and Earth stations, submitted by administrations, for inclusion in the formal coordination procedures or recording in the Space Master International Frequency Register. This involved analysis and processing of applications with respect to the provisions of the Radio Regulations and Rules of Procedure on the use of frequency spectrum related to space services. Mr. Matas represented the ITU at the UN COPUOS meetings. He is an ITU World Radiocommunication Conference (WRC) veteran with participation at all WRC since 1992. On several WRC's he served as a secretary on the agenda items related to frequency allocations and regulation of Radionavigation Satellite and Space Science service or a senior spokesperson on space regulatory matters. He organized the first two ITU-R Small Satellite Symposiums. Mr. Matas holds a degree in radio engineering from the Czech Technical University of Prague, Czech republic.

Dr. Darren Mcknight is currently Technical Director for Centauri (formerly Integrity Applications, Inc. (IAI)) based in Chantilly, Virginia. He leads teams to develop creative solutions across widely disparate domains: global space technology awareness, preventing strategic surprise, modeling infectious disease outbreaks, empirical and analytic assessments of orbital debris, and workforce productivity. Dr. McKnight's latest book, *Make Yourself Indispensable*, leverages his years of serving as productivity catalyst for a variety of government and commercial clients in a wide variety of technical domains. As a member of the International Academy of Astronautics' (IAA) Space Debris Committee, he has been active in position paper development, selection of symposia papers, and execution of the annual International Astronautical Congress. Darren has authored over 100 technical papers and presented them in 18 countries. He has appeared on tens of TV, radio, and newspaper interviews including with Discovery Channel, BBC, CBC, Space News, The Space Show, etc. Dr. McKnight received his B.S. from the United States Air Force Academy, his Master's Degree from the University of New Mexico, and his Doctorate from the University of Colorado.

David Meltzer as the Secretary General of the Global VSAT Forum (GVF). Meltzer has over 25 years of experience in the satellite industry, including serving as a board member for both a regional satellite operator and for a mobile satellite operator. Previously, he served for 16 years in various business and legal roles at Intelsat, culminating in serving as Intelsat's General Counsel and Executive Vice President for Regulatory Affairs. Most recently, Meltzer served as the General Counsel and Chief International Officer of the American Red Cross where he led its legal, international disaster relief, and development activities.

Nishith Mishra is currently engaged by the Center for Research in Air and Space Law, Institute of Air and Space Law (IASL), McGill University, as a Research Assistant and Coordinator and regularly assists the Center with its various projects and academic initiatives. He is a current LL.M. (Thesis) Candidate at the Institute of Air and Space Law, Faculty of Law, McGill University. He joined the Master of Laws (Air and Space Laws) Program of at McGill University in Fall 2018 as a Nicolas M. Matte Fellow and has subsequently been awarded the Graduate Excellence Award in Law (2019) and the Stephen Smith–James McGill Graduate Law Award (2019) for his academic performances.

Prior to joining IASL, he completed his Bachelor of Law B.A. LL.B. (Hons.) Program from National Law University Delhi, New Delhi, India, in 2013 and has worked as a civil and commercial litigator, a private-equity and foreign direct investment transactional lawyer, as well as an associate consultant (Aviation and Space) in New Delhi, India. He wishes to pursue professional and academic engagements in Space Law and Policy matters/initiatives.

Mina Mitry is Co-Founder and Chief Executive Officer of Kepler Communications. Mina combines his aerospace background with an impressive capacity to break down complexity and manage calculated risks. Under his leadership Kepler was named one of the most innovative companies in the world by Fast Company.

Sa'id Mosteshar is Professor of Space Policy and Law, Director of the London Institute of Space Policy and Law (ISPL), and Fellow of the Royal Aeronautical Society (FRAeS). A practicing Barrister and California Attorney, with degrees in physics and econometrics, he advises governments, international agencies, and space corporations on policy and law. Sa'id has served as a member of the UK Space Leadership Council and Adviser to its Delegation to UN COPUOS. He received the 2016 International Institute of Space Law's Distinguished Services Award for "services to the international community and developments in the field of Space Law both as an academic and a practitioner."

Dr. Sreeja Nag is a Senior Research Scientist at BAER Institute, based in NASA Ames Research Center. She is also the Autonomy Ssystems Engineer at Nuro, helping build and validate some of the first self-driving robots on public roads. Her research interests include distributed space systems, space robotics for Earth observation, planning and scheduling of constellations, and space traffic management. Sreeja received her Ph.D. from the Department of Aeronautics and Astronautics at Massachusetts Institute of Technology, Cambridge. As a student, she led the SPHERES Zero Robotics program and has served as an International Fellow at the European Space Agency (ESTEC), NASA's Jet Propulsion Lab, and Goddard Space Flight Center. She has also worked with small satellite startups on systems architecting and constellation design.

Alexandre Najjar is a Consultant at Euroconsult, based in Paris since 2016, and is the Editor-in-Chief of the 5th edition of Euroconsult's Prospects for the Small Satellite Market research report. His expertise focuses on launch vehicle and satellite market studies, the manufacturing industry, access to space, emerging markets, and constellations. He is a regular contributor to Euroconsult's research reports as well as client-specific consulting missions related to launchers and satellites, New Space, and the industrial and economical aspects of the space sector. He has been involved in a wide range of consulting missions covering mega-constellations, spaceports business models, small satellite launch solutions, dedicated launchers, the verticalization of industrial actors, electric propulsion, as well as in-orbit servicing.

Carlos Niederstrasser is a Systems Architect with Northrop Grumman Innovation Systems, working on strategic activities, new business pursuits, and special initiatives. Some of the programs Carlos has supported at NGIS include the Mission Extension Pods, the Antares Accident Investigation Board, and the Dawn interplanetary spacecraft. Carlos is a member of the steering committee for the Khalifa University Space Systems and Technology Program in the UAE. His annual "Small Launch Vehicle Survey" has become the definitive compendium of world-wide small launcher development efforts. Carlos holds degrees from Princeton University and Stanford University.

Jeff Osborne is Co-Founder and VP Business Development at Kepler Communications. His ability to think outside of the box and take risks is a refreshing spin on traditional views of business development. Before starting Kepler, he founded and ran a number of student teams at the University of Toronto developing suborbital rockets and small satellites. Jeff's leadership has allowed Kepler to secure impressive commercial and government contracts whilst still in its early growth stages.

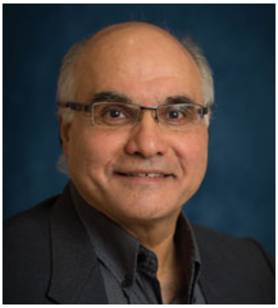
Maxime Puteaux is a Senior Consultant at Euroconsult and has been based in Paris since 2012. He is the Editor-in-Chief of the 22th edition of Euroconsult's *Satellite to be Built and Launched by 2028*. His expertise focuses on launch vehicle and satellite market studies, the manufacturing industry, access to space, as well as emerging markets and constellations. Maxime manages Euroconsult's research reports as well as client-specific consulting missions related to the industrial and economical aspects of the space sector.

Jonathan Rall has a Bachelor of Science degree in Electrical Engineering from Washington University in St. Louis, MO, and a B.S., M.S., and Ph.D. in Physics from American University in Washington, DC. He is currently the Associate Chief Scientist for Programs and Projects within NASA's Office of the Chief Scientist (OCS). Dr. Rall has held a number of positions in NASA including the Planetary Research Director at NASA Headquarters, the Associate Director of the Solar System Exploration Division at NASA's Goddard Space Flight Center, and has spent two decades as an active Research Scientist at NASA developing novel, laser remote sensing techniques for Earth and planetary science applications.

Frank Robert is Associate Vice President of A.T. Kearney and Space Practice Lead for Australia/NZ and a member of the Communications, Media, and Technology practice in Australia. He has contributed to development of space policies and strategies for several decades. He has served on the Australian Space Agency Advisory Group since its formation. He has contributed to several NASA Planetary missions and as well as planning for leading-edge commercial spacecraft. He has competencies in telecommunications, satellite, spectrum, fixed and mobile services, corporate strategy, technology strategy, new products and services, R&D enhancement, and network economics. He is the principal author of an A.T. Kearney White Paper on creating/optimizing economic impact of an Australian Space Agency, Space Policy and Legislative environment. He also led in establishing A.T. Kearney's collaboration with two space law practices. Further he has supported the formulation of strategy for three major multi-spacecraft satellite operators, one involving as Fixed Satellite Services Satellite and two for Mobile Satellite Services.

Mr. Robert received his B.A. from Amherst College in Economics with minors in Geology and Astronomy and his M.B.A. from Cornell University with minors in Radio Astrophysics and Optical Astronomy. He had the great privaledge of working under NASA Grant with Thomas Gold on electrostatic movement of Lunar regolith and under Carl Sagan on Martian suface morphology.

Commodore Mark Roberts is a Faculty Member of the London Institute of Space Policy and Law and Chairman of the Air and Space Power Association. He is the Defence and Security lead for RHEA Group in the UK. Mark is also the project director for the Spaceport 1 Consortium, developing a vertical orbital launch capability in the Outer Hebrides. Previously Mark undertook a variety of lead consultancy roles in the defense, security, energy, education, and transportation sectors and was the Operations Director for the Security Business in a large infrastructure company. Before moving into the commercial world, Mark was in the Royal Air Force, where he was an operational pilot and commanded both 12 Squadron and RAF Lossiemouth. Mark was Director of the Air Staff in MoD (2007–2010), with Space and Cyber Policy in his portfolio, and Head of Capability Deep Target Attack, with responsibility for Combat Air, Complex Weapons, Land Engagement, and elements of the Queen Elizabeth Class Carrier Programme.



Dr. Safieddin (Ali) Safavi-Naeini received his B.Sc. in E.E. from the University of Tehran, Tehran, Iran, in 1974 and both M.Sc. and Ph.D. in E.E. from the University of Illinois (Champaign-Urbana), USA, in 1975 and 1979, respectively. He is a Professor in the Department of Electrical and Computer Engineering at the University of Waterloo and holds the NSERC/C-COM Satellite Systems Industrial Research Chair in Intelligent Radio/Antenna and Novel Electromagnetic Media. He is also the Director of the Center for Intelligent Antenna and Radio System (CIARS) at the University of Waterloo.

His research activities deal with wide range of applications of electromagnetic devices and systems. He has published 200+ journal papers and 400+ conference papers in international conferences. He has led several international collaborative research programs with research institutes in Germany, Finland, Japan, China, Sweden, and USA.

Mike Safyan, Vice President of Launch, Planet. In 2011, Mike Safyan joined the eight-person founding team at Planet (known as "Cosmogia" at the time) where the company was building the first iterations of its Dove cubesat in a Cupertino garage. Since then, Planet has expanded to a global organization leading the NewSpace industry, with the world's largest fleet of Medium-resolution and High-resolution Earth Imaging satellites. Mike is responsible for Planet's Launch strategy and has overseen the launch of over 350 Planet satellites across 22 launch attempts. Mike received his B.S. in Aerospace Engineering from UCLA and an M.Sc. in Space Studies from the International Space University in Strasbourg, France. He started his career working on lunar rover designs for the Barcelona Moon Team competing for the Google Lunar X-Prize and then joined the PhoneSat team at NASA Ames where he worked as a Systems Engineer developing ultra low-cost cubesats utilizing smartphone technologies. In 2018, Mike received the SSPI Promise Award, which recognizes outstanding achievement by satellite industry professionals under the age of 35.

Dr. Mark Skinner joined The Aerospace Corporation in 2017 as a Senior Project Leader for Space Traffic Management in support of the FAA in the development of civil and commercial space traffic management. Prior to joining The Aerospace Corporation, Skinner was with the Boeing Company, heading up the commercial space situational awareness group, conducting research into observational and analysis techniques to advance the state of the art in space surveillance, and developing infrared sensing techniques of resident space objects. Skinner began his career in aerospace in 1991 at Pennsylvania State University as a research faculty member. He also worked on NASA's Chandra great observatory mission. Afterwards, he continued involvement with Chandra, Kepler, and additional civil space new business efforts. He next moved to Ball Aerospace in Boulder, CO, where he served on the NASA Structure and Evolution of the Universe advisory committee. For the last 7 years, he has served as a private sector delegate for the US State Department to the UN COPUOS Expert Group on space debris and space situational awareness. Skinner has published and presented scores of technical papers for various journals and conferences, including the International Astronautical Congress, *Acta Astronomica*, SPIE, *Nuclear Instruments and Methods*, the *Astrophysical Journal*, and the Astronomical Society of the Pacific. Skinner received a Bachelor of Science degree in physics, and a Bachelor of Science in the Humanities and Science from the Massachusetts Institute of Technology. He received a Doctor of Philosophy in experimental astrophysics from the University of Wisconsin-Madison, and a Masters of Business Administration from the International Space University in Strasbourg, France.

Dr. Arunas G. Slekys is the Vice President of Corporate Marketing at Hughes Network Systems, LLC, and the elected Chairman of the Board of the Global VSAT Forum, one of the key organizations promoting the satellite industry. His 40-year career in telecommunications spans technology R&D and business development worldwide. His career began at NASA/Caltech's Jet Propulsion Laboratory and then Bell-Northern Software Research where he played a key role to pioneering 1G/2G/2.5G cellular systems and terminals. He then served as the founding Senior Vice President of R&D for NovAtel Communications, where he co-authored two patents for packet data over cellular. He as served the past 25 years at Hughes Network Systems as Vice President/GM of Wireless, Broadband Satellite Networks and Corporate Marketing.

In 1991, Slekys received the Alberta Centennial Engineering Award for attaining the highest distinction in his profession. He holds a B.Sc. in Electrical Engineering from the University of Toronto, an M.Sc. from the University of Illinois (Urbana-Champaign), and a Ph.D. in Computer/Communications Eengineering from UCLA.

Professor Herman Steyn is head of Satellite Engineering and Control Systems at Stellenbosch University (SU). He holds a Master's Degree in Electrical and Electronic Engineering from SU, a Master's Degree in Satellite Engineering from the University of Surrey in the UK, as well as a Ph..D from SU. Prof. Steyn's space experience started with the development of Africa's first fully indigenous satellite called SUNSAT during the late 1990s. He then had a 4-year stint as Principal Engineer and Team Leader for satellite control systems at Surrey Satellite Technology Limited, where he participated in many European Space Missions, for example, the Rosetta mission to a comet. He returned to South Africa in 2002 as Head of Product Development and Executive Director at SunSpace Information Systems (SA's first satellite engineering company), where he helped to develop, build, and commission earth observation satellites for international customers and SumbandilaSat for the SA government. In 2005 he joined SU full time and established a satellite engineering group in the Electronic Research Laboratory to develop low-cost nanosatellites. He established a spin-off venture from the university with some of his graduate engineers called CubeSpace, supplying ADCS components and systems for CubeSats and other nanosatellites.

Dr. Su-Yin Tan is a Senior Lecturer in the Geomatics Program and Director of the Applied Geomatics Research Laboratory at the University of Waterloo, Canada. She teaches courses on geographic information systems, remote sensing, and spatial data analysis. She is also a Faculty Member and elected member of the Academic Council of the International Space University (ISU), where she regularly serves as a Core Chair and Space Applications Department Chair for the Space Studies Program (SSP) and lectures at the Masters of Space Studies (MSS) program.

Dr. Tan is a distinguished Gates Scholar and received her Ph.D. degree from the University of Cambridge (UK), two Master's degrees from Oxford University (UK) and Boston University (USA), and B.Sc. (Env) from the University of Guelph (Canada). She was previously a Visiting Fellow at the University of

Cambridge; Visiting Researcher at the Environmental Change Institute, University of Oxford (UK); and member of Christ Church College. She received the 2014 Outstanding Performance Award for exceptional contributions to teaching and scholarship at the University of Waterloo.

Dr. Tan has an interdisciplinary background in the environmental sciences and spatial analysis methodologies in a range of application areas, such as climatology, ecosystem modelling, and remote sensing. Originally raised in Papua New Guinea, she has a diverse international background and built a record of teaching and research excellence in North America, Australia, Asia, South America, and Europe. She maintains an interest in issues related to space technologies and environmental applications.

Dr. Morio Toyoshima received a Ph.D. degree from the University of Tokyo, Tokyo, Japan, in 2003 in Electronics Engineering. He joined the National Institute of Information and Communications Technology (NICT) (former CRL, Ministry of Posts and Telecommunications), Japan, in 1994 and soon after was engaged in research for the Engineering Test Satellite VI (ETS-VI) optical communication experiment and later involved in the Ground-to-Orbit Laser-com Demonstration (GOLD) experiment with NASA's Jet Propulsion Laboratory. He joined the Japan Aerospace Exploration Agency (JAXA) (former NASDA) for the development of the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) from 1999 to 2003.

In December 2003, he became a Senior Researcher of the Optical Space Communications Group, NICT. Starting in October 2004, he spent a year as a guest scientist at Vienna University of Technology, Austria, in the field of optical space communications. In 2006 he conducted the ground-to-OICETS laser communication experiments in NICT. He was involved in the development of a Small Optical TrAnsponder (SOTA) for a 50 kg-class micro-satellite and conducted laser communications and basic quantum communications experiments from 2014 to 2016. His research interests are laser beam propagation through atmospheric turbulence, space laser communications, and quantum cryptography. He is now the Director of the Space Communications Laboratory, the Wireless Networks Research Center in NICT, since 2011.

Dr. Richard Welle is a Senior Scientist in The Aerospace Corporation's xLab, where he focuses on the development of new applications for CubeSat-class spacecraft, with a particular emphasis on CubeSat-scale optical communication systems and technologies. Prior to this, Welle was Director of the Microsatellite Systems Department in the Space Materials Laboratory for 10 years, where he was responsible for the Aerospace program developing CubeSats and other kg-class spacecraft, as well as supporting various non-satellite programs and developing new research and technology programs in the field of microsatellites.

Welle joined The Aerospace Corporation in 1986, supporting launch vehicles and satellite systems over a range of disciplines including thermophysics and heat transfer, reacting/radiating flows, multiphase and cryogenic flows, electric propulsion, and mechanical systems. Since 2005 his work has focused on microsatellites and microsatellite systems. Welle earned his bachelor's degree in physics and chemistry from Southwest State University, Marshall, Minnesota, his master's degree in physics from the University of Tennessee Space Institute, and his Ph.D. in aerospace engineering from the University of Southern California. Welle has over 60 technical publications and has been awarded over 25 patents on technologies in the areas of small satellites, microfluidics, identification taggants, solar power, ultrasonics, and optical communications.

Contributors

G. S. Aglietti Space Institute, University of Auckland, Auckland, New Zealand

Audrey L. Allison International Space University, Strasbourg, France
The Boeing Company, Arlington, VA, USA

Tony Azzarelli Azzurra Telecom Limited, London, UK

Morgan Bailey Rocket Lab, Huntington Beach, CA, USA

Christoph Beischl London Institute of Space Policy and Law, London, UK

Pierre Bousquet Science project Department, French Space Agency, CNES, Toulouse, France

Vitali Braun IMS Space Consultancy GmbH at ESA Space Debris Office, European Space Agency, Darmstadt, Germany

Jeroen Cappaert Spire Global, Glasgow, UK

Wen Cheng Chong Kepler Communications, Toronto, ON, Canada

Adriana Elysa Alimandro Corrêa Directorate of Satellites, Applications and Development, Brazilian Space Agency (AEB), Brasília, DF, Brazil

W. G. Cowley Institute for Telecommunications Research, University of South Australia, Adelaide, SA, Australia

Eric Dahlstrom International Space University (ISU), Strasbourg, France

Ken Davidian Office of Commercial Space Transportation, Federal Aviation Administration, Washington, DC, USA

Kiruthika Devaraj Planet Labs Inc., San Francisco, CA, USA

David Draper NASA Headquarters, Washington, DC, USA

Joseph D. Fargnoli New York Space Alliance, New York, NY, USA

David Finkleman Sky Sentry, LLC, Colorado Springs, CO, USA

Steven Freeland Western Sydney University, Sydney, Australia

Helen Grant NASA Headquarters, Washington, DC, USA

Michael Grasso Blue Origin, Washington, DC, USA

James Green NASA Headquarters, Washington, DC, USA

Robert Harvey Planet, Inc., San Francisco, CA, USA

Yvon Henri OneWeb, London, UK

Henry Hertzfeld Director, Space Policy Institute, Elliott School of International Affairs, George Washington University, Washington, DC, USA

Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

Theresa Hitchens Center for International and Security Studies at Maryland (CISSM), Silver Spring, MD, USA

Ram S. Jakhu Institute of Air and Space Law, McGill University, Montreal, QC, Canada

Martin Jarrold GVF, London, UK

Christopher D. Johnson Secure World Foundation, Washington, DC, USA

Sanat Kaul International Foundation for Aviation, Aerospace and Drones, New Delhi, India

Vatsala Khetewat International Space University (ISU), Santa Barbara, CA, USA

Christoffel J. Kotze NOEZ Consulting & Design, Yzerfontein, South Africa

Chris Kunstadter AXA-XL, New York, NY, USA

Rene Laufer University of Cape Town, Cape Town, South Africa

Baylor University, Waco, TX, USA

Shane Laverty Kepler Communications, Toronto, ON, Canada

Rodrigo Leonardi Directorate of Satellites, Applications and Development, Brazilian Space Agency (AEB), Brasília, DF, Brazil

Vanessa Lewis Kepler Communications, Toronto, ON, Canada

Matt Ligon Planet Labs Inc., San Francisco, CA, USA

Timothy J. Logue Thales Alenia Space, Arlington, VA, USA

Arthur C. Clarke Foundation Board, Washington, DC, USA

Pacific Telecommunications Council Board, Honolulu, Hawaii, USA

Timothy Maclay OneWeb, McLean, VA, USA

Scott Madry The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

Amit Maitra The Foundation for Emerging Solutions Inc., Oakton, VA, USA

Peter Martinez Secure World Foundation, Broomfield, CO, USA

Attila Matas Senior Satellite Regulatory Consultant, OrbitSpectrum, Geneva, Switzerland

Darren McKnight Centauri, Chantilly, VA, USA

David Meltzer GVF, London, UK

Nishith Mishra Faculty of Law, Institute of Air and Space Law, McGill University, Montreal, QC, Canada

Mina Mitry Kepler Communications, Toronto, ON, Canada

Sa'id Mosteshar London Institute of Space Policy and Law, London, UK

Clay Mowry Blue Origin, Washington, DC, USA

Sreeja Nag Nasa Ames Research Center and Baer Institute, Mountain View, CA, USA

Alexandre Najjar Euroconsult, Paris, France

Carlos Niederstrasser Northrop Grumman Space Systems, Northrop Grumman Corporation, Dulles, VA, USA

Jeffrey Osborne Kepler Communications, Toronto, ON, Canada

Joseph N. Pelton Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA
International Space University (ISU), Strasbourg, France

Maxime Puteaux Euroconsult, Paris, France

Jonathan Rall NASA Headquarters, Washington, DC, USA

Frank A. Robert Kearney Consulting, Melbourne, VIC, Australia

Mark Roberts London Institute of Space Policy and Law, London, UK

Safieddin (Ali) Safavi-Naeini Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada

Mike Safyan Planet Labs Inc., San Francisco, CA, USA

Bernardo Schneiderman Telematics Bus. Consultants, Irvine, CA, USA

Mark A. Skinner The Aerospace Corp, Arlington, VA, USA

Arunas G. Slekys Corporate Marketing, Hughes Network Systems, Germantown, MD, USA

Willem Herman Steyn Electronic Engineering, University of Stellenbosch, Stellenbosch, South Africa

Su-Yin Tan Department of Geography and Environmental Management, University of Waterloo, Waterloo, ON, Canada

Morio Toyoshima Space Communications Laboratory, National Institute of Information and Communications Technology, Koganei, Japan

Richard P. Welle The Aerospace Corporation, El Segundo, CA, USA

Part I

Introduction

Introduction to the Small Satellite Revolution and Its Many Implications

Joseph N. Pelton and Scott Madry

Contents

Abstract

This chapter provides a broad introduction to this Handbook on small satellites. It offers information as to why this Handbook was created and its primary uses. It provides guidance as to the structure of the Handbook and its Appendices and a useful information as to how the text of this Handbook and its references can be employed to understand about the history, the technology of small satellites,

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

S. Madry
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_1

ground stations and systems for users of these small satellites, the operation of these facilities, launch services, as well as definitions concerning the many different types of these small satellites that exist today. It also provides information, explanations, and definitions about the economic, legal, policy, and regulatory aspects of these systems. It has an entire section devoted to providing information about the many diverse and growing aspects of applications and services that can be used by employing small satellites and how they are uniquely able to provide some of the newer and more entrepreneurial space-based services. There is a chapter that relates the uses of small satellites as a means to achieve the United Nations Sustainable Development Goals (SDGs) for 2030. In short this Handbook seeks to provide a comprehensive set of information about all aspects of smallsats, their uses and applications, the related ground systems, their launch and operation, as well as related economic, legal, policy, business, and financial aspects of these new types of space systems. Finally it seeks to address key issues and challenges for the future that include frequency allocation and management, orbital space debris, space traffic control and management, as well as competitive technological, business, economic, and financial issues. It also notes that the COVID-19 pandemic will have a major impact on the world economy and that this will include a major impact on the small satellite and launch industries. In short there will likely be a number of bankruptcies in this field as a direct or indirect consequence, but these setbacks do not impact the innovative technologies or other information presented in this handbook.

Keywords

Cubesats · Disruptive technologies · Electronic beam-forming ground antennas · Geosynchronous Earth orbit (GEO) · High-throughput satellites (HTS) · Launch vehicles · Low Earth orbit (LEO) · Medium Earth orbit (MEO) · Orbital space debris · “Smallsats” · Satellite constellations · UN Sustainable Development Goals · Global Navigation Satellite Services (GNSS) · Precision Navigation and Timing (PNT)

1 Introduction

There are many excellent books and articles now available on all aspects of small satellites. This is a field that has exploded in activity and global interest in the past decade. There are a wide range of individual sources about the technology, others on the applications and services, and yet others about the economics, launch arrangements, policy and regulation, and social and political consequences. Yet there has not previously been a comprehensive and interdisciplinary source of information that collects all of this information together in a holistic way – until now. This Handbook of small satellites seeks to provide a complete overview of all aspects of the small satellite field.

Thus leading experts from around the world have been recruited to provide in one reference source the latest technical, operational, financial, regulatory, and service information about small satellites on a global basis. This provides information from the smallest femtosat (below 100 g in size) up to the largest and most sophisticated small satellites that range in size up to 500–600 kg in mass. Such "smallsats" are being deployed in so-called mega-LEO satellite constellations that OneWeb, Planet, SpaceX, Telesat, Boeing, LeoSat, Comstellation, and others are deploying or proposing to deploy in the next few years.

The COVID-19 pandemic that occurred in 2020 has caused health and economic consequences of staggering worldwide consequences. This horrific pandemic will impact the small satellite and launch industry in the months ahead. Already LeoSat and OneWeb small satellite constellations have declared bankruptcies, and others will follow. There will be more failures of small satellite constellations, launcher companies, and other associated space services companies. Despite these economic failures, the innovative new small satellite technologies, the new more efficient launch systems, the new ground systems, and the many other innovations discussed in this Handbook remain valid and very useful sources of new enterprise in this field. In the late 1990s, the original small satellite constellations saw major economic collapses. The economic failures constituted by Iridium, Globalstar, ICO, and Orbcomm made a huge impact on satellite development and the ready access to capital financing for some time. Yet recovery was achieved in the years that followed. The same seems likely to occur. Despite these setbacks the information in this Handbook remains useful and quite relevant.

Thus this Handbook provides information about the historical development of "smallsats" as well as an explanation of the various types of "smallsats" that are being developed and launched today. It also provides the latest information about the space and ground system technology and the relevant applications and services, as well as the economic, policy, regulatory, legal, business, and social aspects of this burgeoning field of space activity.

This book seeks to provide information from the perspective of all those interested in space satellites. It thus seeks to provide useful information for the student experimenter and for those undertaking smallsat projects for civilian space agencies and military and defense agencies. It also provides useful information suitable for so-called "NewSpace" business enterprises engaged in small satellite-related businesses as well as the political and legal officials that provide the regulatory oversight for small satellite systems. This includes information about the efficient allocation and oversight of the frequency spectrum needed for these systems to operate effectively.

This Handbook on small satellites addresses key issues such as orbital space debris, end of life removal of small satellites from orbit, new ways to design and build satellites, frequency spectrum coordination, as well as innovative ways to address the problems of jamming and interference. It even addresses new approaches to the efficient use of space resources and satellites such as placing hosted payloads on larger satellites. It addresses the new opportunities for achieving cost-efficient "space-like" services from high-altitude platform systems (HAPS).

It is the hope of all the contributors to this reference work and from the scores of participants from around the world that this Handbook will be found helpful. In particular it is hoped that the many articles that follow, plus the many references to books and articles found in endnotes, can serve as a useful guide to the design, manufacture, deployment, use, oversight, and business developments needed for the future success of "small satellites" enterprises around the world. The burgeoning number of smallsat systems and launches represent a powerful element in the growth of "NewSpace" or "Space 2.0" ventures. These NewSpace businesses have sprung up around the world. They are now giving new impetus to a rapidly expanding space industry. In time these space enterprises will expand to become a "trillion dollar" industry. These NewSpace industries will help sustain a growing world economy. In short, "smallsats" will touch everyone. They will aid enterprises that range from the ecology to banking, from fishing to mining, and from airline travel to health care and education.

This is not to say that "smallsats" will replace large satellites. Large and powerful high-throughput satellites, for instance, are best positioned to provide broadcast television services to small low-cost satellite dishes. Other satellite services, such as Precision Navigation and Timing (PNT) services and those designed to provide military- and defense-related intelligence, will likely continue to require larger space and high-power levels as well. The bottom line is that different services and applications will likely require different types of satellites of varying sizes and power levels.

The technical, operational, and economic reasons for the "right type" of satellite in terms of size, power level, architecture, and mass will be explained in later sections of this chapter. Instead of a "replacement" of large and powerful satellites, we will see a sort of coexistence of all types of satellites from tiny and small to medium and large scale. Nevertheless, small satellites seem likely to provide an ever-expanding range of services in the coming decade.

Even in the area of larger satellite design and deployment, innovations that come from the smallsat field seem likely to have a major impact. Technology from the field of scientific satellites has been traditionally transferred over to the area of application satellites. For instance, the three-axis body-stabilized satellite with enhanced pointing accuracy and enhanced solar power efficiencies that was first developed for planetary research missions was rapidly transferred to the field of application satellites. The same transfer of technological innovation will also be the case with "smallsat" innovations. Miniaturization, enhanced testing, or manufacturing efficiency techniques that come from "smallsat" programs are being and will be shared and transferred to "large satellite" programs. The case of Canada's new three-satellite RADARSAT Constellation is perhaps an excellent case in point.

2 Scope and Structure of This Handbook

This Handbook of small satellites seeks to provide a comprehensive overview of the small satellite field. It thus addresses the history of small satellites and provides insight into the technology and its evolution over time both in terms of the spacecraft, the tracking, telemetry, and command aspects of its operation, and the corresponding changes to the ground segment for users of this technology. Such innovations represent a critical part of the evolutionary path that has furthered and enabled the feasibility and economics of small satellites. Key new features such as improved and accelerated testing processes, the use of hosted payloads, high-altitude platform systems, active debris removal, on-orbit servicing, new ground systems with electronic tracking capabilities, and more will be addressed as well.

After the technological and operational aspects are presented, the next section will address the key aspects of small satellite design, engineering, and manufacture. This will also address business-related concerns such as contracting, resiliency and sparing philosophy, and protection of intellectual property rights.

The next section addresses the great complexity of applications and services and the many different types of small satellites that can be deployed to meet the needs associated with the increasingly diverse range of services as well as the many types of organizations and units that are now pursuing the active deployment and use of small satellites. This even includes the use of small satellites by defense agencies and military ministries. The distribution of smallsat uses for 2018 as developed by Bryce Space and Technology consulting shows the following breakdown. This was 11% for communications, 41% for technology development and verification, 2% for military and intelligence purposes, 37% for remote sensing, 6% for scientific purposes, and 3% for other or unknown uses. But this snapshot of current uses does clearly show current trends. The overwhelming usage that is shown by either national filings or filings with the International Telecommunication Union suggests that communications or networking applications will vault into the number one purpose in the coming years as mega-LEO systems are deployed for this purpose in the future (Bryce Space & Technology 2019).

The final major element of the Handbook addresses the economic, legal, and regulatory issues and constraints that are concerned with the increasingly complex field of small satellites.

This is followed by the conclusion section that assesses all of the current trends, major technical, economic, social, and regulatory issues that are pending, and how this relates to the small satellite revolution and Space 2.0 industries. This synoptic final analysis provides a coherent overview of the field of small satellites around the world. This final analysis relates the key trends in the area of small satellites and its ups and downs to broader world goals and objectives such as the United Nations' 17 Sustainable Development Goals (See Fig. 1) and the work of the Davos World Economic Forum.

There are also a series of appendices that provide information on small satellite projects and activities as well as information related to regulatory actions and policies as well as a glossary of terms. In light of the transitory nature of developments in this fast-moving field, an effort is made to provide website addresses with current URLs so that the current status of projects can be obtained from the official site for small satellite projects. Collectively this Handbook should provide comprehensive information about every aspect of the fast-moving world of small satellites.

Fig. 1 New capabilities offered by smallsats can benefit developing nations and the UN Sustainable Development Goals (Graphic courtesy of the United Nations)

3 Historical Background

Small satellites are not new. The very first satellites that were launched into orbit in the late 1950s and early 1960s such as Sputnik I, Explorer 1, Oscar 1, SCORE, Relay, and Syncom were all "small satellites." At the time, there was of course no thought being given to whether spacecraft were "small," "medium," or "large" in size in those pioneering years. The lift capacity of the launch vehicles in those days, especially those in the USA, could only launch what are now considered small satellites. Thus in the earliest days, the antennas were often simple dipole antennas, and the power was quite limited (see the Oscar 1 satellite shown in Fig. 2).

These very early satellites typically did not exceed the volume of a large beach ball, and their mass was only a few kilograms. This was because these early satellites were largely experimental in nature, limited to launch vehicle capacity, and expectations were accordingly low as to spacecraft size.

These first satellites were thus largely designed to prove that such technology could truly function in outer space. There were limited expectations as to what capacity these spacecraft might make in terms of actually offering commercial services.

Even the first "operational satellites" such as Early Bird (Intelsat 1), Molniya 1, the Initial Defense Satellite Communication System (IDSCS) satellites, and ANIK-1 were relatively modest in their throughput capabilities (i.e., typically less than a few 100 telephone circuits). These early satellites were also quite low in power (i.e., less than 100 watts) and had rudimentary stabilization systems. These earliest satellites accordingly required sophisticated ground stations with huge aperture antennas to receive and transmit signals. They had to be of this size and

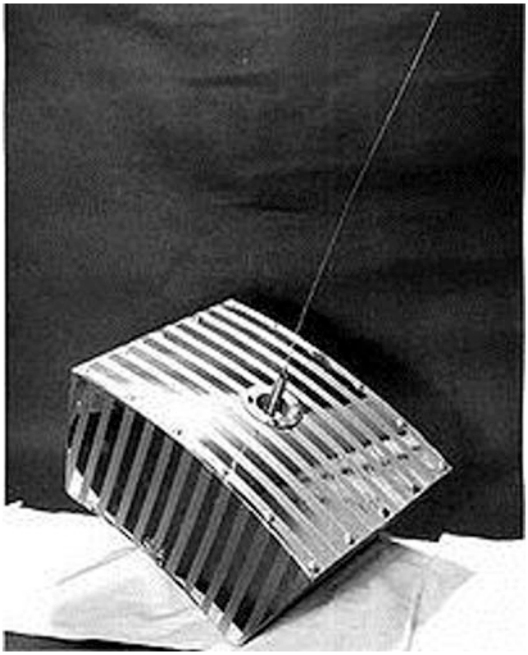


Fig. 2 The Oscar 1 amateur ham radio satellite was an early “smallsat” (Graphic courtesy of the Amateur Satellite Organization (AMSAT))

power to be able to communicate effectively with these early small and low-powered satellites as they circled the Earth.

The first Intelsat Standard A Earth stations that operated in tandem with the first few generations of Intelsat satellites, for instance, were gigantic steerable antenna systems. These gigantic facilities were 30 m (i.e., nearly 100 ft) in diameter and weighed perhaps several tens of tons. These stations were also expensive to operate. These mammoth facilities required staffing on a continuous 24 h a day and on 7 days a week basis with a staff of perhaps 50–60 people. They had cryogenic cooling systems to boost the receiving sensitivity of the antenna’s electronics and massive steering capabilities that were very exact. These huge antenna systems were thus almost like radio telescope systems and cost in the range of $5 million to $10 million dollars apiece. This was at a time when a dollar was valued at three to four times as much as it is today. In the earliest days of satellite communications, the largest investment was thus in the ground stations and not the satellites (Pelton 2003).

But this changed rather quickly in the years and decades to follow.

This major trend in satellite development became known as technology inversion. This phrase referred to the fact that the satellites moved to become more complex and massive. Ground antennas on the other hand became simpler and smaller. Each new generation of the Intelsat satellites, for instance, quickly grew in mass, power, antenna size, and technical sophistication such as adding three-axis stabilization. This allowed precise pointing of the satellite antenna system toward specific locations on Earth as high-gain antennas were added to the satellites.

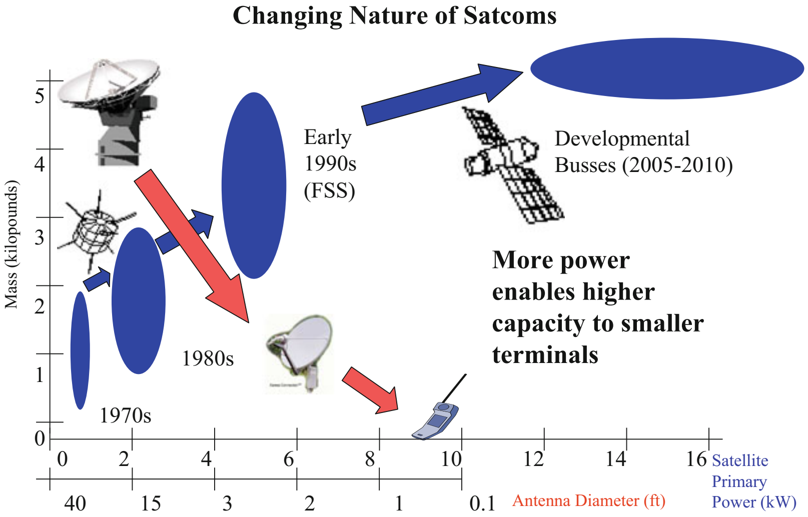


Fig. 3 The technology inversion: satellites grew in size and ground systems shrank (Graphic courtesy of the author)

The objective of this trend was to allow ground antenna systems to be smaller and less costly and to achieve higher throughputs for communications satellites. And communication satellites indeed represented the number one practical application for the satellites that were deployed in the 1960s, 1970s, 1990s, and 2000s.

This 50-year trend from the 1960s to the 2010s is clearly depicted in Fig. 3. The figure below shows this process of technology inversion. During this five-decade-long evolution, the satellites became bigger, higher-powered, and more capable, while the ground stations kept shrinking in cost and size. The current smallsat revolution is serving to reverse some aspects of this longer-term trend.

The primary application for satellites during this time was for satellite communications. And when satellite communications were demonstrated to be possible from geosynchronous orbit (sometimes known as the Clarke Orbit in honor of Arthur C. Clarke who first proposed this type of orbit for global communications in 1945), there was a sudden and indeed voracious demand for bigger and better comsats to fill the demand for international communications, global television broadcasts, and networking associated with international trade, which outstripped the capacities of international coaxial cable networks. The increasing cost efficiency of each new generation of satellites, improved launch vehicle capabilities, improvements in ground antenna systems, the demand for television channels everywhere, and need for long-distance communications around the world led to higher and higher capacity satellites and indeed more different types of satellite networks.

Over a period of some 50 years, the trend in the satellite world was predominately defined by the growth profile shown in Fig. 3. The satellites, especially those for communication services, grew bigger and bigger. The large-scale solar arrays on these increasingly more powerful satellites generated much more power, and there were also larger battery systems to provide backup power during periods of eclipse. The satellites evolved to have three-axis body stabilization that allowed very precise pointing capabilities and also allowed the solar arrays to be constantly oriented to get the greatest amount of exposure to the sun. This, in turn, allowed very large aperture antennas on the satellites to be deployed, so they could be constantly pointed to specific locations on the Earth. This, in turn, enabled increasingly concentrated and tightly spot beams and the ability to reuse spectrum multiple times since the spot beams could be geographically isolated from one another.

These design innovations in the antenna systems to create tightly defined spot beams as they were added to these much larger satellites also saw the addition of polarization isolation in the transmitted beams. These innovations allowed more and more intensive reuse of radio-frequency spectrum. The more powerful and more capable satellites allowed the use of smaller and less expensive ground antenna systems.

The mass, size, and power of satellites thus grew and grew. Although the satellites in the sky were more expensive, the ever-expanding number of user antennas on the ground could be smaller and smaller and much less costly to acquire and eventually automated so that no staff was needed.

The increase in the critical dimensions of the satellites increased their size and power by a factor in the range of 200 times, but the throughput and lifetime performance increased proportionally to a much greater degree. The giant communication satellites of today such as the Intelsat Epic Satellites, the ViaSat-1 and ViaSat-2, and the EchoStar Jupiter satellites have tens of thousands the times of throughput capacity and ten times greater lifetime of the earlier satellites when the field of satellite communications began (see Fig. 4).

There has been a staggering increase in performance that is only paralleled by the increase in the performance of computers over the past 50 years. The increase in cost efficiency and improved performance of communication satellites is staggering when one considers “then” versus “now.” The Intelsat 1, known as Early Bird, launched in 1965, had a capacity of only a few 100 voice circuits compared with the millions of voice circuit or the thousands of television circuit capabilities demonstrated by today’s high-throughput satellites.

In the mid-1980s and 1990s, however, the model of how satellites might evolve for the future began to develop new branches and new schools of thought. CTA and Orbital ATK (now owned by Northrop Grumman) developed a smaller geosynchronous satellite platform with lower power known as the GEOStar-1. This new smaller GEO satellite formed the basis of new satellite communications ventures for developing countries. New platforms of different sizes were developed for different types of users with different levels of service requirements.

Other companies, however, took the idea of smaller commercial satellites in a whole new direction entirely. They began designing constellations of many smaller satellites deployed in low Earth orbit (LEO) for various purposes. These included the Iridium satellite system, the Globalstar satellite system, and the ICO system that were to provide land mobile satellite services to handheld satellite phones. Orbital

Fig. 4 The ViaSat-2 satellite can transmit at a rate of 160 gigabits/s (or the equivalent of 10,000 times the capacity of the Early Bird Satellite of 1965), and its lifetime is 10 times longer (Graphic courtesy of ViaSat)

ATK came up with the idea of even smaller LEO satellites for message relay, and this system was known as Orbcomm. Yet another company that was backed by Craig McCaw and Bill Gates thought it could utilize new frequency spectrum in the millimeter wave spectrum (i.e., the Ka-band) to create a massive so-called “mega-LEO” system. This system was first known as the Calling Satellite System and then renamed Teledesic. This system was to have had 840 satellites plus 80 spares. This system design was to have many innovative features such as the use of phased array antennas on the satellite so as to create the effect of permanently “painted” beams on the ground so that the ground system could be simplified. Thus all of the pointing and switching of beam would be done on the satellite (Teledesic History n.d.). During the 1990s and 2000s, there were many different satellite designs, for many types of satellite services, in different frequency bands, with quite different types of ground systems, and different schemes for their launch into different types of orbits.

What all of these systems had in common was to design, manufacture, and launch a large number of “smaller” satellites into large-scale constellations – mostly in low Earth orbit (LEO). Instead of deploying large and expensive satellites in GEO orbit, there would be a much larger number of smaller satellites launched into LEO orbit much closer to Earth. Some of the orbits proposed were as much as 40 times closer to the Earth surface than the geosynchronous Earth orbit (GEO) satellites. The driving idea was to find more cost-efficient ways to design, manufacture, test, and launch these satellites. They all sought to lower the costs of manufacturing and launch these smaller satellites. They also intended to exploit and leverage the "power advantages" and the much reduced signal delay associated with the lower orbits. The so-called path loss was associated with the weakened signal that had to travel back to Earth from an orbit that was some 35,870 km (22,230 miles) in distance away. Latency was the time lag required for the signal travel to reach the ground from a distance almost a tenth of the way to the Moon.

The signals transmitted from a satellite or sent up to a spacecraft spread out in a circle. This meant that because of the spreading circle, the power loss was a function of the square of the distance traveled. If the satellite was 40 times further away from the Earth, the path loss was not 40 times less, but actually 1600 less (or 40^2). This power advantage inherent in low-orbiting satellites could serve to make the user terminals much smaller and less expensive. The plan, in the case of the land mobile satellite systems, was to create satellite handheld phones that could "talk" to these lower Earth orbit (LEO) satellite constellations. The problem with the design of the small satellites for constellations that would completely cover the Earth was that of solid geography. The closer the satellites were to Earth, the more satellites had to be launched to get global coverage. The closer the satellites were to the ground, the lesser the amount of the coverage. This was somewhat the reverse of issue of a radio or television antenna on the ground. The taller a TV or radio antenna extends, the more coverage it has. The Iridium system with one of the lowest planned orbits came up with a design thus ended up with a constellation that required 66 satellites plus at least 8 spares (Iridium Satellite Constellation n.d.).

This shift in design concept to create low Earth orbit constellations of small satellites versus the deployment of just three bigger and higher capacity satellites in GEO orbit in order to create total Earth coverage was a major change in satellite architecture. The earlier model had been to manufacture, meticulously test, and qualify a small number of large, complex, and expensive highly unique satellites that were then launched into GEO orbit. This new model was envisioned to be quite different. James Stuart, the designer of the Teledesic satellite, stated clearly his vision to me as we worked on the Teledesic system design together at the University of Colorado in the late 1980s. "We are going to design and build these satellites like TV sets or Video Cassette Recorders (VCRs). And through large scale production and automated manufacturing of components and maybe even robotic integration we can achieve large economies of scope and scale" (Conversation with James Stuart at the University of Colorado in the late 1980s n.d.).

But despite the optimism that accompanied all of these small satellite constellations, a rather devastating crush of bankruptcies were to follow. Starting in August 1999, Iridium, Globalstar, ICO Ltd., Teledesic, and Orbcomm all declared bankruptcies.

The reasons for these bankruptcies actually differed. In some cases it related to creating totally new markets for new services. In other cases it related to the long time it took to design, manufacture, and deploy a very large network of small satellites and ground control systems plus marketing and selling handsets or small ground antennas before any revenues could be realized. In some cases it related to the performance of the handsets. In other cases it was because the estimated cost of building the satellites was greatly off. The initial estimated cost of deploying the

Teledesic satellite system was about $4 billion. When the Teledesic system actually went into bankruptcy, the estimated costs had topped $9 billion. The bottom line is that small satellite constellations as a business venture that financial investment banks and investors were willing to back became extremely anemic. Some of those that bought up the shares of systems such as Iridium actually tried, unsuccessfully so, to sue the backers of those systems for fraud. None of the factors are helpful to the deployment of commercial small satellite constellations.

In fact, some technical and financial experts are suggesting that a number of satellite ventures, including the SpaceX Starlink venture with the most small satellites in their constellation proposals of anyone, might be at risk, due to both underfunding and technical and operational constraints. Satellite analyst Tim Farrar has said: "There are several multi-billion dollar NewSpace satellite projects that could suffer the same fate (i.e. the bankruptcy of Iridium). . ... What will that meand for investor perceptions? Will non-NewSpace incumbents benefit? And more fundamentally, is the NewSpace bubble about to burst?" (Farrar 2018).

The failure of one small satellite constellation will not alter the dynamic course and success of "NewSpace" ventures. Space 2.0 is really not about how many small satellites are built but a new way of thinking about space and the creation of new business models. It involves marshalling technological innovation, especially in the areas of IT, digital equipment, and artificial intelligence, to create new more cost-efficient space systems that can open entirely new markets. Yet at the same time, a large number of bankruptcies of "NewSpace" ventures and failure of small satellite constellations will undoubtedly have a negative effect on the space industry around the world. It is as simple as "Success breeds success, and failure brings other failure."

4 The Beginnings of Small Satellite Innovation

But there were other key factors to consider on the small satellite frontiers. Technical experts worked with amateur radio operators to design and build at low cost small satellites for global radio connectivity. These satellites known as Oscar 1, Oscar 2, etc. proved that low-cost satellites were possible to design and build and that simpler methods and materials could produce viable spacecraft at lower cost (AMSAT Live Oscar Satellite Status Page n.d.). NASA and other space agencies created the concept of the cubesat that was 10 cm × 10 cm × 10 cm in size.

The initial programs encouraged university students and researchers to design and build their own space experiments. Over the past three decades, the cubesat experimental design process created a widespread interest in space experimentation. This process has now grown and grown. Over time more and more university students, and then even high school and secondary school students, were offered the chance to design and build their own space experiments. This "cubesat" process has now led to thousands of cubesats to be launched into orbit. Today there are a number of companies with websites online where students and interested individuals from around the world can order a standardized cubesat frame and other key components that can be easily fit into one's cubesat project.

Beginning in 2009, Bob Twiggs, a faculty member at Morehead State University, formally proposed a "PocketQube satellite" that was one-eighth the size of a cubesat. This "picosat" configuration that was 5 cm × 5 cm × 5 cm in size was first flown in November 2013 with four PocketQube satellites packaged together with the Unisat-4 launch. The new Vector R launch vehicle is now expected to offer regular PocketQubeSat launches. The popularity of "PocketQubeSats" is expected to grow as buses, kits, and components are now available online, and this lower-cost alternative to cubesats becomes better known (Pocketqube Satellites n.d.). More information about this new type of "picosat" is provided in the chapter about the "femtosats" and "picosats" that follow.

The miniaturization associated with cubesat projects thus gave rise to a whole new mentality about what is a "satellite" and what can be accomplished by achieving miniaturization of key components in a satellite, the fabrication of quite small spacecraft. The idea was not only to use quite small digital processors, miniaturized sensors, and other very small components but also to be less reliant on extensive, time-consuming, and expensive components. If one of these quite small and much less expensive satellites were to fail, then the idea was to build and launch another one.

What is amazing to some is that all of the critical elements of a satellite can be crammed into the confines of a 10 cm × 10 cm × 10 cm cube. As shown in Fig. 5, these elements include power supply, antennas, sensors, or instruments that are the

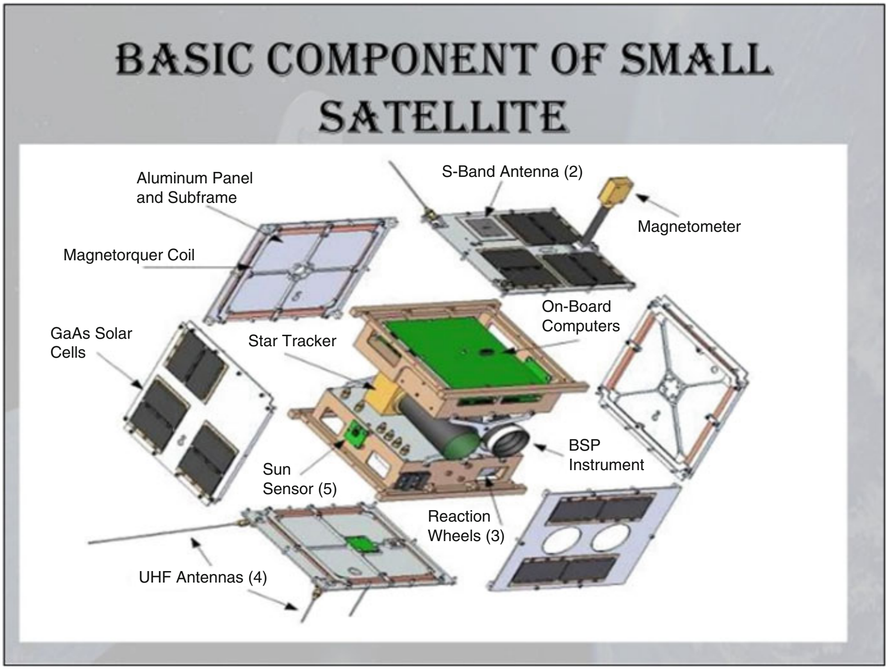


Fig. 5 Exploded view of components of a "cubesat"

“payload,” star trackers or sun sensor, onboard computer and digital memory systems, reaction wheels, and thermal control systems. Some even have a fully functional three-axis stabilization thruster system.

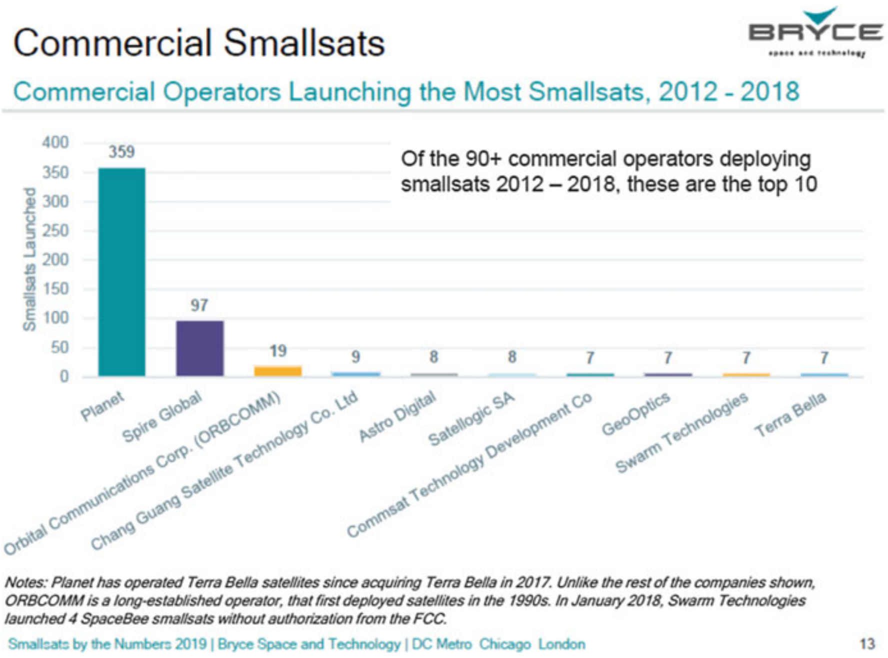
Some have said that this new small satellite approach to space systems was the start of something quite new for the overall industry. Observers look back and say that the “smallsat revolution” was one of the key stimulating factors that have led to what is now called “Space 2.0” or “NewSpace.” This new “Silicon Valley”-type thought process was based on a flurry of questions like “what if we did things differently?” There were questions such as the following: How can we reinvent the space industry to make it better, more agile, and entrepreneurial in style? How can we improve on the R&D processes of the past 30 or 40 years that were largely based on the military-industrial processes and how civilian space agencies have been doing business? How can we do things thinking more like “Silicon Valley” industrial innovators and entrepreneurial business people? How can we create new more agile industrial modes of innovation? How can we do things more quickly with more rapid prototyping? How can we create, build, and test new types of satellites at significantly lower costs, more rapidly, and with less mass? How might we innovate by using the miniaturization of components and “digital processors and sensors” such as those involved with designing digital computers and new electronic and IT industrial products?

If one looks at the launch history of small satellites during the period 2012 through 2018, it can be seen that the predominant source of these new smallsat deployments has been from start-ups who have embraced entirely new models of how to design, test, launch, and operate smallsat system. Planet and Spire Global, two smallsat start-ups, have been responsible for about 40% of the over 1000 smallsats launched, while the much longer established Orbcomm network deployed less than 2% (see Fig. 6 that features a graph showing the top 10 commercial launchers of smallsats out of over 90 commercial operators. In addition over 200 nonprofits launched smallsats as well) (Bryce Space and Technology 2019).

Quite parallel to the new way of thinking about the design and manufacture of small satellites came the new way of thinking about creating more efficient launch vehicles, reusable rocket systems, and space planes that are safe enough to carry people on suborbital flights or even into orbit. Suddenly everyone involved in “NewSpace” or what some call “Space 2.0” began to question the way things had been done in the past and began seeking new ways forward (Pelton 2019).

The new commercial mentality has increased launch options and reduced the cost of launch operations. The number of smallsat launches from 2012 to 2018 is over 1300, but over 700 were launched in 2017–2018, and if filings are an indication, that number will continue to increase. Some 104 cubesat systems (most of these being 3-unit systems) were launched on a single Indian polar satellite launch vehicle in February 2017 (PSLV-C37 Successfully Launches 104 Satellites in a Single Flight n.d.).

During the period 2012–2016, 68 smallsats were lost due to launch failure, but only one of these came in the 2017–2018 period which showed many more launches and much fewer launch failures (Op cit, Bryce space and technology) (Fig. 7).



Commercial Smallsats

Commercial Operators Launching the Most Smallsats, 2012 - 2018

Of the 90+ commercial operators deploying smallsats 2012 – 2018, these are the top 10

Notes: Planet has operated Terra Bella satellites since acquiring Terra Bella in 2017. Unlike the rest of the companies shown, ORBCOMM is a long-established operator, that first deployed satellites in the 1990s. In January 2018, Swarm Technologies launched 4 SpaceBee smallsats without authorization from the FCC.

Smallsats by the Numbers 2019 | Bryce Space and Technology | DC Metro Chicago London

13

Fig. 6 Commercial satellite operators launching smallsats (2012–2018) (Graphic courtesy of Bryce Space and Technology)

5 New Ways of Thinking About How to Design, Manufacture, and Launch Satellites

The way this new way of thinking about satellites in terms of the design, manufacture, and testing actually did not start in Silicon Valley at all. One of the places this new way of thinking started was at the University of Surrey just outside of London. Some very smart engineering faculty such as Professors Barry Evans and Martin Sweeting started to work in small satellite technologies with engineering students at the university in 1981 and was formally incorporated in 1985 as Surrey Satellite Technology, Ltd. This is also now known as the Surrey Space Center and headed by Sir Martin Sweeting. This company has been acquired by Airbus, but it is still a separate company within this very large aerospace company. This company, in 1985, designed and built the University of Surrey-1 (UOS-1) satellite that demonstrated that a small satellite could be designed and built with miniaturized components and high-performance digital processors to accomplish a number of sophisticated functions in orbit within a small and relatively inexpensive satellite. The rest is history.

Today the Surrey Space Center can claim a number of distinctions within the "small satellite world" that includes (i) building and arranging for the launch of 2–4 small satellites per year since its first small satellite projects; (ii) arranging for

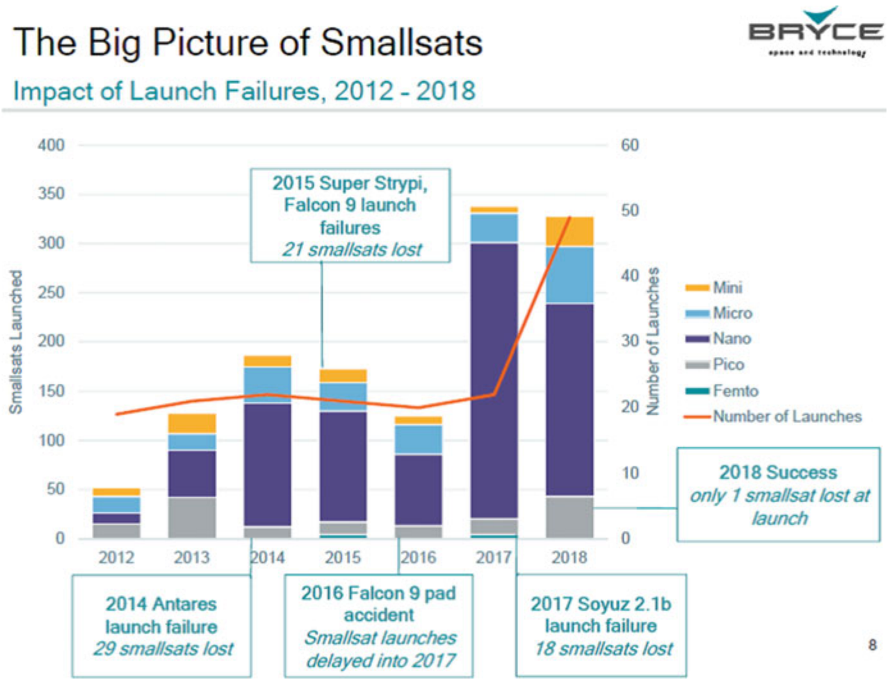


Fig. 7 The Changing profile of small satellite launches (Graphic courtesy of Bryce Space and Technology)

35 launches from 8 different launch sites around the world and manufacturing a total of 60 satellites that have now been launched; (iii) at the current time having 10 satellites and 12 payloads in production; and (iv) conducting 18 satellite training programs for various programs and countries around the world to spread the knowledge about how to design and build small satellites (Surrey Satellite Technology Limited n.d.)

There is also a small satellite research and manufacturing center in the USA. This is known as the Space Dynamics Laboratory (SDL) that is a part of the Utah State University Foundation and is located in Logan, Utah. SDL combines the talents of local aerospace companies with researchers, faculty, and engineering students at Utah State University. SDL has been in existence since 1959 at the very start of the Space Age and has designed and built many small satellites over the years. Utah State University and SDL, together with a wide range of sponsors, and especially the American Institute of Aeronautics and Astronautics, host an annual small satellite conference in August in Logan, Utah (Small Satellite Conference n.d.).

This conference has been running since 1987 when the first conference was held. A complete listing of papers presented at this conferences ever since its founding is available in a special digital library that has been created to preserve the thousands of papers that have been presented at the conference for over three decades. These papers can be accessed via this website: https://digitalcommons.usu.edu/smallsat/. This extensive collection of articles can be accessed under such headings as missions, subsystems, structures and materials, signal processing, applications, and more (Digital Library of Papers Presented at the Small Satellite Conference Since 1987, Digital Commons Library, Utah State University, Logan, Utah n.d.).

6 The Many Different Types of Small Satellites

As the history of "smallsats" has evolved since the 1980s, it has evolved in many different directions.

First: There have been those that have pursued student-based satellite experiments such as the cubesat program to design very small and low-cost systems. Some of these have been as small as 01–09 g femtosatellites or picosatellites (i.e., 10–100 g) but are most typically cubesats that might have a mass of about 3–5 kg in most of these student exercises. Today most student experimental cubesats might be released from the Japanese module on the International Space Station that was built for such smallsat deployments.

Second: Others have developed more sophisticated smallsats for highly sophisticated scientific experiments that are for space agencies or military- or defense-related agencies. Some of these are in the 1–6-unit cube satellite range, while others are quite a bit larger and in some cases are designed as constellations such as the European Space Agency's three-satellite "Swarm" constellation or NASA's MMS four-satellite constellation. These satellites are currently measuring the Earth's magnetosphere and seeking to detect how magnetic North and magnetic South poles are shifting. Defense agencies are also beginning to build or contract for small satellite constellations for various activities related to their missions.

Third: Groups such as SSTL in Surrey, England, and the Utah State University have assisted countries or organizations that wish to create small satellites for specific applications as they first enter the field of space services. In this case they provide assistance and training for these entities or national space initiatives to create their first satellites for such purposes as data relay, remote sensing, or emergency services.

Fourth: There are a growing number of commercial organizations that are designing larger-scale small satellite constellations for remote sensing (i.e., Planet), position location (i.e., Spire), or communications or data networking (i.e., O3b and SpaceX). These satellites can range from 3-unit cubesats such as the "Doves" of the Planet system for remote sensing up to 500 km communications satellite in large-scale LEO constellations, such as those planned by Space X, Boeing, Telesat, and others.

Fifth: There are those that have decided to place "hosted payload" packages on larger satellites such as the Aireon System that is flying on the Iridium NEXT system. The US Federal Aviation Administration's Office of Space Transportation, known as FAA-AST, has created its own satellite classification system as shown in Table 1. (The classification system as provided in Table 1 for femtosats to nanosats is almost universally agreed. The definitions for microsats, minisats, and above, however, do vary.)

Table 1 Definition of types of “smallsats” based on mass

Mass classification system for “smallsats” in kgs (kg)
Femto 0.01–0.099 Kg (10–99 g)
Pico 0.1–1 (100 g to 1 kg)
Nano 1.1–10 (generally akin to cubesats)
Micro 10.1–200 Kgs
Mini 201–600 Kgs
Small 601–1200 Kgs
Medium 1201–2500 Kgs
Intermediate 2501–4200 Kgs
Large 4201–5400 Kgs
Heavy 5401–7000 Kgs
Extra heavy >7001 Kgs

Source: FAA AST, The Annual Compendium of Commercial Space Transportation 2018

Table 2 seeks to sort out the great diversity of “smallsats” that now exists. This diversity in size, mass, orbit, power, application, lifetime, functionality, and ability to maneuver and deorbit is confusing (see Table 2).

What is not obvious in the chart is that small satellites are more adept at providing some services than others. It is possible to shrink some key components of a satellite such as digital processors and sensors, but there are limitations with regard to other components. Satellite antennas and their “gain” (or transmission efficiency) are related to their aperture size which correlates to the square of their radii and the inverse square of their radio frequencies. There are limits on power due to the size of solar cell arrays. The area of the photovoltaic exposed to the sun is directly correlated to the power they can generate. The bottom line is that in the case of telecommunication services that depend on power and antenna aperture size, there are constraints on how much can be done with small satellites for communication services.

As noted earlier, there is advantage for small satellites when they are deployed in much lower orbits. A lower altitude orbit does allow the advantage of reduced path loss and reduced transmit beam spreading. But satellites can only sustain a LEO orbit if they are above about 160 km. In fact they actually need to be higher for two reasons. They need to be higher to achieve broader coverage without unacceptably high levels of switching between beams and from satellite to satellite. As one orbit satellites at lower and lower altitudes, the number of satellites needed for global services goes up exponentially and thus the need for switching frequency that affects reliability and continuous sustainability of service. Also satellites deployed in constellations need to be higher in orbit to stay in orbit for many years. Otherwise gravity and atmospheric drag on the satellites would make them deorbit much more quickly. The International Space Station at an altitude of about 300 km, for instance, has to be quite frequently re-boosted to stay in orbit.

The bottom line is that small satellites are well suited to data relay and optical remote sensing, but the usage of small satellites for broadband services such as for television broadcasting and for active radar imaging is really incredibly difficult to

Table 2 A guide to the many types of small satellites and their uses (This chart needs to be fixed)

The many applications, sizes, and characteristics of so-called smallsats								
Function/size	Telecommunication	Messaging/ data relay	Amateur radio	Remote sensing constellation	Relay to and from ground systems	Meteorological	Scientific experiment	Student experiments
Small mission 100–500 kg	Typical (see, e.g., OneWeb or Telesat constellation)	Typical (see, e.g., Orbcomm)	Not applicable	Typical for some commercial constellations	Typical (see, e.g., Orbcomm)	Typical for LEO and larger	Typical	Rare
Microsat 25–99 kg	Occasional	Typical	Typical	Sometimes	Often	Not applicable	Often	Sometimes
1 U–6 U CubeSat 1–25 kg	Not applicable	Rare	Occasional	Possible, e.g., Planet	Occasional	Not applicable	Sometimes	Typical
Nano-, pico-, or femtosat∗(10 kg–10 g)	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Occasional	Not applicable	Typical

[a] Definitions can vary, but a nanosat will typically be in the 1–10 kg range (also this can be a cubesat). A picosat is in the 100 g to 1 kg range and a femtosat is in the 10–100 g range. Smallsats in commercial constellations can often be in the 50–500 kg range, but not always. Planet has 3-unit cubesats that are less massive (All rights reserved by Joseph N. Pelton. Licensed to Springer Press for this book)

provide from LEO satellite constellations using small and lower-power satellite. This is simply a matter of technical design for both the satellite – based on power limitations – and in the case of home-based television reception installed low-cost user ground terminals.

Broadcast satellite systems to the home to low-cost receiving dishes work very well with consumer dishes that are constantly pointed in a fixed direction and do not have to track the satellite. These television broadcast satellite systems that currently provide over 25,000 television channels worldwide also require spacecraft with large aperture antenna dishes and the ability to transmit at very-high-power levels. Low Earth orbit satellites that travel at high speed across the horizon require tracking capability in the ground system (thus adding cost and complexity) and spacecraft with much higher power, large aperture antennas, and suitable spectrum suited to broadband services. Small satellite constellations can support data relay, digital communications for Internet services, and reasonable throughput data links, but direct to the home television remains best suited to GEO satellites and to user ground systems now installed in millions of homes and systems designed to service apartment buildings and condo units. Indeed most of the small satellite constellations that are currently planned for deployment are largely geared to providing new data connectivity to underserved or unserved regions of the world where Internet-based services are quite limited or even nonexistent.

In the case of remote sensing satellites, optical and ultraviolet sensors can be miniaturized with small sensors and passive collection of light and UV signals from the ground. Such systems can operate quite efficiently from low orbit constellations at modest power levels. Indeed such systems as Planet with hundreds of 3-unit cube satellites now operating can collect data and download it quite efficiently on a global basis. Radar systems are another matter. These types of satellite sensing system require high power that must be transmitted down to the ground and then be reflected back up. This does not mean that radar sat operations cannot be accomplished from smaller satellites, but it does mean that power levels constitute a problem and that this represents a challenge for small satellites in the radar sensing area. Canada is currently deploying its new “RADARSAT Constellation” that is quite a bit smaller than its initial first-generation RADARSAT deployed over a decade ago. This new constellation is composed of three satellites in this new network having relatively high power. Even though they are nearly 500 kg per satellite and as can be seen, the satellite has rather substantial solar arrays to support significant levels of operational power. The design of these new satellites has borrowed ideas from the smallsat revolution that allows them to be smaller than the original Canadian RADARSAT enables but still allows for their efficient operation. In short, design improvements and more efficient components can also be transferred to the design and operation of larger satellites to make them more cost-effective and easier to launch (RADARSAT n.d.) (see Fig. 8).

Finally, there are satellite services for Precision Navigation and Timing (PNT). In this case the prime constraint is the very high cost of precise atomic clocks that are deployed on these types of satellites. The network of satellites and the size of the constellation are optimized on the basis of effective global coverage and a

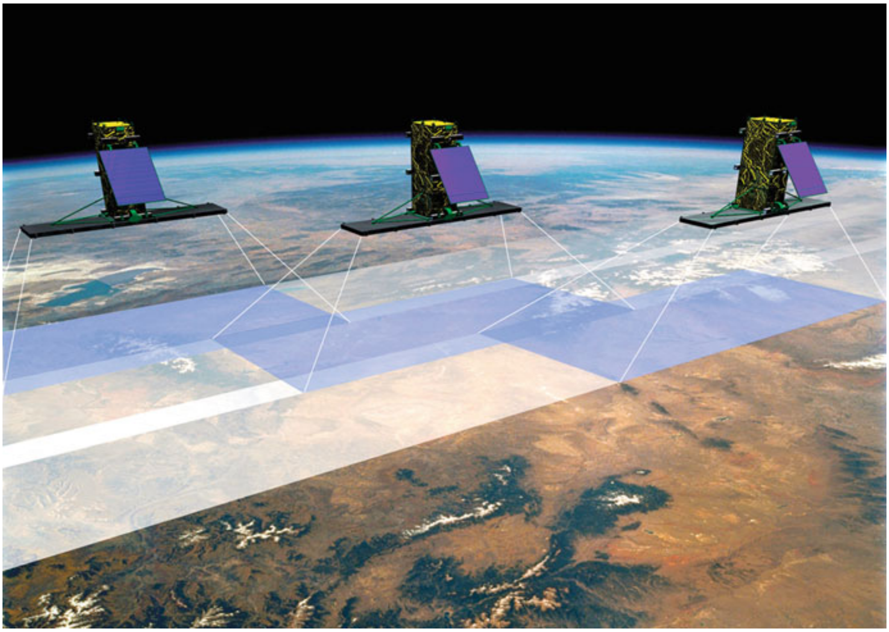


Fig. 8 The new three-satellite Canadian RADARSAT constellation is powerful enough to perform its mission (Graphic courtesy of the Canadian Space Agency)

minimization of the number of clocks that are needed. Deploying of a larger number of smaller satellites in a constellation would drive up costs since it would require the use of more atomic clocks.

The bottom line of this analysis of the relative merits of smallsats, smallsat constellations deployed in LEO orbits, and large and sophisticated satellites generally deployed in GEO orbits is to conclude that there is no single solution that is best. There are different solutions for different applications and services that result in different answers as to the most economic and logical design for satellite services. In some cases small satellite constellations, especially in the case of optical remote sensing, seem to offer a clearly superior answer. Systems, such as the Planet network, seem to provide the most economic and technically sophisticated network design for at least rapid repeat of sensing coverage. Large-scale LEO or MEO networks for digital networking such as represented by O3b, or systems such as those being deployed by Telesat, Boeing, SpaceX, or others, may prove quite cost-effective. The economic feasibility of LEO networks to support corporate enterprise networks for very-high-speed networking using rather large and sophisticated "small satellites" such as that proposed by the LEOSAT system remains to be proven economically. There are questions as to whether LEO smallsat systems designed to provide very high data rate corporate services will be able to provide the needed technical level of standards of service.

7 The Challenges of Design, Manufacture, and Testing of Smallsats

The field of small satellites has led to a host of innovations. This has resulted in a wide range of innovations that has changed a wide range of practices. Many of these innovations have permeated the space industry and affected the practices of space agencies, defense-related space agencies, and traditional aerospace manufacturers. It is interesting to note that some of those planning to fabricate large-scale small satellite constellations include not only SpaceX but also Boeing and AirBus and traditional communications satellite operator Telesat. SES and Intelsat, the two largest traditional satellite operators, have taken more than passing interest. SES has now taken full control and has been expanding the O3b constellation. Intelsat came very close to being directly merged with the OneWeb constellation, and this project was not completed due to Softbank withdrawing its offer of financing.

The change caused by small satellite systems ripples through today's space industry and can now be seen throughout the industry. One of the biggest areas of change relates to design, manufacturing, and testing. The traditional way that application satellites such as for communications or remote sensing were procured was through a set of specifications. These could be via a performance set of specifications that left it to the manufacturer to come up with a design that would meet these performance specs. Commercial operators of satellite systems used this form of procurement because it avoided specification changes and overruns. It capped expenses. This approach could also add incentive fees for meeting schedules and reliable performance. The other approach was to use a design specification that spelled out how the satellite was to be designed and spelled out materials and components to be used and even testing processes. This design specifically more typically came from defense agencies. These types of contracts with design specifications were awarded under a cost plus fee basis and constituted a more expensive form of contracting.

The procurement of satellites was seen as a long, arduous, and demanding process with many steps along the way that were stretched out over many years. There were initial design reviews (IDRs) between the procuring party and manufacturer to start the process. These were followed by other design review and ultimately a final design review, followed by actual manufacture of subsystems with testing undertaken, followed by systems integration and final testing. Some of the largest satellite operators had a team of engineers and scientists at the manufacturers' plant to oversee the manufacturing and test of the satellites. Typical production cycles were 36 months to even 48 months for the most sophisticated large-scale satellite. Production and final testing of large GEO satellites of this type were for a limited number of satellites ranging from perhaps three to six in number. Costs were in the tens of millions to even hundreds of millions of dollars, especially for defense-related satellites that might be especially designed with radiation-hardened components.

When the first commercial small satellite constellations were designed and built for Iridium, Globalstar, and Orbcomm, the whole paradigm as to how one should design, manufacture, and test satellites began to change drastically. One might, for example, use the Iridium system as an example of the change. The procurement was for 100 satellites, not 3 to 6, in number. The concept was to design and build the satellite production line that resembled automated production lines and to use 5 sigma quality and validation standards to produce a satellite of the highest quality so that extensive and expensive testing of each and every satellite was no longer necessary. The idea was to produce satellites not over periods of months and years but in terms of days. When the last of the Iridium satellites were rolling off the production lines at the Motorola plant, they were being produced at the rate of one every 4.5 days.

There were many design innovations that were geared not only to provide new and improved functionality to the satellite but also to aid improved manufacturing and testing reliability. These innovations included the use of phased array antennas that eliminated the need for the precise shaping of transmitting and receiving antennas. Also all of the satellite electronics use solid-state amplifiers rather than radio tubes. Remarkably the accelerated manufacturing and scaled-back testing of each satellite produced a remarkable reliability record. The initial Iridium satellite system that was deployed in 1997 and 1998 is only now being replaced by generation NEXT satellites nearly 20 years later, even though they were originally designed for a 6–7-year lifetime. The Iridium system was also designed with intersatellite links to aid sparing and backup as well as allow the entire global network of 66 satellites plus 8 spares to be controlled by two tracking, command, and control Earth station facilities. All of these innovations have been subsequently included in subsequent small satellite constellations.

This is not to say that Iridium was unique. The engineers, scientists, and production personnel that were involved with the design, manufacturing, and testing of other new small satellite systems such as Globalstar and Orbcomm use many of the same innovations to cut costs, increase production times, limit testing costs, and use solid-state technology. Others provided different innovations. The particular design of the Orbcomm satellites allowed cost reductions related to the ability to launch more satellites more efficiently at the same time, use lower-cost Pegasus launch vehicles, and lower stabilization costs. The common factors that are seen throughout the small satellite industry today are the much more rapid mass manufacturing techniques as well as new and much more efficient approaches to quality and validation testing and verification techniques.

Today the innovation in manufacturing and accelerated testing continue apace. Today there are continuing efforts to use automated manufacture of components in the production of smallsats. This includes the concept of additive manufacturing of components to create consistency of production. The key to reliable 3D printing involves high-quality standards for materials that are used in the printers as well as improved printer designs. It is possible that innovations here can also allow components to weigh less and thus reduce the amount of mass to be launched in large-scale constellations. The other key issue remains the extent to which one can use off-the-shelf components rather than much more expensive space-qualified materials and components.

In some cases inexperienced designers can jump to conclusions about where, when, and how one might use such off-the-shelf materials for wiring, thruster jets, fuels, and digital processors. These might pass tests on the ground but will perform differently in space. This can lead to shorts, fires, or failures in the outer space environment. NASA, ESA, and other space agencies have created test facilities to confirm whether certain materials, wiring, or component elements can be safely utilized in space without overheating, creating a fire, or leading to other hazardous conditions. The key is to recognize that a change in temperature, pressure, or gravity can alter the safety and performance of various materials, wiring, gases, etc. Expert advice needs to be sought when planning to use off-the-shelf materials or non-space-qualified components such as processors, electronic equipment, heat pipes, reaction wheels, fuels and thruster jets, etc.

There are a range of new approaches that are being used with regard to verification and validation testing. One approach that is used with cubesat-type systems such as the "Doves" or 3-unit cubesat remote sensing satellites in the Planet network is to assume that a certain percentage of these satellites will fail but that the constellation has a sufficient population for the network to perform smoothly. Another strategy is to produce enough units at sufficiently low cost to be able to provide sufficient number of spares to replace any satellites that fail. Most small satellite system designers try to do a "type qualification" of their initial satellite under the most stringent conditions. Thus they strive for the highest levels of consistent production so that their first, their tenth, and their hundredth products are produced exactly the same and to the most consistent standards.

There are countervailing influences here. In the case of the Planet production of their smallsat "Doves," there is a team that is consistently seeking to improve their performance. The past generations of satellites, in terms of upgraded performance, were perhaps 4–5 years apart. In the case of Planet, their improved design and upgraded performance may come only months apart. Constant improvements are being sought. The key is to ensure that upgrades in design and performance do not degrade consistency of production, reliability of design, and production quality.

8 Key Challenges for Small Satellite Constellations Related to Regulatory and International Process Issues

Clearly there are a number of advantages that come with the deployment of small satellites that are typically deployed in low Earth orbit. These advantages are (i) reduced transmission path loss due to their deployment in low Earth orbit; (ii) use of lower cost components and more off-the-shelf components that reduce costs; (iii) ability to achieve economies of scope and scale not only in their manufacturing but perhaps especially so with regard to accelerated validation and quality testing; and (iv) also their reduced size and mass and lower orbits making them easier to launch and at a lower cost. For instance, a total of 88 Planet satellites were launched on a single Indian Polar Satellite Launch Vehicle in February 2017. In fact additional 16 cubesats were also launched to set a record of 104 satellites being launched at one time on a single rocket (Foust 2017).

But there are also challenges and difficulties that are also present with the global trend to launch more and more satellites into orbit. There are very real regulatory, spectrum allocation, RF interference, and other constraints that must be addressed.

These difficulties include such problems as (i) orbital debris mitigation and concern about the so-called Kessler syndrome; (ii) radio-frequency coordination and interference avoidance with regard to other LEO satellite constellations and particular concern with regard to interference to satellite in GEO that have protected status; (iii) sufficient RF spectrum and orbital space to accommodate all of the many smallsats now proposed for launch (note: the number of small satellites now proposed for launch exceed 20,000 if they were all placed in orbit); (iv) likely insufficient launch capacity to accommodate the launch of all these systems in a short period of time nor sufficient launch capacity to replenish these satellites when they reach end of life (i.e., 5–7 years); and (v) sufficient ground segment transceivers with tracking capability (i.e., especially electronic tracking capability) to meet the demand for user ground systems.

The detailed market studies that have been carried out concerning these new small satellite consortiums, however, have concluded that only some of these systems will actually be deployed and operated. The Northern Sky Research study has estimated that perhaps only 7000 or so of the minisatellites will be deployed (Northern Sky Research 2018). Further, the Space Works study has concluded that perhaps about 2600 of the nanosat/microsats will finally be deployed in the next 5–8 years (SpaceWorks Announces Release of 2018 Nano/Microsatellite Market Forecast 2018).

These are severe challenges that pose an unprecedented number of problems to be addressed and solved in a short and increasingly urgent period of time for the small satellite industry. Some analysts suggest that many of the proposed systems will not be able to obtain the needed financing to build and launch all of the systems that have been proposed. Thus one of the possible solutions to the various problems noted here might be solved by the simple fact that far fewer of these small satellite constellations will be launched than those that have been proposed. For instance, in the 1980s, the US Federal Communications Commission (FCC) actually approved licenses for 17 new Ka-band satellite systems to be deployed. After the dust had cleared, it turned out that only two of those systems were in fact launched and operationally deployed.

The issues of radio-frequency spectrum and interference represent major issues that are not new. The International Telecommunication Union has sought to find ways to accommodate the growing demand for new application satellite services for many decades. There was an Extraordinary Administrative Radio Conference in 1959 followed by the 1963 Radio Conference that made the first radio-frequency spectrum allocations for NewSpace services. There have been ITU sessions every 4 years since. The latest ITU World Radiocommunication Conference was held in 2019. This represents 15 such ITU World Radiocommunication Conferences since the start of the Space Age. The issues that have been addressed, debated, and sometimes resolved have only increased in scope and intensity of debate. Over the years additional spectrum has been allocated for satellite services. There has been allocation of frequencies in the VHF and UHF bands, largely for mobile, scientific, and military satellite uses. There have been allocations in the C-band, X-band, Ku-band, Ka-band, and most recently the Q/V band for civilian and military uses. As the allocations have moved to higher and higher frequencies, larger bands of spectrum, as large as 2500 MHz frequency bands, have been assigned to satellite use. Smaller bands for meteorological, precision navigation and timing, and remote sensing services have also been allocated (Allison 2014).

Yet, at the same time, there has been additional pressure exerted to convert frequencies, such as those in the S-band and the C-band to broadband mobile services to accommodate the needs for new services such as 5G cellular service.

Other conflicting values have also been exposed, and new regulatory constraints have been imposed at these ITU World Radiocommunication Conferences. This has resulted in assigning “protected status” for GEO satellites vis-a-vis non-geostationary satellites. There has been a division of allocated bands for communications into various specific uses. These have included such specifically defined services as fixed-satellite services (FSS), mobile satellite services (MSS), and broadcasting satellite services (BSS).

Developing countries have felt that the “first come, first served” allotment of frequency use and orbital location registration has worked to their disadvantage. Further countries may agree to global allotments of spectrum for particular uses in their region (i.e., the world of frequency use is divided into three regions, namely, Region 1, Europe and Africa; Region 2, the Americas; and Region 3, Asia and Australasia), but then they add a footnote to say that they take exception for this usage in their own country. Often the world of terrestrial radio usage and the world of satellite communications can come into conflict. The new stratospheric usages associated with UAVs and high-altitude platform systems have complicated spectrum allocation disputes and conflicts even further (Ibid.).

The world of Geo satellites is reasonably straightforward in that there are spacing rules for different types of satellite services. Geo satellite locations are registered in the ITU’s international frequency register after intersystem coordination procedures are conducted. Satellites that drift north or south from the equator more than 7° North or South of the Equator are no longer considered in GEO orbit.

The world of small satellite experimental spacecraft and large satellite constellations in LEO orbits becomes ever more confusing in that more and more constellations are being proposed within increasingly complex and larger orbital configurations. Some of these will have intersatellite links, while others do not. There are currently no precise limits as to how exactly many satellites might be launched within a single constellation of small satellites nor precise standards for station-keeping exactness. When the earliest systems like Iridium, Globalstar, and Orbcomm came online with a maximum size of around 70 satellites (i.e., 66 satellites plus spares), the idea of limits on the number of satellites and their proximity might not have seemed important. But today the largest of the SpaceX constellations now proposed for operation in the Q/V bands would deploy a rather spectacular number of satellites.

9 Regulatory and Technical Innovations to Cope with Orbital Space Debris

The staggering number of small satellites that have now been proposed for launch in the coming years is in excess of 20,000. This has given rise to very serious concerns about orbital space debris. Figure 9 provides a recent inventory of the debris now in Earth orbit and a breakout of where over 6300 tons of debris now orbits the planet.

And these concerns are not only on the part of experts such as those that monitor satellite orbits and debris such as the US Air Force's Joint Space Operations Center (JSpOC) Mission System (JMS). Actually, the companies that are spending billions of dollars to deploy these huge satellite constellations are themselves concerned about their potential risk and possible liabilities (Op cit Northern sky research, small satellite research, 5th Edition).

The problem of the regulatory guidelines about orbital debris removal is obvious to anyone who examines the "math" associated with the current debris removal guidelines that say debris, including defunct satellites, should be removed from orbit within 25 years of the end of life of satellites. This now out-of-date guideline for debris removal was originally based on the time that debris goes through based on two solar max cycles (which occurs over an 11-year period and creates the maximum atmosphere drag on debris). The LEO small satellites have a lifetime of about 5–7 years. Constellations numbered in the thousands will take years to deploy. The replacement cycle will have to take place within 7 years and so on into the future.

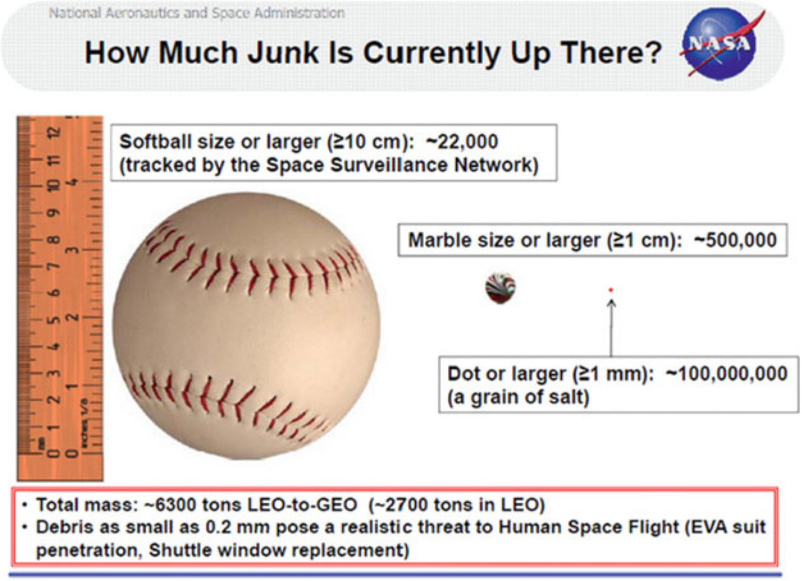


Fig. 9 NASA status of space debris which will only increase as more constellations are deployed (Graphic courtesy of NASA)

The removal of satellites based on a 25-year cycle guideline no longer makes sense. The math simply does not work. Controlled deorbit of satellites at the end of life represents a space safety challenge, and there are serious risk elements to be considered. Operators of these systems are themselves advocating new guidelines that are drastically shorter than the current 25-year guideline.

The current estimates are that there will be a collision in orbit between once in 5 years and once in 10 years, depending on which model (i.e., ESA or NASA) is used. What we do know is that each and every collision contributes to the amount of debris in orbit and especially that in polar orbits and low Earth orbits. Some may believe that since small satellites have smaller cross sections, the chance of a collision is less, but what the small satellites lack in size their sheer volume more than makes up for in terms of on-orbit collision probabilities. The bottom line is that the orbital debris problem and the risk of continuing on-orbit collisions continue to increase in seriousness. This means that active debris mitigation processes are important.

New strategies for coping with orbital debris continue to develop. The abilities for on-orbit servicing and active debris removal or even repurposing of debris in orbit continue to evolve. Currently there are efforts under way to provide new standards and regulatory provisions with regard to rendezvous and proximity operations (RPO). This is an area that needs serious attention as the current debris environment in space continues to worsen (Pelton 2015).

10 Conclusions and Future Directions

This Handbook on space satellites seeks to be as comprehensive and far-reaching as possible. It seeks to cover the technology in terms of the satellites; the ground systems and launchers; the applications, services, and markets; the security concerns; and the regulatory, policy, standards, and economics associated with small satellite systems of all types. It seeks to distinguish the smallest small satellites (i.e., femtosats, picosats, nanosats, and cubesats) from the larger microsats and minisats. Experts from around the globe have been recruited to contribute to this Handbook from the academic world, the regulatory world, and the space industry world. Its objective is to provide useful information about the companies that participate in the small satellite industries, the many small satellite constellations that are now in service or planned, as well as the many companies seeking to provide launch services to support the world of small satellites. In light of the fast-moving nature of the industry and many changes that are occurring almost daily, it is recommended that researchers refer to the URL addresses provided in most instances to determine the latest information. Any omissions or key changes not included in this Handbook are entirely unintentional.

11 Cross-References

- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Commercial Small Satellite Systems in the “New Space” Age

- ▶ Overview of Cubesat Technology
- ▶ The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and CubeSats

References

A.L. Allison, *The ITU and Managing Satellite Orbital and Spectrum Resources in the 21st Century* (Springer Press, Cham, 2014)

AMSAT, Live Oscar Satellite status page (n.d.). https://www.amsat.org/status/. Last accessed 30 May 2019

Bryce Space and Technology, Smallsats by the numbers 2019, p. 6 (Jan 2019a)

Bryce Space and Technology, Smallsats by the Numbers (Feb 2019b)

Conversation with James Stuart at the University of Colorado in the late 1980s (n.d.)

Digital Library of Papers Presented at the Small Satellite Conference Since 1987, Digital Commons Library, Utah State University, Logan, Utah, (n.d.). https://digitalcommons.usu.edu/smallsat/. Last accessed 8 July 2019

T. Farrar, Is the new space bubble about to burst? Room Space Journal **4**, 45–47 (2018)

J. Foust, Space news, India sets record with launch of 104 satellites on a single rocket (17 Feb 2017). https://spacenews.com/india-sets-record-with-launch-of-104-satellites-on-a-single-rocket/

Iridium Satellite Constellation (n.d.). https://en.wikipedia.org/wiki/Iridium_satellite_constellation. Last accessed 30 May 2019

Northern Sky Research, Small satellite research, 5th edn (Dec 2018). https://www.nsr.com/research/small-satellite-markets-5th-edition/

J.N. Pelton, *Basics of satellite communications*, 1st edn. (International Engineering Consortium, Chicago, 2003)., 2nd Edition 2006

J.N. Pelton, *New solutions for the space debris problem* (Springer Press, Cham, 2015)

J.N. Pelton, *Space 2.0: key trends in the 'new space' industry* (Springer Press, Switzerland, 2019)

Pocketqube Satellites (n.d.). https://en.wikipedia.org/wiki/PocketQube. Last accessed 16 Mar 2019

PSLV-C37 Successfully Launches 104 Satellites in a Single Flight (n.d.). https://www.isro.gov.in/update/15-feb-2017/pslv-c37-successfully-launches-104-satellites-single-flight

RADARSAT, Constellation Mission (n.d.). https://digitalcommons.usu.edu/smallsat/on, http://www.asc-csa.gc.ca/eng/satellites/radarsat/default.asp. Last Accessed 30 June 2019

Small Satellite Conference (n.d.). https://smallsat.org/. Last accessed 15 June 2019

SpaceWorks Announces Release of 2018 Nano/Microsatellite Market Forecast (30 Jan 2018). https://spaceworkseng.com/spaceworks-announces-release-of-2018-nanomicrosatellite-market-forecast/

Surrey Satellite Technology Limited (n.d.). https://www.sstl.co.uk/about-us. Last accessed 15 June 2019

Teledesic History (n.d.). https://en.wikipedia.org/wiki/Teledesic. Last accessed 30 June 2019

Historical Perspectives on the Evolution of Small Satellites

Scott Madry and Joseph N. Pelton

Contents

Abstract

This chapter reviews the history and the evolutionary development of small satellites and of launch vehicle systems and the evolution of orbital space debris over time. It suggests that the development of space technology, space systems, and rocket launchers has occurred in response to various military, political, economic, scientific, and business mandates. This history that as now cover a period of over a half century has evolved in an almost haphazard fashion, largely

---

S. Madry (✉)
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_2

without concern for the space environment in Earth orbit and the need to pay attention to the long-term sustainability of outer space activities. Such concerns for "sustainability" have only come into focus since the 2010s. It also notes that the concept of "smallsats" has continued to evolve and change in many ways over time.

This chapter notes how technical innovation, disruptive technologies, new commercial space opportunities, and entrepreneurial aspirations have all contributed in the past decade to fuel the newest aspects of "New Space" or "Space 2.0" and "smallsat" development. This has created new opportunities to use space systems in new and innovative ways – especially for new entrants and users from developing economies. Yet these new commercial space initiatives and especially new large-scale "smallsat" constellations have also given rise to the problems of excessive amounts of space debris in Earth orbit. There are now particular concerns about the need for space traffic control and management that arise from the fear of runaway proliferation of space debris, known as the Kessler syndrome. This "Kessler syndrome" posits that there could be a real future possibility of a growing avalanche of space debris accruing over time with new major collisions in space happening every 5–10 years. This history seeks to give a comprehensive view of the new opportunities that small satellite systems and new launch systems could bring to global economic growth and new space-based services but also to note negative developments and concerns that need to be addressed to ensure the longer-term sustainability of the space around Earth – especially LEO, MEO, and GEO orbital regions. This history thus seeks to place the development of small satellites into some context that compares their current state of technical and operational evolution in without repeating the historical notes already provided in Chap. ▶ "Introduction to the Small Satellite Revolution and Its Many Implications"

Keywords

Disruptive technologies · Explorer 1 · Kessler syndrome · Launch vehicles for small satellites · Miniaturization · "New Space" · Off-the-shelf components · Orbital space debris · Satellite constellations in low Earth orbit · Small satellites · "Space 2.0" · Space traffic control/space traffic management · Sustainability · Sputnik 1

1 Introduction

The history of space and small satellites dates back to the start of the space and even the age of Isaac Newton. When Newton first grasped the concept of gravitational force, he not only understood the gravitational attraction between the Earth and falling objects, but also how artificial satellites could achieve orbit. He was able to calculate what it would take, in terms of accelerative force, to achieve orbital velocity. In his book, *Principia Mathematica*, written in 1685–1686, he produced an illustration showing how a cannon ball fired with sufficient speed would be able to achieve orbit (Writing of Principia Mathematica n.d.) (Fig. 1).

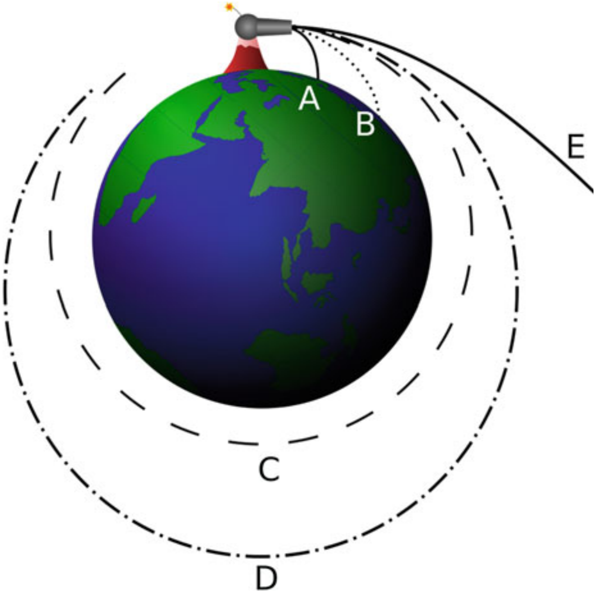


Fig. 1 Isaac Newton's conception of the launch of a satellite from *Principia Mathematica* (1686) (Recreation of Newton's concept of cannon ball launched into Earth orbit). By user: Brian Brondel – Own work, CC BY-SA 3.0. https://commons.wikimedia.org/w/index.php?curid=1657849

Thus, it could be said that the launch of a small satellite was first specifically envisioned, based on a clear conceptual knowledge of the physics involved, at the end of the seventeenth century.

And the very first satellite launches by the USSR with Sputnik 1 and by the USA with Explorer 1 were both small satellite launches. It has been noted by Space Traffic Control advocate Stuart Eves that the very first launch in October of 1957 of Sputnik 1 put not only a small satellite into orbit but the first space debris objects as well. Eves notes that the ejected nose cone, the upper stage of the R-7 rocket stage, and even the Sputnik 1 satellite itself that stopped transmitting after several days of operation all become the first three debris objects in Earth orbit (Eves & Space Traffic Control 2019). Today the many debris objects in Earth orbit, with over 40% of them in low Earth orbit (LEO), have led to rising concern that space debris could eventually deny humans safe access to space.

From the very first days of the space age in the late 1950s and late 1960s, the efforts were to find new ways to make practical use of space systems that extended beyond the earliest use of space as rockets as military instruments to deliver bombs and destruction during times of wars. The creation of civilian space agencies such as NASA thus began to develop satellite applications such as for telecommunications and broadcasting, for remote sensing, Earth observation, meteorology, navigation, precise timing, and so on. In other cases space systems developed for military purposes such as the GPS were adapted to perform a wide range of practical purposes such as aircraft safety, self-driving cars, and mapping. The space agencies and the largest commercial activity, namely, satellite communications, followed a pattern of "bigger and better" spacecraft with more power, wider radio-frequency spectrum allocations; this pattern was shown in Fig. 3.

In the 1970s and 1980s, there were a number of initiatives undertaken first by amateur radio operator technicians and engineers and then by projects initiated by the Surrey Space Centre with regard to non-real-time data relay and machine-to-machine relay and lower-resolution remote sensing activities involving small satellites. These few "off the beaten path" activities were, at the time, not considered "mainline" undertakings. The main space businesses with the large streams of revenues were involved either with major governmental and military projects or commercial satellite activities that were engaged in designing, building, and launching larger and larger satellites.

In the late 1980s and 1990s, however, there began to be a number of new ideas percolating in the industry about what satellites could do in terms of mobile communications satellite services. Most of these new concepts involved the idea of deploying low Earth orbit (LEO) constellations. Most of these new initiatives concentrated on how to deploy lower latency satellite services and using very small handheld user terminals that could provide narrowband data and voice services. There was a lot of thought about how to use more effectively efficient digital compression techniques and application-specific integrated circuits to achieve user transceivers that could be used for personal communications.

2 Evolution of New Small Satellite Systems in Low Earth Orbit for Telecommunications Services

Perhaps the most significant of these new initiatives was the Iridium Satellite network, which was spearheaded by Motorola. The concept that was advanced envisioned a 66 satellite LEO constellation with spares that would utilize phased array antennas on the satellites, inter-satellite links, and new ground antennas that could be made smaller and more efficient using digital processing and application-specific integrated circuit (ASIC) firmware.

This innovative "smallsat" LEO system sought to break the mold of relying on advancement through deploying larger and larger satellites in GEO orbits. This effort to design a system with smaller satellites in low Earth orbit was spearheaded by Motorola and network of partners that Motorola recruited from around the world. Motorola already had a great deal of experience with handheld radio units for cellular radio communications services and high-quality, mass production of consumer products, but a limited amount of satellite experience. It formed a global partnership to design, manufacture, and launch this LEO constellation. Along the way it recruited knowledgeable people from the global Intelsat community and sought a number of commercial participants from the Intelsat network to join in the partnership. It came up with a very innovative design that used 3 phased array antennas to create some 48 reasonably high-powered spot beams. See Fig. 2 (Gupta and Swearingen 2016).

The design was fairly sophisticated for a small satellite and included the ability to create four inter-satellite links to connect to the two satellites to before and after it in the North-South orbit as well as the two satellites to the East and West in the constellation. Despite the sophistication of the design with the phased array antennas and the inter-satellite links, the goal was set to produce these satellites on a rapid production line. And by the end of the production, the Iridium satellites were being produced in a 4.5-day sequence. This was in contrast to the production of large GEO satellites on an 18–24 month or even longer production cycle. Although these satellites were first conceived to have a 7-year lifetime, many of these satellites operated in the range of 15–18 years (see Fig. 2).

The second initiative that followed closely on the heels of Iridium was the Globalstar mobile satellite communications system. In this case the plan was to deploy some 50 small satellites in a LEO constellation covering the Earth between 70° North and 70° South since they saw little market from seals and polar bears. Globalstar also envisioned voice and data satellite communications to handheld units from small satellites in LEO orbit. The INMARSAT network for maritime and aeronautical mobile communications and operated a series of GEO-based satellites also moved to spin off a new venture known as the ICO (or International Circular Orbit). This new venture began to plan and deploy a constellation of 15–18 satellites in MEO orbits. Finally the Orbital Sciences Corporation proposed a constellation of quite small satellites for store and forward data links and machine-to-machine communications (Ibid.).

These various initiatives began to introduce a number of highly innovative technologies. These were, among other aspects, (i) in the design of small satellites and their antenna systems; (ii) in the systems for management and operation of global constellations of satellites in low orbit to avoid collision and to control deorbit activities; (iii) in the design of handheld user units as well as smaller-scale mobile and portable units for military or defense-related use; (iv) in the use of inter-satellite links; and (v) in global billing systems and country access codes that these systems used. The market studies and strategic business plans for these systems were a different matter. In 1998 not long after these systems were

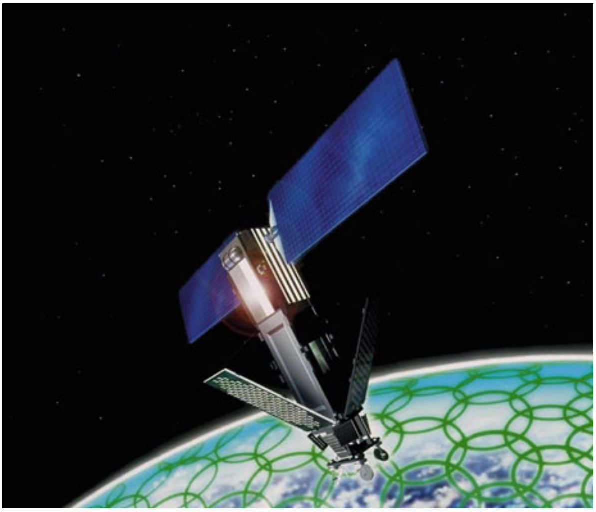


Fig. 2 Iridium satellite in low Earth orbit with spot beam patterns shown below. (Graphics courtesy of Iridium)

deployed Iridium and Globalstar systems declared bankruptcy. The ICO system declared bankruptcy without ever deploying any spacecraft. The Orbcom system which was a much lower-cost system with a smaller capital investment continued to operate longer, but it too was forced to declare bankruptcy as well.

The technologies for these LEO constellations had some issues with link margins especially when handheld units were expected to operate from inside of an automobile or other vehicle. Yet, all three systems (i.e., Iridium, Globalstar, and Orbcom) worked technically despite some initial bugs and improved in the performance over time. Both the small satellite constellations and the ever-improving ground systems and user handsets and user terminals all demonstrated that such systems could provide satellite services directly to end users. Clearly there were problems inside of cities with high rises, in forests, and inside of buildings and cars, but these were problems that second-generation systems with higher power could solve.

The Iridium system provided useful new information about how to operate large-scale constellations and new ways to replace operating spacecraft with technical difficulties with replacement satellites. Iridium engineers developed a clever way to deploy 66 instead of 77 satellites in their constellation by adjusting their orbital elevations and also how to replace efficiently failed satellites with spares on a single launch.

First they raised their orbit slightly to a new deployment altitude of 781 km. At this height they found that they could eliminate 11 satellites from their constellation. The original plan was to have 77 satellites (Note: The atomic number of Iridium is 77) that would be deployed in seven different planes populated by 11 satellites each. With the higher altitude, they were able to go to 6 planes of 11 satellites each and thus reduce the constellation number to 66 satellites (Op cit, Stuart Eves p. 10).

The other lesson learned, in terms of efficient deployment, was to discover a way to populate the Iridium constellation with replacement satellites in two different planes with a single launch which would be carrying multiple satellites. In this particular case, they launched the replacement satellites into an altitude of only 666 km instead of 781 km. They then quickly boosted satellites with onboard thrusters into the correct plane where replacements were needed. They then waited until the remaining satellites meant for replacement of satellites in the adjacent plane to drift into the proper plane position at the lower altitude and they then boosted them up into the proper location 115 km above (Op cit, Stuart Eves p. 10).

The technical problems were challenging. Clearly there were problems of satellite design and performance. And there was an even greater need for improved ground systems design for user transceivers. There were in need of the technology that would come decades later in the form of electronic beam forming and tracking systems that can replace more expensive physical tracking systems that require dishes to physically track satellites as the move across the sky. Technical challenges were addressed and mainly solved over time. It was the market, charging tariffs, and financial failures of all these systems, however, that created the real shock waves, bankruptcies, and crises in financial markets.

And the problems were not limited to mobile satellite services. Further problems for small satellites deployed in constellations came from the Teledesic system proposed around this time. This was the ahead of its time proposal for a so-called MegaLEO system. This proposal advanced the idea of a LEO constellation capable of providing broadband digital services for fixed satellite services via a huge constellation (about a 1000 satellites). The fact that this Teledesic system, backed by billionaires Bill Gates and Craig McCaw, also experienced bankruptcy further discouraged the idea of providing commercial satellite services from small satellite constellations deployed in LEO orbit. As noted in the introductory chapter, this string of bankruptcies took its toll on smallsat constellation concepts. The idea of moving from GEO-based systems to LEO constellations using “smallsats” for communications services was abandoned for years to come.

Although the idea of new entrants providing LEO-based services from “smallsat” in a LEO constellation essentially went on pause, the idea of LEO constellations never went entirely away. Several things served to change the landscape. The Iridium, Globalstar, and Orbcom satellites were bought out of bankruptcy and the reorganized businesses found a way to achieve profitability. Part of this success was based on the low cost of acquiring the satellites from the bankrupt organizations, and part was due to market development. Second-generation satellites for these systems have all now been deployed, and financial viability has been established for all these networks. Ground user systems have greatly improved. Further systems for use on aircraft and marine systems have improved and market demand has increased. Twenty years allows time for many improvements.

Also, most significantly the concept of cubesats was born, and their design, fabrication, and testing for in-flight operation have rippled through universities in the USA and around the world. This development process has found technicians, engineers, and scientists engaged in intensive studies focused on miniaturization of virtually all of the components that were involved in creating and manufacturing truly small operational satellites. This process has led to the development of miniature remote sensing devices. We have seen the creation of exceeding tiny digital processors and digital communications systems. The performance of satellites and especially user terminals has been enabled by all sorts of specialized software, small star and sun sensors, improved and miniaturized stabilization systems, small thrusters, innovative small solar array systems, tiny batteries, small antenna systems, and more. Many of these miniaturized systems were thus invented and successfully deployed for university student experiments, but can today be utilized in commercial systems. New systems such as passive deorbit systems using inflated balloon systems can deploy at end of life to create atmospheric drag. We have seen creative deployable and slide-out body structures and antenna extension systems. These innovative designs have allowed very small cubesats to become highly functional and efficient as antenna and solar arrays deploy and the body structure doubles in space-based configurations.

Many of the experimenters have not only created compact but highly functional new and creative cubesat designs, but they have also found that they could use much lower-cost off-the-shelf components in these satellites. The end result is that an amazing capability could be fitted within these small satellites that were only 10 × 10 × 10 cm in size (or about four in cubes). Even when they have been scaled up to a three-unit cubesat (i.e., 10 × 10 × 30 cm), they are still quite small in mass, and their functionality is increasingly amazing. Of course the savings come not only from having smaller satellites and units that use lower-cost off-the-shelf components. The biggest cost savings is on launch costs. Planet that deployed 88 three-unit cubesats they call "Doves" (i.e., their solar arrays evoke the image of a bird's wings) in a single launch on an Indian PSLV accomplished this entire deployment for a cost less than a third the cost of major communications satellite launch.

Instead of satellites that came from space agency designers, large aerospace companies and military agencies, we saw the emergence of small satellites created with an entirely new mindset. These cubesats created by young innovators and entrepreneurs became the starting point from which to question conventional thought about how big a satellite had to be to accomplish its various missions.

From this starting point, we even saw the invention of ultra-small femtosats, picosats, and nanosats that could accomplish many tasks once thought to require very large satellites that took years to design, manufacture, and test which were ten times, a hundred times, or even larger in size.

This new mindset some have called "Silicon Valley" meets the aerospace industry, or Space 2.0, or just "New Space." Regardless of what one calls this new mindset, it has become the motive power that has given rise to a host of new commercial "smallsat" ventures. This in turn has also helped to fuel a new commercial effort to create new more cost-efficient launch systems as well.

There were engineering students and budding entrepreneurs who jumped at the chance to design and build very small satellites that could engage in commercial remote sensing, data relay, automatic identification services, and even communications services by building and launching constellations of these smallsats.

Undertakings in the "New Space" arena had many sources of inspiration. One such inspiration was the Ansari XPrize. This created the challenge to develop commercially a space plane that could fly with crew of two on a suborbital flight into space and back and then do it again within 8 days. Only if all of these conditions were met would the new space plane developer be entitled to collect a $10 million challenge award. This feat was rather miraculously accomplished in 2004. This remarkable achievement created a huge impetus toward private new space ventures. The key aspect of this challenge was not only that the Burt Rutan and Paul Allen succeeded and actually won the prize in 2004 but that dozens of teams were formed around the world. These various private venture entrepreneurs sought to prove that they could create the new technology to make this happen.

There are now many ventures that have blossomed from efforts to create new and lower-cost launch vehicles, new small satellite ventures for remote sensing, or new ventures for satellite communications and networking services, especially in the underserved areas of the world.

3 The Rebirth of Small Satellites for Telecommunications Services

There is a remarkable man named Greg Wyler who, perhaps more than any other, has given impetus to the current boom in LEO constellations for telecommunications and networking services. He began a quest some two decades ago to provide domestic telecommunications services in Africa. He looked at various models that would deploy fiber-optic cable systems and found that none of these business models would work financially. He finally had his "aha" moment when he looked at the idea of using satellites to cover not just one country, but to create a satellite system that would cover the entire equatorial region of the world as had been first proposed by Brazil in their "string of pearls" satellite along the equator. Wyler decided that as a first step he and his partners would create a medium Earth orbit (MEO) constellation called O3b. This system would be named O3b for the Other Three Billion people in the equatorial region of the world that had limited access to telecommunications, educational services, health care, potable water, and nutrition. He was able to recruit a number of partners such as SES of Luxembourg that operated one of the world's largest GEO networks, Google, Liberty Global (the cable television and Internet service provider that was started by John Malone) HSBC bank, and a number of other backers for this $1.3 billion venture. It began with 4 satellites in its MEO constellation and then grew to 8, 12, and then 16 satellites to provide broadband services with greatly improved latency over GEO satellites. This network was sold to SES that now owns the entire network.

But Greg Wyler had a much more ambitious second act in mind. He left his position at Google and along with Brian Holtz and David Bettinger to start WorldVu in 2014. They created a company with about 30 employees to design and build a large constellation of small satellites that would blanket the world with around 900 satellites to provide low latency broadband services. This number has now been scaled back to about 600 satellites (Henry 2018).

In January 2015 it was renamed OneWeb and key investors started to come into the $3 billion smallsat system. As now planned it is to begin as a 648 network, but plans to expand over time.

There were many innovations here that one can attribute to Weyler and his partners. One of these was that one of the larger investors in the project was AirBus that was selected as the contractor to build this network of 110 kg small satellites. Another large investor was Arianespace which was contracted for the launch of many of the satellites. Thus the companies that provided a significant amount of the financing for this MegaLEO system were also the contractors for building the satellites and launching many of the satellites (https://www.oneweb.world/) (see Fig. 3).

One of the concerns that was discussed with Weyler on the occasion of his being awarded the Arthur C. Clarke Innovator Award was the problem of safe operation of this large network, avoidance of interference with GEO satellites and ground

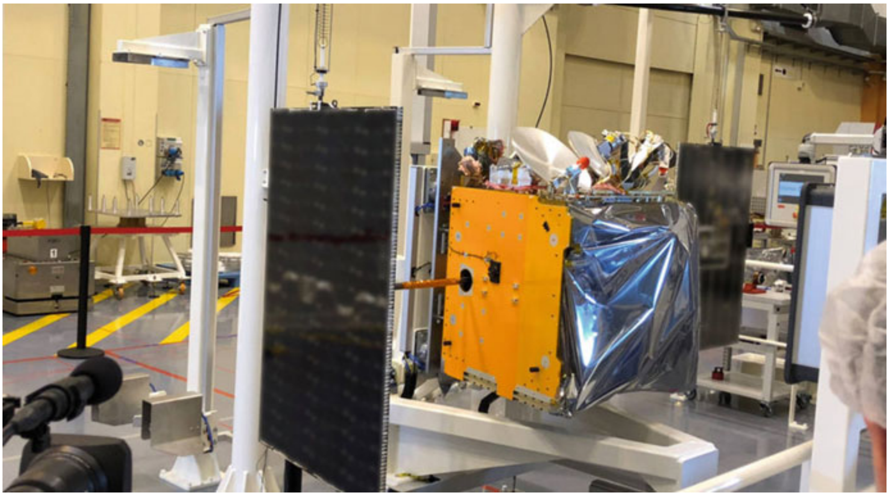


Fig. 3 One of the 110 kg. OneWeb satellites in production in Toulouse, France. (Graphic courtesy of AirBus)

systems, and disposal of the OneWeb satellites at end of life. The altruistic Weyler admitted concerns about avoiding interference and noted that the 25-year period for disposal of satellites at the end of life was inadequate and that this was in 2016 before the spate of additional large-scale systems were proposed for launch (Talk with Greg Wyler in Washington, D.C., n.d.).

OneWeb, however, set off an avalanche of other "smallsat" constellations that were to follow. Some of the constellations, just for telecommunications and networking services, that were to follow are listed below (see Table 1).

4 The Evolution of "Smallsat Ventures" for Remote Sensing, Tracking, and Weather Monitoring

The many new ventures use "smallsats" to provide commercial services in such areas as remote sensing, vehicular and ship tracking, and automatic identification services (AIS) and began to blossom starting around 2010. Many of these started from university-based cubesat.

The Planet Labs Remote Sensing System: This is a story that started quite close to home in that the author of this particular article was teaching at the International Space University (ISU) at its Space Studies Program held at NASA Ames in the Summer of 2009. In partnership with my colleague Dr. Scott Madry, we were co-chairing the Space Applications Department. One of the 20 or so "students" in the department was a very bright and compelling young man named Will Marshall who was also working as an intern at NASA Ames at the time as well as being an ISU participant.

During these NASA Ames sessions, Scott Madry gave a number of enthusiastic talks and demonstrations related to "smallsat" and their utility to a growing list of

Table 1 Some of the "smallsat" constellations for networking (Chart by J. Pelton all rights reserved)

Country	Constellation	Number of sats	Radio-frequency bands
Canada	CANPOL-2	72	LEO and highly elliptical Earth orbit in VHF-, UHF-, X-, and Ka-bands
Canada	Telesat constellation	117 sats plus spares	LEO in Ka-band
Canada	COMSTELLATION	Nearly 800 satellites	LEO in Ka-band
Canada	Kepler	15 to start and 120 in time	LEO in Ku-band
France	Thales Group's MCSat	Between 800 and 4000 in time	LEO, MEO, and highly elliptical Earth orbit in Ku- and Ka-bands
Liechtenstein	3ECOM-1	264	Ku- and Ka-bands
Norway	ASK-1	10	Highly elliptical Earth orbit in X-, Ku-, and Ka-bands
Norway	STEAM	4257	Ku- and Ka-bands
UK	UK / L5 (OneWeb) (Has now declared bankruptcy)	600–750 and increased number in time	Ku- and Ka-bands
USA	Boeing	1396–2956	V-band in 1200 km orbit
USA	SpaceX	Up to 4000	Ku- and Ka-band
USA	SpaceX	7500 plus	V-band
USA	USA/Leosat (Has now declared bankruptcy)	80 to start	Ka-band

remote sensing applications. He stressed how miniaturization and new small-scale components were making very capable new "smallsats" possible for remote sensing activities. Will Marshall took his ISU learning experience to heart. With his clever young colleagues he went on to organize right there in Silicon Valley a new enterprise called Planet Labs. These enterprising entrepreneurs designed three-unit cubesats that they called "Doves." They managed to find backers in the fertile startup soil of Silicon Valley and their new enterprise took root in the skies.

They began deploying and improving with each one of their successive batches better and better "seeing eye" birds. This enterprise continued to grow and prosper until it truly took wing in 2017. They made arrangements to have 88 of their Doves to be launched on an Indian PSLV rocket that placed 2 regular-sized satellites plus a record total of 104 cubesats into low Earth orbit (LEO) as of mid-February 2017 (Indian PSLV Rocket set for Record-Breaking Launch with 104 Satellites, Spaceflight 2017).

The also made an epic arrangement with Google that sold the title of the high-resolution Skybox satellites to Planet Labs in a deal whereby Planet Labs also changed their name to simply "Planet." Part of the sales agreement involved their signing a long-term contract to provide data to Google on a long-term basis (Kaplan 2017).

Amazingly the "Planet" enterprise was started in the garage of the well-known "rainbow mansion" in Silicon Valley, and their Doves are fabricated in what the

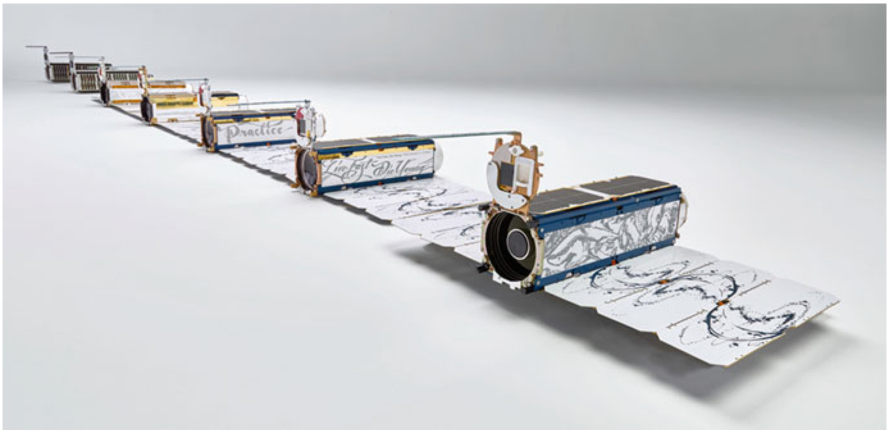


Fig. 4 Several of the Dove cubesat ready for launch (note the individualized art on each satellite). (Graphic courtesy of Planet)

young entrepreneurs call their “Clean Enough Room” in their headquarters, now in San Francisco. This amazing young startup company is now operating in close partnership with one of the world most valuable corporations, Google. It now manages a fleet of hundreds of “Dove” three-unit cubesat plus the entire Skybox/Terra Bella system that Google has sold to Planet as well as several satellites acquired from a German supplier. The part of the story involving remote sensing and “smallsat” startup leading to Skybox and Terra Bella comes next (see Fig. 4).

The Skybox Imaging Company launched in 2011: Another example of rather remarkable startup magic is the case of the four students from Stanford University’s School of Engineering that had the idea that they could design 100 kg small satellites which were only 30 × 30 × 30 cm cubes – about the size of a mini-refrigerator using off-the-shelf components. They submitted the concept for a class project and then decided to make it happen. Their concept was that these “SkySats” could provide high-resolution submeter resolution imaging for the commercial remote sensing market. They managed to convinced several venture capital firms that this was a viable business plan and raised some US$91 million by April 2012 which was sufficient capital to create and start launching this imaging system. The Skybox Imaging startup managed to raise a total of US$91 million of private capital from Khosla Ventures, Bessemer Venture Partners, Canaan Partners, and Norwest Venture Partners to develop and launch the SkySat constellation (SkySat n.d.). Their concept was to not use any expensive “flight-qualified” hardware and instead rely upon commercial electronic and automotive parts, as well as open-source software, including image processing routines developed in the medical industry.

This led to the first launch of SkySat-1 on a Russian Dnepr rocket on Dec. 11, 2013, from Yansy, Russia. This first of the series proved that high-resolution imaging (less than 1 meter) from these “smallsats” was possible and this led to the next launch of a SkySat-2 via a Soyuz 2/Fregat Russian rocket on July 8, 2014. A contract was awarded to SSL to 13 more SkySats according to a refined SkySat-C design. The first four of this series that were built under contract by SSL and then launched on an Indian PSLV (Polar Satellite Launch Vehicle) by the Indian Space Research Organization. The SSL contract covered the building of 13 of the SkySat C design that provides a much higher resolution than the Dove cubesat units. The fully deployed system envisions a network of 25 SkySats to be deployed to create a high-resolution system with frequent global updating capability.

As all of this technical and operational progress was being made, the business and financial arrangements were also rapidly evolving as well. In 2016 the Skybox Imaging Company was sold to Google for a reported price of $500 million. In 2017 Google rebranded the satellite imaging company Terra Bella and then proceeded to sell this system to Planet Labs for a financial arrangement that was indicated to be something like $300 million, but with a long-term service contract to provide imaging data to Google at an advantageous price (Google's Skybox Imaging has new name, business model 2016). This case study underlines the "Silicon Valley" effect that seems to permeate the "New Space" revolution with all of the actors in this case, namely, Planet Labs, Skybox Imaging/Terra Bella, and Google all firmly based in the Stanford, San Jose, Mountain View, and San Francisco area. Today Planet Labs and Terra Bella have morphed together to become just Planet, and they acquire remote sensing of the entire globe every day, including the first video movies from space (see Fig. 5).

The Spire Small Satellite Constellation that started in 2012: The Spire "smallsat" venture is another university-spawned venture. This new system has now deployed several "smallsat" prototypes for a cubesat constellation system that is intended to provide a variety of global tracking, data analytics, and weather monitoring services. It has under contract from the US National Oceanic and Atmospheric Administration (NOAA) launched an experimental smallsat for trial testing of meteorological monitoring and weather tracking services. This startup company has successfully demonstrated a range of new services can be provided by commercial cubesat systems, including automatic identification services, vehicular and ship tracking, data analytics, and even weather tracking. It was founded in 2012 and too started in an unexpected way with its initial capitalization came from a social media campaign (Foust 2016).

Spire was founded initially to develop and launch an experimental cubesat named ArduSat. This company got its money to do this as a crowd-funded project. This first cubesat was named Ardusat and in the rapid construction and launch environment that was typical of many cubesat projects was first launched on August 3, 2013. Thus one of the features that makes this commercial smallsat venture rather unique at the time was that it was made financially possible via a Kickstarter solicitation on the Internet. This initial funding of just over $100,000 led to a round of funding from venture capitalist. This "seed round" had participation by Emerge, Grishin Robotics, Shasta Ventures, Beamonte Investments, and the largest investment coming from Lemnos Labs. In late July 2014, Spire announced an additional $25M "Series A" funding from several venture capital firms that included RRE Ventures, Mitsui & Co., Global Investment, Qihoo 360 Technology, and Moose Capital.

Fig. 5 Planet SkySat 72 cm image of downtown San Francisco, California. (Image courtesy of Planet)

Emerge continued to invest in this second round as well. Spire announced on June 30, 2015, a $40 M traunch in “Series B” capital investments headed by Promus Ventures with participation from Bessemer Venture Partners and Jump Capital and then in November, 2017, yet another round of financing at $70 M through a “Series C” offering, and it also opened a European office in Luxembourg. This lightning fast series of financing sequences and its ability to build its initial series of small cubesats contract for their launch and get them into orbit signified that this was a whole new animal in the aerospace field that did almost everything differently.

The company’s first three ArduSat satellites that were the first test cubesat systems have now been released from the Spire operational satellite constellation in order for it to focus on educational experiments in space for activities that can be carried out for as low as $125 per experiment.

On January 21, 2018, two Lemur-2 CubeSats were launched as part of the payload of a Rocket Lab Electron. These two the experimental prototypes represented the test version of an ultimate small satellite multi-sensor constellation of 125 spacecraft that can perform weather measurements as well as tracking and AIS applications. Spire intends to manufacture and operate this Lemur constellation itself and obtain launch via contract from several suppliers including Arianespace.

The satellites are multi-sensor. Data types such as Automatic Identification System (AIS) service are used for tracking ships, and weather payloads measure temperature, pressure, and precipitation. AIS data is meant for use in illegal fishing, trade monitoring, maritime domain awareness, insurance, asset tracking, search and rescue, and piracy (Spire: Space to Cloud Data & Analytics n.d.).

5 Conclusion

The world of small satellites might seem to many as if this is a totally new phenomenon that has exploded almost overnight. In fact this is a development that started with engineers building the tiny Oscar 1 for amateur radio some 40 years ago. The first low Earth orbit (LEO) satellites for mobile communications and data relay, i.e., Iridium, Globalstar, and Orbcom, were small satellites as well as the Surrey satellites designed and build at what is now Surrey Satellite Technology Ltd. Clearly there has been a lot of innovation and outside the box thinking that has fueled today's small satellite industries and systems as well as all the experimentation and testing of concepts that has come with all of the cubesats and even smaller satellites that are now a part of the so-called “smallsat” world.

Every new idea and development stands on the shoulders of earlier inventors, scholars, philosophers, writers, science fiction visionaries, and free thinkers. The world of smallsat innovation is no different, even though it truly has had a fresh crop of very innovative thinkers that has fueled change in the space industry in the past decade. And the revolutionary thinking has far from run its course. The articles that follow show just how remarkable the innovations now known as “Space 2.0”or “New Space” have been in just the past decade. The ability to do more with less and to find new and innovative ways to launch small satellites into space at even lesser cost is changing the world of space and expanding the range of space ventures in truly remarkable ways.

6 Cross-References

- ▶ Historical Perspectives on the Evolution of Small Satellites
- ▶ Introduction to the Small Satellite Revolution and Its Many Implications
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Cubesat Technology
- ▶ Overview of Commercial Small Satellite Systems in the “New Space” Age
- ▶ The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and CubeSats

References

S. Eves, Space Traffic Control (2019) AIAA, Reston, Virginia, pp. 3–5

J. Foust, Spire deploys four satellites from Cygnus *Space News* (26 November, 2016)

Google's Skybox Imaging has new name, business model, (May 9, 2016) SpaceNews https://spacenews.com/googles-skybox-imaging-has-new-name-business

R. Gupta, D. Swearingen, "Mobile satellite communications markets: Dynamics and trends" chapter 8, in *Handbook of Satellite Applications*, ed. by J. Pelton, S. Madry, S. Camacho-Lara, 2nd edn., (Springer Press, Switzerland, 2016)

C. Henry, "OneWeb scales back baseline constellation by 300 satellites" Space News (Dec 13, 2018). https://spacenews.com/oneweb-scales-back-constellation-by-300-satellites/

Indian PSLV Rocket set for Record-Breaking Launch with 104 Satellites, Spaceflight, (Feb 13, 2017). https://spaceflight101.com/pslv-c37/indian-pslv-rocket-set-for-record-breaking-launch-with-104-satellites/

D. Kaplan, Why Google Sold Satellite Imaging Unit Terra Bella To Planet Labs (February 6, 2017). https://geomarketing.com/why-google-sold-satellite-imaging-unit-terra-bella-to-planet-labs

SkySat (n.d.) https://en.wikipedia.org/wiki/SkySat. Last accessed March 15, 2019

Spire: Space to Cloud Data & Analytics (n.d.). https://www.spire.com/. Last accessed March 15, 2019

Talk with Greg Wyler in Washington, DC (n.d.) On the occasion of the Arthur C. Clarke Awards

Writing of Principia Mathematica (n.d.) https://en.wikipedia.org/wiki/Writing_of_Principia_Mathematica. Last access March 15, 2019

Part II

The Many Types of Small Satellite

Overview of CubeSat Technology

Richard P. Welle

Contents

Abstract

A CubeSat is a small satellite designed to be deployed from a standardized container to facilitate launch as an auxiliary payload. The CubeSat Design Specification places rigid limits on satellite dimensions to enable containerization and places a number of restrictions on the contents and function of the satellite to ensure that it poses no risk to the launch. The resulting ready and inexpensive access to space has fostered a culture of risk and innovation that has led to short development cycles and very rapid advances in the capabilities of CubeSats. From the first launch of six containerized satellites in 2000, the cumulative number launched has doubled about every 2.5 years and passed the 1000 mark in 2018. Initially intended to promote satellite development programs in educational settings, the CubeSat

---

R. P. Welle (✉)
The Aerospace Corporation, El Segundo, CA, USA
e-mail: richard.p.welle@aero.org

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_3

form factor has been enthusiastically adopted for technology-demonstration flights, science missions, and commercial applications.

Keywords

CubeSat · Containerization · Risk · Mission assurance · Rideshare · Standardization

1 Introduction

In a narrow definition of the term, a CubeSat is a satellite that conforms to one of various CubeSat Design Specification documents describing satellites based on single or multiple units of a 10-cm cube. The original CubeSat Design Specification was developed at California Polytechnic State University in San Luis Obispo (Cal Poly) starting in 1999 and is based on the Poly Picosat Orbital Deployer (P-POD) that was developed at the same time (Puig-Suari et al. 2001). Since then, various derivative CubeSat standards have been developed, each based on an alternative deployer, that are more or less compatible with the Cal Poly standard. What all have in common, though, is that the deployer provides a standard interface with a launch vehicle in the form of a closed container that is designed to carry a secondary payload while ensuring minimal risk to the launch vehicle and primary payload. The P-POD is a simple box with a door and a spring mechanism. Figure 1 shows a photograph of a three-unit (3 U) deployer. The door is opened on command by a signal sent from the launch vehicle, and the spring mechanism pushes the CubeSat(s) out of the box with an ejection speed on the order of 1 m/s. This and other CubeSat

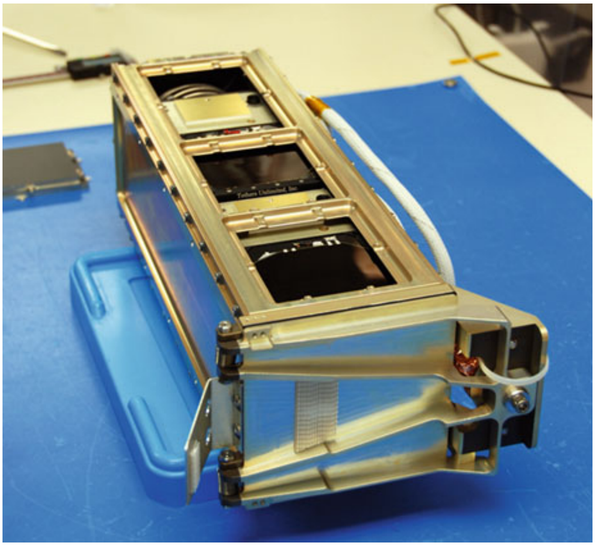


Fig. 1 Photograph of a P-POD CubeSat deployer containing two 1.5 U CubeSats, with access panels removed. (Aerospace Corporation image)

deployers are designed around a standard “unit” volume that is approximately a 10-cm cube. This dimension was selected based on the concept that a volume of 1 liter was a reasonable working volume for an experimental satellite and provides adequate surface area for solar cells on each face (Heidt et al. 2000). While the one-unit (1 U) CubeSat size was prevalent in the first years after the standard was established, many CubeSats today are three units (3 U) or larger. Figure 2 shows a photograph of a 3 U CubeSat with deployed solar panels. The popularity of the 3 U size is a result of that being the size of the most common deployers; the original P-POD was designed to deploy three one-unit (1 U) satellites, with the three satellites configured in a single stack. Although the original intention was to launch three 1 U satellites, a 3 U CubeSat deployer can also carry a single satellite that is 10-cm square and 34-cm-long, two satellites each 17-cm-long (1.5 U), or any combination of satellites that total 34 cm in length.

A somewhat broader definition of the term CubeSat could extend to any small satellite designed to be launched from a closed container. The first satellites fitting this definition were deployed from the Stanford-built Orbiting Picosatellite Automated Launcher (OPAL) in 2000 (Cutler and Hutchins 2000), while the first satellites conforming to the narrower definition of CubeSat were launched in 2003 (Swartwout 2013). While both senses of the term CubeSat refer to standardization of dimensions as well as containerization, the overwhelming majority of containerized satellites launched to date are based on the 10-cm unit cube, and the term CubeSat is most commonly interpreted in this narrower definition. Thus, for the remainder of this chapter, the term CubeSat will be used in the narrower sense, while the broader set of satellites including all those deployed from containers will be referred to as containerized satellites. Although not conforming to the generally accepted scientific usage for scaling prefixes, some additional related terms commonly used in the small-satellite community categorize satellites based on mass rather than physical dimensions and include microsatellite (mass between 10 and 100 kg), nanosatellite (mass between 1 and 10 kg), and picosatellite (mass between 100 and 1000 g). CubeSats can fall into any of these three categories.

Fig. 2 Photograph of a 3 U CubeSat with deployed solar panels. (Aerospace Corporation image)

While the small size typical of CubeSats has supported reduced launch costs, the key innovation of the concept, responsible for both the low cost and ready availability of launch opportunities, is the containerization and associated simplification of the launch interface. The original intent of the CubeSat standard was to provide a simple, reliable, and repeatable interface with a launch vehicle to reduce the effort (and cost) of integrating a secondary payload. The goal was to enable inexpensive flight opportunities that could be used by universities for educational purposes, and the majority of early CubeSats were developed by educational institutions for research or training purposes. Eventually the utility of the CubeSat standard was recognized beyond the university, and the form factor was adopted by government laboratories as well as industry, as a vehicle for technology demonstrations, for science missions, and ultimately in commercial applications.

2 The CubeSat Design Specification

The CubeSat is generally defined in terms of the CubeSat Design Specification (CDS), which defines the interface between the CubeSat and the deployer and sets tight constraints on such factors as dimensions, mass, and potentially hazardous materials. The current version of the CDS is available from www.cubesat.org. The original P-POD CubeSat deployer was designed to satisfy several requirements (Puig-Suari et al. 2001). The three key requirements that supported the rapid growth in CubeSat development were the following: (1) the deployer must protect the launch vehicle and primary payload from any interference from the CubeSats; (2) the deployer must have the ability to interface with a variety of launch vehicles with minimum modifications and with no changes to the CubeSat standard; (3) the resulting CubeSat standard should be easily manufactured without using exotic materials and expensive construction techniques. The first requirement ensured that launch providers and primary payload owners could accept CubeSats on a rideshare basis with minimal risk. The second requirement ensured that launch providers would not have to go through the launch qualification process for the deployer more than once and further ensured that CubeSat builders could start projects without having to identify (and pay for) the launch up front – they could be comfortable knowing that a launch opportunity could be found once the satellite development process was sufficiently advanced to be certain of a launch-readiness date. The third requirement ensured that CubeSats could be built, if desired, at a cost commensurate with typical university budgets.

The CubeSat Design Specification developed for the original P-POD has undergone some evolution as experience was gained with early flights (e.g., removing the prohibition on propulsion and adding limitations on magnetic fields), but the basic requirements outlined in 2001 are still satisfied. The latest version of the CDS is available from www.cubesat.org and should be reviewed thoroughly by anyone planning a CubeSat project. The key requirements of the CDS fall into four broad areas: mechanical, electrical, operational, and do-no-harm requirements.

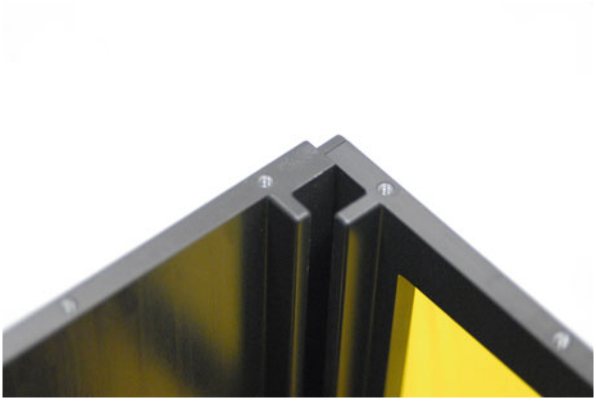


Fig. 3 Close-up photograph of a CubeSat test pod showing the deployer rails on one edge. (Aerospace Corporation image)

Mechanical requirements specify the physical dimensions of the CubeSat (presented in the form of mechanical drawings for each CubeSat size) that allow it to interface properly with the deployer. For most current CubeSat specifications, the mechanical interface is a set of four rails spaced at 10 cm that slide along corresponding rails in the deployer. The four black CubeSat rails are visible on the long edges of the CubeSat in Fig. 2, while the corresponding deployer rails are visible in Fig. 3. The CDS specifies rail dimensions, materials, and surface properties to ensure that the CubeSat will eject from the deployer without binding. The mechanical requirements also set limits on the maximum mass of the CubeSat (on a per unit basis) and limits on the location of the CubeSat center of mass.

Electrical requirements are principally designed to ensure that the CubeSat will remain powered off prior to deployment and include a requirement that there be a deployment switch on the CubeSat that will disconnect all power systems while the CubeSat is in the deployer. Additional inhibits are required to ensure that there will be no inadvertent radio-frequency (RF) transmissions while in the deployer.

Operational requirements include legal requirements (licensing for RF and, if in the United States, licensing for remote sensing), limitations on orbital debris, and start-up restrictions that prohibit actuation of any deployable hardware (such as solar panels) in the first 30 min after ejection of the CubeSat and prohibit any RF transmissions in the first 45 min.

Additional general requirements and testing requirements are designed to ensure that the CubeSat is incapable of doing harm to the launch vehicle and/or primary payload. These requirements include limits on propulsion systems, total stored chemical energy (batteries), materials outgassing, and hazardous materials (including a complete prohibition of pyrotechnics). Testing requirements include random vibration testing, shock testing, and thermal vacuum bakeout (to ensure proper outgassing of components) performed to test levels as specified by the launch provider or P-POD integrator.

Having a standard set of requirements is beneficial to both the launch provider and the CubeSat builder. For the launch provider, the CDS ensures that the CubeSat, as an auxiliary payload, will do no harm. Furthermore, any launch provider can establish the capability to launch CubeSats by qualifying a CubeSat deployer (the P-POD, or its equivalent), without having to delve into the details of each CubeSat that might be launched. For the CubeSat builder, the CDS provides a set of rules that must be met. However, more significant for the CubeSat builder is that the CDS provides for a standard interface that, if met, allows the CubeSat to ride to space on a broad range of launch vehicles with minimal integration effort. This means that a CubeSat complying with the standard will have a selection of ride opportunities at competitive prices and that these ride opportunities will be frequent.

In principle, satellites built to conform with the CDS should be capable of riding on any launch vehicle flying a CubeSat deployer. In practice, launch vehicles come with a variety of launch environments (particularly in the area of vibration loading), and the suitability of a potential ride will depend on whether the CubeSat was built to hold up under the relevant launch environment. While it is possible to build a CubeSat to survive even the most severe vibration environment, for most launch vehicles, such a satellite would be overbuilt. In practice, satellites are often designed for “typical” launch environments rather than extreme environments, possibly leading to rejection of certain launch opportunities that may come with unacceptable environments. Further, some launch providers may occasionally place restrictions on CubeSats beyond the minimum requirements of the CDS. For example, some launch providers may have a complete prohibition on propulsion systems. Other launch opportunities may involve transit through the International Space Station (ISS), in which case the satellites have to be designed and tested to man-rated space systems specifications. Finally, some CubeSat builders find it necessary to build a satellite that does not conform to all aspects of the CDS (e.g., by exceeding the maximum allowable mass or by having a pressure vessel). In this case, the CDS provides a process to request waivers, which are subject to approval by the launch integrator and/or launch provider (and possibly by the owners of other payloads on the launch vehicle).

The CubeSat Design Specification was created with the intention of encouraging flight opportunities for educational purposes. The first CubeSat launch, carrying six university-built CubeSats, took place in 2003. Of the first 100 CubeSats flown (which took until 2012), over 75 were university-built, only three were commercial, and the remainder were built by or for government organizations (NASA and the DoD). However, by 2012, the CubeSat standard began to be recognized by industry as a valuable tool for technology-demonstration flights, and 1 year later, in 2013, the first CubeSat developed for commercial services was flown. The pace of flights of containerized satellites (almost all of them conforming to the CubeSat standard) has continued to accelerate. Since the first flight in 2000, the cumulative number of containerized satellites launched has doubled about every 2.5 years (see Fig. 4). By early 2019, the total number of CubeSats launched had passed the 1000 mark, with just under 300 coming from universities, about 150 from government, and nearly 600 from commercial sources (including over 450 from just two companies, Planet Labs and Spire) (Swartwout 2019).

The CubeSat Design Specification established the defining characteristics of the CubeSat itself: the size, mass, etc., as well as limitations to ensure minimal risk to the

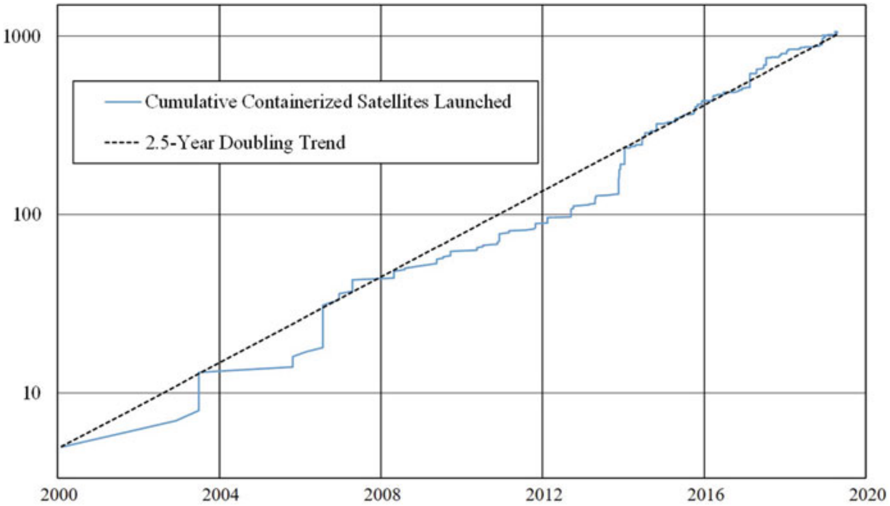


Fig. 4 Cumulative total of all containerized satellites launched as a function of date, compared to a 2.5-year doubling trend. (Aerospace Corporation figure based on data from Swartwout 2019)

host vehicle or primary payload. What was not anticipated was the entirely new approach to space systems enabled by the CDS. A key outcome of the CDS was that the space launch business, at least for kg-class spacecraft, was effectively containerized; the launch provider delivers a box to orbit (the P-POD, or equivalent); and the satellite developer need only design and build a satellite that fits in the box. The CubeSat deployer is analogous to the standardized shipping container that has revolutionize cargo transportation around the world over the past half century by making it possible to pack any cargo into a standardized container and then ship the container to a destination, where the cargo is unpacked. The containers are moved over the road, rail, and ocean transport networks with little regard to their contents, so the transport providers can focus only on efficient transport of the containers without having to develop efficient means of handing all the diverse cargos that might be shipped in the containers. At the same time, cargo owners need only deal with how to pack the cargo into the container, without needing to be concerned about the details of how the container is handled between the point of origin and the destination.

In a similar manner, the CubeSat container provides a standard interface between the launch provider and the satellite. The consequent simplification of the integration process reduces costs for the launch provider and provides a set of standards for the satellite developer which, if satisfied, will allow the CubeSat to ride on any of a number of launch vehicles. Thus, the path to space for a CubeSat is vastly simpler than for traditional satellite programs. It is this ready launch availability, combined with the original goal of the CubeSat as a teaching tool, that leads to a new approach to satellite development. While traditional satellites are built with little tolerance for risk, the low cost of the CubeSat and the availability of high-frequency, low-cost rides to space reduces the cost of a failure and encourages a culture of tolerance to risk, not for the launch vehicle or primary payload but for the CubeSat itself.

3 Risk Tolerance

When the CubeSat was originally conceived as a teaching tool, there was a high value placed on innovation and risk taking. For education purposes, this makes sense; one can learn as much (or more) from a failure as from a success. However, many non-educational programs recognized the potential of the risk-tolerant approach to CubeSats for supporting a program of rapid technology development. For example, technology-demonstration missions can often be flown with a high risk tolerance, particularly when the missions are part of a series of technology-demonstration exercises. Under these circumstances, an anomaly encountered on one flight can serve to inform the design of subsequent flights. Since the development cycle can be very short, a goal of demonstrating a particular technology in space can be applied to a series of flights rather than to a single flight. Under this approach, any single flight can have a high tolerance to risk under the expectation that a series of flights spread over a reasonable time interval will ultimately be able to satisfy all the program objectives.

Similarly, the opportunity to fly a high-risk mission at nominal cost encouraged entrepreneurs to establish programs that required multiple generations of spacecraft designed on a very short cycle, with the understanding that there may be failures on orbit and that any failures would provide lessons leading to improved designs in the next generation of the satellite. In this approach, the success of the program is defined not by the capabilities of the first satellite to fly but by the capabilities of the nth generation of satellite.

This is not to say that all CubeSats can be built using a risk-tolerant approach. For university satellite programs where learning is the primary goal, a risk-tolerant approach is certainly appropriate. For programs focused on technology evolution and/or maturation where the ultimate goal is an operational system or process that may take several years to develop, a risk-tolerant approach will likely be appropriate. However, for programs that are one-off science missions or technology-demonstration missions where the loss of a single satellite will severely impact program success, the tolerance to risk should be much lower, and more traditional approaches to satellite mission assurance must be implemented.

4 Elements of the Risk-Tolerant CubeSat Approach

Many aspects of the risk-tolerant CubeSat approach derive from a goal to keep costs low enough that a satellite failure would not be intolerable. An example of things that CubeSat programs can do to keep costs down is the use of commercial off-the-shelf (COTS) electronics. Traditional satellite programs will use only (or mostly) space-rated (radiation-tolerant) electronics. Typical COTS electronics can tolerate a limited amount of radiation, however, and this limit is rarely reached in low Earth orbit

(LEO) where most CubeSats fly. As such, typical CubeSats will fly exclusively or almost exclusively with COTS electronics. Issues that are encountered due to radiation in one satellite project can be mitigated through elimination of suspect components in subsequent flights, but there is often no systematic effort to evaluate the radiation tolerance of electronic components selected for a flight project.

A corollary to this is that CubeSats are often designed with short lifetimes in mind. For an educational project, the design and build effort provides the majority of the training with an additional gain during initial on-orbit checkout and operations. Beyond that, the marginal value of the satellite for educational purposes is limited. Similarly with technology-demonstration missions, once the technology has been demonstrated (unless on-orbit lifetime is part of the demonstration), there is little marginal value in continuing to operate the satellite. As such, many CubeSats are not designed with lifetimes in excess of 1 year in mind.

Another approach to minimizing costs is to limit the testing regimen throughout the program. In many CubeSat programs, a large portion of the environmental testing can be deferred until completion of the initial satellite build. The overall simplicity of most CubeSats often allows issues encountered late in testing to be corrected quickly because the entire satellite can be dissembled and reassembled in a matter of hours or days. This approach can lead to missed launches if there is insufficient margin built into the schedule to allow correction of issues discovered late in testing. Some CubeSat developers will build an engineering model that is a nominal duplicate of the flight model. Ideally the engineering model will be built before the flight model, with the experience gained through its build and test being available to inform the build and test of the flight model. The engineering model is then available on the ground for testing, software checkout, and anomaly resolution after the flight model is delivered.

Similarly, CubeSat development programs often forgo extensive modeling of spacecraft performance, particularly in the area of mechanical integrity. This can be partially justified in that CubeSats are so small that they become rugged simply by being more compact. Nevertheless, there may still be mechanical issues discovered in testing that could have been caught with careful modeling. However, with CubeSats it may be less expensive simply to expect testing to catch some issues that are then corrected through redesign after testing.

CubeSat developers also often forgo redundancy in the various satellite subsystems; CubeSats typically fly with a much larger compliment of potential single-point failures than traditional satellites. A corollary to this, however, is that the low cost of CubeSats, particularly the marginal cost of building and launching spares, makes it possible to approach redundancy by flying an entire duplicate satellite. Of course, this approach will not mitigate design issues, but it will mitigate workmanship issues, some radiation-induced issues, and operational issues.

An extension of this approach is sequential redundancy where CubeSats are developed as a series. The first of the series is delivered and launched, and the experience gained through the design, build, test, and operations of the first model is then applied to the development of the second unit. Similarly, the design of the third unit is informed by lessons learned with the second unit. In this approach, the success of the program is defined by the success of the first satellite in the series that accomplishes the full mission. Of course, the program goals may evolve as the satellite series progresses, leading to a continuing development effort reaching for ever-advancing goals. The point of the CubeSat Design Specification was to ensure easy access to space at a cost where a satellite failure was not intolerable. The redundant-satellite approach or, even more so, the sequential redundancy approach means that a satellite failure is not necessarily a mission failure.

The sequential redundancy model is used to some extent in all satellite programs involving experienced builders; lessons learned in the build of one satellite are applied to any future satellite where they are useful. However, with traditional satellites the time cycle for this is typically several years long; some complex satellites may be in the development phase for a decade or more and the final design frozen many years before launch. With CubeSats, the development cycle can be measured in months rather than years, so experience builds up rapidly. A related benefit of the CubeSat approach to satellite design is that the fast cycle time typical of such projects means that a team can be kept together through many projects. Thus, a small, dedicated team of engineers can build up the experience of multiple satellite projects, on a timescale short enough that there is not a lot of turnover on the team, and any experience gained by the team is retained.

Although the risk-tolerant approach to CubeSat development can be a valuable tool for advancing the state of the art in CubeSat capability and reliability, it is not applicable in all cases nor, perhaps, even in the majority of cases. The high tolerance to risk is really appropriate in only two circumstances: either a single satellite is being developed in an educational setting where the process of designing and building the satellite has as much or more value than actually flying the satellite or a satellite is being developed as part of a long-term series of satellites where the end goal is a satellite design with capabilities well beyond what can easily be achieved in a single development stage, and the potential for anomalies (or outright failures) in intermediate satellite designs are taken into consideration in the overall plan. The sequential redundancy approach is appropriate if the program goal is either technology maturation for its own sake or the development of a capability that is far beyond the current state of the art and cannot reasonably be achieved in a single design effort.

Although one may be tempted to implement a risk-tolerant approach in the development of a technology-demonstration mission, one must be very careful in this if the technology-demonstration mission is not one of a larger series. Specifically, if a mission has the goal of a flight demonstration of a specific technology and only one flight is planned, then the tolerance for risk is likely to small. The expectations for the mission must be clearly understood, both by the CubeSat developer and by the customer, before assuming that a risk-tolerant CubeSat approach is appropriate.

5 Mission Assurance

The risk tolerance described above is limited in that it applies only to the question of whether the satellite will successfully perform its intended function. The other key aspect of mission assurance is the safety of flight. Safety of flight risks are issues that could potentially harm other mission partners, from the start of launch processing to spacecraft separation on orbit.

Traditional space programs have a low tolerance to risk in either area, so when multiple traditional satellites would ride on a single launch vehicle, they would have had similar approaches to mission assurance. With CubeSats as rideshare, a single launch vehicle may have payloads with widely differing risk tolerances flying together. In response to this, the DoD Space Test Program developed a method for Rideshare Mission Assurance (RMA) that allows multiple satellites with varying risk tolerances to fly on a single launch, while protecting each satellite from risks to on-orbit performance posed by other payloads on the same launch (Read et al. 2019). RMA allows launch partners to accept self-imposed risks to the performance of their own payloads without being exposed to flight safety risks from other payloads.

The objective of the RMA process is to provide mission partners with an assurance that all payloads included on a mission will do no harm to each other or to any operational aspect of the launch. To this end, a set of do-no-harm criteria are defined that parallel similar requirements in the CDS. The principal requirements fall into the categories of launch environments (vibration, acoustic, shock), contamination, debris mitigation, pressure vessels, electromagnetic interference, and electrical inhibits (three inhibits are required to prevent unintentional activation of propulsion systems, any deployable structures, and any transmitters). A more detailed discussion of RMA is provided in (Read et al. 2019) along with a detailed checklist of tests and evaluations needed to ensure compliance with the RMA process.

6 Launch Considerations

Beyond the strict limitation on size and mass, the principal constraint on CubeSat missions is driven by the fact that all CubeSats launched (at least to date) have been as rideshare payloads. Being a rideshare means that the orbital parameters are selected by the primary payload on the launch or, at best, selected by agreement among a number of small payloads. The impact of launching as a rideshare varies depending on the mission. For most educational missions and many tech-demo missions, the orbital parameters are a secondary consideration; particular orbits may be desired, but a range of orbits will still satisfy the mission requirements. In such cases, there are likely sufficient launch opportunities that a ride satisfying the mission requirements will be available within a reasonable wait. In a few cases, a technology-demonstration mission may require a very specific orbit, in which case the wait for launch may be long.

Most operational missions, on the other hand, are likely to have more specific orbital requirements. In this case, the opportunities for rideshare might be insufficient. For missions requiring large numbers of satellites, one option is to design the mission with the intention of building an ad hoc constellation using quasi-random orbits (Gangestad et al. 2015); subsets of the constellation are deployed from multiple launch vehicles going to orbits that are selected based on their relative value to the overall mission of the constellation. An alternative, if the constellation is large enough or has to be distributed over a number of well-specified orbital planes, is to purchase a dedicated launch or launches. While most launch vehicles are designed with payload capacities well beyond anything useful for dedicated CubeSat launches, there are a number of entries in the new generation of small launch vehicles currently under development. Even though most of them will probably never fly, some are likely to make it to market. As of this writing, the Rocket Lab Electron, with a payload capacity in the range of 200 kg (depending on orbit), has already completed ten successful launches.

As the CubeSat industry has matured, the number of launch vehicles capable of carrying CubeSats has grown substantially. In 2018 there were 21 space launches carrying a total of 214 CubeSats, involving 9 different types of launch vehicles. For organizations developing one or a few CubeSats, launch services are typically obtained through a launch broker – organizations that consolidate collections of CubeSats from various developers and act as the interface with the launch provider. Launch brokers work with CubeSat developers to identify launch opportunities and support the launch providers by ensuring that the requirements of the CDS are being met by all the CubeSat developers. One launch option worth noting for US educational and nonprofit organizations is the NASA CubeSat Launch Initiative (CSLI), a program that provides free or reduced-cost access to space for CubeSats from qualifying organizations (CubeSat Launch Initiative). This program has supported the launch of over 80 CubeSats to date.

7 Missions

Although the first launch conforming to the CDS in 2003 included one science mission (Flagg et al. 2004), there was a perception for many years that CubeSats were too small to conduct useful science or other operational missions. In the first decade of CubeSat launches, over 70% were developed either for educational purposes or for technology demonstrations. Over time, however, both science-funding agencies and commercial ventures began to recognize the potential of CubeSats for operational missions. In 2008, the National Science Foundation began supporting CubeSat-based science investigations. In 2013, Planet Labs launched the first of what would become the world’s largest CubeSat constellation with the goal of imaging the entire land mass of the Earth every day. In 2015, the National Academies of Sciences, Engineering, and Medicine undertook a study of the potential utility of CubeSats for science missions (National Academies of Sciences, Engineering, and Medicine 2016) and concluded that “CubeSats have already produced high-value science. CubeSats are useful as instruments of targeted investigations to augment the capabilities of large missions and ground-based facilities, and they enable new kinds of measurements and have the potential to mitigate gaps in measurements where continuity is critical.” As of this writing, over one third of all CubeSats launched to date are part of the Planet Labs imaging constellation, and many other science and commercial satellites have been successfully deployed. Of the 214 CubeSats launched in 2018, less than 40% were categorized as educational or technology-demonstration missions.

The most obvious implication of the CubeSat Design Standard is the constraint on mass, volume, power, etc. that derives from the requirement to launch within a small box. This constraint is well understood and, in most cases, can quickly be used to determine whether a given mission can be accomplished using a CubeSat. In general, many missions will be constrained by simple physics; one cannot squeeze a 1-meter telescope into a CubeSat. But one should be careful in applying the physics constraint to any given mission. For example, it is straightforward to demonstrate that a 3 U CubeSat will not provide ground imaging at 50-cm resolution. So if the mission planner starts by assuming that the goal of the mission is imaging at 50-cm resolution, then a 3 U CubeSat is precluded by definition. But one should ask if the resolution is really the mission. Most often the mission involves determining something about the ground being observed: land use, vegetation, cloud cover, water quality, or another parameter. It is worth asking if the actual mission could be better served by lower-resolution, more frequent observations. The requirements should be about the information to be obtained, not about how it is obtained. Similarly, when designing an imaging system at a larger ground sample distance, say 20 m, it is possible to achieve this in a 3 U CubeSat. However, if the mission requirements call for a field of view that is too large, the optics will no longer fit in a 3 U CubeSat, and a larger satellite will be required. If the requirements specify the data to be obtained rather than the satellite field of view, it is possible to explore the trade between a single larger satellite and some number of CubeSats, each with a smaller field of view but flying in formation to cover the same area.

In general, missions that will remain out of reach for CubeSats are those that require large apertures or high-power instruments or those that require multiple instruments on a single platform. Outside those constraints, CubeSats have the potential to continue to expand their role in the space enterprise. An area where CubeSats may excel is in applications that benefit from distributed sensing, where a swarm or constellation of CubeSats can provide measurements with high temporal and spatial coverage, or in communication applications where, again, high temporal and spatial coverage can benefit the user on the ground. This has been demonstrated by Planet Labs with their use of over 100 CubeSats to provide regular daily imaging of the entire land surface of Earth. Similarly, Spire Global has launched over 100 CubeSats that are used for a number of applications including tracking maritime traffic and aircraft and for weather measurements using GPS radio occultation (Bosch 2019).

Although one tends to think of space missions in terms of services provided or mission data returned to Earth, the role of CubeSats in providing training opportunities should not be discounted. When developed as training missions, the risk tolerance can (and possibly should) be high, which will both enhance the learning opportunity and keep the costs down. The continuing importance of this role is illustrated by launch data indicating that about one in seven of all CubeSats launched in 2018 were developed by educational institutions.

Finally, the technology-demonstration mission continues to be an important role for CubeSats, with over 50 technology-demonstration CubeSats flown in 2018. This category of missions includes pathfinders for components or instruments that may subsequently fly on larger missions or prototype CubeSats that may be the basis for subsequent constellations of CubeSats.

8 Supporting Technologies

Like any satellite program, there is a minimum set of basic satellite bus functions that, depending on the mission, are essential to the success of a CubeSat flight. Functions required for essentially all missions include power, communications, and command and data handling (flight computer). Functions required for a significant fraction of missions include attitude control and navigation. Most CubeSat missions can be completed without propulsion (early versions of the CDS actually prohibited propulsion, a requirement that has now been relaxed), but many more complex missions are being developed that require propulsion for orbit maintenance or orbit changes.

The technologies to support these basic bus functions have been evolving rapidly, and any recitation of the current state of the art would quickly become obsolete. NASA's Small Spacecraft Technology Program (SSTP) compiled a report on the state of the art in 2013 and issued a revised version in 2015. Starting in 2016, the report was moved to an online format and is updated on approximately an annual basis (State of the Art of Small Spacecraft Technology).

Some noteworthy trends have been the rapid advance in communications capability and in the performance of attitude control systems. As of 2012, nearly all CubeSats operated with downlink rates of 9.6 kb/s, and a very few had systems with data rates approaching 1 Mb/s (Mission Design Division Staff Ames Research Center 2014). As of 2019, the peak downlink rate reported from a CubeSat reached 1.6 Gb/s (Devaraj et al. 2019). Similarly, the best pointing precision reported for a CubeSat as of 2012 was about 2 degrees (Mission Design Division Staff Ames Research Center 2014). However, by 2019 integrated attitude control systems for CubeSats were demonstrating pointing precisions two to three orders of magnitude smaller; the ASTERIA mission flown in late 2017 achieved about 2 millidegree body pointing in a 6 U CubeSat and 140 microdegree pointing of an imaging payload using a secondary piezo translation stage to control image placement on a focal-plane array (Pong 2018).

Navigation, at least for satellites in LEO, is easily obtained to a precision of 10 m or less using onboard global navigation space system (GNSS) receivers, including GPS receivers. If precise navigation is not required, then satellite operators can rely on the US space-tracking services (18th Space Control Squadron), which publishes regular updates on the orbital parameters of most satellites at a precision of 1–2 km.

The supporting technology that is perhaps the least mature as of this writing is propulsion. While electronic systems scale well to smaller sizes and are based on rapidly-evolving technologies developed for the consumer electronics industry, propulsion systems typically rely on physical phenomena that do not scale well from large to small and use technologies not often applicable in other industries. As such, the options for CubeSat-scale propulsion are limited but are expanding. The simplest systems use cold gas as a propellant; while these can be relatively easy to integrate and are fairly reliable, they can present a challenge in that they will typically require a waiver of the prohibition on pressure vessels and can provide only a very limited delta-v capability. Chemical propulsion systems present multiple challenges: the chemical reactions and heat transfer do not scale well to small sizes, the high thrust typical of chemical propulsion will produce torques on the spacecraft that may be beyond the capacity of the attitude control system, and the propellants will be restricted by the CDS. Several electric propulsion systems scaled for CubeSat applications are in development, using a wide range of propellants. While these systems may ultimately provide very high delta-v capability, the power limitations on CubeSats will limit the maximum thrust of electric propulsion systems, and any orbit changes will be slow. On the other hand, small electric propulsion systems can provide many years of orbit maintenance.

9 CubeSat Industry

At the start of the CubeSat era, there were few or no commercial vendors capable of providing CubeSat-compatible satellite systems, and essentially all CubeSat programs were “home-grown.” Within a few years, existing and newly formed vendors began offering CubeSat-specific systems including flight computers, power systems, radios, sensors, and complete attitude control packages. Thus, it is possible, for example, for a university program to acquire many or all of the satellite systems through commercial vendors and integrate them in-house to produce a complete satellite. Alternatively, the builder can select which satellite systems will be developed in-house and purchase the rest on the commercial market. A few companies were also formed for the purpose of offering CubeSat development and operation as a service. As such, it is now possible for a customer (e.g., a scientist wanting to fly a small instrument) to contract with a commercial firm to provide a relatively complete satellite service such that the customer need only develop and deliver the payload, which is then integrated, tested, launched, and operated by the commercial vendor.

As with the list of CubeSat technology status, the list of companies providing components and/or services continues to evolve, and any recitation of commercial services would become obsolete in short order. As such, the reader is again referred to NASA’s Small Spacecraft Technology Program (SSTP) report on the state of the art in CubeSat technologies (State of the Art of Small Spacecraft Technology).

10 Conclusion

The creation of the CubeSat standard has led to a very rapid proliferation of satellites in the 1–10-kilogram mass range. Initially these satellites were developed primarily for educational purposes, but their potential value in technology demonstrations and in operational missions did not go unnoticed, and the commercial market for CubeSat systems, CubeSat services, and data produced by dedicated CubeSat constellations has expanded rapidly. The cumulative number of containerized satellites launched has been doubling every 2.5 years since the first launch of six in 2000, and the trend shows no sign of leveling off. The range of missions and the fidelity of data produced by these missions have also continued to grow. The creativity of the

CubeSat community has enabled a number of programs that would have been deemed impossible in kg-class spacecraft 20 years ago.

In general, the approach to mission assurance taken by the CubeSat developer community has been much more relaxed than with traditional satellites. For educational and, to some extent, technology-demonstration projects, this tolerance to risk is appropriate. The potential for high-frequency flight opportunities has led to the concept of serial redundancy in CubeSats. This is the recognition that a high risk tolerance for any given flight is acceptable if the flight is part of a series of flights aimed at incremental technology advances; for any given flight in the series, the risk of failure is offset by the potential gains across the series as a whole. This concept of serial redundancy has led to very rapid advances in the capabilities of space systems but is appropriate only for programs involving multiple flights over an extended time period. However, the lessons learned through sequential redundancy can be, and have been, applied to new missions, yielding highly reliable satellites for a broad range of missions.

11 Cross-References

- ► Commercial Small Satellites for Business Constellations Including Microsatellites and Minisatellites
- ► Overview of Commercial Small Satellite Systems in the “New Space” Age
- ► The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and CubeSats

References

18th Space Control Squadron. www.space-track.org. Accessed 17 Dec 2019

G. Bosch, (2019). GNSS Radio Occultation in Advanced Numerical Weather Prediction Models GEOmedia 23, no. 3 (2019)

CubeSat Launch Initiative. https://www.nasa.gov/directorates/heo/home/CubeSats_initiative. Accessed 17 Dec 2019

J. Cutler, G. Hutchins, OPAL: Smaller, simpler, and just plain luckier. Presented at the 14th AIAA/USU conference on small satellites, august 2000 (2000), https://digitalcommons.usu.edu/smallsat/2000/All2000/45

K. Devaraj et al., Planet high speed radio: Crossing Gbps from a 3U Cubesat. Presented at the 33rd AIAA/USU conference on small satellites, Aug 2019 (2019), https://digitalcommons.usu.edu/smallsat/2019/all2019/106

S. Flagg et al., Using nanosats as a proof of concept for space science missions: QuakeSat as an operational example. Presented at the 18th AIAA/USU conference on small satellites, Aug 2004 (2004), https://digitalcommons.usu.edu/smallsat/2004/All2004/53

J.W. Gangestad, J.R. Wilson, K.L. Gates, J.V. Langer, Rideshare-initiated constellations: Future CubeSat architectures with the current launch manifest. 31st space symposium, technical track, Colorado Springs, Colorado. Presented 13–14 Apr 2015 (2015)

H. Heidt, J. Puig-Suari, A. Moore, S. Nakasuka, R. Twiggs, CubeSat: A new generation of picosatellite for education and industry low-cost space experimentation. Presented at the 14th

AIAA/USU conference on small satellites, Aug 2000 (2000), https://digitalcommons.usu.edu/smallsat/2000/All2000/32

Mission Design Division Staff Ames Research Center Small Spacecraft Technology State of the Art, NASA/TP-2014-216648/REV1 (2014)

National Academies of Sciences, Engineering, and Medicine Achieving science with CubeSats: Thinking inside the box (The National Academies Press, Washington, DC, 2016). https://doi.org/10.17226/23503

C.M. Pong, On-Orbit Performance & Operation of the Attitude & Pointing Control Subsystems on ASTERIA. Presented at the 32nd AIAA/USU Conference on Small Satellites, Aug 2018 (2018), https://digitalcommons.usu.edu/smallsat/2018/all2018/361

J. Puig-Suari, C. Turner, W. Ahlgren, Development of the standard CubeSat deployer and a CubeSat class PicoSatellite. In 2001 IEEE aerospace conference proceedings (cat. No. 01TH8542) (Vol. 1, pp. 1–347) (IEEE, 2001)

A. Read, P.S. Chang, B.M. Braun, D.D. Voelkel, Rideshare Mission assurance and the do no harm process. Aerospace Report No. TOR-2016-02946-Rev A. 28 Feb 2019 (2019)

State of the Art of Small Spacecraft Technology. https://sst-soa.arc.nasa.gov/ Accessed 17 Dec 2019

M. Swartwout, The first one hundred CubeSats: A statistical look. JoSS **2**(2), 213–233 (2013)

M. Swartwout, CubeSat Database, Saint Louis University (2019), https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database. Accessed 17 Dec 2019

Overview of Commercial Small Satellite Systems in the "New Space" Age

Timothy J. Logue and Joseph N. Pelton

Contents

Abstract

"New Space" or "Space 2.0" initiatives are changing the space industry and not in modest or one-dimensional ways. We are today experiencing change in profound ways that permeate the entire space enterprise. Thus smallsats and "New Space-related" changes now impact almost every aspect of the space industry.

T. J. Logue (✉)
Thales Alenia Space, Arlington, VA, USA

Arthur C. Clarke Foundation Board, Washington, DC, USA

Pacific Telecommunications Council Board, Honolulu, Hawaii, USA
e-mail: logue.tim@gmail.com

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_4

These should not be seen as mere disparate or unrelated parts, but as key pieces of a whole revolution in the space industry. There are many changes that are occurring in the world of commercial space, which taken together should be seen as enabling forces. These "parts" are coalescing together to allow significant changes to occur throughout every dimension of the space industry.

In short, all of these various "disruptive" changes are a part of an overall gestalt. It is driven by what might be called a new way of thinking and analysis born of a way of thinking associated with Silicon Valley – namely, an approach that questions old ways of doing things. It asks not how can things be improved but how can new ways of thinking make significant changes that revolutionize how things are done. There is a constant search for major strides that are sweeping – rather than baby steps.

Out of "New Space" thinking has come new technologies, new market entrants, new launcher systems, new ways of financing space ventures, new satellite architectures, efficient new small satellite designs, new types of ground antenna systems with electronic tracking, and market shifts toward networked services. Over-the-Top (OTT) data streaming of entertainment and gaming services and demand for networking access in rural and remote areas of the world are just a few examples. These forces of change and new ways of thinking are converging together to create an integrated nexus of change in the space industry that has produced among other things the great spurt of activity related to commercial small satellite constellations and an effort to bring broadband digital services to the entire world.

Many of the companies in the global aerospace world that have built satellites, launch vehicles, ground antenna systems, provided satellite services, and insured and financed space enterprises for many years have been caught off guard by the swiftness of the change and are now struggling to find their footing in the swirling eddies of transforming markets, spacecraft, ground system, and launcher technologies, and even the regulatory framework that controls these industries.

This chapter explains that this dramatic change in the design, manufacturer, launch operations, architecture of satellite constellations, and business models of those operating small satellite constellations can only be understood in the context of all the forces of change that are coming from perhaps a dozen different basic shifts in the space industry. Those who think one-dimensionally or narrowly about shifts in technology, market forces, capitalization, and global operations will miss the overall scope of this change. This overview of commercial small satellites is actually designed to capture this larger picture. This chapter focuses on what might be called synoptic change in space industry. It is now an industry that is completely beset by new and "disruptive" ways of thinking about every aspect of commercial space industries – the various markets, the changing modes of financing new systems, the diverse technological components of its products and services, and all of the associated regulatory processes.

Keywords

Airbus · Angel investors · Blue Origin · Boeing · Crowd Funding · CubeSat · Electronic pointing phase array ground system · Kickstarter · LauncherOne · Microsats · Minisats · "New Space" · OneWeb · Reusable launch vehicles · Rocket Lab · Rounds of financing · Small satellite launch vehicles · Sierra Nevada · Space 2.0 · Surrey Space Technology Ltd (SSTL) · SpaceX · Thales Alenia Space Vector

1 Introduction

There are many commercial technology-based enterprises that started off with just one or two persons tinkering with a new idea in a garage or basement trying to see if they could turn a concept into a meaningful product or service. On the other hand, the earliest satellites launched into orbit may have been small, but they were essentially all governmental projects backed by serious resources and teams of scientists and engineers.

When volunteer scientists and engineers put together the OSCAR 1 amateur radio satellite, launched in 1961, it helped to begin thinking about how to design and build low-cost satellites. This spark eventually spawned a whole school of thought about how to design, build, launch, and operate satellites that percolated through many academic institutions. Many colleges and universities were intrigued by the idea of the cubesat which was a standardized approach to small satellites developed by California Polytechnic State University (Cal Poly) and Stanford University in 1999. For nearly 15 years, the cubesat phenomena remained largely an academic enterprise with the majority of these small satellite projects coming from colleges and universities. The idea was largely to provide an avenue for students to test concepts as to how to design and build satellites more effectively and to carry out in-orbit experiments, when "rides to orbit" could be found, which was not always easy.

But, by 2013 the majority of cubesat launches were, for the first time, commercial or amateur projects that were not just academic undertakings but a serious new type of entrepreneurial space venture. Books written on this sweeping miasma of change have documented how the space business, as driven by small satellites and new types of launcher systems, are transforming the space enterprises in significant ways. Examinations of this dramatic shift, such as *Space 2.0: Revolutionary Advances in the Space Industry* and just published in 2019, seem all but ready for a second edition in 2020 given the rapidity of change in this fast-moving world of innovation and industrial transformation (Pelton 2018).

"New Space" enthusiasts were suddenly converting small satellite projects into real commercial ventures or at least test launches of prototypes for full-fledged commercial smallsat projects (CubeSat).

NASA, ESA, and other space agencies that had started programs to stimulate cubesat student experiments expanded their smallsat programs to spur corporate innovation, spur new small satellite ventures, assist with launches, and initiate their own smallsat experimental projects (NASA Venture Class Procurement Could Nurture Ride 2015).

Today Cal Poly has a structured partnership with 40 other academic institutions to provide the latest version of the cubesat specification (9th version), and there are now specifications for pocketqubes that are one eighth the size of a cubesat and even femtosats that are in the 10–100 g mass range. This supportive environment for the design, building, and launch of small satellites of the cube satellite class or below has grown in the last 25 years, and this trend will likely continue.

Today, according to the UN Office of Outer Space Affairs, some 9,000 satellites have now been launched into Earth orbit and to date less than 10% are associated with commercial satellite constellations. However, based on filings and licensing by national governments, this balance is set to change and change dramatically. Over 20,000 commercial satellites are now proposed to be launched in the next 5 years or so, and most of these are associated with small satellite constellations. The OneWeb and SpaceX Starlink constellations represent the majority of these launches. Amazon has also announced plans to launch its own constellation of thousands of satellites, which it calls Kuiper. This dramatic shift in the number of satellites to be launched and the rise of so-called MegaLEO smallsat constellations gives rise to concern about orbital collisions and even the possibility that deorbiting satellites from large constellations could strike an aircraft or a vulnerable point on the ground. The following

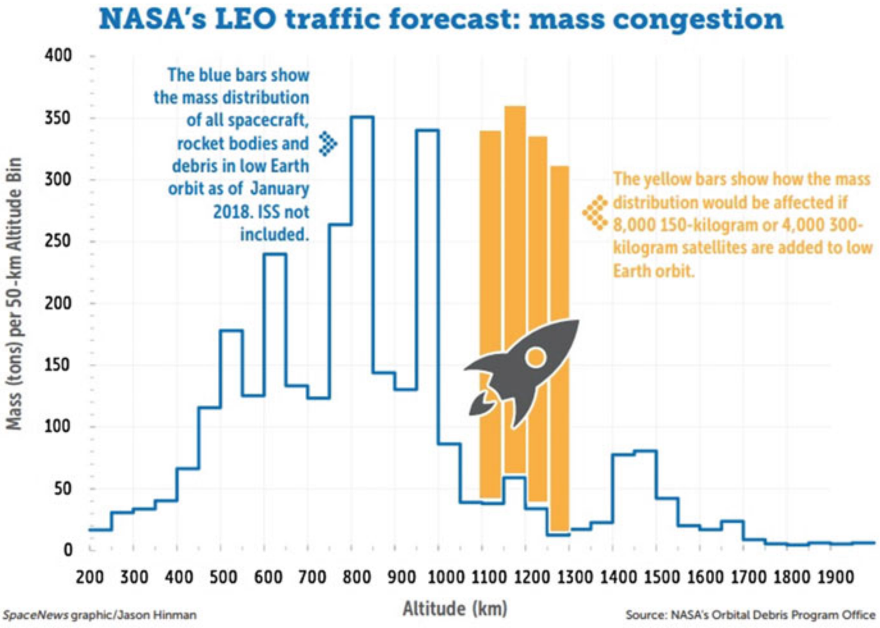


Fig. 1 NASA projected traffic congestion forecast in specific LEO orbit altitudes. (Graphic courtesy of NASA)

graphic shows how deployment of new MegaLEO constellations would create new levels of mass congestion as they are deployed at specific altitudes (see Fig. 1).

The world of small satellite constellations is thus moving rapidly forward. There are new technologies that are enabling constellations to be designed, built, launched, and operated more efficiently. There are new types of digital markets, particularly in the digital streaming and networking services arena, that are quickly developing. There are also new mechanisms to fund these various new ventures and new players in the space application field that are disrupting normal patterns of investment. Finally, there are new concerns with regard to orbital space debris, space situational awareness, space traffic management, and regulatory and liability provisions that all may require change to accommodate this new space environment and almost chaotic pattern of change in the space industry. Each of these new patterns related to commercial small satellite systems will be analyzed in the following pages.

2 Small Satellite Constellations and the New Technologies that Enable These New Systems

The rather steady and deliberate evolution of space technologies and systems and launch operations has been disrupted. It is really not productive to seek to determine which is the “chicken” and which is the “egg” in this rapid period of change. The overall trend is that many innovators in the aerospace industry have embarked on developing new technologies and new modes of operation across all sectors of the aerospace industry (Madry et al. 2018).

Launch Services: The new technology in the launch services industry is blossoming everywhere. There are a number of start-up launch services companies that are seeking to develop launch systems that operate with reusable first stage rocket components such as Blue Origin and SpaceX.

Others such as Virgin Galactic, Sierra Nevada, and now failed Swiss Space Systems have sought to extend the reusability associated with spaceplane development to provide small satellite launch capability.

Vulcan Inc. with its Stratolaunch Systems has sought to eliminate the need for expensive launch sites as well as provide new launch efficiency with regard to large mass air-launched rocket systems that represent an extension of approaches first developed by Orbital Sciences and Burt Rutan.

Yet others such as Vector in the USA, Rocket Lab in New Zealand, and many other start-ups in China, Europe, Israel, etc. have focused on developing highly efficient and quite small launchers for small satellites in particular (see Fig. 2).

India with its Polar Satellite Launch Vehicle (PSLV) and China with its Long March family of launch vehicles have simply focused on creating a conventional launcher that could be manufactured at lower cost and high reliability.

These various and diverse launch service initiatives have fed off of one another. These varied and more efficient launcher systems have served to drive down launch costs significantly in the past 5 years. For many decades launcher systems grew bigger in their capabilities, but the cost per kilogram of mass launched remained

Fig. 2 Efficient Electron launch vehicle offers new options for small satellites. (Graphic courtesy of Rocket Lab)

quite high. Today the cost of launching small satellites either on dedicated small launchers or packaged together on larger rocket systems is rapidly declining.

All of this innovation and these new launch systems that offer lower cost ways to orbit have forced the conventional providers of launch services such as Arianespace, Boeing, Lockheed Martin, United Launch Alliance, and Russian launch manufacturers and services providers to develop new and lower cost launch capabilities to compete with these new providers of launch services. The Ariane 6 vehicle will only have a modest increase in lift capability over the Ariane 5, but its cost per kilogram is expected to be cut in half. The United Launch Alliance's effort to cut costs is focused on the Vulcan launcher. More than a dozen lower-cost launch systems from start-ups in China, Israel, the USA, and Europe are aimed at capturing the small satellite launcher market and to compete with Vector, Rocket Lab, and LauncherOne for this sizable new market.

In several cases the approach to lowering cost is focused on reducing the high cost of operating launch sites. Options such as Stratolaunch and the carrier vehicle for LauncherOne represent one approach. Another concept is to develop simple, truck-mounted launch operations such as that developed for the Vector launcher.

Piggyback launches from larger launch vehicles such as the Polar Satellite Launch Vehicle that launched a record number of 104 cubesats remain extremely cost efficient. The same is true for the dispenser system on the International Space Station that now offers two options for smaller cubesats and more recently for nearly 1-m^2 satellites after the smallsats have been delivered along with other cargo to the station. The various launch options for small satellites continue to grow rapidly. The bottom line is that lower launch costs help to fuel the small satellite revolution in a significant way by lowering the cost to orbit and providing more rapid access to space.

New Ground Systems with Electronic Tracking of Satellites: The next key technology that enables the deployment of small satellite constellations for communications and networking is the new ground systems with electronic tracking capabilities. There is a mad scramble for the manufacturers of user terminals for satellite communications to bring new flat panel antennas with electronic tracking capabilities to market. Flat panel antennas are seen as a needed breakthrough permitting the rapid installation of ground equipment in new or usually restricted places, such as aircraft, smaller ships and yachts, and in rural and remote areas, opening up or expanding markets beyond what can typically be done with traditional parabolic ground terminals especially for MegaLEO constellation services. At the Satellite 2019 Conference and Exposition in Washington, DC, Gilat, SatixFy, Kymeta, Isotropic Systems, ThinKom, Alcan Systems, C-Com, Wafer, EM Solutions, Hughes Network Systems and Phasor were in various ways seeking to respond to this rapidly changing Earth station market in new and innovative ways. The suppliers of these new flat panel antennas include established suppliers, entirely new start-ups, and start-ups with big name backers. Perhaps most notable in this regard is the Kymeta flat panel antennas that feature the use of meta-materials. This innovative product is backed by Microsoft founder Bill Gates, among others (see Fig. 3).

Phasor, the developer of a modular design for antennas that can electronically track LEO satellite signals, is developing a flat antenna that would have increased

Fig. 3 Kymeta flat panel antenna with electronic tracking. (Graphic courtesy of Kymeta)

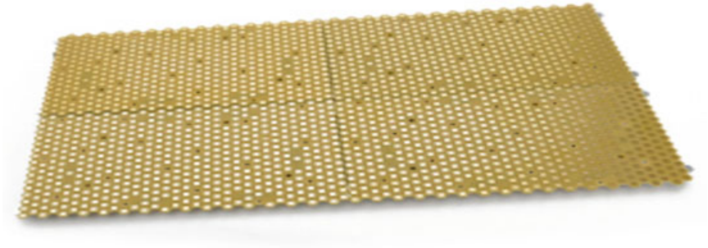


Fig. 4 Phasor modular flat antenna that can be shaped to conform to the sides of aircraft. (Graphic courtesy of Phasor)

sensitivity performance and could be adapted to conform to the side of an aircraft for mobile communications between airplanes and LEO constellations (see Fig. 4).

The principal advantage of GEO orbit satellites in Clarke orbit has always been that user antennas did not need to physically track the satellite's movement across the sky. These satellites seemed to remain fixed in place. LEO satellites, depending on their altitude, typically traverse across the sky in about 5–10 min and thus need ground terminals with rapid tracking capability. If the tracking is done using electronics rather than physical tracking of the satellite's path across the sky, then the Earth station's reliability is increased, and moving parts eliminated entirely. Currently, the cost of these flat panel, or conformal-shaped, antennas for aircraft is relatively expensive compared to classic fixed dishes, but the economies of scale of mass production are bringing these costs down rapidly.

There is clearly trade-offs in technical performance and cost efficiencies involved here. One must consider the relative gain in effective power performance of a LEO satellite which is perhaps 40 times closer to earth than a GEO satellite. This closer altitude provides a significant effective power increase in performance that is some (40 × 40) or 1600 times greater than from a geostationary satellite. Since the signal from a satellite spreads like a widening circle and the area of a circle is calculated as πr^2, the path loss or the effective strength of an electronic signal is represented by the square of the spreading circle.

In addition, there is another key gain in LEO systems. This is in the signal's latency, or path delay, which is 40 times less for a LEO satellite that is 40 times closer to Earth. In a world where digital networking is the prime mode of communications, this suggests that LEO networks, as well as MEO networks, will be better suited for digital networking and streaming services via the Internet. This is especially true for two-way communications links for either data or voice, where delays are most noticeable. The current betting is that these closer-to-Earth satellite constellations will be able to capture a larger market share over GEO satellites over time. A key market driver will thus be how rapidly do flat panel antenna costs come down and how good will their technical performance be at both providing service and avoiding interference to GEO satellites and injecting additional RF interference into adjacent radiofrequency bands used for radio astronomy, GNSS services, etc. The biggest concern of all is over-congestion of LEO orbits that results in collisions and the creation of orbital debris which could create major disruptions for all types of space-based services. This issue will be discussed further in this chapter and elsewhere in this handbook.

3 New Efficiencies in Small Satellite Manufacture

Yet another significant change that has come with the small satellite revolution is new and improved ways of designing, manufacturing, and testing small satellites in large production runs. Early New Space satellite developers used Silicon Valley-like approaches that saw every launch of a handful of satellites as a way to test new technologies and manufacturing techniques. Innovations were rapidly incorporated in the next batch and tested on-orbit like upgrades to software. However, to become commercially viable, these operators and manufacturers needed to shift to a different model that focused on an easily reproducible product designed for manufacturability. In the classic space industry, the production of a handful of GEO satellites in any 1 year by any one manufacturer did not allow for large production run efficiencies and cost-effective means of quality assurance testing. Each satellite was essentially handcrafted and painstakingly tested based on the not unrealistic view that it had to operate for 15 years or more and was largely out of reach after successfully reaching geostationary orbit. Only a few spacecraft, having suffered mishaps in the early stages of their deployments when the space shuttle was still operating, had any chance of being rescued and either sent on their way or brought back to earth for retrofit and relaunch. Today there are strides being made in on-orbit servicing. NASA and DARPA are funding relevant research, and there are some commercial initiatives in this field, but there is still a long way yet to go.

But the production of a large number of satellites with standardized component parts poses a challenge for any manufacturer, whether seasoned or New Space. Supply chains had to be streamlined and prepared for mass production and on-time delivery of parts with high reliability, low cost, and high quality had to be perfected. If the New Space constellation is to be based on "off-the-shelf" components, traditional space equipment suppliers may need to be trained not to go through the painstaking quality checks and testing usually demanded. Alternatively, nontraditional suppliers may have to be briefed on the unique demands of space manufacturing, even if the equipment to be supplied was said to be "off-the-shelf," usually denoting equipment repurposed from established commercial applications on Earth. The development of additive manufacturing added a new potentially cost-saving approach which could reduce costs and manufacturing times. Testing regimes were altered to focus on full testing of the first handful of satellites in a production run using high-quality acceptance standards. Thereafter, only rudimentary testing is to be used for full production runs. Some of these production and testing technique had been developed during the mid-1990s, when the first commercial constellations were developed and launched for Iridium, Globalstar, and Orbcomm, but the lessons learned then, if still remembered, had to be significantly adapted for constellations involving hundreds and thousands of satellites, using the latest production technologies and techniques. Moreover, the commercial success of these constellations maybe based at least partly on the speed and efficiency of production. Whereas it takes only three geostationary satellites to cover most of the earth, for New Space LEO constellations to achieve full market coverage, the satellites must be built quickly and launched in large batches or else operators' revenue will be severely constrained by incomplete coverage. The gap between first launch and full coverage cannot be understated, since many New Space satellites are being designed for relatively short lifetimes on-orbit, often under 6 or 7 years. Thus, while the first satellites launched in a constellation have only limited opportunities to generate revenue, they are already degrading in the harsh space environment. Thus, completion of the constellation quickly becomes critical. This is especially true for smallsat constellations providing telecommunications services, as well as Earth observation systems whose key selling point is rapid revisit of (almost) every point on the Earth.

The incremental costs of satellites on large production runs should decrease significantly. In the case of highly automated production systems, the cost of manufacturing small satellites in thousands of units largely becomes the cost of the materials in the spacecraft. If operators of LEO smallsat constellations can significantly reduce the cost of manufacturing, reduce the cost of quality acceptance and independent verification and validation testing, significantly reduce the cost of launch, and increasingly automate the operation of large constellations, then the total cost of a constellation can be reduced significantly, largely through economies of scale. On the other hand, if the failure rate of such highly automated small satellites continues to be high, such as the 5 small satellites out of the first 60 Starlink satellites launched mid-year 2019, the problem of derelict small satellites remaining in space becomes of prime concern. This issue is discussed further below and elsewhere in this handbook with regard to orbital space debris (O'Callaghan 2019).

It is further anticipated that new flat panel antenna systems with electronic tracking can follow a similar cost reduction curve. SpaceX has filed a petition with the Federal Communications Commission asking for type licensing of a million broadband user terminal transceivers to work with its Starlink satellite constellation. The planned deployment of one million of these future broadband units represents tangible evidence of efforts to achieve major future cost reductions associated with flat panel user antennas (Nyirady 2019).

4 New Markets Such as Over-the-Top Data Streaming Via Commercial Small Satellites

The commercial satellite market is a nearly $300 billion a year enterprise, and the largest sectors are satellite services that represent about $130 billion dollars in annual revenues – followed closely by ground systems sales of about $120 billion. The largest portion of that services market represents subscription sales for direct broadcast satellite services that are now offered as an alternative to cable television subscription services. These industries – both direct broadcast satellite television and subscription television services – are currently experiencing rapid change as many consumers around the world are shifting from watching video via cable TV or DBS subscription to data streaming and viewing videos on laptops or even cell phones, rather than conventional television sets. The advent of 5G cellular service will likely accelerate this trend.

Most analysts foresee the market shifting away from cable TV or DBS subscription-based services delivered from broadcasting satellites or in the case of cable television, fixed service satellites. This shift allows providers such as Amazon Prime, Netflix, Fubo, Hulu, Sling TV, Now TV, Sky Go, and dozens of Internet-based video streaming services to compete with cable TV subscription or direct broadcast satellite TV services. This shift is currently hitting subscription service providers such as HBO, Starz, Cinemax, etc. the hardest. Most of these OTT services offer video programming and broadband access at much lower rates that via cable TV subscription services or the offerings via satellite broadcast networks such as

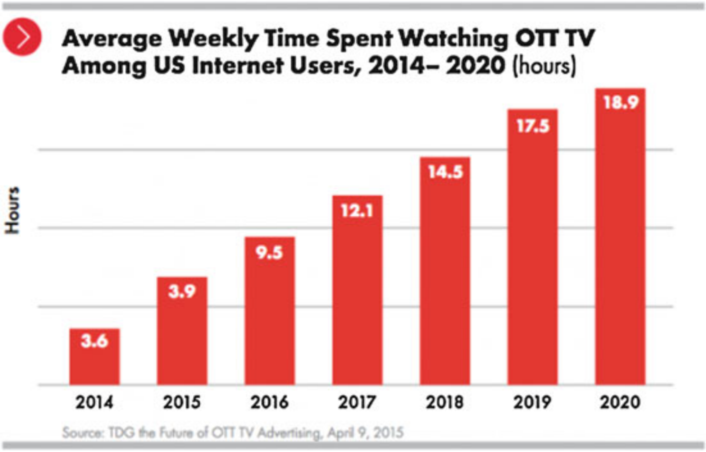


Fig. 5 The rapid rise of OTT television viewing. (Source courtesy for TDG)

DirecTV, Dish, SkyTV, or other DBS providers around the world (The New TV – The State of the New TV Industry).

One of the key questions is how will these video services be paid for in the future. Today video programming is paid for in various ways, often through a combination of subscription fees and paid advertising inserted along with the programming. In the OTT digital streaming model, the subscription fees are less, but advertising with OTT services is now largely absent. However, it is envisioned that ads will become an important part of the future revenue streams (see Fig. 5).

The advantage of GEO-based systems providing direct broadcast television services to fixed dishes is seemingly being lost to data networks that provide services via broadband digital streaming using OTT distribution processes. This is particularly true for users who are opting to have their service provided to smaller computer screens or cell phones rather that television sets. In many cases, such as services offered by Hulu, subscribers are able to control their viewing schedule and see programming when they want rather than when scheduled networking programmers dictate.

Currently direct broadcast satellite service sales, such as for DirecTV, Dish, and SkyTV, are seeing slowing growth rates or even modest declines in the range of 1–2% annually in revenues. This trend is expected to continue. When 5G cellular becomes more widely available and the new small satellite constellations are deployed globally to support 5G services, the revenues within the traditional satellite industry could shift in a way that sees a decline in cable television subscriptions, in subscriptions to direct broadcast satellite services, and in paid entertainment channels subscribed to via either cable or DBS systems.

If small satellite constellations are successfully deployed to provide global broadband Internet access, entertainment distributors, such as Netflix, Hulu, Sling TV, Now TV, Sky Go, and dozens of others now offering streaming entertainment, will be tempted to seek new customers through them. This, in turn, could greatly impact the structure of satellite networks and how these businesses are operated.

Fig. 6 Graphic showing many of the new applications that 5G could provide. (Graphic courtesy of NewTec)

In addition, broadband 5G will be much more than an enabler of more OTT video services. The concept of 5G is that it will open up a host of new applications from driverless cars, to finding a parking place more easily, to improvements in water systems, electrical grids, and more generally grouped under the concept of the Internet-of-Things (see Fig. 6) (What Next for Satellite in a 5G and OTT Era 2018).

The key question is whether 5G and interactive IoT services will be augmented by broadband satellite systems in GEO, MEO, or LEO orbits and whether low latency will be considered essential to many of these applications. Some applications related to IoT monitoring and feedback, such as utility operations, may have a high tolerance for GEO satellite delay and can also be well served by cubesat type LEO systems. But other 5G applications, such as sensors related to driverless cars, may have more exacting limits that require superfast interactive networking and can be only well served by very broadband LEO systems, likely complementing terrestrial wireless systems.

This projected near term future has been described in the following terms by iDirect market analysts. “Today, we are on the verge of seeing what a truly ‘connected world’ looks like. It’s projected that soon there will be 6 billion people, 30 billion devices and 50 billion machines online. That’s essentially everyone and everything connected, across every geography, supporting every application from consumer broadband, mobile gaming and connected cars to global business networks, ships, planes, soldiers, first responders and connected farms” (The 5G Future and the Role of Satellites).

It will be perhaps another decade before it will be sorted out clearly as to which type of satellite service will respond best to which aspect of these burgeoning new data networking markets. These markets may be different for different regions of the world and especially differentiated for applications in developing and highly developed economic markets. What is clear is that there will be an explosive growth in machine-to-machine communications, data networking, and various types of video services in the coming decade. This should sustain growth in terrestrial and satellite service markets and perhaps also engender growth in new areas such as high altitude platform systems. Satellite networks, because of their inherent global accessibility and global coverage, will be part of this mix. Reduced latency of connection as provided by LEO and MEO constellations is expected to drive this satellite growth, while high-throughput satellites in GEO orbit can also fulfill part of this new growth as well.

5 Small Satellites and Their New Backers

The communications satellite industry for five decades or more has been sustained by companies that grew out of the aerospace industries, as well as telecommunications, broadcasting and entertainment companies, or large enterprises associated with the so-called military-industrial complex. These backers and customers relied largely on geostationary satellites to connect far-flung corners of the world and distribute video and later broadband Internet-related services. This support and patronage allowed steady and sustained growth that spread the use of satellite communications across the globe. Satellite services were embraced by most countries of the world, and nearly all joined or used the Intelsat satellite system, which was originally established as an intergovernmental treaty organization until its privatization in 2001. Dedicated national satellite systems or leased capacity on global networks, such as Intelsat, SES, Eutelsat, Telesat, Iridium, Globalstar, Inmarsat, and other systems, extended satellite telecommunications and broadcasting services to virtually every country and territory in the world. Other applications such as remote sensing satellite systems, global navigational satellite services/ precise navigation and timing systems, and meteorological satellite services widened further the extent and impact of global satellite services, though these specialized systems relied even more on the needs of government and government-related customers. While attempts were occasionally made to privatize these services and to attract private capital, especially to remote sensing and meteorological services, commercial markets were for many years too small to support such investments.

Only in the last 10 years have nontraditional financial and business backers expanded into the space sectors. The business world of aerospace and communication has been joined in a dynamic and disruptive way by the world of cyberspace, networking, data streaming, and OTT video services. In short, the world of Silicon Valley, Google, Facebook, and social media has joined the world of commercial satellite services. And as is the custom in this digital world of commerce, these new investors did not look for improvement or change in modest 5% incremental gains. They seek disruptive innovations that change business models and reinvent the way an industry operates in great leaps forward (Madry 2019).

Much of what is described as "New Space" or "Space 2.0" can be traced back to Silicon Valley and entrepreneurial thinking. Skybox and Planet Labs that have reinvented the world of remote sensing came from young people thinking outside the box. They found ways to undertake remote sensing in ways that were ten times less costly than the commercial enterprises highly reliant on government customers that preceded them. The small satellite revolution has now moved to the world of satellites and digital networking (Pelton 2018).

The technology that has led to new ways of designing and building satellites, of designing and manufacturing launch vehicles and ground antennas, and so on has been described earlier in this chapter. But, the driving force behind these various innovations is the entrepreneurial thinkers who envisioned new ways of designing these commercial space industries and seeking new sources of capital investment attuned to disruptive enterprises and new ways of doing business (Madry 2019).

This has not only led to major innovations in how every aspect of how commercial space enterprise is done today but also how such ventures are financed. The new enterprises are today not only being backed by companies like Google, Facebook, Qualcomm, and others from the world of computers and cyberspace but financial institutions that have been investing in these higher growth industries.

And the change in capital formation to support new smallsat initiatives does not end there. Angel investors, investment capital firms, venture capitalists, investment bankers, and others who are pursuing crowd-sourcing opportunities as means to invest in the next big growth industry are finding ways to invest as well. There are now many new start-up commercial satellites systems that have started with such innovative sources of funding. The Spire small satellite system got started with a Kickstarter funding initiative that led to a series of rounds of funding by angel investors.

In the case of Planet Labs and Spire, they have ensured their futures with long-term anchor client contracts to supply data for years to come. In the case of Planet Labs, now just Planet, they are supplying remote sensing data for years to come. In the case of Spire, they have a long-term data supply contract with the European Space Agency worth billions of dollars.

There are other potential investment groups such as sovereign wealth funds, technology investment corporations such as SoftBank of Japan, and other investors that have fueled the rapid growth of many new systems. OneWeb has used an interesting method of including many of its suppliers as investors in the new system. Thus Airbus Defence and Space, which is building the small satellite spacecraft; Virgin Galactic and Arianespace which are providing a significant part of the launch services for the network; Grupo Salinas of Mexico, a major mobile services supplier; and Qualcomm, a major equipment supplier, are all investors in OneWeb. At one point Intelsat and OneWeb were going to merge together with SoftBank financing the transaction costs, although this arrangement was never consummated. Instead, Intelsat remains an investor and close technical advisor and partner.

In OneWeb's latest round of investment, its 7th round, it raised $1.25 billion. These investors included the Japanese conglomerate SoftBank, Mexican conglomerate Grupo Salinas, Qualcomm, and the Rwandan government. There are now some 20 private investors that include aerospace corporations, launcher companies, high-tech computer and Internet companies such as Qualcomm and Google, media companies, as well as large conglomerate investment firms, investment banks, and sovereign funds (Sheetz 2019).

The world of space applications has thus changed dramatically with a new range of investors from the Internet and investment banking world that were not part of this type of business a decade ago. There is clearly a great deal of new technology evolving in the world of small satellites, but much of the change and entrepreneurial spirit that abounds in this field has come from many of the new players who are expecting new (and higher) types of profits from their investments and substantial new benefits from the new technology.

There are some from the financial and space communities who well remember the experience from the first wave of new non-geostationary systems of the 1990s, such as the Iridium, Globalstar, and Orbcomm mobile communications systems, and the broadband Teledesic system. Those ventures ended in bankruptcy, though some have emerged and continue as going businesses. Those with long memories, however, are concerned with the high level of enthusiasm and the massive numbers of filings that now exist in national licensing proceedings and international frequency coordination processes. Currently, there are over 20,000 small satellites proposed for launch in new constellations that suggest the possibility of some significant financial risks with at least some of the new systems. The OneWeb and Starlink systems are just the first of these systems. Additional systems proposed or under construction have yet to find anchor customers for their new systems. The potential for new traffic based on expanded Internet connectivity, 5G broadband cellular systems, Internet-of-Things (IoTs) traffic, automatic identification services, and more is clear, but converting that potential into signed contracts for services represents both a challenge and potential risk.

And, that risk is not just in terms of signed contracts from paying customers, there is also concern about the potential creation of massive amounts of orbital debris. Just managing the traffic in space so that satellites in these large constellations avoid colliding with other objects – possibly defunct spacecraft or rocket launcher stages that remain in orbit – is a major risk and potential long-term barrier to future space infrastructure.

6 Rising Concerns About Orbital Space Debris and New Coping Mechanisms

The people most aware of the space debris problem and concerned about the potential of collision with space debris associated with their new LEO and MEO networks are the very operators of these systems. OneWeb, which is deploying its large-scale network, and SpaceX, which has also now started to deploy an even larger MegaLEO system, have noted their level of concern about this problem and called for responsible operations and effective government regulations, supporting new initiatives began by the US government (Maclay et al. 2019).

They have explained in some detail their own plans to deorbit their own satellites at the end of life of their spacecraft and to bring all of their defunct satellites into a “disposal orbit” that would serve to bring all of these end-of-life satellites back down within 1 year. SpaceX even announced that it would actively deorbit 2 of its first 60 Starlink satellites soon after launch in order to simulate end-of-life disposal. Three other satellites of the first 60, however, failed to activate and were being counted on to deorbit without control and pointing. These early setbacks highlight the potential challenges of deorbiting the hundreds and eventually thousands of additional satellites to be launched by SpaceX, OneWeb, and others (O'Callaghan 2019).

They have also indicated plans to maintain a clear picture of possible conjunctions (collisions) that might occur. The US Air Force, after sometimes equivocal support for providing such warnings, have stepped up their efforts and close cooperation with the private space industry in recent years, especially after an Iridium satellite collided with an old Russian rocket stage in 2009. Long term, the administration of Donald Trump has announced plans and introduced legislation in the US Congress to shift traffic management responsibilities to the US Commerce Department, which already licenses new remote sensing systems. There are detailed plans for carrying out improved space situational awareness that would alert operators of large networks when conjunctions might occur. Thus, those that plan to launch many satellites into low Earth orbit have joined forces with regulatory agencies such as the FCC and the Department of Commerce in the USA to address the need for better space situational awareness, some form of improved space traffic management, and much more strict guidelines for deorbiting of satellites at the end of their life (Brookin 2017).

OneWeb has proposed to launch its satellites into a lower orbit and test them for reliability and functionality before placing them into their operational orbits (Brookin 2017).

Yet, despite all of these efforts and stated goals to manage space debris and prevent satellite collisions that could create thousands of pieces of new debris, the current situation is still considered dangerous. As more satellites are launched, that concern will grow. Efforts by the UN Committee on the Peaceful Uses of Outer Space to develop new guidelines for space debris removal and address the very difficult issue of space traffic management have over the past 5 years made only modest gains.

Currently pending issues with regard to orbital space debris and space situational awareness and space traffic management include the following:

- Concerns about large numbers of deorbiting satellites possibly hitting an aircraft (based on the study by Aerospace Corporation and other analyses).
- Coordination and information sharing between private companies providing space situational awareness data and defence agency operations.
- Improved methods of providing possible conjunction information about potential in-orbit collisions so as not to overload alert systems so that warnings of real possible collisions are taken seriously and evasive actions are taken. These might include improved use of artificial intelligence algorithms to focus on most serious possible collisions.
- Adoption of new "best practices" guidelines to encourage debris removal down from 25 years from end of life to 1 year from end of life.

- National actions to focus on and adopt new regulatory processes related to commercial constellations and debris removal and conjunction avoidance (U.S. Space Policy Directive 3 being one such example) (U.S. Space Policy Directive 3 2018).

7 Conclusions

The development of space applications for many decades followed the trajectory of bigger and better (and more complex) satellites that were more and more cost-effective. These were launched on bigger and better launch vehicles. The small satellite revolution that accompanied the “New Space” revolution has suddenly transformed the paradigm of how to respond to growing demand for digital communications services and the best way to improve satellite applications. This chapter has provided an overview of how new small satellite constellations and the new low latency services that they can provide are a part of the new space industry revolution. The ability to design, build, and test small satellites more cost effectively and launch them at much lower cost into low orbit constellations is changing the entire space industry. It is creating new regulatory issues and concerns but opening doors to innovation and allowing new entrepreneurial ventures to enter these new markets. This chapter has provided an overview of many aspects that will be covered in more detail in later parts of this handbook of small satellites.

The many new commercial satellite constellations that are now being designed and manufactured would not be possible without the new and improved satellite technologies covered in Part 3, the new launcher capabilities described in Part 4, the new approaches to manufacturing discussed in Part 5, the new ground antenna systems discussed in Part 6, and the new uses of small satellites described in Parts 7 and 8. The quite small satellites known as cubesats in some ways pioneered the larger and more sophisticated microsats and minisats that are more typical of very large constellations that are being manufactured and launched today. But the innovations that came with these smallest of the small satellites blazed the trail for the current commercial systems that are staging the next phase of the small satellite revolution.

8 Cross-References

- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Commercial Small Satellite Systems in the “New Space” Age
- ▶ Overview of Cubesat Technology
- ▶ The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and Cubesats

References

J. Brookin, SpaceX and OneWeb broadband satellites raise fears about space debris. *Ars Technica*, October 4, 2017. https://arstechnica.com/information-technology/2017/10/spacex-and-oneweb-broadband-satellites-raise-fears-about-space-debris/

CubeSat. https://en.wikipedia.org/wiki/CubeSat. Last accessed 15 June 2019

T. Maclay, W. Everetts, D. Engelhardt, Responsible satellite operations in the era of large constellations. *Space News*, January 23, 2019

S. Madry, *Disruptive Space Technologies and Innovations: The Next Chapter* (Springer Press, Cham, 2019)

S. Madry, P. Martinez, R. Laufer, *Innovative Design, Manufacturing and Testing of Small Satellites* (Praxis Publishers, Cham, 2018), pp. 17–19

NASA Venture Class Procurement Could Nurture Ride, Small Sat Trend. *Space.com*, June 8, 2015. https://spacenews.com/editorial-nasa-venture-class-procurement-could-nurture-ride-small-sat-trend/

A. Nyirady, SpaceX wants FCC Approval of 1 Million Satellite Broadband Earth Stations. *Satellite Today*, February 13, 2019. https://www.satellitetoday.com/government-military/2019/02/12/spacex-wants-fcc-approval-of-1-million-satellite-broadband-earth-stations/

J. O'Callaghan, 'Not Good Enough' – SpaceX reveals that 5% of its Starlink satellites have failed in orbit so far. *Forbes*, June 30, 2019

J. Pelton, *Space 2.0: Revolutionary Advances in the Space Industry* (Springer Press, Cham, 2018). Chapter 1

M. Sheetz, Space Startup adds $1.25 billion from SoftBank and other to mass produce Internet satellites. *CNBC*, March 18, 2019. https://www.cnbc.com/2019/03/18/oneweb-adds-1point25-billion-from-softbank-and-others-for-satellites.html

The 5G Future and the Role of Satellites, iDirect. https://www.idirect.net/wp-content/uploads/2019/01/The-5G-Future-and-the-Role-of-Satellite-White-Paper-2019.pdf

The New TV – The State of the New TV Industry. *IAB.Com*. https://video-guide.iab.com/new-tv. Last accessed 15 June 2019

U.S. Space Policy Directive 3, National Space Traffic Management Policy, June 18, 2018. https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/

What Next for Satellite in a 5G and OTT Era. *Newtec*, June 8, 2018. https://www.newtec.eu/article/article/satellite-5g-ott

The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and CubeSats

Rene Laufer and Joseph N. Pelton

Contents

Abstract

The term small satellite (or “smallsat”) is almost intentionally vague. In fact, it covers a surprisingly broad range of miniaturized spacecraft – usually defined by its mass. The smallest type of “smallsat” is the tiny “femto satellite” that can have a mass that ranges up to 100 g (or about 3.5 ounces). The next larger class is the “pico satellite.” This type of “smallsat” is defined as ranging from 100 g to 1 kg (or about 2.2 pounds) in mass. A pico satellite is also considered to represent the mass most commonly attributed to a 1-unit CubeSat which has the dimensions

---

R. Laufer (✉)
University of Cape Town, Cape Town, South Africa

Baylor University, Waco, TX, USA
e-mail: rene.laufer@me.com

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_5

of 10 cm × 10 cm × 10 cm – or a cube that is 2.53 in. on each side. Then there is the so-called nano satellite which ranges from 1 to 10 kg – often a multiunit CubeSat. CubeSats, currently, come in sizes that range from a 1-unit spacecraft up to 6 units, or the equivalent of 6 CubeSats in volume.

What is sometimes overlooked when we talk of "smallsats" are miniaturized experiments which are not independent free flyers. Such systems are considered hosted payloads that can fly on larger spacecraft and derive their power, thermal control, orientation, and commands from the host satellite on which they are mounted in space. These hosted payloads can vary from a few grams to several kilograms, but are typically below 10 kg in mass. Another more recent innovation is the ability to send up experimental packages to the International Space Station (ISS). Companies that facilitate this type of small space experiments include NanoRacks for NASA or Space Applications Services for ESA. These companies manage such facilities on the ISS that are operated by astronauts to carry out experiments that are typically designed by students, academic institutions, or even small companies. This approach is highly cost-efficient especially for student experiments. Future space habitats like the Bigelow Aerospace Genesis habitats and larger facilities like the Chinese Space Station are conceived as test beds for low gravity experiments by governmental, military, corporate, or private experiments. This various types of "hosted" small-scale space missions are designed to be cost-efficient, consolidate launch operations, and also avoid the problem of creating orbital space debris.

But so-called smallsats do not stop with femtosats, picosats, and nanosats. The concept of a small satellite or miniaturized satellite continues to include even larger spacecraft as well. Thus there are "microsatellites" (which are typically defined as ranging from 10 to 100 kg or up to about 220 pounds) and even so-called minisatellites ranging from 100 to 500 kg. Sometimes the range for "minisatellites" is stated as from 100 to 1000 kg, but this is less common.

The spectrum of such small spacecraft sizes thus ranges from about 10 g up to 500 kg in mass. This is a gigantic range that constitutes a ratio of 1 to 50,000 between the tiniest and the biggest of these types of spacecraft. The range is so vast that it essentially makes the term "smallsat" almost meaningless without further information.

In order to make an equivalent analogy, this would be much like saying that a child's toy airplane glider made out of balsa wood and a single-engine private airplane are the same class of aircraft.

In short, one thus needs to know mass, volume, power, stabilization capabilities, operational frequencies, and more to understand what any "smallsat" actually is in fact. This chapter starts the handbook by addressing just the tiniest of "smallsats" and their uses.

It discusses the characteristics and surprisingly wide range of applications of "femto satellites," "pico satellites," "nano satellites," and "CubeSats" that have developed over the past 20-year period. The miniaturization of sensors, digital processors, power supplies, and other components has made these smallest of spacecraft impressively capable.

Keywords

CubeSat · "Femto satellite," Hosted payload · Microsatellite · Minisatellite · NanoRacks · "Nano Satellite," "NewSpace," Office of Outer Space Affairs · Orbital space debris · "Pico satellite," Registration Convention · Smallsat · Space 2.0 · United Nations Committee on the Peaceful Uses of Outer Space (COPUOS)

1 Introduction

The definition of femtosats, picosats, and nanosats has been provided above. These types of smallsat are typically used to carry out experiments or to test components, but usually not for commercial projects, at least not in units smaller that 3 U CubeSats. The various categories of small satellites and their definitions in terms of mass need not be repeated. It should be noted, however, that the definitions do sometimes vary. A useful discussion of the various types of small satellites and their various uses can be found in the introduction to the recent book on small satellites titled *Innovative Design, Manufacture and Testing of Small Satellites* (Madry et al. 2018).

The following chart, however, seeks to provide some general perspective on what sorts of applications are common using the larger types of "smallsats" versus those that are indeed quite small (see Table 1).

Thus it is possible to divide this discussion between the larger types of "smallsats," i.e., minisatellites, microsatellites, and in some cases 3- to 6-unit CubeSats. This class of larger smallsat is increasingly being used for commercial purposes and most typically being deployed as operational satellite constellations. These commercial smallsats are thus being divided from the truly small satellites discussed in this chapter. These tiniest of space vehicles are the focus of this initial chapter that will be addressing femto satellites, pico satellites, and nano satellites. A CubeSat is usually a nanosat. Multiple unit "CubeSats" nowadays often cross over between the nano- and microsatellite category (NASA).

Table 1 can assist in providing an overview of applications – historically predominately used to undertake experimental tests, to demonstrate the viability of a particular technology, or even just to relay signals from ground-based systems.

2 "Femtosats": Small Satellites of Up to 100 Grams

One might think that a "femto satellite" of only a few grams would be too small to accomplish anything of value. Yet due to miniaturization, it is possible to create an amazing set of capabilities in a very small device. Figure 1 shows such a system that is equipped with an antenna, gyroscope, microcontroller, magnetometer, and solar cells to provide power – all on one electronics board (Space Exploration 2019).

The fingers that hold this extremely small spacecraft (often also called a "chipsat") show its amazingly small scale.

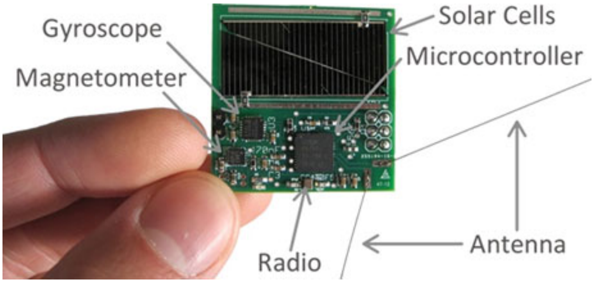
Table 1 The types of small satellites and typical applications

The many applications, sizes, and characteristics of so-called smallsats

Function/ size	**Telecommunication constellation**	**Messaging/ data relay**	**Amateur radio**	**Remote sensing**	**Relay from ground systems**	**Meteorological**	**Scientific experiment**	**Student experiment**
Minisat (100–500 kg)	Typical (see, e.g., OneWeb and Starlink)	Typical (see, e.g., Orbcomm)	–	Typical for some commercial constellations	Typical (see, e.g., Orbcomm)	Typical for LEO and larger	Typical	Rare
Microsat (10–100 kg)	Occasional	Typical	Typical	Occasional	Often	Occasional	Typical	Often
Nanosat (1–10 kg) (multiunit CubeSat)	–	Much more common, i.e., Sky and Space Global	Occasional	Now much more common, i.e., lanet	Occasional	Occasional	Typical	Typical
Pico or femtosat[a] (10 g–1 kg)	–	–	–	–	Occasional	Occasional	Typical	Typical

[a] Based on chart prepared by Joseph N. Pelton and Ram Jakhu. All Rights Reserved. Licensed to Springer Press for this publication

Fig. 1 A “femtosat” or “chipsat”. (Graphic courtesy of Space Stack Exchange)



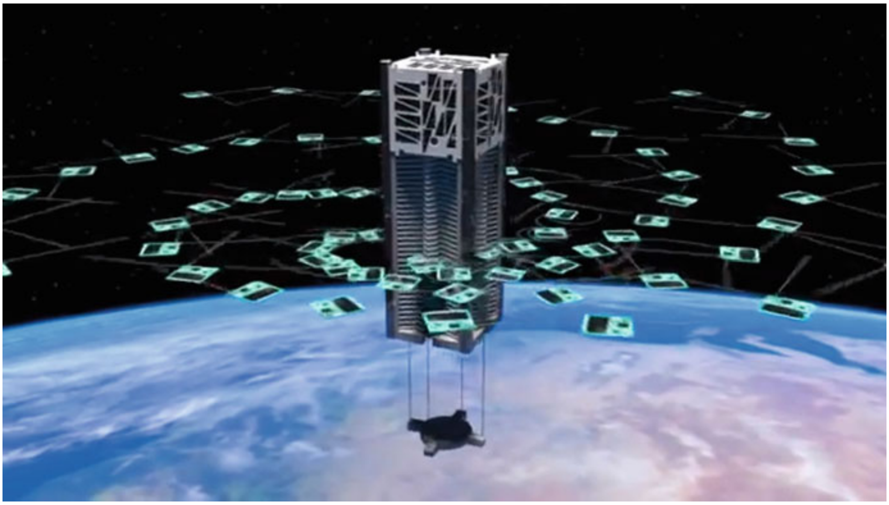


Fig. 2 Kicksat surrounded by a swarm of “femtosats”. (Graphic courtesy of NASA)

Such a tiny spacecraft often does not have the power or capability to communicate directly with Earth or over any greater distance, but a swarm of such miniaturized devices can collect remote sensing or in situ measurement data and then relay it to a close by host satellite. The Kicksat satellite shown with a swarm of “femtosats” or “chipsats” demonstrates how such a configuration would in principle look like in space (NASA 2018) (Fig. 2).

With the Kicksat-2 mission, NASA released 100 chipsats from a 3-unit CubeSat to test the ability of these tiny (3.5 cm^2 or 1.5 in^2) Sprite Chipsats. One objective of this project was to collect data and relay the collected information back to the 3-unit CubeSat host satellite. Such type of data collection method could be used in future, for example, to perform measurements in the proximity of asteroids or other celestial bodies. (Ibid.)

The idea of using “chipsats” in collaboration with one or more larger spacecraft to collect and transmit information is being developed and tested not only by NASA but also by other space agencies and research organizations. One concern that does arise with this type of configuration is that proliferation of orbital space debris. This should be a concern regardless of whether such research missions are in Earth orbit or elsewhere. Solutions that might be found with regard to “femtosats” and “chipsats” might be the possibility of rendezvous and recollecting these elements at the end of such a mission. This or other solutions should also be explored and tested before this type of highly distributed system is utilized extensively.

3 “Picosats”: Small Satellites of 100 Grams to 1 Kilogram Mass

CubeSats with dimensions of 10 cm × 10 cm × 10 cm and a mass of 1 kg for 1 unit (the standard actually allows up to 1.33 kg) are the most common representation of a pico satellite and have pioneered the latest phase of the small satellite revolution. The preponderant number of these projects for the last two decades since the inception of the idea of the CubeSat standard in 1999 has mostly come from academic or research institutions.

There are now literally hundreds of CubeSats that have been launched (mostly now in the multiunit CubeSat nano satellite size). Early examples of CubeSat type projects include (Smallsat Mission Examples and Design Suggestions 2019):

- QuakeSat from Stanford University which was designed to capture extra-long frequency (ELF) precursor signals prior to earthquakes (launched in 2003).
- XI-IV and CUTE-1 from Tokyo University and Tokyo Institute of Technology, respectively. Both achieved several objectives including verification of off-the-shelf components as well as testing transmission and sensing components.
- AAU CubeSat from Aalborg University tasked with testing a camera on a chip system.
- Can-X from the University of Toronto is designed to test the performance of an Atmel ARM microprocessor, gallium arsenide solar cells, CMOS imagers, active magnetic controls for detumbling, and three-axis stabilization.

The earliest CubeSat projects were largely experimental projects developed at universities with little systematic specifications as to power supply, thermal control, antennas, wiring, control units, and stabilization. The only requirement set by funding institutions like NSF and NASA in the USA to universities was the form factor of the CubeSat standard. As the enthusiasm and global interest in CubeSat systems grew, the alternatives available for the provision of CubeSat frames, power, digital controls, antenna systems, motherboards, and other components offered by suppliers have multiplied exponentially. Just some of the many options readily available online include Interorbital (1 kg and 1.33 kg kits), CubeSatShop (kits, buses, and off-the-shelf components), Pumpkin CubeSats (kits, components, and

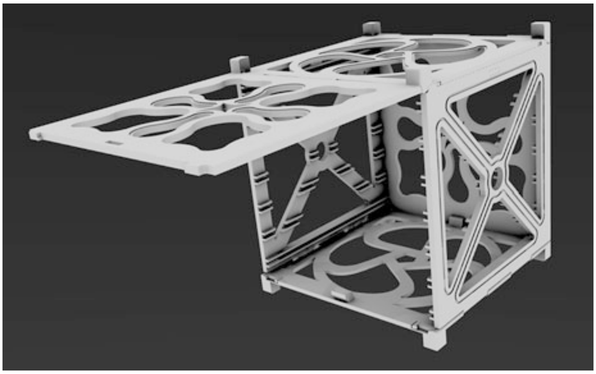


Fig. 3 One of many CubeSat buses that are available for creating a CubeSat today. (Courtesy of Cubesatkit.com)

software), Innovative Solutions in Space (offering CubeSat and PocketQube sat kits and components), GomSpace (supplier for components including electric MEMS propulsion based in Denmark), or Clyde Space (based in Scotland with CubeSat missions commissioned by ESA) (Where to buy CubeSats 2019).

Access to space options now open includes CubeSat missions (and small hosted payload experiments) that can be launched up to the International Space Station to being conducted on-board allowing large cohorts of students to carry out space-based experiments. Tens of thousands more students all over the globe have competed to put together detailed proposals for space experiments to actually fly in space via space agency offered flight opportunities. The cost of arranging for a launch is still sufficiently high that the number of CubeSats actually going into space remains relatively small. The process of designing, making, testing, qualifying for launch, and actually launching is daunting, and the cost is typically over $100,000 or even more depending on the complexity of the payload and the necessary subsystems. Nevertheless the ready availability of kits that can be ordered online all around the world has made this opportunity much more widespread (see "'Picosats': Small Satellites of 100 Grams to 1 Kilogram Mass") (Fig. 3).

A similar approach based on the CubeSat specification leads to a new version within the picosat category known as a PocketQube. In 2009, PocketQubes were developed by CubeSat co-inventor Robert Twiggs at Morehead State University with support from Kentucky Space. The idea was to provide a lower cost option for student experimentation in a standardized way. Pocketqubes are 5 cm × 5 cm × 5 cm in dimension or one-eighth the size of the 10 cm× 10 cm× 10 cm CubeSat (see Fig. 4) (By PocketQubeShop 2019).

Although the majority of PocketQube projects are undertaken as academic programs, there are already at least three start-up companies that assist with components and launch arrangements for the launch of PocketQube satellites, for example, GAUSS Srl, Fossa Systems in Italy and Alba Orbital in the UK. Most of these projects use off-the-shelf components, and a typical PocketQube satellite has a mass of often 200 g and less – especially appealing due to its lower cost not only to

Fig. 4 A pocketqube picosatellite that is one-eighth the size of a CubeSat. (Graphic courtesy open access commons)

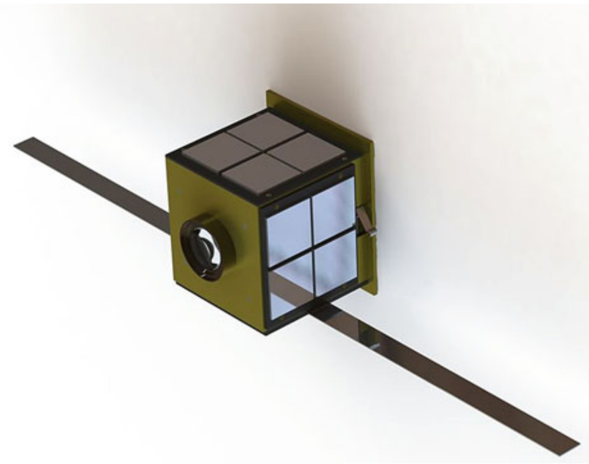
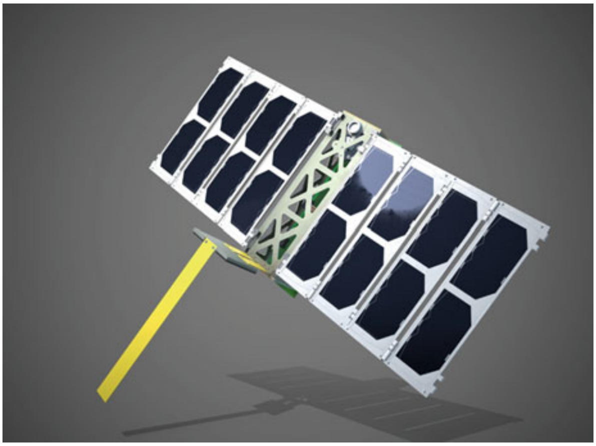


Fig. 5 ESA's Unicorn 2 CubeSat from its Ares development program. (Graphic Courtesy of the European Space Agency)



academic experimenters but also to component testers and amateur radio satellite builders (Pocketqube satellite 2019).

What has accompanied the development of PocketQube satellites has been the availability of consolidated launch configurations designed to accommodate these pico satellites. This has, for example, led to the development of the Unicorn missions under funding provided by the European Space Agency's (ESA) Artes program. Within this program 3-PocketQube-unit pico satellites and multi-PocketQube (up to 96) deployers were developed and tested (Pelton 2016), (Alba Orbital Ltd. | ESA's ARTES Programmes 2019) (see Fig. 5).

Pico satellites in the range of up to 1 kg are often limited in what activities that they can carry out in their volume envelope to accommodate certain type of instruments (e.g., optical payloads) or the ability to transmit signals and therefore data over longer distances. Thus they, like femtosats, are most likely to test

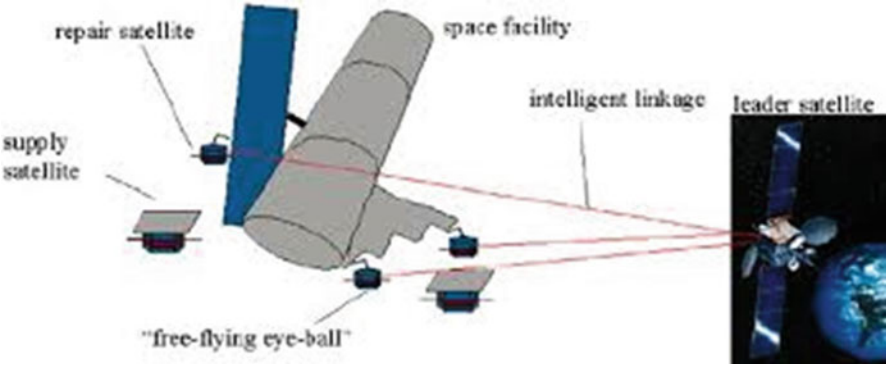


Fig. 6 Pico satellites as "flying eyeballs" in space. (Graphic Courtesy of DARPA)

components or in more and more concepts are to be adjuncts to larger spacecraft – leading into the area of federated and fractionated spacecraft.

One concept that has been examined is that of an inspector or "free flying eyeball" that could be connected to a spacecraft engaged in Rendezvous and Proximity Operations (RPOs) in space (e.g., for in-orbit servicing). Such small pico satellites could provide useful information to docking with a satellite that is being refueled or serviced in space.

In this case there would be a valuable space facility, a supply ship that carries such free flying "eyeballs" or inspector spacecraft that would provide information from various angles to assist with the safe docking and supply operations (see Fig. 6).

Studies done over the last 20 years (e.g., by Drs. Ivan Bekey and Joseph Pelton or at the University of Surrey) examined the possibility of creating large reflectors with a phased array feed system flying in space to create a large number of spot beams (perhaps many thousands in number that would only be a half or perhaps a quarter of a degree in size). Each free flying reflector could be flat since the feed system would use phased array technology to create the large number of beams for a space-based cellular communications system.

The most exotic extension of such a concept for a large-scale space-based communications system would be to create a massive free flying phased array composed of thousands of specifically designed pico satellites. Figure 7 describes such a very large-scale communications satellite virtual antenna system consisting of 100,000 free flying phased array elements with each element having a mass of down to 23 g – therefore in the femtosat range. There would still be a need for a "satellite feed system" flying at the center of the virtual antenna to form the beams within the large distributed array (Iida et al. 2003).

While this example uses femtosats, the first type of distributed phased array network for digital communications will more likely be scaled to something like a hundreds to one thousand elements with a mass of around 500 g in space. These initial entirely theoretical studies acknowledged that there were be many practical problems to be addressed. This included not only how the massive arrays in space would be deployed but, even more importantly, how would this massive "clutter" of

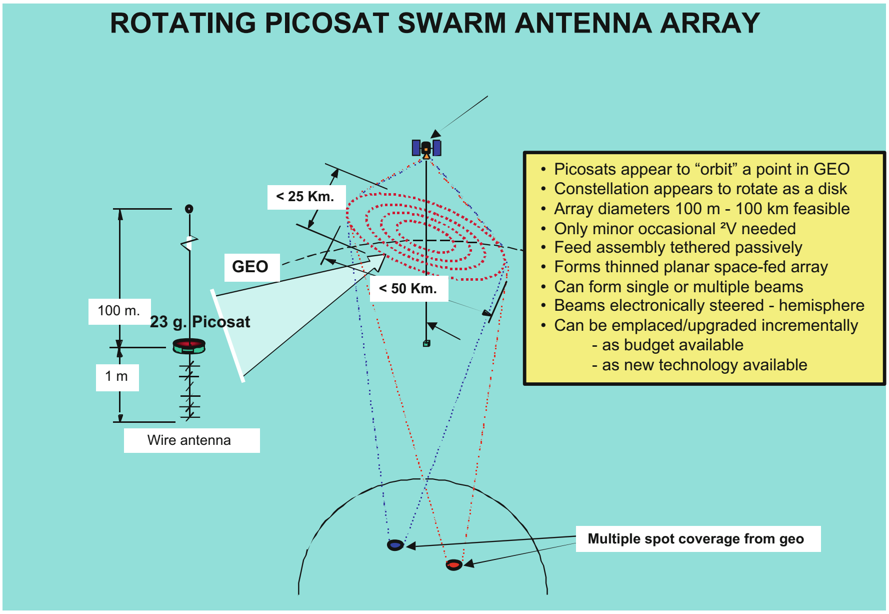


Fig. 7 Creation of a picosat phased array swarm to create super antenna system in space. (Graphics courtesy of Ivan Bekey and Joseph Pelton, All Rights Reserved)

tiny spacecraft elements be collected and deorbited safely at the end of life of this communications swarm, without creating significant orbital space debris posing a threat to other spacecraft. Also there are questions as to whether such an array, when deployed in GEO orbit, would create unacceptable problems and interferences with other satellites operating in the geosynchronous orbit arc (Pelton 2010) (see Fig. 7).

4 Nanosats and Multiunit CubeSats: Small Satellites of Up to 10 Kilogram

While the CubeSat standard grew to become a revolutionary success in the field of small satellites (in particular in the pico satellite category), the constraints of a 1-unit CubeSat became obvious very quickly in terms of the limitations in the extremely small volume and mass for a payload after all necessary satellite subsystems are accommodated. Also institutions like NSF and NASA in the USA or ESA in Europe realized early that the scientific return per cost of a 1-unit CubeSat is quite small in relation to the effort and cost. Based on the CubeSat standard, encouraging the building of multiunit spacecraft, 2-unit (2 U) and especially 3-unit (3 U) nano satellites of around 2.5–4 kg mass became the new common size of CubeSats.

Larger CubeSats (3 U and the more and more common 6 U “six-pack” nano satellites) benefit especially from sizing effects of a similar size/similar mass service segment of the satellite for 2 U, 3 U, or often 6 U spacecraft, therefore increasing the available payload envelope significantly. With such larger payload opportunities especially remote sensing and communication services, payloads became feasible – as shown with Planet's (formerly Planet Labs) "Dove" 3 U Earth observation satellites.

More recently such cost and performance advantages of multiunit CubeSats have attracted research groups and space agencies such as the US Department of Advanced Research Projects (DARPA), NASA, ESA, JAXA, and other scientific research and commercial organizations. There are now more and more missions that are 3-unit spacecraft (30 cm × 10 cm × 10 cm) up to 6-unit spacecraft that have a volume up to 6 liters. These nanosats then typically range from 4 to 10 kg in mass.

This access to complete 3 U or 6 U kits with software and hardware has now made this small satellite technology available not only to professional researchers and university experimenters. There are nonprofit organizations such as the Arthur C. Clarke Institute of Space Education (ACCISE) that recruits student participation in on-orbit experimentation. This international initiative that works closely with the National Center for Earth and Space Sciences Education (NCESSE) focuses on US student participation, but organizations like UNISEC-Global supports small satellite activities all over the world, and UNISEC-Global members already were responsible for several dozens of small satellite missions. As of March 2019, ACCISE and NCESSE had completed some 15 space missions to the International Space Station and carried over 150 student space experiments to the ISS dating back to 2011 (Clarke). UNISEC-Global targets to have 100 countries involved in (small satellite) space missions by 2020 and provide access to space for students in every country on the globe by 2030.

5 The Future of Truly Small-Scale Satellites

Today there are many questions arising about the increasing number of small satellite missions and their future – especially regarding orbital space debris. Those questions are about as to whether there should be new requirements put in place that go beyond the United Nation's voluntary guidelines for orbital debris mitigation by removal from orbit within 25 years after the end of life as adopted in December 2007 (Space Debris Mitigation Guidelines). There are questions as to whether there should be passive systems deployed at end of life for CubeSats and smaller that usually do not have any active means to deorbit. There are, in fact, also a wide range of technical, operational, regulatory, reliability, and frequency interference concerns that small satellite deployments have raised and that the Working Group on the Long Terms Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space (COPUOS) has considered in recent years. On one hand there has been an interest in encouraging innovation and creativity and promoting space technology that is of a scale and type that is suitable for use by emerging and developing nations. Yet on the other hand, there are concerns about near Earth orbital space as a limited resource, growing RF interferences, and activities that might work against the long-term sustainability of space.

6 The Technical Issues and Challenges

It is still not clear how much further technical progress can be made to create smaller, smarter, and more capable satellites to provide new types of services or improve and expand existing ones. Constraints that once required satellites to be massive and much larger in volume have been overcome with miniaturization and new electronic beam forming technology that have allowed satellites and ground systems more efficient and low Earth orbit satellites much more viable for many more purposes.

Further improvements have come from increased use of commercially available off-the-shelf components, automation in manufacturing and testing processes, and other entrepreneurial innovations that have allowed simplification of design. Key innovations have also been seen in launch vehicles design. Here innovations have included the use of new materials (e.g., Rocket Lab) and an evolution toward reusable rocket systems (e.g., SpaceX and Blue Origin). We have seen reduced costs and even the elimination of launch facilities by the addition of carrier vehicles that allows high altitude launch from the air (e.g., Virgin Galactic).

The very smallest spacecraft as represented by femtosats and PocketQube satellites have seemingly come up against limits created by the need to communicate with ground-based systems. Communications over longer distance require power and antenna gain to communicate. There are clear limits to broadband communications to and from space-based femtosats, picosats, and even nanosats. For such very small satellites, there are physical limits posed by power levels, antenna gain, and transmission path loss with which to contend. Even so innovations such as federated and fractionated distributed mission concepts might help address some of these technical limitations while also providing opportunities to reduce the cost of access to space for student experimenters as well as commercial entrepreneurs (Joseph 2015).

One example of multipurpose units is the Faraday 1 smallsat platform. This was developed by SSTL and is now provided as a consolidator of smallsat missions by the British company In-Space. In this particular case, In-Space is combining five different experimental missions. In all cases the small-satellite participants wish to provide in-space testing of new technology.

The launch in this case was the Electron rocket from New Zealand. This integrated approach serves to create efficiencies with regard to cost, communications, operations, power, and frequency use. In short there are many benefits from having several different payloads from different customers combined in a single mission – not to mention the added benefit of minimizing orbital debris issues (British In-Space Missions 2019).

Certainly the technical challenges will only continue to increase as the seemingly difficult problems of limits to miniaturization seem to be reached at least in areas like optical payload and communications systems.

7 The Legal and Policy Challenges

As one notable example, the French Government has enacted the French Space Operations Act (FSOA) that will impose a fine for any French spacecraft launched that is not deorbited within 25 years after end of life. This would appear to serve as a model regulation for other nations to follow with regard to putting teeth behind the UN COPUOS voluntary guidelines. The problem is that plans to launch as many as 20,000 and more LEO small satellites into orbit in the next few years with lifetimes of perhaps 5–8 years have now called into question the viability of the 25-year guideline adopted over more than a decade ago. The world of space technology and space innovation is moving quite rapidly, but the world of national and global space policy and regulation is moving quite slowly in comparison. The UN voluntary guidelines actually took some 18 years from start to finish to be adopted. This timetable is not well suited to today's space-related issues.

8 Conclusions

The world of the small satellites and the innovative design techniques and fascinating experimental and even practical uses that are now being used within femtosats, picosats (such as CubeSats or PocketQubes), and nanosats (such as multiunit CubeSats) has created the start of a new era in space systems. Small satellites, including the very smallest of these systems, have shaken the applecart of the entire space enterprise around the world. It has led to a revolution in not only how satellites are conceived, engineered, manufactured, and tested, but it has also stimulated a new view on the design, engineering, and manufacturing of launch vehicles.

Some have said that this revolution has come from the world of computer science intersecting with the world of aerospace. Another way of putting this has been to say: "Silicon Valley has discovered the world of the military-industrial complex and re-invented it." This means that there has not been a single change whereby miniaturization has made satellites smaller. It means that a whole series of mind-sets have been uprooted and many different things have been disrupted and reinvented. The list of these changes is startling to examine (Pelton 2019).

Things that are different in the world of space today due to the "smallsat" revolution includes (but is certainly not limited to) (i) satellites are much smaller due to miniaturization of computers and digital controls and avionics, more use of low Earth orbits, and innovations in the design of antennas having electronically formed beams rather than shaped by antenna dishes both in space and on the ground; (ii) satellites are moving toward mass production and innovations such as the use of additive manufacturing; (iii) design cycles are being rapidly speeding up with perhaps two or more new design cycles every year rather than every 5–7 years; (iv) changes to sparing philosophy and large-scale deployment of small satellites have led to the use of many more available off-the-shelf components and less requirements for expensive space qualified hardware; (v) more reliance for innovation and changes being accomplished by changes to software rather than new black boxes and hardware; and (vi) significant economies being accomplished via lower launch costs. This is certainly not only a matter of smaller and less massive spacecraft and more cost-efficient launchers but also a move to reusable launchers, lower cost launch sites or elimination of traditional launch sites, and more.

The terms Space 2.0 and NewSpace are used for good reason. The world of space as it existed at the start of the space age and as it was defined by governments, space agencies, military organizations, and very large aerospace companies, largely under the control of governments, has changed a very considerable amount since the start of the twenty-first century. Private development like the SpaceShipOne spaceplane to win the Ansari XPrize in 2004 is an example of such a key aspect of that change. The birth of a host of new private space industries such as SpaceX, Blue Origin, Sierra Nevada, Virgin Galactic, Rocket Lab, OneWeb, and many others represents a key indication of a space industry that is more entrepreneurial, more innovative, and more able to respond to disruptive technologies, process, and reinvention of how things get done. If there is one icon that represents that change, it is the “CubeSat” that represents the change within the aerospace world.

9 Cross-References

- ► Network Control Systems for Large-Scale Constellations
- ► Overview of Commercial Small Satellite Systems in the “New Space” Age
- ► Overview of CubeSat Technology

References

Alba Orbital Ltd. | ESA’s ARTES Programmes. 9 Sep 2019. https://artes.esa.int/contractors/alba-orbital-ltd|https://artes.esa.int/contractors/alba-orbital-ltd

British In-Space Missions Plans for Carpool Satellite Launch this Year from New Zealand. 22 Jan 2019. http://www.satnews.com/story.php?number=1041308065

By PocketQubeShop – Own work, CC BY-SA 3.0. 9 Sep 2019. https://commons.wikimedia.org/w/index.php?curid=32717744

A.C. Clarke, Institute for Space Education. 9 Sep 2019. http://clarkeinstitute.org/. Last accessed Mar 2019

T. Iida, J.N. Pelton, E. Ashford, *Satellite Communications in the 21st Century: Trends and Technologies* (AIAA, Reston Virginia, 2003). Chapter 7

N. Joseph, *Pelton, New Solutions for the Orbital Debris Problems* (Springer Press, New York, 2015)

S. Madry, P. Martinez, R. Laufer, *Innovative Design, Manufacture and Testing of Small Satellites* (Praxis by Springer Press, Cham, 2018), p. 2. Chapter 1

NASA, Kicksat-2, 26 Sept 2018. https://www.nasa.gov/mission_pages/station/research/experiments/2374.html

NASA, What are Smallsats and CubeSats. 9 Sep 2019. https://www.nasa.gov/content/what-are-smallsats-and-cubesats. Last accessed 15 Mar 2019

J.N. Pelton, *Trends and the Future of Satellite Communications* (Springer Press, New York, 2010)

J. Pelton, *New Solutions for Orbital Debris Removal* (Springer Press, Cham, 2016)

J. Pelton, *Space 2.0: The Revolution in the Space Industry* (Springer Press, Cham, 2019)

Pocketqube satellite. 9 Sep 2019. https://en.wikipedia.org/wiki/PocketQube. Last accessed 15 Mar 2019

Smallsat Mission Examples and Design Suggestions. 9 Sep 2019. Department of Electrical Engineering, National Cheng Kung University. http://www.iaalab.ncku.edu.tw/picosat/DownLoad/93%BE%C7%A6~(%A4W)%AB%D7%BD%D2%B5%7B%A4%BA%AEe/missionexample.pdf

Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. http://www.unoosa.org/pdf/publications/st_space_49E.p. 22 Dec 2007

Space Exploration. 9 Sep 2019. What is the smallest operational artificial satellite? https://space.stackexchange.com/questions/925/what-is-the-smallest-operational-artificial-satellite. Last accessed 15 Mar 2019

Where to buy cubesats. 9 Sep 2019. Online http://www.spacetechasia.com/where-to-buy-cubesats-online/. Last accessed 16 Mar 2019

Commercial Small Satellites for Business Constellations Including Microsatellites and Minisatellites

Joseph N. Pelton and Rene Laufer

Contents

Abstract

The smaller version of “smallsats” known as “femtosats,” “picosats,” and “nanosats” or “cubesats” was discussed in the preceding chapter. These very small spacecraft, plus small hosted payloads, or tiny space experiments that are carried out in the Nanoracks experimental platform on board the International Space Station provide a gateway into space that can allow students to conduct experiments without huge multimillion dollar investments.

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

R. Laufer
University of Cape Town, Cape Town, South Africa

Baylor University, Waco, TX, USA
e-mail: rene.laufer@me.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_6

The commercial uses of “smallsats” for 1-unit cubesats and below are extremely rare. Increasingly, there are commercial systems, however, that are using 3U cubesats particularly for automatic identification services (AIS) and for messaging, machine to machine (M2M), and Internet of Things (IoT) connectivity. The other prime commercial applications by 3U and above cubesats are for remote sensing with lower resolution in cases where rapid updates of information and data analytics are the prime purpose of a small satellite constellation.

Thus small space units such as cubesats and even smaller pocketqubes are typically used for student or scientific experiments or used for proof of concept for a much larger follow-on activity. This means that most commercial networks are using the larger class of microsats and minisats for their constellation designs. Thus this chapter is focused on the burgeoning growth of “smallsats” for commercial networks and the “NewSpace” or “Space 2.0” constellations that employ larger spacecraft. These satellites are still far smaller than the typical commercial and space agency research spacecraft that has grown to the size that ranges from 1000 Kg on up many thousands of Kgs.

There is now a huge and rapidly growing new commercial market for what are called “microsats” (e.g., 10–100 kg or 22–220 pounds) and “minisats” (e.g., 100–500 kg or 220–1100 pounds). Others, however, define minisats as being from 100 kg up to 1000 kg (or 220–2200 pounds). These types of “smallsats” unlike those discussed in the preceding chapter are typically being deployed for commercial missions and applications and most often for large constellations to create a global service. Space agencies, military agencies, and established research organizations are finding that these smaller but highly capable satellites can be used for scientific exploration in orbit and in deep space and for proof of concept for larger missions.

These microsatellites and minisats are most often launched in low Earth orbit (LEO) but not exclusively so. GEO-orbiting spacecraft and deep space missions can also use this type of “smallsat” that are performing ever more complex and difficult missions. Even radarsats that require substantial power levels because they require “active sensing” have been deployed as constellations using this type of smallsat such as Canada’s most recent Radarsat Constellation.

This chapter provides the background of the earlier “smallsat” constellations that failed financially, the resurgence in the technologies, financial support, markets for these new “smallsat” systems, and the regulatory and other challenges still to be faced in this highly dynamic market that is still in what might be considered a second shakeout phase of development.

Keywords

Commercial smallsat constellations · Electronic beam forming · Globalstar · HawkEye 360 satellite constellation · Iridium · Metamaterials · Microsatellites · Minisatellites · “NewSpace,” Off-the-shelf components · Orbcomm · Phased array antennas · Planet · Remote sensing constellations · SpaceX · Starlink

1 Introduction

The demand for “smallsats” is currently projected to increase and rise to a high level as demand for geosynchronous satellites for telecommunications and remote sensing appears to be falling.

The estimates as shown in Fig. 1 indicate that based on historic growth patterns as many as 2600 nanosats and microsats might be launched from the period 2020 through 2024. These estimates as developed by SpaceWorks suggest that the rate of these microsat launches might rise to a high of nearly 700 launches per year by 2022 if current market forecasts for full deployment continue for smallsats in the range of 1–50 kg. (Neiderstrasser 2019).

Yet, as high as these estimates are for microsats, the estimates for minisats (in the range of 50–500 kg) may conceivably be as high at 20,000. Although most estimates discount the full deployment of all licensed microsats and proposed for launch to a much reduced number, even the discounted figures are tremendously high.

The projections by Northern Sky Research in their studies indicate a wide range of possible launches for microsatellite in the range up to 500 kg for large-scale constellations that include networks for OneWeb, LeoSat, Telesat, two systems for SpaceX, Boeing, Comstellation, Theia, and a number of other currently proposed constellations. Even in the case of these constellations, there continue to be filings to add to the size of these networks that are now working their way through licensing processes at the national or international level.

Thus Northern Sky Research has indicated that there is an opportunity of anywhere from 10,000 to 20,000 microsatelllites to be launched over the next 6–7 years. This assessment, however, was made before the Covid-19 corona virus impacted the global economy. In contrast to these historically high number of satellites, there has been a large dip with regard to GEO satellites, especially for telecommunications. In this case there have only been nine large-scale GEO satellites ordered in the past couple of years. Part of this change, of course, is that the new high-throughput satellites are so highly efficient. These huge high-throughput satellites (HTS), at up to 150 gigabits/second, represent the throughput capabilities of 20–30 conventional GEO satellites of the past. Just as there is now a smallsat revolution seemingly underway involving low Earth orbit constellations, there is another revolution underway with regard to the superefficient and very cost-effective high-throughput satellites in GEO (Russell 2018).

There are clearly reasons why the number of possible launches of minisats varies so very widely. If one takes just the case of the SpaceX Starlink systems, one sees that these two currently filed and licensed smallsat systems together would constitute, when fully deployed, some 12,500 new smallsats in low Earth orbit (LEO) – this is far more than all communications satellites currently operating and all comsats ever launched into orbit. This system that would cost over $10 billion if fully deployed involves some 4500 operating in Ku-band and Ka-band frequencies and around 7000 operating in the extremely high-frequency V-band between 40 and 75 GHz.

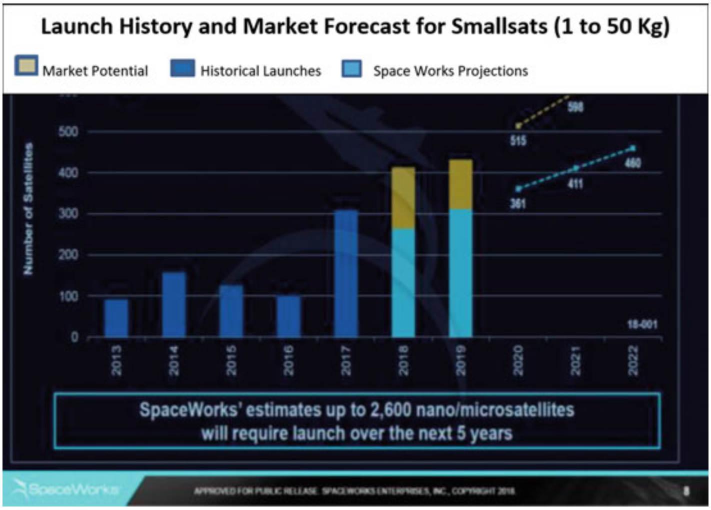


Fig. 1 Projected increases in "smallsat" launches. (Graphic courtesy of SpaceWorks)

And this is not some abstract concept; serious deployment of this network to challenge the OneWeb constellation has now also begun in earnest. Early on May 24, 2019, a reusable Falcon 9 satellite deployed 60 of the Starlink satellites in low Earth orbit in what seems to be the start of deploying a vast array of small satellites into low Earth orbit (LEO). And these satellites are not tiny cubesats but 500 pound (227 kg) spacecraft, many times the size and mass of the Intelsat I (Early Bird) satellite that started the age of global satellite communications in 1965 54 years earlier (Thompson 2019).

The truly vast size of these "megasatellite" systems and the large amount of capital that must be raised to pay for the manufacture and launch of these new systems – some of these constellations containing thousands of satellites – contribute to the uncertainty in the projected number of microsat launches. Thus there is today uncertainty of market forecasts as to the number of smallsats to be manufactured, the number to be launched, and the revenues that will be derived from smallsat constellations designed to provide telecommunications and networking services around the world (Torrieri 2018). There was significant uncertainty in smallsat forecasts even before the Corona virus impacted the global economy. Thus today most projections see a downturn in volume and even more bankruptcies such as has been the case with One Web, Leosat, Vector, Firefly, etc.–with more to follow.

This has set off a large number of "smallsat" launch vehicle development efforts. According to a study conducted by Northrup Grumman in 2018, there are over ten countries seeking to develop new "smallsat" launch capabilities. This is led by some 20 such commercial developments in the United States alone (Op. cit, Carlos Neiderstrasser).

Other developments are widely distributed around the world, i.e., China (six projects), Spain (three projects), the United Kingdom (three projects plus a joint project

Table 1 Potential and actual developers of new "smallsat" launch vehicles

New smallsat launcher developments around the world			
Organization	Vehicle name	Country	Date
ABL Space Systems	RS1	USA	Q3 2020
Aphelion Orbitals	Helios	USA	2021
Bagaveev Corporation	Bagaveev	USA	2019
bspace	Volant	USA	2018
Celestia Aerospace	Sagittarius Space Arrow CM	Spain	2016
Cloud IX	Unknown	USA	N.A.
CONAE	Tronador II	Argentina	2020
CubeCab	Cab-3A	USA	2021
Departamento de Ciencia e Tecnologia Aeroespacial	VLM-1	Brazil	2019
ESA	Space Rider	Europe	2020
Firefly Aerospace	Firefly Alpha	USA	Q3 2019
Gilmour Space Technologies	Eris	Australia/ Singapore	Q4 2020
Interorbital Systems	NEPTUNE N1	USA	N.A.
ISRO	PSLV Light	India	Q1 2019
LandSpace	LandSpace-1	China	H2 2018
Launcher	Rocket-1	USA	2025
LEO Launcher	Chariot	USA	Q4 2018
Linkspace Aerospace Technology Group	NewLine-1	China	2020
One Space Technology	OS-M1	China	2018
Orbex	Orbex	United Kingdom	N.A.
Orbital Access	Orbital 500R	United Kingdom	2020
PLD Space	Arion 2	Spain	3Q 2021
Rocketcrafters	Intrepid-1	USA	Q1 2019
RocketStar	Star-Lord	USA	2018
Skyrora	Skyrora XL	UK/Ukraine	N.A.
Space Ops	Rocky 1	Australia	2019
SpaceLS	Prometheus-1	United Kingdom	Q4 2017
SpinLaunch	Unknown	USA	N.A.
Stofiel Aerospace	Boreas-Hermes	USA	2019
Stratolaunch	Pegasus (Strato)	USA	N.A.

(continued)

Table 1 (continued)

New smallsat launcher developments around the world			
Organization	Vehicle name	Country	Date
VALT Enterprises	VALT	USA	N.A.
Vector Space Systems	Vector-R	USA	H2 2018
Virgin Orbit	LauncherOne	USA	H1 2018
Zero2Infinity (Strato-balloon)	Bloostar	Spain	2017

Data derived from the information provided in a paper by Carlos Niederstrasser, Northrop Grumman, 32nd Annual AIAA/Utah State University (AIAA/USU Conference on Small Satellites, 2018)

with Ukraine), as well as single projects in Argentina, Australia, Australia/Singapore, Brazil, pan-European (ESA), India, and New Zealand (Ibid.) (See Table 1).

The extent to which there are many challenges unknown in the future development, manufacture, launch, and operation of large-scale constellations using smallsats cannot at this stage be overstated.

2 Historical Background

There is not an exact time when the use of commercial smallsats in constellations first came to the fore, but it is convenient to start with the smallsat constellations for land mobile satellite communication which were first planned and launched beginning in the 1990s.

It was in the mid-1990s that the Iridium and Globalstar satellite networks were designed as smallsat constellations bean. These smallsat constellations numbered in the range of 50–70 satellites were in many ways the pioneers. The smaller Orbcomm network was also started in this time frame. Two other proposed networks that were proposed, started, but ended in bankruptcy before launch, namely, ICO and Teledesic, are also part of the early days of the smallsat revolution that began in the 1990s, seemed to pause in the early years of the twenty-first century, and then have come roaring back in the 2010s.

The Iridium and Globalstar smallsat constellations were constituted with the minimum number of spacecraft sufficient to provide continuous coverage for mobile communications services at the LEO selected for these systems. Constellations in LEO-based polar orbits designed to provide Earth observation, meteorological coverage, and remote sensing services had even been deployed with smaller-sized constellations since continuity of service was not required in these cases.

In the late 1980s and early 1990s, the ideas began to percolate. There were various proposals for large-scale constellations with hundreds or even thousands of smaller-scaled satellites deployed in LEO networks. This new type of satellite architecture was premised on a number of innovative ideas.

(i) These ideas included the following rationale with regard to the use of "smallsat" constellations: (i) Smaller satellites in low Earth orbit (LEO) would be able to provide more power with greater efficiency because of lower path loss. The argument was that since they could be up to 40 times closer to the Earth's surface, they would be able to deliver the equivalent of 1600 times greater intensity of power distribution based on "path loss" formulas.
(ii) These satellites would operate with much less transmission delay (or latency) due to being much closer to Earth.
(iii) These new smaller but much more numerous satellites could be mass-produced and be more efficiently tested for performance because of their much larger production runs.
(iv) The design of these "smallsats" might be able to use more off-the-shelf and lower-cost components because of the larger production runs and sparing philosophy that would simply replace any defective satellite with another "smallsat."
(v) Although there were many more satellites to be launched, the launch of low orbiting spacecraft is easier to achieve and easier to operate than spacecraft launch all the way out to geosynchronous orbit – almost a tenth of the way to the Moon.

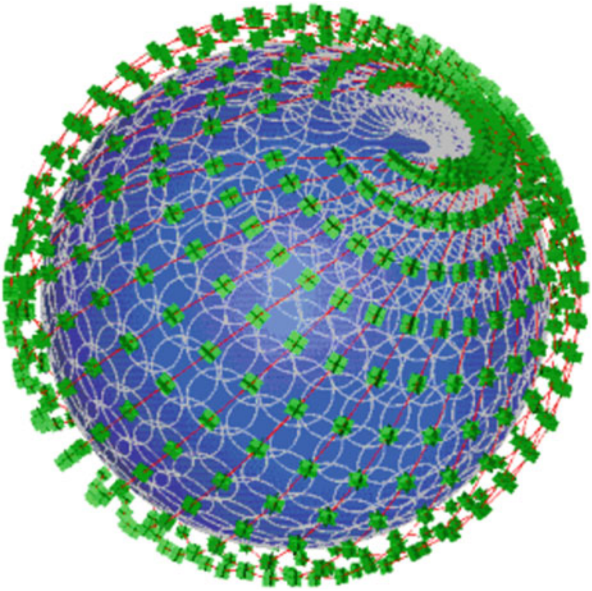
Despite these perceived advantages, there were several significant disadvantages. These were:

(i) The satellites, in low Earth orbit, would have much shorter lifetimes, typically of about 5–8 years, in that their orbit would decay and deorbit over time.
(ii) The GEO-orbiting spacecraft did not require ground stations or user terminals to track them since the GEO sats always appeared to hover over one fixed spot in the sky and thus did not require constant tracking of the satellite as it moved across the sky.
(iii) The signals coming to and being emitted from the satellite would have to be rapidly switched from beam to beam (about once a minute) and from satellite to satellite (about every eight minutes) in the most rudimentary constellations.

This constituted a particular challenge for telecommunications satellites in terms of potentially dropped calls since a typical telephone call lasts over 5 min and this would have required precision switching of beams four or five times for each call. In an environment with millions of calls on line in a global network, this would require an enormous precision of electronic switching accuracy that certainly challenged the state-of-the-art capabilities of the time when these first systems were proposed and the low orbits envisioned for the spacecraft.

For a variety of financial, marketing, operational, and technical problems, the initial systems that deployed LEO satellite constellations, or proposed to do so, all had financial and operational difficulties and ultimately experience bankruptcies. These included the Orbcomm data message relay satellite network, the Iridium, Globalstar, and ICO land mobile communications systems and the Teledesic megaLEO broadband system.

Fig. 2 The 280 small satellite constellations proposed for the Teledesic 2 to have been constructed by the Boeing Corporation. (Graphic courtesy of Global Access Commons)



This last system, backed by Bill Gates and Craig McCaw, was to have been a Ka-band high data rate communications satellite network to support both fixed and mobile communications of all types. This highly innovative satellite systems design that would have deployed a host of new technologies initially envisioned the use of nearly a thousand satellites, including 80 spare satellites.

In the design process, the initial network that would have been built by the Boeing Corporation was reduced to 280 smallsats in low Earth Orbit. This system that would have provided broadband services, rather than thin stream communications for mobile voice communications, was the most ambitious of the earlier "smallsat" constellation. Its bankruptcy, along with Iridium, Globalstar, Orbcomm, ICO, and other proposed LEO constellations, ended the first round of enthusiasms for such types of satellite networks (See Fig. 2).

Today, the early failures and bankruptcies of the early commercial smallsat constellations are considered to be, or at least hoped to be, behind us some 30 years later. There are certainly key advances in communications satellite technology, higher performance switching systems, more experience with high-volume manufacturing, additive and 3D manufacturing and automative testing techniques, improved experience with inter-satellite links, new developments in ground systems that can provide electronic tracking of LEO satellites, and AI-controlled satellite management systems for large-scale constellations. All of these advances have contributed in a renaissance in the what, where, when, and how of LEO satellite constellation design and operation.

New innovations in network control systems artificial intelligence applied to constellations operations to avoid satellite conjunctions and interference to GEO satellites, ground and satellite antenna design, pointing and operation, and efficient manufacturing and testing techniques are all important. All of these advances, plus new and expanded demand for various space-based services, have led to many new proposals for new commercial small satellite constellations to be deployed in the next decade.

The 2020s seem to be the time for deployment of a large number of small satellites. These range in size from 3-unit cubesats (around 5 kgs in mass) such as for the planet remote sensing network (now with over 400 Dovesats in orbit) up to 250–500 kg small satellites to support networks for worldwide networking services such as for Orbcomm, Linksat, the Telesat constellation, and over a dozen other constellations.

3 The Case Study of the OneWeb Smallsat Constellation

One of the reasons that the Teledesic satellite system went into bankruptcy was that the estimated costs for manufacturing of the satellites were underestimated. In the case of the OneWeb Satellite Constellation, the costs of production of the satellites are reportedly significantly underestimated. It seems that the prudent step has recently been taken to reduce the constellation size from around 900 to 600 satellites. This should prove to be a key way to control cost since this will not only reduce the cost of the manufacture and testing of the satellites but will also directly serve to reduce initial launching costs as well. The speculation is that this reduction was driven by the need to raise over a billion dollars in capital that was not readily available (Todd 2018).

If it were not for OneWeb's bankruptcy this system would have been perhaps the first to market, and if possible support from the U.K. government materializes this could still possibly be the case. Greg Wyler, who first conceived to this type of system to serve underserved portions of the world, cleverly tested the idea by organizing the O3b medium Earth orbit (MEO) satellite network. This O3b network, with its name standing for the "Other Three Billion," was designed to provide service to the equatorial regions of the world where some three billion people live with low incomes, inadequate health care and education, poor housing, limited access to potable water and food, and limited access to electricity, lighting, and telecommunications and networking capabilities. This network was started in partnership with the SES satellite network and other partners and is now wholly owned and operated by the SES company, headquartered in Luxembourg, and is one of the world's largest satellite operators.

The experiment with the O3b satellite constellation in MEO orbits led to the much more ambitious further step that has been championed by Wyler. This was a move to provide a network that would allow even smaller ground stations less latency or network delay. This was the OneWeb network that Wyler hoped to deploy in 2021-22 before bankruptcy (Fig. 3).

This network is challenging on many different scales starting with the big three listed below:

1. There is a need to build and quality-test the satellites at sufficiently low cost to be financially viable.

Fig. 3 The highly complex constellation deployment plan for the OneWeb constellation. (Graphic courtesy of OneWeb)

2. There is the challenge of launching the network in an efficient and timely manner so that the very large number of satellites makes it into orbit in sufficient numbers within a narrow time constraint sufficient to provide the global service requirements and not break the budget.
3. There is the difficulty of ongoing viable operations that include avoiding collision of a huge number of satellites; not interfering with other satellites, especially in the GEO arc; and installing a large number of ground systems to interface with users.

With regard to challenge 1, OneWeb has reduced the number of satellites in the original constellation, presumably in part, because of cost overruns in producing the satellites and because of the need for raising more capital.

With regard to challenge 2 of a speedy and massive launch deployment campaign, one can look to the experience of the Iridium Next constellation. Here there was the problem of heavy dependence on a single launcher system. A launch failure when there is only one system does shut down launch operations when the failure analysis occurs. The deployment of the Iridium Next Satellite network was, for instance, seriously delayed by the SpaceX Falcon 9 launch vehicle failure. The following risk assessment was reported in 2016 by TeleAstra concerning the Iridium Next system where only some 70 satellites – not many hundreds – were being deployed. This launch risk assessment was provided in this case several years ago.

“The real issue is that SpaceX has a launch manifest with 26 other launches prior to Iridium NEXT. Once the Falcon 9 launches begin it has taken about one month between launches. This means that the replacement constellation cannot begin to provide new service until early 2018. In the mean time the old satellites are aging, wearing out, or running out of fuel" (TeleAstra assessment of iridium next launch deployment risks. Part 10, 2017 report.). In this case the first-generation satellites continued to operate many years beyond their expected lifetime, and the Iridium Next system is fully deployed, but the point is well taken.

Challenge 3. Even if challenges 1 and 2 can be surmounted, there are still an ongoing series of issues to be addressed. It is an exacting effort to create "fail safe" artificial intelligent control systems that are fully tested to ensure that there are no collisions within the large-scale constellation, that the satellites are pointed away from GEO satellites as they cross the equatorial arc, and that conjunctions with spurious debris are avoided. There are deployment and operational issues of getting thousands, tens of thousands, or perhaps even a million new ground systems installed and operating.

4 The Enormous Challenges of Deploying the SpaceX Starlink System and Achieving Financial Viability

If the OneWeb System faces challenges to be technically, operationally, and financially successful, then the challenges associated with the SpaceX Starlink Systems are much, much greater. This is because the number of satellites, the capital investment, and business model challenges are all much larger.

The challenge of manufacturing, qualifying, and testing of some 12,500 smallsats is an unprecedented set of tasks in the history of commercial satellite undertakings. At $10 billion this would be the most expensive satellite system, and some 7500 satellites would be operating in the V-band spectrum which has never been used operationally for telecommunications and networking services. To some this is a risk comparable to betting on the 3 race exacta at a horse race with long odds on all the horses, but then Elon Musk has already accomplished many long odds challenges with PayPal, Tesla, and SpaceX.

And not all of the risks to the megaLEO satellite network are out in space. In one of the recent actions by SpaceX, it has submitted a petition to the US Federal Communications Commission for a huge investment on the ground as well. In this petition permission is being sought to deploy on the order of one million ground systems to connect to these microsatellites in order to link to users in the underserved locations around the world so that the Starlink satellite network can serve the underserved or unserved populace of the world.

This petition sought approval to receive blanket approval for up to a million Earth stations that would be used by customers of the Starlink satellite for internet networking service. The petition that was filed on behalf of a sister company called SpaceX Services sought that these Earth stations could be considered for "type approval" rather than individual licensing and approval. The design for these Earth stations is now identified as being exclusively based on a flat-panel, phased array system that would be able to transmit and receive signals operating in the Ku-band to

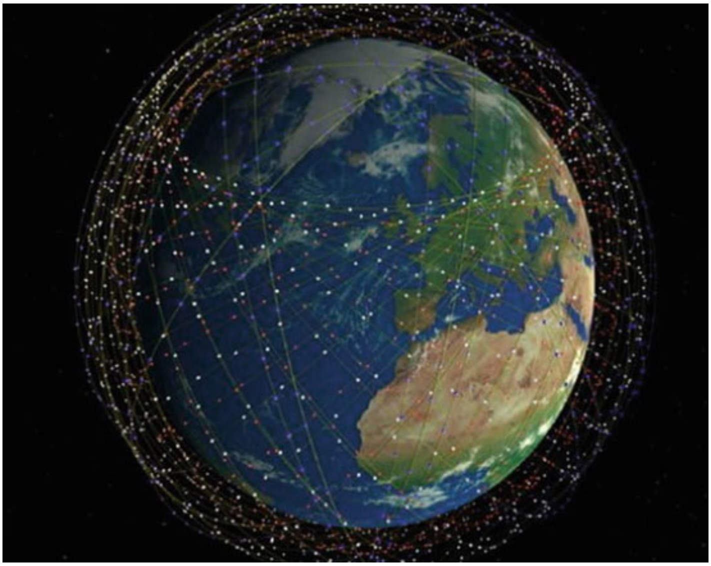


Fig. 4 The megaLEO constellation of smallsats know as the Starlink constellation. (Graphic courtesy of Thales Alenia)

and from the Starlink constellation. Presumably a similar approach will be taken for the V-band system that SpaceX has also proposed (Boyle 2019) (See Fig. 4).

The other aspect of the Starlink constellation is that it is being designed not only to provide access to rural and remote areas of the world that have limited broadband Internet service capabilities, but it is also conceived as a broadband network that would provide very high trunking throughput connections that could compete with fiber-optic networks. Some believe that only if this huge network can serve the developed and the developing world can it achieve sufficient revenues to support the large capital investment that it requires to succeed financially.

In the latest SpaceX filings with the FCC, it is proposed that that the Starlink network would be deployed, at least partially in a much lower orbit than first proposed. This new deployment plan is explained on the basis of seeking to minimize the problems associated with orbital space debris and also with the desire for minimal transmission delay. Low latency, or in effect, very fast end to end connectivity is needed to be competitive with fiber links. In particular the latest proposal from SpaceX is that 1584 of the 4400 plus satellites in the Starlink constellations would be deployed to an altitude of 550 km (342 miles) as opposed to the 1150-km (715-mile) orbit described in SpaceX's initial round of filings with the FCC (Boyle 2018). This filing was made after SpaceX had unexpectedly launched two experimental prototype "TinTinA and TinTInB" satellites into lower orbits than their previous filings had indicated (Grush 2018) (See Fig. 5).

The SpaceX filing has said in support of its lower orbit proposal: "This move will help simplify the spacecraft design and enhance the considerable space safety attributes of SpaceX's constellation by ensuring that any orbital debris will undergo rapid

Fig. 5 The TinTin test satellite for the Starlink constellation by SpaceX Services. (Graphic courtesy of SpaceX)

atmospheric re-entry and demise, even in the unlikely event that a spacecraft fails in orbit." It will also remove a small number of satellites from the constellation design.

The SpaceX filings have indicated that there is also a close focus on the latency issue. It was indicated that the latency experienced with the TinTin experimental satellites is currently 25 ms, but with the network deployed as proposed, it should only experience 15 ms delays. Or as Elon Musk has expressed it, this would support interactive computer game participation. Skeptics thus have indicated that it was latency performance and not concern with regard to orbital debris that has moved the network altitude to a lower level.

The bottom line is that the SpaceX Starlink constellations will face the same types of challenges that OneWeb will face plus a few more. The cost of manufacturing and launching 12,500 satellites and have them operational by 2025 and keeping the costs down to 10 billion dollars is a huge challenge. To this amount must be added the cost of the ground segment that is using the new electronic beam forming technology. Further there can also be issues related to tariffs that might be imposed on ground systems as well as issues within various countries that are not members of the World Trade Organization (WTO) as to local landing rights and other trade or tariffing issues involving local telecommunications and networking companies.

There are also important technical issues involved with the operation of very large and complex megaLEO networks in order to avoid collisions or conjunction with orbital space debris. The ability to provide the high-speed switching from one beam to another at very short intervals and to operate inter-satellite links in very short order that link between multiple satellites to complete a transoceanic link are new challenges to the world of satellite operation. It is remarkable how similar how the technical, operational, financial, and ground system implementation challenges that SpaceX with the world's largest satellite constellation will face in the next five years, that the Teledesic System faced two decades ago. The latest challenge has come from astronomers who are now complaining of visual pollution of the heavens.

5 The Many Other Microsat and Minisat Constellations and the Challenges that They Face

The preceding analysis of the OneWeb and SpaceX Starlink was chosen to be highlighted since these two constellations represent on one hand the first of the megaLEO systems to be deployed and on the other hand the largest system that is planned to be deployed. These two systems are useful case studies for analyses but are still not completely representative of the many smallsat constellations now planned and the wide diversity of services that they might offer in the next few years. The technical, operational, and financial plans for these two systems nevertheless serve to help identify some of the basic issues and challenges that all of these various smallsat constellations will face. There are an ever-growing number of smallsat constellations that are still being envisioned, and the size of these smallsats ranges from the low end of microsats or the high end of nanosats (such as 3-unit cubesats) with a mass of only a few kilogram up to the high end of microsats with a mass up to 500 kg. The diversity is still very great in proposed small satellite constellations. HawkEye 360 only has 3 of 18 smallsats deployed and it is providing new RF Geolocation services. Karousel is to have 12 ellipitical orbit satellites and it is designed for video programming services. At the other extreme is the SpaceX Starlink and V-band networks with a proposed network of over 12,500 smallsats. This exceedingly wide range of planned and proposed networks is shown in Table 2. This diversity is too great to make many generalized statements about smallsat constellations. Thus each proposed commercial smallsat constellation deploying microsat or minisat networks must be considered and assessed on its individual merits (See Table 2).

Various sources of inspiration and backing have led to the proliferation of various new smallsat constellations. In Canada, the Canadian government has backed programs to design and build small satellites. It created a $100 million Innovation Fund for rural communications and small satellites. It also created a streamlined regulatory process to encourage small system. This effort seemed to pay off and to spur innovation in this field (Pugliese 2019).

Indeed at this time there are 13 identified initiatives to create small satellite constellations that represent a total of over 300 new satellites with at least 3 new systems yet to be publicly announced (Boucher 2018) (See Table 3).

There have been additional promotional efforts to encourage smallsat experimentation and new commercial developments. In the United States, there have been numerous conferences, funder conferences, and NewSpace- and incubator-related activities in Silicon Valley, Utah State University, in cooperation with the AIAA, the New York Space Alliance, and more.

In China there has been strong governmental support for new small launcher industries and new small satellite ventures. This has led to a number of new Chinese ventures. These small satellite and launch vehicle startups include the following smallsat constellations Commsat, Hongyan, Lucky Start, and Xinwei. In New Zealand, the government has not only included strong support for the Rocket Lab's small satellite launcher program. New Zealand has now started a global recruitment drive to bring space entrepreneurs to New Zealand as immigrants. All of these efforts are aimed at creating new high-tech jobs and encouraging enterprises to support the

Table 2 Basic information on various planned small satellite constellations

State	Constellation	# of sats	Radio-frequency bands
Canada	CANPOL-2	72	LEO and highly elliptical Earth orbit in VHF-, UHF-, X-, and Ka-bands
Canada	Telesat constellation	117 satellites plus spares	LEO in Ka-band
Canada	COMSTELLATION	Nearly 800 satellites	LEO in Ka-band
Canada	Kepler constellation	15 Gen-1 and eventually 140	LEO in 1100 Km orbit using cellphone frequencies
France	Thales Group's MCSat	Between 800 and 4000	LEO, MEO, and highly elliptical Earth orbit in Ku- and Ka-bands
Liechtenstein	3ECOM-1	264	Ku- and Ka-bands
Norway	ASK-1	10	Highly elliptical Earth orbit in X-, Ku-, and Ka-bands
Norway	STEAM	4257	Ku- and Ka-bands
United Kingdom	L5 (OneWeb)	650–750	Ku- and Ka-bands
USA	Boeing	1396–2956	V-band in 1200 km orbit
USA	SpaceX	Up to 4000	Ku- and Ka-bands
USA	SpaceX	7500 plus	V-band
USA	LeoSat	Initially about 80	Ka-band
USA and intern'tl partners	Theia	112 constellations	Combined networking and remote sensing constellation
USA	Planet	400 to 500 3U cubesat and Terra Bella Sats	Remote sensing system that combines Skybox/Terra Bella satellites, Planet Lab "Dove" satellites, 6 SSTL "Eye" Satellites
USA	Karousel LLC (project of Viasat)	12 Satellites	Elliptical Orbits to use Ku- and Ka-bands for TV video programming streaming
USA	HawkEye 360	3 Satellites	RF frequency use and AIS monitoring net

Note: This table is prepared by J. Pelton for lectures for the SpaceLab program at the University of Cape Town, and all rights are reserved. This chart is licensed for this publication on a one-time use basis

growth of NewSpace economic enterprises for the twenty-first century. And the examples provided above with regard to the United States, China, and New Zealand are illustrative of efforts elsewhere. The large number of new efforts shown in Appendix C on small satellite constellations and in Appendix D with regard to new launch vehicle industries shows how these new enterprises are spreading worldwide.

What must be considered – amid all this new enthusiasm for space – is the possibility of oversupply of new small spacecraft offering a panoply of new networking bandwidth services, new remote sensing, automatic identification services

Table 3 Canadian smallsat constellations pending deployment. (See http://spaceq.ca/13-canadian-commercial-satellite-constellations-in-development/)

Organization	Name of sat constellation	Number of sats planned	Type of orbit	Service planned
Aireon	Hosted payload on Iridium Next	66	LEO	Aircraft navigation and surveillance
exactEarth	AprizeSat	75	LEO	Automatic identification service (AIS)
CB2.0 Communications	Clarke Belt 2.0	24	HEO	Internet of Things, 5G mobile backhaul services and connectivity
GHGSat	GHGSat	13	LEO	Global emission monitoring
Govt. of Canada	Radarsat Constellation	3	LEO	Remote sensing
Helios Wire	Helios Wire	28	LEO	Internet of Things, M2M data relay
Kepler Communications	Kepler	140	LEO	Internet of Things, M2M data relay
NorthStar Earth and Space Inc.	Northstar	40	LEO	Remote sensing using optical, infrared, and hyperspectral sensing
UrtheCast	Optistar	16	LEO	Combined optical and synthetic aperture radar sensing
Wyvern	Wyvern	1	LEO	Hyperspectral sensing
At least 3 other small sat constellations pending public announcement	Pending publication	?	?	?

(AIS), and other space services around the world. The competition that comes from this disruptive technology and disruptive business models could drive global markets to be priced below incremental costs. In the world of communications and networking satellites, this is not only a matter of new smallsat constellations competing against each other, but there are other dimensions here as well. At the same time there are new high-throughput satellite systems that are disrupting GEO satellite markets. There are also fiber nets connected to 5G systems that are being deployed around the world. Short disruptive technologies in the telecommunications and networking world are transforming global markets and making competition virtually explode in both the developed and developing world.

The listings in Table 2 of new smallsat constellations are not exhaustive, and new systems keep being filed, and even those that are already filed are changing orbits and adding satellites or design features. Today these systems are dominated by US-, Canadian-, and European-based networks, but systems from other parts of the world may still be filed in coming months and years. The appendices found at the end of the handbook are as current as possible, but it is wise to go to indicated websites to get the latest and updated information. The Covid-19 related economic downturn, the rapid rate of technical innovation, and the uncertainty in financial markets and emerging bankruptcies, all suggest turbulent times ahead for new smallsat constellations.

6 The Future

The future of microsats and minisats is currently unclear. Today the world of satellite manufacturing and space launch systems is in a period of transition. The global trend that has existed for nearly 50 years has been toward bigger and more capable satellites with more power and larger aperture antennas for communications and larger remote sensing satellites.

This course has successfully been pursued by such global communications satellite providers such as Intelsat, SES, Telesat, Eurosat, EchoStar, and DirecTV to extend their markets and reduce cost. The same has been true for those providing space-based remote sensing for many decades such as Spot Image, WorldView, GeoEye, Digital Globe, QuickBird, and IKONOS. The world of space-based applications is clearly changing not only for telecommunications but also remote sensing and many new services such as for automatic identification services (AIS) and frequency monitoring. There are many innovations that continue to appear in the world of smallsat constellations. This is very much the case for commercial space services now being offered by 3-unit cubesats, microsats, and minisat constellations.

The graphic in Fig. 6 shows a new landscape in the world of remote sensing that is being driven by start-up constellations using a lot of smallsats, drones, or high-altitude platforms (HAPS), in lieu of a few large-scale satellites. This map of innovators in the remote sensing world shows just how pervasive the changes are becoming as 20 new startups are identified here (Ivanov 2017).

Fig. 6 The exploring number of disruptive new ventures in remote sensing. (Graphic courtesy of AgFunder)

This changing world has yet to come into focus. Some of the new start-up constellations will fail, but others will succeed. In some cases first-generation constellations will fail at first try, but will reinvent themselves with new owners, new management, or creative mergers. The first satellite constellations for mobile services such as Iridium, Globalstar, and Orbcomm went through such transitions to emerge with new strength and improved business plans. The future will remain in a shakedown period through the mid 2020s. The outcomes for the success, failure, or perhaps reinvention of the dozens of smallsat constellations now being launched or proposed will remain unclear until the later part of the 2020.

7 Conclusion

The world of smallsat constellations is clearly swirling with change. There have been major technical changes that have also served to reduce cost. We have seen the miniaturization of various electronic sensing devices, of digital processing and memory systems, and of thrusters, stabilization systems, as well as other components onboard spacecraft. We have also seen the development of ground stations with the ability to electronically form beams to track spacecraft as they move across the horizon. In some instances, these new smallsats can be fabricated using off-the-shelf components. These factors combine to reduce the volume, mass, and cost of satellites to a striking degree. And this is not all. The smaller and lighter smallsats also serve to reduce launch costs – a lot. Further the launch into low Earth orbit with many of the smaller spacecraft being launched at the same time, rather than painstakingly being launched into a precise geosynchronous orbital slot, also serves to reduce cost as well, although this is offset by the fact that many more spacecraft must be launched to create a fully populated global coverage system.

The name of this revolutionary series of changes known as “NewSpace” or “Space 2.0” reveals a lot. The amount of disruption to the various space industries is significant. At the same time newly engineered GEO satellites, called high-throughput satellites, have likewise been disruptive in that these satellites can be ten times more cost-efficient or even more so. This has also served to disrupt markets.

Satellites in low Earth orbit have the power advantages that come from much less path loss or beam spreading that is associated with sending a signal all the way to or from the GEO orbit. Newly deployed commercial satellites in constellations deployed in low Earth with masses that might range from 5 to 500 kg are quite different from their GEO forebears which might have a mass of 5000–8000 kgs. Each one of these smallsat systems may have a different size, shape, configuration, mission, and orbit and a different means of launching. Yet these systems are still recognizable as different from the large spacecraft that have been dominating the commercial satellite industry up until just a few years ago.

There is still not a single rule that applies. Large GEO satellites are still highly cost-effective and still dominant for the most lucrative of all satellite services which is direct broadcast television services that can also provide direct digital services such as software downloads and others to the edge services via DVB-RCS2, DOCSIS, and other such video broadcast standards. The innovations with miniaturization and satellite constellation design are certainly not yet complete. The further development of new interactive ground systems with electronic beam forming and employing meta-materials will be key to reducing costs and these additional innovations.

Perhaps the most interesting part of the unfolding saga with regard to the development of new smallsat constellation of microsats and minisats is not which of the new systems will succeed or fail. The most interesting question is what new applications and services will evolve. Already the new economics and thought process associated with the NewSpace revolution has seen new systems being planned and launched to provide such innovative and unexpected services. We have seen new networks designed to capture the automatic identification service (AIS) signals from ships and other vehicles (i.e., the Spire and HawkEye 360 systems). The HawkEye 360 system is also designed to provide global monitoring of frequency use that might be used to identify sources of frequency interference and assist with law enforcement in such areas as drug smuggling, illegal fishing, or even crimes against humanity.

8 Cross-References

► Overview of Commercial Small Satellite Systems in the "New Space" Age
► Overview of Cubesat Technology
► The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and CubeSats

References

M. Boucher, 13 Canadian commercial constellations in development, Space Q, November 18, 2018. http://spaceq.ca/13-canadian-commercial-satellite-constellations-in-development/

A. Boyle, SpaceX sets its sights on a lower orbit for Starlink broadband network for first satellites, Geek Wire, November 8, 2018. https://www.geekwire.com/2018/spacex-sets-sights-lower-orbit-starlink-broadband-networks-first-satellites/

A. Boyle, "SpaceX seeks FCC approval for up to 1M Starlink satellite earth stations, Space & Science, Geek Wire, February 8, 2019. https://www.geekwire.com/2019/spacex-fcc-starlink-million-earth-stations/

L. Grush, FCC approves plan to launch 7000 beaming satellites, The Verge, November 15, 2018. https://www.theverge.com/2018/11/15/18096943/spacex-fcc-starlink-satellites-approval-constellation-internet-from-space

I. Ivanov, Remote sensing market map: 20 remote sensing startups and the varied data that fuels them, AgFunder News, November 9, 2017. https://agfundernews.com/remote-sensing-market-map.html

C. Neiderstrasser, Small launch vehicles – a state of the industry survey. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4118&context=smallsat. Last accessed 15 Mar 2019

D. Pugliese, Canada' Leo constellation fund draws interest from Telesat and MDA, Space News, July 5, 2019. https://spacenews.com/canadas-leo-constellation-fund-draws-interest-from-telesat-mda/

K. Russell, 2018 Could be a revolutionary year for smallsats, Via Satellite, January 10, 2018. https://www.satellitetoday.com/innovation/2018/01/10/2018-revolutionary-year-smallsats/

A.L. Thompson, SpaceX launches 60 Starlink satellites on thrice-flown rocket, sticks landing, Space Flight, May 24, 2019. https://www.space.com/spacex-launches-60-starlink-internet-satellites.html?utm_source=notification

D. Todd, OneWeb reduces constellation size from 900 to 600 satellites, Seradata, December 18, 2018. https://www.seradata.com/oneweb-reduces-constellation-size-from-900-to-600-satellites/

M. Torrieri, Megaconstellations: recipe for disaster or biggest opportunity yet? Via Satellite, March 24, 2018. https://www.satellitetoday.com/innovation/2018/01/10/2018-revolutionary-year-smallsats/

Part III

The Technical Challenges of Designing and Implementing Small Satellite Systems and Projects

Overview of Small Satellite Technology and Systems Design

Joseph N. Pelton and David Finkleman

Contents

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

D. Finkleman
Sky Sentry, LLC, Colorado Springs, CO, USA
e-mail: dfinkleman@comcast.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_7

Abstract

The key and ongoing challenge of small satellites has been to create new systems or capabilities that could accomplish key technical tasks or deliver services with reasonable reliability and proficiency, but within smaller parameters of mass, volume, and, in many cases, cost as well. In other cases there have been focused efforts to find alternative technologies, systems, or components that could approximate the function of larger systems or technologies, but which would allow a significant mass, volume, and/or cost reduction. However, communication, surveillance, and other missions will require relatively large constellations of small satellites, whereas one or a few larger satellites would suffice. Large constellations increase collision risk and are more likely to experience failures even though individual members might be very reliable.

For many years the design of experimental or applications satellites has started with designing a spacecraft with the objective of accomplishing a specific task, mission, or targeted objective. This led to the second step where system design engineers proceeded to design the spacecraft that had the capability in terms of lifetime, reliability, pointing ability, power system, antennas, onboard processing equipment and software, sensors, antennas, or payload equipment to carry out the mission and then arrange for a launch vehicle.

Engineers exercised an abundance of caution with large safety factors and space qualified components with exceptionally high reliability. This led to satellites regularly exceeding design lifetime by factors of two or three. Engineers learned that they need not have been so highly conservative. Missions with durations of only a few years could use off-the-shelf components and less demanding reliability. This experience facilitated smaller satellites.

Developers of small satellites have often approach the design activity as if it were a strategic planning process, taking a specified constraint of mass and volume and seeing how much operational or research capability could be fitted into these limitations and then redesigning the new system to enhance its service or experimental output. This type of thinking has in many ways has helped to create the so-called world of “NewSpace” or “Space 2.0” and being able to do more and more with less and less. This has produced remarkable improvements in productivity and has enhanced technical design.

There are many innovations that now making small satellite industries thrive. These include new manufacturing techniques such as additive manufacturing, new cost-effective launch systems, and new user devices on the ground such as flat panel antennas, whose costs are now reducing. This chapter, however, seeks to provide an overview the new technology and systems associated with the design of small satellites themselves.

This overview chapter thus seeks to give some insight into the progress that is being made into the better design and more effective use of small satellite structures, power systems, antenna, sensors, stabilization, and pointing systems as well as the other key components, systems, and subsystems critical to small

satellites' successful operation. These innovative designs are important to the success of all types of small satellites that range from CubeSats and smaller on one hand plus the microsats and minisats that are key to deployment of the new large-scale commercial constellations. Innovations that apply to one type of small satellite can and often do apply to other types as well.

Finally this section addresses not only technical advances that relate to small satellites as free flyers in space but two other innovations that may become increasingly important in the future. Thus innovations related to hosted payloads that can fly on other satellites – large or small – represent another type of "small satellite." These are also addressed as well as high-altitude platforms (HAPs) that can serve the same function as a small satellite for an island country or in a constellation can provide services akin to that of a satellite.

Keywords

Attitude Determination and Control Systems (ADCS) · Batteries · Constellation design and deployment · CubeSat · Digital processors · High-altitude platform systems (HAPs) · Hosted payloads · Microsatellites · Minisatellites · Miniaturization · Off-the-shelf components · Phased array antennas · PocketQube · Radio frequency (RF) and optical system design · Reaction wheels · Satellites as software defined digital processors · Satellite payload · Satellite radio design and operation · Sensors · Small satellite deorbit considerations · Small satellite registration and frequency allocations · Small satellite structures · Solar arrays · Spacecraft bus · Spacecraft power · Stabilization · Synthetic aperture radar · Thermal systems · Torque rods · Thrusters and microthrusters

1 Introduction

The first satellites that were launched from Sputnik 1 to Score to Relay, Telstar, Syncom, and Early Bird were all small satellites. The demand for greater ranges of commercial services and more sophisticated experimental missions quickly changed to size, mass, and volume of satellites and so-called small satellites such as the AMSAT "OSCAR" satellites, designed and built by amateur volunteers, was seen as only a sideline. The primary use of commercial satellites for telecommunication, broadcasting, and networking services that were deployed in Clarke or geosynchronous orbit led to deployment of satellites that were many metric tons in size. This was because the large antenna size and high power systems were needed to compensate for the large "path loss" associated with transmitting signals the nearly 36,000 km between GEO satellites and Earth.

The switch from analog to digital processing based telecommunications satellites was perhaps the first key step in the evolution toward the recognition that small satellites might have a more important in the world of space applications in the future.

The faster and more capable digital processors became, the smaller these units became. Integrated circuits, monolithic devices, and application-specific integrated circuits (ASICs) all became key to the processing of signals for telecommunications, remote sensing, meteorological satellites, and Global Navigation Satellite Systems (GNSS). Also the sensors used for imaging or tracking stars also became digitized as well.

The next large step came when satellite service innovators decided to try developing low Earth orbit (LEO) satellites for mobile communications and also proposed LEO satellites broadband services. Satellite systems such as Iridium, Globalstar, Orbcomm, and Teledesic all proposed to use of the LEO orbit. The objective was to gain the advantage of low-latency transmission and significantly less path loss due to the spreading of the signal that originated at GEO orbit. In the case of mobile satellite service, the satellite would be moving relative to the transceiver on the ground, and so tracking of the satellite would be required in any event. The low Earth orbits, the digital processing of satellite signals, and the ability to use application-specific integrated circuits in the user devices combined to allowed the cost of user devices to be greatly reduced.

The mobile satellite systems (i.e., Iridium, Globalstar, and Orbcomm) proved that this type of technology could work in practice. Further these systems demonstrated that small, compact, and relatively inexpensive transceivers could communicate with LEO satellites that move swiftly overhead and across the horizon as quickly as in 7 min or so. The phased array antenna system that was deployed on the Iridium system also demonstrated that electronically steered signals could work effectively to provide a commercial mobile satellite signal. The second-generation Globalstar mobile satellite system joined in using phased array antennas that used electronic steering of signals rather than relying on dish antennas that required physical tracking via a moving satellite antenna system.

The Teledesic system, which sought to provide truly broadband communications, rather than just voice or data services (as in the case of Iridium and Globalstar) or low rate data (as in the case of Orbcomm), represented the greatest technical challenge. In the case of Teledesic, it set the objective of supporting gigabit/second speeds or video transmission services. Although this multi-billion dollar LEO satellite network was never deployed, it provided a clear theoretical basis for how this type of high-throughput satellite system might operate. In many ways Teledesic provides a firm theoretical basis for the type of new satellite services that current broadband mega-LEO constellations are now in the process of introducing during the 2020s.

In the 1980s and 1990s, the combination of technologies that is now undergirding the current small satellite revolution thus all started coming together. These included (i) constellations of satellites in LEO-based networks; (ii) highly efficient digital communications systems that could use digital encoding and forward error correction that now include Trellis, Turbo, and High Efficiency Video Coding (HEVC) and (H.264) encoding systems (How to configure… 2019); and (iii) phased array antennas and flat panel antennas that can be used as satellite antenna systems and simpler systems for user transceivers on the ground.

In close parallel ground-based cellular networks and Wi-Fi and WiMax wireless networks were expanding to provide broader and broader band services. The third-generation cellular system gave way to the fourth-generation cellular network that are today giving way to the 5th Generation networks that are now operating in the millimeter wave bands. Likewise the latest generation of high-throughput satellites (HTS) were also operating at faster and faster speeds and at higher frequency bands such as the so-called Ka bands (30 GHz and 20 GHz) and now the V bands (48 GHz and 38 GHz). Essentially wireless and satellite networks were both seeking to provide broadband data and video streaming services to consumers at speeds and competitive costs similar to that offered via fiber-optic cable systems. Fiber networks offered blazing speeds and low costs. Yet fifth-generation cellular and high-throughput satellite networks were playing rapid catch-up capabilities to offer mobility as well as broadband and ever lower costs as well.

The final act in this small satellite revolution was the “NewSpace” or “Space 2.0” innovations. Here, suddenly, was a spate of important new innovations. These innovations included (i) lower launch costs via reusable launchers and small launchers built out of new materials; (ii) new methods of efficient manufacturing, including additive manufacturing; (iii) miniaturization of electronic components, sensors, digital processors, and many other elements that can be used in small satellite networks; and (iv) innovative ways to use off-the-shelf components other approaches to developing and testing small satellites to be built and efficiently tested through the processes developed at the Surrey Space Centre, the Surrey Space Technology Ltd., and Utah State University Space Labs.

In the sections that follow, a brief overview discussion is provided first of the technical challenges to be met in terms of viable and safe operation, followed by the need for technical innovations related to performance. Many technical, operational, or systems aspects are concerned with the design and deployment of small satellites that are discussed in the remaining articles found in Part 3 of the Handbook (NASA 2019).

2 Technical Challenges to Be Met by Small Satellite Developers and Operators

There are a number of challenges that are key to successful and safe operation of small satellites. These represent capabilities that are not only key to small satellites but for the long-term sustainability of space and operation of all types of satellites as well. The first in importance is the key technical challenge of safe operation for the entire time of small satellite mission from launch to deorbit (Earle et al. 2019).

2.1 The Challenge of Safe Operation

Safe operation is the paramount requirement. This is achieved most effectively through precise observation, maneuverability, and communication. Each of these objectives can be quite technically challenged. Other aspects of small satellites still have significant knowledge gaps – especially when it comes to safe operation. Many of these safety challenges were codified by young space professionals studying under the auspices of the Space Generation Advisory Council and the International Space University (Esionwu 2014).

There are particular deficiencies in controllable and predictable end of life disposal as well as precise managing exceptionally large constellations of small satellites. Most small satellites reside in low Earth orbits. A number of these rely on atmospheric drag to dissipate orbit energy and thus cause reentry within a few years without any specific provision for deorbit on demand. This will not be sufficient if in the future, there are many thousand small satellites occupying LEO. Elements of each independent mega constellation must be replaced either on schedule or because of unexpected failure. Numerous inoperative satellites present in orbit for many years will represent a growing problem over time. Very small satellites, such as CubeSats and even smaller, often cannot accommodate reliable, on demand, reentry systems (Puig-Suari et al. 2008).

Thus there are proposals to limit small satellites launches that lack the ability to deorbit on demand to quite low orbits such as below 300 km, or to be launched not as free flyers but within a joint platform that has a deorbit capability, or to have passive systems to speed deorbit processes (Pelton 2015).

As constellations of satellites that are much more massive than a few kilograms and deployed in larger numbers, the concern certainly grows. Exquisite collaboration and coordination will be required to accommodate such increased traffic in LEO. Those that are planning to deploy so-called Mega-LEO constellations of small satellites understand the demands of managing thousands of small satellites with compacted coordination. Some proponents of small satellite constellations are considering higher altitudes, and indeed 03b has plans for a significant new mPOWER MEO network.

Some analysts believe this might also have difficulties. Even though fewer satellites are necessary, they must have more electrical energy and power systems and must also have larger antennas, and, in general, be larger. The trade-off between more and smaller satellites against fewer, larger, and longer-lived satellites at higher altitude with a larger cross section that might become a target for collision has not been well addressed.

2.2 Communications and Controllability Challenges

Small satellites must be able at least to downlink data. These communication links enable ranging at least and perhaps angular resolution sufficient for reasonable orbit determination. However, observations of this nature for the smallest of the small satellites are gathered over extremely short arcs and are often conducted with small antennas with poor angular resolution. Gathering and processing sufficient information to determine orbits may require several passes, and there are gaps between observations that are long enough for orbits to change materially due to environmental variability during the intervals when the satellite cannot be observed.

When many small satellites are deployed in succession, it is very difficult to discriminate among them. Some unique electromagnetic emission or reflection is required. If there is full two-way linkage, a satellite can be queried explicitly. Otherwise, observable maneuvers must be commanded, and which satellite executes that maneuver is identified. This is a common occurrence with radio-controlled model aircraft and commercial light aircraft lost over expansive wilderness.

Several small satellites have never been found by any of these schemes, particularly those suffering some debilitation on deployment.

This raises other issues. If the satellite trajectory cannot be controlled or even known very well, then how well can observations of other bodies in space or on the Earth accurately be registered in any reference frame?

2.2.1 Maneuverability

All satellites should be able to maneuver for station-keeping and to diminish the probability of collision. The minisats and microsats that are being deployed in large constellations all have significant maneuverability, but CubeSats and below may not have this capability. If time is not a serious constraint and urgency is not involved in avoiding an orbital conjunction, a few low thrust actions may be adequate. Again with sufficient time warning the command to fire a thruster need not be applied very early. Figure 1 demonstrates this for a past real conjunction with impulsive chemical thrusters.

Maneuver timing is typically not the critical path in collision avoidance. Maneuver planning almost always take much longer. Consequently, observations, orbit update, and communicating commands to a satellite are the critical elements. This is much easier for GEO than for LEO. This favors the French Space Agency (CNES) "middle man" process or the European Space Agency (ESA) ESOC process that both confirm US Joint Space Operation Center (JSPOC) warnings and execute avoidance based on trustworthy, well-understood analysis and data. This is hardly possible for the preponderance of small satellites which do not have the same type of analytical process capability.

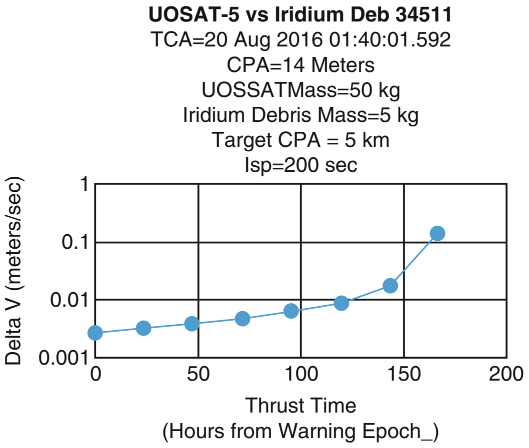


Fig. 1 Thrust levels required depending on advance warning of potential conjunction between smallsat and Delta launch vehicle. (Graphic courtesy of US Air Force)

There are several excellent surveys of small satellite propulsion alternatives. There are chemical, electrochemical, and electric thrusters for small satellites, but few for vehicles as small as CubeSats. Propulsion must not jeopardize large, primary payloads. Both chemical and electric systems add some risk to the launch. Therefore, pressurized cold gas and even water are being considered and indeed have in some cases actually tested. Passive resistance type systems for small satellites to aid deorbit capabilities, such solar sails and aerodynamic devices, have been discussed, but passive systems are not responsive or reliable enough for this type of collision avoidance application.

Avoidance maneuvers cannot be developed more than a few tens of hours in advance because satellite trajectories cannot be estimated with actionable precision more than a few tens of hours in advance, particularly in drag-dominated low Earth orbits.

All of these possibilities are practical for long-term, modest orbit or attitude adjustment, but they seem unsuitable or unreliable for relatively short notice collision avoidance.

Small satellites in conjunction with other small satellites, depending on their size and thruster capability, almost always, have no avoidance alternatives (Tummala and Dutta 2017).

Since desirable missions all favor the same orbit regimes, collisions among small satellites should not be discounted. Conjunction management between small satellites and larger satellites that can maneuver enough to avoid catastrophe becomes the sole responsibility of the larger satellite, which requires more energy to adjust its orbit than the small satellite would.

Having optimized orbit architecture, one must assure that the probability of encountering other satellites during the mission is acceptable. The hypothetical small satellite experiences close approach within 20 km of a Thor Agena D rocket body. The relative geometry between a launcher and a possible small satellite conjunction is very consequential. This is particularly so when the launcher is nearly perpendicular to the satellite's velocity vector. Depending on the duration of the mission, it is important to observe the object closely for most of the mission as well as check regularly for other close approaches. Several satellites approached within 50 km at the time the analysis was conducted.

2.2.2 Observability

If an object in orbit cannot maneuver, knowing where it is becomes critical. The object must be discernible either passively either by its own emissions or reflections of background radiation. Or it might be illuminated actively. The degree to which the object's state of motion can be determined or its future state estimated depends on the distribution of observation opportunities and the density of observations acquired during each observation interval (Finkleman 2013).

Observability should be among principal considerations for the design of a spacecraft of vehicle and also can influence the choice of orbit architecture. As an example, consider a single small satellite for which there are sufficient optical observables. Assume that mission requirements allow any reasonable altitude or inclination. The task is to find an orbit during which there is the greatest cumulative time of observation given a small set of ground-based sensors.

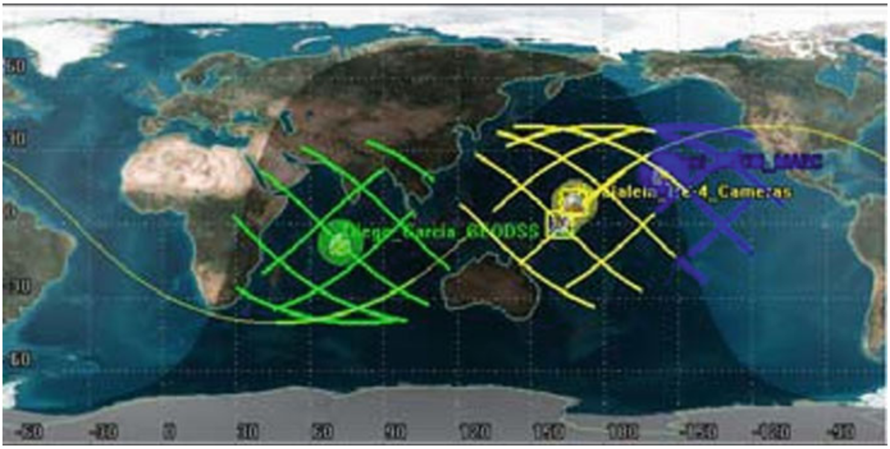


Fig. 2 Small satellite orbit designed for greatest time of observation from designated observation locations. (Courtesy of the US Air Force)

This is shown in Fig. 2 below that depicts a typical situation with tracking instruments around the world that in this case involves tracking facilities in Hawaii (indicated by tracking data in blue), Kwajalein (indicated by tracking data in yellow), and Diego Garcia (indicated by tracking data in green). These three stations are utilized to undertake the assigned tracking.

Safe operation thus often requires some compromise in mission capability. For a single satellite to "see" most of the Earth over time (and thus to be seen), the inclination and apogee should be as high as possible. For example, if one wishes to monitor synoptic energy balance, there would be only rare and brief opportunities for the designated sensors to gather data for orbit estimation. "In this case, the optimal parameters for longest cumulative observation over the course of a day were: inclination 32°, eccentricity 0.1, apogee altitude 8490 km. The observation passes over the course of the day for the satellite chosen for analyses are shown in bold lines in Fig. 2."

> There is also an opportunity to observe small satellites almost ubiquitously with radio telescopes. Almost all satellites have significant radio frequency signatures from instrumentation and internal electronics, not to mention communication devices. Very precise orbit observations are feasible, and the observations can also reveal anomalies in electrical devices onboard. (Finkleman 2016)

3 Small Satellites and Attitude Determination and Control Systems (ADCS)

Constant improvement is being made in the attitude determination and control systems (ADCS) for small satellites. Many of the first of the cube satellites launched well over 20 years ago were fairly crude devices that often were designed by students for short-term experiments and had little or no capabilities for attitude determination and control systems (ADCS). In more recent years, increasingly sophisticated systems and sensors have been developed both to detect the orientation of small satellites and capabilities to maintain stability and even three-axis stabilization. A systematic study of over 350 nanosatellites in the 1–10 kg range in a survey for the period 2003 through 2016 has produced the following findings.

> The ADCS information of 357 nanosatellites were available for statistical analysis. Of the 357 nanosatellites only 5% had no ADCS, 17% used passive magnetic control, 2% used gravity gradient stabilization, 6% used other passive methods of stabilization (e.g., aerodynamic), 2% were spin stabilized, 11% used active magnetic control, 3% were momentum wheel stabilized, and 54% were reaction wheel 3-axis stabilized. (Xia et al. 2017)

It is not clear if this survey can be taken as truly representative of small satellites. But it can be reasonably assumed that significant progress has been made in this area since the earliest days of small sat experimentation. One can thus reasonably assume that at for at least most microsats and minisats that are being launched in today's large constellations a high percentage of these satellites have reaction wheel three-axis stabilized capabilities and also have thruster jets that can allow these larger small satellites to be deorbited from low Earth orbit (LEO) at end of life.

There is still concern for all small satellites not so equipped. There is especial concern for femto-satellites (e.g., chipsats), pico-satellites (e.g., PocketQubes), nanosats (e.g., CubeSats), and even microsats and minisats that are not equipped with attitude determination and control systems (ADCS) nor thruster jets for deorbit capability. Indeed these systems also generally lack passive systems to that can be deployed to assist with deorbit. This suggests that all such truly small satellites without such capabilities should only be launched at lower altitudes, such as 300 km or below, to insure that they will naturally deorbit due to gravitational effects, especially during solar max period when the Earth's atmosphere expands and creates additional drag conditions.

4 Power, Energy Storage, and Power Conditioning Systems for Small Satellites

The power systems for small satellites much like larger satellite depend on a combination of solar arrays that collect energy from the sun and batteries for periods when satellites are obscured from the sun. The further constraint of small satellites is, of course, the limited volume and mass associated with these type spacecraft. Craft as small as picosats (i.e., PocketQubes) still can display solar cells, but in limited number. For CubeSats batteries similar to those used in cellphones, i.e., lithium batteries, can be recharged and support missions that last months and even years (see Fig. 3). Small satellites with short lifetimes might subsist on energy stored in batteries at launch. Solar cells are the only way to replenish energy on orbit.

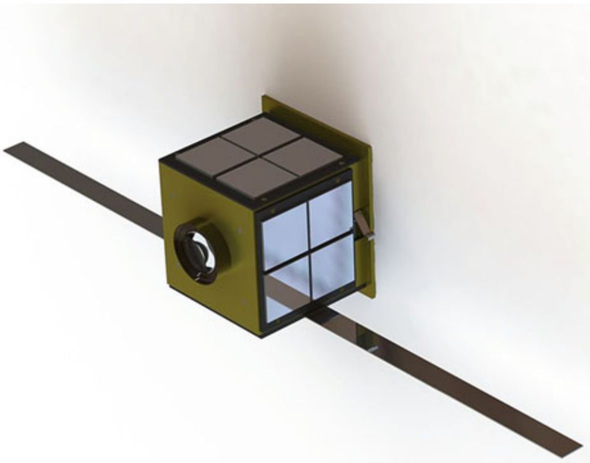


Fig. 3 This PocketQube design only had room for four solar cells since the antenna extension mechanism was deemed more important. (Graphic courtesy open access commons)

Energy often is not extractable with characteristics that onboard electronics require. Relative to large satellites, small satellites lack the design parameter space among orbit, operational access, solar illumination, thermal management, electronics, and other essentials.

The issue of power system design with small satellites often hinges on the cost of the photovoltaic cells that are used. The amorphous silicon PV cells are the lowest in cost. Other more sophisticated cells such as gallium arsenide cells, or violet solar cells with multiple gates, or in future years perhaps quantum dot units can produce more power and can be coated with glass to have longer life. These are trade-off decisions that must be against program cost constraints, desired lifetime, and mass and volume limits. Fortunately small satellite programs can benefit from research that is being undertaken for terrestrial applications or much larger and expensive satellite programs.

5 Small Satellites and Antenna Performance

There is now considerable experience with the Iridium, Iridium Next, and Globalstar OG2 satellites and other smallsat programs that is helpful in the design of high performance phased array antennas. Smallsats, particularly those in the 50–500 kg range are capable of creating a large number of spot beams to achieve a high degree of frequency reuse and to concentrate power quite effectively. The three keys to satellite efficiency and capacity are available spectrum, power concentration, and complexity as achieved through efficient multiplexing, digital encoding, and forward error correction. The latest satellite technology is able to deliver on all three of these dimensions.

Progress in phased array antenna design with electronic beam forming using electrical or optical processing and unique capabilities such as meta-materials or new technology will be key to progress in the small satellite constellations that are now planned for deployment in coming years.

Larger apertures are more effective than smaller ones. Diffraction and the basic laws of physics rule. Small satellites can embody antennas much larger than the satellites themselves. Using shape memory composites, large antennas with complex figures can be rolled and stored in narrow tubes for deployment on orbit. Research organizations have engaged origami artists to develop large objects that can be stored in small spaces.

Phased array antennas are possible for small satellites. However, they suffer sidelobes that monolithic antennas do not experience. They are not as energy efficient, and they are electronically complex. Although the state of the art enables relatively useful small phased arrays, innovative dish antennas can still provide the best technical and cost performance. It is, of course, possible to combine dish reflectors with phased array feed systems. Producing and feeding the electromagnetic energy to be transmitted are also technologically demanding.

Electronically shaped beams and phased array antennas and feed systems have merit when energy must be transmitted or exchanged among many space, airborne, and terrestrial platforms. Higher frequencies experience less diffraction, but they cannot be produced as efficiently as lower frequencies. The highest practical frequencies are optical, light. Optical links between satellites have a long and painful development. Alignment between widely separated, rapidly moving satellites is a challenge. Optical links to the surface of the Earth experience scattering, absorption, and other deleterious phenomena in the atmosphere.

5.1 Small Satellite Radio System Design and Possibility of Optical Links and Processing

The design of radio devices to support various missions related to telecommunications, networking, data relay, tracking, telemetry, command, and other key functions continue to evolve and improve over time. In the earliest days of small sat development, the radio systems were simple and often were operating in the VHF and UHF spectra, but today increasingly sophisticated radio technology is being developed to support broadband throughput needs and radio devices that are operating in the super high frequencies and extremely high frequencies and much more sophisticated and also much higher in cost. There have also been suggestions that optical communications could be used in the case of some small satellite applications such as for intersatellite links. Optical technology such as in the form of optical processing could also be used to replace digital electronic processing as this technology matures.

5.2 Small Satellite Structures

The key to CubeSats is the standardization that allows important components and subsystems to be interoperable and widely available. This standardization of CubeSats into elemental units that can be joined is important. This enables interoperable deployment and launch vehicle fixtures that now range from 1 to 6 units, up to 12 unit, and even up to 27 unit systems (i.e., 30 cm cubes) and also assists with lowering the costs of testing as well as the possibility of accelerating the testing process. This process of standardization of platforms and platform sizes has now even transferred to conventional satellites that are now typically constructed to go on a limited number of platforms. These platforms are often geared to particular sized launch vehicles. There are today suppliers of standardized structures that are not only available online for 1 unit, 2 unit, 3 unit, and 6 unit cube satellites but also are available for PocketQube kits and structures that are exactly one eighth the size of a CubeSat.

This standardization of cost-effective and reliable smallsat structures thus aids at every stage of design, component and subsystem acquisition, construction, testing, and launch service arrangements. The key is not so much in the structures and the materials used in the structures, but the standardization and ease and lower cost of acquisition.

5.3 Deorbit Concepts for Small Satellites

Concerns about the deorbit of small satellites have grown as the number of launches of various sizes of smallsats have risen almost year by year. The prospect for the future of more and more smallsat launches has led to increased concerns about orbital debris and improved ways to remove these satellites at end of life. Along with these concerns has come an increased focus on better space situational awareness, the need for space traffic control, and new ways to address the longer-term sustainability of outer space activities. The 21 new guidelines adopted by the UN General Assembly and the UN Committee on the Peaceful Uses of Outer Space (COPUOS) represent some progress, but there are many other ideas that have been suggested. These ideas include restriction of small satellites without active deorbit capabilities to a particular altitude so that natural deorbit occurs in a reasonably short period of time, consolidation of small satellites into joint missions that would contain an active deorbit capability, requirements for passive systems to aid deorbit, etc. (Guidelines for the Long-Term. . . 2019).

There is quite a bit of technology under development to aid with deorbit of defunct satellites. These developments include lower cost and miniaturized attitude determination and control systems as well as stabilization, pointing, and orientation systems (i.e., devices such as magnetic toque rods and miniature reaction wheels) and low cost and miniaturized thrusters, as well as passive systems to create atmospheric drag. These systems are key to being able to remove small satellites from orbit in a timely way. Yet one of these can cause controlled reentry to a specific location or reveal what might survive reentry. It will take a combination of technology and regulatory reform to address the orbital debris problem effectively.

5.4 Small Satellites and Spectrum Allocations and Registration

There are no allocations of satellite frequencies related to telecommunications, remote sensing, or any other applications that are specifically restricted to small satellite activities. The allocations are based on the application and the three ITU regional districts. There are certainly some applications such as amateur radio frequencies or data relay and messaging where smallsats are used. The issue is the rather that small satellite are sometimes not properly registered with the United Nations or their frequency usage not coordinated through the International Telecommunication Union in the designated way. Efforts are being made to see that these procedures are systematically followed.

The future of commercial space applications seems to be headed toward the deployment of more and more smallsat constellations to provide very large networks in LEO and yet others in MEO. Further these networks appeared poised, based on filings, to move to higher and higher frequencies such as Ka band and V band. It is important that these networks be thoroughly coordinated to avoid interference with protected GEO-based networks as well as to avoid interference with other LEO and MEO systems, high-altitude platform systems, and ground-based systems. As more and more of the networks are deployed, especially those in the so-called Mega-LEO systems with thousands of satellites in these constellations, this challenge appears likely to become more difficult. In this regard new technology to minimize interference and new regulatory processes may both become necessary.

5.5 Small Satellites and Advanced Processing and Networking

There are essentially three ways to make satellite services, particularly telecommunications and networking services, more efficient. These involve more power and more highly focused power into smaller catchment areas, more spectrum, and greater bandwidth, through the use of either higher frequencies or methods to reuse frequencies or more efficient ways to process radio signals with great complexity, improved multiplexing, or encoding to send more bits per Hertz. Small satellites are seeking ways to achieve improved capabilities in all three of these areas. This means use of LEO or MEO constellations so as to concentrate power more efficiency and to avoid the extreme path loss and latency that comes from operating in the GEO orbit. This means finding more ways to reuse spectrum by means of spot beam and thus to allow geographic separation of beams, the use of higher frequencies so as to increase available bandwidth, and use of more efficient phase shift keying and other advanced multiplexing systems coupled with advanced coding and forward error correction.

Digital communications, digital processing, and ever more sophisticated software defined modulation, multiplexing, and processing systems to move satellite communications closer to the absolute efficiencies of the Shannon's Law limits have allowed satellites to gain greater and greater efficiencies. Essentially coder/decoder (Codec) systems in satellites have allowed satellite efficiencies to increase from a level of one bit per Hz to six or even seven bits per Hz simply through advanced software processing of signals. Small satellites, just like large satellites, are digital processors in the sky whose functionality is defined by its software. The key to more efficient small satellites will be through the development of ever better processing systems.

Such enhancements involve both the satellites and terrestrial systems. But terrestrial systems and networks are driven by other established and significant uses. It is unlikely that established terrestrial networks will agree to widespread and expensive changes just to accommodate small satellites. If the small satellites must seek compatibility with existing terrestrial networks, they might no longer be small and inexpensive. These are just some of the dilemmas that small satellite operators will face in years to come.

5.6 Small Satellites and Flight Software, Software-Driven Designs, and Network Control

The future of small satellites is being driven by a significant number of technologies. It is perhaps true that it is new software and artificial intelligence that may end up as one of the very most important drivers of change and innovation. Flight software, network control for satellite constellations, and even use of software to drive the future design of actual satellites are increasingly a part of the mix that is shaping the smallsat revolution. There are at least two key articles in the technology section of the Handbook on Small Satellites that cover the various ways that software and software innovation are shaping the future. These articles discuss the way that small satellites are designed as well as how modest upgrades in performance or reliability are made to small satellite designs as multiple generations of commercial small satellites are created with an ever increasing rapidity that may even come several times within a single year. There is a future for artificial intelligence and software innovation in almost every aspect of the world of small satellites. These can include flight software and network control of a small satellite constellation and in spacecraft design and innovation – from one generation to another in the fast moving spacecraft engineering and performance.

5.7 Optimizing Payloads for Remote Sensing and Monitoring

Most of the articles in Part 3 of the Handbook of Small Satellites address the technical challenges of small satellite and its component elements in terms of design, manufacturing, reliability, cost efficiency, and network operation. There are several articles that address the design and performance of the communications and networking payload and one that addresses the payload characteristics of small satellites for remote sensing. It was the miniaturization of sensors and particularly sensor processing for remote sensing that led the way forward in the small satellite revolution. The first wave was in miniaturized optical sensors. Over time infrared, near-infrared, hyper-spectral sensors, and synthetic aperture radar sensing systems have all been redesigned and shrunk down so as to be used in small satellites that range from 3U CubeSats to minisats. In light of the power requirements associated with radar sensing, that use active rather than passive sensing processes, synthetic aperture radar smallsats are typically larger than

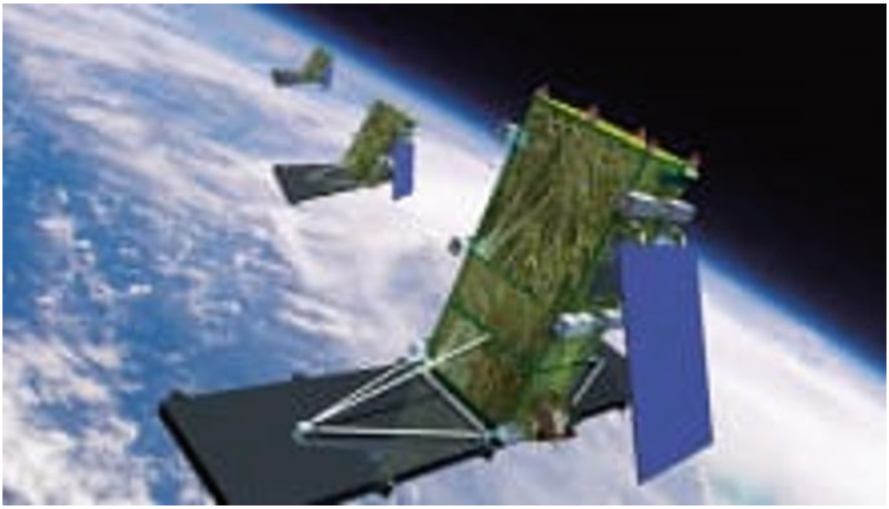


Fig. 4 The new deployed three Canadian RADARSAT constellation that represents the higher end of smallsat design. (Graphic Courtesy of the Canadian Space Agency)

optical remote sensing satellite systems. The Canadian newly launched Canadian RADARSAT Constellation Mission (CRM) deployed in June 12, 2019, represents the largest type of smallsats now used for synthetic aperture radar imaging (Foust 2019) (see Fig. 4).

5.8 Hosted Payloads as a Form of Small Satellite

There are many ideas behind the small satellite revolution. These have included finding ways to use better and more compact designs, creating high efficiency miniaturized components, discovering ways to use off-the-shelf components, developing accelerated and lower cost testing procedures, locating lower cost launch services, as well as developing economies of scale by deploying more small satellites in a constellation. As a part of this process of developing smaller and high efficiency satellites of small scale, it became clear that if one could place a functional payload on a larger satellite where it shared a launch, power, tracking, telemetry and command capabilities, etc. new efficiencies could be gained.

A guest, however, must not inconvenience the host The guest must meet its requirements while joined with the host wherever the host mission requires it to be. These compromises may be possible for some missions, but not for all.

Such a hosted payload might go on a large satellite for the purposes of technology demonstration, but if the host payload were small enough, it might even go on a microsat or a minisat. This, for instance, has been the case with the Aireon ADS-B hosted payload that has been launched onboard of all of the Iridium-NEXT satellites with its 66 satellite constellation (see Fig. 5).

Fig. 5 Aireon hosted payload on Iridium-NEXT satellite. (Graphic courtesy of Iridium)

Thus this handbook has examined this approach to a satellite and provided examples of this approach to small satellite deployment and operation for experiments, technology verification, and even implementation of commercial services.

5.9 High-Altitude Platforms (HAPs) as an Alternative to Small Satellites

Finally the concept of high-altitude platform systems and stratospheric systems is also included in this *Handbook of Small Satellites*. This is because platforms positioned in the stratosphere can be used to create the coverage to provide comprehensive overview or electronic services to an entire island nation or a country with a modest territory. Such high-altitude platforms (HAPs) can provide a range of important governmental services or commercial services. These can, for instance, include high-resolution and hyper-spectral remote sensing, law enforcement, forestry management, agricultural monitoring, fire detection, and particularly communications and broadcasting services (see Fig. 6).

Frequency spectrum has been allocated for UAV- and HAP-type services, and this type of service might be offered by a variety of different technologies that include zeppelins, dirigibles, automated aircraft, and solar-powered platforms. Even the concept of a type of platform that is provided power to operate electric engines and which would be beamed up from the ground have been considered, but not implemented. These transmissions could possibly be microwave, millimeter wave, or even laser-emitted power. Today some companies such as Thales Alenia are offering such systems to deploy high-altitude services by such stratospheric platforms. There have been projects to deploy such systems in countries as large as Japan that would have included the need

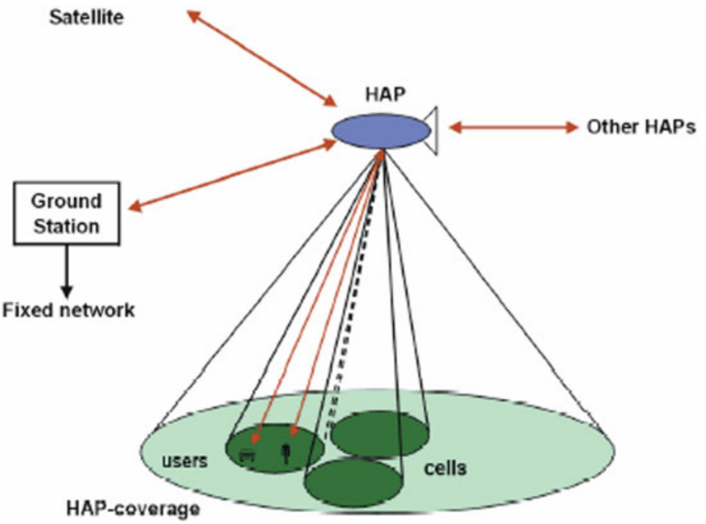


Fig. 6 High-altitude platform (HAP) diagram for telecommunication services. (Graphic from the Global commons)

to deploy as many as 15 such platforms, but his particular program has been discontinued for a number of practical and technical reasons.

6 Conclusion

Small satellites are revolutionary opportunities for organizations and nations. Often the companies building or operating small satellites will have limited financing and other resources. These capabilities should be encouraged and exploited. This article begins with citing the challenges and the risks of unfettered exploitation of this technology. It notes the bounds on the ability of smallsats from minisats and microsats down to nanosats and picosats. It notes the difficulty of small satellites meeting the constraints imposed on larger satellites.

None of these constraints are normative, and very few are broadly legally enforceable. Space mission and commerce stakeholders should consider this small satellite dilemma and arrive at acceptable compromises before compromise ceases to matter if space debris issues mushroom out of control through the lack of regulatory action or at least broad-based agreement on best practices.

Improved technology is essential. The technology that drives innovation in the fields of information, communications, computers, and energy is becoming more powerful each year. The world of small satellites seems to be among the very most dynamic. This is because it is driven by a true sense of innovative thought that is sometimes called “NewSpace” or “Space 2.0.” Many of these innovations grew out of the computer industry and a sense of breakthrough innovation rather than seeking merely a small 5% or 10% gain.

Regardless of the original stimulus, the effort to improve what is possible with small satellites and how they are deployed and used now pervades the industry. Thus there is an effort to increase performance everywhere and in every domain. Thus there is research and innovation related to:

(i) Attitude Determination and Control Systems (ADCS)
(ii) Power systems
(iii) Antenna systems
(iv) Radio and optical communications systems
(v) Use of artificial intelligence and improved software to improve smallsat performance
(vi) Enhancement of their structural design
(vii) Finding better ways to deorbit satellites at end of life
(viii) Improvement of the performance and cost for user terminals on the ground and on the move
(ix) Use of artificial intelligence to design better spacecraft and control constellation networks
(x) Use of advanced processing systems and AI to create better payloads for telecommunications and networking and/or improve sensors for remote sensing
(xi) Creation of even smaller hosted payloads to ride piggyback into space
(xii) Exploration of yet other alternatives to small satellites in the form of high-altitude platforms that can deploy new payloads for communications, broadcasting, law enforcement, agricultural and forestry management, navigation, or other services in perhaps even more cost-effective ways for island countries and other smaller territories

The technology section that follows has sought to be as comprehensive as possible. The articles that follow are filled with innovation and new ideas. It is hoped that this resource will prove useful. Ultimately the goal should not be to make satellites smaller and smaller as an end in itself. The key is to find suitable missions that are suitable for and compatible with small satellite systems and then optimize small satellites that are compatible with those missions. It is accomplishing goals and missions that are the ultimate aim.

7 Cross-References

- ► Flight Software and Software-Driven Approaches to Small Satellite Networks
- ► High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ► Hosted Payload Packages as a Form of Small Satellite System

▶ Network Control Systems for Large-Scale Constellations
▶ Power Systems for Small Satellites
▶ RF and Optical Communications for Small Satellites
▶ Small Satellite Antennas
▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
▶ Small Satellite Radio Link Fundamentals
▶ Small Satellites and Structural Design
▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
▶ Stability, Pointing, and Orientation

References

D. Earle, et al., Technical knowledge gaps in niche use cases of small satellites, AAS 17-950, IAA-AAS-CU-17-03-09. Last accessed Oct 2019

C. Esionwu Jr., *Cubesat Launch History* (Kingston University, London, 2014)

D. Finkleman, *Preserving the Space Environment Collaboratively* (UN Committee on the Peaceful Uses of Outer Space, Technical Subcommittee, February 2013), http://www.unoosa.org/pdf/pres/stsc2013/tech-06E.pdf. Last accessed Oct 2019

D. Finkleman, *IAASS Space Safety Conference*, Huntsville, May 2016., iaass.space-safety.org/wp-content/uploads/sites/34/2012/05/Programme-v3-with-posters-TS-15022016.pdf. Last accessed 31 Oct 2019

J. Foust, SpaceX launches Canadian radar satellites. Space News (June 12, 2019), https://spacenews.com/spacex-launches-canadian-radar-satellites/

Guidelines for the long-term sustainability of outer space activities of the Committee on Peaceful Uses of Outer Space adopted (2019), https://www.unoosa.org/oosa/en/informationfor/media/2019-unis-os-518.html

How to Configure Encoder for Satellite TV Transmission, http://www.sattvengg.com/2016/09/how-to-configure-encoder-for-satellite.html. Last accessed 28 Oct 2019

NASA, State of the art of small spacecraft technology, https://sst-soa.nasa.gov. Last accessed 30 Oct 2019

J. Pelton, *New Solutions for Orbital Debris Problems* (Springer Press, New York, 2015)

J. Puig-Suari, et al., The CubeSat: the picosatellite standard for research and education, in *AIAA Space 2008 Conference*, AIAA 2008-7734, San Diego, September 2008

R.A. Tummala, A. Dutta, An overview of cube-satellite propulsion technologies and trends. Aerospace **4**, 58 (2017)

X. Xia, G. Sun, K. Zhang, S. Wu, T. Wang, L. Xia, S. Liu, in *NanoSats/CubeSats ADCS Survey*, 29th CCDC Chinese Control and Decision Conference, Chongqing, 28–30 May 2017, Proceedings CCDC, pp. 5151–5158. (As noted by W. H. Steyn in Part 3. 2 of the Handbook of Small Satellites)

Stability, Pointing, and Orientation

Willem Herman Steyn

Contents

W. H. Steyn (✉)
Electronic Engineering, University of Stellenbosch, Stellenbosch, South Africa
e-mail: whsteyn@sun.ac.za

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_8

Abstract

This chapter gives an overview of the attitude determination and control system (ADCS) of spacecraft, focusing on small satellites. The ADCS is an important subsystem to insure satellite orientation stability and accuracy of pointing various payloads at specific targets. The introductory section will give an overview of the active ADCS feedback loop and lists some requirements and typical control methods utilized. The next section presents some background theory in attitude dynamics, kinematics, and the significant external disturbance torques in low earth orbit (LEO). Then some techniques used for angular rate and attitude determination are presented, followed by the control laws for magnetic detumbling and reaction wheel attitude control. A complete section is dedicated to a practical example of the calculations to determine the pointing accuracy and stability of a high-resolution (Hi-Res) imaging payload on a minisatellite. Finally the chapter concludes with examples and specifications of typical ADCS sensor and actuator hardware that are commercially available.

Keywords

Attitude determination · Attitude control · Passive and active stabilization · Disturbance torques · Coordinate frames · State estimation · Detumbling · Feedback control · Pointing accuracy · Platform stability · Star trackers · Reaction wheels

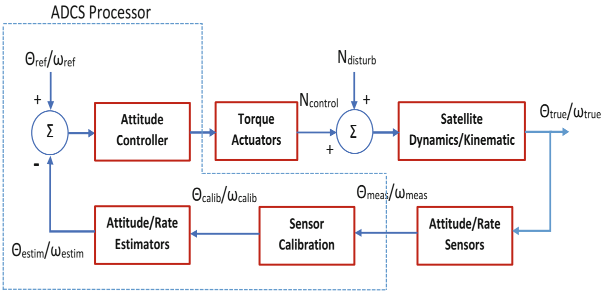
1 Introduction

The use of active attitude control and determination on small satellites is growing, but still less than 60% of all orbiting nanosatellites are 3-axis stabilized. According to an ADCS survey in 2017 by the Chinese Academy of Sciences (Xia et al. 2017) of nanosatellites (mass between 1 and 10 kg), 483 were launched successfully since 2003 until 2016. The ADCS information of 357 nanosatellites were available for statistical analysis. Of the 357 nanosatellites, only 5% had no ADCS, 17% used passive magnetic control, 2% used gravity gradient stabilization, 6% used other passive methods of stabilization (e.g., aerodynamic), 2% were spin stabilized, 11% used active magnetic control, 3% were momentum wheel stabilized, and 54% were reaction wheel 3-axis stabilized. In a 2014 review (Janse van Vuuren 2015) of 42 small satellites (excluding CubeSats) from 6.5 to 94 kg launch mass over the past 25 years, 5% had no control, 19% only passive control, and 76% some form of active control. The list of ADCS sensors was magnetometers (90%), sun sensors (80%), Earth sensors (10%), GPS (33%), rate sensors (40%), and star trackers (35%). The list of ADCS actuators was permanent magnets (20%), magnetic torquers (80%), momentum wheels (8%), reaction wheels (40%), propulsion systems (18%), gravity-gradient booms (15%), and control moment gyros (3%).

2 Attitude Determination and Control Subsystem (ADCS) Overview

The attitude determination and control system (ADCS) detumbles, stabilizes, points, and rotates a satellite into a desired orientation (attitude) despite any external or internal disturbances torques acting on it. A satellite's payload requires a specific pointing direction whether the payload is a camera, a science instrument, or an antenna. Satellites also require a specific orientation for thermal control or power control, i.e., to acquire the sun for their solar panels. The ADCS system uses sensors in order to determine a satellite's attitude or angular rates and actuators to maneuver the vehicle to a required orientation. The ADCS needs to achieve the various mission and payload objectives such as pointing accuracy, stability, rotation rate (slew), and sensing with many physical constraints such as mass, power, volume, computer power/storage, the space environment, robustness/lifetime, and cost. The ADCS is a synthesis of two subsystems the attitude determination system (ADS) and the attitude control system (ACS) which controls the attitude/angular rate of a satellite as depicted below in Fig. 1.

An example of ADCS sensor and actuator hardware for a small 3-axis stabilized satellite is shown in Fig. 2. In this example all the ADCS sensors, actuators, and processors communicate via a distributed dual ADCS CAN (Controller Area



$\Theta_{ref}/\omega_{ref}$: Reference attitude/rate
$\Theta_{true}/\omega_{true}$: True attitude/rate
$\Theta_{meas}/\omega_{meas}$: Measured attitude/rate
$\Theta_{estim}/\omega_{estim}$: Estimated attitude/rate
$N_{control}$: Actuator Torque
$N_{disturb}$: Disturbance Torque

Fig. 1 ADCS block diagram

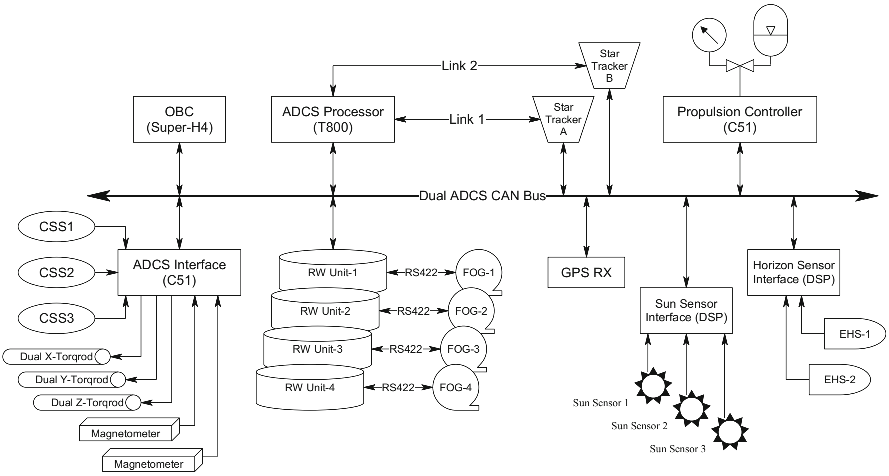


Fig. 2 Example ADCS hardware for a small satellite

Network) bus. The ADCS processor is dedicated to the attitude control system, although the OBC (onboard computer) can serve as a backup ADCS processor. The text in brackets indicates the type of processor used. The ADCS interface samples the coarse sun sensors (CSS1,2,3) and magnetometers and commands the magnetic torquer rods. The reaction wheel units (RW unit-1,2,3,4) are mounted in a tetrahedral configuration for redundancy and interface the fiber-optic gyros (FOG-1,2,3,4) for accurate angular rate measurements. A global position receiver (GPS RX) is used to accurately measure the satellite's orbit position, velocity, and time. A propulsion controller is implemented to control a cold gas propulsion system to do small orbit corrections and maintenance. The accurate absolute attitude sensors are the star trackers (A, B), sun sensors (1,2,3), and earth horizon sensors (EHS-1,2).

3 ADCS Requirements and Control Methods

In this section only active attitude control methods will be considered as most small satellites currently no longer use exclusively passive methods, e.g., permanent magnets to track the local magnetic field direction, gravity gradient torque to align the satellite's long axis with the nadir/zenith direction, and drag-induced aerodynamic torques to align the center-of-pressure (CoP) to center-of-mass (CoM) vector toward the orbit velocity vector. Although these passive methods can damp oscillations of the relevant body axis direction with libration/nutation dampers (typically viscous fluid tubes or rings), the rotations around this stabilized body axis cannot be controlled. For this reason these passive methods will mostly be combined with an active attitude or angular rate controller.

The need for active attitude control is determined by the small satellite mission and its attitude requirements. As mentioned in the introduction, most small satellite missions have specific attitude pointing and stabilization requirements, and thus an ADCS with some capability is needed. Active attitude control also comes in different flavors. Simple tumbling control modes can be implemented with the minimum of hardware and power requirements. Stabilized attitude (roll, pitch, and yaw angles controlled to a constant attitude) can be achieved using a momentum wheel, while full 3-axis control has the ability to perform commanded slew maneuvers which places the most demanding requirements on volume, mass, and power resources. A list of requirements that are usually considered for satellite ADCS are summarized in Table 1 below.

The methods for active attitude stabilization and control are briefly discussed in the following paragraphs:

3.1 Gravity Gradient Assist

It exploits Newton's law of general gravitation and through the use of gravitational forces can always keep a specific spacecraft axis nadir pointing. This is achieved by using a boom extending a small distinct mass (usually a magnetometer in order to minimize magnetic interference) from the spacecraft (which becomes the second distinct mass) by some distance. These two masses which are connected by a thin and light boom can then be used to exploit the difference in gravitational pull on the main satellite platform and on the additional mass (magnetometer) due to the difference in their distance from Earth. This small difference can be sufficient to enable the satellite/additional mass system to be aligned with the radius vector at all times as an orbiting pendulum. The gravity gradient stabilization scheme can be beneficial for coarse pointing (~5 deg) around the nadir axis, while the other two axes still will need

Table 1 General ADCS requirements

Requirement	Definition
Determination/sensing	
Attitude knowledge accuracy	Accuracy of a satellite's orientation estimation with respect to the truth
Attitude range	Range of angular motion over which the accuracy must be met
Control	
Pointing accuracy	Accuracy of a satellite's attitude control with respect to a commanded direction
Pointing range	Range of angular motion over which control performance must be met
Operating conditions	Parts of the orbit where attitude control is needed, such as eclipse/daylight
Stability/jitter	A specified angle bound or angular rate limit on short-term, high-frequency attitude motion
Slew rate/agility	Minimum slew or angular rate required to perform a rapid maneuver
Attitude drift	A limit on slow, low frequency vehicle motion
Settling time	Maximum time allowed to settle at the commanded attitude or angular rate

to be stabilized. The oscillations of the nadir-pointing axis are called librations and can be damped with an active magnetic controller. The rotation around the nadir direction can also be controlled by an active magnetic controller or a moment exchange actuator, e.g., a reaction or momentum wheel for higher accuracy.

3.2 Magnetic

By approximating the Earth's magnetic field in low earth orbit (LEO) as a dipole, it is possible to have a satellite fitted with a magnetometer to measure the Earth's magnetic field vector and use magnetic coils or rods (magnetorquers) to generate torques to control the satellite's attitude and angular rates. Due to a constraint in the direction of these magnetic torques, i.e., they are zero in the direction of the local magnetic field vector, these control torques cannot perfectly compensate for external disturbance torques on the satellite's attitude. This means for accurate attitude pointing the magnetic torques must be combined with passive control torques, e.g., gravity gradient or passively stable aerodynamic torques. The active magnetic torques can also be used to manage the angular momentum buildup on momentum exchange actuators, e.g., to ensure zero bias speeds on reaction wheels or offset reference speeds on momentum wheels.

3.3 Spinners

Spinning a satellite body generates an angular momentum vector which gives inertial stiffness to the satellite's attitude by keeping the spin axis fixed in inertial space. The angular momentum generated provides gyroscopic stiffness to the spinning satellite, making it less prone to external disturbances and more stable for propulsion thruster firings. Spinning the satellite after detumbling into a Y-Thomson attitude (Thomson 1962), where the satellite will align its maximum moment-of-inertia (MoI) axis normal to the orbit plane. This scheme will ensure a low-energy control method using a known spinning attitude with predictable antenna gain for ground communications or solar panel placement for a predictable power input.

3.4 Bias Momentum 3-Axis

For a 3-axis stable attitude, a momentum bias with a single momentum wheel aligned to the pitch axis normal to the orbit plane. Gyroscopic stiffness is used in order to control the vehicle by keeping the momentum wheel spinning at a biased reference speed. Small variations in the wheel speed allow for the control of the pitch axis. Yaw-roll coupling for nadir-pointing applications can be used to control the other two axes. Combined with magnetic controllers, the yaw-roll oscillations (nutations) can effectively be damped and the momentum wheel speed maintained at the biased reference speed. Although the satellite will be 3-axis stable, only the pitch axis can be controlled easily and accurately to a reference attitude. The roll and yaw axes will be controlled to zero angles.

3.5 Zero Momentum 3-Axis

In these systems, reaction wheels are used for each spacecraft axis in order to compensate for external disturbances and to implement various commanded attitude maneuvers. This is the most versatile and accurate attitude control system as pointing and slewing of any satellite axis are possible towards various earth and inertial targets, e.g., ground stations, earth imaging ground targets, sun, moon, stars, etc. A measured or estimated pointing error is used to torque the reaction wheels to ensure angular momentum exchange between the wheel discs and the satellite body to reduce the pointing error to zero. External torque disturbances can lead to wheel angular momentum buildup and eventual saturation. The increase in angular momentum to saturation levels requires a desaturation strategy which is called “momentum dumping” or unloading. This is achieved by using magnetorquers and to a much lesser extend thrusters (typically for larger satellites), thus enabling the wheels to operate around zero speed values. This strategy will also ensure the lowest reaction wheel power consumption as wheel power increase significantly with wheel speed.

3.6 Small Satellite ADCS Accuracies

The typical attitude control accuracies and constraints that can be obtained using the active control methods of the previous sections are summarized in Table 2. The accuracies listed depends also on the satellite’s orbit (external disturbance torques) and satellite size. Smaller satellites are normally less accurate due to a higher sensitivity to external disturbance torques and less accurate attitude and angular rate sensors.

Table 2 ADCS accuracies and constraints

Active control method	Actuators	Accuracy 1-σ	Constraint
Gravity gradient and magnetic, 3-axis stable	Boom and 3-axis magnetorquers	5°	Boom axis toward nadir, free rotation around boom axis (yaw)
Spinners, 2-axis stable	3-axis magnetorquers	10°	Spin axis direction inertially fixed
Bias momentum, 3-axis stable	Momentum wheel and 3-axis magnetorquers	2°	Wheel spin axis direction inertially fixed, free rotation around spin axis
Zero momentum, 3-axis stable	3-axis reaction wheels and 3-axis magnetorquers or thrusters	0.01°	No constraint, accuracy depends on attitude knowledge

4 ADCS Background Theory

4.1 Coordinate Frame Definitions

A satellite's attitude is normally controlled with respect to the orbit referenced coordinates (ORC), where the Z_O axis points toward nadir, the X_O axis points toward the velocity vector for a near circular orbit, and the Y_O axis along the orbit plane anti-normal direction. The aerodynamic $\mathbf{N}_{Aero}$ and gravity gradient $\mathbf{N}_{GG}$ disturbance torque vectors are also conveniently modelled in ORC. The satellite body coordinates (SBC) as defined in the body frame will nominally be aligned with the ORC frame at zero pitch, roll and yaw attitude. See Fig. 3 for a representation of these coordinate frames. Since the sun and satellite orbits are propagated in the J2000 earth-centered inertial coordinate frame (ECI), we require a transformation matrix from ECI to ORC coordinates. This can easily be calculated from the satellite position $\overline{\mathbf{u}}_I$ and velocity $\overline{\mathbf{v}}_I$ unit vectors (obtained using the position and velocity outputs of the satellite orbit propagator):

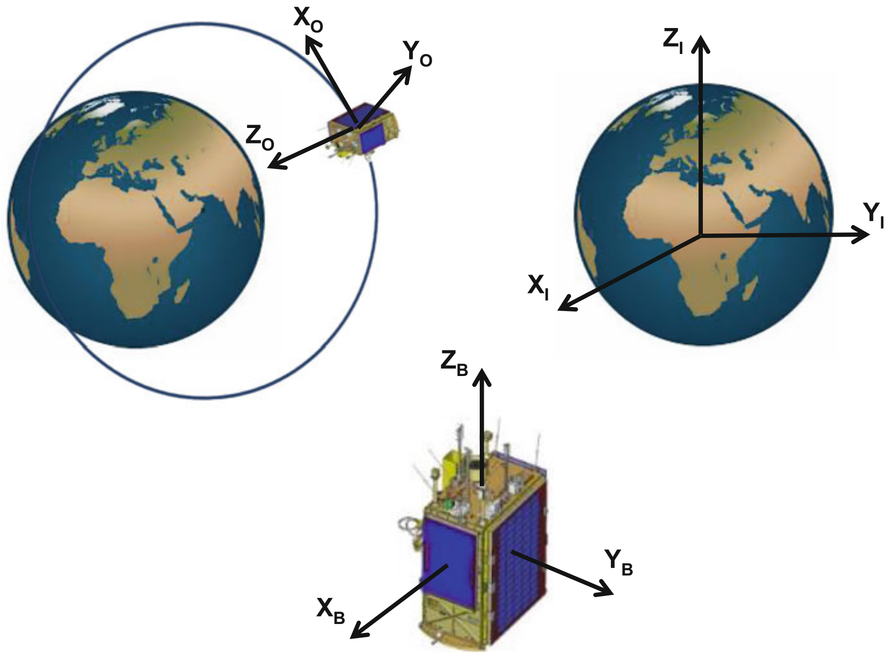


Fig. 3 Orbit (ORC), inertial (ECI), and spacecraft body (SBC) coordinate frames

$$\mathbf{A}_{I/O} = \begin{bmatrix} (\overline{\mathbf{u}}_I \times (\overline{\mathbf{v}}_I \times \overline{\mathbf{u}}_I))^T \\ (\overline{\mathbf{v}}_I \times \overline{\mathbf{u}}_I)^T \\ -\overline{\mathbf{u}}_I^T \end{bmatrix} \tag{1}$$

4.2 Attitude Kinematics

The attitude of an earth orbiting satellite can be expressed as a quaternion vector **q** to avoid any singularities to determine the orientation with respect to the ORC frame. The ORC reference body rates, $\omega_B^O = [\omega_{xo}, \omega_{yo}, \omega_{zo}]^T$, must be used to propagate the quaternion kinematics as:

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix} = 0.5 \begin{bmatrix} 0 & \omega_{zo} & -\omega_{yo} & \omega_{xo} \\ -\omega_{zo} & 0 & \omega_{xo} & \omega_{yo} \\ \omega_{yo} & -\omega_{xo} & 0 & \omega_{zo} \\ -\omega_{xo} & -\omega_{yo} & -\omega_{zo} & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{2}$$

The attitude matrix to describe the transformation from ORC to SBC can be expressed in terms of quaternions as:

$$\mathbf{A}_{O/B} = \begin{bmatrix} q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 - q_2q_4) \\ 2(q_1q_2 - q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & 2(q_2q_3 + q_1q_4) \\ 2(q_1q_3 + q_2q_4) & 2(q_2q_3 - q_1q_4) & -q_1^2 - q_2^2 + q_3^2 + q_4^2 \end{bmatrix} \tag{3}$$

Note: In Eqs. (1) and (2), a quaternion definition is used where the first three elements of the quaternion form the vector part and the last element the scalar part of the quaternion. Another definition where the scalar part of the quaternion is in the first element is also commonly used. The former quaternion definition will be used throughout this chapter.

The attitude is normally presented as pitch θ, roll φ, and yaw ψ angles, defined as successive rotations, starting with the first rotation from the ORC axes and ending after the final rotation in the SBC axis. If a Euler 213 sequence (first θ around Y_O, then φ around X, and finally ψ around Z_B) is used, then the attitude matrix and Euler angles can be computed as:

$$\mathbf{A}_{O/B} = \begin{bmatrix} C\psi C\theta + S\psi S\varphi S\theta & S\psi C\varphi & -C\psi S\theta + S\psi S\varphi C\theta \\ -S\psi C\theta + C\psi S\varphi S\theta & C\psi C\varphi & S\psi S\theta + C\psi S\varphi C\theta \\ C\varphi S\theta & -S\varphi & C\varphi C\theta \end{bmatrix} \tag{4}$$

with,

$$\mathrm{C} = \text{cosine function}, \quad \mathrm{S} = \text{sine function}$$

and

$$\begin{aligned} \theta &= \arctan 4\left(A_{31}, A_{33}\right) \\ \varphi &= -\arcsin\left(A_{32}\right) \\ \psi &= \arctan 4\left(A_{12}, A_{22}\right) \end{aligned} \tag{5}$$

This Euler angle representation will allow unlimited rotations in pitch and yaw, but only maximum ±90° rotations in roll.

4.3 Attitude Dynamics

The attitude dynamics of an earth orbiting satellite can be derived using the Euler equation:

$$\mathbf{I}\dot{\boldsymbol{\omega}}_B^I = \mathbf{N}_{GG} + \mathbf{N}_D + \mathbf{N}_W + \mathbf{N}_{MT} - \boldsymbol{\omega}_B^I \times \left(\mathbf{I}\boldsymbol{\omega}_B^I + \mathbf{h}_W\right) \tag{6}$$

with $\boldsymbol{\omega}_B^I = \boldsymbol{\omega}_B^O + \mathbf{A}_{O/B}[0 \; -\omega_o \; 0]^T$ the inertially referenced body rate vector, $\mathbf{N}_{GG} = 3\omega_o^2\left(\mathbf{z}_o^B \times \mathbf{I}\mathbf{z}_o^B\right)$ the gravity gradient disturbance torque vector, with $\mathbf{z}_o^B = \mathbf{A}_{O/B}[0, 0, 1]^T$ the orbit nadir unit vector in body coordinates, $\mathbf{N}_D$ is the external disturbance torques (e.g., from aerodynamic and solar pressure forces), $\mathbf{N}_W = -\dot{\mathbf{h}}_W$ is the reaction or momentum wheel torque vector, with $\mathbf{h}_W$ the wheel angular momentum vector, $\mathbf{N}_{MT}$ is the magnetic control torque, ω_o the orbit angular rate (a constant for a circular orbit and a time variable for an eccentric orbit), and $\mathbf{I}$ is the inertia matrix of the satellite.

4.4 External Disturbance Torques

For satellites in low earth orbit, the typical unmodelled disturbance torques are from aerodynamic and solar pressure forces and from magnetic moments. The unmodelled magnetic moments are mostly caused by poor harness layout where current loops can form when supplying power to the spacecraft subsystems. Another source of magnetic moment disturbances, especially significant on nanosatellites, is from currents flowing in solar panels due to the solar cell connections. The latter has caused many CubeSats to spun up when left uncontrolled for long periods of time, and in some cases, they became unrecoverable when eventually reaching a very high spin rate.

4.4.1 Aerodynamic

The dominant external disturbance torque on a satellite at low altitude, as is the case for many small satellite missions, will be aerodynamic torque disturbances caused by the atmospheric drag pressure force on the external surfaces and deployables of a satellite. These torques can be calculated by using the panel method of partial accommodation theory. The external surface of the satellite is divided into several flat segments and the torque disturbance of each segment calculated and summed for the total disturbance torque (Steyn and Lappas 2011):

$$\begin{aligned}\mathbf{N}_{Aero} = \sum\nolimits_{i=1}^{n} \{\rho\,(\mathbf{u}_I, t)\,\|\mathbf{v}_A^B\|^2 A_i cos(\alpha_i)[\sigma_t(\mathbf{r}_i \times \bar{\mathbf{v}}_A^B) \\ +\{\sigma_n S + (2 - \sigma_n - \sigma_t)\cos(\alpha_i)\}\,(\mathbf{r}_i \times \bar{\mathbf{n}}_i)]\}\end{aligned} \tag{7}$$

$$\mathbf{v}_A^B = \mathbf{A}_{O/B}\mathbf{A}_{I/O}\left[\mathbf{u}_I \times \begin{bmatrix} 0 \\ 0 \\ -\omega_E \end{bmatrix} - \mathbf{v}_I\right] \tag{8}$$

with $\mathbf{v}_A^B$ the atmospheric velocity in SBC and $\rho(\mathbf{u}_I, t)$ the atmospheric density at orbit position and local time, see Fig. 4, $\omega_E =$ earth's rotation rate $= 7.29212 \times 10^{-5}$ rad/s, A_i the surface area of segment i, $\cos(\alpha_i) = \bar{\mathbf{v}}_A^B \bullet \bar{\mathbf{n}}_i$ the cosine of angle between unit atmospheric velocity vector and $\bar{\mathbf{n}}_i$ the normal unit vector of segment i, $\mathbf{r}_i$ the satellite CoM to segment i's CoP vector, $S = v_b/\|\mathbf{v}_A^B\|$ the ratio of molecular exit velocity v_b to atmospheric velocity ≈ 0.05 (for a 700 km altitude), σ_n the normal accommodation coefficient ≈ 0.8 (for a 700 km altitude), and σ_t the tangential accommodation coefficient ≈ 0.8 (for a 700 km altitude).

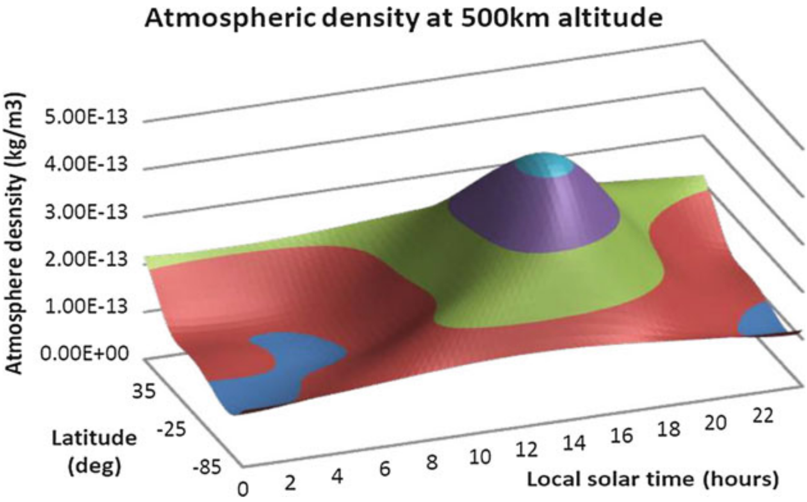


Fig. 4 An example of atmospheric density variation

4.4.2 Solar

The solar radiation pressure force and related torque depend on the absorption, specular and diffuse reflection coefficients of the external satellite surfaces, and deployables. The disturbance torques caused by the solar force are normally about two orders of magnitude less than the aerodynamic disturbances in low earth orbit, and its influence can normally be ignored. Where this force becomes significant is when a large area, highly reflective solar sail is deployed; see (Steyn and Lappas 2011) for a typical solar sail example.

4.4.3 Magnetic Moment

Internal magnetic moments due to currents flowing in an enclosed loop or residual magnetic dipoles from permanent magnets in electric motors, electromagnetic valves, or ferromagnetic material can cause time-varying magnetic moments that are difficult to accurately model or estimate. The sun's rays on solar panel surfaces will also cause magnetic moments normal to the surface and proportional to the sun vector component normal to the surface; the magnetic disturbance torque from a solar panel i can then be calculated as:

$$\mathbf{N}_{M\_SPi} = M_{SPi} H \cos(\alpha_i) \overline{\mathbf{n}}_{SPi} \times \mathbf{B}_B \tag{9}$$

with $\cos(\alpha_i) = \overline{\mathbf{s}}_B \bullet \overline{\mathbf{n}}_{SPi}$ the cosine of angle between the unit sun direction vector $\overline{\mathbf{s}}_B$ in SBC and the $\overline{\mathbf{n}}_{SPi}$the normal unit vector to the solar panel i surface, M_{SPi} the maximum magnetic moment of solar panel i when the sun is normal to the panel, $H = \{0, 1\}$, i.e., 0 when the cosine of angle is negative (sun behind the solar panel) and 1 (sun on solar panel) when positive and $\mathbf{B}_B$ the local B-field vector in SBC.

5 Attitude and Angular Rate Determination

To implement the attitude and angular rate controllers of the next section and to calculate the desired control torques, measurements or estimates of the orbit referenced angular rate vector and attitude quaternion must be known at each sampling instance of the onboard ADCS computer. A quaternion error can be calculated if the reference attitude quaternion and an estimated quaternion representing the current satellite attitude are available. The current satellite quaternion can be determined every sampling period using a TRIAD algorithm (Shuster and Oh 1981) from measured $\overline{\mathbf{v}}_B$ (in SBC) and modelled $\overline{\mathbf{v}}_O$ (in ORC) unit direction vectors from two different attitude sensor types, e.g., magnetometer/sun or sun-earth (nadir) combination of sensors. A more elaborate method QUEST (Shuster and Oh 1981) is optimally combining more than two vector pairs for attitude determination, e.g., from matched star tracker measurements.

As an example, a digital sun sensor can be used to measure the sun direction unit vector $\overline{\mathbf{s}}_B$ in SBC, and an IR earth sensor can measure the nadir unit vector $\overline{\mathbf{n}}_B$ in SBC. If the sun and satellite orbits are modelled, the sun to satellite unit vector in ORC, $\overline{\mathbf{s}}_O$ can also easily be calculated onboard in Eq. (10), and the nadir unit vector in ORC $\overline{\mathbf{n}}_O$ will simply be $[0, 0, 1]^T$, the direction of the ORC Z_O-axis.

The modelled (ORC) sun to satellite unit vector can be calculated from simple analytical sun and satellite (e.g., SGP4) orbit models in ECI coordinates. The ECI referenced unit vector can then be transformed to ORC coordinates using the known current satellite Keplerian angles:

$$\bar{\mathbf{s}}_O = \mathbf{A}_{I/O}\bar{\mathbf{s}}_I \tag{10}$$

with $\bar{\mathbf{s}}_I$ = ECI sun to satellite unit vector from sun and satellite orbit models.

5.1 TRIAD Method for Deterministic Attitude Determination

Two orthonormal triads are formed from the measured (observed) and modelled (referenced) vector pairs as presented above:

$$\begin{aligned} \bar{\mathbf{o}}_1 &= \bar{\mathbf{n}}_B, \quad \bar{\mathbf{o}}_2 = \bar{\mathbf{n}}_B \times \bar{\mathbf{s}}_B, \quad \bar{\mathbf{o}}_3 = \bar{\mathbf{o}}_1 \times \bar{\mathbf{o}}_2 \\ \bar{\mathbf{r}}_1 &= \bar{\mathbf{n}}_O, \quad \bar{\mathbf{r}}_2 = \bar{\mathbf{n}}_O \times \bar{\mathbf{s}}_O, \quad \bar{\mathbf{r}}_3 = \bar{\mathbf{r}}_1 \times \bar{\mathbf{r}}_2 \end{aligned} \tag{11}$$

The estimated ORC to SBC transformation matrix can then be calculated as:

$$\mathbf{A}_{O/B}(\widehat{\mathbf{q}}) = [\bar{\mathbf{o}}_1\ \bar{\mathbf{o}}_2\ \bar{\mathbf{o}}_3][\bar{\mathbf{r}}_1\ \bar{\mathbf{r}}_2\ \bar{\mathbf{r}}_3]^T \tag{12}$$

and

$$\begin{aligned} \widehat{q}_4 &= \sqrt{1 + A_{11} + A_{22} + A_{33}}/2 \\ \widehat{q}_1 &= [A_{23} - A_{32}]/(4\widehat{q}_4) \\ \widehat{q}_2 &= [A_{31} - A_{13}]/(4\widehat{q}_4) \\ \widehat{q}_3 &= [A_{12} - A_{21}]/(4\widehat{q}_4) \end{aligned} \quad \text{or} \quad \begin{aligned} \widehat{q}_1 &= \pm\sqrt{1 + A_{11} - A_{22} - A_{33}}/2 \\ \widehat{q}_2 &= [A_{12} + A_{21}]/(4\widehat{q}_1) \\ \widehat{q}_3 &= [A_{13} + A_{31}]/(4\widehat{q}_1) \\ \widehat{q}_4 &= [A_{23} - A_{32}]/(4\widehat{q}_1) \end{aligned} \tag{13}$$

5.2 Kalman Rate Estimator

To accurately measure low angular rates as experienced during 3-axis stabilization, a high-performance IMU will be required; this will neither fit in a small satellite nor be cost-effective. Low-cost MEMS rate sensors currently are still noisy and also experience high bias drift or temperature sensitivity. A modified implementation of a Kalman rate estimator can be used for the gyroless estimation of the nanosatellite body rates. This estimator was successfully used in many small satellite missions, such as the SNAP-1 nanosatellite mission (Steyn and Hashida 2001). It used magnetic field vector measurements that are continuously available, and the body measured rate of change of the geomagnetic field vector direction can be used as a measurement input for this rate estimator. However, this vector is not inertially fixed as it rotates twice per polar orbit. The estimated inertial referenced body rates will therefore have errors contributed by the magnetic field vector rotation rate. A more accurate estimated rate vector can be determined by measuring the sun vector, which only rotates inertially once per year. As the sun vector measurements are only available during the sunlit part of each orbit, when the sun is within the field of view (FOV) of a sun sensor, the Kalman rate estimator will propagate the angular rates when no measurements are available. A nadir-pointing small satellite is nominally rotating once per orbit within the ORC (around the body -Y_B axis), and full observability, using the sun vector measurement, is typically ensured. The only exception is when the satellite body rate vector is always aligned with the sun vector direction, else the angular rate vector with respect to an almost inertially fixed sun direction can be estimated as $\widehat{\omega}_B^I = [\hat{\omega}_{xi}, \hat{\omega}_{yi}, \hat{\omega}_{zi}]^T$. The expected measurement error will therefore include the sun sensor measurement noise and a negligibly small satellite-to-sun inertial rotation.

5.2.1 System Model

The discrete Kalman filter state vector $\mathbf{x}(k)$ is defined as the inertially referenced body rate vector $\boldsymbol{\omega}_B^I(k)$. From the Euler dynamic model of Eq. (6) without wheel actuators, the continuous time model becomes:

$$\begin{aligned} \dot{\boldsymbol{\omega}}_B^I(t) &= \mathbf{I}^{-1}\left(\mathbf{N}_{MT}(t) + \mathbf{N}_{GG}(t) - \boldsymbol{\omega}_B^I(t) \times \mathbf{I}\boldsymbol{\omega}_B^I(t)\right) \\ \dot{\mathbf{x}}(t) &= \mathbf{F}\,\mathbf{x}(t) + \mathbf{G}\,\mathbf{u}(t) + \mathbf{s}(t) \end{aligned} \tag{14}$$

with

$$\begin{aligned} &\mathbf{F} = [\mathbf{0}], \quad \mathbf{G} = \mathbf{I}^{-1}, \quad \mathbf{u}(t) = \mathbf{N}_{MT}(t) = \ \text{Control input vector} \\ &\mathbf{s}(t) = \mathbf{I}^{-1}\left(\mathbf{N}_{GG}(t) - \boldsymbol{\omega}_B^I(t) \times \mathbf{I}\boldsymbol{\omega}_B^I(t)\right) = \ \text{System noise vector} \end{aligned}$$

The discrete system model will then be

$$\mathbf{x}(k+1) = \boldsymbol{\Phi}\,\mathbf{x}(k) + \Gamma\,\mathbf{u}(k) + \mathbf{s}(k) \tag{15}$$

with

$\boldsymbol{\Phi} = [\mathbf{1}_{3x3}], \quad \Gamma = \mathbf{I}^{-1}T_s$

$T_s =$ Kalman filter sampling period

$\mathbf{s}(k) = N\{\mathbf{0}, \mathbf{Q}(k)\} \ =$ Zero mean system noise vector with covariance matrix $\mathbf{Q}$

5.2.2 Measurement Model

If we assume the satellite-to-sun vector as "inertially fixed" due to the large distance from the earth to sun compared to the earth to satellite and the slow rotation of the earth around the sun, the rate of change of the sun sensor measured unit vector can be used to accurately estimate the inertial referenced body angular rates. The magnetometer unit vector, as an orbit rotating vector, can also be used for continuous measurement updates but with expected rate estimation errors of approximately twice the orbit rate ω_o. For the rest of this discussion and the derivation of the measurement model, we assume the sun vector measurements will be used when they are available to update the Kalman rate estimator. Successive sun vector measurements will result in a small-angle discrete approximation of the vector rotation matrix:

$$\bar{\mathbf{s}}(k) = \Delta\mathbf{A}(k)\,\mathbf{s}(k-1) \tag{16}$$

with

$$\begin{aligned}\Delta\mathbf{A}(k) &\approx \begin{bmatrix} 1 & \omega_{zi}(k)T_s & -\omega_{yi}(k)T_s \\ -\omega_{zi}(k)T_s & 1 & \omega_{xi}(k)T_s \\ \omega_{yi}(k)T_s & -\omega_{xi}(k)T_s & 1 \end{bmatrix} \\ &\approx [\mathbf{1}_{3x3}] + \Lambda\left\{\boldsymbol{\omega}_B^I(k)\right\}\end{aligned} \tag{17}$$

The Kalman filter measurement model then becomes,

$$\begin{aligned}\Delta\mathbf{s}(k) &= \bar{\mathbf{s}}(k) - \bar{\mathbf{s}}(k-1) = \Lambda\left\{\boldsymbol{\omega}_B^I(k)\right\}\bar{\mathbf{s}}(k-1) \\ \mathbf{y}(k) &= \Delta\mathbf{s}(k) = \mathbf{H}(k)\,\mathbf{x}(k) + \mathbf{m}(k)\end{aligned} \tag{18}$$

with

$$\mathbf{H}(k) = \begin{bmatrix} 0 & -s_z(k-1)T_s & s_y(k-1)T_s \\ s_z(k-1)T_s & 0 & -s_x(k-1)T_s \\ -s_y(k-1)T_s & s_x(k-1)T_s & 0 \end{bmatrix} \tag{19}$$

and $\mathbf{m}(k) = N\{\mathbf{0},\ \mathbf{R}(k)\}$ as zero measurement noise, with covariance $\mathbf{R}$.

5.2.3 Kalman Filter Algorithm

Define $\mathbf{P}_k \equiv E\left\{\mathbf{x}_k.\mathbf{x}_k^T\right\}$ as the state covariance matrix, and then the following steps are executed every sampling period T_s, between measurements (at time step k):

1. Numerically integrate the nonlinear dynamic model of Eq. (14):

$$\hat{\mathbf{x}}_{k+1/k} = \hat{\mathbf{x}}_{k/k} + 0.5T_s(3\Delta\mathbf{x}_k - \Delta\mathbf{x}_{k-1})\{\text{Modified Euler Integration}\} \tag{20}$$

with

$$\Delta\mathbf{x}_k = \mathbf{I}^{-1}\left(\mathbf{N}_{MT}(k) - \hat{\boldsymbol{\omega}}_B^I(k) \times \mathbf{I}\hat{\boldsymbol{\omega}}_B^I(k)\right) \tag{21}$$

2. Propagate the state covariance matrix:

$$\mathbf{P}_{k+1/k} = \Phi\,\mathbf{P}_{k/k}\,\Phi^T + \mathbf{Q} = \mathbf{P}_{k/k} + \mathbf{Q} \tag{22}$$

Across measurements (at time step k + 1 and only in sunlit part of orbit):

3. Gain update, compute $\mathbf{H}_{\mathrm{k+1}}$ from Eq. (19) using previous vector measurements $\bar{\mathbf{s}}(k)$:

$$\mathbf{K}_{k+1} = \mathbf{P}_{k+1/k}\mathbf{H}_{k+1}^T\left[\mathbf{H}_{k+1}\mathbf{P}_{k+1/k}\mathbf{H}_{k+1}^T + \mathbf{R}\right]^T \tag{23}$$

4. Update the system state:

$$\widehat{\mathbf{x}}_{k+1/k+1} = \widehat{\mathbf{x}}_{k+1/k} + \mathbf{K}_{k+1}\left(\mathbf{y}_{k+1} - \mathbf{H}_{k+1}\widehat{\mathbf{x}}_{k+1/k}\right) \tag{24}$$

with

$$\mathbf{y}_{k+1} = \bar{\mathbf{s}}(k+1) - \bar{\mathbf{s}}(k)$$

5. Update the state covariance matrix:

$$\mathbf{P}_{k+1/k+1} = \left[\mathbf{1}_{3x3} + \mathbf{K}_{k+1}\mathbf{H}_{k+1}\right]\mathbf{P}_{k+1/k} \tag{25}$$

Finally the estimated ORC angular rate vector can be calculated from the Kalman filtered estimated ECI rate vector, using the TRIAD result of Eq. (12):

$$\widehat{\boldsymbol{\omega}}_B^O(k) = \widehat{\boldsymbol{\omega}}_B^I(k) - \mathbf{A}_{O/B}(\widehat{\mathbf{q}}(k))\,[0\ \ -\omega_o\ 0]^T \tag{26}$$

Figure 5 shows the simulation Kalman rate estimation results of a satellite with a hemispherical FOV digital sun sensor. The satellite is in an approximate 500 km polar orbit with 05h45 LTAN, giving a short eclipse period. The initial ECI referenced body rate vector values are [0.5, 0.0, 1.0] °/s. The estimated rate values track and propagate the true ECI rates accurately. The estimated rates are smooth when they are propagated, e.g., during the eclipse period from approximately 3600 to 4600 seconds. The digital sun sensor has a RMS angular error of 0.1°, and the Kalman rate estimation RMS error is 0.02 °/s.

Figure 6 presents actual Kalman rate estimation results obtained as real-time telemetry data points during the commissioning of a small microsatellite, when using only magnetometer measurements.

5.3 Extended Kalman Filter Estimators

Before any of the wheel control modes can be applied to a satellite, more accurate and continuous angular rate and attitude knowledge will be required. An extended Kalman

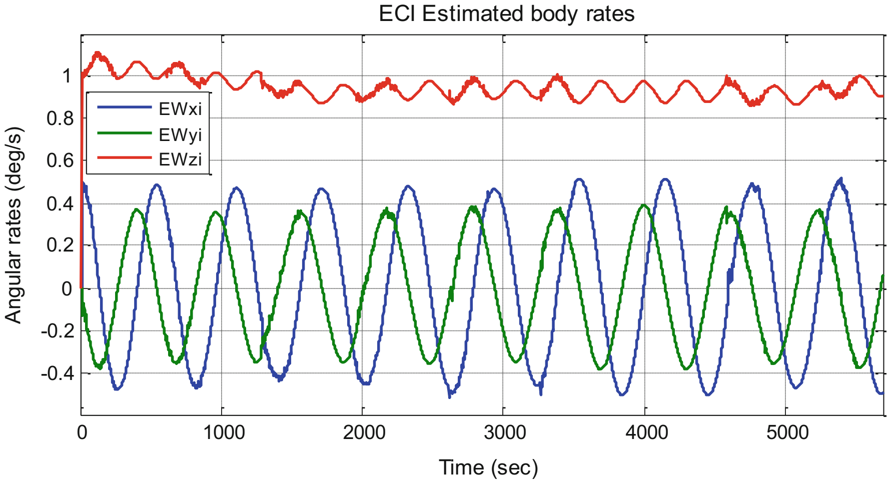


Fig. 5 Simulated sun sensor-based Kalman rate filter results

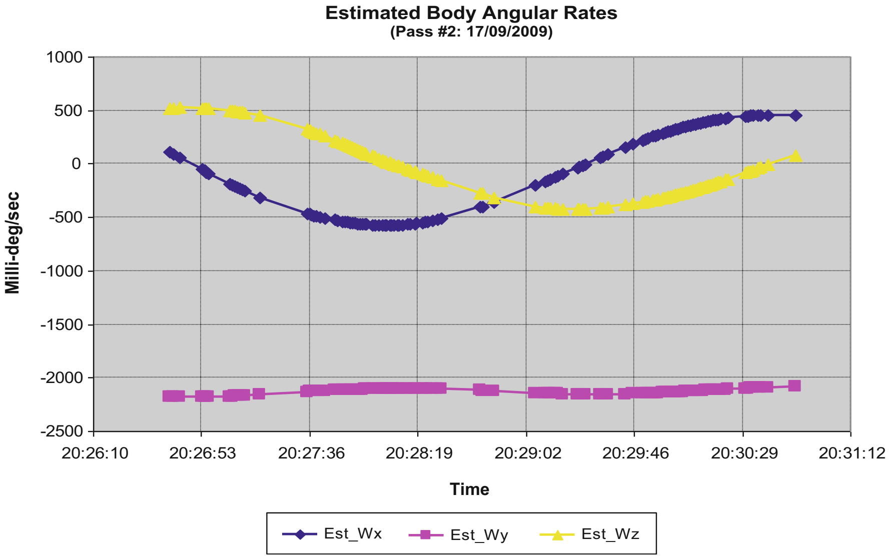


Fig. 6 Onboard magnetometer-based Kalman rate filter telemetry results

filter (EKF) can be used to estimate the full attitude state of the satellite from all attitude sensor SBC measurements (e.g., from magnetometer, sun, nadir, and star sensors) and the corresponding ORC modelled vectors; see (Steyn 1995) for a detailed derivation. The seven-element discrete state vector to be estimated is defined as:

$$\widehat{\mathbf{x}}(k) = \begin{bmatrix} \widehat{\boldsymbol{\omega}}_B^I(k) \\ \widehat{\mathbf{q}}(k) \end{bmatrix} \tag{27}$$

A disadvantage of the full state EKF is that the estimation accuracy will depend not only on the sensor measurement noise but also on the size of the modelling errors in the Euler dynamic model in Eq. (6), i.e., the uncertainty of the spacecraft's moments and products of inertia, the unknown external disturbance torques, and the actual actuator output torques. If the satellite's inertially referenced body rate vector $\boldsymbol{\omega}_B^I(k)$ can be accurately measured with inertial rate sensors (gyroscopes), the EKF does not have to model the spacecraft's uncertain dynamics, and a six-element discrete state vector can be defined as:

$$\widehat{\mathbf{x}}(k) = \begin{bmatrix} \widehat{\mathbf{b}}(k) \\ \widehat{\mathbf{q}}(k) \end{bmatrix} \tag{28}$$

with $\widehat{\mathbf{b}}(k)$ the estimated bias vector of the 3-axis angular rate sensor and inertial rate sensor model:

$$\widehat{\boldsymbol{\omega}}_B^I(k) = \boldsymbol{\omega}_{GYRO}(k) - \mathbf{b}(k) + \mathbf{m}(k)$$

where $\boldsymbol{\omega}_{GYRO}(k)$ is the 3-axis angular rate sensor measurement vector, $\mathbf{b}(k)$ is the rate sensor bias vector, and $\mathbf{m}(k)$ the measurement noise vector. See (Lefferts et al. 1982) for a detailed derivation of the rate sensor-based EKF.

Only extremely expensive and high-performance rate sensors, e.g., fiber-optic and ring-laser gyroscopes, will be able to measure the 3-axis inertially referenced angular rates of satellites with the required accuracy. The angular rate sensor bias can be significant in most sensors, e.g., a MEMS type and when it is required for the attitude to be propagated by integration of the rate sensor measurements, the estimation of the sensor bias becomes mandatory.

The innovation used in the EKF is the vector cross product of a measured body reference unit vector and a modelled orbit reference unit vector, transformed to the body coordinates by the estimated attitude transformation matrix $\mathbf{A}[\widehat{\mathbf{q}}(k)]$:

$$\mathbf{e}(k) = \overline{\mathbf{v}}_B(k) \times \mathbf{A}[\widehat{\mathbf{q}}(k)]\ \overline{\mathbf{v}}_O(k) \tag{29}$$

with $\begin{array}{l} \overline{\mathbf{v}}_B(k) = \mathbf{B}_{magm}(k)/\|\mathbf{B}_{magm}(k)\| \quad \text{or} \quad \mathbf{S}_{sun}(k)/\|\mathbf{S}_{sun}(k)\| \\ \overline{\mathbf{v}}_O(k) = \mathbf{B}_{igrf}(k)/\|\mathbf{B}_{igrf}(k)\| \quad \text{or} \quad \mathbf{S}_{orbit}(k)/\|\mathbf{S}_{orbit}(k)\| \end{array}$, e.g., for magnetic and sun vector pairs

The onboard magnetometer measurements must first be offline calibrated by comparing the measured B-field magnitude to the International Geomagnetic Reference Field (IGRF) model's magnitude. This is can be done by sampling at least a full orbit's raw or pre-launch calibrated magnetometer vector measurements and the corresponding IGRF modelled magnetic vectors. These data samples can then be further ground processed by using an attitude independent 3-axis magnetometer

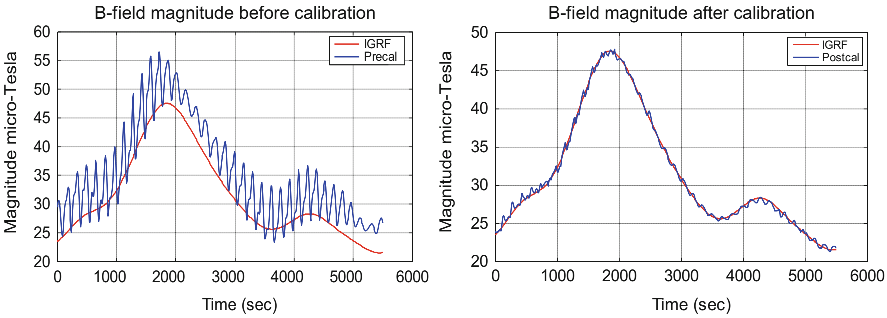


Fig. 7 Magnetometer pre-calibration ($1\sigma = 2.848\ \mu T$) and post-calibration ($1\sigma = 0.365\ \mu T$)

calibration method (Crassidis et al. 2005) to estimate the gain (scaling and orthogonality) matrix $\mathbf{G}_{cal}$ and offset (bias) vector $\mathbf{O}_{cal}$.

Thereafter calibrated magnetometer measurements can be determined for use in the EKF:

$$\mathbf{B}_{magm}(k) = \mathbf{G}_{cal}\mathbf{B}_{raw}(k) - \mathbf{O}_{cal} \tag{30}$$

Figure 7 shows typical pre- and post-calibration comparison results of a magnetometer when the onboard magnetic magnitude is compared to an IGRF model output for a CubeSat in a 400 km International Space Station orbit.

6 Attitude and Angular Rate Controllers

6.1 Detumbling Magnetic Controllers

After release from the launcher stage, the small satellite will first be detumbled using minimum ADCS resources and power, to bring it to a controlled spin rate and/or spinning attitude, typically a Y-Thomson spin (Thomson 1962). A Y-Thomson spin will ensure that the satellite will align its body Y_B axis normal to the orbit plane, i.e., with the satellite rotating within the orbit plane. This not only results in a controlled spin rate but also in a known spin attitude, without the need to estimate onboard the satellite's attitude. The only requirement for a stable Y-Thomson spin will be that the body Y_B axis must have the largest moment of inertia (I_{yy} MOI parameter) and small ($<$ 3% MOI) products of inertia parameters. A simple B-dot (Stickler and Alfriend 1974) magnetic controller will quickly dump any X_B and Z_B axes angular rates and align the Y_B axis to the orbit plane normal vector. Using measurements from a single MEMS rate sensor, the Y_B spin rate can then be magnetically controlled to an inertially referenced spin rate of typically -2 °/s (the reference rate depends on the magnitude of the external disturbance torques and must be high enough to ensure a sufficient gyroscopic stiffness). The magnetic detumbling controllers require only the measured magnetic field vector components (from a 3-axis magnetometer) and the inertially referenced Y_B body rate (from the Kalman rate estimator on Sect. 1.5.2 or a rate sensor measurement) and can be applied continuously. The magnetic-only controllers used during detumbling can be:

$$\begin{array}{llll} M_y = K_d {}^{d\beta}\!/_{dt} & \text{for} & \beta = \arccos\left({}^{B_{my}}\!/_{\|\mathbf{B}_{meas}\|}\right) & \{\text{Bdot controller}\} \\ M_x = K_s\left(\omega_{yi} - \omega_{yref}\right)\,\text{sgn}\left(B_{mz}\right) & \text{for} & \left|B_{mz}\right| > \left|B_{mx}\right| & \{\text{Y spin controller}\} \\ M_z = -K_s\left(\omega_{yi} - \omega_{yref}\right)\,\text{sgn}\left(B_{mx}\right) & \text{for} & \left|B_{mx}\right| > \left|B_{mz}\right| & \{\text{Y spin controller}\} \end{array} \tag{31}$$

with β the angle between the body Y_B axis and the local B-field vector, K_d and K_s are the detumbling and spin controller gains, and ω_{yref} the reference Y_B body spin rate. $M_{x,y,z}$ are the magnetic torquer moments in Am^2 units that can be scaled to pulse width modulated (PWM) outputs $M_{PMW\_x,y,z}$, as most magnetorquers on satellites are current controlled via discrete switching amplifiers. As the magnetorquer magnetic moments can disturb the local magnetic field measurements, we typically limit the magnetorquer on time to 80% of the discrete magnetic controller period T_s to leave a window for undisturbed magnetometer sampling.

The pulse outputs of the magnetorquers are therefore saturated to 80% of the controller period T_s,

$$sat\{M_{PWM\_i}\} = \text{sgn}\left(M_{PWM\_i}\right)\,\min\left\{\left|M_{PWM\_i}\right|, 0.8T_s\right\} \quad \text{for} \quad i = x, y, z \tag{32}$$

The average magnetic moment and torque vector during a controller period can then be calculated as:

$$\mathbf{M}_{avg} = \frac{M_{\max}}{T_s} sat\{\mathbf{M}_{PWM}\} \quad \text{Am}^2 \tag{33}$$

$$\mathbf{N}_{MT} = \mathbf{M}_{avg} \times \mathbf{B}_B \tag{34}$$

with $M_{\max}$ the maximum "on" magnetic moment of the magnetorquer and $\mathbf{B}_B$ the true magnetic field vector SBC.

Figures 8 and 9 show a typical detumbling performance from an initial angular rate of $\omega_B^I(0) = [4, 0, 2]^T$°/sec. During the first 1000 seconds, no control was done, and then the detumbling and Y-spin controller of Eq. (31) were enabled. Within less than an orbit, the satellite was controlled to a − 1°/sec Y-Thomson spin, using only the magnetorquers. The body angular rates were estimated by the Kalman rate filter as presented above utilizing only the raw magnetometer vector measurements.

6.2 Y-Momentum Wheel Controller

From the Y-Thomson body spin of the previous section, a momentum wheel aligned to the Y_B body axis can be used to absorb the Y-body momentum and control the

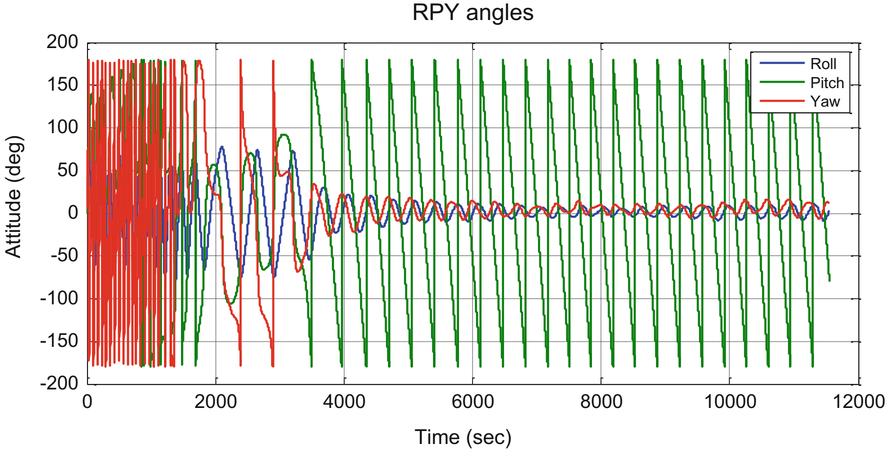


Fig. 8 Attitude angles during magnetic detumbling to a Y-Thomson spin

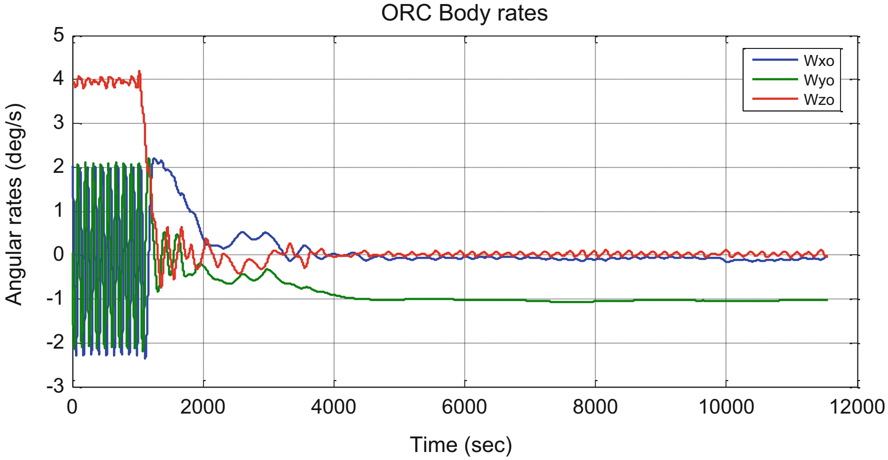


Fig. 9 Angular rates during magnetic detumbling to a Y-Thomson spin

pitch angle with small roll and yaw angles, e.g., to maintain a nadir-pointing attitude for earth imaging payloads and directional antennae for ground station communications. The Y-momentum wheel controller can be implemented with attitude and rate estimations from an EKF, as

$$N_{wy}(k) = K_{py} \arcsin\left(\widehat{q}_2(k)\ \mathrm{sgn}\left(\widehat{q}_4(k)\right)\right) + K_{dy}\widehat{\omega}_{yo}(k) \tag{35}$$

with K_{py} and K_{dy} the proportional and derivative gains.

To maintain the Y-wheel momentum at a certain reference level (corresponding to the initial Y_B body momentum during the Y-spin mode) and to damp anybody nutation rates in the X_B and Z_B axes, a magnetic cross-product control law can be utilized (Steyn and Hashida 2001):

$$\mathbf{M}(k) = \frac{\mathbf{e}(k) \times \mathbf{B}(k)}{\|\mathbf{B}(k)\|} \tag{36}$$

with

$$\mathbf{e}(k) = \begin{bmatrix} K_n \ \widehat{\omega}_{xo}(k) \\ K_h \ \left(h_{wy}(k) - h_{wy-ref}\right) \\ K_n \ \widehat{\omega}_{zo}(k) \end{bmatrix} \tag{37}$$

where K_n is the nutation damping gain, K_h is the Y-wheel momentum control gain, and $h_{wy\,-\,ref}$ is the Y-wheel reference angular momentum.

The cross-product controller of Eq. (36) is applied continuously. During initial commissioning, the Y-momentum control mode can be used to calibrate and determine the alignment of all the accurate attitude sensors, i.e., sun and earth horizon (nadir) sensors and star tracker. After the in-orbit calibration and alignment parameters have been determined, the measurements from these sensors can then be included in an EKF to improve the attitude and rate estimation accuracy. Next, the nanosatellite will be ready for a 3-axis reaction wheel control mode, when required for full 3-axis pointing capability.

Figures 10 and 11 present the detumbling results where an offset Y-wheel speed (momentum) can assist to detumble a satellite into a stable Y-Thomson spin for cases where the Y_B axis MOI is not the largest. The detumbling is done during the first orbit

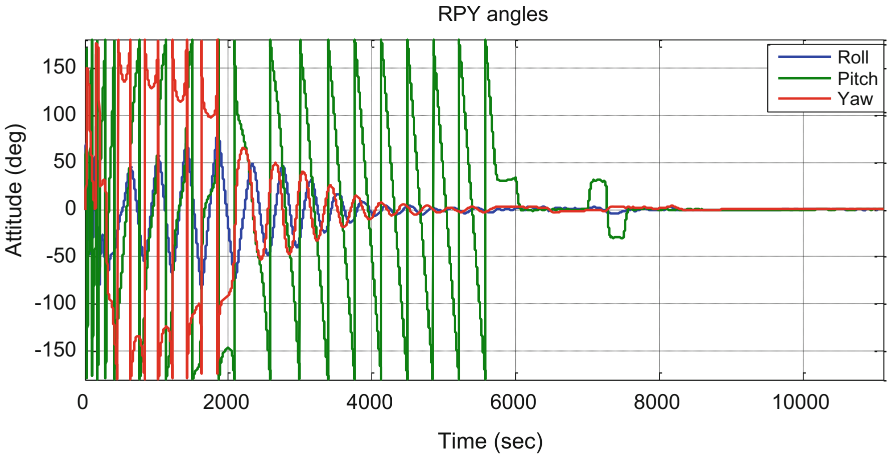


Fig. 10 Attitude angles from Y-Thomson detumbling to Y-Momentum wheel control

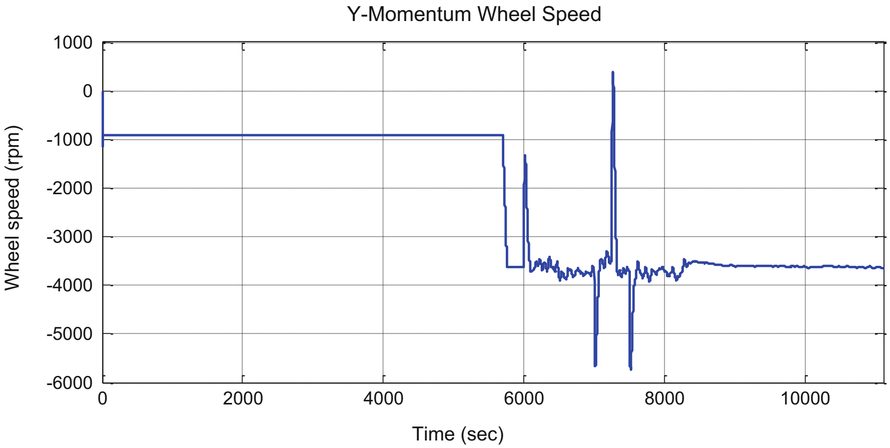


Fig. 11 Y-Momentum wheel speed during Y-Thomson detumbling and Y-Momentum control

until time 5700 seconds with the Y-Wheel speed at −1000 rpm. Then the Y-Wheel speed is ramped to −3700 rpm to absorb the Y-body spin, and at 6000 seconds, the Y-Wheel controller of Eq. (35) is enabled to control the pitch attitude to zero, and the magnetic cross-product controller of Eq. (36) is enabled to damp the roll/yaw nutation and maintain the Y-Wheel angular momentum at a wheel speed of approximately −3700 rpm. At 7000 seconds a pitch reference of +30° and 250 seconds later of −30° is commanded, before returning back to nadir pointing at 7500 seconds.

6.3 3-Axis Reaction Wheel Controllers

From the Y-momentum wheel mode, the X_B and Z_B reaction wheels can be activated and a 3-axis reaction wheel controller implemented using the estimated attitude and angular rates using the EKF of Sect. 1.5.3. The globally stable quaternion feedback controller of (Wie et al. 1989) can be modified to become an orbit referenced pointing control law. The quaternion and rate reference vectors can be generated from a sun orbit model for a sun-pointing attitude (to maximize solar energy generation on deployed solar panels), or it can be a zero vector for a nadir-pointing attitude or any specified constant attitude reference for a specific roll, pitch, or yaw requirement (see Fig. 12). The 3-axis reaction wheel control law (wheel torque vector) to be used for all these cases is:

$$\mathbf{N}_w(k) = K_{P1}\mathbf{I}\vec{\mathbf{q}}_{err}(k) + K_{D1}\mathbf{I}\widehat{\boldsymbol{\omega}}_B^O(k) - \widehat{\boldsymbol{\omega}}_B^I(k) \times \left(\mathbf{I}\widehat{\boldsymbol{\omega}}_B^I(k) + \mathbf{h}_w(k)\right) \tag{38}$$

with $K_{P1} = 2\omega_n^2$, $K_{D1} = 2\zeta\omega_n$ the pointing gains for a required controller closed-loop bandwidth and damping factor. $\mathbf{I}$ is the satellite moment of inertia matrix, $\mathbf{h}_w(k)$ is the measured angular momentum of the reaction wheels:

$\hat{\omega}_B^O(k) = [\hat{\omega}_{xo}(k), \hat{\omega}_{yo}(k), \hat{\omega}_{zo}(k)]^T$ is the body orbit reference angular rate estimate, $\vec{\mathbf{q}}_{err}(k) = [q_{1e}(k), q_{2e}(k), q_{3e}(k)]^T$ is the vector part of the error quaternion $\mathbf{q}_{err}$, where

$$\begin{gathered}\mathbf{q}_{err}(k) = \mathbf{q}_{com}(k) \bigoplus \widehat{\mathbf{q}}(k) \\ \begin{bmatrix} q_{1e} \\ q_{2e} \\ q_{3e} \\ q_{4e} \end{bmatrix} = \begin{bmatrix} q_{4c} & q_{3c} & -q_{2c} & -q_{1c} \\ -q_{3c} & q_{4c} & q_{1c} & -q_{2c} \\ q_{2c} & -q_{1c} & q_{4c} & -q_{3c} \\ q_{1c} & q_{2c} & q_{3c} & q_{4c} \end{bmatrix} \begin{bmatrix} \widehat{q}_1 \\ \widehat{q}_2 \\ \widehat{q}_3 \\ \widehat{q}_4 \end{bmatrix}\end{gathered} \tag{39}$$

with $\mathbf{q}_{com}(k)$ the commanded reference quaternion, e.g., a sun direction quaternion and $\bigoplus$ for quaternion division.

A nominal reaction wheel control mode can be, for example, do sun-pointing in the sunlit part of the orbit and nadir pointing, i.e., $\mathbf{q}_{com}(k) = [0, 0, 0, 1]^T$, in eclipse. The nadir-pointing attitude will ensure optimal antenna coverage for ground communication during eclipse and thermal stability to the imager telescope. Continuous momentum management of the reaction wheels can be done using a simple cross-product magnetic controller (Steyn 1995):

$$\mathbf{M}(k) = K_m \frac{\mathbf{h}_w(k) \times \mathbf{B}(k)}{\|\mathbf{B}(k)\|} \tag{40}$$

with $K_m$the momentum dumping gain.

The tracking of ground targets can also be accurately done by uploading the earth target's coordinates a-priory. A target tracking generator is then used onboard to calculate the commanded quaternion $\mathbf{q}_{com}(k)$ and angular rate vectors for the reaction wheel controllers as derived in (Chen et al. 2000). The geometry during target tracking to calculate the satellite to target vector in ORC is shown in Fig. 12. The 3-axis reaction wheel control law is similar to the quaternion feedback controller of Eqs. (38) and (39), but an integral term of the quaternion error $\vec{\mathbf{q}}_{ierr}$is added for improved tracking accuracy, where:

$$\vec{\mathbf{q}}_{i\,err}(k) \cong \vec{\mathbf{q}}_{i\,err}(k-1) + \vec{\mathbf{q}}_{err}(k) T_s \tag{41}$$

The ground target tracking control law then becomes

$$\begin{aligned}\mathbf{N}_w(k) = K_{P2}\mathbf{I}\vec{\mathbf{q}}_{err}(k) + K_{I2}\mathbf{I}\vec{\mathbf{q}}_{i\,err}(k) + K_{D2}\mathbf{I}\left[\widehat{\boldsymbol{\omega}}_B^O(k) - \boldsymbol{\omega}_{com}^O(k)\right] \\ -\widehat{\boldsymbol{\omega}}_B^I(k) \times \left[\mathbf{I}\widehat{\boldsymbol{\omega}}_B^I(k) + \mathbf{h}_w(k)\right]\end{aligned} \tag{42}$$

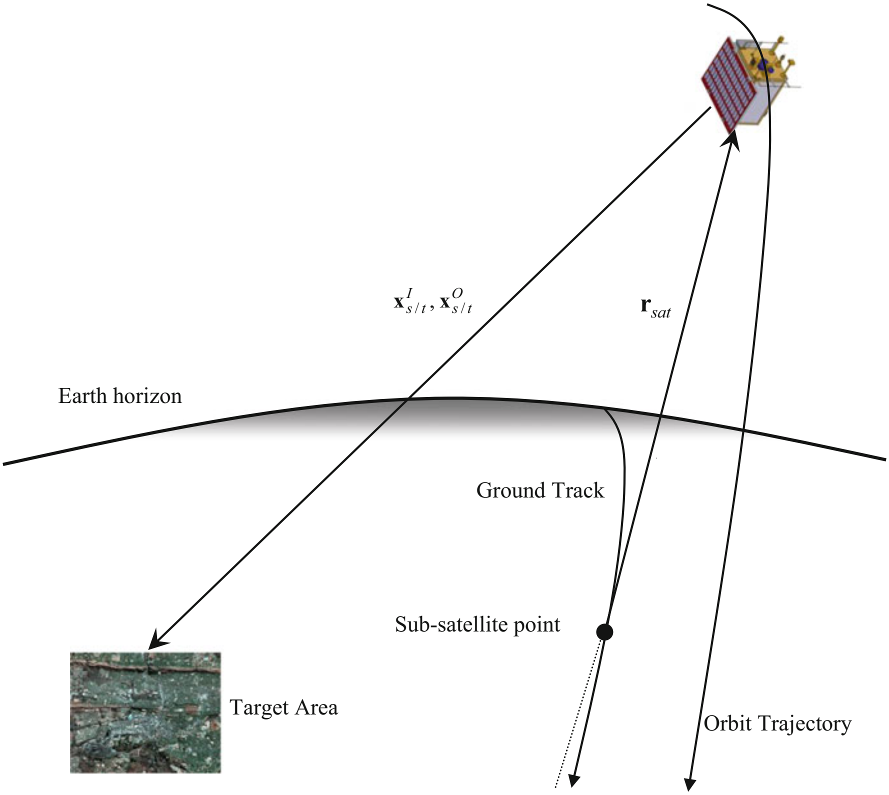


Fig. 12 Target tracking geometry

with $K_{P2} = 2\left(\omega_n^2 + 2\zeta\omega_n/\Delta T\right)$, $K_{D2} = 2\zeta\omega_n + 1/\Delta T$, $K_{I2} = 2\omega_n^2/\Delta T$, ω_n, ζ the dominant second-order closed-loop specifications, $\Delta T = 10/\zeta\omega_n$ the time constant for integral control, and $\boldsymbol{\omega}_{com}^{O}(k)$ the ORC target tracking angular rate commanded vector.

Figures 13 and 14 show the typical performance over an orbit of the 3-axis reaction wheel controllers of a LEO small satellite. Initially the attitude is controlled to nadir pointing (zero RPY). Between 600 and 1600 seconds, a ground target close to the sub-satellite ground track is tracked, with roll angle varying between +2° and – 4°, i.e., for an almost overhead pass. At 2000 seconds a sun-tracking control law is enabled to point the solar panels mounted on the zenith pointing satellite facet toward the sun. During eclipse (from 3099 to 5262 seconds) the sun tracking control law automatically revert back to nadir pointing to ensure improved antennae pointing for ground station communication.

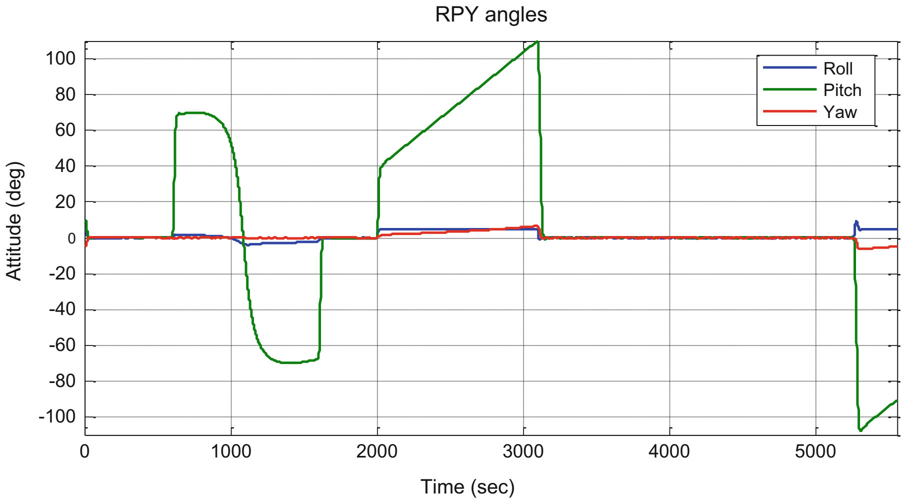


Fig. 13 Attitude angles during target tracking, sun tracking, and nadir-pointing control

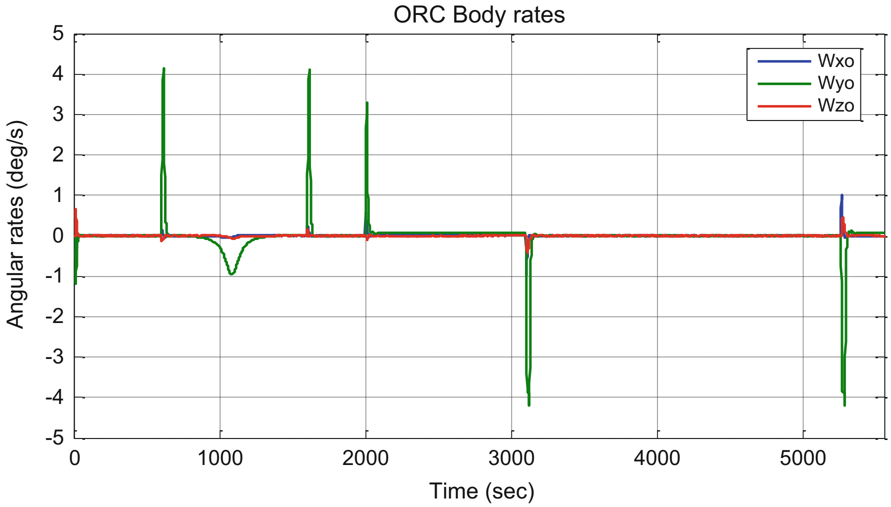


Fig. 14 Reaction wheel speeds during target tracking, sun tracking, and nadir-pointing control

7 Pointing Accuracy and Stability

The ADCS requirements for an earth observation (EO) satellite are mostly driven by the imager, the "main payload." These are determined by the Hi-Res camera as it will present the highest performance requirements for pointing accuracy, pointing stability, and platform agility. This section uses a hypothetical Hi-Res camera and satellite as an example to satisfy the following user requirements:

- Hi-Res ground sampling distance (GSD) of 1 m/pixel resolution on 7 μm square pixel dimensions
- Hi-Res swath of 12 km (assuming 12,000 active pixels per line)
- Agility of 30° roll and pitch rotations in 20 seconds
- Pointing control error of 200 m (1σ) at center of target
- Pointing knowledge error of 20 m (1σ) at center of target
- Pointing stability less than 0.1 pixel smear during time delay integration (TDI) imaging
- Pointing range in pitch and roll at ±30°
- 128 TDI stages (pixel rows) at the maximum integration setting
- 500 km near circular sun-synchronous orbit with 09 h30 am/pm local time at equatorial crossings
- 450 kg minisatellite with principle moments of inertia (MOI) $I_{XX} = I_{YY} = 270$ kgm^2 and $I_{ZZ} = 63$ kgm^2

7.1 Selected ADCS Hardware

7.1.1 Reaction Wheels

Four wheels in a tetrahedral configuration (see Fig. 15) with reaction wheel specifications:

- Maximum torque: $N_{max} = 0.2$ Nm
- Maximum angular momentum: $h_{max} = 10$ Nms (± 5000 rpm)

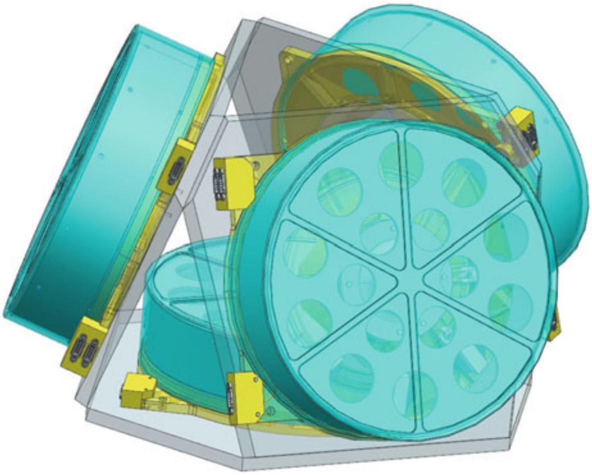


Fig. 15 Tetrahedral reaction wheel configuration

- Speed control accuracy: $\Delta\omega < 0.6$ rpm RMS
- Static unbalance <4.5 g.cm
- Dynamic unbalance <14.4 g.cm^2

7.1.2 Star Tracker

A star tracker with dual optical heads with 60° separation between boresight directions to prevent sun blinding at certain attitude pointing angles. The star tracker specifications are:

- Accuracy: 4 arcsec 1σ in boresight direction and 20 arcsec 1σ boresight rotation for 10 stars at 5 Hz.
- Exclusion angles: 30° sun and Earth
- Max tracking rate: 5 °/sec.

7.1.3 Angular Rate Sensor

A fiber-optic gyroscope (FOG) is selected to measure the angular rates per satellite axis. The FOG specifications are:

- Random walk <0.08 °/√hr → measurement noise = 4 milli-deg/sec (1σ)
- Bias drift <1.5 °/hr. = 1.5 arcsec/sec
- Bias stability <0.05 °/hr. = 0.05 arcsec/sec
- Update rate 10 Hz

7.1.4 Space GPS Receiver

The orbit position is measured accurately with a GPS receiver with the following relevant specifications:

- 3D position accuracy <10 m (1σ)
- Update rate 1 Hz

7.2 Jitter Analysis (Platform Stability)

7.2.1 Stability Requirement

Assume a maximum 10% pixel smear over the 128 TDI stages. For a 500 km orbit, $V_{sat} = 7.613$ km/sec and $V_{ground} = 7.06$ km/sec. Assume an imaging quality factor $Q = 1$, i.e., pixel ground size = GSD.

The exposure time for a 128 stage TDI sensor is therefore $t_{exp} = 128.\mathrm{GSD}/V_{ground} = 18.1$ milli-sec.

The GSD pixel angle: θ_{pixel} (500 km) = $\tan^{-1}$(GSD/500e3) = 0.4125 arcsec.

The stability requirement for roll and pitch pointing is then $\omega_{stability}$(pitch/roll) = $0.1\ \theta_{pixel}/t_{exp}$ = 2.28 arcsec/sec.

For yaw rotations the end pixels will be 6000 pixels from the 12,000 pixel line center; therefore a 0.1 pixel rotation at the end of a line will be $\psi_{pixel} = \tan^{-1}(0.1/6000) = 3.44$ arcsec and $\omega_{stability}(\text{yaw}) = \psi_{pixel}/t_{exp} = 189.9$ arcsec/sec.

The worst-case stability requirement is then for roll/pitch stability = $\underline{\text{2.28 arcsec/sec}}$.

The factors determining the platform stability during TDI integration will be discussed next.

7.2.2 Reaction Wheel Unbalance

Assume a four-wheel tetrahedral reaction wheel configuration with a wheel speed bias of $\omega_{wbias} = 1000$ rpm = 104.7 rad/sec = 16.7 Hz.

Static Unbalance

Assume for the tetrahedral configuration the static unbalance $mr = 4.5$ g.cm = 4.5e-5 kg.m and the worst-case unbalanced wheel disc CoM at 0.3 m from the satellite CoM.

The static unbalance forces in the X_BZ_B and Y_BZ_B plane for pitch and roll disturbance:

$$F_{su} = mr\omega^2 = 4.5\text{e-}5(104.7)^2 \sin(104.7t)\text{N}$$

The static unbalance angular accelerations will be:

$$\dot{\omega}_{x/y} = \frac{0.3F_{su}}{I_{XX/YY}} = 5.5\text{e-}4 \sin(104.7t)\text{rad}/\sec^2$$

The angular rate disturbance amplitude due to static unbalance will then be:

$$\left|\omega_{x/y\ static}\right| = \frac{\left|\dot{\omega}_{x/y}\right|}{\omega_{wbias}} = \underline{1.08\ \text{arcsec}/\sec} \quad (@16.7\text{ Hz})$$

Dynamic Unbalance

Assume for the tetrahedral configuration the dynamic unbalance mrd = 14.4 g.cm^2 = 1.44e-6 kg.m^2. The dynamic unbalance torque amplitude around the body axes causing attitude disturbances will be

$$|N_{du}| = mrd\omega^2 = 1.44\text{e-}6(104.7)^2 = 1.58\text{e-}2\text{Nm}$$

The dynamic unbalance torque around the roll and pitch axes will be

$$\left|\dot{\omega}_{x/y}\right| = \frac{|N_{du}|}{I_{XX/YY}} = 1.58\text{e-}2/270 = 5.9\text{e-}5\ \text{rad}/\sec^2$$

The angular rate disturbance amplitude will then be

$$\left|\omega_{x/y\ dynamic}\right| = \frac{\left|\dot{\omega}_{x/y}\right|}{\omega_{wbias}} = \underline{0.12\ \text{arcsec}\,/\,\text{sec}}\quad (@16.7\ \text{Hz})$$

Therefore the worst-case jitter will be due to static unbalance; this can be reduced by placing the RWs closer to the CoM of the satellite or by reducing the RW bias wheel speed.

7.2.3 Reaction Wheel Control Torque Disturbances

The brushless DC motor (BDCM) control of the reaction wheel speed will induce the following disturbance torques to the satellite body.

Nonlinear Friction

Stiction when crossing zero speeds. A typical stiction torque for a similar sized tetrahedral reaction wheel configuration is 4 milli-Nm. The wheel acceleration in a controller settling time of $10T_s = 1$ sec due to stiction, when the wheel stop and start, is (T_s = reaction wheel controller sampling time)

$$\frac{\Delta\omega}{\Delta t} = \frac{N_{stiction}}{I_{XX/YY}} = \frac{4e-3}{235} = 3.1\ \text{arcsec}\,/\,\text{sec}^2$$

$$\Delta\omega_{stiction} = \underline{3.1\ \text{arcsec}\,/\,\text{sec}}\,(\text{assuming a 1 sec RW controller settling time})$$

This angular disturbance clearly exceeds the stability requirement during imaging; therefore the RW speeds must be prevented from zero speed crossings, i.e., biased reaction wheels will be required in the tetrahedral configuration.

7.2.4 BDCM Torque Ripple

Assume 25% of the nominal torque (20 milli-Nm) during imaging as the torque ripple at the motor's commutation rate multiplied by the reaction wheel bias speed ω_{wbias}. The ripple torque will then be:

$$N_{ripple} = 5\ \text{milli-Nm@100 Hz}\,\{6\ \text{poles x }16.7\ \text{Hz@1000 rpm}\}$$

The ripple torque angular rate disturbance amplitude will then be:

$$\left|\omega_{ripple}\right| = \left(N_{ripple}/I_{XX/YY}\right)/628.2\ \text{rad/s} = \underline{0.006\ \text{arcsec}\,/\,\text{sec}}\quad (@100\ \text{Hz})$$

Reaction Wheel Control Torque

Assume a 1% of maximum tetrahedral torque increment every reaction wheel controller sampling time T_s:

$$\Delta N_{wheel} = 0.01 N_{wmax} = 2.0\ \text{milli-Nm in}\,T_s = 0.1\ \text{sec}$$

The ripple torque angular rate disturbance amplitude will then be:

$$\omega_{control} = \left(\Delta N_{wheel}/I_{XX/YY}\right).T_s = \underline{0.15\ \text{arcsec}/\text{sec}}$$

Reaction Wheel Speed Discretization

Assuming a speed control discretization step amplitude of $\Delta\omega_{wheel} = 0.6$ rpm = 3.6°/sec and reaction wheel moment of inertia I_{wheel} = 1.91e-2 kgm^2, then the wheel speed discretization will cause a body angular rate disturbance of

$$\Delta\omega_{x/y} = \Delta\omega_{wheel} I_{wheel}/I_{XX/YY} = 1.1\ \text{arcsec}/\text{sec}$$

This value is close to the roll/pitch stability requirement of 2.28 arcsec/sec for a 128 stage TDI image sensor. Neither the star tracker or FOG rate sensors can measure down to this low resolution. With only the reaction wheels controlled to an accuracy not worse than 0.6 rpm (1σ), the satellite platform stability requirement will be met.

7.3 Pointing Error Budget

The different contributions to a ground target's pointing error from a 500 km altitude are:

- Attitude knowledge error from the dual star tracker measurements
  Accuracy <4 arcsec (1σ) = 9.7 meter
- GPS position error projected to the ground
  Accuracy of satellite's in-orbit position <10 m (1σ) = 9.3 meter
- Timing accuracy (image timestamp correlation)
  2 milli-sec (1σ) worst case assumed due to software latency = 14.1 meter @V_{ground} = 7.06 km/sec.

Therefore the combined (1σ) geolocation measurement accuracy = **19.5 meter** (satisfies requirement)

- The attitude control accuracy <0.02° (1σ) = 174.5 meter

Therefore, the total (1σ) **pointing control error** = **194.0 meter** (satisfies requirement).

Other possible errors to consider:

- Maximum structural alignment variation (thermal) between main telescope and star tracker boresights <10 arcsec, thus <24.2 meter pointing error that can possibly be compensated for with a thermal model
- Atmospheric optical distortion for off-nadir angles and ionospheric errors for GPS signals

7.4 Satellite Platform Agility

Assume a four-wheel tetrahedral configuration with maximum total torque and angular momentum placed in the Y_B axis direction:

$$\mathbf{N}_{THmax} = \begin{bmatrix} 1.89 \\ 2.0 \\ 1.63 \end{bmatrix} \mathbf{N}_{Wmax} \quad \text{and} \quad \mathbf{h}_{THmax} = \begin{bmatrix} 1.89 \\ 2.0 \\ 1.63 \end{bmatrix} \mathbf{h}_{Wmax}$$

Then,

$$N_{THmax}(Y_B) = 400 \text{ milli-Nm}, \quad h_{TH\,max}(Y_B) = 20 \text{ Nms}$$

$$\omega_{ymax} = 0.7 h_{THmax}/I_{YY} = 0.0519 \text{ rad/ sec} \approx 3.0^{\circ}/\text{ sec}$$

$$\dot{\omega}_{ymax} = N_{THmax}/I_{YY} = \text{Acc} = 0.00148 \text{ rad/ sec}^2 = 0.85^{\circ}/\text{ sec}^2$$

For a bang-off-bang minimum-time rotation around Y_B, we assume 70% of reaction wheel angular momentum is still available to do the maneuver (20% of each reaction wheel's angular momentum is used to bias the tetrahedral configuration, and 10% is available to compensate for external disturbances). The bang-off-bang minimum-time angular rate rotation profile is shown in Fig. 16. The time to accelerate at maximum torque to ω_{ymax} is $t_a = 3.0/0.85 = 3.5$ seconds, and the pitch rotation angle to t_a is $\theta_a = 0.5\omega_{ymax}t_a = 5.25^{\circ}$. The deceleration phase of the rotation profile will take similar time and angle as the acceleration phase; thus the coasting phase for a 30° pitch rotation will take $t_c = (30^{\circ} - 2\theta_a)/\omega_{ymax} = 6.5$ seconds. Therefore, the minimum final time for a 30° pitch rotation will be $t_f = 2t_a + t_c = 7 + 6.5 = \underline{13.5 \text{ seconds}}$. Similar calculations for a 30° roll rotation (X_B axis), where the $\omega_{xmax} \approx 2.8^{\circ}/\text{ sec}$, $t_a = 3.3$ seconds, $\phi_a = 4.6°$, and $t_c = 7.4$ seconds, give a minimum final time $t_f = \underline{14 \text{ seconds}}$. Both these rotation times are less than the requirement of 20 seconds specified in the beginning of this section.

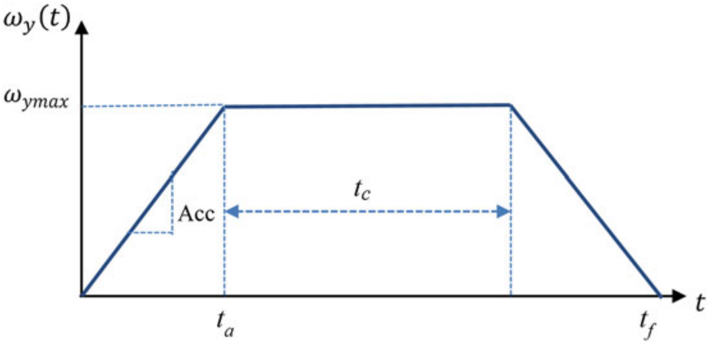


Fig. 16 Pitch angular rate profile during a minimum-time slew maneuver

8 ADCS Sensor and Actuator Hardware

The ADCS sensors typically used on small satellites are limited by mass, volume, and power constraints. Over the last couple of years, the available technology has improved and became more compact and lower power due to an increase in the density of semiconductor integrated circuits and advances in MEMS technology and nanomechanics. Therefore, most ADCS sensor and actuator types flying on larger satellites can now be found in miniaturized form for small satellite use. Although their performance in some aspects are still not the same as their larger and more power hungry bigger brothers, the gap is slowly closing, i.e., where the laws of physics do allow it. The next section will present some examples of these small satellite ADCS components that are available commercially and successfully used in various small satellite missions.

8.1 3-Axis Magnetometers

Fluxgate 3-axis magnetometers give the best noise performance, and their sensitivity and bias errors with temperature are better compared to MEMS type magnetoresistive and magneto-inductive sensors typically used in nanosatellites. The MEMS types with build-in bias and temperature correction circuitry and calibration equations have been used successfully on nanosatellites. For most magnetic control ADCS systems where accuracy is not a hard requirement, the MEMS type magnetometers are ideally suited with their inherent small size and low-power specifications. Table 3 compares the performance parameters of magnetometer types typically used on small satellites.

To reduce the influence of magnetic disturbances from the spacecraft bus, it is advisable to mount magnetometers on the external facets of the satellite and sometimes have them deployable; see Fig. 17 for a 3-axis microsatellite fluxgate magnetometer and a nanosatellite deployable 3-axis MEMS magnetometer.

8.2 Sun Sensors

The sun as a bright inertial object in the celestial sky is perfectly suited for accurate attitude vector measurements using a relative low cost, mass, and power-type sensing device. Sun sensors vary from planar photodiodes or solar

Table 3 Performance parameters of some 3-axis magnetometer types

Magnetometer type	Range (μT)	Scaling (mV/μT)	Resolution (nT)	Noise (pT_{rms}/Hz)	Axes error (°)	Linearity error (%)	Scaling error (%)	Temp coeff (ppm/°C)	Temp bias (nT/°C)
Fluxgate	± 60	166	Analogue	< 10	± 0.1	0.0015	± 0.5	15	0.3
Mag-resistive	± 60	Digital	10	1000	± 0.1	0.1	± 5	2700	10
Mag-inductive	± 200	Digital	13	1200	± 1.0	0.5	± 5	500	5

Fig. 17 Magnetometers: Left, fluxgate (Bartington), and right, CubeSat deployable MEMS (CubeSpace)

Table 4 Performance parameters of high accuracy sun sensors for small satellites

Sun sensor type	FoV (°)	Accuracy (° RMS)	Update rate (Hz)	Power average (mW)	Mass (g)	Size (mm^3)	Supply (VDC)	RadiationTID (krad)
NSS digital fine sun sensor	140	< 0.1	5	37.5	35	$34 \times 32 \times 20$	5–50	10
SolarMEMS digital two-axis SS	120	< 0.1	50	315	35.5	$50 \times 30 \times 12$	5	300

cells where the short circuit current is measured to get a value proportional to the cosine of the sun angle to the surface normal. Six of these sensors mounted with unobstructed hemispherical view each on the facets of a box-type satellite will always give the components of the sun direction vector from up to three sensors facing the sun. Due to earth albedo absorption and a non-ideal cosine response (due to reflections at low angles from the sensor surface), the sun vector accuracy from these coarse sensors is at best about ±5°, but mass and power are negligible. Higher accuracy sensors often make use of MEMS position-sensitive detectors (PSD) and optical windowing to give a sun direction vector measurement from the sun azimuth and elevation measurement angles. Table 4 gives some performance parameters of commercially available sun sensors and Fig. 18 show images of these sensors.

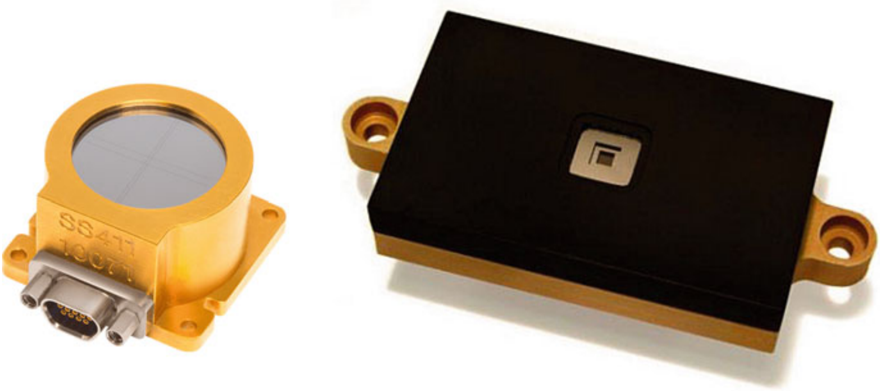


Fig. 18 Digital 2-axis sun sensors: Left, NFSS-411 (NewSpace), and right, SSOC-D60 (Solar MEMS)

8.3 Star Trackers

The most accurate attitude sensors used on small satellites are star trackers. They are sensors with very sensitive light detectors, typically charge-coupled devices (CCD); in some case these sensors are also cooled to reduce the thermal noise for an increased signal-to-noise ratio. The FOV of these sensors depends on the visual magnitude (M_v) stars that can be detected, e.g., for a CCD detector sensitive enough to see a 6.5 M_v star, a FOV of 15° will ensure at least three stars to be visible for more than 99% of the celestial sphere. The stars detected in the FOV will be slightly defocused to enable the star centroid to be accurately determined using a center of gravity method. The separation distances (angles) between all the measured stars are then matched to reference stars in an onboard star catalogue. For example, a unique match will be detected when a matching triangle can be found of three measured and reference stars. All other visible star separation angles will then be matched to generate the maximum number of measured stars in the SBC frame and reference stars in the ECI frame for star tracking.

After the initial processing intensive “lost-in-space” matching process, successive measurements will only be used to track their matched reference stars by searching in a small region around their previous position, assuming a slow rotating satellite. The tracking process is processing less intensive than star matching, and this enables most star trackers to generate vector pair solutions typically between 1 and 10 Hz for further attitude and rate determination use in an EKF estimator. Star trackers on larger satellites have typical RMS accuracies of less than 5 arcseconds in the boresight direction and 15 arcsec in boresight rotation. This performance is made possible by high-quality low distortion optics and very sensitive star detection. For nanosatellites the high CCD power requirement and large optics with sun and earth blocking baffles are inhibiting factors. However, a few nano-sized star trackers have already been developed and some

Table 5 Performance parameters of typical star trackers for small satellites

Star tracker	Accuracy (arcsec 1-σ)	Max track rate (°/sec)	Max update rate (Hz)	Power average (W)	Mass (g)	Size (mm^3)	Supply (VDC)	Baffle sun exclusion angle (°)
Sodern Auriga	6 (cross axis) 40 (boresight)	3	5	1.0	210	56 × 66 × 94	5	34
Adcole Maryland MAI-SS	4 (cross axis) 27 (boresight)	2	4	1.5	282	55 × 65 × 70 (no baffle)	5	45

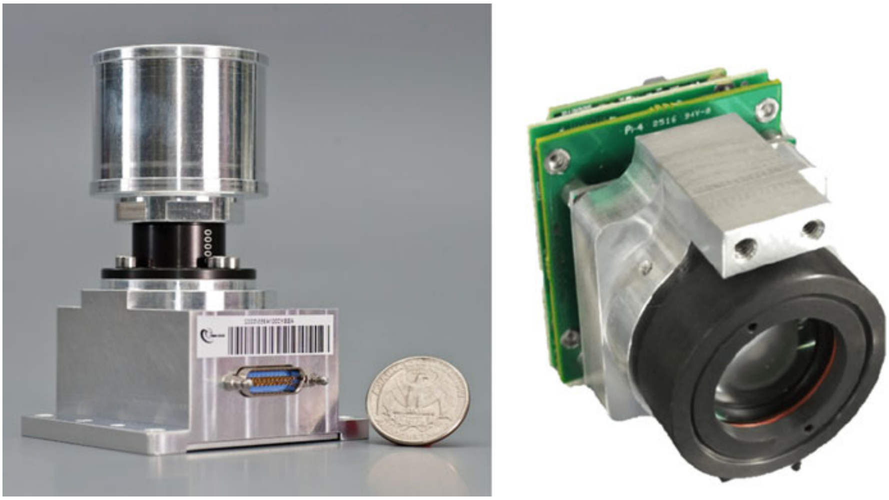


Fig. 19 Star Trackers: Left, Auriga (Sodern), and right, MAI-SS (Adcole Maryland)

also successfully flight qualified. See Table 5 for typical performance specifications of these small satellite star trackers; Fig. 19 shows images of these accurate sensors.

8.4 Angular Rate Sensors

Accurate measurement of the inertially referenced low angular rates of small satellites, during 3-axis stabilization, is possible using low measurement noise and low bias drift fiber-optic gyroscopes (FOG). The development of MEMS rate sensors is continuously improving, almost matching the performance of lower cost FOGs. To measure the initial high tumbling rates of nanosatellites, MEMS rate sensors can be utilized effectively. Table 6 gives a performance comparison between a tactical grade FOG sensor, high-performance 3-axis MEMS angular rate sensor, and an integrated circuit packaged MEMS rate sensor; it is clear that the performance gap is reducing. Fig. 20 show images of these angular rate sensors.

Table 6 Performance parameters of typical angular rate sensors for small satellites

Rate sensor type and model	Range (°/sec)	Noise (random walk) (°/√hr)	Bias drift (°/hr 1-σ)	Max update rate (Hz)	Power average (W)	Mass (g)	Size (mm^3)	Supply (VDC)
FOG 1-axis μFORS-3 U	± 499	0.08	3	1000	1.1	150	21 × 65 × 88	5
MEMS 3-axis STIM300	± 400	0.15	10	2000	1.5	55	39 × 45 × 22	5
MEMS 1-axis CRM100/200	± 75	0.28	24	1000	0.012	0.1	5.7 × 4.8 × 1.2 6.3 × 2.7 × 5.5	3.3

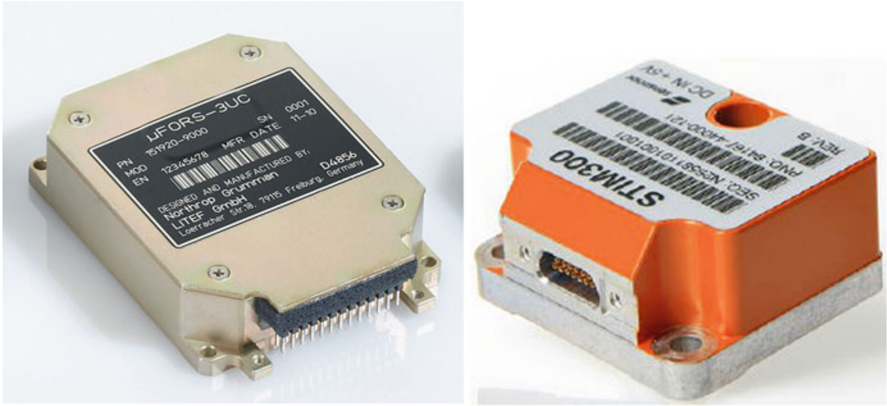


Fig. 20 Single axis angular rate sensors: Left, μFORS-3 U (Northrop Grumman), and right, STIM300 (Sensonor)

8.5 Magnetorquers

Actuators to generate magnetic moments for interaction with the geomagnetic field can easily be scaled for small satellite use. Magnetic torquer rods are preferred due to their smaller volume, power, and mass compared to torquer coils, but sometimes due to layout problems, air-core coils will be used. Torquer rods make use of a low remanence ferromagnetic core, e.g., MuMetal or Supra-50 alloys are suitable. Torquer rods will give a magnetic moment amplification of 80 to 120 compared to an air-core coil; therefore they use less current and power and a smaller enclosed area for a similar magnetic moment. The physical placing of the torquer rods are critical as they can influence each other, and the direction of the generated magnetic moment

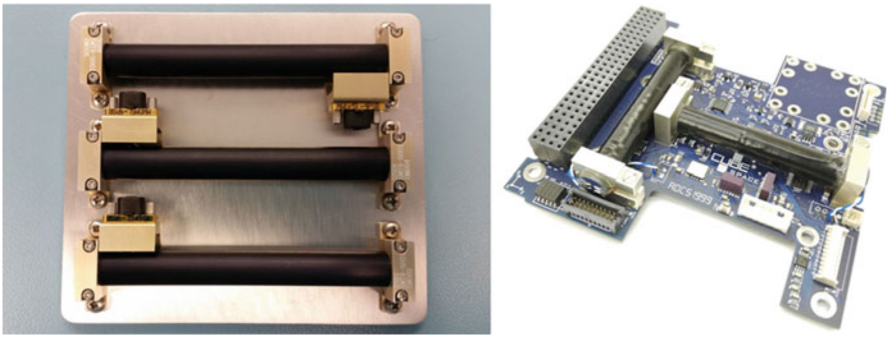


Fig. 21 Magnetorquers: Left, NMTR-X (NewSpace), and right, CubeTorquer (CubeSpace)

Table 7 Performance parameters of typical magnetorquers for small satellites

Magnetic torquer	Magnetic moment (Am^2)	Linearity (%)	Residual moment (Am^2)	Power max (W)	Mass (g)	Length (cm)	Supply (VDC)
NewSpace NMTR-X	1–100	$\pm$ 5	$<$ 0.5%	1.0	30 g/cm length	8–60	5
CubeSpace CubeTorquer small	0.48	2.5	$<$ 0.1%	0.8	28	6	5

can rotate, especially if they are separated by distances less than a rod length (except for a symmetric T-configuration, see Fig. 21). By pulse width modulation of the X_B, Y_B, and Z_B magnetorquer currents, a magnetic moment vector in any desired direction and size can be produced. Table 7 show typical performance parameters for these small satellite magnetorquers.

8.6 Reaction/Momentum Wheels

Reaction/momentum wheels are actuators that operate using the principal of preservation of angular momentum, to exchange the controlled angular momentum in the wheel disc's rotation speed to the body of the satellite. A reaction wheel assembly normally consists of a brushless DC motor (BDCM) with a shaft-mounted disc acting as a flywheel. The flywheel's speed is accurately measured with a shaft encoder to enable a feedback speed control system for accurate angular momentum control. The flywheel's size is chosen according to the momentum storage requirements of a satellite in a specific orbit. The BDCM torque is selected to meet the agility requirements during rotation maneuvers, i.e., how fast the satellite body must rotate during these maneuvers. Precise speed control with optimized low-power requirements and small volume and mass are the driving factors for the wheel choice on small satellites.

Table 8 Performance parameters of typical reaction/momentum wheels for small satellites

Reaction or momentum wheel	Max angular momentum (milli-Nms)	Max torque (milli-Nm)	Max speed (rpm)	Power const speed (W)	Mass (kg)	Size (mm^3)	Static/ dynamic unbalance (gmm/gmm^2)
Vectronic VRW-1	1000.0	± 25	± 6500	3.0	1.8	115 × 115 × 77	< 1/80
CubeSpace CubeWheel small	1.77	0.23	± 8000	0.15	0.06	28 × 28 × 26.2	< 0.03/0.5

The difference between reaction wheels and momentum wheels lies only in the application of the wheel's angular momentum to control the satellite's attitude. A reaction wheel operates in a near-zero momentum bias configuration, i.e., to limit the gyroscopic torques caused by an angular momentum vector during 3-axis attitude rotations. A momentum wheel operates around an offset speed to give an angular momentum bias to the satellite's body for gyroscopic stiffness. This means a momentum wheel will control the satellite's attitude actively in the wheel spin axis direction through momentum exchange (by varying the wheel speed) and passively through gyroscopic stiffness by keeping the attitude in the other two axes.

For a full 3-axis rotation capability, a minimum of three reaction wheels will be required, and the wheel speeds will be controlled around zero average speed. For redundancy reasons and to enable offset wheel speeds (to avoid the wheel torque disturbances at zero speed crossings), more than three reaction wheels can be used while still ensuring a zero average momentum vector applied to the satellite body. For example, four reaction wheels can be used in a forth skewed wheel, tetrahedral, or pyramid configuration (see Fig. 15 for a tetrahedral cluster).

Commercially available small satellite wheels are high-performance micro-mechanical devices, e.g., they are balanced to low static and dynamic specifications to limit wheel vibrations affecting the payload performance, they use special vacuum-rated bearings to ensure a long life in space, and they have to survive the launcher forces and vibrations. The typical performance specifications of these small satellite wheels vary according to their momentum storage capability; see Table 8 and Fig. 22.

8.7 Integrated ADCS Modules for NanoSats

A few complete ADCS solutions are commercially available for nanosatellite missions:

(A) The MAI-500 unit from Adcole Maryland Aerospace is a 0.6 U CubeSat-sized ADCS featuring two star trackers. It has a total mass of 1049 g and size of 100 × 100 × 62.3 mm. The average power consumption during nadir pointing is 2130 mW and specifies a pointing accuracy of 0.1°. See Fig. 23 for a photo of the MAI-500 unit.

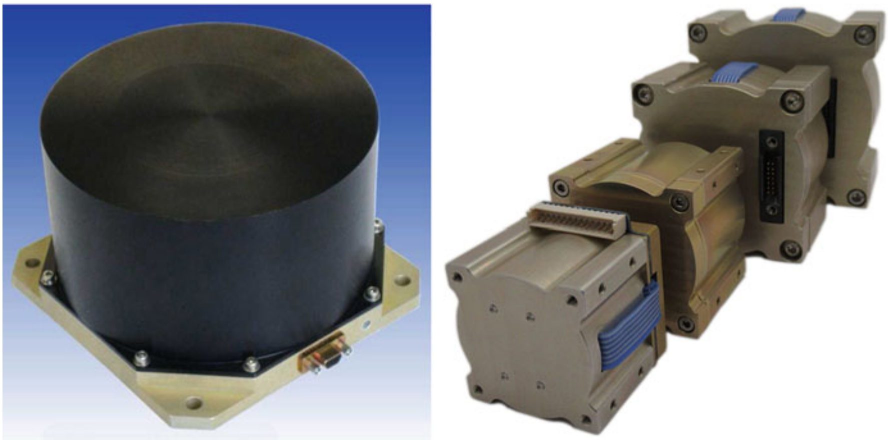


Fig. 22 Reaction/momentum wheels: Left, VRW-1 (Vectronic), and right, CubeWheels (CubeSpace)

(B) The Y-Momentum CubeADCS (CubeSpace) was originally developed for the QB50 mission. A 3-axis reaction wheel integrated ADCS bundle was since developed for higher accuracy pointing capability. These integrated ADCS units are currently flying successfully on several 2 U, 3 U, and 6 U CubeSat missions. An integrated 3-axis CubeADCS flight unit is shown in Fig. 24. It has a total mass of 554 g and size of 96 × 96 × 62 mm to fit into a 0.6 U CubeSat volume. The average power consumption is 571 mW. It is a 3-axis reaction wheel unit with nadir, sun, moon, and ground target pointing capability. It uses Y_B and Z_B magnetic torquer rods plus a X_B torquer coil, 3-axis MEMS rate sensors, coarse sun sensors, and deployable 3-axis magnetometer during low-power angular rate detumbling and safe mode control. For higher pointing ($< 0.1°$ 3-σ) and tracking performance, a CubeSense fine sun and nadir sensor and CubeStar star tracker with stellar gyro capability can be added. A space GPS receiver can also be seamlessly integrated to these units. Various state estimators including a full state and gyro-based extended Kalman filter are implemented to enable the quaternion feedback reaction wheel controllers to do autonomous attitude control.

(C) The iADCS100 (Hyperion) was initially developed to be the most compact high-performance ADCS for 1 U to 3 U CubeSats. The launching customer was the AALTO-1 satellite, launched in June 2017. The unit's layout is shown in Fig. 25. It has a total mass of 400 g, depending on the wheel momentum storage. The size of 95 × 90 × 32 mm will fit into a 0.3 U CubeSat volume. The nominal power consumption is 1400 mW. It is a three-reaction wheel unit with 3-axis target, nadir, and sun-pointing capability. It uses three magnetorquers and a built-in magnetometer for attitude detumbling and safe mode control. For ADCS sensors a ST200 star tracker, 3-axis MEMS rate sensors and plug-in sun sensors are used.

Fig. 23 MAI-500 ADCS unit for CubeSats (Adcole Maryland)

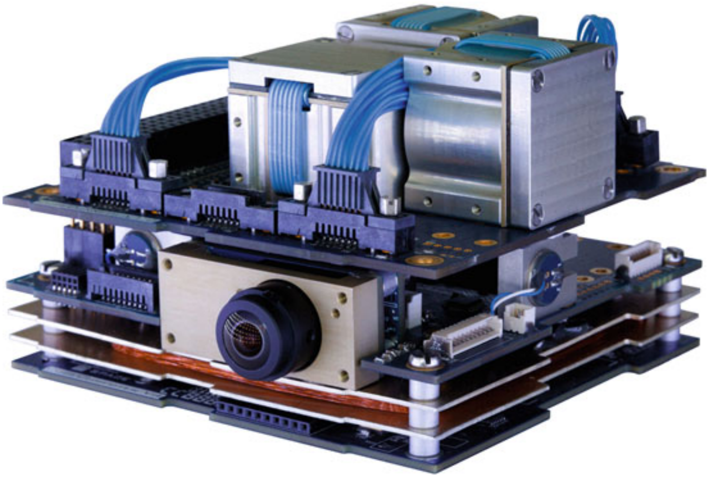


Fig. 24 CubeADCS 3-axis unit for 2 U to 6 U CubeSats (CubeSpace)

9 Future Directions

The ADCS of small satellites is constantly improving as nanotechnology and onboard processing capability enable the miniaturization of hardware and the implementation of more advanced software algorithms. As mentioned in the introduction, most nanosatellites are now launched with full 3-axis attitude control capability. The

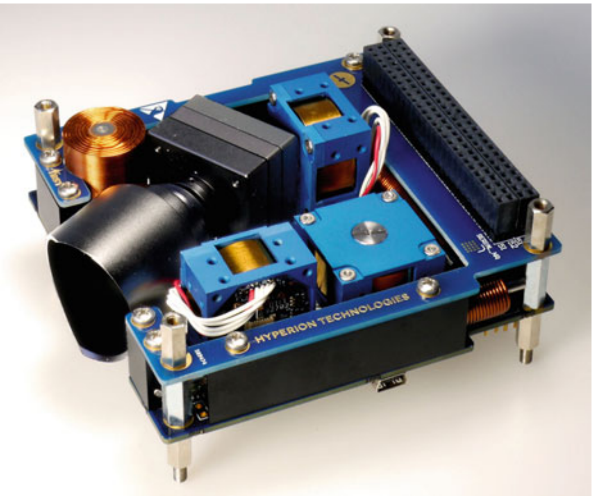


Fig. 25 iADCS100 integrated ADCS unit for 1 U to 3 U CubeSats (Hyperion)

pointing accuracy and stability of small satellites are approaching the performance previously possible only on large satellites. With the improvements in ADCS, more challenging applications, e.g., as found in space astronomy, can now be implemented on small satellites only limited by the payload mass, volume, and power requirements.

Research and improvements in small satellite propulsion systems (e.g., pulse plasma thrusters – PPTs) and accurate, agile actuators (e.g., control moment gyros – CMGs) are still required to further expand their future ADCS capability. However, missions requiring formation flying and large constellations of small satellites are becoming a current reality due to the lowering of costs and the increase in ADCS performance now possible.

10 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ RF and optical Communications for Small Satellites
- ▶ Small Satellite Antennas
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellite Radio Link Fundamentals
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites

References

Adcole Maryland, Online web site: https://www.adcolemai.com/

Bartington, Online web site: https://www.bartington.com/mag-13/

X. Chen, W.H. Steyn, Y. Hashida, *Proceedings of the AIAA GNC Conference on Ground-Target Tracking Control of Earth-Pointing Satellites,* AIAA-2000-4547, 14–17 Aug 2000, Denver Colorado, pp. 1–11

J.L. Crassidis, K.-L. Lai, R.R. Harman, Real-time attitude-independent three-Axis magnetometer calibration. AIAA J. Guid. Control Dyn. **28**(1), 115–120 (2005)

CubeSpace, Online web site: https://cubespace.co.za/

Hyperion, Online web site: https://hyperiontechnologies.nl/

G.H. Janse van Vuuren, *The Design and Simulation Analysis of an Attitude Determination and Control System for Small Earth Observation Satellites*, MEng Thesis, University of Stellenbosch, March 2015

E.J. Lefferts, F.L. Markley, M.D. Shuster, Kalman filtering for spacecraft attitude estimation. AIAA J. Guid. Control Dyn. **5**(5), 417–429 (1982)

NewSpace, Online web site: http://www.newspacesystems.com/

Northrop Grumman, Online web site: https://northropgrumman.litef.com/

Sensonor, Online web site: https://www.sensonor.com/

M.D. Shuster, S.D. Oh, Three-Axis attitude determination from vector observations. AIAA J. Guid. Control Dyn. **4**(1), 70–77 (1981)

Sodern, Online web site: http://www.sodern.com/

Solar MEMS, Online web site: http://www.solar-mems.com/

W.H. Steyn, *A Multi-Mode Attitude Determination and Control System for Small Satellites*, PhD Dissertation, University of Stellenbosch, Dec. 1995

W.H. Steyn, Y. Hashida, *In-Orbit Attitude Performance of the 3-Axis Stabilised SNAP-1 Nanosatellite, 15th Annual AIAA/USU Conference on Small Satellites*, Proceedings SSC01-V-1, Utah State University, Logan Utah, Aug 2001

W.H. Steyn, V. Lappas, Cubesat solar sail 3-axis stabilization using panel translation and magnetic torquing. Aerosp. Sci. Technol. **15**, 476–485 (2011)

A.C. Stickler, K.T. Alfriend, An elementary magnetic attitude control system, in *AIAA Mechanics and Control of Flights Conference, Anaheim California*, Aug 1974

W.T. Thomson, Spin stabilisation of attitude against gravity torque. J. Astronaut. Sci. **9**(1), 31–33 (1962)

Vectronic, Online web site: https://vectronic-aerospace.com/

B. Wie, H. Weiss, A. Arapostathis, Quaternion feedback regulator for spacecraft Eigenaxis rotations. AIAA J. Guid. Control Dyn. **12**(3), 375–380 (1989)

X. Xia, G. Sun, K. Zhang, S. Wu, T. Wang, L. Xia, S. Liu, NanoSats/CubeSats ADCS Survey, 29th CCDC Chinese Control and Decision Conference, Proceedings CCDC, Chongqing, China, 28–30 May 2017, pp. 5151–5158

Power Systems for Small Satellites

Joseph N. Pelton and Scott Madry

Contents

Abstract

The satellite power system is a vital component of all satellites and involves a number of parts. All of these parts play an important role in the success or failure of a small satellite mission. Since electrical power systems have been around since the beginning of the space age, and their function has been well established,

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

S. Madry
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_9

this part of a satellite design for this reason might be taken for granted. It also may be outside the expertise of cubesat builders with limited experience. This is a serious problem, as many telecommunications systems, on the ground or in space, often fail due to a power failure. This can be not only because the power generation or storage system fails but for other seemingly mundane factor such as a simple short in a wiring system that causes a satellite to fail due to a lack of critical power supply or even an electrical fire that destroys the entire satellite. Other sources of failure can come from as simple a problem as the leads from solar cells or photovoltaic cells failing due to contamination or oxidation that creates an overall power failure for a satellite. Experience over the years have confirmed the need to carefully design, manufacture, and test all aspects of a satellite's electrical power system in terms of safety, resilience, and lifetime performance. This important work is often overlooked or minimized in cubesat projects.

This chapter discusses all aspects of electrical power generation, an electrical power distribution system, power storage, and effective design of an electrical power system for all types of satellites that range from a femtosat (10 to 100 grams), a picosat (100 grams to 1 kg), a nanosat (from 1 kg to 10 kg) that includes cubesats, a microsat (from 10 kg to 100 kg), and a minisat (from 100 kg up to 500 kg in some definitions and from 100 to 1000 kg in others). The point is that power systems can command a good deal of the mass and volume of a satellite regardless of its size, and thus the power-to-mass ratio is important in satellites designs and especially so in the case of small satellites. Different approaches to power can thus be taken for different types of small satellites depending on their mission, lifetime requirements, and overall mass and volume. Finally, this chapter seeks to provide information developed by NASA and other objective sources about the suppliers of critical elements of an electrical power system for small satellites and especially with regard to solar power cells and power storage units.

Keywords

Assembly · integration · and test (AIT) processes · Batteries · Electrical power system (EPS) · Electrical power generation · Electrical wiring · Photovoltaic cells · Power management and distribution (PMAD) · Power storage · Power-to-mass ratio · Rechargeable secondary battery · Single and multi-junction solar cells · Single-use primary battery · Solar arrays and panels · Solar power cell · Solar cell junctions of · Spacecraft safety

1 Introduction

The overall design of a small satellite is largely driven by its power budget. This is because it is not atypical for one-third of the overall mass of a spacecraft to be related to its power supply and electrical systems. This is especially true if the spacecraft is being designed to have a sustained lifetime that lasts for a number of years. The application also drives the power requirements, and many satellites require significantly larger power systems than others. It is a mistake to look at the design of a small satellite's electrical power system as simply choosing which solar cells to select or which batteries to purchase. The equation is more complex than this. One should start with the key basics of the small satellite's mission; the smallsats intended lifetime; the orbital configuration in terms of whether it is a LEO, MEO, or GEO orbit; and other parameters. This will fundamentally drive your understanding of the mission objectives and parameters that will define what type of power system is required for your specific needs and budget.

If it is to be a telecommunications or networking mission in low Earth orbit with at least an 8-year lifetime and a particular throughput objective, then this can next allow a reasonable design process for the spacecraft. This initial set of objectives can next lead to developing a reasonable concept as to antenna design as required by the mission, as well as the power requirements, the fuel and thruster system to support the intended lifetime, etc. If it is to be a remote sensing or data analytics project, then there is a need to define basic objectives for revisit times, level of sensor resolution and types of sensors, data storage and data transmission, projected satellite lifetime, and more.

Again, these mission goals and objectives will lead to a clear system definition that can produce a better understanding of the type of satellite to be designed. This includes the power requirements needed to complete the intended mission. In short, one does not start with power requirements. Rather mission goals and resulting design features will serve to define the acceptable boundaries of the power system and clarify its various design features.

On one end of the scale, a short experimental project with a limited lifetime and minimal transmission requirements might result in a single-use primary battery that might be sufficient to provide the needed power until the battery is exhausted and solar cells or other power generation capabilities may not be needed at all. Operational missions with extended lifetimes will clearly require rechargeable batteries, on-board power generation, a process for discharging and maintenance of batteries, a monitoring function to observe the performance of batteries, solar cells, computers, and much more. The redundancy requirements must also be considered.

Overall, the mission objectives will drive the power system design. A radar satellite system that uses active sensing and thus the ability to release power from the spacecraft that can be reflected back to the space will clearly require more power and internal shielding than a passive system that simply analyzes light reflected back from the sun. Active RADAR satellites were famous in the early days of the space era for frying themselves due to the large power pulses required. Early Soviet military RADAR satellites were even powered by nuclear systems to meet these power requirements.

The key elements that designers of the mission will have to consider are (i) power generation; (ii) power storage; and (iii) overall electrical power grid and distribution requirements for the satellite payload (or payloads), as well as for the operation of the satellite bus. The power system design will tend to be different depending on the nature of the mission goals and objectives and clearly different for different types of satellites from the smallest of femtosats (or chipsats), up to the largest of minisats that might be as large as 500 kg or even 1000 kg.

Currently, a large percentage of small satellites have power generation capability and rechargeable batteries. cubesats on up tend to have such a capability. Even pocketqube systems at one-eighth the size of a 1-unit cubesat still have at least four solar cells and operate with a rechargeable battery. One chipsat or femtosat tends to have a single-use primary battery such as might be used in a wristwatch.

Thus, this discussion will start with a consideration of power generation and the predominant form that is used in most small satellites – namely, photovoltaic cells or, as they are more generally known, solar cells.

2 General Approach to the Design of a Small Satellite

There are actually several possible approaches that might be taken with regard to the design, assembly, integration, test, and launch of a small satellite project. One might be planning to design, build, and deploy a very large constellation of small satellites. In this case of an industrial applications project, one might create a vertically integrated system that creates all of the capabilities in-house and proceed to design and build perhaps hundreds or thousands of small satellites in-house. This is the case with SpaceX, Planet, and Spire, for instance. Another approach for an industrial satellite project would be to contract with an overall contractor that will obtain components, either to precise technical specifications or performance characteristic, and manufacture the small satellites for delivery for launch.

In the case of more individualized small satellite projects, one might obtain a complete kit for an entire small satellite from a vendor such as Pumpkin, or in the case of a larger and more sophisticated supplier, from some experienced entity such as Surrey Space Technology, Ltd. The other approach is to custom design and integrate all of the subsystems of a small satellite project in-house. The organization known as Innovative Solutions in Space (ISIS) operates a web-based Cubesat Shop. This is marketed as webshop for cubesats and nanosats and offers over 100 products associated with small sat projects. This website is broken down into the multiple parts or subsystems. These subsystems include antennas, attitude actuators, attitude sensors, cameras and payloads, command and data handling, communications systems, cubesat kits and buses, cubesat structures, ground stations, ground support systems, integrated attitude determination and control systems (ADCS), launch adapters, propulsion and pressurization, software services, solar panels and power systems, and training and simulators. Under these 16 categories, one can find multiple suppliers that correspond to each of these project subsystems. If one is new to the small satellite project area and wants assistance and guidance with regard to all these areas, the cubesat shop can be a useful source of information and guidance to legitimate and qualified suppliers from around the world (ISIS-cubesat Shop 2019).

3 Power Generation for Small Satellites

Although there are some small satellites that might use radioisotopes as a power source, such as planetary probes, and there are some missions that operate with a single-use non-rechargeable battery, these are only a minor exception to the general rule that most small satellites use solar cells to generate power and rechargeable batteries to store energy for the times when the spacecraft is in eclipse. The orbital parameters, including the period of solar eclipse, are vital parameters in the choice of these components.

4 Solar Cell Systems for Small Satellites

Solar cells, or photovoltaic cells, have been used to generate on-board power for satellite from the start of the space age. Consistent progress has been achieved over the decades to improve the efficiency of this technology in their ability to convert the energy from solar radiation into useful electrical power. At the start of the space age, these cells used amorphous silicon and typically had an efficiency of conversion of only about 10% to 13%. Today single P-N junction solar cells used in many solar panels for generating electrical power for homes and offices on Earth perform at comparable levels. Improved performance solar cells that use multiple junctions to capture energy at higher energy levels up to even the ultraviolet spectrum of energy are progressively more efficient, but also more expensive. A depiction of a positive-type to negative-type silicon junction that creates an electron flow is shown in Fig. 1.

The relatively higher performance of multi-junction solar cells that can capture energy at the higher energy green, blue, violet, and even ultraviolet spectra can clearly generate more electrical energy. There has been a careful study undertaken by NASA scientists to identify high-efficiency solar cells that use multi-junction photovoltaics and also solar cells that use high valence number and more efficient semiconductors using materials such as gallium arsenide, germanium, etc. to create

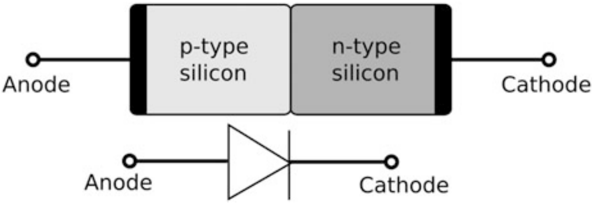


Fig. 1 Depiction of P-type/N-type silicon solar cell configuration. (Courtesy of Global Commons Raffa Maiden By Raffamaiden – BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=21285768)

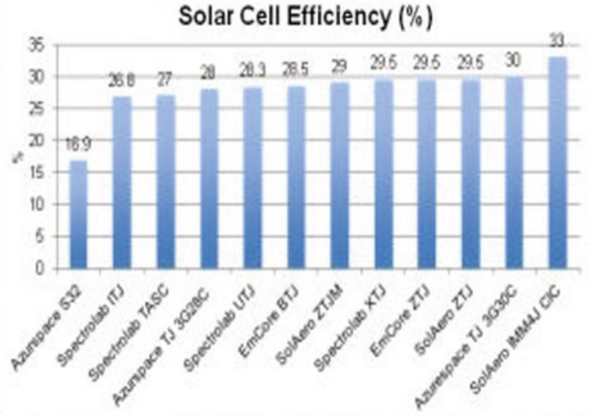


Fig. 2 A comparison of multi-junction solar cells that are possible candidates to use on small satellites. (Graphic courtesy of NASA)

performance efficiencies that are generally in the 26% to 34% levels. The results of these comparative studies are shown in Fig. 2 (NASA, State of the Art, 0.3 Power 2019).

A brief listing of different solar cell manufacturers and some of the key performance characteristics of their solar cell offerings are provided in Annex 1 at the end of this chapter (Table 1).

The convenience of solar panel designs which have been optimized for assembly integration and testing is not the only attractive feature. These panels can come with integrated magnetorquers for orientation and temperature and magnetometer sensors. In larger 3-units, additional integrated features can be integrated into the solar panel design as well. These panels can be obtained for side, top, and bottom cubesat designs. A 1-unit side panel as manufactured by DHV is pictured below. This unit is provided with wiring and connectors and is provided for around $1800 (US) and is available on order in about 4–5 weeks (Fig. 3) (DHV Technology 2019).

More demanding nanosat missions with higher electrical power system requirements can employ not only cubesat panels but deployable solar panels to increase the available electrical power supply. Deployable solar panels are more expensive and are only recommended in cases where the smallsat mission has greater energy needs to perform its intended mission. Below is a series of deployable arrays by EXA (Fig. 4).

5 Electric Power System Design and Wiring

There needs to be a systematic way to supply power to components of a small satellite with associated battery packs. This is a critical part of a small satellite design, assembly, integration, and testing process. Power failures, degraded solar cell performance, wiring disconnects, circuit breaker mishaps, switch-related problems, and other aspects of a satellite's overall power system that can fail represent a large portion of satellite failures of all types – large, medium, or small. Once in

Table 1 NASA assessed suppliers of solar panel suppliers. (Data provided by NASA)

NASA compilation of solar panel suppliers for pocketqubes (5 cm cubes) up to 12 U Cubesats				
Product	Manufacturer	Efficiency	Solar cells used	TRL status
Solar panel (0.5–12 U); deployable solar panel (1 U, 3 U)	Clyde Space	28.3%	Spectrolab UTJ	9
Solar panel (0.5–12 U); deployable solar panel (1 U, 3 U)	Clyde Space	29.5%	Spectrolab XTJ	9
Solar panel (0.5–12 U); deployable solar panel (1 U, 3 U)	Clyde Space	29.6%	Azur Space 3G30A	9
Solar panel (5 × 5 cm, 1 U, 3 U, custom)	DHV	29.6%	Azur Space 3G30C-Advanced	8
Solar panel	Endurosat	29.5%	CESI solar cells CTJ30	9
NanoPower (cubesat and custom)	GomSpace	29.6%	Azur Space 3G30A	9
HaWK	MMA	29.5–30.7%	SolAero XTJ Prime	7
eHaWK	MMA	29.5–30.7%	SolAero XTJ Prime	9
COBRA	SolAero	29.5%	SolAero ZTJ	Unknown
COBRA-1 U	SolAero	29.5%	SolAero ZTJ	Unknown
Space solar panel	Spectrolab	26.8%	SolAero ITJ	TRL 9
Space solar panel	Spectrolab	28.3%	SolAero UTJ	TRL 9
Space solar panel	Spectrolab	29.5%	SolAero XTJ	TRL 9
Space solar panel	Spectrolab	30.7%	SolAero XTJ Prime	TRL

Note: This assembled report by NASA scientists is as of the fall of 2019 and may not be complete in terms of including all possible suppliers from around the world. This chart is indicative of what international suppliers of solar arrays currently provide

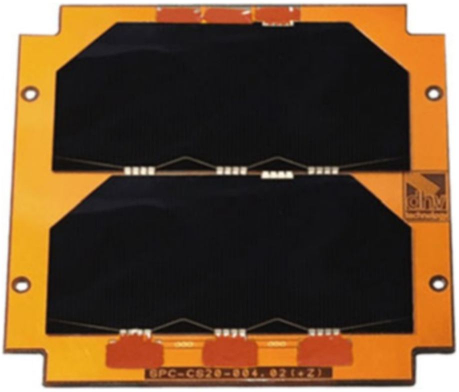
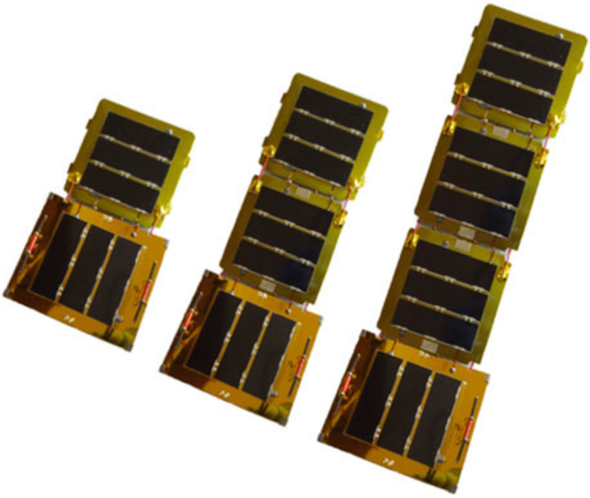


Fig. 3 DHV-CS 1-unit cubesat side panel with two solar units. (Graphic courtesy of DHV)

Fig. 4 Deployable solar array by EXA for high-power missions. (Graphic courtesy of EXA)



space, it cannot be understated that space is a hostile environment. Solar radiation and coronal mass ejections from the sun can and do lead to satellite failures by knocking out the power system. Circuit breakers and the ability to power down a satellite during a major solar storm event are something that large and more expensive satellites have as normal part of their operational routine. Small satellites should be operated with similar concern for these solar radiation and ion blast events from the sun.

One of the systems marketed via the cubesat store is the Crystalspace P1U EPS. This is a compact power supply with battery pack configured for both 1-unit and 2-unit cubesat configurations. This particular product includes a “fast maximum power point tracking boost converter.” This is able to charge integrated doubled battery pack and provide power distribution as required for cubesat configurations. Battery output in the electrical power system is fed through duplicated converters. Depending on the type of system ordered and solar array capabilities, these electrical power systems can provide voltage outputs starting at 3.3 V and up to 12 V. Pinouts and voltage outputs can be custom ordered in order to accommodate specific user needs (cubesat shop, Crystal Space 2019).

Another option is the Endurosat Electric Power System that also provides two battery packs and the following additional features: (i) three solar panel channels in order to provide a channel for each of the cubesats’ three axes and six panel connectors (typically USB connectors unless otherwise specified); (ii) input voltage (per solar panel channel) up to 5.5 V; (iii) input current (again this is for each of the three solar panel channels) up to 1.8 amperes; and (iv) a full guarantee of performance warranty and up to 5 hours of technical support (Endurosat 2019).

There are many other electrical power systems available such as the electrical power system including rechargeable battery packs from ISIS and many other suppliers that can be found on the web and those noted at the end of this chapter. It is important to work with suppliers if there are issues related to the US International Traffic in Arms Regulations (ITAR) or other similar restrictions in other countries such as the European Commission requirements. For the most part, these do not apply to the smaller-sized energy systems.

6 Assembly, Integration, and Testing (AIT)

The key elements of small satellite power systems include solar arrays or solar panels, electrical power systems with regulatory systems for power distribution that include battery packs, electrical wiring, sun sensors for maximum illumination, and magnetorques that can assist with sun orientation. The final missing ingredient is the process known as assembly, integration, and testing (AIT). It is important that well-trained personnel operating in clean rooms (or in some instances "clean enough rooms") carry out this important process. A faulty or somewhat loose wiring or USB plug connection can easily be shaken apart from a vital connection during the dynamic loads encountered during launch. Microsats or minisats for commercial systems are typically tested on shaker tables to simulate the vibrations and so-called pogo effects that can occur during rocket launch operations. After assembly is complete and the small satellite is completely integrated, careful testing is highly recommended. In the case of deployable antenna and power arrays, it is important to check out both of these deployments. Thus there needs to be a careful assessment of whether the antenna deployment and solar array deployments do not complicate or hinder either deployment process. Training of personnel to carry out all of these steps precisely and with quality checks along the way is important. In the case of large-scale small satellite constellations, many of these steps are now completely automated, but the test and assessment are still largely done by trained personnel.

7 Conclusion

The careful design and assembly, integration, and test of the electrical power system (EPS) are a key part of being able to create, launch, and operate a small satellite mission successfully. There are many elements of a satellite project, and it is easy to lose sight of an important step where there are so many parts to the puzzle. This article only addresses the design, assembly, integration, and test of the energy subsystem of a small satellite bus and its payload. It should be remembered that a successful program must also consider the ground stations and the mission control aspects of tracking, telemetry, control, and monitoring (TTC&M) of a mission. If there is a power failure in the ground segment, the mission could be lost in this way as well. Again power failures in the ground stations or the mission control are the most common types of problems that can and do occur in operational satellite systems.

The good news is that there are now many suppliers of small satellites. There are organizations such as Pumpkin and ISIS that can provide a complete cube satellite for launch and also assist with a launch services integrator that can arrange for a launch and launch registration and other administrative and regulatory arrangements from soups to nuts. Many cubesat and even smaller picosat (i.e., pocketqube) projects are training and learning exercises, and thus such projects tend to involve the design, assembly, and integration of all of the key subsystems in order to create an in-depth educational experience. It is important to consider the balance between gaining experience and education on one hand and assuring that "practical" quality assurances and mission goals are fully met on the other. Is this an educational, professional research, or business project? This is a fundamental question to be answered.

It is important to learn and understand about each and every subsystem and component that is essential to a small satellite programs' success. To recap, these elements include (i) antennas; (ii) attitude actuators; (iii) attitude sensors; (iv) cameras and payloads; (v) command and data handling; (vi) communications systems; (vii) cubesat kits and buses; (viii) cubesat structures; (ix) ground stations; (x) ground support systems and mission control; (xi) attitude determination and control systems (ADCS); (xii) launch adapters; (xiii) propulsion and pressurization; (xiv) software services; (xv) solar panels and power systems; and (xvi) training and simulators. Of all of these "parts" of a mission, a reliable, high-efficiency, and well-managed power system is well up there in terms of being a critical aspect of the mission with many single point-of-failure considerations and vulnerabilities.

8 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Antennas
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellite Radio Link Fundamentals
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

Annex 1

Photovoltaic Cell and Solar Array Suppliers

There are a growing number of global suppliers of solar cells and complete solar arrays that include the solar cells with the integrated struts for ready deployment in space. Some manufactures such as Spectrolab can provide either individual solar cells or the fully integrated solar array. Research projects around the world are seeking to drive efficiency up about the current highest levels of around 45%. These research activities are exploring new high valence substrate and absorber materials, spectrum matching techniques, as well as lower-cost fabrication and new production techniques such as the IMM cell that uses metamorphic multi-junction manufacturing techniques. The following listing of multi-junction solar cell and solar array manufacturers is indicative of some of the well-known and tested suppliers.

Representative Photovoltaic Cell Manufacturers

Azur Space

This is a supplier of multi-junction solar cells that are typically triple-junction in design. These cells use a combination of gallium arsenide, germallium, and GaInP materials, and they achieve an efficiency of solar radiation to electrical energy output in the range of 28% to 30%.

Bharat Electronics Ltd. of India

Bharat Photovoltaics has developed its manufacturing capabilities in cooperation with the Indian Space Research Organization (ISRO). ISRO has licensed solar cell and solar panel technology from other suppliers in the USA and other countries and then partnered with Bharat Electronics Ltd. to create a lower-cost supply to the Indian market. Bharat can supply both solar cells and solar panels. These products include monocrystalline, polycrystalline, and thin-film solar cells. It also provides inverters, mounting systems, solar cables, as well as complete photovoltaic systems, terrestrial power systems, as well as satellite applications.

CESI/ENE

The CESI single-junction gallium arsenide solar cells that are deposited on a germanium wafer by ENE are thicker than some three-junction solar cells, but this lower-cost photovoltaic cell can provide a 20% efficiency under the AMO spectrum rating system. This type of cell has been used by the Surrey Space Technology Ltd for small satellite manufacture. Triple-junction solar cells with efficiencies around 27% are also available from these Italian and Belgium teams.

Emcore Corporation

Emcore also manufactures triple-junction solar cells in two different versions. The efficiency of solar energy conversion for these solar cells is typically in the range of

28.5% to 29.5%. Emcore cells are provided in standard sizes but can be provided to custom order in different sizes as well. NASA has used these cells on their own missions.

SolAero Technologies

SolAero Technologies is unique in that it is a collaborative effort with the US Air Force. SolAero Technologies and the USAF are currently developing a new type of cell known as the "metamorphic multi-junction (IMM)" solar cell. This special manufacturing technique has resulted in a lightweight and higher-efficiency cell that is in developmental testing. Current SolAero cell have an efficiency level in the 28% to 30% range. They offer at least four optional solar cell products with ZTJ cell having had extensive in-flight experience. The ATJ, ATJM, and BJT cells are particularly offered to support small spacecraft missions.

Spectrolab

This company has been one of the oldest and most comprehensive providers of solar cells as well as integrated solar arrays. There solar cells range in efficiency from 26% to 30%. The most common products by Spectrolab are the XJT Prime, XTJ, and UTJ solar cells. They are offered in standard and customized sizes. All of the Spectrolab's solar cells are also of the triple-junction design. The UTJ devices are rated at TRL 9 spacecraft applications.

Umicore

Umicore is another provider of triple-junction solar cells. It has been providing high-quality solar cells since the 1990s. Its solar cells with triple N-P junctions or bandgaps for its solar cells consist of indium gallium phosphide (InGaP), indium gallium arsenide (InGaAs), and germanium (GE) layer. These cells are made using a metal-organic chemical vapor deposition (MOCVD) process whereby the InGaP and InGaAs are deposited on germanium wafers. These solar cells have been demonstrated above 30% efficiencies under the AMO spectrum rating system.

Solar Panels and Array Manufacturers

Many of the companies that produce solar or photovoltaic cells also produce solar panels and arrays. In some instances, these panels also include magnetorquers, sun sensors, temperature sensors, and other features. Here are some of the typical providers of high-quality solar arrays from around the world. This is not an exhaustive list, but it includes many of the leading suppliers.

AAC Microtec and Clyde Space

The AAC Clyde Space photon solar arrays and solar panels are optimized to provide power to cubesat and multiple units of cubesats. These systems are designed to provide a high level of power generating efficiency by providing panels that can be position on the long sides of cubesats. If additional power is required, it is possible to have deployed, extendable solar arrays. These panels and arrays are designed to provide convenience in achieving reliable platform integration. Spectrolab XTJ Prime solar cells are typically included on AAC Clyde solar panels and arrays (AAC Clyde Space 2019).

Bharat Electronics Ltd.

See as noted in above information.

DHV Technology

DHV is one of the leading providers of solar panels and arrays. Its website maintains that it has participated in over 50 projects, that 35 satellites are currently utilizing its arrays and panels, and that this adds to some 1700 days of successful operation in space.

Endurosat

Endurosat makes several versions of solar panels. These are of a triple-junction indium gallium phosphide/gallium arsenide/germanium design and the solar cells used in these panels rated to 29.8% efficiency. The panels are of the 1-unit and 3-unit design, and their respective masses are 0.04 kg and 0.155 kg, and this includes a magnetorquer in the configuration. Maximum cell voltages are 2.33 V per cell (Endurosat, Solar Panels 2019).

EXA

The EXA DSA/1A (Titanium Deployable Solar Array for 1 U) is the entry-level product of a family of deployable solar arrays based on artificial muscles for cubesats in the range of 1 U to 6 U. The arrays are composed of five panels, 3 on top and 2 on the bottom, that are attached to the cubesat structure. Available on request are deploy and release contact sensors and also custom options such as sun and temperature sensors. Seven panel configurations are available for very high power missions.

GomSpace

GomSpace, which can undertake complete small satellites, is able to provide two different power systems for cubesats. These both use 30% efficient cells. These units are designed to include a magnetorquer, sun sensors, and gyroscopes. The customizable panels have a maximum output of 6.2 W and 7.1 W, respectively. Cubesat panels can be ordered with an integrated magnetorquer with only a slight mass addition. The 1-unit cubesat panel produces 2.3–2.4 W.

Innovative Solutions in Space (ISIS)

MMA Design, LLC

MMA's latest solar panel design is known as the rHaWK. It seeks to provide for high kW/m^3 solar electrical power production plus longer life, a high level reliability, through new manufacturing techniques significantly lower mass and volume. At the beginning of life, the MMA rectangular rHaWK solar panel can normally produce up to 90 kW/m^3 and at 28 °C over 150 W/kg. The efficiency rating for the solar cells used in the array is currently based on a configuration of the array at 29.5%. The lower-cost ZTJ cells produce 80 kW/m^3 and 130 W/kg at the beginning of life. MMA arrays have been used by both the US Air Force and NASA (MMA Design LLC 2019).

NanoAvionics

The solar panels provided by NanoAvionics are designed for 1-unit to 3-unit cube satellites. This array uses an epitaxial structure. These cells use a combination of gallium indium phosphide, gallium indium arsenide, and germanium for its structural makeup. Its solar panel efficiency is rated to be very close to 29%.

SolAero Technologies Corp

See as noted in above information.

Spectrolab

See as noted in above information.

Cross-References

▶ Small Satellite Radio Link Fundamentals

References

AAC Clyde Space, Photon Solar Panels. https://www.aac-clyde.space/assets/000/000/078/PHOTON_original.pdf?1564954830. Last accessed 15 Dec 2019

Cubesat shop, Crystal Space, 2019 PI U “Vasik”. https://www.cubesatshop.com/product/crystalspace-p1u-vasik/. Last accessed 14 Dec 2019

DHV Technology. http://dhvtechnology.com/. Last accessed 14 Dec 2019

Endurosat, Electrical Power System Data Sheet. https://www.endurosat.com/modules-datasheets/EPS_Datasheet_Rev1.pdf. Last accessed 15 Dec 2019

Endurosat, Solar Panels. https://www.endurosat.com/modules-datasheets/Solar_Panel.pdf. Last accessed 15 Dec 2019)

Global Commons Raffa Maiden By Raffamaiden – BY-SA 3.0. https://commons.wikimedia.org/w/index.php?curid=21285768. Last accessed 20 Dec 2019

ISIS, Cubesat shop. https://www.cubesatshop.com/. Last accessed 13 Dec 2019

MMA Design LLC, rHawk Solar Panels. https://mmadesignllc.com/product/r-hawk-solar-array/. Last accessed 15 Dec 2019

NASA, State of the Art of Small Spacecraft Technology, 03. Power. https://sst-soa.arc.nasa.gov/03-power. Last accessed 14 Dec 2019

Small Satellite Antennas

Kiruthika Devaraj

Contents

Abstract

Antennas are an integral part of the satellite radio communication and navigation system that enables the transmission and reception of electromagnetic energy through free space. The small satellite size, volume, thermal, and material constraints pose a special challenge to the antenna system, and the antenna design is as much a challenge for radio engineering as it is for mechanical/structural engineering. Many new techniques including novel packaging solutions, deployment structures, 3D printing, and advances in the commercial printed circuit board technology have helped to tremendously reduce the volume and mass of antenna structures so they can be integrated on small satellites. Over the last decade, many novel and compact antenna solutions have been developed for small satellites that have enabled the small satellite radio communication systems to compete with much larger class satellites. This chapter presents an overview of the antennas that are most commonly used on small satellites and presents some recent examples of commercial small satellite antennas.

K. Devaraj (✉)
Planet Labs Inc., San Francisco, CA, USA
e-mail: Kiruthika.Devaraj@planet.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_10

Keywords

Gain · Beamwidth · Bandwidth · Cross polarization · Axial ratio · Omnidirectional · Isoflux · Tracking · Telemetry · Command (TTC) · Monopole · Dipole · Patch · Helical · Reflectarray

1 Introduction

Over the last 20 years, mission enabling technologies such as radio systems and antennas have become mainstream, and there has been a surge of activity in various types of small satellite missions – including Earth Observation satellites (such as Planet Labs Inc., Spire, Iceye, Capella Space), communication satellites (such as Starlink, Oneweb, Kepler communication, Lynk), and Internet of Things (IoT) satellites (such as Myriota, Astrocast, Fleet Space, Eutelsat, Swarm Technologies). The capabilities and performance of some of these small satellite communication systems are on par with larger form factor satellites.

Recent advances in 3D printing/additive manufacturing, material science, and commercial printed circuit technology have yielded a number of compact and highly performing antenna solutions that enable these newer classes of missions from a very small form factor platform. Some of these small satellite antennas have flown on over 300 satellites and established contact reliability on Planet's Dove satellites (https://www.planet.com/pulse/planet-openlst-radio-solution-for-cubesats/). Some other antennas have demonstrated impressively high gain, such as JPL's ISARA reflectarray with 33 dBi gain (Hodges et al. 2018). One of these antennas has even made it to deep space orbiting Mars and relaying data back to Earth on the MarCO satellite (Hodges et al. 2017).

1.1 Antenna Requirements

The requirements posed on the antenna subsystem can be split into internal performance requirements and external system requirements.

1.1.1 Performance Requirements

Frequency of Operation

Frequency of operation is set domestically in the USA by Federal Trade Commission (FCC) and internationally by the International Telecommunication Union (ITU) regulations.

Bandwidth.

Antennas need to maintain their performance (gain, beamwidth, and axial ratio) over a specific bandwidth. The actual use case will dictate whether a wideband or narrowband antenna is used. For instance, Tracking, Telemetry, and Command (TTC) radios traditionally are low data rate. Because of this, a narrowband antenna such as a dipole or patch antenna with ~1–3% fractional bandwidth is adequate. The payload radio, however, typically needs a high data rate. Depending on the fractional bandwidth requirements, which may be higher than 10%, broadband antennas such as deployable reflectors, horn antennas, or helical antennas are used.

Polarization

Radio waves passing through the Earth's ionosphere are subjected to Faraday rotation effects where the left and right hand circularly polarized waves propagate at slightly different speeds. Since a linear polarized wave is made up of two equal-amplitude left and right circular polarized components, a relative phase shift is introduced which ends up rotating the orientation of linear polarization. This effect is proportional to the square of the wavelength. While this effect is pronounced with very-high-frequency (VHF) and ultra-high-frequency (UHF) bands, it rapidly diminishes at higher frequencies such as X-band and above. Second, if a linear polarized antenna were to be used on a satellite, the satellite antenna orientation would need to constantly be maintained with respect to the ground antenna orientation during a ground station pass. This would add additional complications to the pointing and tracking requirements of the satellite.

To avoid the complications that linear polarized antennas pose, most satellites use left or right hand circular polarized antennas. These circularly polarized antennas need good cross polarization (cross-pol) discrimination between the two polarizations. Cross-pol is nominally specified as the Axial Ratio (AR) – which is the ratio between the semi-major and semi-minor axis of the polarization ellipse. A rule of thumb is for a single transmit system to have cross-pol levels of about 15 dBc (AR ~3 dB). Some special dual polarization transmit/receive systems that need a high signal to noise ratio for high order modulation (like 32APSK or higher) will need very high cross-pol discrimination of 25 dBc (AR ~ 1 dB), which helps improve the signal to noise ratio.

Efficiency

Satellite antennas require high efficiency so as to optimally utilize the radiation aperture. This requires, depending on the type of the antenna, a combination of the following:

- Low loss tangent materials
- Low surface roughness
- Low loss feed networks
- Optimal taper
- High cross polarization isolation
- Low spillover

Beamwidth and Gain

The mission system needs imposed on the antenna subsystem affect whether a broad beamwidth antenna with low gain, or high gain antenna with narrow beamwidth, is chosen. TTC antennas need wide coverage, so low/medium gain antennas such as dipoles or monopoles, and sometimes patch antennas are used. Payload antennas need high gain, so narrow beamwidth is acceptable since the satellite is either mechanically or electronically steering and continuously pointing and tracking the ground station during a pass.

1.1.2 External System Requirements

Some external requirements are imposed by the fact that these antennas are integrated on a small satellite platform. They also need to survive launch, operate in a space environment, and operate with other subsystems. These subsystems include:

High Reliability and Robustness

- The antennas need to survive the shock and vibrations of the launch environment.
- The antenna deployment mechanism, if any, should work with very high reliability since deployment failure could mean the end of a mission.
- Space poses extreme thermal and vacuum challenges and the antenna performance should not degrade under vacuum conditions or repeated extreme thermal cycling.
- The antenna should withstand space environmental effects including surface erosion from ultraviolet radiation and atomic oxygen, surface charging from space plasma, and structural damage from micrometeoroids. Active antennas should also withstand total ionizing dose and single event upsets from radiation.

Low SWaP (Size, Weight, and Power)

- Size: Small satellites have a very small volume available, so antennas are typically small form factor or need to be packaged in a small volume and deployed on orbit.
- Weight: Along with size, mass is also a limiting factor on small satellites because launch costs are constrained by mass and volume. Using light weight material is key to reducing total antenna mass.
- Power: For small satellite antennas, power is another constraint and certain steps could be taken to reduce total power consumption. For instance, a high efficiency power amplifier could be placed very close to the antenna or integrated into the antenna feed structure so as to avoid long cables and associated losses. The RF power could be reduced and a higher gain antenna could be used or vice-versa so that the effective isotropic radiated power (EIRP) stays constant.

Location Constraints

- Physical location: Antennas need to be physically located on the body of the satellite such that they are optimally utilized. For instance, on a low-Earth orbit (LEO) satellite, the GPS antenna should be mounted on the zenith facing side and the payload antenna should be mounted on the nadir facing side.
- Radiation surface: Depending on the frequency of operation, the entire satellite could become a radiator or ground plane, so antenna analysis and measurements should be done on the integrated spacecraft structure.

Other Constraints

- Multipaction: Under vacuum conditions, an electron avalanche effect called multipaction (multiple + impact) can occur, leading to intermittent disruption in communication subsystems and added noise. This occurs primarily in resonant structures such as cavity filters due to very high voltages of hundreds of thousands of volts in those structures. However, at RF frequencies, depending on the geometry of the structure and frequency of operation, this effect can occur at power levels as low as 5 W.
- EMI: In small satellites, electromagnetic interference (EMI) and self-interference issues need to be considered to ensure that one transmit antenna does not interfere with a sensitive receive system.

1.1.3 Feed Network

The feed network is an integral part of the antenna design, especially for high gain antennas that use antenna arrays. The feed network ensures that the electromagnetic signal is directed to and from the antenna with low attenuation and low phase mismatch. An ideal antenna design will incorporate broadband feed networks so that bandwidth is limited by antenna radiation patterns or gain variations and not by the resonant behavior of feed network. Several impedance matching and bandwidth enhancement techniques are available to enhance the fractional bandwidth of the feed network, which is limited theoretically by Fano's broadband matching theory (Fano 1948). Appropriate phase matching of the feed elements is also required to ensure the antenna meets the cross polarization requirements. For example, aperture coupling for patch antennas improves the bandwidth. For antenna arrays, quadrature hybrids and wilkinson power dividers provide phase matching as well as improved bandwidth.

When an antenna is chosen for a specific mission, its feed network should also be considered, such that the combined antenna/feed network pair maximizes the radiation efficiency and meets all the other performance and external requirements provided above. For instance, a large passive patch array might be less efficient compared to a passive reflect array if the dielectric transmission line losses dominate compared to reflectarray aperture losses. A reflectarray may be less efficient compared to a waveguide slot array, especially at high frequencies such as Ka-band, since the effects of feed positional or angular misalignments are more pronounced at higher frequencies. Some antenna arrays, such as radar antennas, may require specific amplitude and phase weighting to the individual elements so a very specific beam tapering or side lobe level can be achieved.

1.2 Antenna Types

A typical small satellite requires multiple antennas including Tracking, Telemetry, and Command (TTC) antennas, payload antennas, and Global Navigation Satellite System (GNSS) antennas. Additional antennas may be needed for certain missions like radar antenna for radar missions or antennas for intersatellite links. Each of these

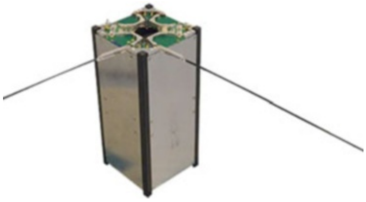
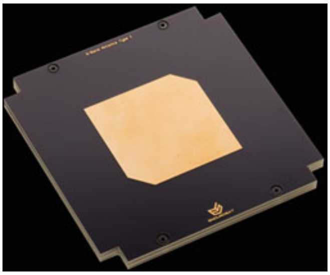
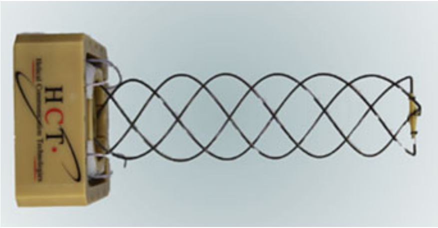
 Figure 1a: Monopole antenna. Graphics courtesy of ISIS.	ISIS Monopole Antenna [5] Four monopole tape spring antennas with a phasing network tying the antennas together in a monopole configuration ● Operating frequency: VHF or UHF ● Beamwidth: Omnidirectional ● Polarization: Linear ● Gain: 0 dBi
 Figure 1b: UHF turnstile antenna. Graphics courtesy of GOMSpace.	GOMSpace Turnstile UHF Antenna [6] The turnstile antenna consists of four monopole antennas combined in a phasing network. ● Operating frequency: 435 +- 5 MHz ● Beamwidth: Omnidirectional ● Polarization: Circular ● Gain: 1.5 dBi to -1 dBi
 Figure 1c: Patch antenna. Graphics courtesy of Endurosat.	Endurosat Patch Antenna [7] S-band medium gain patch antenna with good cross polarization ● Operating frequency: 2400-2450 MHz ● Half power beamwidth: 71 degrees ● Polarization: Left hand circular ● Gain: 8.3 dBi
 Figure 1d: Deployable helical antenna. Graphics courtesy of Helical communication technologies.	HCT Helical Antenna [8] Deployable quadrifilar helical antenna occuputing 5 cm x 5 cm x 10 cm volume ● Operating frequency: 450 MHz, 1.3 GHz or 2.3 GHz ● Half power beamwidth: Can be configured to be isoflux, hemispherical or narrow beamwidth ● Polarization: Right or left hand circular ● Gain: 3 dBi

Fig. 1 Four types of small satellites used on commercial satellites for the TTC systems

antennas has very different sets of requirements from each other. The TTC antennas are typically omnidirectional so that communication can be established with the satellite at all satellite attitudes or pointing modes. The GNSS antennas are typically hemispherical beams that allow for maximizing the number of available GNSS satellites. The payload antennas by contrast are narrow beam antennas with very high gain.

1.2.1 TTC Antennas

TTC radios and antennas need to possess very high reliability since their malfunction could mean the end of a mission. TTC antennas are typically omnidirectional so communication can be established with a satellite under all attitudes or pointing modes. If a single antenna cannot provide near spherical beam coverage, multiple spatially separated antennas are combined or switched to provide an omnidirectional pattern. The TTC frequency bands include VHF, UHF, S, X, Ku, and Ka bands. The data rates of a TTC radio are very low and bandwidth or cross-polarization requirements are not very demanding. At VHF and UHF bands, monopole and dipole antennas are typically used. At S, X, Ku, and Ka bands, patch, helical, horn antennas are used for TTC. Some examples of commercial TTC antennas used on small satellites are given in Fig. 1.

1.2.2 GNSS Antennas

GNSS antennas typically have hemispherical beam patterns. On LEO cubesats, GNSS antennas are mounted on the zenith facing direction so as to maximize the number of GNSS satellites in view of the antennas. Many small satellites have two GNSS antennas (which are most typically GPS antennas). They are often mounted

 Figure 2a: Dual band GPS antenna. Graphics courtesy of Taoglass.	Taoglass GPS Antenna [9] Dual band single feed stacked patch based GPS antenna covering GPS L1+L2 bands • Operating frequency: 1575 MHz (L1) and 1227 MHz (L2) • Beamwidth: Hemispherical • Polarization: Right hand circular with axial Ratio 1.69 dB (L1) and 2.70 dB (L2) • Gain: 5 dBi (L1), 3 dBi (L2)
 Figure 2b: Multiband GNSS antenna. Graphics courtesy of Maxtenna.	Maxtenna GPS/GLONASS Antenna [10] Multiple band Iridium/GPS/GLONASS passive embedded antenna • Operating frequency: 1616-1626 MHz (Iridium), 1575 MHz (GPS) 1602 MHz (GLONASS) • Beamwidth: Hemispherical • Polarization: Right hand circular • Gain: 2.8 dBic (Iridium), -3 dBic (GPS), 0 dBic (GLONASS)

Fig. 2 Two types of GPS antennas used for position determination

on opposite sides of the spacecraft, to get positional and timing knowledge under all spacecraft attitudes. Recently, commercial multiple-band GNSS antennas have been made readily available and provide improved positioning accuracy as well as redundancy in frequency. Two examples of GNSS antennas used on small satellites are provided in Fig. 2.

1.2.3 Payload Antennas

High gain antennas have a narrow beamwidth and require accurate pointing. When tight pointing requirements cannot be met, like with cubesats, a medium gain antenna with ~10–12 dB gain is used for downlinking payload data and high rate telemetry. Some medium gain antennas have an isoflux pattern to compensate for

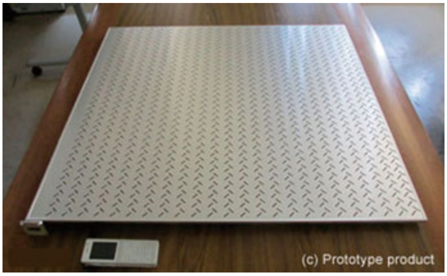
 Figure 3a: 4x4 patch array antenna. Graphics courtesy of Endurosat.	Endurosat Patch Array [11] • Operating Frequency: 8.025-8.4 GHz • Half power beamwidth: 18 deg • Polarization: Right hand circular • Gain: 16 dBi
 Figure 3b: Lens corrected horn antenna. Graphics courtesy of Sage millimeter.	Sage Millimeter Horn [12] K-band low loss lens mounted on a horn antenna to provide high aperture efficiency and low sidelobe levels • Operating Frequency: 25-27 GHz • Half power beamwidth: ~5 deg • Polarization: Linear or circular • Gain: 30 dBi
 (c) Prototype product Figure 3c: Slot array antenna designed for a SAR payload. Graphics courtesy of JAXA [13]	Slot Array Antenna [13] X-band compact, passive, low-mass honeycomb panel antenna with slot array fed with non-contacting choke flanges at deployable hinges • Operating Frequency: 9.5-9.8 GHz • Polarization: Linear • Gain: 36.6 dBi

Fig. 3 (continued)

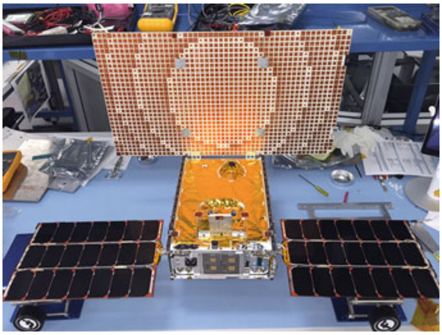
 Figure 3d: Reflectarray that flew on the MarCO mission to Mars. Graphics courtesy of NASA JPL.	MarCo Reflectarray Antenna [3] Ka band folded, three panel reflectarray antenna fed with a microstrip patch antenna, which consumes ~4 percent of the usable spacecraft payload volume with a mass of <1 kg ● Operating Frequency: 8.4 GHz ● Polarization: Right hand circular ● Gain: 29 dBi
 Figure 3e: Membrane reflectarray. Graphics courtesy of DARPA/MMA Design.	DARPA's Radio Frequency Risk Reduction Deployment Demonstration (R3D2) [14] A membrane reflectarray that deploys to 2.25 m in diameter, built by MMA design [15] ● Operational frequency: UHF-Ka band ● Fractional bandwidth: 5-10 percent ● Antenna aperture: 2.25 m diameter ● Aperture efficiency: ~50% ● Polarization: Circular
 Figure 3f: Reflectarray that flew on the Raincube satellite. Graphics courtesy of NASA JPL.	Raincube deployable mesh cassegrain reflector antenna [16] ● Operating Frequency: 35.75 GHz ● Antenna aperture: 0.5 m diameter ● Aperture efficiency: > 50 percent ● Polarization: Right hand circular ● Gain: 42.6 dBi
 Figure 3g: Planar patch array that flew on Iceye X1 satellite. Graphics courtesy of Iceye.	Iceye's Radar Antenna [17] Iceye's radar antenna array deploys to 3.25 m in length and operates at X-band.

Fig. 3 Seven types of antennas used for payload-related services on small satellites

slant range variations. NASA satellites Aqua, Terra, and Aura have isoflux payload antennas. On satellites that have very high data rate and bandwidth needs, it is necessary to use high gain, narrow beamwidth antennas as payload antennas. Whereas big satellites have been historically using large parabolic dish antennas, Fig. 3 provides recent examples of very compact, high gain payload antennas that have flown recently on small satellites.

2 Summary

Any small satellite antenna design should first and foremost start with the mission and satellite requirements. The system link budgets need to be appropriately allocated between the RF power amplifiers, satellite antenna, and the ground station. The satellite attitude control system, timing precision, and ground station tracking systems need to be designed appropriately to meet the pointing and tracking of the antenna beam. Once the antenna design requirements like frequency, bandwidth, gain, beamwidth, cross polarization, and sidelobe levels are established for the mission, an appropriate antenna type is chosen in collaboration with mechanical, structural, and reliability teams. Appropriate electromagnetic solvers such as ANSYS high frequency structure simulator (HFSS), Keysight Advanced Design Systems (ADS), TICRA GRASP, or CST should be used to simulate the antenna performance as a standalone unit and integrate on the satellite structure. The feed network needs to be co-designed with antenna to ensure appropriate impedance and phase matching to the antenna's elements. During fabrication, a good understanding of the material properties and the implications of manufacturing tolerances, stackup issues, and alignment errors will reduce mistakes and the need for multiple manufacturing iterations of the design. Some of these issues such as dielectric tolerances and surface roughness can be simulated a priori, and their effects can be understood before manufacturing begins. After fabrication, antenna characterization is done by measuring return loss with a vector network analyzer, while the antenna beam pattern is measured with a far-or near-field chamber. Gain, cross-polarization, and side lobes should also be measured for the antenna as a stand-alone unit, and after integration on a satellite. For deployable antennas, multiple deployment tests should be conducted and any variations in antenna performance should be measured. If there are large variations during the multiple deployment test, mechanical design tolerances should be revisited. Finally, the satellite should be operated under different operational modes by turning on various subsystems there no longer have EMI implications for the radio.

In conclusion, a broad overview of small satellite antenna design guidelines and recommendations are provided in this chapter, along with some recent examples of small satellite antennas that have flown on recent missions. Small satellite antennas represent both a strong mechanical and structural engineering challenge as well an electromagnetic engineering challenge.

3 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Radio Link Fundamentals
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

References

Endurosat S-band patch antenna, https://www.endurosat.com/cubesat-store/all-cubesat-modules/s-band-patch-antenna/, Nov 2019

Endurosat X-band patch array antenna, https://www.endurosat.com/cubesat-store/all-cubesat-modules/x-band-4x4-patch-array/, Nov 2019

R.M. Fano, Theoretical limitations of the broadband matching of arbitrary impedances, *R.L.E. Technical Report No. 41*, January 2, 1948

GOMSpace turnstile UHF antenna, https://gomspace.com/shop/subsystems/communication-systems/nanocom-ant430.aspx, Nov 2019

HCT deployable quadrifilar helical antenna, https://www.helicomtech.com/helios-deployable-antenna, Nov 2019

R.E. Hodges et al., A deployable high-gain antenna bound for Mars: developing a new folded-panel reflect array for the first CubeSat mission to Mars. IEEE Antennas Propag. Mag. **59**(2), 39–49 (2017)

R.E. Hodges et al., The ISARA mission – flight demonstration of a high gain Ka-Band antenna for 100 Mbps telecom. Proceedings of the 32nd annual AIAA/USU conference on small satellites, August 2018

ISIS monopole antenna, https://www.isispace.nl/product/monopole-antenna-system/, Nov 2019

P.K. Kelly, A scalable deployable high gain antenna–DaHGR, in *Proceedings of the 30th Annual AIAA/USU Conference. Small Satellites (SSC)*, Logan, UT, USA, August 2014

Maxtenna GPS antenna, https://www.maxtena.com/products/f-gps/m1600hct-p-ufl/, Nov 2019

E. Peral et al., RainCube, a Ka-band precipitation radar in a 6U CubeSat, in *Proceedings of the 31st Annual AIAA/USU Conference Small Satellites (SSC)*, Logan, UT, USA, August 2017

Sage millimeter lens corrected horn antenna, https://www.sagemillimeter.com/content/datasheets/SAL-2532732607-KM-S1.pdf, Nov 2019

H. Saito et al., Compact X-band synthetic aperture radar for 100 kg class satellite. IEICE Trans. Commun. **E100.B**, 1653–1660 (2017)

TaoGlass dual band GPS antenna, https://www.taoglas.com/product/36367mm-gpsf-36-gps-l1l2-single-feed-stacked-patch-passive-antenna/, Nov 2019

Small Satellite Radio Link Fundamentals

Matt Ligon

Contents

Abstract

Small satellite radio systems often face link power budget, mass and volume constraints and restrictions. Additionally many small satellite systems are developed by student groups or start-ups with limited development resources. These challenges can be addressed utilizing commercial off the self (COTS) industrial solutions. Practical implementation of satellite links utilizing basic link theory and industrial standards and products is discussed.

M. Ligon (✉)
Planet Labs Inc., San Francisco, CA, USA
e-mail: matt.ligon@planet.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_104

Keywords

Quadrature phase shift keying (QPSK) · Amplitude phase shift keying (APSK) · Encoding · Frequency shift keying (FSK) · Spread spectrum · Digital Video Broadcast-S2 (DVB-S2) · Shannon limit · Modulation · Encoding · Signal power · Signal-to-noise ratio

1 Introduction

The subject of the theory and design of satellite data links is covered rigorously in many texts, papers, and university courses. However, most of the available reference material often burdens the reader with excessive complexity and information that may not be necessary for a practicing engineer to plan and implement a working small satellite communication system. This text intends to sacrifice rigor for clarity.

A thorough study of the subject of radio communications is a big undertaking for the novice. What is provided here is a *minimally complex* and focused discussion on the *key concepts* needed for a student or practicing engineer to understand the full picture of a satellite link at the system level. This chapter outlines the basic theory followed by practical examples of radio hardware and systems. This primer will hopefully provide a solid foundation with which the reader can continue their research into more specific areas of interest.

1.1 Intended Audience

1.1.1 Students

Radio and communication system theory draws on many academic domains. Depending on academic focus, students will specialize in a specific domains like RF engineering, digital signal processing, digital communication, electromagnetics, network design, etc. This chapter aims to aid students in their understanding of the satellite communication system as a whole and provide the broad context and to work with a large-complex system. Demonstration of mastery of these general concepts will be very helpful for a student applying for an internship or entry level position.

1.1.2 System Engineers

Satellite system engineers may not have the specific radio communications domain knowledge to effectively understand communication system design trade-offs and effectively communicate with the domain experts they work with. Mastery of the concepts presented in this primer will be beneficial to those who need to achieve competency in the multiple domains of satellite system design.

1.1.3 Engineers Working on Specific Subsystems of Radio Communication Systems

Engineers working on communication systems often have a limited scope of their work. For example, engineers may develop expertise in antennas or power amplifiers or baseband processing, and this document provides the larger context to the system as a whole.

1.1.4 Start-up Founders

Satellite hardware start-ups whose founders who did not personally have practical communication system understanding will benefit from this chapter and have a working background to be able to perform basic system feasibility studies and be more effective in their hiring process.

2 RF Link Basics

A concise review of basic RF link theory is presented here. In a later section, practical hardware options will be introduced and discussed. The purpose of this text is to provide a high-level view of the satellite link design process. A solid grasp of the “big picture” is very helpful for initial feasibility analysis and early planning.

When approaching the problem of implementing a practical system for data transmission over an RF link, *three fundamental questions* need to be considered:

1. How much “signal power” enters the receiver?
2. How much “noise power” enters the receiver?
3. What level of throughput can be achieved given the ratio of 1 and 2 *(known as signal-to-noise ratio or SNR)*?

2.1 Signal Power

> *Antennas and their design are addressed in this section. This can be a complex subject but for the purposes of discussion all that needs to be understood is that an antenna is a device that transfers “guided” RF energy (energy traveling in a waveguide or coaxial cable) into “free space” radiation or vice versa.*

The determination of how much signal power enters a receiver over a free space link is a *simple geometry problem*.

2.1.1 Transmitting with an Isotropic Radiator

First consider a conceptual (but not actually realizable) antenna known as an “isotropic radiator.” Such an antenna when fed some input transmit power P_T will produce a spherical wave front at distance R with P_T spread evenly across the surface of the sphere.

The surface area of a sphere is given by

$$A = 4\pi R^2 \left(\mathrm{m}^2\right)$$

The "power density" at some distance "R" is thus

$$\frac{P_T}{4\pi R^2} \left(\mathrm{W/m}^2\right)$$

Transmit Antenna

In reality it is impossible for a radiator to produce radiation that is equal power in all directions if such a property was desired. Also, it is often desired to focus the energy such that the power density in some direction is much higher than that of the *isotropic radiator.*

The ratio of the power density produced by an antenna relative to that of an "isotropic" radiator is the "antenna gain" (G_T).

> *An antenna with a gain >1 does not actually output more total energy than it receives at its input. It focuses the energy instead of radiating evenly in all directions. Antenna gain should not be confused with the term "gain" used in the context of amplifiers.*

The "power density" at some distance R given the actual antenna with a gain G_T is given by

$$G_T \frac{P_T}{4\pi R^2} \left(\mathrm{W/m}^2\right)$$

Receive Antenna

At the location of the receive antenna, it is now known what the power density of the incident field is from the preceding equation. The receive antenna can be described as having a "capture area" or "effective aperture," in this case "receive effective aperture" for the analysis (A_R).

The receive power is thus given by

$$P_R = A_R G_T \frac{P_T}{4\pi R^2}$$

2.1.2 Antenna Gain and Effective Aperture

Gain and effective aperture are two equivalent ways to describe how well an antenna focuses energy. Conceptually for the purposes of link analysis, it is easier to think of a transmit antenna in terms of gain and of a receive antenna in terms of aperture.

However, these properties are identical whether the antenna is used in either a transmit or receive configuration, a property known as “reciprocity.”

The relationship between gain and aperture is given by

$$A_E = \frac{\lambda^2}{4\pi} G$$

A derivation of this property can be found in Balanis (2005)

For certain types of antennas like reflector antennas or planar-phased arrays, the “aperture” is intuitive by inspection of the physical collector area. The “effective aperture” for a reflector is typically 60–70% of the actual area of the dish. For a planar-phased array, “effective aperture” can meet or exceed slightly the physical area. For other types of antennas, like a Yagi, the “aperture” is not obvious from the antenna construction.

The key takeaway from the aperture-gain relationship equation is that **for a given aperture, gain increases with increasing carrier frequency.**

2.2 Complete Link

The original receive power equation can be rewritten.

$$P_R = A_R G_T \frac{P_T}{4\pi R^2} \tag{1}$$

Using the aperture-gain relationship as two different equations utilizing either “aperture” or “gain”

$$P_R = G_R G_T \frac{\lambda^2 P_T}{(4\pi R)^2} \text{(this formulation known as Friis equation)} \tag{2}$$

$$P_R = A_R A_T \frac{P_T}{\lambda^2 R^2} \tag{3}$$

There is a **key insight** to be gained by examining the three different formulations of this equation, and these three different formulations of the same relationship describe three general classes of RF links:

1. Fixed aperture to fixed aperture
   Consider a point to point link between reflector antennas. The “aperture” of the antennas does not change with frequency. Equation (3) most directly represents this configuration. Note that “receive power” **increases** with increasing carrier frequency. This type of link is optimal for high throughput and benefits from high carrier frequencies. Links like these will often utilize carrier frequencies in the 10 s of Ghz to maximize throughput. A high throughput spacecraft radio system will generally fall under this category.

2. Fixed gain to fixed gain
   Consider a link between two low-gain antennas. Such a link is useful if communication needs to be maintained in any direction without pointing. Equation (2) most directly represents this configuration. Note that "receive power" **decreases** with increasing carrier frequency. An example of this sort of link would be radio or TV broadcast. Note that typical carrier frequencies for these purposes are no more than a couple of hundred Mhz.

   Ham radio operators operating in the "HF" band (3–30 Mhz) band routinely make contacts over thousands of kilometers with low-gain antennas and moderate transmit power levels. Long-range military communications also use similarly low-frequency links to reach extreme distances. The ionosphere aids this process by reflecting these signals allowing their path to avoid blockage by the curvature of the Earth.
3. Fixed aperture to fixed gain
   Consider a link between a ground-based dish and an omnidirectional antenna on a spacecraft. Such a link is beneficial because it does not rely on the spacecraft being able to point. Equation (1) most directly represents this configuration. Note that "receive power" **is independent** of carrier frequency. A low-speed TT&C (Telemetry, Tracking and Command) spacecraft radio will generally fall under this category since the spacecraft antennas are typically low-gain to provide attitude independent link closure.

> *The above simplified link equations do not include practical link impairments such as atmospheric absorption which is carrier frequency dependent.*

Later discussion will utilize these formulas in logarithmic form as it is more convenient to deal with the extremely large range of power levels dealt with and is the standard approach in practice.

> *An excellent discussion of the logarithmic representation of these sorts of equations and representations of system parameters can be found in Chapter 13 of the "Handbook of Satellite Applications" in the section Understanding Decibels* (Glover 2013). *It is recommended that the reader familiarize themselves with this section in order to follow later sections of this chapter which utilize logarithmic representations.*
> *Internet resources discussing the subject are also readily* available (Decibel Tutorial 2019).

2.3 Overview of Basic RF Satellite Link Calculations

Simple calculations using these concepts allow for quick feasibility and performance estimations for satellite link performance.

2.4 Concepts Not Discussed but Recommended for Further Study

- Antenna and wave polarization
  - Linear polarization
  - Circular polarization
  - Polarization matching
  - Atmospheric absorption

2.5 Noise Power

This section discusses how to determine the "noise power" that enters a radio receiver. As discussed in the introduction, it is the ratio of the signal power to the noise power that will ultimately determine the overall throughput that the link is capable of. The discussion will be limited to "thermal noise" or more specifically "Johnson-Nyquist" noise.

Examples of more complex forms of "noise" that may be encountered

- *Multipath reception, for example, GPS receivers in a dense urban environment receiving multiple copies of the signal at different power levels and phase shifts*
- *Self-interference from emissions from the spacecraft itself. For example, EMI or out of band emissions from other radios*

  SNR is often extended to SINR (signal-to-noise and interference ratio) to account for these sorts of issues.

2.5.1 Noise Power from Matched Resistive Source

Consider a matched resistive source (e.g., 50 ohm termination) connected to the input of the receiver. The power generated by the resistive source is generated by the thermal agitation of charge carriers.

The power entering the receiver (load) is given by

$$P_n = k_b T B \ (\mathrm{W})$$

P_n – Noise power (W)
k_b – Boltzmann constant ~ 1.38e−23 ($\mathrm{m^2 kg s^{-2} K^{-1}}$)
T – Temperature in Kelvin
B – Bandwidth over which power is measured (Hz)

Communication system analysis typically utilizes the bandwidth independent parameter **noise density**.

The total power is bandwidth times the noise density.

$$P_n = B N_0 \ (\mathrm{W})$$

N_0 – Noise density (W/Hz)

The “power density” of the noise can be calculated by dividing the power by the bandwidth

$$P_D = k_b T \text{ (W/Hz)}$$

Note that the power density for the transferred power from a matched resistive source is solely dependent on the physical temperature of the resistive device.

At room temperature (290 K), P_D= 3.73e−21(W/Hz) = −174 dBm/Hz

2.5.2 Noise Power in Real Receiver System

The previous section discussed how the noise power density from a resistive source is solely dependent on its physical temperature.

For a real receiver, it is customary and convenient to determine an “effective noise temperature (Te)” for the receiver system. This allows the calculation of the noise density by multiplying by k_b

$$N_0 = k_b T_E$$

2.5.3 Ideal Antenna

Consider an ideal antenna. Such an antenna has no losses, has a tight beam with no sidelobes and delivers all energy that it picks up to its feed with zero loss.

With an imaginary antenna like this, the “effective temperature” will be determined by whatever radiated sources it is pointing at. If we assume that the targets behave like “black bodies,” their physical temperature will be directly related to the output noise density by the $k_b T$ relationship. For the purposes of this discussion, it is assumed that the beam is narrow enough to only pickup radiation from the target (Table 1).

> *The sun is a convenient reference source for antenna characterization and performance validation* (Morgan 2018).

2.5.4 Real Antenna

A real antenna will suffer from sources of thermal noise other than the intended radiation that it is intended to receive. Consider a ground-based dish antenna used for communication with a spacecraft. Though it is pointed toward the “cold sky,” it will pick up energy from sources like the following:

1. Thermal radiation from the atmosphere
2. Thermal radiation from the earth picked up by sidelobes

Table 1 Temperature of some common radiative sources

Target	Temp (K)	$k_b T$ (dBm)	Notes
Deep space	2.7	−192	Cosmic background radiation
Earth	270	−174	Typical average earth temperature
Sun	5800	−161	Typical average sun surface temperature

3. Radiation from lossy (resistive) paths for the RF current
    (a) Losses on dish surface or antenna elements
    (b) Losses in the feed network and preselect filters

Resources on the subject can be found in (Lambert and Rudduck 1992; Gary 2019; Kraus 1988).

For the purposes of this discussion, a Te value of 100 K can be used which is typical for a ground-based dish pointing at the cold sky.

A space-based antenna which has a beam pointing toward the earth will have a Te value of around 300 K, the temperature from the earth and additional resistive temperature from loss in the antenna itself.

2.5.5 Low-Noise Amplifier

Any receiver system requires active and passive devices to condition the signal for reception. These contribute added noise. Dealing with this impairment is achieved by placing a **low-noise amplifier (LNA)** as close as possible to or integrated with the antenna feed. If the gain of the LNA is sufficiently high, the received signal and antenna/LNA noise will be significantly higher than any downstream noise sources and so can be discarded by them since the LNA will be the dominant source of amplifier noise.

Resources on the subject "cascaded noise" be found in (Kraus 1988; Noise Figure 2019).

The LNA noise performance is specified by a term called "noise figure."

The "noise figure" is the ratio of noise power out of the LNA to the thermal noise from a matched resistive source on the input. Since the thermal noise of a "matched resistive source" is temperature-dependent as discussed before, the noise figure is specified at a "reference temperature," typically 290 K.

The hypothetical 100 K antenna source is not delivering kb∗290 noise density, so the NF is not directly useful for the satcom example.

The "noise figure" can be converted to a "noise temperature" with the following equation:

$$T_N = T_{REF} * \left(10^{\frac{NF(dB)}{10}} - 1\right)$$

For example, if the LNA has a "noise figure" of 1 dB, the Te is 75 K.

Recall the hypothetical ground and spacecraft antennas and the 1 dB NF LNA. The total Te is simply the sum of the antenna Te and the LNA Te.

Ground receiver: Te = 100 + 75 = 175 K
Space receiver: Te = 300 + 75 = 375

The **key point** here in this particular link example is that the noise figure parameter has a larger overall effect on the performance of the ground-based system since the earth pointing antenna is picking up significant radiated energy from the earth. A high-performance earth-based antenna such as one designed for radio astronomy will benefit from exotic (and extremely expensive) cryogenically cooled LNAs, but an earth-pointing space-based communications antenna receives little benefit from a cryocooled LNA.

> *Most integrated dish systems will include the LNA with the feed, and the overall system will be specified with an aggregate Te including the effect of the LNA. This figure of merit is typically called G/T which is the antenna gain divided by Te.*

2.6 Overview of Noise Considerations

When analyzing satellite RF links, the received "noise density" needs to be determined. This is a combination of noise picked up from unwanted radiated sources as well as internally generated noise in the LNA. It is most convenient for satellite links to calculate overall noise sources for the purposes of analysis as an "effective temperature." The overall "noise power" is calculated by multiplying the "noise density" by the bandwidth of interest.

2.7 Concepts Not Discussed but Recommended for Further Study

- Noise figure cascade analysis. This analysis will inform whether or not noise contributions of elements after the LNA can be ignored.
- Detailed antenna temperature analysis.

2.8 Signal-to-Noise Ratio and Link Budgets

2.8.1 Introduction

The previous section discussed how to calculate received signal power and noise/noise density based off some simple properties of an RF link. This section will discuss how to "close the link" and create a "link budget." The goal is to ensure that given the link conditions and the choice of modulation and coding, sufficient signal-to-noise ratio is maintained to meet some requirement for throughput and error rate.

2.8.2 Modulation and Error Correction

The subject of signal modulation and error correction can be a very deep and complex topic. Fortunately the SNR and throughput relationship for various forms of modulation and coding schemes can be found in reference materials and technical documentation.

In this text, the discussion will be limited to two types of modulation. FSK (frequency shift keying) and APSK (amplitude phase shift keying) as almost all satellite point to point links will use one or the other. High-speed links will typically utilize PSK/APSK with complex error correction schemes for maximum throughput. Low-speed/low-power links will often use FSK or M-FSK due to the simple hardware and low power requirements.

> *Complex communication systems such as the multiplexed multibeam links of say the iridium communication system are beyond the scope of the discussion here.*

2.8.3 Modulation

Phase Shift Keying and Amplitude Phase Shift Keying

The most common form of modulation for medium- to high-speed radio links is PSK or APSK. With this form of modulation, the phase and/or amplitude of a carrier wave is changed to encode information.

BPSK (Binary Phase Shift Keying)

The simplest form of PSK is “binary phase shift keying.” In this scheme the phase of the carrier is shifted between 0° and 180° to encode either a 1 or a 0.

A section of the carrier with a duration of the symbol period is known as a “symbol.” In this scheme there is one bit encoded per “symbol.” In such a case, the “bitrate” is equal to the “symbol rate.”

> *Error correction will be discussed later which involves “redundant” bits. In such a case, the bitrate to symbol rate will change depending on the redundancy fraction.*

Figure 1 shows the symbol waveforms of a BPSK modulated carrier transitioning from a “0” to a “1.” This example is unfiltered which would in practice yield unacceptably wide spectral content. Appropriate symbol filtering prevents this

QPSK (Quadrature Phase Shift Keying)

The number of bits per symbol can be increased by encoding multiple bits in a single symbol. With “quadrature phase shift keying,” there are 4 symbol states, 45, 135, 225, and 315°, so 2 bits per symbol can be encoded. The number of bits per symbol can be increased to 3 by using 8 phases, this is known as 8-PSK (Fig. 2).

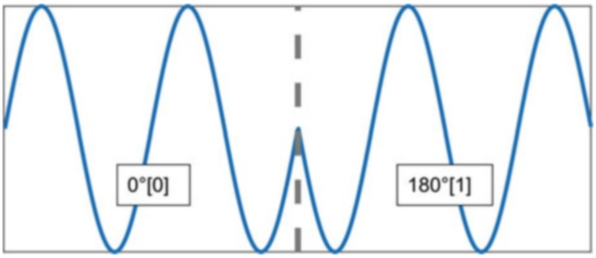


Fig. 1 Example of BPSK modulation format. (Image: Matt Ligon 2020)

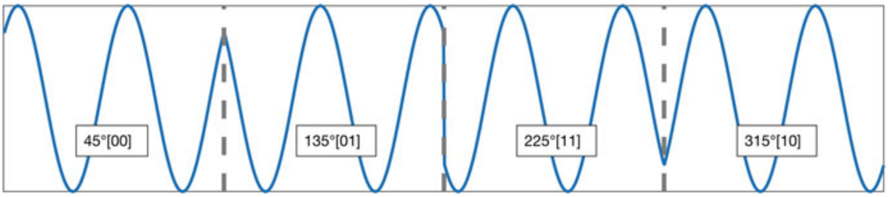


Fig. 2 Example of QPSK Modulated Signal. (Image: Matt Ligon 2020)

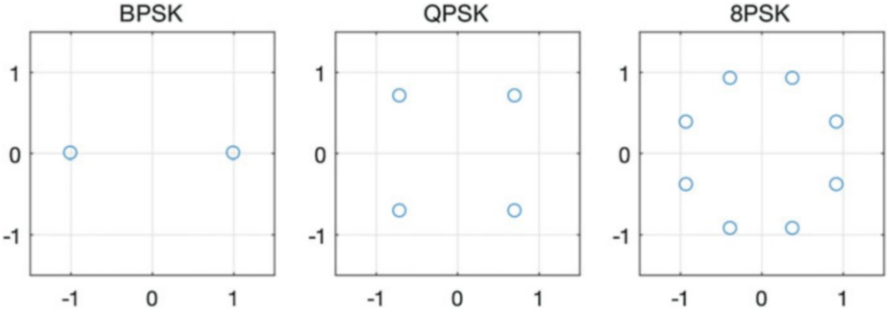


Fig. 3 Constellations for BPSK, QPSK, 8PSK,and 8PSK. (Image: Matt Ligon 2020)

PSK Constellation Diagrams

The common graphical representation for this type of modulation is to represent the symbols on a **constellation diagram**. Such a diagram is a polar plot that shows the amplitude and phase of each symbol.

Figure 3 shows BPSK, QPSK, and 8PSK represented on a "constellation diagram." Note that the 180d phase degree difference is clear from the BPSK plot and the 90d phase degree differences are clear from the QPSK plot and the 45d phase differences for 8PSK.

APSK Constellation Diagrams

Additional constant amplitude symbols could be added with reduced phase difference, 16-PSK, for example. This however is not an efficient use of the available phase-amplitude space. Instead to further increase the number of bits per symbol, amplitude is introduced as a variable resulting in what is called "amplitude phase shift keying." The 16 and 32 symbol constellations are shown below.

Higher-Order Constellation Diagrams

See Fig. 4.

Modulation Types and Required SNR

See Fig. 5.

With added noise, there is variability in the location of the received symbol. The size and spread of the received symbol "cloud" is dependent on the signal-to-noise

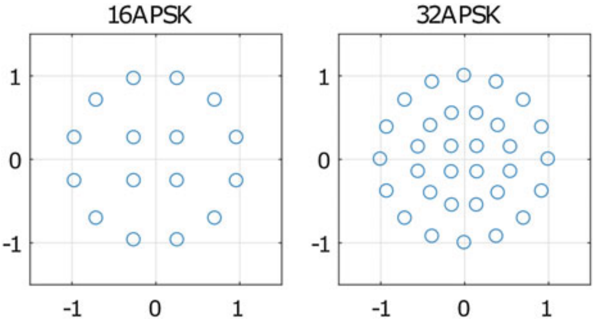


Fig. 4 16APSK and 32APSK constellation diagrams. (Image: Matt Ligon 2020)

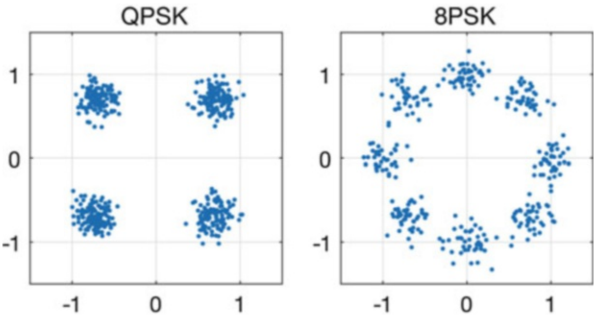


Fig. 5 QPSK and 8PSK constellations with 15 dB SNR. (Image: Matt Ligon 2020)

ratio. The “decision regions” or region that the received signal must fall to be interpreted correctly is smaller as the number of bits per symbol increases. This means that “higher order” (modulations with higher bits per symbol) require higher SNRs for correct interpretation of the received signal.

Alternate Constellation Configurations

These constellation schemes are not the only symbol arrangement used in commercial communication links. They are however particularly useful for satellite links with transmitters that are driven out of their nonlinear region because of their radially symmetric nature.

2.8.4 Error Correction

Due to the presence of noise, some fraction of the symbols will be interpreted incorrectly. Lower SNRs will result in a higher ratio of symbol errors. Practical communication systems deal with this problem by implementing “error correction.”

To put it simply, links that utilize “error correction” schemes add redundancy to the bitstream so that if a fraction of the bitstream is incorrect, the actual message can be reconstructed.

The subject of “error correction” is complex. Different schemes have different levels of performance which is related to the computing complexity of implementation. This text will not dive into the details of this subject, but the curious and mathematically inclined reader is encouraged to study the subject in more depth.

In this text, published specifications will be utilized to analyze practical RF links.

DVB-S2

The discussion of APSK modulation with error correction will be completed by referring to the DVB-S2 standard. The DVB-S2 standard defines packet framing, modulation types, and error correction schemes. The “DVB” refers to “Digital Video Broadcast” and was designed for the purpose of satellite digital television broadcast and backhaul. DVB-S2 is a very useful standard for general satellite data transmission as well.

Because of the considerable industrial investment in both the standard as well as the availability of inexpensive receiver hardware, it is a good option for inexpensive and low cost of development high-speed satellite links for CubeSats and SmallSats. DVB-S2 is by no means the only standard that can be used, but it is a high-performance well-documented standard that is useful as a reference. Traditional satellite systems commonly utilize standards defined by the CCSDS, for example.

Due to the sophisticated error correction implemented by DVB-S2, the processing requirements are high and require the use of FPGAs at high symbol rates. It is a useful standard for high throughput links but is not suitable for low-power low-speed links.

On the transmit side, DVB-S2 IP cores are commonly available for FPGAs. On the receive side, inexpensive commercial receiver hardware is readily available. For example, the TBS6903 PCI-E receiver card that can support 16APSK (5 bits per symbol) at 67.5MSPS (Mega symbols per second) can be purchased for 255USD.

The advantage of using a standard such as DVB-S2 is that there is thorough published information about the link performance and cheap to moderately priced commercially available receiver hardware. DVB-S2 supports QPSK through 32APSK and a variety of different coding rates (ratio of real bits total bits including redundancy). DVB-S2X further extends the available coding ratios as well as modulation types.

A key advantage of DVB-S2 is its implementation of error correction specifically **forward error correction** *based on concatenation of BCH (Bose-Chaudhuri-Hcquengham) with LDPC (Low Density Parity Check) inner coding* (DVB Fact Sheet 2018)

To reiterate, DVB-S2 is only a convenient standard that defines a specific implementation of modulation, framing, and error correction. These implementations are not exclusive to DVB-S2.

The DVB-S2 standard defines 23 MODCOD’s. A MODCOD is a combination of modulation and ratio of data bits to total bits.

Table 2 DVB-S2 MODCOD definitions

Mode	MODCOD	Mode	MODCOD
QPSK 1/4	1	8PSK 5/6	15
QPSK 1/3	2	8PSK 8/9	16
QPSK 2/5	3	8PSK 9/10	17
QPSK 1/2	4	16APSK 2/3	18
QPSK 3/5	5	16APSK 3/4	19
QPSK 2/3	6	16APSK 4/5	20
QPSK 3/4	7	16APSK 5/6	21
QPSK 4/5	8	16APSK 8/9	22
QPSK 5/6	9	16APSK 9/10	23
QPSK 8/9	10	32APSK 3/4	24
QPSK 9/10	11	32APSK 4/5	25
8PSK 3/5	12	32APSK 5/6	26
8PSK 2/3	13	32APSK 8/9	27
8PSK 3/4	14	32APSK 9/10	28

The following table from the DVB-S2 standard (ETSI 2014) specifies the relationship (Table 2).

Example

MODCOD 12 utilizes 8PSK with a code rate of ⅗. Each symbol encodes 3 "total bits" since 3 bits are encoded per symbol with 8PSK. The "⅗" refers to the ratio of "data bits" to "total bits" since extra bits are added for redundancy for the error correction.

If the symbol rate is 50MSPS, for example, that means there are 150 Mbps (3 bits per symbol for 8psk) including code bits and ⅗∗150 = 90 Mbps actual data rate at MODCOD:12

The important question however is how much signal-to-noise ratio is needed to support a certain MODCOD and subsequent data rate.

The DVB-S2 specification provides a table describing the ideal required SNR in the form of EsNo. EsNo is defined as the "energy per symbol" divided by the "noise density." In the table below, the specifications for a real demodulator have been added (Newtec AZ910) (Newtec 2019) to compare performance of a commercially available piece of hardware. In addition, the theoretical "Shannon capacity" has been added.

Shannon capacity and the Shannon-Hartley theorem will be discussed later, but for the purposes of the current discussion, understand that the "Shannon capacity" describes the theoretical maximum performance for a communications link.

ESNO or $E_S/N_0$is the ratio of **energy per symbol** divided by **noise density**.

Note that increases of "bits per symbol" known as spectral efficiency (η) requires higher EsNo, as discussed in the previous section.

Table 3 DVB-S2 modulation and required EsNo

MODCOD	Modulation	Code rate	DVB-S2 (bits/ symbol)	DVB-S2 theoretical EsNo req (dB)	Newtec AZ910 demod EsNo req (dB)	Shannon limit EsNo req (dB)	Shannon limit capacity (bits/ symbol)
1	QPSK	1/4	0.49	−2.4		−3.93	0.66
2	QPSK	1/3	0.66	−1.2	−0.70	−2.39	0.81
3	QPSK	2/5	0.79	−0.3	0.20	−1.38	0.95
4	QPSK	1/2	0.99	1.0	1.40	−0.07	1.18
5	QPSK	3/5	1.19	2.2	2.80	1.07	1.42
6	QPSK	2/3	1.32	3.1	3.60	1.76	1.60
7	QPSK	3/4	1.49	4.0	4.30	2.56	1.82
8	QPSK	4/5	1.59	4.7	5.10	3.02	1.98
9	QPSK	5/6	1.65	5.2	5.50	3.32	2.10
10	QPSK	8/9	1.77	6.2	6.60	3.81	2.37
11	QPSK	9/10	1.79	6.4	6.70	3.90	2.43
12	8PSK	3/5	1.78	5.5	6.30	3.86	2.19
13	8PSK	2/3	1.98	6.6	7.10	4.69	2.48
14	8PSK	3/4	2.23	7.9	8.40	5.66	2.84
15	8PSK	5/6	2.48	9.4	9.70	6.60	3.26
16	8PSK	8/9	2.65	10.7	11.10	7.21	3.67
17	8PSK	9/10	2.68	11.0	11.30	7.33	3.76
18	16APSK	2/3	2.64	9.0	9.60	7.18	3.15
19	16APSK	3/4	2.97	10.2	10.50	8.34	3.52
20	16APSK	4/5	3.17	11.0	11.50	9.02	3.77
21	16APSK	5/6	3.30	11.6	12.10	9.47	3.95
22	16APSK	8/9	3.52	12.9	13.30	10.21	4.35
23	16APSK	9/10	3.57	13.1	13.60	10.36	4.43
24	32APSK	3/4	3.70	12.7	13.60	10.80	4.30
25	32APSK	4/5	3.95	13.6	14.50	11.61	4.59
26	32APSK	5/6	4.12	14.3	14.90	12.14	4.80
27	32APSK	8/9	4.40	15.7	16.10	13.03	5.25
28	32APSK	9/10	4.45	16.1	16.50	13.20	5.37

With understanding of the concepts laid out, the definition **energy per symbol** is discussed below.

If the receive power is Prx and the symbol rate is Rs, it follows that the energy carried by each symbol is Prx/R. This is the **energy per symbol** or E_S

The discussion of “noise power” showed that it is a property of the antenna and receive system. How to simply determine signal power at the receiver was also discussed. By considering the additional variable of the symbol rate, “EsNo” can be calculated, and Table 3 can be consulted to determine the achievable MODCOD.

DVB-S2 and the Shannon Limit

In the previous section, the published behavior of a high-performance commercial standard called DVB-S2 was discussed. The level of performance of the standard can be determined by comparing it to what is known as the Shannon limit. Table 3 shows how many bits per symbol can be received given a certain EsNo. The Shannon limit will show what the maximum possible error free capacity of a "noisy channel" is.

The fundamental relationship between "C" channel capacity (bits per second), "B" bandwidth (Hz), "S" signal power (W), and "N" noise power (W) is given by the "Shannon-Hartley" theorem.

"Noise" in this context refers to "additive white Gaussian noise." Thermal noise has this property.

$$C = B\, log_2\left(1 + \frac{S}{N}\right)$$

The equation will now be reformulated.

Describe "S" as energy per symbol times symbol rate.

$$S = E_S R_s$$

Describe "N" as noise density times bandwidth.

$$N = N_0 B$$

Next it is asserted that $R_S = B$. In reality the ratio between the symbol rate and bandwidth for PSK/APSK is dependent on the implementation of the symbol filter. The discussion here will assume that they are equal.

Why is the minimum bandwidth dependent on symbol rate? This can be understood with a simple conceptual exercise. Imagine a stream of alternating ones and zeroes, 01010101, etc.

If this were to represent this with a sine wave where the peaks were ones and the troughs were zero, a sine wave with a frequency equal to the symbol rate would be needed. A lower-frequency wave would not be able to carry the information.

Rewrite the Shannon-Hartley theorem as follows:

$$\frac{C}{B} = log_2\left(1 + \frac{E_S R_S}{N_0 B}\right)$$

Assuming Rs = B yields

$$\frac{C}{R_S} = log_2\left(1 + \frac{E_S}{N_0}\right)$$

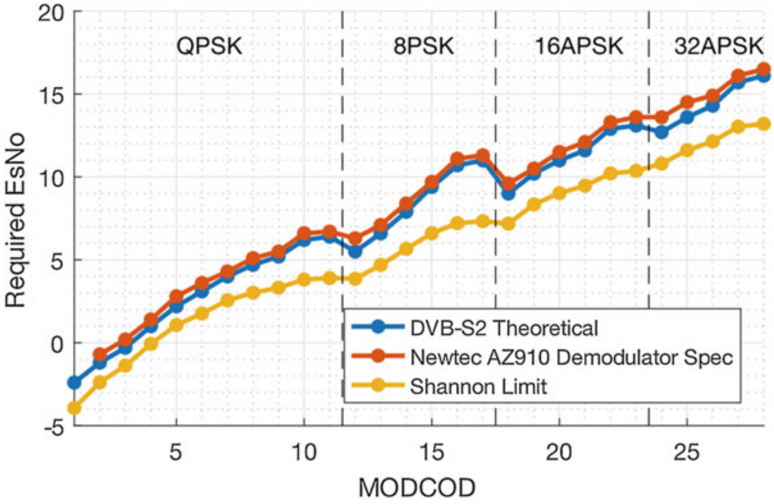


Fig. 6 EsNo required at different MODCODs. (Image: Matt Ligon 2020)

C(bits/s)/Rs(symbols/s) yields "spectral efficiency" η(bits/symbol):

$$\eta = log_2\left(1 + \frac{E_S}{N_0}\right)$$

Refer back to the DVB-S2 performance specification which shows the relationship between "spectral efficiency" and EsNo. The Shannon-Hartley theorem has been rewritten to show the theoretical maximum relationship between the two. The Shannon limit and the DVB-S2 performance are plotted in Fig. 6.

This plot shows the EsNo required for "quasi-error-free" operation of a theoretically ideal DVB-S2 channel, the specification for a commercial demodulator (Newtec AZ910), as well as the theoretical Shannon minimum EsNo required for a given MODCOD. It can be seen that the DVB-S2 implementation ranges from within 1 to 4 dB of the theoretical minimum.

Note the regions where the DVB-S2 plot has a larger deviation from Shannon. These are the regions where there is a smaller ratio of code bits to data bits. The error correction is less effective as the ratio of code bits to data bits tends toward zero. If there were no code bits, ***no error correction at all*** *could be performed.*
Since DVB-S2 is a standard intended for broadcast use, the performance is specified such that a consumer will experience a glitch rarely. This is referred to as "quasi-error-free."

Example DVB-S2 Link Budget

As an example the Planet Labs "Dove HSD" high-speed downlink system is studied. A thorough discussion of the system was published at the 31st Annual AIAA/USU

Table 4 Dove HSD key link parameters

Parameter	Value	Unit	Notes
Transmit power	2	W	
Tx antenna gain	10	dBiC	Circular polarized helical antenna
Symbol rate	70	MSPS	
Max distance	2050	km	Distance at 5d Elevation
G/T	29	dB/K	G/T for ground dish. G is gain, and T is "effective antenna temperature" Planet uses a mix of 4.5 and 5 m diameter dishes.

Conference on Small Satellites. It is recommended that the reader study the paper thoroughly for background on implementation details of both spacecraft and ground systems (Devaraj et al. 2017) (Table 4).

Recall the link equation from the previous section

$$P_R = G_R G_T \frac{\lambda^2 P_T}{(4\pi R)^2}$$

This equation shows how to determine the received power. EsNo needs to be determined to calculate the link throughput.

Recall the relationship between "effective temperature" and "noise density"

$$N_0 = k_b T_E$$

as well as the relationship between signal power, energy per symbol, and symbol rate

$S = E_S R_s$ or $P = E_S R_s$ to match the power symbol in the link equation

Expand the link equation

$$\frac{E_S R_s}{N_0} = \frac{G_R G_T \frac{\lambda^2 P_T}{(4\pi R)^2}}{k_b T_E}$$

and reformulated

$$\frac{E_S}{N_0} = \left(\frac{G_R}{T_E}\right)(G_T)(P_T)\left(\frac{\lambda^2}{(4\pi R)^2}\right)\left(\frac{1}{k_b}\right)\left(\frac{1}{R_s}\right)$$

The specific terms are discussed and given abbreviations and logarithmic units.

$$\left(\frac{G_R}{T_E}\right)[\mathrm{G/T}](\mathrm{dBi/K})$$

Gain of the receive antenna divided by the effective temperature. As discussed prior this G/T term is the standard figure of merit for a ground dish receiver antenna.

$$(G_t)[\mathrm{Gt}](\mathrm{dBi})$$

This term describes gain of the transmit antenna, which is a ratio of power density relative to that of an "isotropic" radiator. The "i" in the unit dBi refers to this.

$$(P_t)[\mathrm{Pt}](\mathrm{dBW})$$

This term describes gain of the transmit antenna. The unit dBW refers to the fact that it is a ratio relative to 1 W

$$\left(\frac{\lambda^2}{(4\pi R)^2}\right)[\mathrm{PL}](\mathrm{dB})$$

This term describes what is called "path loss." This is the reduction of energy density over distance due to the fact that the energy is spreading over a larger "spherical" wave front. The unit is dimensionless and is thus simply dB.

$$\left(\frac{1}{k_b}\right)[1/\mathrm{Kb}](\mathrm{K}\cdot\mathrm{Hz})/\mathrm{dBW}$$

As discussed in the "Noise Power" section, The k_bT term defines the noise power.

$$\left(\frac{1}{R_S}\right)[1/\mathrm{Rs}]$$

This is the symbol rate.

The link equation is now rewritten in logarithmic form. Note that the terms that have been inverted are now subtractions instead of additions.

$$\begin{aligned}\frac{E_S}{N_0}(dBHz) = {} & G/T(dBi/K) + G_T(dBi) + P_t(dBW) \\ & + PL(dB) + [1/Kb]((K\cdot Hz)/dBw) + [1/Rs](1/dBHz)\end{aligned}$$

A tabular link budget based on this equation is shown below. The numbers highlighted in red are summed together to yield the resulting EsNo (Table 5).

Table 5 Example DVB-S2 link budget

Parameter	Value	Unit
Distance	2.05E+06	m
Tx power	2.00	W
Carrier frequency	8.20E+09	Hz
speed of light	3.00E+08	m/s
wavelength	0.04	m
Boltzmann constant [Kb]	−228.59	dBW/(K·Hz)
Symbol rate	7.00E+07	Hz
Tx power dB [Pt]	3.01	dBW
Tx ant gain [Gt]	10.00	dBi
Path loss [PL]	−176.9531265	dB
1/Boltzmann constant [1/Kb]	228.59	(K·Hz)/dBW
1/symbol rate [1/Rs]	−78.45	1/dBHz
G/T [G/T]	29.00	dBi/K
EsNo	**15.20**	dBHz

Note that this link budget does not include any margin, atmospheric loss, antenna polarization mismatch, or other impairments. The resulting EsNo is a theoretical maximum given the basic link parameters

Referring to the DVB-S2 performance chart, it can be seen that an EsNo of 15.20 dB would allow the link to run at MODCOD 26. This is 32APSK with a ⅚ code rate with 4.12 bits per symbol. The example symbol rate is 70MSPS thus yielding a total throughput of 288.4 Mbps.

In reality that speed would not be achievable with the link. In practice the link needs to be run with sufficient margin. Other losses due to pointing inaccuracy, atmospheric attenuation, and other non-idealities need also to be considered (Table 6).

If a total of 5 dB is added to account for margin and impairments, the practical EsNo would be 10.20 dB. This allows the link to be run at MODCOD 19 (16APSK ¾) with 2.97 bits per symbol. At 70MSPS this is 207.9 Mbps.

The level of operating margin can be tuned to achieve maximum throughput

ACM (Adaptive Coding and Modulation)

DVB-S2 supports a wide range of “bits per symbol” depending on the available EsNo. The EsNo at the receiver is most significantly affected by the distance to the satellite. Planet’s Dove and SuperDove systems dynamically command the spacecraft transmitter to adjust the MODCOD to maximize throughput given the existing link conditions. It does not matter if the spacecraft is far away, has some hardware issue with its antennas or transmit chain, or if there is a pointing problem. By

Table 6 Example link budget with margin and additional losses added

EsNo	**15.20**	dBHz
Margin	−3.00	dB
Implementation loss	−2.00	dB
Design EsNo	**10.20**	dBHz

utilizing ACM a link can be maintained under adverse conditions albeit at a reduced data rate.

For **CubeSats and SmallSats**, ACM is very important function to have. Such spacecraft systems have limited power, are often experimental, lack reliable ADCS, and may not perform to the design specification due to rapid development and limited ground performance validation.

Comparison of Planet's SuperDove to DigitalGlobe WorldView-4 Satellite Downlink Performance

The example presented in the previous section was based on the HSD1 (high-speed downlink ver. 1) system implemented in the "Dove" spacecraft system.

Planet's latest CubeSat system "SuperDove" implements an upgraded radio system "HSD2" that utilizes 6× 76.8MSPS channels and can achieve over 1 Gbps.

Planet presented a paper on the implementation of this system at the 31st Annual AIAA/USU Conference on Small Satellites (Devaraj et al. 2019).

The DigitalGlobe WorldView constellation as well as their planned legion constellation operate at data rates of up to 1200 Mbps (DigitalGlobe 2012). Planet's SuperDoves can exceed this rate in peak operating conditions, but their overall average under good link conditions is about 900 Mbps.

The reader may be very surprised that a low-cost CubeSat a tiny fraction of the size and power budget of a WorldView class satellite is capable of similar data throughput rates. The answer to this question illustrates how SmallSats can "punch above their weight" compared to traditional satellite systems (Table 7).

The link budget shown above is from the WorldView-4 FCC filing. The data rate is 400 Mbps per polarization. With both polarizations the total throughput is 800 Mbps.

Examination of this link budget reveals several important insights into the design of the WV4 downlink system.

1. The radio system is designed to meet a 400 Mbps per polarization requirement in a worst-case condition. The system cannot speed up and take advantage of shorter slant ranges or better link conditions. **The system runs at a constant rate regardless of conditions. The system cannot fully take advantage of whatever link conditions are available:**
   (a) Rain loss accounts for 1.7 dB of the budget. The system cannot take advantage of dry conditions by speeding up.
   (b) A full **8.5 dB** of link margin is maintained under these worst-case conditions.

Table 7 WorldView-4 link budget from FCC Filing (DigitalGlobe 2012)

Frequency	8185	Mhz
Orbit height	770	km
Elevation	5	degrees
Data rate	400	Mbps
Bandwidth	200	Mhz
EIRP	57.1	dBm
Slant range	2718.88	km
Ground G/T	31.4	dB/K
BER	3.00E−05	
Required Eb/No (uncoded)	9.4	dB
Hardware implementation BER loss	−2.5	dB
Actual required Eb/No	**11.9**	
Spacecraft antenna diameter	19.7	in
Approx. HPBW	6.3	degrees
Gain of spacecraft antenna	29.1	dBic
Loss between HPA and antenna	−9.8	dB
Pointing loss	−1	dB
Transmitter Po	7.5	W
EIRP	57.1	dBm
Path loss	−179.4	dBm
Total loss (rain)	−1.7	dB
Required Eb/No	9.4	dB
Crosspol interference loss	−0.3	dB
Received C/N	23.4	dB
Implementation loss	−2.5	dB
Available Eb/No	20.4	dB
Downlink margin	**8.5**	**dB**

(c) The transmitter delivers 7.5 W of power, yet there is **9.8 dB** of loss between the transmitter and antenna.

(d) The antenna is **20 in** in diameter. If the power amplifier was placed right at the feed avoiding the 9.8 dB of loss, the antenna could have been approximately 6 in in diameter and produce the same transmitted power density. Additionally, a smaller antenna would require less accurate pointing.

The author has no additional information about the WV4 system other than what is publicly available from their FCC filings. The author's statements are based on some assumptions based on publicly available information.

The point is that designers of SmallSats and CubeSats **need not assume** that their subsystems will necessarily be hopelessly outclassed by traditional systems. Traditional systems typically include large safety margins for performance parameters due to their high-confidence, requirements-driven design approaches.

Small satellite radio systems with limited volume and power resources **should be designed to be able to operate at the maximum possible performance level given available link conditions.**

> *Of course the large difference in telescope aperture between a WorldView satellite and a Planet Dove result in great difference in optical resolution. The example here shows how non-primary subsystem performance need not be assumed to scale with size and cost of the satellite system. As a counterpoint a satellite which has a communications payload such as an Internet satellite will have radio hardware that operates as close as possible to the available theoretical link limit.*

2.9 Overview of Link Analysis

A link analysis for PSK/APSK, specifically as implemented with DVB-S2 was discussed. This information can be used as reference for implementation of a similar system. This discussion covered high-performance links which necessarily involve high power and compute requirements. The next section will cover simpler, lower-power systems for links that do not need high throughput.

2.10 Low-Power/Low-Speed Links and COTS Chip-Based Implementations

Integrated transceiver chips are an attractive option for low- to medium-speed satellite links with very tight power, volume, and cost budgets such as CubeSats; though they are intended for terrestrial use, their range can be extended with external amplifiers. Additionally external frequency conversion can be done to support channel carrier frequencies unsupported by the chip. An example of a CC1110-based satellite radio is the “OpenLST” an open source project released by Planet in 2018 (Klofas 2018).

> *There are several complexities associated with frequency conversion in this context. Feasibility/difficulty is dependent on specific implementation. Additional detail on the subject is out of scope for this discussion.*

The transmit power can be increased with the addition of an external power amplifier which can be selected to meet link requirements.

These integrated chips typically have internal LNAs with relatively high noise figure (and equivalently high effective temperature). A low-noise amplifier with a lower $T_E$can be added to the receive chain and will dominate the overall noise performance as long as its gain is sufficiently high.

A higher reliability system based on FSK or other modulation types could be implemented by utilizing an SDR (software-defined radio). Examination of the published performance of commercial COTS chips however is useful for performance estimation.

2.10.1 FSK-Based Implementations

Typical transceiver chips utilize “2-ary non-coherent frequency shift keying” (2-FSK) to modulate data. With 2-FSK, bits are encoded by shifting the carrier frequency up or down. The size of this shift is called the *deviation*. 2-FSK utilizes two tones to encode data so there is one “bit per symbol.” An excellent reference source for details on FSK can be found on the Atlanta RF website (Texas Instruments).

The primary configuration options for FSK are baud rate (which just means symbol rate), deviation, and receive filter bandwidth.

Higher rate links will need larger deviations and larger bandwidths. Larger bandwidths lead to higher receive noise power, and thus higher signal power is needed as well. With reduced received signal power, the bandwidth must be sufficiently small so that SNR can be sufficiently high. Coherent FSK has higher performance and not dependent on the receiver bandwidth, but the significantly higher processing power required may make it unsuitable for a simple low-power link.

> *Using spread spectrum techniques, reduced bandwidth is not needed with reduced receive power. This is pointed out here so that the reader does not assume that the lower rates necessarily require lower receiver bandwidths at a fundamental level.*

Depending on the device, there is a minimum receiver bandwidth; this will limit the ability for the chip to operate efficiently at very low speeds.

The Texas Instruments CC1110 has a minimum filter bandwidth of 58 khz, whereas the minimum on the CC1125 is 3.8 kHz. The minimum baud rate for the CC1110 is 1.2 khz. The CC1125 does not have a minimum baud rate but does have reference specifications for as low as 300 Hz operation (Texas Instruments).

Doppler Shift

The discussion of narrow channels necessitates a discussion of **Doppler shift** caused by the relative velocity between transmitter and receiver. For example, at 500 Mhz and 500 km orbital altitude, the range of Doppler shift is about +/−10 kHz.

If the carrier frequency offset caused by Doppler prevents reception, **Doppler compensation** must be performed. Based on the orbit geometry, instantaneous expected Doppler can be calculated, and the ground side radio can be tuned to compensate.

Receivers must tolerate some level of carrier frequency offset as frequency references are not perfect. If the offset is small relative to the bandwidth of the signal, it can likely be ignored, though the receiver bandwidth may need to be widened. If the offset is significant, say for the minimum 3.8 khz

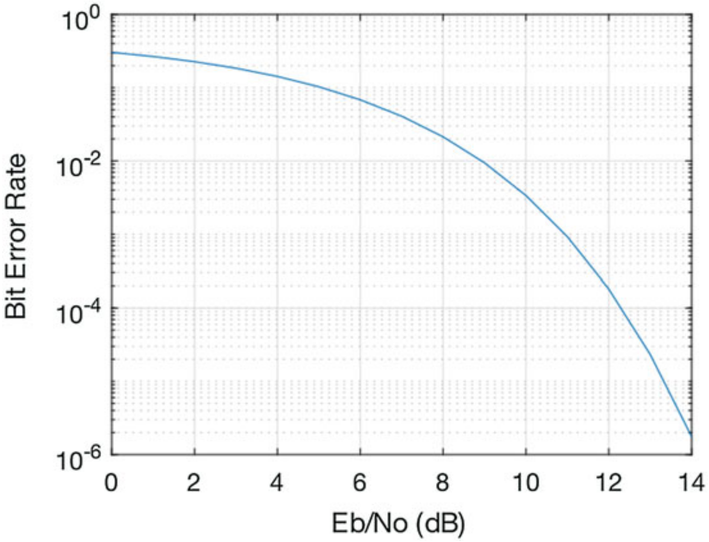


Fig. 7 Theoretical performance of non-coherent 2-FSK. (Image: Matt Ligon 2020)

filter bandwidth of the CC1125, accurate Doppler compensation is an absolute necessity.

The scaling is linear with frequency, so at 2 Ghz the shift would be about +/−40 kHz. Links operating at higher carrier frequencies are more affected by Doppler.

2.10.2 Link Throughput Estimation

In order to estimate the throughput of a chip-based link, the datasheet published performance can be referenced. The datasheets for CC series transceivers list "sensitivity" for different data rate configurations. The theoretical performance of 2-FSK shown in Fig. 7 can also be referenced.

In datasheets for most CC devices, "sensitivity" is the input power level required to achieve lower than a 1% bit error rate. The difference between a 1% BER and, for example, a 10^-5 BER can be determined by referring to the theoretical 2-FSK "waterfall curve" shown in Fig. 7.

A few example link budgets are shown here which show the level of received power for some reference links.

From the datasheets for the CC1125 and CC1310, the "sensitivity" specifications are plotted. Additionally the power required for an ideal 2-FSK receiver at 1% BER is plotted as well as the Shannon limit. These theoretical curves are plotted assuming that the receiver temperature is 900 K. This is representative of the high noise temperature of these chips due to their relatively high noise figure. The performance can be increased with the addition of a higher-performance LNA.

Referring to the example links, the "low-power downlink" (Table 8) could comfortably operate at 1 kbps; the high-power uplink (Table 9) could run

Table 8 Low-power downlink example. 70 cm UHF low-power downlink at 2050 km range

Parameter	Value	Unit
Distance	2.05E+06	m
Tx power	1.00	W
Carrier frequency	4.70E+08	Hz
wavelength	0.64	m
Tx power dB [Pt]	0.00	dBW
Tx ant gain [Gt]	0.00	dBi
Path loss [PL]	−152.12	dB
Rx ant gain [Gt]	10.00	dBi
Rx power [Pr]	−142.12	dBW
Rx power [Pr]	**−112.12**	dBm

Table 9 High-power uplink example. 10 W from 2 m dish 2 Ghz uplink at 2050 km range

Parameter	Value	Unit
Distance	2.05E+06	m
Tx power	1.00	W
Carrier frequency	2.00E+09	Hz
speed of light	3.00E+08	m/s
wavelength	0.15	m
Tx power dB [Pt]	10.00	dBW
Tx ant gain [Gt]	30.50	dBi
Path loss [PL]	−164.70	dB
Rx ant gain [Gt]	0.00	dBi
Rx power [Pr]	−124.20	dBW
Rx power [Pr]	**−94.20**	dBm

comfortable at 200 kbps. The moon link (Table 10) may barely operate at 300 bps when using these sorts of chips, and the very narrow bandwidth would require accurate Doppler compensation.

2.10.3 Spread Spectrum

As discussed prior, the FSK-based CC chips minimum filter bandwidths limited their performance at very low rates and also increased Doppler sensitivity. The utilization of spread spectrum techniques as implemented in an SDR, for example, allows for low bitrate operation at high symbol rates.

Direct Sequence Spread Spectrum

Most commonly, spread spectrum is achieved by encoding a bit with a “spreading code.” The coded data will be increased in length by the size of the code

Table 10 Moon to earth example. Moderate gain (10 dBi) low-power (1 W) tx to 5 m earth dish at 8 Ghz

Parameter	Value	Unit
Distance	3.84E+08	m
Tx power	1.00	W
Carrier frequency	8.00E+09	Hz
speed of light	3.00E+08	m/s
wavelength	0.04	m
Tx power dB [Pt]	0.00	dBW
Tx ant gain [Gt]	10.00	dBi
Path loss [PL]	−222.20	dB
Rx ant gain [Gt]	50.00	dBi
Rx power [Pr]	−162.20	dBW
Rx power [Pr]	−**132.20**	dBm

and thus requires a proportionally higher symbol rate and bandwidth to transmit.

Recall that increasing the bandwidth will reduce SNR. In fact spread spectrum signal power may be up to tens of dB below the noise power. The signal can be retrieved from the noise however because the spreading codes are known. By correlating the received signal with the codes, the data can be retrieved.

The codes used are orthogonal to each other, that is, when correlated with each other, the result is zero.

Shannon Limit Revisited

Shannon theorem shows that maximum channel capacity is achieved with increasing bandwidth, but this reaches an asymptotic limit.

This limit is given by

$$C \approx 1.44 \frac{S}{N_0}$$

Recall that

$$N_0 = k_b T_E$$

The signal power S can now be solved for which is the required signal power level given a receiver temperature Te. In Fig. 8 this has been plotted for Te = 900 K.

The slope of the Shannon limit closely matches that of the trend of the transceiver chips and roughly ranges from 15~20 dB away from the chip sensitivity specification. Recall that a DVB-S2 implementation utilizes highly computationally expensive forward error correction to operate close to the Shannon limit.

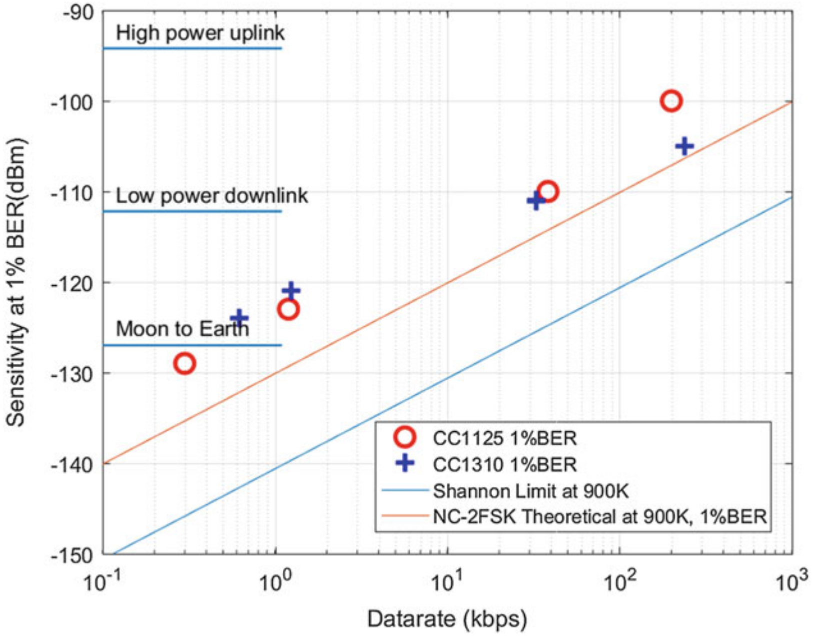


Fig. 8 CC1125 and CC1310 published sensitivities at 1% BER. (Image: Matt Ligon 2020)

2.11 Interference and EMI

The above discussion has assumed that thermal noise was the only noise source. In practice, interference from earth sources can be significant. At 450 Mhz, which is Planet's allocated UHF receive band for Dove and SuperDove, noise power is regularly 20 dB and above the thermal noise floor over large regions of land. Though this band is set aside for earth observation communications, it appears that the widespread usage of nearby bands and their leakage emissions adds up to a significant degree when seen on a wide scale by a spacecraft. At the 2.056 Ghz band that is allocated for earth observation, such interference is minimal, and the system can operate in a thermal noise limited regime.

Another very likely source of interference is self-generated noise from the spacecraft itself. Noise from high-speed clocks, data lines, switching power supplies, as well as leakage energy from transmitters can jam receivers. The effort involved in preventing and or mitigating these sorts of problems is not insignificant and can present an expensive challenge.

3 Conclusion

Satellite radio links utilizing both sophisticated and simple modulation schemes can be planned utilizing basic link theory and published information from industrial standards and products. Standards such as DVB-S2 and CCSDS provide detailed performance information for high-speed, high-performance satellite links. FSK and spread spectrum performance can be estimated from published specifications for commercially available integrated solutions.

4 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Antennas
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

References

C.A. Balanis, *Antenna Theory*, 3rd edn. (Wiley, 2005), pp. 674–675

Decibel Tutorial: dB and dBm vs. Gain and Milliwatts, [Online]. Available: http://www.rfcafe.com/references/electrical/decibel-tutorial.htm. Accessed Nov 2019.

K. Devaraj, R. Kingsbury, M. Ligon, J. Breu, V. Vittaldev, B. Klofas, P. Yeon, K. Kolton, Dove high speed downlink system, in *31st Annual AIAA/USU Conference on Small Satellites*, (Logan, 2017)

K. Devaraj, M. Ligon, E. Blossom, J. Breu, B. Klofas, K. Kolton, R. Kingsbury, Planet high speed radio: crossing Gbps from a 3U Cubesat, in *33rd Annual AIAA/USU Conference on Small Satellites*, (Logan, 2019)

DigitalGlobe, Exhibit 43, July 2012. [Online]. Available: http://licensing.fcc.gov/myibfs/download.do?attachment_key=959105.

DVB Fact Sheet, Sept 2018. [Online]. Available: https://www.dvb.org/resources/public/factsheets/dvb-s2_factsheet.pdf.

ETSI, DVB-S2 Standard, Nov 2014. [Online]. Available: http://www.etsi.org/deliver/etsi_en/302300_302399/30230701/01.04.01_60/en_30230701v010401p.pdf. Accessed Nov 2019.

D. E. Gary, Front End Receiving System, [Online]. Available: https://web.njit.edu/~gary/728/Lecture5.html. Accessed Nov 2019.

D.R. Glover, Satellite radio communications fundamentals and link budgets, in *Handbook of Satellite Applications*, (Springer Science+Business Media, 2013), New York. pp. 311–315

B. Klofas, Planet Releases OpenLST, an Open Radio Solution, August 2018. [Online]. Available: https://www.planet.com/pulse/planet-openlst-radio-solution-for-cubesats/.

J.D. Kraus, Antenna temperature, remote sensing, radar and scattering, in *Antennas*, 2nd edn., (McGraw-Hill, 1988), New York. pp. 774–790

K.M. Lambert, R.C. Rudduck, Calculation and verification of antenna temperature for earth-based reflector antennas. Radio Sci. **27**, 23–30 (1992)

M. Morgan, Determination of Earth Station Antenna G/T Using the Sun or the Moon as an RF Source, in *32nd Annual AIAA/USU Conference on Small Satellites*, (Logan, Utah, 2018)

Newtec, AZ910 Product Leaflet, [Online]. Available: https://www.newtec.eu/frontend/files/leaflet/az910-dsng-and-contribution-demodulator.pdf. Accessed Nov 2019.

Noise Figure, [Online]. Available: https://www.microwaves101.com/encyclopedias/noise-figure. Accessed Nov 2019.

Texas Instruments, CC1110 Datasheet, [Online].

Small Satellites and Structural Design

Joseph N. Pelton

Contents

Abstract

The cost to orbit for 1 kg of mass, using an Atlas launch vehicle, is currently around $20,000 and represents the high end of the range of launch costs. The latest technology represented by a SpaceX Falcon launcher, an ISRO Polar Satellite Launch Vehicle (PSLV) or a small satellite launcher such as the Electron all are significantly less costly. Nevertheless launch cost even by the most efficient launchers into low Earth orbit (LEO) remains quite expensive. In the case of very large space craft such as a high throughput satellite for telecommunications with mass of 5000–10,000 kg, the savings that might come from a highly efficient structural frame that reduces the overall mass by 100 kg, or alternatively allows the payload to be 100 kg larger, might be worth

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_12

something like $2 million dollars per satellite launched. Even for small satellites such as a 3 unit cubesatellite, a very light weight, high strength frame that is thermally stable, and is not adversely affected by high radiation levels, clearly has good value. At this size, however, it is more common to use a lower cost material such as aluminum alloy.

Frame designs for small satellite are getting increasingly more sophisticated. It is possible that a primary frame or even a secondary structure such as a solar cell panel to allow the inclusion of an additional heat sensor, star tracker, or other safety feature or capability to be integrated into the harness design.

Some designs might even allow the addition of a passive de-orbit device that allows the small satellite to more quickly deorbit. In short, some design features for primary or secondary structures are optimized by determining and adding features that reduce both the mass and available usable volume of a small satellite.

The addition of new additive manufacturing capabilities to the arsenal of capabilities available to those who design and manufacture small satellites can increase the performance, cost-effectiveness, or safety of a project.

This article addresses all aspects of a small satellite's design in terms of its mass, strength, volume efficiency, thermal and radiation protective qualities, reliability, and overall structural aspects and efficiency as measured by all of these factors. It analyzes what aspects have been improved over time and what the prospects are for the future to increase structural design and performance. This article analyzes the status and future direction of research related to primary structure related to small satellites. This primary structure is key to a satellite surviving launch and deployment, its operational integrity throughout the spacecraft lifetime up to its end of life. Also considered is the nature and performance of its secondary structures. The structural integrity of these secondary systems are also necessary to support the successful operation of subsystems or components such as solar panels, thermal blankets, radiation shielding, instrument mounts to be properly anchored so as to operate reliably, and so on. Progress is being made on primary and secondary structure design and performance. In many instances, the design of the small satellite and its structural elements are being integrated with essential elements of the spacecraft to reduce mass, increase volume for payload systems, or otherwise increase efficiency. These innovations are sometimes known as multifunctional elements when structures, panels, wiring harnesses, sensors, and other devices are integrated together in the design.

Keywords

Additive Manufacturing · Cubesat · Carbon/epoxy composites · Components · Integrated components · Kits · Longitudinal and Transverse Strength · Microlattices · Multifunctional structures · Opportunity costs · Primary structure and secondary structure · Reliability · Resilience · Shear strength · Small satellite · Spacecraft structural units · Systems engineering · Thermal performance

1 Introduction

The first satellites that were launched were, in fact, small satellites. They were virtually all small platform carrying experimental packages to test out new space technologies. The first emphasis was on testing radio, sensors, and experimental devices and the buses or platforms that carried them were not of particular or special concern. This was particularly the case with regard to the rocket systems of the U.S.S.R. that had developed very powerful rocketry. Some of the earlier soviet satellites in the Sputnik and especially the Molniya series resembled craft that looked more like washing machines than delicately engineered spacecraft designed to reduce mass. In the USA, which had less capable launchers, the design focus was different. The US designers of spacecraft, very early on, began to conceive of satellites buses that had the greatest strength but also required the least amount of mass. The shift from all governmental space operations to commercial systems in US programs, such as Relay (RCA), Telstar (AT&T), Syncom (Hughes), and Early Bird (Intelsat and Hughes), led to research and development to create spacecraft buses that were structurally sound but as light in mass as possible (Pelton 1974).

This led to the development of carbon-epoxy composite structures for the primary structure of a satellite. This type of composite for the primary structure was found to be very strong and the lightest in mass in comparison to such materials as steel, titanium, or metal alloys. These very strong fibers were also extremely resistant to thermal expansion and shear characteristics and still retain compressive strength in both longitudinal and transverse dimensions. As will be discussed later, these primary structural elements can be designed to incorporate other key elements of the satellite's design such as wiring harnesses, sensors such as sun or thermal sensors, etc. Table 1 shows these characteristics for a commercial available carbon fiber/epoxy resin material that is readily now available. Such composites are not only used for the design and construction of spacecraft, but also automobiles, aircraft, and other products where aspects such as strength, durability, and light weight are desirable construction qualities (Carbon/Epoxy Composite 2019).

The use of carbon fiber/epoxy resin composite materials, because of their light weight, thermal stabilities, longitudinal and transverse strength qualities, and durability, became quite common for satellite structure. Indeed this type of composite has been used in the structural elements in the manufacture of a very large number of satellites. Indeed these types of carbon/epoxy are finding their ways into components for aircraft, automobiles, and many dozens of other products. The smallest satellites such as cubesats, pocketques, or chip satellites

Table 1 The strength, shear, and thermal expansion characteristics of carbon/epoxy resin composites

Property	Units	Value
Coefficient of thermal expansion – longitudinal	$\times 10^{-6}\ \mathrm{K}^{-1}$	2.1
Coefficient of thermal expansion – transverse	$\times 10^{-6}\ \mathrm{K}^{-1}$	2.1
Compressive strength – longitudinal	MPa	570
Compressive strength – transverse	MPa	570
Density	$\mathrm{g\ cm}^{-3}$	1.6
Shear modulus – in-plane	GPa	5
Shear strength – in-plane	MPa	90
Ultimate compressive strain – longitudinal	%	0.8
Ultimate compressive strain – transverse	%	0.8
Ultimate shear strain – in-plane	%	1.8
Ultimate tensile strain – longitudinal	%	0.85
Ultimate tensile strain – transverse	%	0.85
Volume fraction of fibers	%	50
Young's modulus – longitudinal	GPa	70
Young's modulus – transverse	GPa	70

The above characteristics are those of RS Stock No. 764-8700, RS Stock No. 764-8703, RS Stock No. 764-8716, and RS Stock No. 764-8707, but they are generally indicative of carbon fiber/epoxy resin composite materials

typically end up not with composites but more likely something like a metal alloy such as a light weight but relatively strong aluminum alloy which is sufficient to the design, since these smallest of satellites tend to be volume limited and not mass limited.

2 Optimized Design of Small Satellites and Structural Design

An optimized design might not be used to reduce the mass of the small satellite but to add additional features or capability. Altering the mass of a small satellite's structural features can thus be seen in the context of an opportunity cost. A better primary structure in terms of lower mass, greater volume, acceptable longitudinal or transverse strength, and or thermal qualities might also be evaluated in terms of allowing additional capability to be added to a small satellite design. Less mass associated with structural design could be reinvested to increase a small satellite's performance, safety features, reliability or ability to de-orbit at end of life.

Indeed a good satellite designer, despite its mass and dimensions, always considers the aspect of "opportunity cost." This is to say that if I can reduce the cost, performance, or mass of a satellite in one aspect of its design, can I produce or can I reinvest that additional mass or volume, etc. to achieve a better result. If I have less mass associated with structure can I increase another capability such as power or processing speeds to produce better overall results in terms of performance of the mission objectives. Systems engineering and assessing opportunity costs are a closely related activity, especially in the world of small satellite design.

The best small satellite structural design is not just limited to its mass, strength, and thermal qualities. The other crucial element is the extent to which it allows the efficient assembly and performance of all the components essential to a small satellite's performance. When one acquires a solar cell panel, that panel could be designed as a structural element of the small satellite and it might also integrate a magnetotorquer or sun sensor or thermal sensor into its design so that the ultimate payload might be more capable. In short, the design of a small satellite such as a cubesat involves volume efficiency as well as mass efficiency. Of the two, volume efficiency is more important, but not if volume efficiency risks reliability and resilience.

3 Small Satellite and Kits and Standardized Structures

There are several ways that one might approach the design, manufacture, test, and deployment of a small satellite. One might start with the idea of doing the entire design and manufacture of a small satellite on a vertically integrated basis either in-house or through a general contractor. This entity will design and try to optimize all aspects of small satellite design, particularly if it is for a large-scale constellation where thousands of small satellites are to be launched. In this case, the idea is to have a structure that is high in longitudinal, transverse, and shear strength, thermally stable, as low in mass and volume as possible, and perhaps adaptable to accommodate elements such as wiring and sensors, and hopefully also low in cost of manufacture and assembly.

The other approach is to acquire subsystems and components from reliable suppliers who specialized in a particular area such as solar panels, magnetotorquers, digital processors, thermal blankets, sun sensors, star trackers, or suppliers of payload systems for telecommunications, networking, remote sensing, data relay, etc. Even prime contractors tend to obtain particular components rather than manufacture every aspect of a satellite.

In the world of small satellites and especially very small units such as at the level of cubesats or qubesats and most particularly when the project is a one off or very limited number of satellites, the ordering of components or kits from specialized suppliers can make a good deal of sense.

Suppliers such as Pumpkin or Innovative Solutions in Space (ISIS) for instance can provide small satellite structures from 1 units up (Pumpkin for instance can provide 1 unit, 6 unit, and 12 unit structural frames). These kits for a cube satellite tend to be manufactured in materials such as an aluminum alloy. The skeletonized structural frame pictured in Fig. 1 by Pumpkin is fabricated from a strong alloy known as Aluminum 5052-H32. This alloy is described as having corrosion resistance and good workability to create a skeletal structure and resistance to metal fatigue and ability to be easily welded. Despite its modest weight, it at least has moderate strength. Since it is used in gas tanks, aircraft fuel lines, appliances, and

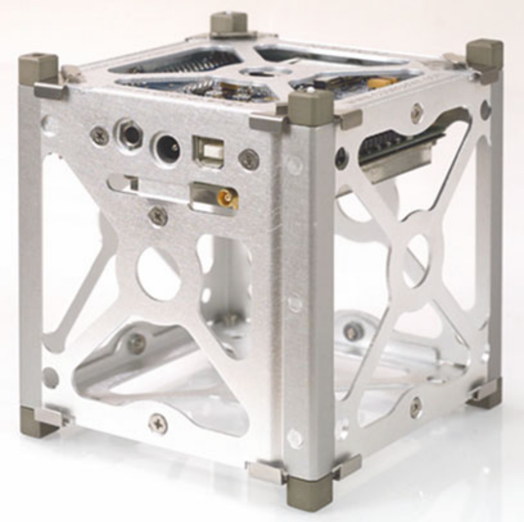


Fig. 1 A skeletal cubesat frame from an aluminum alloy. (Graphic courtesy of Pumpkin)

other applications, its cost is not high. Only in larger microsats and minisats is it common to go to carbon/epoxy composites. See Fig. 1.

The same is true of femtosats (i.e., chipsats) and picosats (i.e., pocketqubes). The systems engineering task in terms of designing the structural elements of these types of small satellites is finding ways to conserve available volume much more than mass. The logic of using kits or assembled units at the level of femtosats and pocketqubes is increasingly clear because the designers of such types of small satellites have already been forces to conserve mass and volume while also meeting structural requirements for strength, shear, thermal integrity, etc. Supplier of kits and launch intergrators for PocketQubes are limited. These include Alba orbital, KSF Space, and GAUSS Srl (see Fig. 2).

The following are some of the suppliers of primary structural systems for satellites at the cubesat level (typically 1 unit up to 6 units and now in some cases up to 12 unit structures). The trend line is that continuing progress has been made in the development of new standards and cost effective structures. Recently, 12 unit structures have been developed by several providers and on the other end more options are beginning to occur with regard to pocketQube units that are 5 cm × 5 cm × 5 cm small satellites that are available for quite small experiments. The fact that the International Space Station is now equipped with dispensing systems that can handle everything from pocketQubes to 12 unit cubesats and thus small satellites from 200 mg to around 90 kg has helped this standardization of structural systems and help lower the cost of such types of smallsats (NASA State of the Art 2018).

- Complex Systems and Small Satellites (C3S)
- Endurosat
- GOMspace

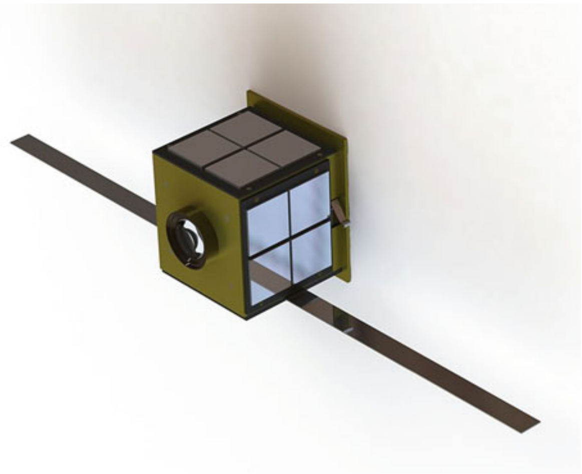


Fig. 2 A pocketqube picosat with camera. (Image courtesy of Alba orbital)

- Innovative Solutions in Space (ISIS)
- NanoAvionics
- Pumpkin
- Radius Cubesat Structures

There are of course other providers and the above list is not intended to be exhaustive. This is the current list of global suppliers for cubesat structural suppliers that appears in the NASA State of the Art of Small Satellite Technology report in their section on Structures, Materials, and Mechanisms (NASA State of the Art 2018).

4 Small Satellite Structure and Additive Manufacturing

One of the key newer elements in the manufacture of small satellites is the introduction of additive manufacture to the building of everything from cubesats to minisats. Additive manufacture can provide a number of advantages to this process.

There are several ways that so-called 3D printing can provide advantages in this regard. If the outside structure and wiring harness for a small satellite are integrated, this can expand the size of the internal volume to accommodate a larger payload. In some designs, the external panels could embed wiring, sun and heat sensors, and even magnetotorquers. This can not only make a small satellite more efficient in terms of payload size, it can also speed up production in the case of small satellites for large-scale constellations (Becedas and Capparros 2014).

The development of suitable standards for materials that can be extruded from additive manufacturing and more adaptable 3D printers with double extruders are now able to cope with the design and manufacture of composite-based satellite structures. This type of double extruders can facilitate the ability to embed functional features into the structure. This can for instance include wiring or sensors and thus create so-called multifunctional structures.

Yet another aspect of additive manufacturing with regard to small satellites that could create yet another benefit is with regard to the minimization of orbital space debris at end of life in terms of its destructive forces on one hand. This new form of manufacturing technique can easily allow for new design possibilities, shapes, and geometries. Such shapes and designs were difficult to achieve in a cost-efficient manner without using 3D printing techniques. These new shapes and geometries might be also designed to facilitate additional atmospheric drag, facilitate release of gases at end of life, or enable ease of repurposing as reusable modules. This type of approach might be compatible with experimental design concepts that have been explored by the US Defense Advanced Research Projects Agency (DARPA) in the context of so-called Satlets.

On the other hand, there is the possibility of using additive manufacturing to create more efficiency shielding techniques for small satellites against potential collision with debris or micro-meteorites as will be discussed below.

5 MicroLattice Structures as a Part of Small Satellite Panels

There are other structural materials other than composites that can make sense for small satellite and their structural design. One of these new possibilities involves the use of metallic lattices or even so-called metallic “micro-lattices” These lattices can play a role in the interior design of structural panels for small satellites. The creation of very light weight but strong metallic lattice structures is one of the possible structural components that are made possible and cost efficient with additive manufacturing techniques. In lieu of foam or other such materials, metallic micro-lattices can be stronger, more resilience, waste less material, and even cost less when fashioned by a 3D printer optimized for this type of design.

With the latest additive manufacturing technique, a metallic micro-lattice could be intentionally designed for a specific need. It is possible to create “negative Poisson rates.” This could allow, for instance, the increased resistance capabilities of a structure, or even to help its protection against collision with a micro-meteorite. This type design could also add to the shear resistance of a small satellite structural panel (Gong et al. 2014).

The capability to make lighter and lighter structural elements via 3D printing continues to improve. The micro-lattice variant that has been designed by Boeing is rather amazingly shown to be 99% air and 1% metal (The lightest metal 2015) (see Fig. 3).

Spacecraft that design orbital space debris shielding in order to lessen the impact energy of debris or micro-meteorites create several layers of shield separated by gaps that could be filled with micro-lattice rather than foam. This may be more the case for microsats and minisats where volume considerations are not quite a severe.

The current approach that is used in most small satellites is typically based on the employment of honeycomb panels. Such honeycomb panels have limited impact

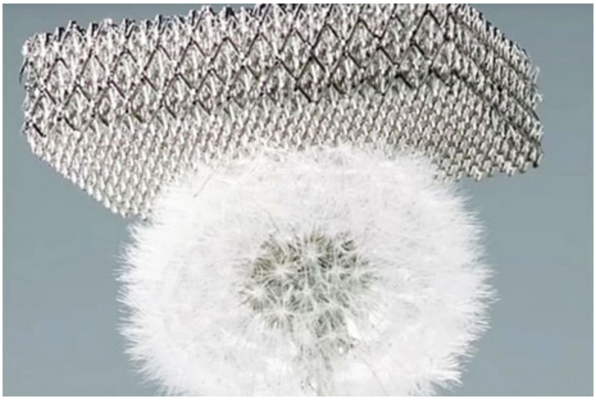


Fig. 3 A super low mass micro-lattice variant suspended on top of a dandelion. (Graphic courtesy of Boeing)

mitigation characteristics. Further the volumetric demands of these honeycomb panels would be challenging to include within the limited volume of a true small satellite such as 1 unit CubeSat standard. The use of metallic micro-lattices is for the future design of debris collision mitigation system. This approach may prove most promising for larger small satellite designs that might be manufactured so that they could be deployed for a large scale LEO constellation.

6 Conclusion

The materials used for the primary structure of truly small chipsats, pocketQubs, cubesats, and up to six unit cubesats will most likely remain metallic materials such as aluminum alloys similar to those discussed in this article. On the other hand, larger small satellites such as microsats and minisats in the range of 10 kg up to 1000 kg may tend to use carbon/epoxy composites. The challenges for the future is the extent to which primary structural elements or even secondary structural elements such as solar cell panels will be designed as highly space efficient components to include harness wiring, sun sensors, thermal sensors, or other quite small units such as magnetotorquer in order to maximize volume for the smallsat payload.

Efficient system engineering will continue to seek to improve small satellite design. This will mean eliminating the inefficiencies of the spacecraft “bus” so as to increase the payload that supports the prime mission for which the spacecraft is being deployed. The idea of considering each and every one of the components of a spacecraft bus as “excess mass” and an impinging occupier of internal volume must be seen as an ‘opportunity cost’ that is taking away power, mass, or volume that could be devoted to the real purpose of a small sat mission. The design of new and improved materials that can be lower in mass and volume, while maintaining longitudinal, transverse and shear strength and be resistant to change as thermal conditions should rise or fall is a clear objective.

The new capabilities that come from additive manufacturing offer a way to pursue these objectives and also reducing the cost of fabrication and material consumption. There are research studies that are seeking to use these new manufacturing techniques to improve the production of multifunctional components or systems, reduce mass, preserve volume for the payload, preserve structural strength and thermal stability, and as find better ways to cope with problems and issues that arise from orbital debris or micrometeorite collisions, as well as to better ways to protect small satellites against collision or to allow these small satellites to be recycled for use within new spacecraft.

Research in materials, structural design, additive manufacturing, thermal and radiation protective materials, multifunctional systems, micro-lattices, recycling of satellite components, and more can help make small satellites better. These innovations can create cubesats that are more cost-effective, more resilient, and better prepared for hazards in outer space include orbital debris collisions, thermal variations, coronal mass ejections, and other design and operational issues.

7 Cross-References

▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
▶ Hosted Payload Packages as a Form of Small Satellite System
▶ Network Control Systems for Large-Scale Constellations
▶ Overview of Small Satellite Technology and Systems Design
▶ Power Systems for Small Satellites
▶ RF and Optical Communications for Small Satellites
▶ Small Satellite Radio Link Fundamentals
▶ Small Satellite Antennas
▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
▶ Stability, Pointing, and Orientation

References

J. Becedas, A. Capparros, *Additive Manufacturing Applied to the Design of Small Satellite Structure for Space Debris Reduction*, vol. 1 (2014), p. 2. https://doi.org/10.5772/intechopen.78762. https://doi.org/10.1051/mfreview/2014001

Boeing, The lightest metal ever (2015), http://www.boeing.com/2015/features/10/innovation-lightest-metal-10-15. Last accessed 21 Dec 2019

Carbon/Epoxy Composite Carbon fibre – Epoxy Resin Matrix (2019), https://www.alliedelec.com/m/d/94dbd134a6050eb5ac2e6e0ad5307516.pdf. Last accessed 18 Dec 2019

X. Gong, T. Anderson, K. Chou, Review on powder-based electron beam additive manufacturing technology. Manuf. Rev. (2014), pp. 1–18

NASA State of the Art on Small Satellite Technology, Section 06: Structures, Materials, and Mechanisms (2018), https://sst-soa.arc.nasa.gov/ .Last accessed 21 Dec 2019

J.N. Pelton, *Intelsat, Politics and Functionalism: Global Communications Satellite Policy* (Lomond Systems, Mt. Airy, 1974)

Small Satellite Constellations and End-of-Life Deorbit Considerations

Vitali Braun

Contents

Abstract

Space missions come with a huge potential to provide global services such as navigation or telecommunication. With decreasing cost to insert satellites into orbit and the further miniaturization, the currently observed launch traffic involves more and more small satellites. Global broadband Internet services delivered by large constellations consisting of thousands of small satellites have been proposed by several companies. Some of the first satellites were already launched. Space debris mitigation guidelines have reached international consensus more than a decade ago and are applied to current space missions. What do they imply for small satellites? And are they still valid for large constellations? If an increasing number of satellites are continued to be inserted into a constrained orbital region, would there ultimately be an issue with sustainability? Research over the past few years has provided some reassuring output that a way toward a sustainable use of outer space does exist – under the current mitigation guidelines and even with operational small satellite large constellations. But there are clear

---

V. Braun (✉)
IMS Space Consultancy GmbH at ESA Space Debris Office, European Space Agency, Darmstadt, Germany
e-mail: vitali.braun@esa.int

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_13

limits, and the international community is faced with an increasing level of responsibility to preserve the commonly shared resource space for future generations.

Keywords

End-of-life · Sustainability · Long-term evolution · Mega-constellations · Disposal · Space debris

1 Introduction

Having achieved the objectives of their satellite mission and barring any mishap before that, any owner or operator is facing the challenge in the inescapable transition from the operational to the disposal phase, assuming that any potential extension of the operational phase has already been applied before. The disposal phase is the time interval during which a satellite completes its disposal actions, with the main objective of permanently reducing its likelihood of a future accidental breakup and to achieve a required long-term clearance of the *protected regions* it had been crossing or operated in ISO (2019). Possible disposal actions range from doing nothing at all; maneuvering the satellite such that it doesn't interfere with any protected region in the near future; targeting a faster orbit decay, for instance, by maneuvering to a lower altitude orbit in the low Earth orbit (LEO) region; targeting an atmospheric reentry with a well-defined impact footprint on the Earth's surface (controlled reentry); to attempting a retrieval of the satellite and a subsequent recovery on Earth, the latter surely being the most expensive option.

Certainly, the *do-nothing-at-all* option after the operational phase results in the lowest direct cost associated with a single satellite mission and may even come with a strong incentive in an intensely competitive market or where missions are selected on a lowest price scheme only (Schaub et al. 2015; Adilov et al. 2013). This is also the case when a satellite is essentially operated until it no longer responds. But any satellite launched into Earth orbit will immediately find itself in company with other active missions, derelict spacecraft, spent upper stages, as well as space debris sharing the very same environment. Leaving a nonoperational satellite in that environment results in an additional potential collision partner for other active satellites, which would be perceived by them as a further operational burden. Even worse, a satellite, after end-of-life and remaining in space for years, or maybe even decades or centuries, may suffer a breakup resulting in hundreds to thousands of fragments lethal to other missions, with Titan Transtage breakups near the geosynchronous region being prominent examples. Left in orbit and potentially approaching an atmospheric reentry in an uncontrolled way, a satellite may also pose a risk to people or infrastructure on ground even many years after its operations have ceased.

In this chapter, today's space environment is described with a focus on orbital regions of interest based on certain applications satellite missions have been designed for. The historic evolution of the space environment and the number of objects on orbit serves as an indication how individual actors, policy decisions, applications, and events (like explosive breakups) continue to shape that environment. With the proliferation of space debris, we put the safe operation of satellites in space and the valuable services they provide at risk. Space debris environment evolution models provide the means to study possible future scenarios. In many different recent studies, the impact of future launch traffic on the space debris environment, involving small satellites and potential large constellations thereof, has been addressed and will be summarized herein.

The rationale for space debris mitigation actions results from such analyses, and environment evolution models allow to evaluate the efficacy of different mitigation strategies. This ultimately leads to the discussion of methods to assess the impact of a given mission on the space debris environment. Perceiving the near-Earth space environment as finite, it is only reasonable to address the idea of a *capacity*, essentially leveraging a satellite-specific environment criticality index to a maximum number of objects a certain environment or orbital region can accommodate during a time period in a sustainable way.

Given that our society today heavily relies on the complex infrastructure in space and assuming that this technological dependence is very likely to intensify in the future, we clearly have to address the sustainable use of the resource space in order to ensure that future generations may likewise benefit from space.

2 The Space Debris Environment

In March 1958, the satellite Vanguard 1 was launched into low Earth orbit (LEO). Having a mass of only about 1.5 kg, the small satellite conducted a very successful scientific mission improving our knowledge in the areas of geodesy and atmospheric research. Operations ceased in May 1964 when Vanguard 1 turned to a derelict spacecraft in an 4000 km × 650 km orbit with a remaining orbital lifetime of a few centuries. Today, it is the oldest human-made object in Earth orbit, sharing that environment with about 19,800 objects (space-track.org 2019), which consist of active and derelict satellites, rocket bodies, and other space debris. But Vanguard 1 is not the only example of a historic signature in today's orbits, which is why understanding our current space environment and, maybe even more importantly, discussing any potential future scenarios are inevitably linked to events and decisions in the past which shaped that environment.

The evolution of the number of on-orbit objects is shown in Fig. 1. After more than 5800 launches and 530 debris-generating events (ESA Space Debris Office 2019), the catalogued orbital population today is clearly dominated by nonfunctional objects, with only about 10% thereof being active satellites (Union of Concerned Scientists 2019). While fragments from explosive breakups of rocket bodies have had the major share in the orbital population since 1961, the situation has distinctly changed after the Fengyun-1C anti-satellite test in 2007 and the collision between Kosmos-2251 and Iridium 33 in 2009, adding in total more than 5700 debris

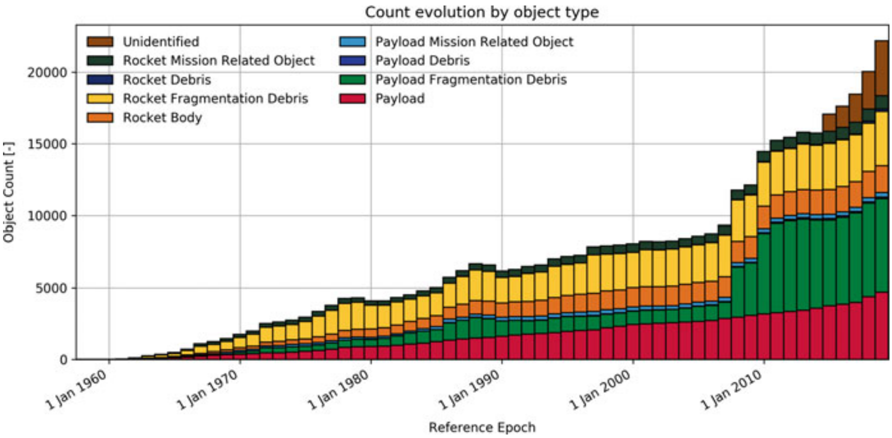


Fig. 1 Count of number of objects in orbit for different object types (https://discosweb.esoc.esa.int, as of August 23, 2019. ©ESA 2019)

fragments. There is one more notable feature in Fig. 1, namely, the objects labelled as *Unidentified* which appear as part of the population since 2015. Those are not new objects but mostly the result of a combination of data coming from two different entities: the satellite catalogue (SatCat) maintained by the US Air Force's 18th Space Control Squadron (18 SPCS) and the catalogue provided jointly by the JSC Vimpel Interstate Corporation and the Keldysh Institute of Applied Mathematics (KIAM). Many of the objects in the Vimpel catalogue are correlated to the ones from the SatCat, but there is a remaining subset of objects, mainly in higher altitude orbits, which have not found their way into the US catalogue. Moreover, as their origin could not be determined, they remain categorized as unidentified for the time being which, in fact, is also true for a few objects in the US catalogue.

Evidently, no single catalogue can ever claim completeness, and the object count evolution in Fig. 1 is only referring to the subset of objects we are able to monitor continuously via ground-based observations, limited by observability constraints and sensor sensitivity. The numbers in Fig. 1 are often referred to in literature as on-orbit objects larger than 10 cm, which more or less reflects on current sensor limits. Space debris models, such as ESA's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER), provide a comprehensive picture of the environment given the evidence we have. In its latest version (available from https://sdup.esoc.esa.int), the MASTER model counts about 34,000 objects larger than 10 cm at the reference epoch of November 1, 2016. By modelling known debris-generating events and calibrating them with actual measurements (Braun et al. 2019), MASTER provides us with estimated object numbers as if we were unaffected by observability and sensitivity limits.

Being designed to fulfil a specific mission, operational satellites have been launched to orbits that accommodate best for the given mission objectives. As those satellites and their associated rocket upper stages are the main source for any debris generated, it does not come as a surprise that the distribution of space debris more or less follows the one of their progenitors, at least for larger objects sizes. Figure 2 shows the spatial density, that is, the number of objects per volume element of one cubic kilometer, as a function of the orbital altitude in LEO for objects larger than 10 cm according to MASTER. The most congested altitude band is between 700 and 900 km. It is the preferred region for Earth observation satellites and a typical choice for Sun-synchronous orbit missions. Clearly visible are the two distinct peaks in the collision fragments from the Fengyun-1C (at about 850 km) and the Kosmos-Iridium (slightly below 800 km) events, both of which occurred in the very same congested region. The spatial density shows a steep decline toward lower altitudes due to increased atmospheric drag which acts against the direction of motion, thereby lowering the objects' orbital altitude over time and effectively acting as a natural sink mechanism for the space debris environment.

The increasing number of objects in Earth orbits has a major impact on the operation of satellites. Over the past few years, collision avoidance has become a standard process for any maneuverable satellite in LEO, for example, ESA's Space Debris Office reports on 27 collision avoidance maneuvers (CAMs) in 2018 conducted by 8 satellites (Braun 2019). Taking the entire LEO satellite fleet operated by the European Space Operations Centre (ESOC) into account, an average number of one to two CAMs are required per year and per spacecraft (Braun 2019). An ESA study concluded that each avoidance maneuver can be associated with an overall cost of approximately EUR 25,000 (Krag et al. 2018). Extrapolating this number to about 580 alerts above the maneuver threshold, assumed to occur annually in LEO, results in a potential yearly damage of EUR 14.5 million (Krag et al. 2018).

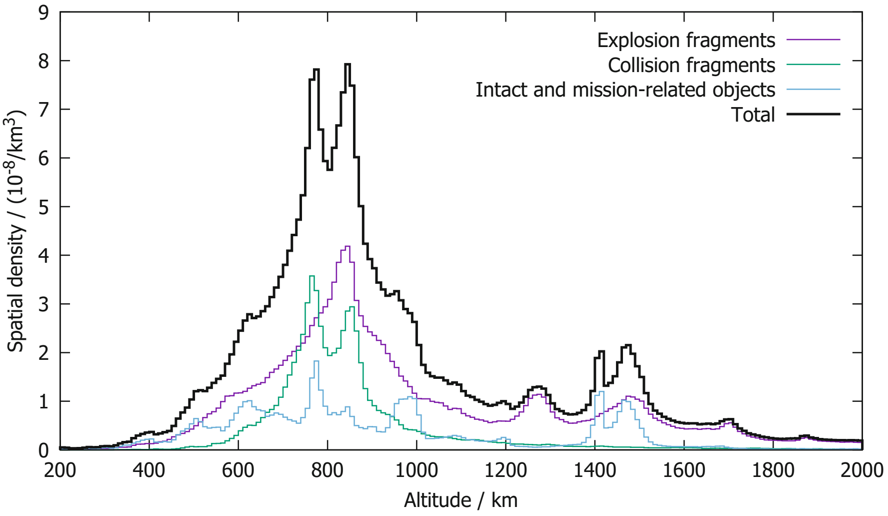


Fig. 2 Spatial density in the LEO region for objects larger than 10 cm according to the MASTER model on November 1, 2016. (©ESA)

The consequences of a collision can be manifold. A widely accepted criterion to assess whether an impacting object is lethal or not is the energy-to-mass ratio for that event: if the kinetic energy of the impactor divided by the mass of the target satellite is above 40 J/g, it is generally considered a catastrophic collision resulting in a complete fragmentation of the target satellite (McKnight 1991). For instance, an aluminum sphere of 10 cm diameter hitting a 1500 kg LEO satellite with a typical impact velocity of 10 km/s results in an energy-to-mass ratio of about 50 J/g. The higher the impact velocity, the smaller a lethal object can be. This became quite evident in August 2016, when Sentinel-1A was hit by an impactor of about 1 cm in size (Krag et al. 2017) into its leading solar array wing. A picture taken by an onboard camera confirmed a 40 cm impact feature that also explains the permanent power loss of about 5% for the mission. The MASTER model estimates about 900,000 objects larger than 1 cm, and a flux analysis for the Sentinel-1A orbit reveals that the annual probability of an impact with objects larger than 1 cm is about 6%. The Sentinel-1A mission survived this impact without major consequences. Certainly, if the main body would have been impacted, the outcome could have been significantly worse, ranging from the loss of components over subsystems up to the entire mission. However, it is not only the individual mission affected after such an event. The Sentinel-1A event resulted in a total number of seven tracked fragments, which also appeared as chasers (or secondary objects) in the regular collision avoidance screenings of other ESA satellites. With even higher numbers of fragments, the effects will be non-negligible in the operations of other missions: the fragments of the Fengyun-1C and the Kosmos-Iridium event combined make up about 40% of all conjunction events (where the collision probability went above 10^{-6}) for the satellites screened by ESA's Space Debris Office since 2015.

The effect of collision fragments triggering new collisions and potentially leading to a self-sustained growth in the object numbers has been described by Kessler and Cour-Palais (1978) and became known as the *Kessler syndrome*. It basically means that if in a certain region a critical density of objects is reached, the self-sustained cascading effect would further increase the density without even adding new objects into that orbital region through new launches. This has been confirmed by more recent long-term environment evolution studies (e.g., Liou 2011), where even a future no-launch scenario resulted in an overall orbital population growth due to mutual collisions. The time when this tipping point had been passed was estimated to be in the 1990s (Bastida Virgili and Krag 2011). It is therefore likely that the conditions for a self-sustainable growth are already met in the altitude band between 700 and 900 km and remediation measures, such as active debris removal, might be required to stabilize that region in the future.

The threat posed by the space debris environment, as outlined above, has been recognized as critical by the international community during the 1990s. With officially establishing the Inter-Agency Space Debris Coordination Committee (IADC) in 1993 and culminating in the adoption of the United Nations Technical Report on Space Debris in 1999 (United Nations (UN) 1999), the way toward an international consensus on space debris mitigation had been paved.

3 Space Debris Mitigation

The IADC Mitigation Guidelines (IADC 2007) have been endorsed by the UN General Assembly in 2007 and formed the required international consensus as the basis for subsequent standardization (e.g., ISO-24113:2011) and adoption into national laws (UNCOPUOS 2019a). The main intent is to reduce short- and long-term space debris generation via dedicated mitigation measures. As of today, the only discrimination made is between launch vehicles and spacecraft, which means that all mitigation measures apply equally, whether the mission is public or private, whether it is a large scientific satellite or a tiny *femtosat*.

For satellites in any orbital region, the mitigation guidelines entail to limit the release of debris and minimize the breakup potential during normal operations, to limit the probability of accidental collision with known objects, and, after end-of-life, to passivate the satellite and limit its presence in either the LEO or the GEO protected regions. The *LEO protected region* is defined as the spherical region that extends from the Earth's surface up to an altitude of 2000 km, whereas the *GEO protected region* is a segment of the spherical shell defined by the altitude band between 35,586 and 35,986 km (geosynchronous altitude ±200 km) and latitudes between ±15 degrees with respect to the equatorial plane (IADC 2007).

Even though there are some small satellites (<500 kg) that are launched into geosynchronous orbits, those typically have a few hundreds of kilograms of mass. The vast majority of satellites, especially with a mass below 100 kg, are launched into the LEO region. For instance, for the nano-/microsatellites in the range between 1 and 50 kg, less than 2% of those are expected to go beyond the LEO region in the projected period from 2019 to 2023 (SEI 2019). Therefore, the focus in the following will be on LEO missions.

The disposal phase for any satellite mission in LEO consists of two major steps: limiting its presence in LEO to a maximum of 25 years followed by a passivation of the spacecraft. The so-called *25-year rule* has been accepted based on long-term environment evolution analyses (see also next paragraph) showing an acceptable future trend in the orbital population. For satellites without any maneuvering capability, and therefore lacking the means to avoid collisions, it is understood to set the starting point of that 25-year period already at the time the object is inserted into the environment, whereas for maneuverable satellites that period starts only after the end of the mission. Several options to accomplish the removal of a satellite from the LEO protected region exist and are given in order of preference in ISO (2019):

1. Retrieving it and performing a controlled reentry to recover it safely on the Earth
2. Maneuvering it in a controlled manner into a targeted reentry with a well-defined impact footprint on the surface of the Earth to limit the possibility of human casualty
3. Maneuvering it in a controlled manner to an orbit with a shorter orbital lifetime that is compliant with the 25-year rule
4. Augmenting its orbital decay by deploying a device so that the remaining orbital lifetime is compliant with the 25-year rule

5. Allowing its orbit to decay naturally so that the remaining orbital lifetime is compliant with the 25-year rule

Unless any of the first two options is selected, a passivation of the satellite is required. In general, this implies that the satellite design already foresees measures to permanently deplete all remaining onboard sources of stored energy, such as discharging batteries and making sure they do not recharge again, venting pressure vessels and safe or stop any moving parts like momentum wheels or flywheels.

With retrieval or targeted reentries being very uncommon disposal options for small satellites, the general approach is to launch them into sufficiently low orbits which would comply with the 25-year rule through natural orbital decay. Alternatively, if there is maneuvering capability or the option for orbital decay augmentation after end of mission, for instance, via drag sails, higher altitude orbits can be selected. A more detailed set of recommendations, specifically for small satellites, is provided by IAA (2019). Figure 3 shows the destination orbits (by perigee and apogee altitude) of small satellites with mass below 50 kg. Obviously, the more recent launches tend to put small satellites into lower orbits, but this cannot be attributed to the parallel development of space debris mitigation guidelines alone: it is rather the fundamental change in how small satellites are being launched. The first missions had to find opportunities for piggyback launches, where the primary payload would determine their orbit. It shouldn't come as a surprise that many of those first missions had been injected into typical orbits Earth observation satellites

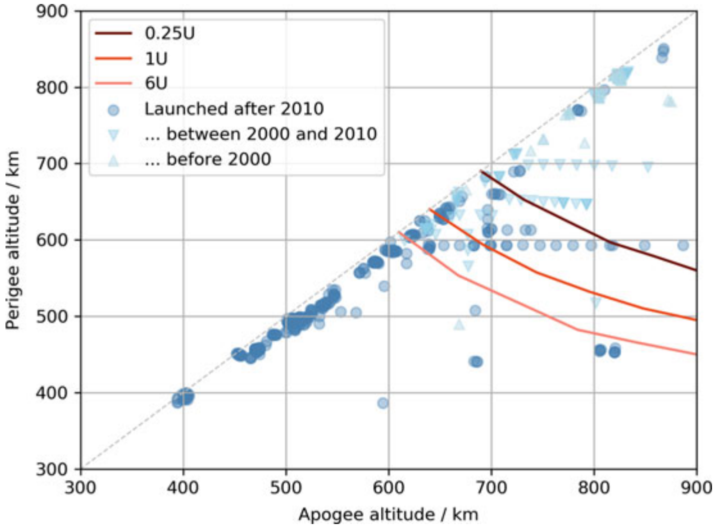


Fig. 3 Destination orbits according to ESA's DISCOS database for on-orbit satellites (as of September 2019) with mass below 50 kg. Altitude limits for a natural orbit decay within 25 years (simulated with ESA's DRAMA/OSCAR tool) indicated for 0.25 U, 1 U, and 6 U CubeSats, for randomly tumbling EOL attitude and a mass of 0.25, 1, and 6 kg, respectively. (©ESA)

occupy, for instance, in Sun-synchronous orbits around 800 km. With ride shares and especially dedicated small satellite launches becoming a reality in the last few years, the picture has clearly changed. From a space debris mitigation perspective, this can be called a positive trend (if launch providers apply the available mitigation standards and guidelines), which is also confirmed by ESA's latest environment report (ESA Space Debris Office 2019): for satellites with a mass below 10 kg, the LEO lifetime compliance has increased from 70.9% to 77.6% over the course of 10 years (2000 vs. 2010). Moreover, looking at the small satellites below 50 kg, as displayed in Fig. 3, it can be said that for all launches since the year 2000, about 26.4% of the satellites currently on orbit have a lifetime beyond 25 years. For those launched since 2010, that number drops to 16.0% and for objects launched since 2015 even to 6.7%. Figure 3 indicates the altitude limits for three different types of CubeSats below which a compliance with the 25-year rule through natural orbital decay can be expected. For near-circular orbits, this threshold is typically around 600 km but depends on the specific satellite design, its assumed attitude mode after disposal, and the applied solar activity forecast method the estimated lifetime is susceptible to. There are many uncertainties in the lifetime estimation process and thus in the compliance verification of any end-of-life disposal plan. Nevertheless, commonly accepted methods and processes on how to perform such analyses have been established, for instance, on ISO level (ISO 2016), and form the basis for tools used by agencies, industry, and academia worldwide in early mission design phases, such as NASA's DAS (Liou et al. 2019), CNES' STELA (CNES 2019), or ESA's DRAMA software (ESA 2019).

The preference of lower altitude orbits comes with another advantage in view of the small satellite failure rates that are still rather high with 42.6% of all launched small satellites between 2009 and 2016 showing either partial or total mission failure (Jacklin 2019). With access to space becoming more affordable, many new entrants come with a generally lower experience in space hardware compared to traditional entities. In addition, shorter design and development cycles do not necessarily imply a positive effect when it comes to reliability. It does not mean that granting everyone access to space is something bad – rather the contrary. But from a perspective of a sustainable space debris environment, it is preferred to have such missions in altitudes where they would naturally comply with guidelines and failure can thus be an option. In other words, if reliability is difficult to assess for any newly developed system, a recommendation could be to go to higher altitude orbits only after a certain design has been proven to work, for instance, via a precursor mission or a checkout in a low altitude orbit.

While the reported failure rates apply to single small satellite missions, the situation might be completely different for small satellite constellations. If a constellation operator can demonstrate a subset from the envisaged constellation working flawlessly, it might be reasonable to assume that the entire fleet would operate with a high success rate, given the identical satellite design. But what is a sufficiently high success rate given that today's mission to deploy large constellations typically targets orbital altitudes around 1000 km? Any satellite failing at those altitudes would remain in the environment for centuries or even millennia. It is therefore crucial to address the environmental impact any large constellation deployment may have and to carefully design the required end-of-life strategy (IADC 2017).

4 Small Satellite Constellations and the Future of the Environment

The concept of satellite constellations has been around since the beginning of space flight, where a group of similar satellites would be used to achieve a certain objective in areas including navigation, telecommunication, meteorology, Earth observation, and reconnaissance. While most of the historic and operational constellations would typically consist of dozens up to a few hundreds of satellites, a rather recent development is to provide low-latency global broadband Internet services through a space-based infrastructure consisting of thousands of small satellites. A very high number of satellites, in a large constellation, are required to obtain a global broadband coverage, whereas the low-latency requirement would demand a deployment in lower altitudes. The most prominent examples include:

- Project Kuiper by Amazon, proposing a constellation of 3236 satellites in LEO according to a filing with the FCC on July 4, 2019.
- The first six satellites were launched in February 2019, but this system has currently declared bankruptcy.
- SpaceX's Starlink constellation consisting of 4425 up to 11,943 satellites, with a first batch of 60 satellites launched in May 2019.

Even though the potential impact of satellite constellations on the space debris environment has been subject of study long before the announcement of any of the abovementioned large constellations (e.g., Anselmo 2001), the current space debris mitigation guidelines are based on the outcome of long-term environment evolution projections without foreseeing any distinct constellation deployment in the models. It was therefore only reasonable that concerns had been raised on whether the recommended mitigation practices were sufficient to limit the growth of the on-orbit population given that thousands of new satellites may become part of that environment very soon. Therefore, several investigations were initiated, mainly involving researchers with capabilities to run long-term environment evolution studies, and coordinated on IADC level, in order to show how a potential future with large constellations in orbit might look like and to provide further technical input to the ongoing policy and guidelines discussions on long-term sustainability. It is important to understand that one does not even get close to predicting the future of the environment with any of the available models. However, if reasonable assumptions are being made and there is an international consensus on the modelling approach, then it is possible (and in fact being done) to base policy decisions on the outcome of such studies. They do not provide credible estimates on the exact total number of objects the population is going to have at a certain point in time, but they allow studying the relative effects when certain mitigation measures are introduced. As an example, the 25-year rule reached consensus after the simulation results obtained by different entities had shown a limited growth of the environment – compared to a reference scenario without disposals in LEO that showed an exponential increase in object numbers indicative of a collisional cascading runaway situation.

Before discussing the outcome of the recent studies on the effects of large constellations, it is important to understand the modelling approach and the assumptions typically made in such simulations in order to ease the interpretation of the results and to be aware of the various uncertainties and the sensitivity of certain parameters.

The first step is to select a reference population representing the current space debris environment. At IADC, as an input to the studies on large constellation, it was agreed to select the MASTER reference population from January 1, 2013 for all objects larger than 10 cm (about 20,000 objects in LEO). The size threshold means a trade-off between those objects relevant for the simulation, i.e., being lethal in a sense of potentially causing catastrophic breakups, and the required computational resources. For the selected objects in that population snapshot, the orbital evolution can be computed until any given point in the future. Typically, projection spans between 100 and 200 years are foreseen.

As new satellites are certainly going to be launched in the future, the next inevitable step consists of defining a launch traffic model. Figure 4 shows the launch traffic to the LEO protected region until 2018. While civil and defense missions were

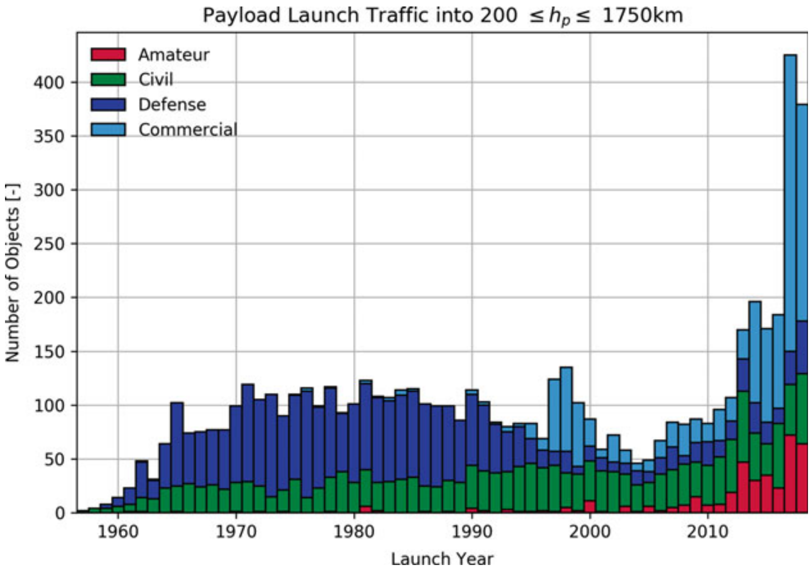


Fig. 4 Payload launch traffic to the LEO protected region (ESA Space Debris Office 2019. ©ESA 2019)

predominant until the early 1990s, amateur and especially commercial missions initiated the paradigm change toward what is referred to as *NewSpace* today. A researcher in 1985 might have perceived a very comfortable situation observing that there was a launch record of roughly 100 satellites per year into LEO for the past 15 years and even a more or less stable share between defense and civil missions. It would have been a reasonable assumption back then to say that things might remain like this for quite some time and therefore to assume a stable launch rate of 100 satellites per year for the future evolution studies they had envisioned. The same researcher 30 years later would be faced with a certain issue: seeing the commercialization, the trend toward smaller satellites, new launch opportunities (ride shares and dedicated small satellite launches), and the announcements made on a possible deployment of large constellations, it is a rather daunting task to make any launch traffic projections, especially for a 100-year time horizon. In past IADC activities, it was generally assumed that the launch record of 8 years may be concatenated to cover the projection span. For instance, when using the IADC 2013 population, the launch record from 2005 to 2012 would be taken such that all launches in the future resembled the very same activity, with only a decent jitter applied to the orbital elements of each payload newly added to the simulation. However, the launch activity between 2005 and 2012 was substantially different from what we see today, especially if market forecasts (e.g., SEI 2019) are taken into consideration, which rather confirm the trend of several hundreds of satellites launched into LEO in the coming few years. In order to account for this effect, many researchers have augmented their models to follow the 2005–2012 cycle and superimpose a trend derived from recent small satellite launches and current market forecasts.

The launch traffic model adds objects to the environment generally assumed to be operational for a certain period, where either they would have no orbit control and thus follow a natural orbit evolution due to external perturbations or they would perform station-keeping and/or collision avoidance maneuvers. In the latter case, it can be assumed that a satellite would successfully avoid any potential collision while it is operated. After its operational phase, that satellite would join the set of objects that are susceptible to collisions and at any simulation step be evaluated by the breakup event model. As an example, the model would check whether at any given time step two objects share the same volume element in space. If this is the case, a collision probability for that encounter would be obtained, and, based on the result, a collision may be triggered or not. In the former case, a breakup model (very common is NASA's Standard Breakup Model EVOLVE 4.0 (Johnson et al. 2001)) would generate fragments of a given size, area-to-mass ratio, and velocity increment, which are subsequently added to the population. The breakup event model would also be used to trigger explosive fragmentations, generally applied to the subset of on-orbit rocket bodies. Again, one may take the history of on-orbit explosions and extrapolate a trend for the future, but then it is also reasonable to assume that passivation would be successfully applied to all future launchers and at a certain point no explosive breakups would occur any more. The latter approach is sometimes preferred to better isolate and compare mitigation measures in a collision-driven growth of the environment.

With the assumptions made above, one simple reference scenario can already be created without any post-mission disposal (PMD) measures so that both satellites and rocket bodies are left on their orbits after their mission. Mitigation activity is added to the model and includes passivation, PMD, and active debris removal (ADR) measures. An exemplary simulation output is shown in Fig. 5. Without any mitigation measures, a nonlinear increase in the number of objects in LEO can be observed, which effectively means that catastrophic collisions would occur more frequently over time – a prerequisite for a collisional cascade. With passivation alone, the number of objects after 200 years is already halved, but a nonlinear trend is still discernible. Adding PMD (with a success rate of 90%) on top leads to a still growing population. Finally, a complete remediation of the environment could, in theory, be achieved by ADR depending on the rate of objects being actively removed from the environment. In Fig. 5, an example is given for five satellites being actively removed per year.

Having established a reference scenario for the background population without any deployment of large constellations, the effect of inserting thousands of small satellites into distinct altitude bands can now be studied relative to that scenario. A generic large constellation was devised in Bastida Virgili and Krag (2015), with a total of 1080 active satellites at 1100 km altitude, and distributed in 20 orbital planes with an inclination of 85 degrees. The full set of model parameters from that study is given in Table 1.

Several operational and end-of-life options were considered to see what the impact on the environment might be, measured in the total number of objects and the cumulative number of catastrophic collisions after 200 years. In addition, the obtained graphs provide additional information whether there is an indication of a runaway situation or not. It was observed that the PMD success rate appears to be the most sensitive parameter, as shown in Fig. 6 for the mean environment evolution trends from a detailed Monte Carlo analysis. The impact of a large constellation can

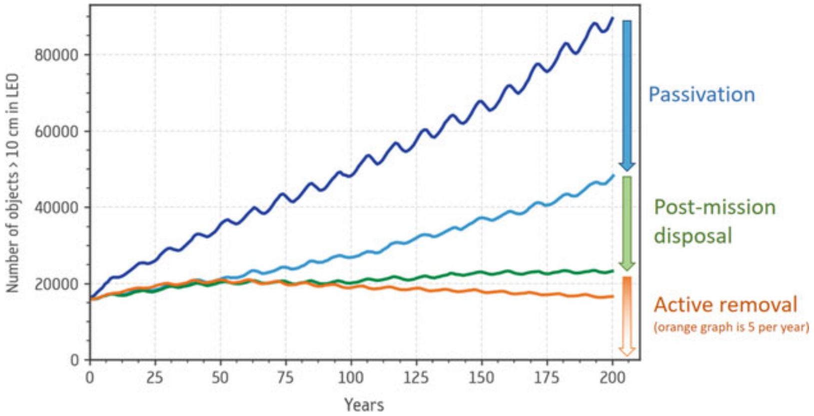


Fig. 5 Example for the evolution of object numbers (>10 cm) in LEO over 200 years for different mitigation strategies. (©ESA)

Table 1 Simulation parameters for a generic small satellite mega-constellation in Bastida Virgili and Krag (2015)

Parameter	Value
No. of satellites	1080
Orbital altitude	1100 km
No. of orbital planes	20
Orbit inclination	85 deg
Mass per satellite	200 kg
Average cross section	1 m^2
Full operational capability	2021
First launch	2018, with 20 launches/year until 2021
Operational lifetime	5 years
Replenishment	12 launches/year
No. of satellites per launch after 2021	18
Upper stage behavior	Immediate reentry after satellite release
Mission-related objects released	None
Collision avoidance	Yes
Constellation lifetime	50 years
End-of-life strategy	Lowering only perigee altitude such that remaining lifetime is <25 years
Background population	MASTER reference population from May 1, 2013; launch traffic 2005–2012
Background population PMD success rate	90%
Explosions	None

essentially be separated into three parts: a steep increase in the on-orbit object population during the constellation buildup and replenishment phases; followed by a period of a decreasing population while the remaining satellites after disposal are still on their decaying orbits; and, finally, a long-term, gradual increase in the population due to collisions involving long-lived, failed constellation satellites.

Assuming a 100% success rate for the disposal of constellation satellites, it is even possible to return to an environment where there would be basically no sign that a constellation ever existed (magenta graph). Applying the same PMD success rate as for the background (90%), a notable difference is observed after 200 years, but the trend (green graph) is very similar to the background population, and also the growth rate is on the same order, so that one could call such a scenario acceptable. In fact, later studies (e.g., Bastida Virgili et al. 2016a) introduced a Wilcoxon rank sum test to show that the null hypothesis of a nonexistent long-term impact had to be rejected (at a 5% significance level) for PMD success rates below 95%. Further reducing the PMD success rate leads to an increase of the object growth rate in LEO after the constellation lifetime, as shown for the 50% case in Fig. 6 (blue graph). In that case, it is already very obvious that the constellation has a long-term impact on the environment. It should be emphasized that Fig. 6 is only showing the mean trends.

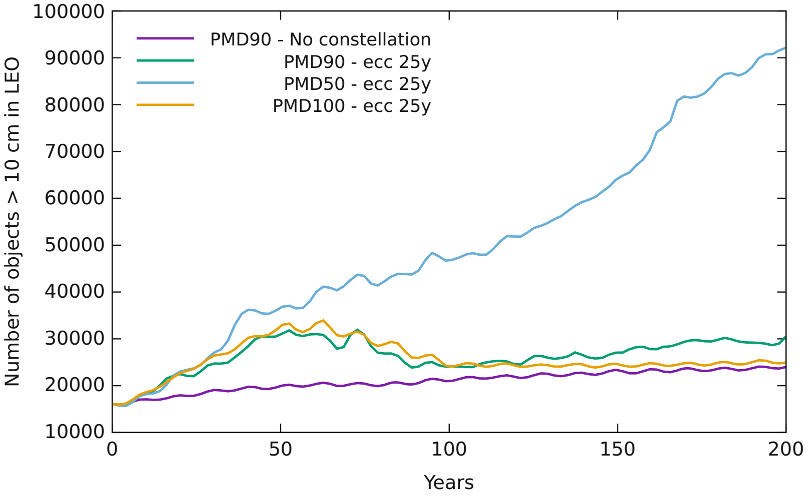


Fig. 6 Evolution of the number of objects in LEO varying the PMD success rate for constellation satellites. (Bastida Virgili and Krag 2015. ©ESA, 2015)

Other representations included the assessed uncertainty from the different Monte Carlo runs and showed that variations from that mean can be quite high, even though they do not contradict the interpretation given here (Bastida Virgili et al. 2016a). A high PMD success rate is therefore required, as otherwise many failed satellites will end up stranded in the constellation's operational altitude and suffer from collisions at some point. Another finding was a positive correlation between the constellation lifetime and the PMD success rate: increasing the former demands to be more successful in the disposal phase in order to end up in similar scenarios after the constellation has ceased.

More detailed analysis followed later, after the initial identification of significant parameters for the long-term impact on the environment had been made, e.g., (Bastida Virgili et al. 2016a, b). Combining the results of different environment evolution models, it was confirmed that the highest priority for any large constellation should be on the PMD success rate. The effect of further reducing the remaining orbital lifetime after disposal, for instance, from 25 years to 10 years, was discernible, as the interaction with lower altitude satellites and the potential for a collision would be reduced. A trade-off between PMD success rate and the residual lifetime would be always biased toward the former. As an example, a 90% PMD success rate combined with a 25-year remaining lifetime strategy resulted in the same number of objects in LEO over the projection period as a scenario with 85% PMD success rate and disposal orbits with a 5-year remaining lifetime (Lewis et al. 2017). However, the failure rate is typically not selectable by the constellation operator and may be even unknown at the beginning when the constellation is being built up. One option is to insert the first satellites into low orbital altitudes and have an initial checkout phase followed by a transfer to the operational orbit. In that case, any early orbit failure will leave a satellite stranded at altitudes that are highly affected by residual drag, thereby leading to a quick natural removal from the environment.

Satellites being part of the background population would experience a non-negligible impact of such a large constellation operated at much higher altitudes, as the disposed constellation satellites would start crossing their operational orbits. The efforts in terms of collision avoidance would clearly increase, with an example being the five- to tenfold increased flux estimated for the International Space Station (ISS) during the constellation's operational lifetime (Lewis et al. 2017; Peterson et al. 2016). Adding high numbers of small satellites into lower altitudes below 600 km only exacerbates this effect (Bastida Virgili et al. 2016b).

Similar results for slightly different constellation parameters were also obtained by other researchers (e.g., Kitajima et al. 2016). In essence, one may conclude that the more general results obtained for the space debris environment evolution in earlier studies, e.g., (Anselmo 2001), were confirmed by the more recent analyses that put a focus on the impact large constellations may have: a full adherence to the currently existing mitigation guidelines (incl. the 25-year rule) may avoid a destabilization in the long-term evolution of the environment, if accepted PMD failure rates for constellation satellites would be limited even further. This would also be in line with the currently recommended end-of-life disposal reliability of 90% in ISO-24113 as a bare minimum. Further measures that have an influence on the environmental impact already during the design phase are to decrease the constellation satellites' cross section and to increase the individual constellation satellite's lifetimes (Lewis et al. 2017). Nevertheless, an impact on the environment will always exist, at least on the short-term during the operational phase of the constellation with an increase in collision avoidance efforts for all other operators.

Even though these findings provide some reassurance that the environmental impact of small satellite large constellations can be addressed and significantly reduced through careful mission design, there is an important caveat: the conclusions drawn from the investigation of the environmental impact of a single constellation to not always lend themselves to be applied if multiple large constellations are being operated. Moreover, even the increase of the number of intra-constellation satellites beyond the about 1000 satellites (as used in most analyses) may lead to different conclusions. For instance, in a constellation of 4000 satellites, the influence of whether conducting operational collision avoidance for the constellation satellites or not is much more pronounced than in a 1000 satellites case (Kitajima et al. 2016). This is understandable, as quadrupling the number of satellites in the constellation and applying the same PMD success rate mean that after any given time interval, the expected number of failed satellites at the constellation's operational altitude is four times higher. In other words, a linear increase in the constellation size may result in a nonlinear increase in the number of self-induced catastrophic collisions (Lewis et al. 2017). This finding has been also confirmed for non-constellation traffic: the expected increase in small satellites being launched into near-Earth space requires us to rethink the "big space" paradigm. Certain altitude bands (around 800 km) appear to show a future increase in spatial density even if no further launches would occur (Somma et al. 2019). Also other altitudes, as the ones proposed for large constellations, show the tendency of a limited capacity in terms of a maximum number of satellites that could be inserted for a given time interval. A notion of the need to control the growth of the number of objects in the environment is thereby attained.

5 Environment Control: The Concept of Capacity

The current set of space debris mitigation guidelines apply to single satellites and launch vehicles. Although their formulation is based on technical input gathered from long-term environment evolution studies, there is no dynamic way of accounting for significant changes in the environment that were not foreseen in those studies, like the substantial transformation of launch traffic with increased commercialization of the space sector or the current adherence levels to mitigation guidelines as opposed to expected ones. Moreover, it was noted earlier that a linear change in the behavior of an individual object has a nonlinear response when the number of individuals is high enough. Recognizing that each satellite may leave a certain footprint during its presence in the space debris environment, it seems only reasonable to come up with a metric or index formulated such that relevant aspects of the satellite's mission affecting the environment evolution are captured. Applying such an index globally, one may take this approach one step further and come up with the concept of environment capacity: if a certain environment evolution trend for a given period appears to be acceptable to the international community, one can compute the cumulated index and thus obtain the available resources to the community over the same period.

Several authors have studied ways of classifying intact satellites with respect to their environmental criticality. The *Figure of Merit* (FOM) developed in Utzmann et al. (2012) allows ranking objects according to their preference for active debris removal. Similar ranking schemes have been devised and extended to be applied in other areas such as the *Criticality of Spacecraft Index* (CSI) in Rossi et al. (2015), which has been later modified to assess parameter sensitivities of certain large constellations designs (*Criticality of Constellation Index* (CCI) Rossi et al. 2017); the ranking scheme to evaluate the Italian satellites' disposal strategy compliance in (Anselmo and Pardini 2015); the *Environment Criticality* (EC) index in (Kebschull et al. 2017); or the *Environmental Consequences of Orbital Breakups* (ECOB) in (Letizia et al. 2017). Most of those formulations are based on a very simple relationship for the index:

$$Index = Probability \times Severity,$$

where the *probability* quantifies the likelihood of a collision (and subsequently a catastrophic breakup) for a given orbit subject to the background space debris population, whereas the *severity* provides an estimate of the potential breakup consequences.

Providing flux estimates for any given target orbit, the MASTER model has been used in many formulations, e.g., for the EC or the ECOB index, to come up with a value for the probability at distinct epochs but also to compute an integrated value over the mission lifetime (or the entire on-orbit time) capturing both the evolution of the target orbit and the background population.

The severity term generally quantifies the impact a fragmentation of the target satellite would have on the environment, including active satellites. For instance, if a breakup is likely to occur in densely populated orbital regions, the severity term will correspondingly be higher compared to cases with breakups in regions with low activity. More complete solutions, like for the ECOB index (Letizia et al. 2019), take also into account that fragment clouds evolve over time and thus affect different orbital regions and active satellites in the future.

The application of an index, or any other comparable risk metric, will capture the impact of a single mission on the environment. It will discriminate between large and small satellites, it will favor missions in naturally compliant orbits over high altitude ones, etc.

Having established the formulation of the index for single satellites, it is straightforward to compute the *cumulative index* for the entire on-orbit population of intact satellites. The strength of this cumulative index, when carefully constructed, is that it quantifies the notion of space as a limited resources discussed earlier. In such a representation, the state of the environment can be evaluated, and different mitigation strategies may be compared with respect to each other. An example for the cumulative ECOB index is shown in Fig. 7. It compares three

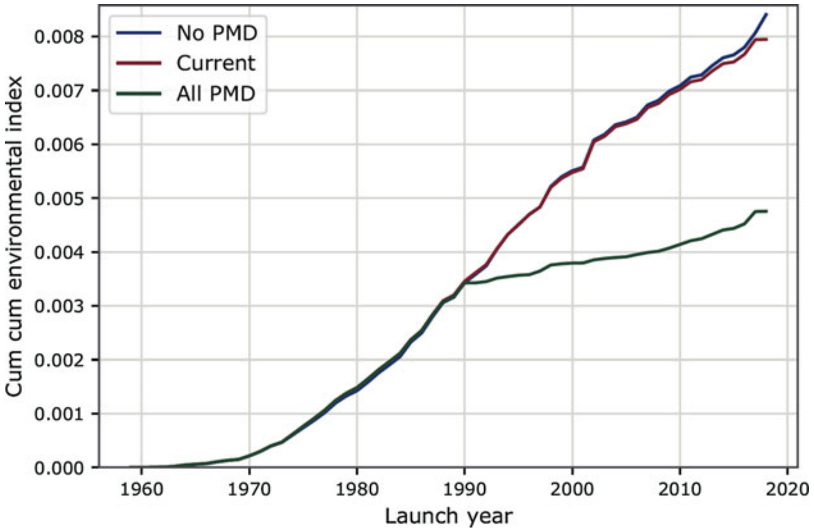


Fig. 7 ECOB cumulative index as a function of time for different mitigation scenarios. (©ESA, 2018)

different strategies that were assumed to be applied since 1990 in order to see how the environment would have evolved until today. The *No PMD* scenario would see satellites just left in their operational orbits after the end of mission; in the *Current* scenario, the actual environment as it evolved until today can be found, whereas the *All PMD scenario* shows an evolution where all satellites launched after 1990 would have been disposed of after their operational lifetime. In essence, if end-of-life mitigation measures would have been applied since the 1990s as they are recommended today (of course, they did not exist back then), the cumulative index would have been only half of what it is now. Interestingly, the current situation is very close to the *No PMD* scenario. In other words, a low level of adherence to the mitigation guidelines does not differ too much from a scenario where operators just do not dispose of satellites after their end of mission. It may also indicate that the satellites being disposed are not necessarily the most critical ones in the environment.

In this sense, the formulation of an index can be used as a metric to describe the environment capacity. Without loss of generality, an example is being discussed in Letizia et al. (2019), where it is assumed that the international community could agree on a long-term environment evolution trend with a rigorous implementation of space debris mitigation guidelines and an associated PMD success rate of 90% corresponding to what they could define as a sustainable use of the resource space. It is possible to compute the cumulative index for such a scenario, which had a value of 2.4 over 100 years in Letizia et al. (2019). All missions that are supposed to be launched over the next 100 years are thus thought to consume at most an index of 2.4. If started in 2020, a certain index for all satellites launched in that year could be obtained, along with what remains for the subsequent 99 years by just subtracting what was consumed in 2020. This way, an important feedback mechanism could be introduced, where mitigation measures were directly translated to lower consumption and thus an increased capacity to launch more satellites.

Even though such an approach does not currently exist, it does not seem unrealistic that consensus might be reached in the future. In fact, the International Telecommunications Union's (ITU) registration process for frequency allocation works in a similar fashion, where registration is expected between 7 and 2 years before the date of *bringing into use*, and may serve as an inspiration for a capacity register (Letizia et al. 2019). Any mission designers might check their satellite's index estimate via a publicly available service and compare to similar missions followed by the capacity allocation for a possible launch.

Recognizing near-Earth space as a valuable resource where a sustainable consumption is desired, and given the free access to space according to the *Outer Space Treaty*, the space debris problem is another area that relates to the *tragedy of the commons*. One important aspect in this context is in which order entities would be allowed to harvest from that resource. In Letizia et al. (2019), the *first-come, first-served* approach is elaborated in analogy to the ITU registration process, but discussions have just begun, and the outcome remains to be seen. The likely slowdown in the deployment of smallsat constellations as a result of the Covid-19 virus, may help to resolve the issue of the equitable use of the global commons.

6 Conclusion

Many important services modern society relies on are delivered by satellite technology from near-Earth orbits. It is noble common goal to maintain these benefits or even to further expand for generations to come, but then issues related to sustainability need to be addressed. The increasing traffic in Earth orbits has given rise to concerns of a potential instability due to a collisional cascading effect, also referred to as the Kessler syndrome. This is not an issue in the far future – it needs to be addressed now, observing that research indicates repeatedly that a certain tipping point condition may have been already reached in altitudes around 800 km.

International consensus on space debris mitigation has been reached on UN level more than a decade ago, followed by an ongoing process of the adoption of those guidelines into standardization processes and national laws. In order to minimize the potential to generate space debris, any satellite or launch vehicle needs to limit its presence in the LEO and GEO protected regions. While current levels of adherence to post-mission disposal (PMD) guidelines are at about 60% for payloads (excluding naturally compliant ones, the PMD adherence level drops to merely 20% (ESA Space Debris Office 2019)) and about 80% for rocket bodies (ESA Space Debris Office 2019), it is encouraging to observe that especially small satellites are being increasingly inserted into sufficiently low orbits, where the remaining on-orbit lifetime is below 25 years.

For small satellite constellations, where plans to launch thousands of satellites into significantly higher altitudes at about 1000 km have been announced, a strict adherence to mitigation guidelines is required. Many researchers have confirmed that any impact of such a single large constellation on the environment can be minimal to negligible, if a high PMD success rate (>95%) would be attained. In case of multiple large constellations, also this could not be sufficient. Moreover, this is clearly beyond what is observed in LEO today and may serve as a serious constraint in a competitive market. Even though a certain trade-off may be possible when reducing the remaining on-orbit lifetime way below the required 25 years, the PMD success rate would still be the driving parameter: an exemplary analysis showed that 5 years remaining lifetime could allow for a trade-off with the PMD success rate to 85%. It has also been shown that a careful design of the constellation operations may address end-of-life issues already at relatively low additional cost, including the minimization of the satellite's cross section or the insertion into low altitude orbits. While there are ongoing discussions on whether more stringent requirements are required for large constellations or whether small satellites should be treated differently, the current analyses indicate that the existing set of guidelines need to be strictly applied by everyone.

Satellite collisions, which are expected to be the main driver of the object population growth in the future, are not only a subject of matter after the end-of-life measures have been taken. With increased space traffic in a highly dynamic environment, where there are difficulties to track and catalogue all potentially lethal objects, it is in the self-interest of any satellite operator to become even more responsible toward safe operations in space including collision avoidance measures.

The recent case of the close approach between ESA's Aeolus and SpaceX's Starlink satellite (Foust 2019) was indicative of the common need for more accurate data and methods but also procedures and protocols being established and exchanged within the community. Addressing this need, the recent adoption of the *Guidelines for the Long-term Sustainability of Outer Space Activities* by the UN's Committee on the Peaceful Uses of Outer Space (UNCOPUOS 2019b) can only be reassuring.

Given that responsible space operations and full adherence to mitigation guidelines are granted, potentially with a few large constellations in space with sufficiently low environmental impact, this may nevertheless be insufficient to keep space sustainable. With too many satellites being launched, as can be the case with space infrastructure being commercialized and maintained to a high degree by profit-maximizing firms (Adilov et al. 2013), runaway conditions may still be reached. One example is in the launch of multiple large constellations, where not all of them find their business case achieved. A worst-case scenario in a potential bankruptcy could mean that all of the already launched satellites of that failed constellation would remain in space for centuries.

In a constrained environment, such as the LEO region, traffic needs to be controlled in order to guarantee sustainability. Where that limit is may be debatable, but the recent proposals to establish a rating scheme appear promising. With the likelihood of a collision and the impact such an event would have on operators and the environment in general factored into a single index, any space mission can be evaluated already before its launch. Moreover, a cumulative index could support the establishment of a capacity register for any given orbital region and thus limit the number of missions launched in a given time period as a consequence. This may be perceived as a step to constrain the freedom to access space guaranteed by the *Outer Space Treaty*, but recognizing space as a limited resource, noting that the Outer Space Treaty also calls to avoid harmful interference, and acknowledging that any satellite operated in space is actually consuming part of that commonly shared resource, it seems only reasonable to agree with Hegel: freedom is the recognition of necessity.

7 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Antennas
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

References

N. Adilov, P. J. Alexander, B. M. Cunningham, Earth orbit debris: An economic model. Available at Social Science Research Network (SSRN 2264915), 2013

L. Anselmo, The long-term evolution of the space debris environment, in *3rd European Conference on Space Debris,* Darmstadt, 2001

L. Anselmo, C. Pardini, Compliance of the Italian satellites in low earth orbit with the end-of-life disposal guidelines for space debris mitigation and ranking of their long-term criticality for the environment. Acta Astronaut. **114**, 93–100 (2015)

B. Bastida Virgili, H. Krag, Analyzing the criteria for a stable environment, in *AAS/AIAA Astrodynamics Specialist Conference,* Girdwood, 2011

B. Bastida Virgili, H. Krag, Small satellites and the future space debris environment, in *30th International Symposium on Space Technology and Science (ISTS),* Kobe, 2015

B. Bastida Virgili, J.C. Dolado-Perez, H.G. Lewis, J. Radtke, H. Krag, B. Revelin, et al., Risk to space sustainability from large constellations of satellites. Acta Astronaut. **126**, 154–162 (2016a)

B. Bastida Virgili, H. Krag, H. Lewis, J. Radtke, A. Rossi, Mega-constellations, small satellites and their impact on the space debris environment, in *67th International Astronautical Congress,* Guadalajara, 2016b

V. Braun, *Impact of Debris Model Updates on Risk Assessments* (NEO and Debris Detection Conference, Darmstadt, 2019)

V. Braun, A. Horstmann, B. Reihs, S. Lemmens, K. Merz, H. Krag, Exploiting orbital data and observation campaigns to improve space debris models. J Astronaut Sci. **66**(2), 192–209 (2019)

CNES, STELA website. (CNES). Retrieved from 4 Sept 2019. https://logiciels.cnes.fr/en/content/stela, 2019

ESA, Space Debris User Portal. (ESA) Retrieved from 4 Sept 2019. https://sdup.esoc.esa.int/

ESA Space Debris Office, ESA's Annual Space Environment Report. Darmstadt, 2019

J. Foust, ESA Spacecraft Dodges Potential Collision with Starlink Satellite. Retrieved from Space News (2019). https://spacenews.com/esa-spacecraft-dodges-potential-collision-with-starlink-satellite/

IAA, *A Handbook for Post-Mission Disposal of Satellites Less than 100 Kg* (International Academy of Astronautics (IAA), Paris, 2019)

IADC, *IADC Space Debris Mitigation Guidelines.* IADC-02-01 Revision 1, 2007

IADC, IADC Statement on Large Constellations of Satellites in Low Earth Orbit, IADC-15-03. IADC Steering Group, 2017

ISO, *Space Systems – Determining Orbit Lifetime (ISO 27852:2016)* (ISO, Geneva, 2016)

ISO, *Space Systems – Space Debris Mitigation Requirements (ISO 24113:2019)* (ISO, Geneva, 2019)

S.A. Jacklin, *Small-Satellite Mission Failure Rates, NASA/TM-2018-220034* (NASA, Moffett Field, 2019)

N.L. Johnson, P.H. Krisko, J.-C. Liou, P.D. Anz-Meador, NASA's new breakup model of EVOLVE 4.0. Adv Space Res. **28**(9), 1377–1384 (2001)

C. Kebschull, P. Scheidemann, S. Hesselbach, J. Radtke, V. Braun, H. Krag, E. Stoll, Simulation of the space debris environment in LEO using a simplified approach. Adv. Space Res. **59**(1), 166–180 (2017)

D.J. Kessler, B.G. Cour-Palais, Collision frequency of artificial satellites. J Geophys Res. **83**, 2637–2646 (1978)

S. Kitajima, S. Abe, T. Hanado, S. Kawamoto, Influences of mega-constellations on the orbital environment, in *67th International Astronautical Congress,* Guadalajara, 2016

H. Krag, M.A. Serrano, V. Braun, P. Kuchynka, M. Catania, J. Siminski, et al., A 1 cm space debris impact onto the sentinel-1A solar Array. Acta Astronaut. **137**, 434–443 (2017)

H. Krag, S. Setty, A. Di Mira, I. Zayer, T. Flohrer, Ground-based laser for tracking and remediation – an architectural view, in *69th International Astronautical Congress,* Bremen, 2018

F. Letizia, C. Colombo, H. G. Lewis, H. Krag, Extending the ECOB space debris index with fragmentation risk estimation, in *7th European Conference on Space Debris,* Darmstadt, 2017

F. Letizia, S. Lemmens, B. Bastida Virgili, H. Krag, Application of a debris index for global evaluation of mitigation strategies. Acta Astronaut. **161**, 348–362 (2019)

H.G. Lewis, J. Radtke, A. Rossi, J. Beck, M. Oswald, P. Anderson, et al., Sensitivity of the space debris environment to large constellations and small satellites. J Br Interplanet Soc. **70**(2017), 105–117 (2017)

J.-C. Liou, An active debris removal parametric study for LEO environment remediation. Adv Space Res. **47**(11), 1865–1876 (2011)

J.-C. Liou, J.N. Opiela, A.B.. Vavrin, B. Draegar, P.D. Anz-Meador, C.L. Ostrom, C. Sanchez, *Debris Assessment Software User's Guide: Version 3.0, NASA/TP-2019-220300* (NASA, Houston, 2019)

D.S. McKnight, Determination of breakup initial conditions. J Spacecr Rocket. **28**(4), 470–477 (1991)

D.L. Oltrogge, S. Alfano, Collision risk in low earth orbit, in *67th International Astronautical Congress,* Guadalajara, 2016

G.E. Peterson, M.E. Sorge, A.B.. Jenkin, J.P. McVey, Effect of cubesats on collisions and long-term debris growth in near-earth environment, in *67th International Astronautical Congress,* Guadalajara, 2016

A. Rossi, G.B. Valsecchi, E.M. Alessi, The criticality of spacecraft index. Adv Space Res. **56**(3), 449–460 (2015)

A. Rossi, E.M. Alessi, G.B. Valsecchi, H.G. Lewis, J. Radtke, C. Bombardelli, B. Bastida Virgili, A quantitative evaluation of the environmental impact of the mega constellations, in *7th European Conference on Space Debris,* Darmstadt, 2017

H. Schaub, L.E. Jasper, P.V. Anderson, D.S. McKnight, Cost and risk assessment for spacecraft operation decisions caused by the space debris environment. Acta Astronaut. **113**, 66–79 (2015)

SEI, *Nano/Microsatellite Market Forecast*, 9th edn. (SpaceWorks Enterprises Inc, Atlanta, Georgia, 2019)

G. Somma, H.G. Lewis, C. Colombo, Sensitivity analysis of launch activities in low-earth orbit. Acta Astronaut. **158**, 129–139 (2019)

space-track.org, (2019, Aug 23). Retrieved from https://www.space-track.org

UNCOPUOS, *Report of the Committee on the Peaceful Uses of Outer Space.* Vienna: COPUOS 62nd session, 2019a

UNCOPUOS, *Space Debris Mitigation Standards Adopted by States and International Organizations* (UNCOPUOS, Vienna, 2019b)

Union of Concerned Scientists, 2019, January 9 *UCS Satellite Database*. (Union of Concerned Scientists) Retrieved 10 Sept 2019, from https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database

United Nations (UN), *Technical Report on Space Debris,* New York, 1999

J. Utzmann, M. Oswald, S. Stabroth, A. Wagner, I. Retat, *Ranking and Characterization of Heavy Debris for Active Removal* (International Astronautical Congress (IAC), Naples, 2012)

Spectrum Frequency Allocation Issues and Concerns for Small Satellites

Morio Toyoshima and Attila Matas

Contents

Abstract

Many small-satellite missions have been launched and many more are planned. Small-satellite projects and missions are becoming very active because of some of their advantageous features, such as low latency. As the development cycle and the mission duration for small satellites are short, the relaxation of the regulation and easy deployment are discussed. The current situation with regard to the regulatory aspects for nanosatellites and picosatellites, especially in terms of frequency allocations, is described in this chapter.

M. Toyoshima (✉)
Space Communications Laboratory, National Institute of Information and Communications Technology, Koganei, Japan
e-mail: morio@nict.go.jp

A. Matas
Senior Satellite Regulatory Consultant, OrbitSpectrum, Geneva, Switzerland
e-mail: am@orbitspectrum.ch

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_14

Keywords

Nanosatellite · Picosatellite · CubeSat · Frequency allocation · International Telecommunication Union (ITU) · International Telecommunication Union Radiocommunication Sector (ITU-R) · Radio Regulations (RR) · Geostationary orbit (GSO) satellite · Non-GSO satellite · Advanced Publication Information (API) · Date of Bringing Into Use (DBIU) · Short Duration Mission (SDM) · Space Operation Service (SOS) · World Radio Conference (WRC) · Master International Frequency Register (MIFR)

1 Introduction

The number of small-satellite missions has increased recently. More than 200 launches were conducted in 2018 and more than 400 nanosatellite launches are forecasted in 2019 (Erik Kulu 2019). As the number of launched small satellites increases, there are some frequency-allocation issues for small satellites. This chapter describes the current situation for spectrum-allocation issues and concerns for small satellites.

2 Characteristics of Small Satellites

Small satellites have advantages such as being faster to build and deploy, lower in cost, and having less path loss as well as transmission delay. Figure 1 shows an 1U-size CubeSat which is standardized with the dimensions of 10 cm × 10 cm × 10 cm. The faster development duration can be less than 1 year. The cheaper development cost can be less than tens of thousands of dollars for simple CubeSats. Faster implementation can be done by using modular and standardized CubeSat equipment, and miniaturized equipment can be used based on the latest technology. On the other hand, there are some drawbacks, such as limited launching opportunity, none or little orbit control, small or unreliable power source, limited lifetime, limited mission types, and limited regulatory certainty. Small satellites, however, provide a means for testing emerging

Fig. 1 An example of 1U-size CubeSat

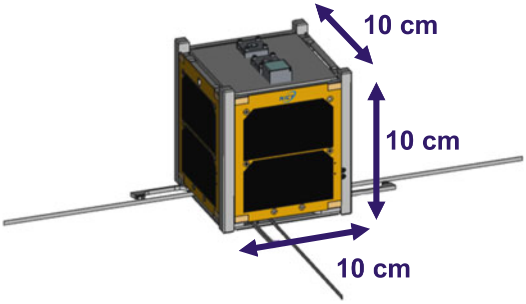


Table 1 Typical characteristics of small satellites

Denomination	Mass (kg)	Max. bus power (W)	Typical cost (USD)	Max. dimensions (m)	Development time (years)	Mission duration (years)
Smallsat (Minisat)	100–500	1000	30–200 M	3–10	3–10	5–10
Microsat	20–100	150	10–150 M	1–5	2–5	2–6
Nanosat (1U-6U CubeSat)	1–20	20	100 k–10 M	0.1–1	1–3	1–3
Picosat	0.1–1	5	50 k–2 M	0.05–0.1		

Note: There are various definitions of small-satellite categories that are used and development times and mission durations vary to a degree around the world

technologies, offer opportunities for new satellite operators that might not otherwise have considered or been able to afford the use of satellite technologies, and operation or demonstration in a variety of practical space-based applications according to the satellite mass categorized as shown in Table 1 (Report ITU-R SA.2312 2019). Moreover, small satellites are easy to be launched with a larger host satellite as piggy-back.

3 Definition of Small Satellites

There is no regulatory definition for small satellites in the International Telecommunication Union Radio Regulations (RR). There are only definitions for geostationary (GSO) and non-GSO satellites. Most of small satellites will be launched in the low earth orbit (LEO); therefore, small satellites belong to non-GSO satellites (ITU-R WP7B 2019; Matas 2018). The characteristics and spectrum requirements of satellite systems using nano- and picosatellites in ITU-R were studied and reported in ITU-R SA.2312 characteristics, definitions, and spectrum requirements of nanosatellites and picosatellites, as well as systems composed of such satellites and ITU-R SA.2348 current practice and procedures of notifying space networks currently applicable to nanosatellites and picosatellites (Report ITU-R SA.2312 2019; Report ITU-R SA.2348 2019). The small-satellite community was interested in relaxation of the RR and easy deployment of their non-GSO satellites. The regulatory aspects for nanosatellites and picosatellites in Resolution 757 at World Radiocommunication Conference 2012 (WRC-12) of the ITU resolves to invite WRC-18 to consider whether modifications to the regulatory procedures for notifying satellite networks are needed to facilitate the deployment and operation of small (nano- and pico) satellites and to take the appropriate actions. But the quick decision made at WRC-15 was that there was no need for any special regulatory procedures to facilitate the deployment and operation of nano- and picosatellites.

4 Small Satellite with Short Duration Mission

Small satellites with short duration mission (SDM) are discussed in terms of technical characteristics and spectrum requirements in ITU-R Study Group 7 – Working Party 7B (ITU-R WP7B) (Report ITU-R SA.2312 2019) and the results of these studies are presented in the Report ITU-R SA.2425 studies to accommodate spectrum requirements in the space operation service for non-geostationary satellites with short duration missions and Report ITU-R SA.2426 technical characteristics for telemetry, tracking, and command in the space operation service below 1 GHz for non-GSO satellites with short duration missions (Report ITU-R SA.2425 2019; Report ITU-R SA.2426 2019). WRC 15 decided about a new RES 659 Studies to accommodate requirements in the Space Operation Service (SOS) for non-GSO satellites with SDM and invited the ITU-R to study the spectrum requirements for tracking, telemetry, and command (TT&C) in the SOS for the growing number of non-GSO SDM satellites. A new term "short duration mission (SDM)" as stated in the Resolution 659 is used for the first time in the ITU-R, which refers to a non-GSO satellite system having a limited period of validity of not more than typically 3 years. There is currently no particular regulatory definition for non-GSO SDM satellites. The ITU-R Study Group 7 – Working Party 7B (ITU-R WP7B) developed at the CPM19- Report to the WRC-19 (CPM Report 2019) four methods to satisfy WRC-19 Agenda Item 1.7 (*to study the spectrum needs for telemetry, tracking, and command in the space operation service for non-GSO satellites with short duration missions, to assess the suitability of existing allocations to the space operation service and, if necessary, to consider new allocations, in accordance with Resolution 659 (WRC-15))* and two new reports (Report ITU-R SA.2425 2019; Report ITU-R SA.2426 2019) how to satisfy this action item:

1. Method A proposes no change to the RR.
2. Method B1 proposes a new SOS (Earth to space) allocation for non-GSO SDM systems in the frequency range 403–404 MHz.
3. Method B2 proposes a new SOS (Earth to space) allocation for non-GSO SDM systems in the frequency range 404–405 MHz.
4. Method C proposes to use the SOS allocation in the frequency band 137–138 MHz for downlink and the band 148–149.9 MHz for uplink and to provide appropriate associated regulatory provisions in the RR for non-GSO SDM TT&C links.

Since the existing RR does not take into account the short development cycle and the short lifetimes of non-GSO SDM, a simplified regulatory regime and recording procedures for non-GSO SDM is required. Based on missing regulatory regime for non-GSO SDM, the ITU-R Study Group 4 – Working Party WP4A developed a method as described in the CPM19 Report to the WRC-19 (CPM Report 2019) Agenda Item 7-Issue I – to address this issue that consists of modifications to the existing regulatory procedures for Advanced publication information (API) and Notification of satellite networks and systems that are not subject to Section II of

RR Article 9, to facilitate the recording of non-GSO SDM systems in the MIFR. The most important aspects of the new draft Resolution Simplified regulatory regime for non-GSO SDM satellite systems proposed by the ITU-R WP4A are:

- SDM satellites, operating under any space service not subject to ART 9 Section II (ITU Radio Regulations 2016), shall follow the RR with the exceptions stipulated in this resolution.
- The application of the simplified regulatory regime shall have no impact, as compared to networks not applying the simplified regulatory regime, on the regulatory sharing status of the allocations to services, both terrestrial and space.
- SDM satellites using spectrum allocated to the amateur radio service shall operate under ART 25 (ITU Radio Regulations 2016).
- The total number of satellites in a SDM satellite constellation shall not exceed 10 (t.b.d. by WRC 19) satellite;
- The maximum period of operation and validity of frequency assignments of a SDM satellite shall not exceed 3 years from the date of bringing into use (DBIU), which is equal to the satellite launch date, without any possibility of extension.
- SDM satellite systems shall have a single launch date associated with the first launch (in the case of systems with multiple launches).
- SDM satellites for which the regulatory regime in this resolution is applied will not accrue any special or additional rights under the RR over those satellite systems not applying this regime.

5 Frequency Allocation for Small Satellites

Main purposes of small satellites are used for amateur satellite, space operation, Earth observation satellite, space exploration satellite, weather monitoring satellite, and so on. There are some instances where 1U-6U satellites are used for commercial purposes and such uses and spectrum allocations are consistent with the processes related to such services for telecommunications, remote sensing, RF Geolocation, etc. As an example, the frequency band for nanosatellites is shown in Fig. 2 (Erik Kulu 2019). As can be seen from W-band and laser/optical in Fig. 2, the higher frequency bands will be used more in future small-satellite missions. The typical frequency allocated for small satellites are shown in Table 2 (Matas 2016). For the allocation of frequencies, the world on the Earth has been divided into three "radiocommunication" regions as described in provision No. 5.2 of the ITU Radio Regulations (Timmerman 2018): exclusive allocations, which are favored in cases that involve broad international use of equipment; shared frequency allocations, which are applied to maximize the use of the available spectrum when two or more radiocommunication services can effectively utilize the same frequency band. A shared frequency band can be allocated to more than one service (primary or secondary). Stations of a secondary service shall not cause harmful interference to stations of primary service, cannot claim protection from harmful interference from stations of a primary service, and can claim protection, however, from harmful

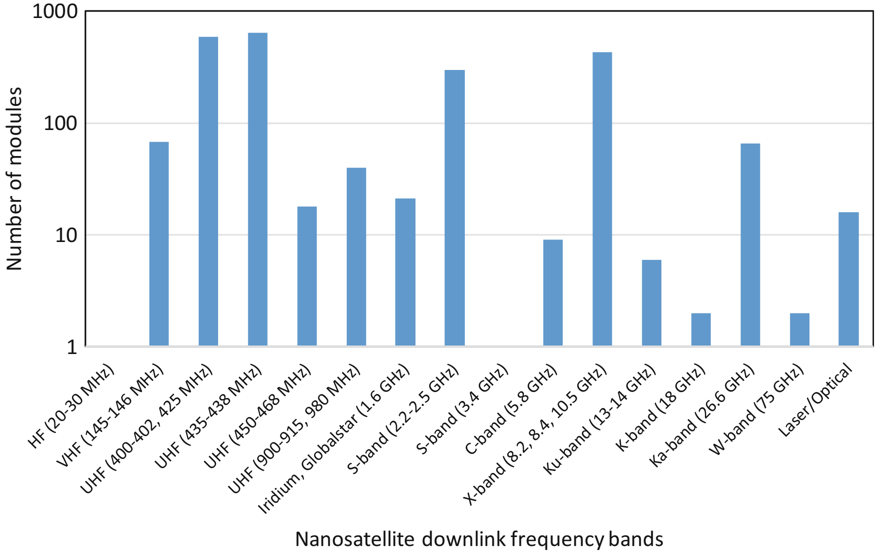


Fig. 2 An example of frequencies allocated for nanosatellite downlink bands

interference from stations of the same or other secondary service(s) to which frequencies may be assigned later (Timmerman 2018).

According to No. 4.4 of the RR (Timmerman 2018) Administrations of the Member States shall not assign to a station any frequency in derogation of either the Table of Frequency Allocations in this Chapter or the other provisions of these Regulations, except on the express condition that such a station, when using such a frequency assignment, shall not cause harmful interference to, and shall not claim protection from harmful interference caused by, a station operating in accordance with the provisions of the Constitution, the Convention, and these Regulations.

The determination of whether or not a frequency assignment to a transmitting station is capable of causing harmful interference to the stations of another administration operating in accordance with the Radio Regulations does not lie only on the side of the administration operating the transmitting station that may be producing the interference and other administrations should have information about a use under No. 4.4 to assess its interference potential or identify the source of harmful interference. For this reason, an administration intending to use a frequency assignment to a transmitting station under No. 4.4 has to notify to the Bureau this frequency assignment, pursuant to Article 11 (Timmerman 2018), if possible prior to bringing it into use.

When notifying the use of frequency assignments to be operated under No. 4.4, the notifying Administration shall provide a confirmation that it has determined that these frequency assignments meet the conditions and that it has identified measures to avoid harmful interference and to immediately eliminate such in case of a complaint (ITU Rules of Procedure 2018).

Table 2 Typical frequency allocated for small satellites

Frequency band	Service	Symbol	Type of allocation
401–403 MHz	EESS (E-S)	EW	Primary
401–402 MHz	SOS (S-E)	ET	Primary
449.75–450.25 MHz	SOS (E-S) SRS (E-S)	ET EH	No. 5.286-only subject to No. 9.21 (other No. 4.4)
1215–1300 MHz	ESSS (active), SRS	Ex, EH	Nos. 5.330–5.335A protecting RNSS and RL
1427–1429 MHz	SOS (E-S)	ET	Primary
2025–2110 MHz	EESS (E-S, S-S) SOS (S-E, S-S) SRS (E-S, S-S)	EW ET EH	Primary
2200–2290 MHz	EESS (S-E, S-S) SOS (S-E, S-S) SRS (S-E, S-S)	EW ET EH	Primary
2290–2300 MHz	SRS (S-E) (deep space)	EH	Primary
8025–8400 MHz	EESS (S-E)	EW	Primary
8400–8500 MHz	FX, MOB SRS (S-E)	EH	Primary
8550–8650 MHz	(EESS), (SRS) (active)	Ex, EH	Primary
9300–9800 MHz	(EESS), (SRS) (active)	Ex, EH	Primary
9800–9900 MHz	(eess) (active) (srs) (active)	Ex EH	Secondary
10.6–10.7 GHz	(EESS), (SRS) (passive)	Ex, EH	Primary
13.25–13.75 GHz	(EESS), (SRS) (active)	Ex, EH	Primary
22.21–22.5 GHz	(EESS), (SRS) (passive)	Ex, EH	Primary
22.55–23.15 GHz	(ISS), (SRS) (E-S)	ES, EH	Primary (No. 5.338A)
23.6–24 GHz	(EESS), (SRS) (passive)	Ex, EH	Primary

Notes: *EESS* earth exploration-satellite service, *SOS* space operation service, *SRS* space research service, *EW* space station in the earth exploration-satellite service, *ET* space station in the space operation service, *EH* space research space station, *ES* station in the inter-satellite service

Amateur-satellite service (EA) can be used for small satellites. Amateur service is defined as a radiocommunication service for the purpose of self-training, intercommunication, and technical investigations carried out by amateurs, that is, by duly authorized persons interested in radio technique solely with a personal aim and without pecuniary interest in RR 1.56. Amateur-satellite service is also defined as a radiocommunication service using space stations on earth satellites for the same purposes as those of the amateur service in RR 1.57. The frequency allocation for EA is shown in Table 3 (Timmerman 2018).

Table 3 Frequency allocations for amateur satellite service

Wavelength	Frequency band (MHz)	Applications
10 m	28,000–29,700 (primary)	This band is used primarily in conjunction with an input or output in the 144 MHz band
2 m	144–146 (primary) Satellite: 145.794–146	These bands are in heavy use by numerous amateur satellites for inputs and outputs
70 cm	435–438 (secondary) RR No. 5.282	
23 cm	1260–1270 (secondary) Earth-to-space only RR No. 5.282	These bands are used as alternatives to the 144 MHz and 435 MHz bands because of congestion
13 cm	2400–2450 (secondary) RR No. 5.282	
9 cm	3400–3410 (secondary) Regions 2 and 3 only RR No. 5.282	
5 cm	5650–5670 MHz (secondary) Earth-to-space only RR No. 5.282	These bands are used for experimental amateur satellites
	5830–5850 MHz (secondary) Space-to-earth only	
3 cm	10.45–10.5 GHz (secondary)	These bands are used for experimental amateur satellite communications
1.2 cm	24–24.05 GHz (primary)	
6 mm	47–47.2 GHz (primary)	These bands are used for experimental amateur satellites
4 mm	76–77.5 GHz (secondary)	
	77.5–78 GHz (primary)	
	78–81 GHz (secondary)	
	81.0–81.5 GHz (secondary) RR No. 5.561A	
2 mm	134–136 GHz (primary)	
	136–141 GHz (secondary)	
1 mm	241–248 GHz (secondary)	
	248–250 GHz (primary)	

6 International Frequency Coordination, Notification and Recording in the ITU Master International Frequency Register

An Administration shall send to the Bureau a general description of the network for the Advanced Publication Information (API) not earlier than 7 years and preferably not later than 2 years before the planned DBIU of the satellite network or system as shown in Fig. 3 (Matas 2016). A clear majority of the non-GSO small satellites operates in the frequency bands not falling under formal ART 9

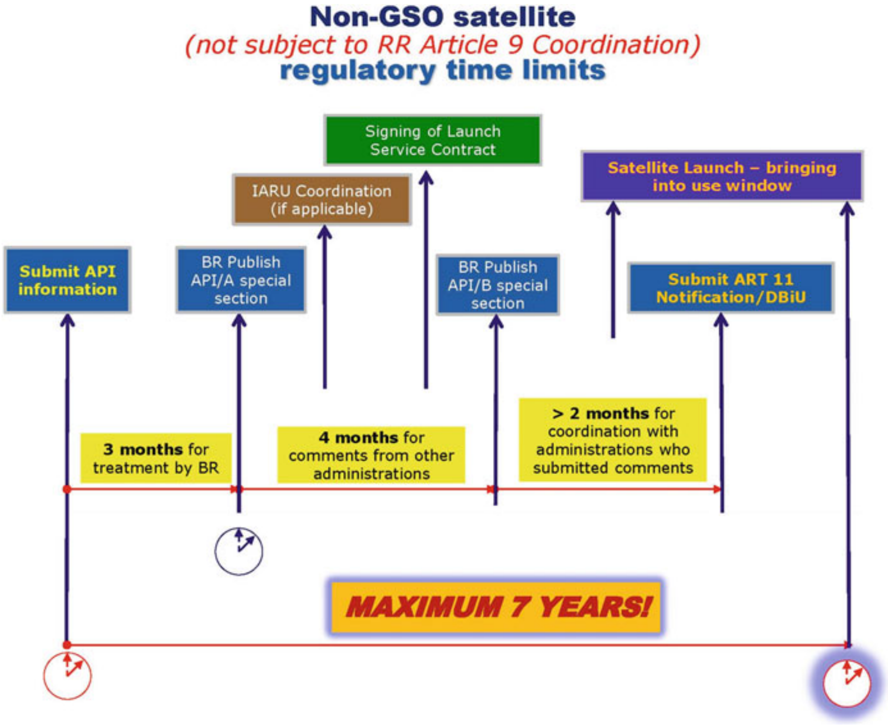


Fig. 3 Basic international frequency coordination procedure for small satellites

coordination procedure. Shortest regulatory limit for non-GSO not subject to coordination from API up to Notification/DBIU is no more than 9 months. The API is published after 3 months through International Frequency Information Circular (IFIC) at the ITU. Following to the publication of the API, comments from other administrations are accepted for 4 months. The international frequency coordination is then conducted with administrations who submitted any comments. The regulatory time-limit represents crucial information for bringing a satellite network into use and submitting notices for recording in the Master International Frequency Register (MIFR). The notified DBIU of any assignment to a space station of a satellite network shall be no later than 7 years following the receipt of the API.

Requirements for administrations to notify satellite frequency assignments and associated orbital positions for recording in the MIFR, declaration of bringing satellite into use, and protection of these assignments from harmful interference are the key pillars of the ITU RR international orbit/spectrum regime.

7 Conclusion

The current situation of the regulatory issue for small satellites was described. There is no regulatory definition for small satellites in ITU-R RR, but in general small satellites belong to non-GSO satellites because most of them are launched into the LEO. A non-GSO satellite system having a limited period of validity of not more than typically 3 years can be referred as SDM. As it is expected that the number of small-satellite missions will increase, the new frequency bands are allocated for non-GSO SDM systems, which corresponds to the relaxation of the regulation for small satellites because of the short development cycle and the SDM. Higher frequency bands will be used more for small-satellite missions in the future.

8 Cross-References

- ► Flight Software and Software-Driven Approaches to Small Satellite Networks
- ► High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ► Hosted Payload Packages as a Form of Small Satellite System
- ► Network Control Systems for Large-Scale Constellations
- ► Overview of Small Satellite Technology and Systems Design
- ► Power Systems for Small Satellites
- ► RF and Optical Communications for Small Satellites
- ► Small Satellite Antennas
- ► Small Satellite Constellations and End-of-Life Deorbit Considerations
- ► Small Satellites and Structural Design
- ► Stability, Pointing, and Orientation

References

CPM Report on technical, operational and regulatory/procedural matters to be considered by the World Radiocommunication Conference 2019, https://www.itu.int/md/R15-CPM19.02-R-0001/en. Accessed 23 Aug 2019

Erik Kulu, Nanosats Database, www.nanosats.eu. Accessed 23 Aug 2019

ITU Radio Regulations, Edition of 2016, Printed in Switzerland, Geneva, 2016, ISBN 978-92-61-19121-4, https://www.itu.int/pub/R-REG-RR/en. Accessed 23 Aug 2019

ITU Rules of Procedure, Edition of 2017, Printed in Switzerland, Geneva, 2018, ISBN 978-92-61-22541-4, https://www.itu.int/pub/R-REG-ROP/en. Accessed 1 Sept 2019

ITU-R WP7B studies, https://www.itu.int/en/ITU-R/study-groups/rsg7/rwp7b/Pages/default.aspx. Accessed 23 Aug 2019

A. Matas, The ITU space regulation – a key element to access space. International Astronautical Congress (IAC) 2018, IAC-18.E7.7-B3.8.6.x42748 (2018)

A. Matas, Services and frequency bands for small satellites. ITU Radio communication Bureau at ITU Symposium and Workshop on small satellite regulation and communication systems Santiago, Chile, 7–9 November 2016, https://www.itu.int/en/ITU-R/space/workshops/2016-small-sat/Documents/04-AM-ART5.pdf. Accessed 23 Aug 2019

Report ITU-R SA.2312 – Characteristics, definitions and spectrum requirements of nanosatellites and picosatellites, as well as systems composed of such satellites, https://www.itu.int/pub/R-REP-SA.2312. Accessed 23 Aug 2019

Report ITU-R SA.2348 – Current practice and procedures for notifying space networks currently applicable to nanosatellites and picosatellites, https://www.itu.int/pub/R-REP-SA.2348. Accessed 23 Aug 2019

Report ITU-R SA.2425 Studies to accommodate spectrum requirements in the space operation service for non-geostationary satellites with short duration missions, https://www.itu.int/pub/R-REP-SA.2425. Accessed 23 Aug 2019

Report ITU-R SA.2426 – Technical characteristics for telemetry, tracking and command in the space operation service below 1 GHz for non-GSO satellites with short duration missions, https://www.itu.int/pub/R-REP-SA.2426. Accessed 23 Aug 2019

H. B. Timmerman, IARU Satellite Advisor, Frequency Cordination for Amateur Satellite Service, ITU Geneva, 29 November 2018, https://www.itu.int/en/ITU-R/space/workshops/2018-SmallSat/Presentations/25.pdf. Accessed 23 Aug 2019

Flight Software and Software-Driven Approaches to Small Satellite Networks

Robert Harvey

Contents

Abstract

There is a growing market for satellites that fall into the "Microsat" and "Nanosat" classifications. Many of these satellites are designed and manufactured by small groups such as in academia, startups, or small incubator teams inside larger organizations. These environments tend to be fast-paced and will likely eschew traditional aerospace life cycles and design paradigms in favor of rapid prototyping, consumer electronics parts, and even on-orbit testing. Microsats

R. Harvey (✉)
Planet, Inc., San Francisco, CA, USA
e-mail: Rob.harvey@planet.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_87

have somewhat different flight software implications and requirements than traditional satellites. This chapter discusses some of the flight software aspects of Microsats, along with design trades, processes, and the role of the flight software group in small organizations. Certain aspects of the flight software are called out for Microsats, including satellite safe modes, configuration updates, on-orbit software upgrades, and security. The flight software life cycle for Microsats is discussed in the context of a shifting and multiple-launch schedule. The intent of the chapter is to lay out guidelines for new flight software engineers such that while building out new Microsats, they also lay the groundwork for launching their product at scale.

Keywords

Planet · FSW · Flight software · Satellite telemetry · Satellite constellations · Cubesat, Microsat

1 Introduction

At the time of this writing, Planet Labs Inc. ("Planet") operates one of the largest satellite constellations in history (chapter ▶ "Planet's Dove Satellite Constellation"). Planet's approach to satellite design and operation is a departure from traditional methods, including a focus on using consumer-off-the-shelf (COTS) components, leveraging the Cubesat form factor and launching early and often with primary and secondary payload opportunities. In the beginning, this approach to satellites was largely unverified and certainly not applied to scale. This novel approach has implications for the flight software (FSW) and the flight software engineer, not least of which is that the flight software engineer may be working on an aggressively small team and the lines related to traditional functional roles may be blurred. The intent of the chapter is to lay out the challenges that can face new flight software engineers when working toward Microsat missions and provide a way of thinking that can ensure mission success for Microsat designs that may eventually be launched at scale. The content that follows is based on the author's experience at Planet; it is not based on any extended experience in the traditional aerospace fields. This does not reflect the opinions of Planet Labs.

2 Flight Software and Microsats

Is flight software for Microsats different than flight software for traditional satellites? There is an argument that Microsats are inherently the same as other satellites (although generally smaller) and therefore the flight software should have the same properties as any previous flight software system, regardless of design heritage. There is assuredly much truth in this. Microsat flight software systems must address power, thermal, and guidance concerns. They are responsible for telemetry and system limit checking, as well as enabling the payload to execute on its mission. There is a vast heritage of documentation and design for traditional flight software that should be considered and potentially used for any Microsat mission.

However, these similarities are most pronounced when the flight software is considered as a decomposed system, looking internally at the functional blocks inside the flight computer itself. Taking a step back, some differences start to become apparent: items such as shorter development life cycle, the blurred role of the flight software engineer, the global software ecosystem for the mission, the abbreviated and sometimes opportunistic launch schedule, the tight integration of subsystems, and the contract manufacturing process. These items will create a different environment for the flight software engineer than traditional satellite design.

For a fleet of Microsats, the differences become even clearer. In this model it is likely that iterative hardware design is taking place and every launch opportunity diversifies the satellite hardware in orbit, which must be handled by flight software. This is magnified by "tech demos" and the desire to test features in space whenever possible (definitely not traditional). In the case that many identical satellites are launched at once, the reality is that Microsats degrade at a faster rate and have less redundancy which means that the functional capabilities degrade and become diversified over time across the constellation (months to several years). This also must be addressed in flight software.

The concept of operations for Microsats is also different. In a fast-paced launch environment and especially with tech demos, it is likely that flight software is not completely ready prior to launch. The reality in this case is that on-orbit software updates must be common, reliable, and generally not exciting. It is also likely that FSW resets may be common and may even be the preferred way to achieve a known state in the satellite. This is a far cry from very expensive satellites where a reset may be decided by committee and can result in expensive downtime.

The methodology for building Microsats is also different from regular (and more costly) satellites. Traditional aerospace design will use a tremendous waterfall life cycle, from requirements down through testing and deployment. The waterfall life cycle itself is often a large living artifact, being copied from program to program and tweaked as appropriate for dates and details of the new program. This development process is intended to ensure contract value to the customer, enforce milestones for product maturity, ensure compatibility between components developed by different vendors, and keep complicated projects on track. In contrast, the reality for Microsats is that they tend to be built in agile and limited resource environments such as academia, space startups, and even small incubator groups in much larger organizations. The designs are less complicated and the risk posture is completely different. Requirements are often eschewed for rapid prototyping, and design documentation is often replaced with whiteboard conversations. The feeling of moving rapidly motivates the (small) team and often is completely necessary to meet an aggressive launch date with a new product design.

It is unfortunately the case that aggressive timelines tend to erode standard SW engineering practices. There could also be pressure to deliver an initial (suboptimal) working design in order to secure funding. The resulting pitfall for Microsat projects unfortunately is that you will eventually be successful and you will pay for your shortcuts later. There is then an appropriate balance in Microsat development methodology that is somewhat difficult to achieve, namely, to be lightweight, fast, robust, and future-proof.

Regarding whether Microsat flight software is different than traditional flight software, Microsat FSW components may be very similar to regular satellite programs, but the path to achieving mission success with Microsat FSW can be quite different. Being aware of the above points, especially early in the development cycle, can contribute to initial mission success, long-term company success, as well as a smoother running organization. Some of these points will be discussed as appropriate in the rest of this chapter.

3 Role of the Flight Software Team

In the lightweight planning world of Microsats, it is insightful to consider the reality facing the flight software team. In small team environments, team members will likely be stretched across multiple disciplines, and the "flight software team" could be a somewhat loosely defined organization. These members of the flight software team could have diverse experience with respect to developing software, sometimes being non-SW subject matter experts with some coding background. It should be noted that the earlier the team subscribes to standard software engineering practices, the more robust the system will be to on-orbit testing, modification, new hires, and feature requests. Standard practices would include coding for unit test, modular design, re-factoring when needed, consistency in coding standards, and continuous integration (CI) methods.

It is very useful to define the scope of work for the flight software team as early as possible. Microsats are limited in volume, and it is often the case that much of the avionics must be compressed into a few printed circuit boards in order to provide room for the payload. This generally limits the ability to buy pre-built subsystems which can be integrated into the satellite bus. The result is that many subsystems end up being homegrown, and inevitably they require some form of software. Consider Fig. 1 which shows a somewhat generic diagram for a Microsat system.

The satellite block on the left contains the avionics (top) and the payload (bottom). The avionics are controlled by a flight control computer (FC) which must deal with power, attitude control, GPS, and the tracking, telemetry, and control (TT&C) radio. Note that many of the blocks are indicated with their own Microcontroller (uC). The payload as shown has its own processor (payload computer) and is shown integrated with a high-speed radio and the payload sensor through a field-programmable gate array (FPGA). The flight control computer is the device first thought of when discussing the responsibilities of the flight software team. This is also the device that will have a functional block representation that is similar to flight computers pretty much everywhere. As can be realized quite rapidly when looking at the diagram, there are a multitude of other processors besides the FC that could require software, and this can easily fall into the flight software group

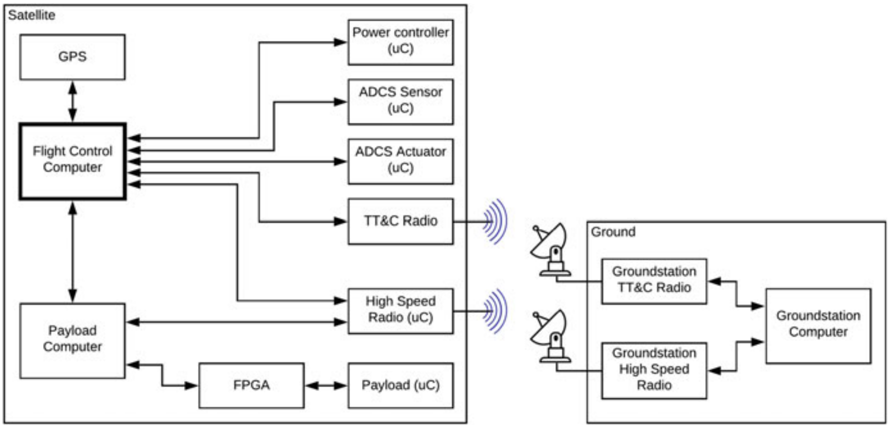


Fig. 1 Example satellite and ground system. (Image © 2019 Planet Labs Inc., licensed for one-time publication)

purview (every block in the diagram could be an independent software project). There are some things that are less obvious but still impactful to FSW. All of the devices with software must be software upgradeable post-launch. This includes devices that have third-party software on them! So even without primary responsibility for device software, there is still a requirement to develop a way to upgrade software on that device.

It might seem that the payload system is developed by the payload team in isolation, but this is not the case. There are likely to be common device drivers (especially for sensors and I/O) and also common telemetry, message protocol, and transfer routines. In some cases, the Microsat design does not have a clean boundary between payload and avionics, and the various software components need to coexist on a processor. This places a requirement on the flight software team to build portable, robust code and to possibly consider multiple processor architectures when architecting the code layout, repository, and build system. It may also be an opportunity to speak with the payload engineers about coordinating software engineering practices.

It is also the case that FSW responsibility may extend to the ground system (GS). If custom radios are being used, the code might be similar between the satellite and the ground, or maybe the communication link is the proprietary technology being developed. In the case that the GS is from a third party, it is still likely that communication libraries for message serialization/deserialization and telemetry ingestion will have common components with the satellite FSW.

There is another reality for the flight software engineer that must be considered. The tools to test out the satellite at the board level and full-build level do not write themselves. In a very small team, sometimes the best way to test out the hardware is with the actual flight software, and who better to write the interface and testing tools than the flight software team? This is not a bad scenario, but it needs to be taken into account, and it needs an owner (flight software team or not). It should be noted that it is rare for the on-orbit control procedures to map well to test procedures which implies care in separating one from the other. If there is a dedicated test team available, there may still be a FSW role to develop software components to interact with the satellite, even if the test code is decoupled from it.

The above paradigms may seem daunting for a small team. In a completely custom Microsat design, the processor and FPGA count can easily hit a dozen. Software work may not be confined to just satellite components. Early knowledge of this should be considered an opportunity:

- To ensure that all work is considered in the schedule
- To check the work against available staff
- To drive interconnect design, code architecture, and code reusability
- To revisit subsystems that might be available off the shelf

The important takeaway here is that the FSW role is not confined to the "flight computer": there is a larger software ecosystem that can include multiple processors, multiple systems, and multiple disciplines. In a lightweight planning environment, the details of all this work may not be captured, and not accounting for this work can lead to a stressful environment.

4 Flight Software Life Cycle

Planet has launched satellites on more types of rockets than almost any commercial company (chapter ► "Planet's Dove Satellite Constellation"). The reality is that the life cycle for any given Microsat iteration (and launch) will be overlapping with other launches, sometimes aggressively so. This obviously impacts not only flight software but other development groups as well. Figure 2 shows a single mission life cycle on the top and then multiple instances of this overlapped for three launches at the bottom.

At a high level, the top sequence is similar to any satellite program. A Microsat program will of course have differences: the requirements phase may be abbreviated, the day-to-day planning may be laid out using established Agile methodologies (likely more familiar to the technical team), the integration and test phase may be limited by access to flight simulation capabilities, and it is almost for certain that the overall time frame will be significantly shorter.

An impactful time for flight software (and everyone else) is when the first printed circuit boards for flight hardware arrive in-house (start of board verification). There is a collision of disciplines who will want to check out the boards. Flight software will presumably have been developing software on development boards or possibly non-form factor in-house boards. Electrical engineering will first do initial board bringup for smoke test, power rails, etc. Almost immediately after this, there will be the request to "talk" to the board (assuming it has a processor on it). Does the

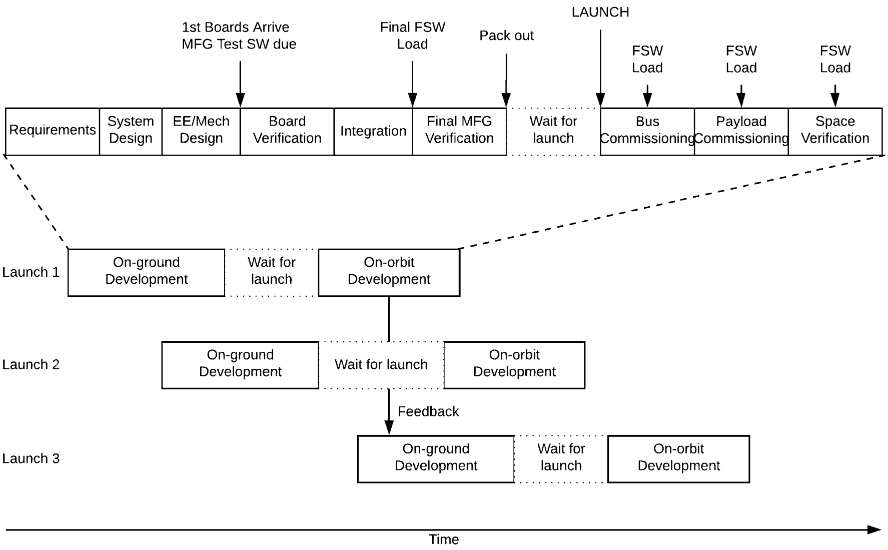


Fig. 2 Flight software life cycle. (Image © 2020 Planet Labs Inc., licensed for one-time publication)

software exist to do this? Be very mindful of this period in the life cycle, and consider carefully what the expectation will be from a software standpoint and then plan for it. This includes both satellite software and test harness software. Is the flight software team responsible for both? How can the flight software be ready if this is the first time that flight hardware has been available? In many cases the flight software needs specific flight hardware in order to be written, especially for drivers. The flight software engineer should also be cognizant of critical path timing not accounting for development work on the actual flight hardware. Note also that there is a distinction between test software and full flight software support for a given device or system on the satellite. A device or subsystem may be identified as not requiring full software support at launch, but the hardware will have to be validated on the ground regardless.

The launch date (or more accurately the pack-out date) will be a huge driving factor in schedule. The Microsat or possibly small fleet of Microsats will likely be a secondary payload for the targeted launch meaning that the actual launch date will be determined by a third party and potentially occur at a point which creates an overly aggressive schedule. The Microsat team will have to meet the payload integrator's window for delivery which may mean prioritizing development to ensure that critical systems are complete and robust while other systems are pushed off to a future on-orbit flight software or payload software upgrade. This may strike some readers as a disastrous or at the least irresponsible situation. How could one possibly launch a satellite without a full software suite that has been rigorously tested on flight hardware on the ground? This is the reality of Microsats.

The goal of any flight software team should be to optimize around this reality. This will involve a heavy focus on the on-orbit flight software update design including a bootloader and security capabilities as well as prioritizing the truly mission-critical components as early as possible (see section "Satellite Safe Mode").

Once pack-out has occurred, the flight software team will likely be working with the satellite operations group to prepare for new concept-of-operations (con-ops) procedures. There will also be ongoing development for flight components that have not had full software support implemented yet (potentially newer sensors or payload). Once launch has occurred, there will be possible flight software upgrades, for issues related to bus commissioning, payload commissioning and then infant mortality, experience with slow decay of components and workarounds, etc. Note that any schedule for the program should include work after the launch and not just terminate at launch. This is important when multiple launches are in play, discussed next.

There is an argument to say that many of the above issues are just schedule related. If there is time to do everything correctly, then the satellite and software will be fully featured, and you will be done at pack-out. Except for on-orbit component failures, this could possibly be true for a launch or two. In a growing company which is iterating on satellite design, building out on-orbit capability, and trying to maintain service-level agreements (SLAs), this is most assuredly not true. Consider the bottom part of Fig. 2. Multiple launches are occurring in order to prove out hardware design and meet SLAs, on-orbit and on-ground development is overlapped, and many iterations of hardware are in play. Consider that critical feedback from an on-orbit satellite design becomes available in the middle of board verification for a future launch and new boards must be created to account for it (note that time frames are shown such that the feedback can skip a launch). This is new, unplanned work for multiple teams, but the schedule is fixed by the third-party launch date. Possibly there is a critical problem with an on-orbit satellite component that must be addressed immediately by the FSW team, but there is also an ongoing and critical board bringup underway. The on-orbit issue will take precedence, especially if the mission is jeopardized. Or potentially a launch date happens to occur just before the pack-out for a subsequent launch, meaning that there is a requirement to support on-orbit commissioning while at the same time the on-ground manufacturing phase is at a critical juncture.

The point is that multiple-launch schedules can interact with each other in somewhat unpredictable ways, and the time to be allotted for development is hard to calculate. With vagaries in launch dates and idiosyncrasies in Microsat hardware, it is rare for software development work to be complete at pack-out even if the schedule is closely monitored, unless there are multiple teams available to handle the different phases in the various ongoing life cycles (unlikely in a small company). Being able to decouple software development work from the launch schedule is actually a very important opportunity. Planning out a robust system architecture with emphasis on mission safety and on-orbit flight upgrades will help enable this.

5 Flight Software and Processor Selection

In the Microsat development process, the flight software team should be participating in design discussions related to processor and sensor selection. Anything related to software should be considered from the standpoint of software toolchains, open-source versus closed-source code, space heritage, code reusability, and complexity. There are also questions related to processor load and memory sizing that the FSW team should be involved with. Note that when viewed as a software development problem, a Microsat project has much in common with other systems which are operated remotely and need to be robust against power loss and possible frequent software updates. This includes Internet of Things (IoT) projects and even some automotive projects. Much of the following will look familiar to people who are experienced with those systems.

Any processor selection should be judged against a list of requirements. The requirements should be carefully selected to meet the mission goals and maintain mission safety. In many cases, there is no obvious choice even after the requirements have been assessed. This means judging which requirements are most favorable to the teams and mission. Selection of a particular processor can also be intertwined with other devices, such as sensors (which might support a particular bus). Figuring out the requirements for processors can be somewhat daunting; the following bullet items lay out some informational groundwork for the process:

- **Space heritage** – Electronic devices which have already been proven to work well in space are ideal choices if they are available and meet the mission requirements. This can reduce early and unexpected mortality for Microsats. It can also reduce the cost of performing radiation testing on critical devices. The difficulty with space heritage parts is that they are either very expensive or difficult to identify because of export restrictions and a lack of public documentation. NASA has a published list of radiation tested parts that can be interesting to look over (NASA n.d.). Note that “space heritage” is sometimes blindly assumed to be a positive thing, but it is possible that a device has space heritage but performed poorly.
- **Off-the-shelf software** – Selecting parts that have readily available third-party software that can be applied to the mission can save time and allow the flight software team to focus on other flight software projects for the satellite. As mentioned in **Role of the Flight Software Team**, there will always be multiple software targets in the spacecraft. The organizations behind the off-the-shelf software presumably have already spent time debugging and verifying the software and possibly also time validating the associated hardware component(s). There are possible difficulties here, the first of which is that the third-party software may only be sold or compatible with hardware which may not fit in the satellite (Microsats tend to have a very constrained volume, and the payload generally dominates with the avionics packed around it). The second is that often only a particular component of the third-party software is desired, but it is very difficult to decouple from the complete system or the underlying protocols. Often this frustration will just lead designers to create the software “in-house.”

- **COTS, or not** – There are radiation-hardened and radiation-tolerant electronic parts that may be worth considering, especially in the safety-critical domain. These will tend to be much more expensive and generally of a much older electronics vintage (less capable) than regular consumer-off-the-shelf (COTS) parts. In Microsats, it may be possible to use a radiation-hardened MCU or FPGA, but it will be unlikely to be able to use a full rad-hardened subsystem due to cost and bulk. As Microsats will generally be majority COTS based anyway, this option may not be useful, but it is worth considering. If there is a safety-critical area where a rad-tolerant part is being considered, it may be useful to consider some of the safety-critical automotive MCUs and components that are now available. Note that the effect of radiation on COTS components is an intense area of study (Sinclair and Dyer 2013) and may require its own team.
- **Common build systems** – There will be multiple processors in the design, with the possibility of multiple manufacturers, different CPU cores, and different build systems and environments. It is very advantageous to limit the number of build tools and environments that are required to build all of the software targets for the satellite. This should only be done as appropriate, but it is much better to select a single, slightly suboptimal solution for multiple use cases and then to try and drive down on optimal and unique processors at every opportunity. Note that this is a “soft” requirement, in that it is intended to allow for smoother development, higher efficiency across the team, and possibly a lighter load on the team when it comes to supporting build and artifact publishing infrastructure. Over the long term, this can be a very appropriate choice.
- **Debug capabilities** – The software team should understand the debug options available for the processors that are being selected. At the least, this should include JTAG support which can be used for debugging as well as boundary scan verification during manufacturing. There may be other debug options that are desired, potentially some kind of embedded trace module. The debug options for very high-speed devices and memory could be more complex, but this should be considered when choosing these devices.
- **Board support packages (BSP)** – A significant portion of the work in flight software is in writing drivers. Processors which have a comprehensive board support package for a board that might have similar characteristics to the flight hardware can be very beneficial. Note that there are two levels for drivers, there are the peripherals that are pinned out of the chip (UART, I2C, ADC, etc.), and then there are the drivers for all the sensors and actuators that are connected to the processor. The availability of a hardware abstraction layer (HAL) is also beneficial since this can make porting between operating systems and processors easier (see section “Flight Computer Software Design”).
- **Processor speed** – It is necessary to select a processor that is powerful enough to execute all its required functions in a timely manner. This will be a function of the processor’s clock speed, as well as memory access timing and any hardware acceleration that is relevant (floating point units, cryptographic cores, DSP instructions, etc.). It is highly valuable to run processor intensive algorithms on third-party development boards to try and benchmark throughput requirements

for possible processor candidates. Also be aware that repeated access to devices on a communication bus, and the addition of new devices, can add up and impact available throughput which can be aggravated when sensors are unavailable (failed or disconnected) and device access time-outs start accumulating. This can cascade and cause throughput problems if not handled appropriately. Once there is an idea of the computation-intensive operations and the bus operations, the processor requirement should probably be increased 50–100% for future growth. Note that the above statements are more relevant for the flight computer and processors which are more embedded in nature. The payload compute system may have a different set of requirements, likely involving fast read/write memory and bus support. Also be aware of any circumstances which may require the control loops to run at a faster rate. This will require more processor capability.

- **Peripheral and bus options** – An audit of the available processor pins should be completed. This is more of an electrical engineering (EE) and system design role, but it is worth mentioning. The iterative nature of Microsats is generally accumulative, in that devices and capability will likely be added as opposed to swapped. This will require more general-purpose I/O (GPIO) pins and more traffic and addressable parts on the various communication buses. Do not select a processor that is immediately maxed out for peripheral capability and bus I/O. It is also useful to try and limit the types of communication buses that need to be supported, regardless of their availability on a given processor.
- **Open source versus closed source** – Buying closed-source code from a vendor may be an option for accelerating development. It may also meet some requirement for reliability or real-time responsiveness. Note that there is a difference between buying source code from a third party and compiled code (libraries). Not having the actual source code can make it difficult to debug and fix critical issues in a timely manner. Source code from a third party may come with build environment and seat licensing issues that can complicate development and notably also server-side continuous integration. Open-source code is becomingly an increasingly valid method for building out Microsat capabilities and systems.
- **Avionics versus payload** – It should be recognized that the requirements for the payload computer and the flight computer are different. Although it might be initially desirable to combine the two functions into a single processor, it may be better to keep them separated and optimized for each function. The flight computer must be reliable and continuously active. It is directly responsible for satellite safety and this should not be compromised. The payload computer could be shut off for extended periods and reset if there is any detected problem. An error in the payload memory will not cause the satellite to spin up or generally cause harmful behavior, especially if the flight computer is monitoring telemetry from the payload system and can take appropriate action. The avionics will likely require a less complex processor than the payload which is easier to make robust. It is also undesirable to impact the avionics system with a payload software change. There are other differences which are addressed in the next bullets.

- **Internal versus external memory** – Larger processors will tend to have more complicated memory which is located externally to the chip. It may be possible to select a smaller processor for the flight computer that has some form of internal memory that would be more robust to layout and manufacturing issues. The payload system will likely have much different memory requirements, including very fast read/write access and very large data storage requirements. It should be noted that large, fast, and complex memory devices such as solid-state drives (SSDs) are much more prone to failure than simpler flash implementations (Costenaro et al. 2015). It is important to realize that a memory device that is chosen for high-speed data collection and large storage capability may not be an appropriate place to have operating system or program memory. Note that complex memory devices may be performing maintenance operations under the hood with their own microcontroller (such as wear leveling). This will have its own failure modes and again could be less robust than a simple flash implementation.
- **Error-correcting code (ECC) capability** – There are many COTS processors and memory devices with ECC. These devices are generally able to correct for a single bit flip and detect a double bit flip. This type of technology can protect against single-event upsets (SEU) which are one likely type of radiation damage expected in low earth orbit (LEO) (Sinclair and Dyer 2013). Note that this is particularly desirable for devices which are continuously on where boot CRC checks and a reloading of random-access memory (RAM) are not taking place. Some automotive safety-oriented processors will also be able to check memory in I/O registers and throughout the memory pipeline, not just RAM and flash. The use of ECC may not make the system "radiation-tolerant," but it is a readily available technology that can mitigate these kinds of errors, and it should be incorporated where possible.
- **Operating system (OS) selection** – Processor selection will be tied to the operating system selection. In most cases, this will be a real-time OS (RTOS). The flight software team should be comfortable with the RTOS capabilities and maturity with respect to the processor. Although possible, it is generally not a good idea to start off a new program with a port of an RTOS to a new processor. Certain processors may force a more limited set of RTOS options onto the team which must be weighed against the perceived benefits. If multiple processors require an RTOS, it will be beneficial to select the same RTOS as appropriate. Note that the payload system may benefit from a different OS, maybe even an OS without full RT support such as Linux. This might enable a better development experience on the ground for the payload team and provide a much more feature rich environment that is similar to a laptop or desktop. For limited processors, it may make sense to forgo an OS entirely and generate a bare-metal implementation. This can initially be simpler and faster to get to a testable product. However, care should be taken as bare-metal projects tend to suffer from a lack of software structure and code entropy can take its toll as multiple developers work on the program. There is also an assumption that a tasking infrastructure is not needed which can become problematic as more sensors are added and delays start to pile

up in the processing chain. In many cases, a bare-metal decision may just be putting work off to a later date when the code will need to be re-factored and potentially rewritten for an RTOS.

The above talking points will hopefully be useful but are not comprehensive. For any device selection, there are the standard questions about end-of-life (EOL) time frame, supply chain, second source, environmental limits, and process technology. There may also be the need to radiation test critical devices. These are issues for the larger team.

The above conversation is focused on processors, but other devices (such as sensors) which must be accessed through software should also be evaluated for software impact. It is appropriate to standardize the possible sensors in the satellite design. It should not be the case that there are two different kinds of temperature sensors on different boards that could possibly be the same device. This doubles the software work and will siphon off time that could be spent on other tasks.

When assessing processors and devices, the flight software team should always remember to advocate for homogeneity where possible because this can have a direct impact on the flight software team workload. Also be careful of selecting a processor for a very specific reason such as an embedded security feature. These decisions can influence the general software architecture and may make porting to new processors very difficult.

6 Software Build System Architecture

As mentioned in previous chapters, the flight software team will likely be responsible for multiple processors on board the spacecraft with each requiring a different software image. They may also be responsible for ground software and/or dictionaries that are used in ground systems communicating with the spacecraft. There will also be multiple generations of spacecraft that will need to be supported, which will likely require different software or configuration. This is a difficult situation to manage from a build and release standpoint, and defining an appropriate software build architecture early on in development can be very helpful. Figure 3 demonstrates a possible build architecture that can support multiple platforms over multiple generations. On the left are the inputs to the build system; build artifacts are generated as the flow moves down and to the right. The first takeaway is that the inputs on the left are likely managed by different teams which means that a process needs to be negotiated between teams that allows for smooth integration of new information (data format, release management, release notes, etc.).

6.1 Build Process Inputs

The following bullet points define the input blocks on the right side of Fig. 3:

- **Satellite HW Specification Database** – The electrical engineering (EE) team will be designing multiple boards for each satellite. As new generations of

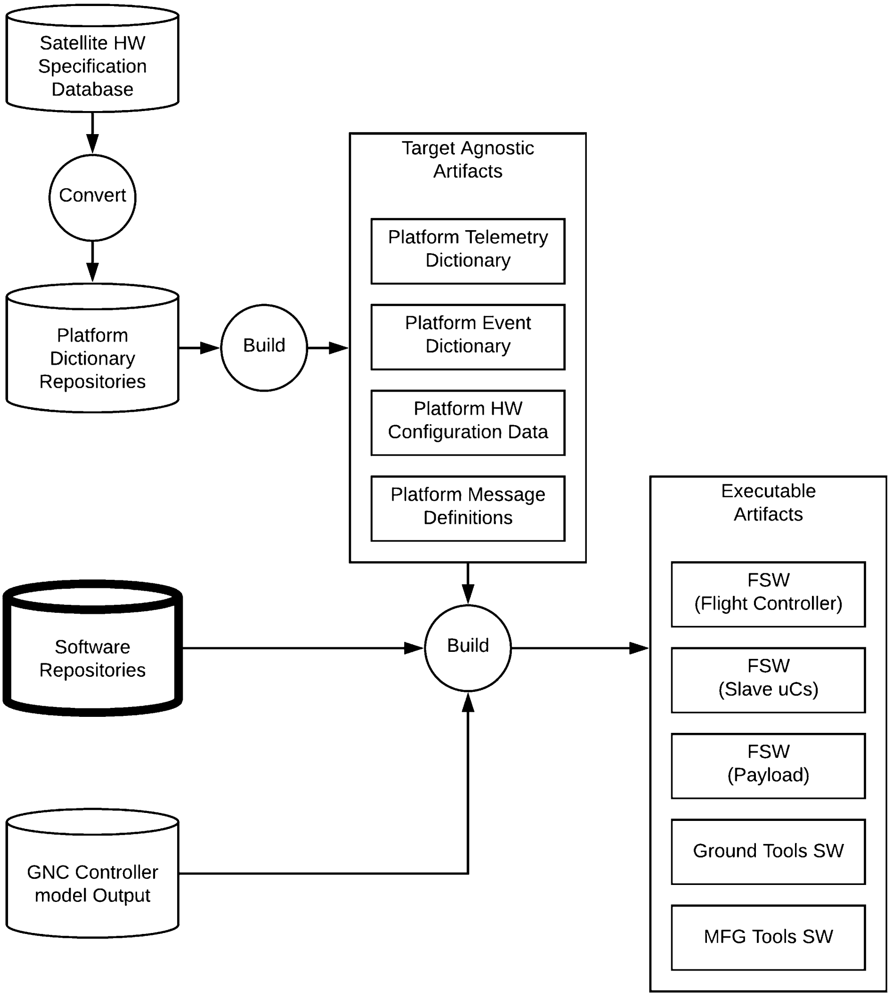


Fig. 3 Flight software build architecture. (Image © 2011 Planet Labs Inc., licensed for one-time publication)

satellites are created, the board designs will change, and this information must be transferred to the software team in some kind of reliable way. In order to fully describe what the software must do, this database can be very detailed. It should contain the list of all processor GPIOs and their functions, topology for communication buses and device addresses on the buses, a list of sensor devices (make and model), mapping of power rails to devices, power rail control information, and even resistor values where appropriate for sensor reads. This documentation will likely be contained in a format that is easy to integrate and use with EE tools. It will have to be exported to the platform dictionary repository. The necessity of this information being maintained correctly and at this level of detail is often noted when the team must go back in time and investigate older designs that may be having on-orbit issues. Note that a documentation system that does not allow easy detection of small changes will be hard to use in any event.

- **Platform Dictionary Repositories** – Each satellite variant (platform) will have a unique set of characteristics that should be maintained in the platform dictionary repository. This will include the definition (configuration) of the satellite hardware, imported from the EE HW specification database as shown in Fig. 3. Each platform will also have a unique set of telemetry channels and event descriptions that must be described and maintained. The intent behind the platform dictionary is to have a code-agnostic, single source of truth for the platform information. This information can have its own set of tools, rules, and schema to ensure that the data is consistent. It should be possible to generate the platform information for each satellite variant at any time. This system can also be used to define protocols and message structure.
- **Software Repositories** – The software repositories contain code, build instructions, and other collateral that is required to build the flight software and potentially other software as well. This may be one or multiple repositories depending on how the flight software team structures the code base. The software repositories are combined with the output of the platform dictionaries at build time to create the executables that can be loaded to the various processors in the satellite ecosystem.
- **GNC Controller Model Output** – A common model in satellite design is to use a third-party tool to build all the guidance, navigation, and control (GNC) models and then export the models as C code which can be integrated into the flight software. The GNC design will generally be owned by the GNC group and not FSW. The integration of the auto-generated code and the FSW must be well understood, since the inputs to the guidance algorithms must be well-conditioned, correspond to the right frame of reference, and have the right units. The output must also be understood so that actuators can be driven appropriately. The GNC model output may differ for satellite iterations and variants, and the GNC output should be versioned and described. Note that it would be possible to store the model code in the same repository if desired.

6.2 Build Process Artifacts

The intent of the build system is to generate artifacts that can be used to run and improve the satellite ecosystem. There are two kinds of build artifacts generated in Fig. 3, target-agnostic artifacts and executable artifacts which are target specific. Note that the target-agnostic artifacts can be used as input for building the executable artifacts, but they can also be exported to other teams for ingestion in other build environments. The target-agnostic artifacts may tend to be in declarative languages such as JSON or YAML, which can be consumed by multiple groups operating in different coding languages and operating environments. It might be the case that the artifacts target certain coding languages and some output artifacts can be consumed directly by those languages (like C headers or Python libraries). The point of having the target-agnostic artifacts is that an update to a platform dictionary can be rolled out and tracked across multiple systems with only a single change, not by having to coordinate independent changes in multiple code bases. The rollout to a live system must be orchestrated, and the satellite ecosystem must support more than one active platform. When operating and building satellites for any length of time, it will be the case that multiple platform definitions will always be in play. Note that the idea of target-agnostic artifacts (or artifacts that are published and used by multiple systems) is hardly new. The CCSDS has published documents related to this concept for many years (CCSDS 1987, 1992).

6.2.1 Target-Agnostic Artifacts

- **Telemetry dictionary** – Each satellite platform will have a unique set of telemetry channels that are used to monitor and control its operation. Telemetry information that is created on the satellite will generally not be self-describing due to file size concerns and may also be in binary format. The telemetry dictionary is used to convert machine-generated telemetry points into human-readable data points. It is also used to describe the relationship between the telemetry point and the hardware (source device or subsystem), provide design context if appropriate (description), and also give the units. The telemetry dictionary can be used to convert telemetry in real time (during a radio pass), potentially into graphical displays for operators. It can be used by back-end tools to display historical data, and it can also be used by developers to understand how to build out automation. These scenarios will all involve different tooling and coding languages which is why the dictionary must be code agnostic. The telemetry dictionary will exist across the ecosystem and should be immediately indexable by satellite platform type with multiple telemetry dictionaries existing at once. Note that it is possible for some telemetry channels to be common across satellites (attitude parameters, for instance). This is generally dependent on the subsystem. How one handles the common parameters is up to the designer, either by generating a new (but duplicated) list or by using some kind of inheritance.
- **Event dictionary** – The event dictionary has much in common with the telemetry dictionary. The distinction here is that telemetry is considered time series data (like system voltages), whereas events are one-time data (like a configuration change, limit check warning, etc.). Events tend to have more complex data structures associated with them which makes it appropriate to build out a separate event system from the telemetry system. The manner in which the event dictionary is used is similar to the telemetry dictionary except it will have to describe the more complicated data structure for each event.
- **Hardware (HW) configuration data** – Each satellite variant should start with a hardware configuration which will enumerate the bus layout, the individual device hardware, and the device configuration. This will come in large part from the EE interconnect information. It will also include physical data related to the satellite such as sensor and actuator mounting alignments. The HW configuration information can be pulled into the FSW build process in a similar way that device trees are used in an

operating system (OS). A device tree is generally a binary blob that an OS knows how to parse that describes how it is connected to external hardware (like clock source, pin assignments, etc.). There is another important job for the HW configuration information which is to be imported into the mission operations center (MOC) satellite database with an entry for each new satellite. This database is critical to satellite operations, especially at scale. The MOC database will contain this hardware information; it will detail which software version is on each processor and what the backup software version is. It will detail the current operational mode for each satellite, and it will provide information about security keys, power models, calibration data, etc. Very importantly it will also track degradation of satellites over time which can be tracked against the original HW configuration. The full extent of the MOC database will not be described here, but when flight software is loaded on-orbit and needs to adjust based on new or degraded hardware on a particular satellite variant, it is likely that information will come from the MOC database.

- **Message definitions** – Communication with the satellites will be through a defined interconnect. It is useful to create and store the message definitions such that they can be used to generate message serializers and deserializers on both the satellite and the ground. These serializers/deserializers will be pulled into the flight software as part of the build process. They can also be exported to groundstation code and manufacturing code as appropriate.

6.2.2 Executable Artifacts

The executable artifacts are more recognizable than the target-agnostic artifacts. The need to address multiple deliverables is discussed in **Role of the Flight Software Team**.

- **Flight software for flight computer** – This is the software image for the flight computer. This will likely also include the bootloader image for the flight controller.
- **Flight software for slave microcontroller(s) (uC)** – As mentioned in a previous section, there will be many microcontrollers and possibly microprocessors in the Microsat design that require software. The build process will have to generate all of these software products, and it is likely that the build products will require different tools and possibly different build environments. This may include bootloader images for some of the processors.
- **Flight software for payload** – The payload computer and system will require software. This software may or not be in the same code repository as the avionics flight software. Depending on how the payload processor is architected, this could include bootloader images.
- **Ground tools software** – This would include ground-side radio software, groundstation software, possibly data analysis software, and maybe components that are interoperable with mission control.
- **Manufacturing tools software** – This includes software that might be needed to interface with the satellite while it is on the production line, potentially using a different (and protected) interconnect definition that is only appropriate on the ground.

It should be noted that Fig. 3 shows the build inputs and artifacts but does not indicate where the artifacts are stored. Artifacts will have to be published to some location that makes them available to satellite operations and manufacturing personnel while still meeting any security considerations. The above build architecture is fairly complex, and it may be appropriate to leave out certain pieces until they are needed or to implement it in a different fashion. Ultimately, there will need to be a server level build option which can reliably, repeatedly, and automatically execute the build, unit test, and publishing pipeline steps. However, it is still useful to understand why the design is laid out this way in order to avoid future problems.

7 Flight Computer Software Design

The flight computer is responsible for maintaining the satellite in a power-positive, ground-responsive, and thermally survivable envelope. It is also responsible for enabling the payload to succeed in its mission, through execution of time-sequenced flight control commands, attitude adjustments, orbital maneuvers (if applicable), and power sequencing of payload components. The flight computer must enable the Microsat to downlink its payload data as appropriate. In general, there is the same command and telemetry requirement as all flight computers. There is a significant amount of existing and comprehensive literature about satellite design that should be considered when developing the flight computer architecture (Brown 2002; Wertz et al. 2011). There are also third-party vendors who offer flight software products specifically for Microsats who may be able to supply part or all of the flight computer components, allowing the team to focus on other components such as the payload and its software.

NASA has open-sourced a comprehensive flight software suite called the “Core Flight System” (NASA 2014, 2019). There is a wealth of experience behind this effort, and it is very informative to investigate. There are many similarities between the content of this section and the CFS, which is to be expected since they solve some similar problems. The CFS is actually a superset with respect to functionality since many different kinds of missions can be supported (including deep space), whereas the content here is for LEO Microsats. The CFS may be appropriate as a candidate for Microsat FSW. If one can use the CFS, many capabilities may come for “free” at a later date when they are required. The downside to the CFS is that it can be complex, and the initial learning curve will be steep. In the case that only certain components are desired from CFS, it is a little difficult to separate them out from the larger system. The CFS is also currently ported to certain operating systems which may not be appropriate for the processor that was selected for the flight computer, or the processor may be not be sized appropriately. Note also that the CFS does not necessarily solve certain software problems on the satellite, such as the infrastructure for supporting the local communication bus or integration of sensors and actuators (highly dependent on hardware design). This will somehow have to be integrated into the CFS system. The build system and artifacts for CFS may not match well with other processors or programs that the software teams are working on, including server-side continuous integration (CI) and build. Integrating custom over-the-air protocols may also be more work. However, it might be the case that third-party groundstations are going to be used, and these use some kind of standard protocol schemes, such as those defined by the Consultative Committee for Space Data Systems (CCSDS). The CFS may be able to support some of these protocols natively. In any event, this should all be evaluated from the point of the satellite ecosystem and requirements.

Figure 4 details a possible software architecture for the flight computer. This is a static view of the software that demonstrates the hierarchy between components. The blocks that are on the bottom are generally independent of the ones on top. It should be noted that many of the blocks here are consistent with the NASA CFS diagrams and should be consistent with almost any flight computer design. This is the architecture for the flight computer, but note that there are many components in the diagram that would also be applicable to microcontrollers or other processors in the satellite. This is an opportunity for code reuse and modularity that should be taken advantage of.

Figure 4 has several layers which are described below:

- **Applications** – The application layer as defined here represents the high-level functions that the flight computer must perform. These are generally mappable to requirements such as thermal management, power monitoring, spacecraft attitude tolerances, and time maintenance and distribution. The flight computer must be able to provide enough telemetry for each of these applications to be monitored against its design and performance envelope. Note that at the software level, the code for an application may be split among a task, an interrupt service routine, and potentially an asynchronous messaging handler while still sharing common data. The “Command Processor” is the externally facing consumer of messaging which can provide protocol related capability and is a gateway to the internal messaging bus. The “Power” application will monitor the power state of the system and effect brownout or safety related actions as appropriate. It will also be used to command various parts of the satellite to power on and off. The “Thermal” application will maintain the satellite in its thermal envelop by monitoring temperatures and activating thermal control systems as appropriate. The thermal application will be subject to any restrictions that are being enforced by the power application. The “Runtime Sequencer” will accept arrays of instructions from the ground that represent sequences of future states of the spacecraft. The runtime sequencer will ensure that the satellite state is executed as defined in the timing of the sequences by issuing commands to the other applications. The sequences represent the steps that the spacecraft must execute to complete some phase of the mission (like pointing at a groundstation for downlink). Note that the runtime sequencer should ensure that satellite changes are atomic. It must also be robust against sequence interruption and failure.
- **Services** – Services as defined here are software constructs which enable the applications to perform their jobs. Some of these may not have related requirements but are dictated by software design. This includes internal messaging

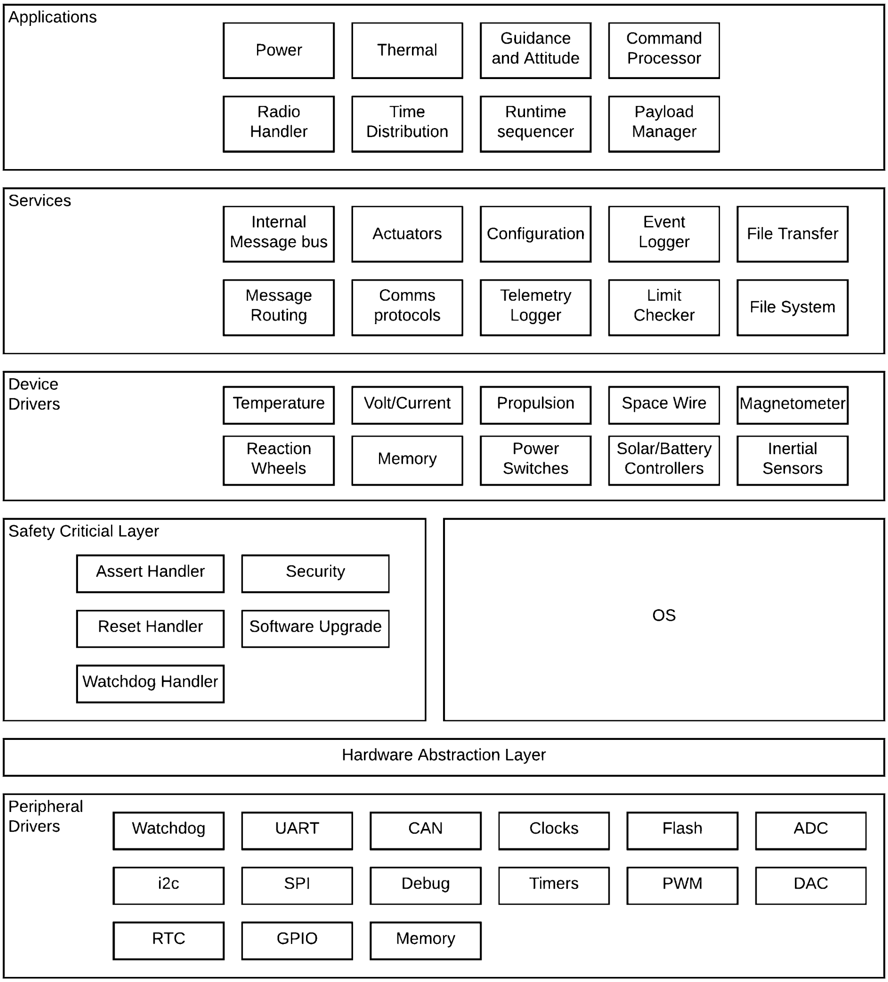


Fig. 4 Flight computer software architecture. (Image © 2011 Planet Labs Inc., licensed for one-time publication)

buses, configuration services, telemetry and event logging services, file system implementations, etc. Note that it is important for these services to be independent of the satellite-specific content. It is not appropriate to build a telemetry or configuration service that is unique to the telemetry or configuration for a given spacecraft variant. This will allow easy portability to new satellite systems.

- **Device Drivers –** Device drivers will be required for all components that are accessed through the various communication buses (such as SpaceWire, UART, I2C, SPI, etc.). They will have command sets and register definitions which are not local to the processor. These are distinct from devices which are natively supported by the processor chip architecture (see peripheral drivers below). Note that the intent would be that these device drivers are portable to other processors. The device drivers will often have to be written by the flight software team. The device driver layer is shown over the OS, but it is possible that applications may be written to bypass the OS and access these devices directly. This is highly dependent on the OS and possibly memory ramifications (allocation/deallocation, direct memory access, etc.).

- **Safety-Critical Components and OS** – This layer has somewhat less of a strict definition to it, in that the relationship between the safety specific components, the OS, and other components may be more complicated than the simple layer approach shown. The safety-critical components are called out explicitly because they are some of the most important software features in the spacecraft. These must be well-designed, robust, tested, and extremely well understood. These features are discussed in further detail in sections "Satellite Safe Mode" and "Security".
- **Hardware Abstraction Layer (HAL)** – This layer is self-explanatory. It abstracts the OS and the higher-level features from the specifics of the hardware implementation. A good HAL means that porting the flight computer software over to a new processor will be easier (e.g., if the flight computer chip is end-of-life (EOL), design changes require a more powerful processor or potentially for a different satellite product). The HAL may be tightly integrated into the peripheral driver layer.
- **Peripheral Drivers** – The processor will require drivers for all peripherals that are to be used to control and monitor the spacecraft. These are generally the peripherals which are part of the processor and have associated internal registers and pins. This code will generally be processor type specific and can many times be available in board support packages or third-party code repositories.

The flight computer architecture as presented here is only one possible example. When designing the system, the flight software team should always look to minimize or eliminate blocks when appropriate (e.g., by standardizing on an external communication bus and external sensors). They should also be looking to share code wherever appropriate among various processors.

8 Flight Software and System Design

There are many aspects of the satellite system design and larger ecosystem that impact flight software or can be impacted by flight software. The following details some specific cases that will be helpful when building out flight software. It is also useful to call out some topics which deserve special attention, including satellite safe mode, software upgrades, and security.

8.1 Satellite Safe Mode

Microsats are generally not designed with the same redundancy and reliability as traditional satellites. This is obviously the result of the much reduced cost. However, they still require the concept of a “safe mode” that the satellite can enter when a fault occurs or for a general mission safety condition. An understanding of the satellite safe mode should be built up very early in the design process, and components related to the safe mode should be prioritized and worked on first in order to give them maximum runtime on the ground prior to launch.

The safe mode should involve a minimum number of subsystems and should allow those systems to have authority over as much of the rest of the satellite as possible. An absolute minimum set of subsystems would be the flight computer, the power control board, and the TT&C radio (assuming no subsystem redundancy). Focusing on these subsystems is extremely important.

Two common failures with Microsats are electronic latchups and processor memory corruption. Latchups can often be cleared by removing power from the device and then reapplying it. This creates two design considerations; first, the ability to remove power from the satellite and its subsystems should extend as far upstream as possible in the power infrastructure. Second, it is very useful to ensure that the flight computer firmware can control power to as many subsystems as possible (as opposed to systems being driven by a non-switchable high-level power bus). This may allow the flight computer to detect and assert a fix, instead of having to force a satellite-wide reset or maybe wait for a planned low-power state (brownout) event if the latchup is exceptionally bad. It is also a good idea to ensure that the flight software is able to actively bring the satellite into a power-on reset (POR) state after a software reset. This means actively asserting all devices under control into a known state, either through direct I/O pin manipulation or setting registers in devices which are connected via communication buses. The flight software should also be capable of actively shutting down power to subsystems in a benign and orderly way. The firmware should be able to make assessments of which buses it believes are healthy.

From an operational point of view, it should be possible to try and address a device failure first through flight computer commands, then through a flight computer reset, and then possibly through a full satellite reset. It should be the case that the flight computer can request (or force) a full satellite reset in some way. From a recovery standpoint, it may also be useful to be able to use the TT&C radio to reset the satellite in response to a radio message, assuming that this can be done as a secure operation.

Watchdogs should be implemented on the satellite in order to try and bring the satellite back into a known state if there is a fault that renders one or more of the safe-mode subsystems unreliable. Processor internal watchdog capabilities should always be used if available. It may be desirable to implement an external hardware watchdog of some kind. All critical systems should have a recurring requirement to “pet” the watchdog and push off its reset function. In the case that a watchdog triggers, the faulty system should be considered completely unreliable, and the watchdog system should not use that system for recovery (by design). It is useful to have some watchdog countdown timer implementation that is reset after every contact with the ground. Note that any system that can reset the satellite should not have a pathological condition where it continually resets the satellite and the time between resets is very short.

The processor assert handler also plays a role in the safe mode of the spacecraft. The assert handler can be called from either hardware or software. The triggering of an assert could be from an unexpected operational request or from undetected memory errors. The assert handler should be designed using the same concepts as the watchdog implementation, and the result of triggering an assert could be a reset of the processor or possibly of the spacecraft. The various possible asserts should be categorized and actions taken as appropriate.

From the flight software perspective, the reset sequence for the satellite should be considered carefully. As noted above, resets of the flight computer and other processors can be a useful tool for trying to bring the satellite into a known state. As such, the path that the reset sequence takes as it executes will be an integral part of the safe mode implementation. A processor will likely go through some kind of bootloader code before starting the application. What happens if this bootloader code remains active for any period of time or stays active because of an application failure? The flight computer bootloader may be one of the most important pieces of software that the flight software team will write. It may have to contain hardware initialization code to ensure that the satellite is properly and safely configured. It may have security requirements or it may have to deal with the TT&C radio. The bootloader will have to ensure that an application that it intends to launch is integrity checked and possibly authenticated, and it must understand what to do when this fails. The bootloader is very importantly one of the few software components that is generally not updated in space. There are other considerations as well for flight software, for instance, the flight computer should prioritize and initialize the most critical systems first and then proceed down through the less critical systems.

Memory errors are another common form of radiation-induced error on spacecraft. Processors and FPGAs should be capable of detecting and/or fixing memory errors at some level (for instance, with ECC). When an uncorrectable memory error has occurred, the processor should immediately be considered suspect. One of the safer approaches is to tie an uncorrectable ECC error into some kind of hard reset circuitry which could be triggered through the absolute minimum amount of software (maybe through only an interrupt service routine with no application code). Another approach is to disable the watchdog monitoring code (ensuring watchdog will fire) and then to try and capture as much information about the state of the processor as possible before attempting a reset through software. This can dramatically aid debug work. This is a less robust approach, but it also allows for the possibility of shutting down high-power systems that might be active in a benign way.

The safe mode should have a very well-understood outcome for guidance and control. The simplest model is to shut down all active guidance, stop all actuators, drop into a low-power mode, stop executing on pre-stored command sequences, and await instructions from the ground. This will put the satellite into a tumbling state, which would have to be understood from a systems standpoint (total possible spin-up, pathological solar panel pointing, etc.). The next level up would be to assert some basic form of guidance to at least keep the satellite from tumbling. Care and thought should be put into this kind of design because at some level, an algorithm such as this will have to assume that certain sensors and actuators are functioning correctly. If these sensors and/or actuators have failed or are somehow calibrated incorrectly (for instance, through memory corruption), then the impact of applying a guidance mode could be disastrous. This kind of design would expand the boundaries of the critical systems required for safe mode.

8.2 Atomic Configuration Updates

It should be possible at any given point to have a clear understanding of the configuration of the satellite. More importantly, the satellite should never end up in a state where only partial configuration has been applied. This places a requirement on the system design to ensure that configuration changes are atomic. The potential for partial configuration changes could occur during interrupted radio links or if the satellite is executing pre-stored command sequences and some form of fault occurs that aborts the set of command sequences before they are completed. The satellite may then not execute a command sequence that was intended to restore some background state for the spacecraft.

Configuration is used in two senses here; there is the concept of “configuration data,” such as calibration data, satellite sensor frame data, security settings, payload settings, current orbital parameters, guidance parameters, etc. This tends to be longer-term data which is updated from the ground during a radio link pass. There is also the way in which the satellite is “configured” at runtime, such as varying power rail settings for payload and heaters, satellite pointing mode for solar panels, etc. This generally comes from the satellite flight software design and the ongoing execution of pre-loaded sequences to execute on the mission. Both of these types of changes should be atomic in nature and should be revertible (if appropriate) at reset or fault.

This idea of atomic configuration updates may seem obvious, but configuration information can be spread across multiple systems and subsystems. It may also be the case that certain configuration data is required to be updated more often and considered less critical, creating the desire to implement different messages for different configuration parameters. It may also be the case that different system owners have devised different schemes for how they ingest configuration requests.

The amount of configuration data for a satellite, even a Microsat, is considerable. It is unlikely that the whole configuration state can be applied at once, even if desirable. A system-level breakdown of configuration data into manageable and appropriate groupings is appropriate, ideally with each element in the group then being atomic in nature.

For configuration data, it is appropriate to create wrapper logic around configuration set commands that can atomically apply new configuration (once verified) and which more importantly can assert a known or default state at reset or fault. Verification of the data should involve a cyclic redundancy check (CRC) or potentially security-related verification (HASH) depending on how security is implemented and should also include bounds checking where appropriate.

For runtime configuration of the satellite (pre-loaded command sequences), it is useful to define a higher-level “manager” application that will ingest the request for state change and act on it as appropriate (as opposed to executing some low-level command directly). This manager function can then also contain the logic for reset or fault cases and can restore default or safe state as appropriate.

8.3 On-Orbit Software Upgrades

As stated previously, the philosophy for Microsats should be that software upgrades while in orbit should be reliable, possibly often and not exciting. As mentioned in **Flight Software Life Cycle**, there are many reasons why the flight software may not be ready at the time of launch. It is also the case that since full space simulation may not be possible on the ground, lessons learned during actual on-orbit testing can only be incorporated using on-orbit flight upgrades. Verification of payload may be even more tied to on-orbit testing, and updates to the payload software should be expected.

Planning out software upgrades to the satellite is one of the most important system design questions to be answered by the flight software team. This includes the flight computer, peripheral microcontrollers, and the payload system.

Processors should always be able to maintain at least two different images for software, with one being active and the other idle and available for update. This means that memory architectures should be sized appropriately for two images, as well as multiple copies of configuration data, redundant security information where appropriate, and room for a bootloader. Payload data should (if possible) be kept in a separate memory device than the flight software. It will have a different use profile and will likely require a much larger memory device which may be less tolerant of the space environment. When updating flight software, it is useful to enforce a design where both flight software images get updated in a ping-pong fashion such that one is just ahead of the other in version. The advantage of this is that it reduces the “staleness” of the software in orbit. The impact of stale software can be a tedious, long road of sequential updates that must be executed by the satellite operations group to bring the satellite up to date if a flight system must be reverted to a backup copy of software that is extremely old.

Software upgrades will be somewhat sporadic with respect to the mission life cycle and could potentially cause large peak loads on radio links and internal bus links between processors. It is important to ensure that these links are sized appropriately for software upgrades and avoid the tendency to only focus on the steady-state operation of the satellite with respect to bus and communication design. It should not be the case that the processor selection and flight software design result in software image sizes that are beyond or barely within the transfer capability of the satellite uplink. It should also be taken into consideration how long the satellite may be unable to focus on its mission while in the software upgrade mode. When uplinking software updates to the satellite, the design should be robust against losing the radio link, subsequently being able to resume the upload at a later time without resending data.

In the software upgrade design, it is possible to consider both atomic upgrades of the software and partial upgrades. An atomic upgrade would replace the entire image with an uplinked version. This version can be tested and validated on the ground for each satellite variant as appropriate. It is also possible to have a partial update scheme, using a package manager or virtual container for high-level operating systems or by uplinking a “binary diff” file that can be applied to static content on the satellite, integrity checked, and then loaded into nonvolatile memory. Partial upgrades can reduce bus traffic but have two downsides. The first is that a series of partial updates applied to various satellite iterations can be hard to test, track, automate, and revert. This can be very painful for satellite operations. The second is that a partial upgrade does not protect against corruption of the existing content on the satellite (for instance, through memory corruption). It is useful to be able to minimize the software cross section that cannot be updated atomically in orbit, in particular for unrecoverable radiation damage. In most cases, it should be possible to update everything except the bootloader.

8.4 Accountability in Operations

In a fleet of Microsats, the level of automation in satellite operations will be quite high. There will likely be a computing infrastructure that is monitoring the satellite fleet and generating data analytic reports that are fed into the various organizations in the company. The monitoring capability will be tied into an automated escalation and alarm system. Generally there will not be live personnel monitoring the satellite system 24/7. This automated monitoring will benefit from satellite data that is easy to machine parse and which is consistent in time stamp. For simple time-series values such as voltage, current, spin rates, etc., the monitoring is straightforward, and there can be a threshold set for both warning and fault levels. However, it is also useful to find alternative solutions for cases where the automation must perform complex processing on the received data in order to arrive at a conclusion; this includes having to apply some kind of waveform processing to time-series data, for instance, trying to estimate battery charge state from historical current and voltage levels (which may be sparse or incomplete).

The need for hardware-related telemetry on a satellite is more obvious than the need for system-level telemetry and monitoring. In a Microsat ecosystem, there are multiple systems in play, and each of them may be rapidly evolving, including mission control software, groundstation software, radio software, and satellite software, not to mention possible changes in groundstation hardware and cloud-computing infrastructure. When operating a fleet of Microsats, it is likely that there are legitimate reasons for some payload windows to fail; this includes technical reasons and also operating reasons such as aggressive time windows, operating close to the edge of the power envelope, etc. The point is that there will always be a high level of general noise that can make a new failure difficult to detect and isolate. Once detected, it can become a very daunting exercise to figure out why certain operations have not taken place if the observability of the system is poor, especially if they are finally noted as a general downward trend in system-level performance. Observability is then extremely important to be able to track down and diagnose issues that arise in the program.

In general, the flight software team and all other developers should embrace this idea of system "observability," the notion that at any given time, it is possible to trace how the satellite got into a particular fault state or failed to execute on its payload mission for some interval. This "observability" should also be designed such that it is easy to integrate into the automated monitoring system. An example of why this is important is measuring fleet-wide system performance against a customer service-level agreement (SLA) for a remote sensing type of mission. First, it is important to understand that there are a very large number of reasons that payload remote sensing data does not make it to the customer. Consider Fig. 5, which lays out how a payload acquisition request results in product being delivered to the customer. For convention, the left half of the diagram is labeled as "Reaction Time" which is the time between payload data request and payload data acquisition. The right half is labeled "Latency"; this is the time between payload data acquisition and delivery to the

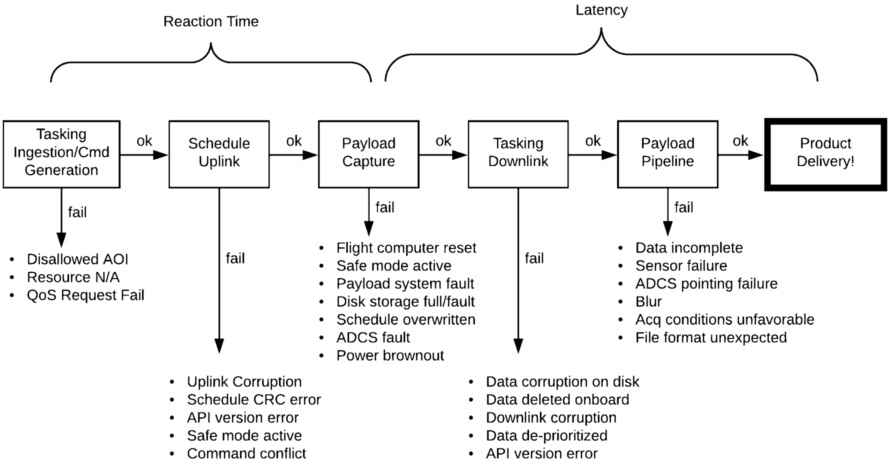


Fig. 5 Accountability for payload delivery. (Image © 2011 Planet Labs Inc., licensed for one-time publication)

customer. Both the reaction time and the latency may have SLA-related limits. For each step in the process, there are some example failure conditions listed.

The leftmost block is the initial task request, which may fail due to an inappropriate area of interest (AOI), satellite resource conflict, or potentially a failure due to an unmeetable quality of service request. Once declared acceptable, the request is turned into a series of command sequences that must be uploaded to the satellite, which is the next block in the sequence. There are multiple reasons that this can fail as well, including the satellite being in safe mode, potentially a command conflict, or the radio pass just happens to fail for equipment or planning reasons. This pattern continues to the right until data delivery to the customer. At the system level, each step of the process will have a non-zero failure percentage that must be observable and monitored. As can be seen from the rest of the diagram, there are many fault paths for the payload sequence (and many that are not shown). The intent for the system monitoring should be twofold: first, the customer facing team must be able to answer the question of why a particular payload sequence was not acquired, and, second, it must be possible to rapidly track down which step in the process has degraded. And then use that information and the observability built into the design to understand why the SLA may be at risk.

The reality here is that it can be very difficult to estimate the impact of what appears to be a small change, but (by design) it should be very easy to monitor it once it is deployed. Changes are always being made to the system, and this must be built in to the monitoring expectation. Early on in the design process and at regular intervals, the team should audit the event and telemetry streams and ensure that high-level functions in the end-to-end satellite ecosystem can be monitored easily. Each team should also be on the lookout for changes which may derail payload delivery and ensure that those events are reported and ingested into the automated monitoring.

8.5 Security

A critical aspect of the satellite ecosystem is the security posture and security implementation. The security posture for a mission will vary depending on the perceived value and lifetime of the mission. An academic mission of a single Microsat may have a less rigorous posture than a large satellite fleet that has ongoing launches for replenishment (and a longer window for security practices to become stale). The security posture will also be dictated by regulatory bodies such as NOAA in the USA. In any event, a satellite mission should have a security plan that comes from the security posture (requirements) which allows the security to be implemented in a way where risks are properly assessed and appropriate measures taken to achieve the desired level of security.

There is a reality that security design on a Microsat may not be given as much priority as other components and subsystems in the spacecraft. This is especially true in the early phases when basic systems are being developed, resources are short, and there is a significant chance that the early Microsat will not even reach full mission status after launch. There is then a likelihood that security features will be implemented “over time” as the design and potentially the company become more mature. From a flight software standpoint however, it is very beneficial to understand the eventual security capabilities early in the design process and identify the possible impacts to the flight software design. The use of standard security paradigms can greatly aid this process, and they should be considered (this will also help to avoid creating security vulnerabilities). The literature around security practices and possible implementations can be daunting, but an applicable and good starting point for a Microsat satellite design is to understand the IP security (“IPsec”) open standard Wikipedia article and then the various standard documents themselves (Kent 2005; Kent and Seo 2005). A good satellite-based security document to read after IPsec is the “Space Data Link Security Protocol-Summary of Concept and Rationale” published by CCSDS (CCSDS 2018). This document can reinforce some of the IPsec concepts through a satellite-based example. When choosing a security paradigm, the encrypted and authenticated option should be preferred. Note that an interesting aspect of the CCSDS implementation is the concept of the “authentication bit mask” which allows for selective exclusion of some fields in the message authentication code (MAC) which can make the application of authentication slightly more flexible.

The CCSDS publishes many security-related documents which are worth reading: the “Security Guide for Mission Planners” (CCSDS 2019a) is a good overview of security for the whole mission. It also lays out how the various CCSDS security documents are interrelated. The “Report on the Application of Security to CCSDS Protocols” (CCSDS 2019b) also has great information on security for satellites.

Returning to the flight software team, the goal of the team should be to break down security requirements into capabilities and then come up with a schedule to implement them, preferably as soon as possible. Availability of these capabilities can provide security to the Microsat even when the security plan is not completely fleshed out. At a high level, these capabilities will relate to requirements for hardware and software cryptographic capability, tamper detection, the storage of crypto keys in nonvolatile memory, and implications for the design of communication protocols. It is easy to fall into the trap of building out mission functionality first and then being in an awkward position trying to implement security on top of the resulting implementation. It is best to try and avoid this.

Before examining possible security capabilities, it is worth mentioning some concepts that can impact the flight software security design at a fundamental level. The first is the concept of a security boundary and a cryptographic module, and the second is the notion that the endpoints of a security paradigm may terminate in different places on the ground.

In the context of satellite security design, establishing the security boundary means having a clear understanding of how data and commands transition from a trusted to an untrusted domain and vice versa. A cryptographic module defines the perimeter within which cryptographic processing is performed, such as command and telemetry decryption and encryption. From a flight software standpoint, establishing the security boundary and cryptographic module on the satellite will help identify which devices on the satellite must have cryptographic capability and access to keys and which do not. This may also impact how devices are interconnected.

With a less stringent security posture, the security boundary could be defined as being at the physical satellite boundary itself, potentially at the interface where the satellite feeds data to/from the radios. The cryptographic module could encompass all the devices except for the radios, so keys could be freely shared among all devices, and one or more devices would be responsible for key management and cryptographic operations. This model imposes fewer design constraints in terms of satellite design and may be adequate for a satellite with a less stringent security posture.

With a more stringent security posture, the security boundary could again be defined as being at the physical satellite boundary itself, but with a singular subsystem (device or devices) forming the cryptographic module responsible for key management and cryptographic operations. While this may impose more design constraints, it should (hopefully) provide for tighter control around the security processing on the satellite. Having the security code separate from other satellite functionality should also support easier auditing of the security operation. Note that security boundaries and cryptographic modules also apply to ground systems that perform encryption and decryption of satellite data.

It is important to understand that the endpoints for security capabilities may vary depending on the purpose. Figure 6 indicates some possible security paradigms. Note that these concepts are also discussed in CCSDS references (CCSDS 2011, 2019b). The point here is that there are security links that can terminate at the local groundstation and also security links which can potentially terminate in dedicated or cloud-based servers for the mission operations center (MOC) and payload processing. It is therefore inappropriate to focus on a security paradigm which is only designed for the over-the-air (OTA) datalink, for instance, and it must be the case that secure messages can be routed from a groundstation through the ground network to the appropriate downstream endpoint (mission control or payload processing). In the diagram, “Mission Operations Center” represents the server or cloud-side processing system which automatically manages the satellite constellation. The following describes the links in Fig. 6:

1. **Mission Operations Center and Satellite** – The connection shown here is that of a traditional “bent pipe” where the groundstation merely relays packets back and forth (both telemetry and command). The groundstation may implement some form of data link security and may have the authority for message retries.
2. **Groundstation and Satellite Radio** – It may be the case that the round-trip delay between the groundstation and mission operations center is inappropriate for certain operations, and there is a desire to implement some autonomy on the groundstation itself. A prime example of this is adaptive coding and modulation (ACM) where it is desired to keep the feedback loop driving the radio as tight as possible. Automatic repeat request (ARQ) can also be done locally at the groundstation.

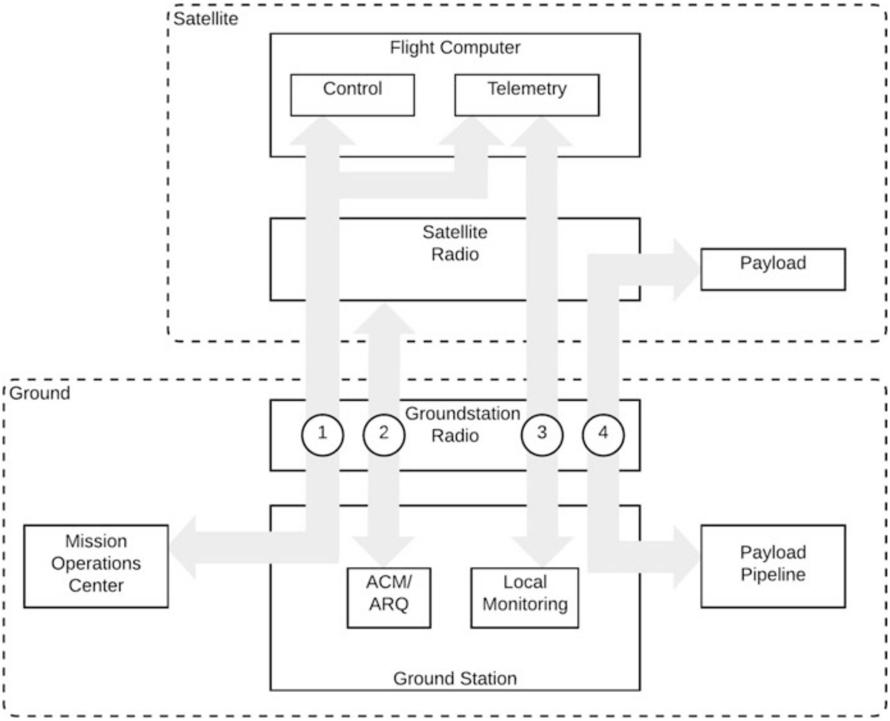


Fig. 6 Security routing endpoints. (Image © 2011 Planet Labs Inc., licensed for one-time publication)

3. **Groundstation and Satellite Telemetry** – This is a more uncommon case, but there may be a reason for satellite telemetry information to be available at the groundstation. This would typically just comprise telemetry received directly from the satellite.
4. **Satellite Payload-to-Payload Pipeline** – The payload data will likely be delivered directly to a cloud-computing endpoint or potentially a customer endpoint for pipeline processing. The ground system will have to understand how to route this information to the payload endpoint. Note that it may be the case that the payload does not have to be encrypted at all. This will depend on business and regulatory conditions.

8.5.1 IPsec Concepts and Capabilities

The concepts behind the IPsec model represent capabilities that will very likely need to be implemented on the satellite. Note that implementing simple models for these capabilities while still following best practices for the actual encryption and authentication can go a long way in securing the satellite. The following list gives some context around the capabilities that may be useful to the flight software team:

- **Security association (SA)** – The security association is an agreement between two entities about how they will use security capabilities and practices to communicate in a secure fashion. The security association for an early stage Microsat can be simple, potentially decided entirely in advance with no runtime negotiation and based on pre-loaded symmetric keys. The pre-loaded keys can be used directly for encryption and authentication purposes. There should be a security association entry for each security relationship in the system (as shown in Fig. 6). At a minimum, the SA should have a version and detail a minimum set of cryptographic algorithms to be used (encryption, MAC), key attributes, and a list of valid key IDs. Alternatively for satellites desiring more flexible key rotation, the SAs on board the satellite may be updated using a form of key exchange to generate fresh traffic protection keys (CCSDS 2011). Consideration needs to be given to the number of message round trips required for the establishment of an SA as this adds latency to the process.
- **Security header** – The security header is added to the data content and is intended to indicate how the corresponding data should be decrypted and also to allow for authentication of the data. The name "security header" is presented to be generic, in that the header can be designed as appropriate for the Microsat system. It should have similar parameters as the Encapsulating Security Payload (ESP) from IPsec (Kent 2005) where necessary, such as the Security Parameter Index, the initialization vector (IV), a sequence number, and an ICV or MAC. The CCSDS document for the Data Link Security Protocol (CCSDS 2018) has both a "security header" and a "security trailer" which when combined have similar fields to the ESP. Since authentication is generally a good idea, combining the CCSDS "security header" and "security trailer" may be an appropriate choice to consider. Note that the IPsec definition is tied to IP and the CCSDS design reference above is tied to a data link layer. It may be appropriate to create a security header that is agnostic of protocol or communication layer.
- **Security Parameter Index (SPI)** – The SPI is included in the security header and indicates which SA the content is intended to be used for. For a Microsat, this can be as simple as a scalar value which indicates which security association (SA) to use. It is potentially useful to also include a version into the field in addition to the SPI.

8.5.2 General Concepts and Capabilities

- **Software cryptography** – From a software standpoint, the types of cryptographic algorithms must be understood and implemented. It is useful to try and identify cryptographic libraries which are appropriate for the processor in the device selection phase. There is no reason that this should be done in-house. Note that software cryptography can create a large burden on the processor that must be accounted for. It is also an idea to ensure that there is headroom to grow on the processor in the case that the cryptographic algorithms must change. Cryptographic libraries can be very comprehensive and will likely contain many more algorithms than the satellite system needs, consider removing unused routines from the software, and also remove security algorithms that are no longer considered secure.

- **Hardware cryptography** – In the design and device selection phase, there should have been some consideration of hardware security capabilities. This would be either hardware implementations of cryptographic algorithms (like the advanced encryption standard AES) or maybe hardware acceleration with floating point libraries or digital signal processing (DSP) blocks. Note that hardware cryptographic capabilities are not upgradeable so if the hardware is unable to provide sufficient protection at a later date (for instance, if the key length or cryptographic algorithm is insufficient), then the update will have to be moved to software, or a new processor must be selected and integrated. A way of reducing the risk of this would be selecting cryptographic algorithms and key lengths that are thought to be secure for the expected lifetime of the satellite constellation. For constellations with a design lifetime of many years, designing in crypto agility can be challenging due to emerging quantum computing capabilities.
- **Key storage** – The flight software must be able to store the permanent keys that are provisioned at manufacturing, and it must do this in a reliable way. In the flight software work, the store will likely be one of the larger efforts. The key store must be persistent, potentially duplicated for redundancy, and protected against write failure. Note that in a Microsat, security keys are likely maintained in flash, and flash is generally fairly robust when not written to. It is a really good idea to not use a flash storage device that implements a flash translation layer (FTL) under the hood. This could mean that the memory storage device is actually moving the keys around for wear leveling, and a radiation event could be detrimental if it disrupts this write operation. The key management scheme should be tied into the SA that is discussed above, with each SA being associated with at least a pair of keys. For more complex security schemes, there will likely be a hierarchy of keys such as master keys and traffic encryption keys (CCSDS 2011) and also the notion of key life cycles and cryptoperiods. This will have to be reflected in the key storage design.
- **Protocol definitions** – It is important to ensure that the security header can exist in the protocol definitions from the start. When using third-party communication designs, this will likely not be a problem. However, in a home brew system, there may be some data overhead concerns if the maximum radio packet size is small. Care should be taken as well to ensure that the security implementation (encryption) does not interfere with any message routing implementations.
- **Replay protection** – Protection against the replaying of previously sent commands is almost as important as the authentication of commands. IPsec achieves this through the use of a sequence number associated with each SA that is incremented on each packet sent. The receiver tracks the sequence number for each SA and enforces ordering to reject replayed (repeated) packets. There should always be replay protection built into the design.
- **Fallback plan** – There should be a well-understood design for the security system if there is some kind of degradation or compromise. This may be a fallback security key or key store or potentially a different algorithm suite that is not normally used. It should be predictable to the satellite operations group when the fallback plan is activated.

Having the SW/HW cryptographic capabilities, the key storage, the SA, and the security header design will allow for implementation of a reasonable first level of security. If these aspects are handled correctly for the initial (or early) Microsat design, then the flight software team may only have a supporting role when the system is scaled up to many satellites. The bulk of the extra work will be in key management on the ground, both inside the mission operations center and the manufacturing process.

Security must be understood in all aspects of operation, including software upgrades and during resets and faults. Security must be active during the software upgrade process, and a failure in the upgrade should not result in a compromised security position (there should never be a possibility that the security is not active). The security design should also be robust against loss of time on the satellite, and as in any system, the security will only be as good as the weakest link.

9 Conclusion

When developing Microsat software, it is important to properly understand the scope of work involved for the flight software team and also the development life cycle when multiple launches are taking place. This will enable the flight software team to develop appropriate architecture and build philosophies that allow critical software components to be delivered in a timely fashion. The flight software team should ensure that on-orbit software upgrades and an appropriate safe mode are well established as early in the design process as possible. The environment in which the flight software team operates can be challenging for long-term planning and development. Where possible the flight software team should look to the future and ensure that they try and position themselves for future success at scale. This includes focusing on items such as building observability into the design, identifying security capabilities, and being involved early on in the processor and device selection process. A successful Microsat company could end up with a very diverse set of satellite hardware in orbit, both from ongoing developmental improvements and from random degradation of hardware once it gets into the space environment. The flight software team should plan for the implications of this reality and help ensure that the company can successfully operate a diverse fleet of satellites.

10 Cross-References

- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Planet's Dove Satellite Constellation
- ▶ Power Systems for Small Satellites

- ► RF and Optical Communications for Small Satellites
- ► Small Satellite Antennas
- ► Small Satellite Constellations and End-of-Life Deorbit Considerations
- ► Small Satellite Radio Link Fundamentals
- ► Small Satellites and Structural Design
- ► Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ► Stability, Pointing, and Orientation

References

C.D. Brown, *Elements of Spacecraft Design*, Education Series (AIAA, Reston, VA, 2002)

CCSDS, *SFDU Operations: System And Implementation Aspects, Report Concerning Space Data System Standards, CCSDS 610.0-G-5*, Green Book, Washington, DC, February 1987

CCSDS, *Standard Formatted Data Units – A Tutorial*, Report Concerning Space Data System Standards, CCSDS 621.0-G-1, Green Book, Washington, DC, May 1992

CCSDS, *Space Missions Key Management Concept*, Report Concerning Space Data System Standards, CCSDS 350.6-G-1, Green Book, Washington, DC, November 2011

CCSDS, *Space Data Link Security Protocol-Summary Of Concept And Rationale*, Report Concerning Space Data System Standards, CCSDS 350.5-G-1, Green Book, Washington, DC, June 2018

CCSDS, *Security Guide for Mission Planners, Report Concerning Space Data System Standards, CCSDS 350.7-G-2*, Green Book, Washington, DC, April 2019a

CCSDS, *The Application of Security to CCSDS Protocols*, Report Concerning Space Data System Standards, CCSDS 350.0-G-3, Green Book, Washington, DC, March 2019b

E. Costenaro, A. Evans, D. Alexandrescu, E. Schaefer, C. Beltrando, M. Glorieux, *Radiation Effects in SSDs*, Flash Memory Summit, IROC Technologies, Santa Clara, 2015

S. Kent, *IP Encapsulating Security Payload (ESP)*, RFC 4303, ISOC, December 2005

S. Kent, K. Seo, *Security Architecture for the Internet Protocol*. RFC 4301, ISOC, December 2005

NASA, core *Flight System (cFS) Background and Overview.* (2014), PDF File, https://cfs.gsfc.nasa.gov/cFS-OviewBGSlideDeck-ExportControl-Final.pdf. Accessed 1 Nov 2019

NASA, *Radiation Effects and Analysis – GSFC Radiation Database*. NASA website (n.d.). Retrieved from https://radhome.gsfc.nasa.gov/radhome/RadDataBase/RadDataBase.html. Accessed 15 Dec 2019

NASA, *core Flight System – A paradigm shift in flight software development*. (NASA website, September 13, 2019), https://cfs.gsfc.nasa.gov/Introduction.html. Accessed 1 Nov 2019

D. Sinclair, J. Dyer, *Radiation Effects and COTS Parts in SmallSats,* 27th Conference on Small Satellites, AIAA, August, 2013

J.R. Wertz, D.F. Everett, J.J. Puschell, *Space Mission Engineering: The New SMAD* (Space Technology Library, Hawthorne, 2011)

Network Control Systems for Large-Scale Constellations

Jeroen Cappaert and Sreeja Nag

Contents

Abstract

Network control systems for large-scale constellations of small satellites are of critical importance to the successful and safe operation of smallsat systems – especially in the case of remote sensing networks but also for other applications. As the level of complexity of the space segment and the ground segment of these networks increases so does the level of complexity of the network control systems that are used. Today small satellite constellations such as those represented by

---

J. Cappaert (✉)
Spire Global, Glasgow, UK
e-mail: jeroen@spire.com

S. Nag
Nasa Ames Research Center and Baer Institute, Mountain View, CA, USA
e-mail: sreejanag@alum.mit.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_16

Planet and Spire represent the two largest small satellite constellations in operation, but in the near future, there are many new constellations that may require network control of many thousands of smallsats. There are challenges associated with initially deployment, configuration of spare satellites, operation of large constellation, and de-commissioning and de-orbit of smallsats that require a high level of sophistication and technical expertise. All of these levels of complexities and methods to create effective network control systems for large-scale constellations are addressed in this chapter.

Keywords

Artificial intelligence (AI) · Machine learning · Mission control · Scheduling · Planning · Tasking · Figures of merit · Delay-tolerant networking · Software-defined networking (SDN)

1 Introduction

In recent years, there has been a proliferation of smallsat constellations. There are now over a dozen companies now having fully operational constellations and commercializing their telecommunications, networking, automatic identification system (AIS), remote sensing, and RF geolocation products. These small satellite constellation operators now have a special focus on how to achieve the most efficient and optimal use of their spacecraft assets. Most modern smallsat constellations are no longer operated on an on-demand basis. Instead most of these smallsat systems collect or communicate data on the basis of software programming. Thus most of these spacecraft operate at their own pace. Further in the case of remote sensing and other systems, there is a trend toward processing of data on-board the satellite to greatest extent possible. If it is possible to pre-process the data on-board before bringing it to the ground, it can lead to greater efficiencies at several levels.

The goal of a network control system for a smallsat network thus typically becomes to translate direct customer demands into the operational plans for the satellite networks without commands or specific requests for data coming from the ground. This process is called, especially for remote sensing satellite systems, asset tasking. This method of optimizing the usage of the space and ground segment assets via network control software is key to the successful operation of smallsat networks (see Fig. 1). As such, network control is now central to achieving mission and business success. In short optimized network control systems are key to determining achieving the highest return on investment and the most efficient asset allocation in orbit and on the ground.

2 Smallsat Constellations

A Euroconsult study has projected that, over the next 10 years, about 8600 smallsats will be launched, at an average of 835 per year as of 2023. They also project that this will grow to an average of 880 launched per year by 2028.

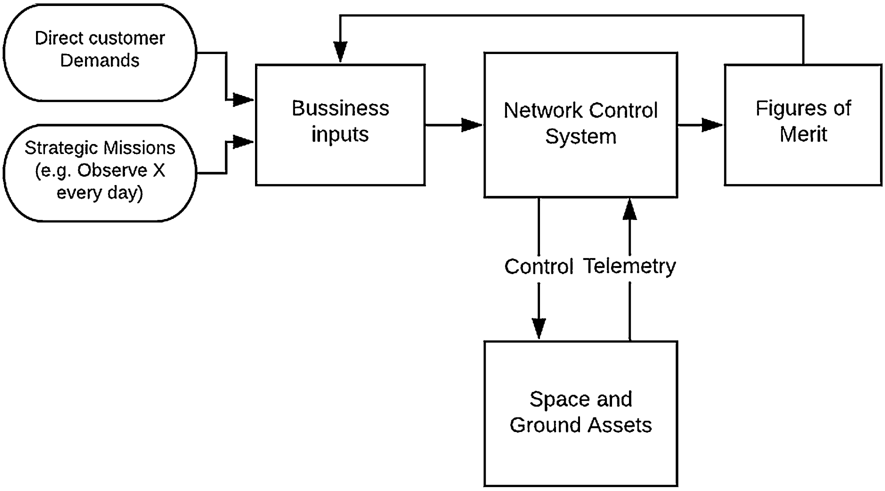


Fig. 1 Network control as part of business process

According to the Euroconsult study, 322 smallsats were launched in 2018. Of these launches about 40% were for constellations (Euroconsult 2019).

Proposed constellation sizes range from 10s of satellites to 100s and 1000s. A few operational constellations already exist today in the range of 10s and 100s of satellites (e.g., Planet, Spire).

This trend toward the use of more efficient software, optimized network control systems, and the use of pre-processing where possible is not restricted to smallsat networks. These same dynamics are also driving fundamental change in the way large networks of satellites are operated.

In the past it was feasible to manage and control a few satellites by means of an on-the-ground team of operators. It was even for larger networks of perhaps 20 in number by means of simple automation and a scripting process followed by manual operators on the ground. This approach however becomes increasingly unwieldy for larger constellations. Human errors – sometimes called cockpit errors – become more likely as network operations grow in size. There is a threshold – of perhaps a constellation of 50 satellites – that forces a change to a completely different level of automation.

A constellation of 50 or more, such as was first demonstrated by the Iridium and Globalstar constellations, requires a different approach. At this level of complexity, the satellites can no longer be thought of as individual assets. This is because the complexity of interaction is increasing exponentially, which can be shown analytically (Alderson and Doyle 2010). A network of this size has to be considered as a holistic combine. It becomes necessary for space assets to be continually optimized. Automated network control can then be programmed to provide maximum product value.

One must start from a purely practical perspective to consider what satellite operators are able to achieve. It is very challenging for operators to constantly monitor and in real time resolve anomalies that occur within a constellation larger than perhaps 20 satellites operating in low Earth orbit (LEO) and truly impossible at a level of 50 satellites. This is because the complexity of interaction is increasing exponentially. If one considers the case of a modern smallsat constellation, the complexity becomes very great indeed. Such a constellation could have:

- Greater than 100 satellites. These might be distributed in many orbital planes.
- There could be ground station at 50 or more locations.
- There might be well over 1000 satellite contacts per day.
- The level of communications throughput and data download might be collectively measured in gigabytes per second.
- Satellites might have varying data requirements and have been programmed to provide multiple services or data products.

With this amount of complexity, manual control essentially becomes impossible. Automated and programmed systems are needed for network control. This then allows operators to focus on providing the needed responses and inputs to the system. The role of human operators thus becomes that of balancing business priorities and re-acting to specific issues or anomalies that might require attention.

3 Network Control System Functionality

All these elements of optimized systems operations are shown in Fig. 2 with the many parts of a network control system depicted. There are many aspects to consider. These elements include but are not limited to the following (Cho et al. 2018).

- **Satellites**: a typical smallsat constellation and the satellites deployed in it are built up over time. This may include the use of rideshare launches. In such cases the constellation can be less “managed” than traditional constellations that can utilize dedicated launches.
- **Ground stations**: Smallsat operators typically rely on a ground station network that is not monolithic in nature. Rather these ground stations may well be constituted by multiple owners and service providers. The result of this diversity of providers and terminals is a ground network that has capabilities that might widely differ. For example, on some stations there might just be a downlink available, while other stations can send commands as well as receive data.
- **Mission control**: The mission control centers can also differ. One facility could be a traditional physical mission control center. Others might be designed as completely cloud-based distributed control center. Such a facility could have limited on-shift operators.
- **Schedules**: Scheduling is also key concept that drives asset allocation. Transit and payload schedules are traditionally generated centrally from the mission control

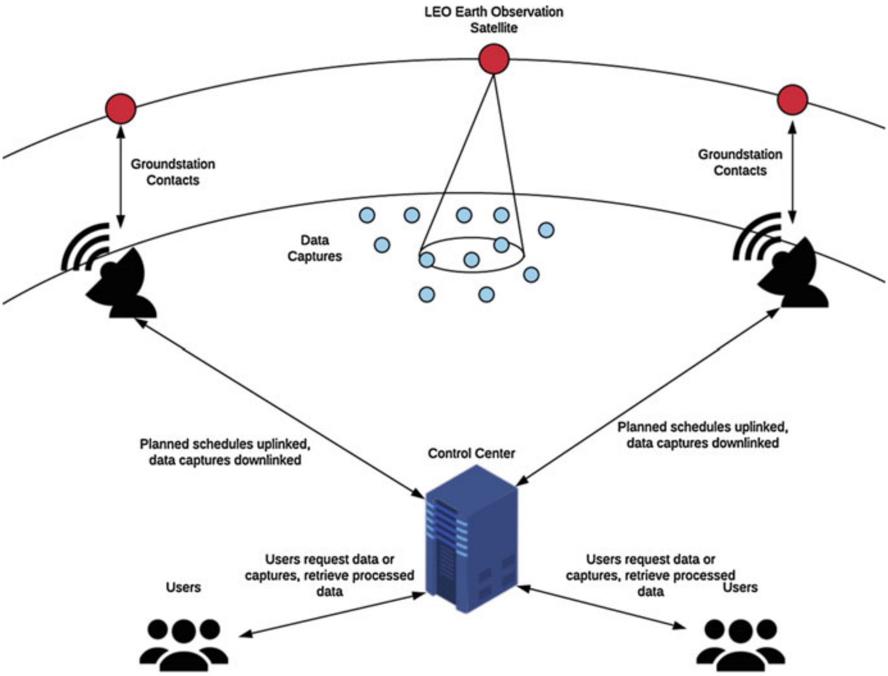


Fig. 2 Illustration of the elements of a network control system and need for flexible network control

center. In modern systems, however, network control varies depending on whether spacecraft are programmed with on-board satellite autonomy.

- **Customers/users**: Internal users and customers have varying needs. These may vary by season or other variables. Factors that might vary include changing number of measurements per day or once per day, week, month, etc. There can be some form of a one-off on-demand requirement such as a measurement at a specific time and place. Users could also specify multiple interfaces as to where and when to retrieve data.

Smallsat constellations come in various forms and sizes and now comprise many applications, but generally the goal of network control can be generalized to the following:

- Optimize both the ground and space segment assets so as to provide the maximum return on investment.
- Ability to exploit the satellite system to allow maximum flexibility to respond to customer demands and changing market needs.

In the case of a communications constellation, the goal is typically to determine how to route given volumes of throughput optimally. Alternatively, the objective for an Earth observation constellation is to schedule data collections efficiently as well as to find the best route to relay data to the ground. Both problems are highly interconnected to routing efficiency. The use of network control systems t to achieve routing efficiency is considered in the rest of this analysis.

3.1 Figures of Merit

A figure of merit provides a way to best gauge the performance of a network control system and is especially key for Earth observation services. The rationale for establishing a figure of merit typically considers one or more of the following criteria.

- **Revisit time**: This is the time between subsequent observation and/or coverage of the same geographical area. This is key for both networking and Earth Observation services. It's an important aspect as it defines the intervals during which coverage or service is not provided.
- **Refresh time:** This is the time between subsequent observations of the same asset (e.g., in the case of asset tracking like automatic identification systems (AIS), automatic dependent surveillance (ADS-B), or machine-to-machine (M2M) communications).
- **Latency**: This represents the time between an observation and data delivery to customer or the time to provide data networking connectivity. Sometimes this also includes the time required to command a spacecraft to take a certain measurement.
- **Coverage**: This provides a precise measure of the geographical coverage of a satellite constellation. This defines the percentage of the Earth's surface (or an area of interest) that is covered. Similarly, asset coverage can be defined as the ratio of assets that is covered (ships, buildings, airplanes).

3.2 Constraints

A network control system thus needs to be flexible and responsive in order to take into account various operational constraints. The principal constraints include:

- **Energy constraints**: It is important to ensure that the stored energy in the spacecraft battery is always sufficient to meet power needs of the mission and the spacecraft bus as well as meet the associated needs during the times of solar eclipse. All scheduling of spacecraft activities needs to take into account the satellite's power budget. There also needs to be some reasonable margin. In short scheduling of service must always respect power availability plus some margin.
- **Thermal constraints**: There are also thermal constraints that must be considered in the provision of services. Each of the spacecraft's subsystems must be used only if the temperature expected in that interval is within an acceptable range. If a

particular payload observation or communication windows are found out of range, then this service capability must be cancelled.

- **Data balance or storage capacity**: There must be care taken to ensure that the storage space remaining on the spacecraft is more than adequate to meet mission objectives. This includes the capability to always be aware of the storage capacity and downlinking capabilities in terms of data rate and windows that are available for such data transfers.
- **Subsystem compatibility constraints**: There can be competing power, thermal, or other constraints that must be considered. This means that network control systems must be programmed so that non-compatible subsystems are not used at the same time or that all operational requests are compatible for the times they are in use. For example, high-power transmitters and a sensitive receiver might operate effectively at the same time. Other payload elements might have competing pointing, thermal, or other requirements.
- **Geographical constraints**: In some cases there are constraints related to operating over certain geographical areas. For example, one might want to operate payloads only over land, deserts, oceans, or arctic regions. Additionally, an operator might want to restrict service in polar regions so as to recharge batteries. Thus the geographic constraint would hinge on whether is above highly trafficked areas or not.
- **Regulatory constraints:** It is also important to make sure that all operations are conducted within the limits of space operation frameworks and applicable licenses. Satellite communication services are restricted in many ways, but there are also constraints on Earth observation satellites and other applications. Those who are launching communications satellite systems might have to coordinate with other operators on a non-interference basis. This can result in the need to duty cycle radios, implement communications blackout windows, or point away for geostationary satellites, which have protected status, to reduce the risk of interference. Additionally, operators must take care not to exceed power flux density limits set by the ITU since many satellites might be communicating at the same time. Any network control systems need to take these constraints into account.

3.3 Challenges

Some of the main challenges for a satellite network control system are examined below.

3.3.1 Heterogeneity

Smallsat constellations, which include hundreds or more satellites, are deployed in different generations. Thus these satellites may have different capabilities. Thus these networks might contain satellites that are in some ways heterogeneous in design. This is due to the iterative development process over time. Constellations are built up piecewise as hardware is developed and improved. Geosynchronous satellites might have lifetimes of 15 to 18 years, but constellations with LEO satellites may be replenished much more often than traditional satellite systems. This results in a constellation that can be composed of dozens of hardware versions, some of which might be minor, while others might be more significant.

Another reason for differences in hardware of satellite design, or even operational frequency bands, can be a satellite operator purchasing satellites from other networks. Sometimes acquisitions can come from completely different satellite networks (e.g., Planet and the initial SkySat constellation).

Smallsat systems can also be different, not just in terms of hardware differences, but there can also be a variety of software versions across the constellation. A single satellite might be composed of subsystems each running their own software version and each being software-upgradeable. This is a manageable issue, but it requires considerable discipline to make it work. Unique software configurations might arise as well as satellites experience key issues and/or major anomalies. There may be the need to create workaround solutions that are unique to one satellite or a particular cluster of smallsats. Every satellite tends to develop a unique "personality," based on the specific hardware and software features and potential anomalies or workarounds in place (Open Networking Foundation 2012).

Any network control system needs to take into account these differences when scheduling its assets.

3.3.2 Orbital Patterns

While some smallsat constellations are actively managed and station is kept to special parameters, many are not. Other constellations are more irregular and rely on available rideshare opportunities. For example, see Fig. 3a–c. These figures provide a comparison between the Spire, Planet, and Iridium orbits. The difference in launch strategy results in satellite to ground station transit patterns that are quite different for these three constellations. Satellites might see a ground station a few times an hour regularly for a while, only to have hours-long contact gaps later.

This usually results in figure of merit distributions with a long tail. For example, Fig. 4 shows the latency distribution of the Spire constellation and ground network. While latency is normally very good, due to the orbital configuration, sometimes

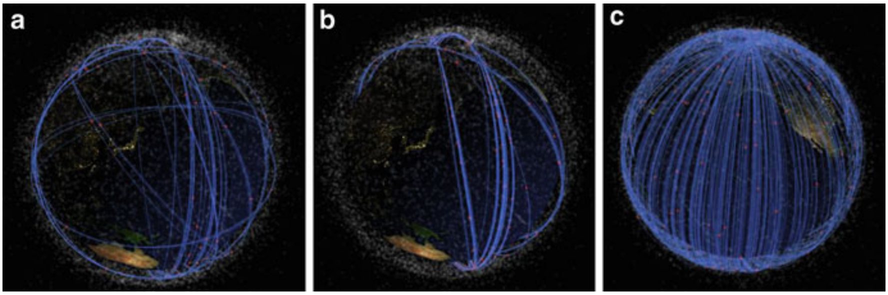


Fig. 3 (**a**) Spire's LEMUR constellation. (**b**) Planet's Flock constellation. (**c**) Iridium

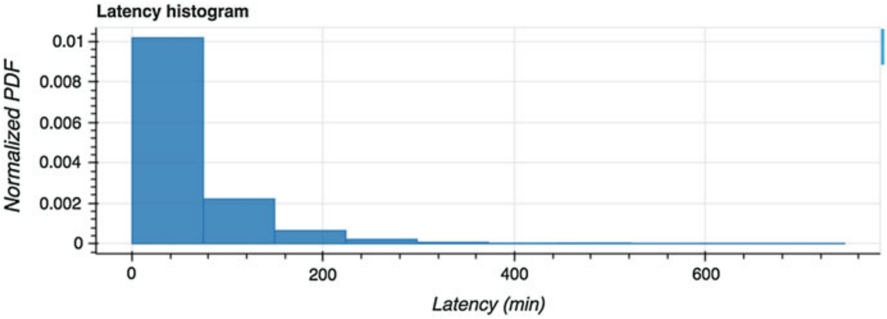


Fig. 4 Latency patterns for the Spire constellation (Graphic courtesy of Spire)

there are large contact gaps between satellites, resulting in a few periods with long latency that skew the average latency.

3.3.3 Multi-customer Nature

Many modern constellations no longer serve one type of customer or might even operationally produce more than one type of data from multiple payloads. The need to manage and control the competing priorities between various data types can be difficult. These challenges become even greater as various data types are added, the volume of data transfer grows, and latency requirements differ. Additionally, within a single data type, multiple different service levels could and often do exist. For example, captures relating to emergencies (e.g., imagery for natural disasters, ship data following collisions, etc.) could have higher priority needs than “standard” captures. Any network control system thus needs to be flexible so it can consider various data types and different tiers of data. One might end up with a latency-data volume curve as shown in Fig. 5, where various tiers of data volumes are downlinked at various latencies as well as different data speeds.

4 Network Control Subsystems

- On Fig. 6 an example is shown of what a constellation network control system might look like. The various components are discussed (Cho et al. 2018) below.

4.1 Satellites

4.1.1 On-Board Automation

The main goals of the on-board automation include at least the following four objectives:

- **Checkout and commissioning of satellites:** The efficient deployment and commissioning of multiple satellites in a constellation is a demanding task.

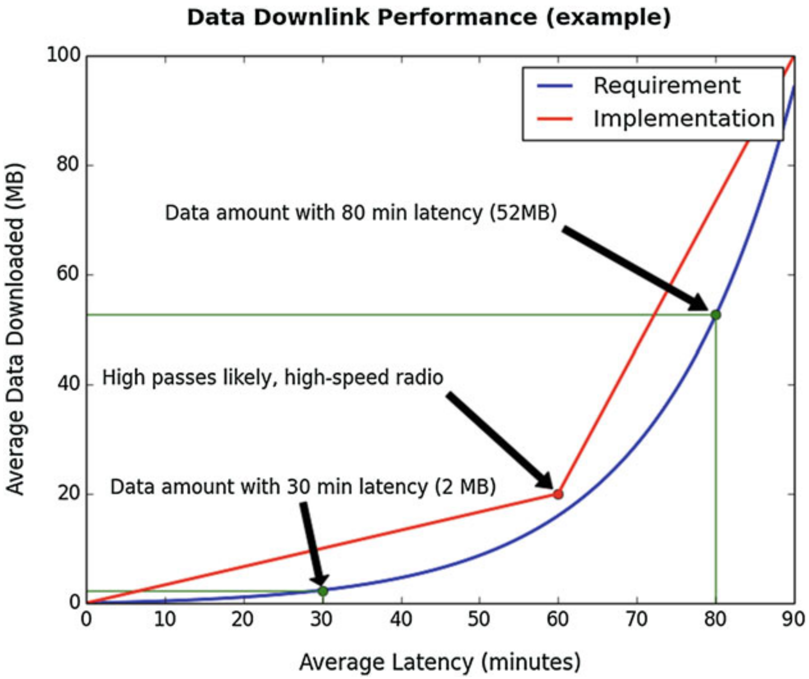


Fig. 5 Example of latency-volume curve (Graphic courtesy of Spire)

This can mean the deployment, checkout, and commission of multiple satellites that are deployed from one launch vehicle. Thus the managing satellite commissioning for many, many satellites across dozens of vehicles over a wide span of time is cumbersome. For example, Planet moved to a fully automated commissioning system which was probably essential since they were involved with the launch, checkout, and commissioning of 88 satellites associated with a single launch by a Polar Satellite Launch Vehicle (Doan et al. 2017).

- **Tasking payloads and communication radios.** For many small satellite constellations, there is a formal process to create "tasking schedules." These are typically generated by the mission control system on the ground and synchronized periodically with the spacecraft for a specific time interval (e.g., 24 h). Various levels of automation might exist on the spacecraft. Such automation serves to make this task easier and more efficient. In the case of automation, a task list might be quite simple. There might just be a list of commands with timestamps (e.g., "turn on payload one"). Alternatively there might be a higher-level list of subtasks (e.g., "complete a payload collection on payload one and prepare the data for downlink"). In some of the more advanced network control systems, more autonomy might be given to the spacecraft. In this case there might be a more flexible task provided. This might result in a tasking such as "Complete 10 payload windows with optimal geographic distribution in the next 24hrs."

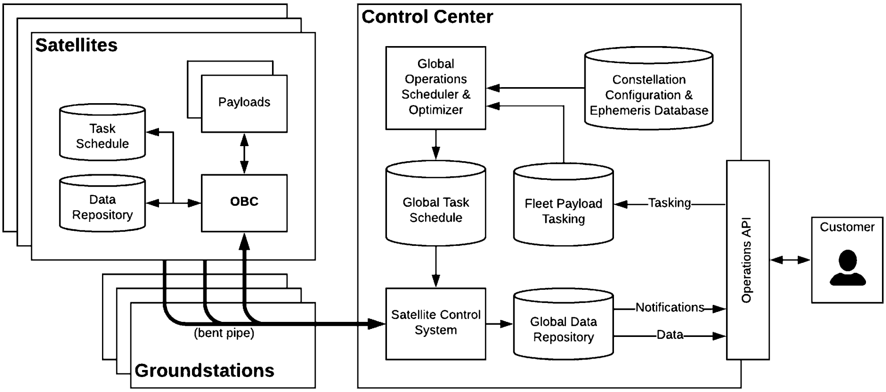


Fig. 6 Components of typical network control system

- **Managing spacecraft data.** In the case of different payload data types, there might be a need for different types of data handling. Data might exist in various forms and conditions. These might include ring buffers, databases, and plain text or binary files. For example, native data type will be allowed to determine the best storage tool. In the case of IoT message, it might be best to create a database. In the case of raw radio frequency collection, this process might work better with binary files. Data size and data latency are among the factors that contribute to these decisions. In the case of data with low latency requirements, it is best to avoid large files that would take a long time to download. The on-board computer can also apply data compression where appropriate and pre-process the data to prepare it for downlinking. Thus it is best to encode large files in advance of downlink.
- **Collect telemetry, monitor system health, and recover where needed.** Lastly, it is the task of the on-board computer to monitor health for all subsystems. It is also tasked with the responsibility to collect system telemetry and perform fault detection and isolation and recovery as required. Traditionally the on-board computer would be tasked to "flag" any faults and transmit them to the ground in order to alert operators. In more advanced systems, especially in the form of 0 recurring and simpler faults, this might be programmed to be handled through an automated recovery process. The latest systems employ modern machine learning telemetry systems. This allows longer-term trending of telemetry data and a greater ability to identify indicators of impending system failures.

4.2 Ground Stations

In most systems, the ground stations act simply in bent-pipe mode. This means that data is transmitted directly to the control center without buffering or processing. The advantages of this architecture would be in the form of enhanced security. This is to say that no data would ever be left unencrypted on a ground station. It would also decrease latency in that data can be streamed directly to the control center without having to wait to complete a satellite pass.

4.3 Control Center

4.3.1 Configuration and Ephemeris Databases

As indicated above, each satellite usually ends up having what might be called a unique personality. This then results in the need for a per-satellite configuration database. Such a detailed database can keep track of things like (i) satellite frequency configuration, (ii) licensing jurisdiction, (iii) status of subsystems, (iv) status of watchdogs, (v) timestamps of the last time maintenance procedures were executed, (vi) software interface versions, (vii) ADCS control modes, (viii) telemetry alerting limits, and other data peculiar to an individual satellite. Whenever tasks are scheduled and executed, the satellite configuration database is used to determine how to interact with a specific satellite. This would include decision as to what software interfaces to use. This key database would also contain the ephemeris information for satellites.

In addition, the database can contain ground station characteristics. This would alert the scheduler as to which satellites are compatible with which ground stations.

4.3.2 Operations Scheduler and Optimizer

To make the best use of all assets, a globally optimal ground system transit and on-board tasking schedule needs to be generated.

The block diagram shown in Fig. 7 shows how an optimizer fits into the large satellite control process. The input for the optimization process is derived from business-level goal functions. These might take the form of "Collect X MB of data at Y min of latency" or "optimally cover a specific area of interest." Business objectives can also change over time. Thus, the goal functions are not necessarily static. High-level functions need to be translated into actionable satellite operations interface variables. This is where figures of merit are employed. Thus figure of merit

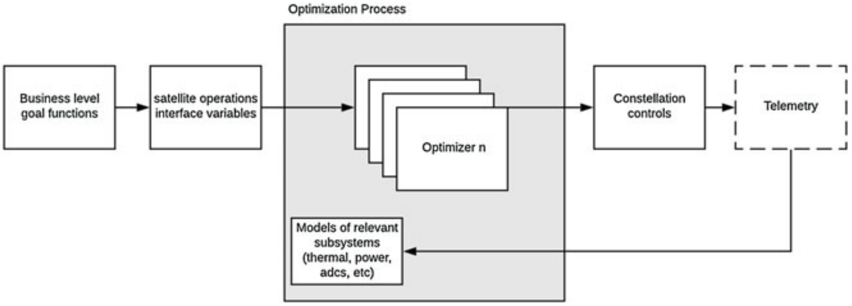


Fig. 7 Example of optimization process

conditions are then fed into the optimization process. The output from this process will be translated into constellation control parameters. These then become specific tasking schedules, the setting of telemetry limits, etc. This ultimately becomes a circular process after these parameters are executed and telemetry data collected. This informs the control center on the level of success achieved compared to the initial goals.

4.3.3 Optimization Strategy

On-Board Optimization

One option is for the ground to output contact schedules as well as a set of objectives for each spacecraft which in theory it can autonomously pursue. Each spacecraft would in this case need its own optimizer. This would include its own thermal and power models, priority maps, etc. This optimizer would need to computationally be programmed to run efficiently on the on-board computer.

Some advantages with this approach are relatively simple ground-based scheduling; more resiliency against unpredictable hardware behavior that was not foreseen during scheduling, such as an instrument failing to turn on; and ability to react to evolving phenomena to observe.

On the other hand, there are disadvantages with this approach: less fine-grained control with a less deterministic outcome that might potentially result in performance further away from a global optima and the higher levels of on-board autonomy, requiring more complex satellite side code.

Ground-Based Optimization

This approach entails an entire schedule (as optimized on the ground) to be uplinked to each satellite. This would be expected to be followed under nominal operations. This has the advantage that it provides very fine-grained control over what the constellation is asked to do with a deterministic outcome.

Hybrid Optimization

A third option would be a hybrid optimization that bridges the above two approaches. This approach generates a globally optimal schedule on the ground. Yet there is also enough intelligence on the satellite to intervene when operational conditions deviate from assumptions made during the generation of the ground-based schedule.

Such an intervention might, for example, allow satellite to throttle back instrument usage if the amount of data throughput is backing up. It might also activate an instrument to expend energy stored in excess of what was expected.

Algorithms in Literature

A number of planning and scheduling algorithms have been published, and at a very high level, in open literature for single large satellite missions. Key examples are represented by Automated Scheduling and Planning Environment (ASPEN) for EO-1 satellite. Another example is the Advanced Spaceborne Thermal Emission and

Reflectance Radiometer (ASTER) that is utilized on the Terra satellite as well as the high-resolution imagery from the IKONOS commercial satellite. It is also used for scheduling observations for the geostationary GEO-CAPE satellite or image strips over Taiwan by ROCSAT-2.

Stochastic algorithms have been proposed and computationally simulated for single spacecraft (Xhafa et al. 2012) and multiple payloads (Jian and Cheng 2008) and comparative merits documented for satellite fleets (Globus et al. 2002). While they offer accurate solutions, the cost of initial condition dependence, exponential time to converge, and large training sets make them very limited in mission applications. (Abramson 2012; Robinson 2017) have developed a coordinated planner that can handle a continuous stream of image requests from users by finding opportunities of collection and scheduling air or space assets to maximize collected utility. Agent-based autonomous scheduling has been implemented on NASA's Deep Space 1 (Schetter et al. 2003).

Some analysts have (Bunkheila et al. 2016) demonstrated the ability to provide for the scheduling of the scan of single LEO orbiting satellite by dividing the areas of interest and choose the sequence of strips of coverage by this method. This is based on various distance functions for an ideal orbit. It fixed scanning times based on roll and pitch angles and is therefore able to compute the temporal feasibility of pointing without modeling the Attitude Determination and Control (ADC) system or its uncertainties.

Simulation studies have optimized the scheduling for single Cubesat downlink to a network of ground stations (Spangelo and Cutler 2012) or multiple payloads' downlink to existing stations (Jian and Cheng 2008), within available storage and energy and access time constraints. Studies have also combined single satellite scheduling with information sharing across satellites for a weak consensus on feasible charging, downlink, and observation schedules (Kennedy et al. 2015) using fixed view imagers.

Scheduling observations for constellations of large satellites with payload repointing has been formulated for the French Pléiades constellation (Lemaitre et al. 2002) (Damiani et al. 2005) and COSMO-SkyMed constellation of synthetic aperture radars (Bianchessi and Righini 2008). Schedulers for Cubesat constellations such as the 200+ Dove spacecraft fleet operated by Planet Labs, Inc. (Boshuizen et al. 2014) assume static orientation of the sensor in orbit and only schedule duty cycles for payload power. Accounting for full reorientation in multi-spacecraft missions imposes computationally expensive constraints on scheduling spacecraft slews between payload operations. It is only recently that scheduling with slew-time variations has shown reasonable convergence using hierarchical division of assignment (He et al. 2019) and step-and-stare approaches using matrix imagers (Shao et al. 2018) and dynamic programming to account for utility maximization with ADC modeling (Nag et al. 2018). Planet Labs has published a preliminary scheduler used to operate their agile Skybox spacecraft fleet (Augenstein et al. 2016). Spire uses a similar approach for their RF sensing fleet. Agile observation schedulers that can recompute science value real time and autonomously reschedule observations across a constellation have demonstrated utility in simulation (Nag et al. 2019).

EOS is well suited for the mixed integer linear programming (MILP) approach because to perform any activity at any time instant (or not) can be modeled as a binary integer (e.g., ROCSAT-2 scheduler), and CPLEX can solve such formulations efficiently. However, MILP allows for only linear constraints and a single objective function, and there is no guarantee of reaching an optimum in linear time. The first drawback can be addressed using linear bounds to otherwise nonlinear variables (under-constrained formulation). The lack of a single, linear objective can be addressed using a Lagrangian sum of multiple objectives or a convex function representation of the objective. However, such approximations take away from accuracy and cutting plane bounds need not always be reliable. As examples, MILP has been successfully formulated for EOS for PLEIADES and the SPOT series, GEO-CAPE, and adapted as Constraint-based Interval Planning in the EUROPA planner for Deep Space 1. Constraint programming is not restricted to integer variables and linear equations/inequalities. Variables can be intervals or anything in the finite domain and constraints can be arithmetic or symbolic.

EOS can also be framed as an orienteering problem because it is a selective traveling salesman problem (TSP) where agents are required to visit as many checkpoints as possible within a time frame, each associated with a weight. The target captures can be assigned weights and orbital or subsystem constraints set up to represent travel times between captures and the objective is to maximize the weighted sum. The prize-collecting TSP not only minimizes travel time but also penalizes for unvisited cities. However, the interplay between orbital access to required captures by fast-moving LEO satellites and ACS-dependent slewing times causes the time for the traveling salesman to go from one capture to another to be highly dependent on the absolute time either capture is accessed. Variable time further adds to TSP solution complexity.

While dynamic scheduling across the full state space is known to generate an astronomical number of paths, unsolvable in polynomial time, branch-and-bound-like approximations to the dynamic programming (DP) approach have demonstrated a practically suboptimal resolution of the NP-hard non-restricted problem. DP has also been applied to the dynamic scheduling problem after it is decomposed into several simple, static problems defined by a rolling horizon, which is automatically appended with waiting tasks as current tasks are completed.

4.3.4 Asset Profiling

To be able to optimize assets, one must know the capabilities of these assets. While a good first guess is to use an analytical approach based on theoretical performance of assets, the asset performance changes over time (e.g., degradation), there can be variability in the actual performance between satellites, and different satellites might have different constraints (e.g., performance differs between different orbital planes). Because of these issues, it’s possible to integrate automated asset profiling into the optimization process. Based on real satellite telemetry, expected figures of merit are determined that can then be fed into an optimizer. Using machine learning techniques, it’s also possible to anticipate asset performance over time. It’s also possible to alert on sudden changes in performance characteristics (e.g., a drop in

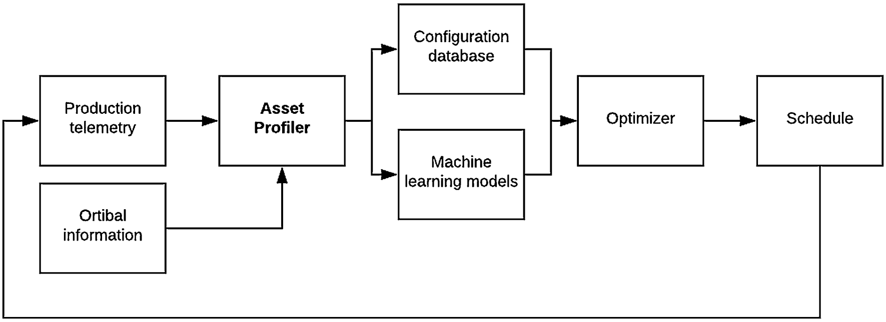


Fig. 8 Example of asset profiling process

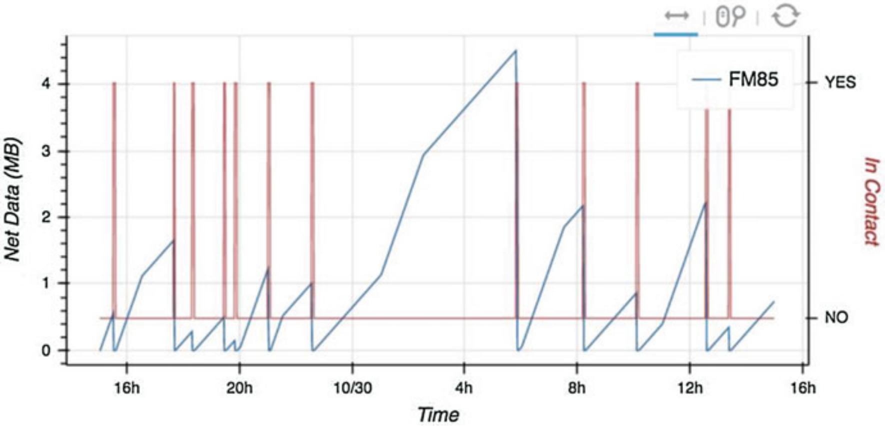


Fig. 9 Example of asset profiling model

downlink volume or collected observations). Figure 8 shows an example of asset profiling integration.

An example of a plot that could be obtained by an asset profiler is shown in Fig. 9. This example shows a model of the payload data generation rates on-board a satellite. As time goes by, the data volume on board increases until the satellite is in contact with a ground station and the data buckets are emptied. These models can be used to determine which satellite is most in need of a ground station contact, to optimize for data latency.

4.4 Operations Interfaces

While in a large-scale operations system, satellite operators cannot directly interface with each satellite all of the time, certain interfaces are required to ensure they can input priorities into the system, react to issues, and monitor health.

4.4.1 Priority and Request Management

Typically, any network control system will have a method of interfacing with the inputs of the optimization process. It is the task of operators to translate business priorities into actionable goal functions for the constellation. This may take the form of defining constellating wide figures of merit (e.g., system data throughput, or data collected under a certain latency target). When ad hoc requests come in, operators normally have override mechanism to command the satellites as needed outside the process.

4.4.2 Health Monitoring and Incident Management

Given the level of automation present, the main job of satellite operators is not to directly command or task assets but rather to monitor the constellation for any anomalies that might occur and manage those appropriately. To be able to do this effectively, an incident management system is required that can link back to operational data, on-ground test results, and any other information that can help resolve the issues at hand. Operators can then feed this information back to engineering development teams as new satellite versions are being developed.

5 Network Control with Intersatellite Links

If intersatellite links are present on a constellation, the concept of operations is changed quite drastically. It should be noted that the presence of intersatellite links doesn't necessarily imply a real-time connection between satellites and the ground. One particularly interesting concept is the delay- or disruption-tolerant network. This type of system has been designed for networks lacking continuous connectivity (Nag et al. 2019). This approach significantly decreases the latency associated with data getting from source to destination while tolerating intermittent connectivity.

Similarly, the advent of software-defined networks (concept shown in Fig. 10) has provided an abstraction toolset that can simplify the design of networked constellations. Some of the benefits include isolating multiple virtual networks, isolating various data flows (e.g., TT&C vs. data), more efficient sharing of spectrum, and enabling a more flexible network control structure. Additionally temporospatial SDNs enable additional benefits such as advanced packet routing and usage of orbit and attitude knowledge in data routing (Barrit and Eddy 2015).

Various proposed data routing algorithms are also available in literature for intersatellite-link constellations, e.g., Fig. 11 (Bunkheila et al. 2016).

6 Machine Learning and AI Applications

A few uses of machine learning and AI applications in network control systems have already been mentioned above, such as telemetry trending or asset profiling, but these are far from the only applications, and as larger constellations are deployed,

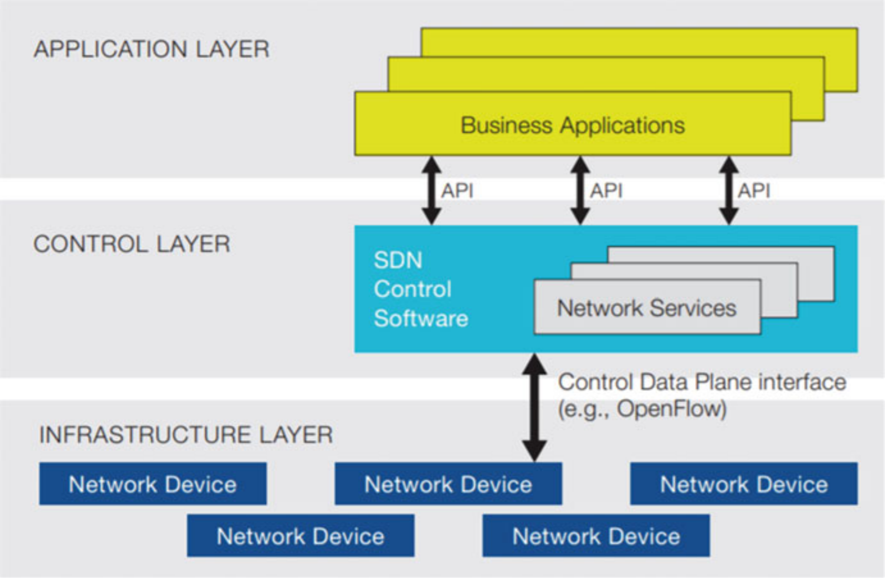


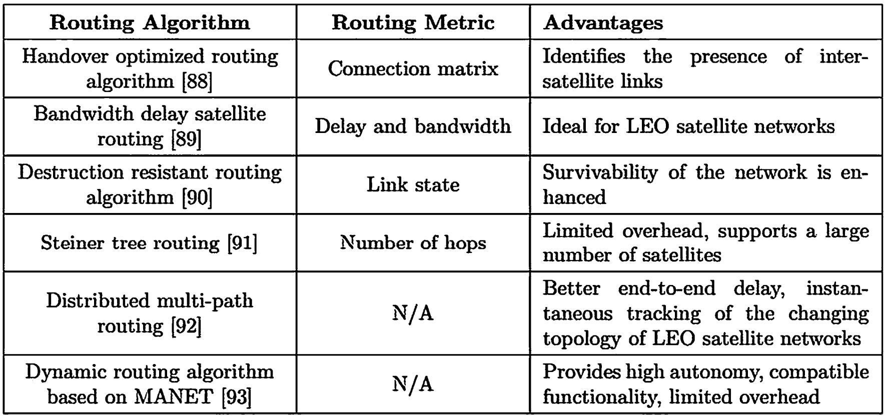
Fig. 10 Software-defined networking concept (Open Networking Foundation 2012)

more and more useful applications appear. This is particularly true in the area of remote sensing and Earth observation.

Machine learning and AI applications are driving innovations in on-board data processing or simply pre-processing. Mechanically, this explosive growth in launches of private and public satellites has induced an exceedingly rapid growth for space-generated data. ESA observation satellites reached requirements of close to 150 terabytes per day in 2018. This volume and definition of data has contributed to the across-the-board rise in users for space-generated data. The volume and reliability of this data have tremendously improved. Further the speed of delivery has been reduced to almost real-time capabilities for certain data categories. This process has created considerable issues in the management of the data flows, with delays, defaults, and crucial data reaching the user a long time after it ceased to be operationally useful.

However, the latest technological developments in chip-making have made possible the pre-processing of data directly at the satellite level. Thus data analytics in space has progressively reduced the amount of data to be downloaded back to ground stations.

This factor process of on-board processing of data improves constellation efficiency greatly. It also reduces the demands on staff, equipment, and other the infrastructure on the ground and also reduced the power speeds required for the satellite transmissions. Moreover, it allows the raising of the speed at which critical information is transmitted to users by allowing the satellite to prioritize independently which data will be downloaded first, thus decreasing latency for truly relevant



Routing Algorithm	Routing Metric	Advantages
Handover optimized routing algorithm [88]	Connection matrix	Identifies the presence of inter-satellite links
Bandwidth delay satellite routing [89]	Delay and bandwidth	Ideal for LEO satellite networks
Destruction resistant routing algorithm [90]	Link state	Survivability of the network is enhanced
Steiner tree routing [91]	Number of hops	Limited overhead, supports a large number of satellites
Distributed multi-path routing [92]	N/A	Better end-to-end delay, instantaneous tracking of the changing topology of LEO satellite networks
Dynamic routing algorithm based on MANET [93]	N/A	Provides high autonomy, compatible functionality, limited overhead

Fig. 11 Available routing algorithms for intersatellite links (Radhakrishnan et al. 2016)

information, as well as allowing the satellite to autonomously direct sensors and make time-critical decisions.

In parallel, many new machine vision chips have stimulated interest by allowing smaller platforms to accomplish many more analytics. This increased capability includes the ability to run complex pattern determination and identification programs. There is an increasing consensus across the space ecosystem that this development is potentially a game changer for many current space-based products. Many feel it is likely to create profoundly disruptive applications that will largely exceed the capabilities of current space-based platforms in generating large sets of “smart,” directly actionable data.

For example, the ESA-supported HyperScout-2 mission carried a Myriad 2 neural networking chip (Esposito et al. 2019). Spire’s LEMUR2 satellite is carrying a Nvidia Jetson AI computing device in an ESA-supported demonstration mission. The range of potential applications is wide and includes cloud detection and removal from imagery, RF fingerprinting, RF IQ analysis and de-interference, pattern detection, and many others.

7 Conclusion

Network control systems are often-neglected systems but are becoming more and more important as operators move from manual operation of a few satellites to operating large constellations where optical asset allocation is very non-transparent.

As complexity increases, more tools are required to offload operations from a team of operators to a true network control system. Part of the complexity of finding the optimal asset utilization for a constellation is the heterogeneity of a lot of smallsat networks. Modern network control systems leverage the appropriate tools to distribute the right levels of automation and autonomy between space and ground assets.

For constellations with intersatellite links, existing tools such as disruption-tolerant network (DTN) and software-defined networking (SDN) can be leveraged to enable packet routing, as compared to algorithm development from scratch.

Lastly, the application of machine learning and the use of newly developed AI-oriented chipsets provide a large opportunity to increase the on-board autonomy of spacecraft.

8 Cross-References

- ► An Overview of Small Satellite Initiatives in Brazil
- ► Planet's Dove Satellite Constellation
- ► RemoveDEBRIS: An In-Orbit Demonstration of Technologies for the Removal of Space Debris
- ► The Kepler Satellite System
- ► The OneWeb Satellite System

References

M. Abramson, *Earth Phenomena Observation System (EPOS) for Coordination of Asynchronous Sensor Webs*. NASA Contract Report (2012). https://esto.nasa.gov/2012test/conferences/estc-2002/Papers/A5P1(Abramson).pdf

D.L. Alderson, J.C. Doyle, Contrasting views of complexity and their implications for network-centric infrastructures. IEEE Trans. Syst. Man Cybern. Part A Syst. Hum. **40**(4), 839–852 (2010)

S. Augenstein, A. Estanislao, E. Guere, S. Blaes, Optimal scheduling of a constellation of earth-imaging satellites, for maximal data throughput and efficient human management, in *Twenty-Sixth International Conference on Automated Planning and Scheduling*, 2016

B.J. Barrit, W. Eddy, *Temporospatial SDN for Aerospace Communications*. Semantic Scholar (2015). https://pdfs.semanticscholar.org/7da3/6c18aafb29b1620dc78a89d3e7e6115b5570.pdf

N. Bianchessi, G. Righini, Planning and scheduling algorithms for the COSMO-SkyMed constellation. Aerosp. Sci. Technol. **12**(7), 535–544 (2008)

C. Boshuizen, J. Mason, P. Klupar, S. Spanhake, Results from the planet labs flock constellation. Presented at the AIAA/USU Small Satellite Conference, Logan, Utah, 2014

F. Bunkheila et al., A new algorithm for agile satellite-based acquisition operations. Acta Astronomica (2016). https://www.sciencedirect.com/science/article/abs/pii/S0094576515302629

D.-H. Cho et al., Optimization-based scheduling method for agile earth-observing satellite constellation. J. Aerosp. Inf. Syst. **15**(11), 1–16 (2018). https://www.researchgate.net/publication/327982972

S. Damiani, G. Verfaillie, M.-C. Charmeau, An earth watching satellite constellation: How to manage a team of watching agents with limited communications, in *Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems*, 2005, pp. 455–462

D. Doan, R. Zimmerman et al., *Commissioning the World's Largest Satellite Constellation*. Semantic Scholar (2017). https://www.semanticscholar.org/paper/Commissioning-the-World%E2%80%99s-Largest-Satellite-Doan-Zimmerman/77884ab008f482712c4a3d9457f6611f1006b391

M. Esposito et al., In-orbit demonstration of artificial intelligence applied to hyperspectral and thermal sensing from space, in *SPIE Conference*, Aug 2019. https://spie.org/Publications/Proceedings/Paper/10.1117/12.2532262?SSO=1. Last accessed 4 March 2020; https://nebula.esa.int/content/delay-tolerant-network-flexible-communication-eo-satellites. Last accessed 5 March 2020

Euroconsult, *Prospects for the Small Satellite Market* (2019). http://www.euroconsult-ec.com/shop/index.php?id_product=116&controller=product. Last accessed 4 March 2020

A. Globus, J. Crawford, J. Lohn, R. Morris, *Scheduling Earth Observing Fleets Using Evolutionary Algorithms: Problem Description and Approach* (Academia, 2002). https://www.academia.edu/28374353/Scheduling_earth_observing_fleets_using_evolutionary_algorithms_Problem_description_and_approach

L. He, X.-L. Liu, Y.-W. Chen, L.-N. Xing, K. Liu, Hierarchical scheduling for real-time agile satellite task scheduling in a dynamic environment. Adv. Space Res. **63**(2), 897–912 (2019). https://doi.org/10.1016/j.asr.2018.10.007

L. Jian, W. Cheng, Resource planning and scheduling of payload for satellite with genetic particles swarm optimization, in *IEEE Congress on Evolutionary Computation, 2008. CEC 2008.(IEEE World Congress on Computational Intelligence)*, 2008, pp. 199–203

A. Kennedy, A. Marinan, K. Cahoy, J. Byrne, T. Cordeiro, Z. Decker, W. Marlow, S. Shea, Automated Resources-Constrained Science Planning for the MiRaTa Mission, 29th Annual AIAA/USU Conference on Small Satlelites (2015)

M. Lemaitre, G. Verfaillie, F. Jouhaud, J.-M. Lachiver, N. Bataille, Selecting and scheduling observations of agile satellites. Aerosp. Sci. Technol. **6**(5), 367–381 (2002)

W.-C. Lin, D.-Y. Liao, C.-Y. Liu, Y.-Y. Lee, Daily imaging scheduling of an earth observation satellite. IEEE Trans. Syst. Man Cybern. Part A Syst. Hum. **35**(2), 213–223 (2005)

S. Nag, A.S. Li, J.H. Merrick. Scheduling algorithms for rapid imaging using agile Cubesat constellations. Advances in Space Research **61**(3), 891–913 (2018)

S. Nag, A. Li, V. Ravindra, M. Sanchez Net, K.M. Cheung, R. Lammers, B. Bledsoe, Autonomous scheduling of agile spacecraft constellations with delay tolerant networking for reactive imaging, in *International Conference on Planning and Scheduling (ICAPS) SPARK Applications Workshop*, Berkeley, 2019. https://openreview.net/pdf?id=rJeDNZq5FE

Open Networking Foundation, *Software-Defined Networking: The New Norm for Networks*. 13 April 2012. White Paper from the Open Networking Foundation. https://www.opennetworking.org/images/stories/downloads/sdn-resources/white-papers/wp-sdn-newnorm.pdf

R. Radhakrishnan et al., *Survey of Inter-satellite Communication for Small Satellite Systems: Physical Layer to Network Layer View IEEE Explore* (Fourth Quarter 2016). https://ieeexplore.ieee.org/document/7466793

E. Robinson, *Optimized Stochastic Coordinated Planning of Asynchronous Air and Space Assets*, 11 Jan 2017. https://arc.aiaa.org/doi/abs/10.2514/1.I010415

T. Schetter, M. Campbell, D. Surka. Multiple agent-based autonomy for satellite constellations. Artificial Intelligence **145**(1-2), 147–180 (2003)

E. Shao et al., Area coverage planning with 3-axis steerable, 2D framing sensors, in *Scheduling and Planning Applications Workshop, International Conference on Automated Planning and Scheduling*, Delft, 2018

S. Spangelo, J. Cutler, *Optimization of Single-Satellite Operational Schedules Towards Enhanced Communication Capacity,* 16 Aug 2012. https://arc.aiaa.org/doi/abs/10.2514/6.2012-4610. Last accessed 5 March 2020

F. Xhafa et al., *Genetic Algorithms for Satellite Scheduling Problems*. Semantic Scholars (2012). https://pdfs.semanticscholar.org/70b1/afcf68533e712802d6cd5c1e42a0c2951438.pdf

RF and Optical Communications for Small Satellites

W. G. Cowley

Contents

Abstract

All satellites require communication links. This chapter compares the use of radio frequency (RF) with optical links for small satellites. Even in the case of small satellites, free space optical (FSO) links now offer very useful options. FSO communications have some unique advantages and disadvantages compared to RF satcom. The latter will always have a role, but for throughput, security, and licence-free operation, FSO communications are increasingly worth considering. This chapter provides an overview of these two options, making comparisons where possible. The last section reviews some recent developments in both areas.

W. G. Cowley (✉)
Institute for Telecommunications Research, University of South Australia, Adelaide, SA, Australia
e-mail: bill.cowley@unisa.edu.au

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_88

Keywords

Satellite communications · Free space optical · Laser communication · Radio frequency · Modulation · Channel coding · Fading · Turbulence · Ground station · Antenna · CubeSat · Software-defined radio · Spectral efficiency

1 Introduction

A major issue with small satellite RF communications is the difficulty of obtaining licenced spectrum. Given that the RF spectrum is a finite resource with increasing demands from both terrestrial and space applications, this is a critical constraint for many projects. In some cases, such as cellular communications and high-capacity communication satellites, the recent use of spot beams that allow frequency reuse has provided some relief to spectrum availability. This is not usually an option for small satellite satcom.

FSO communications offer advantages of orders-of-magnitude higher data rates, increased security, and licence-free operation. However the very low-divergence optical beams require high pointing accuracy, and in any earth-space scenario, weather effects (such as cloud obstruction) must be taken into account. As shown below, even in clear skies, the fading effects of Earth's atmosphere can cause significant loss. Fading can be mitigated to a larger extent than obstruction, which requires spatial diversity for robust communications. With respect to FSO pointing, this requirement is often the most demanding aspect of the payload and may also impose significant constraints on the platform's attitude control and dynamic response.

This chapter is set out as follows. The next section starts with an overview of first RF and then FSO communications payloads, describing the chief characteristics of each, plus how they have evolved in the last couple of decades. Selected topics, including antennas, performance metrics, and atmospheric impairments, are explored in section "Key Issues". Finally section "Small Satellite Examples" describes some case studies of both RF and FSO payloads with the aim of illustrating topics covered earlier in the chapter. Other comparisons of RF and FSO satcom may be found in (Hemmati et al. 1996; NASA n.d.; Kaushal and Kaddoum 2017).

2 Communications Payload Overview

Figure 1 shows a block diagram for either RF or FSO communications payloads. Despite their differences, they share most functions. The rest of this section describes these building blocks for each type of comms payload and outlines various realization options. In addition the likely boundaries between analog and digital representation of the signals are summarized.

2.1 RF Payloads

RF communication techniques are fairly mature but still evolving in small satellites. For very tight mass and power constraints (e.g., CubeSats) with low data rates, the use of simple modulation schemes such as frequency-shift keying (FSK) operating in the VHF or UHF bands has been traditional. Power and mass requirements are very modest for LEO applications requiring only kbit data rates. The functions shown in blue in Figure 1, such as modulation, demodulation, and amplification, were originally implemented with analog or low-complexity digital electronics and are moving progressively to become software-based or use application-specific integrated circuits (ASICs). These small satellites use simple antennas such as quarter-wave monopoles, either singly or phased to provide circular polarization (CP) (see section "Antennas and Pointing").

Figure 1 also applies to the ground components of a small satellite communication system. Of course it is much easier to achieve antenna gain and higher transmit powers on the ground, so many (RF and FSO) satellite links take advantage of this and can be designed with simpler space segment requirements. For all satcom, balancing the link budget, usually in both directions, is an art which also requires system-wide trade-offs. Several satcom link budgets described in this chapter may be explored with a software app available at (lowsnr.org n.d.). For the low-frequency CubeSats described above, the corresponding ground station (GS) equipment usually includes a tracking Yagi antenna system, ideally with a low-noise amplifier mounted at the antenna to achieve the best signal to noise (SNR) ratio. The indoor equipment of this GS may consist of a commercial UHF transceiver connected to a PC which carries out the low-bandwidth modulation and demodulation functions in software.

New approaches for small satellite RF communications payloads are likely to provide more functions implemented in software (or firmware) rather than dedicated

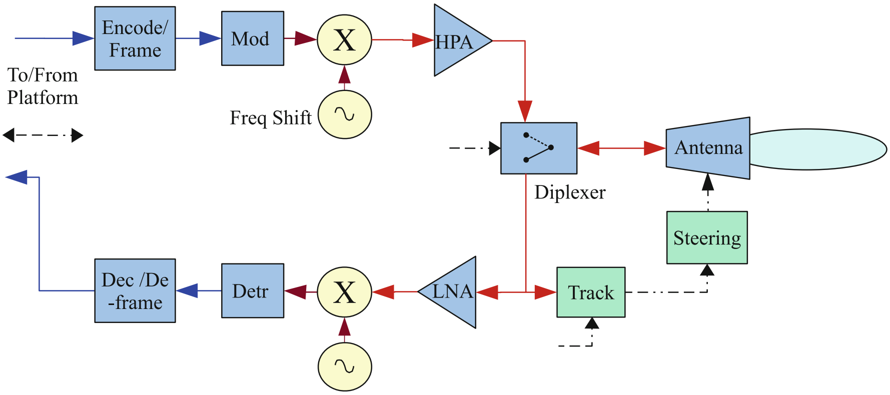


Fig. 1 Generic RF and FSO communications payload assuming a common antenna. RF payloads may not require green functions, and FSO payloads may not require yellow functions

electronic hardware, better use of allocated RF bandwidth, and the migration to higher frequency bands. Many of the operations shown in Figure 1 now use a "discrete time" (or sampled) representation of the signal, with sufficient sampling rate to avoid aliasing. Thus digital signal processing (DSP) functions such as filtering, frequency shifting (shown in yellow in the figure), decimation, interpolation, modulation, demodulation, encoding, and decoding are used where possible, giving better performance, more flexibility, and greater functionality. This approach is called software-defined radio (SDR). Some processing of the signal, such as amplification and filtering of the signal at the carrier frequency, must still be handled in "continuous time" with analog electronics. The recent advent of specialized application-specific integrated circuits (ASICs) which include hybrid analog and digital stages allowing signal digitization and synthesis functions (plus frequency shifting to intermediate frequencies) (e.g., Analog Devices n.d.) is very attractive in terms of power efficiency, flexibility, and performance.

CubeSats are no longer limited to low frequencies; small RF payloads are commercially available up to Ka-Band, e.g., (SWIFT-KTX n.d.). Advances in microelectronics now allow much smaller and more power-efficient RF electronics operating at microwave frequencies. Whereas it used to be challenging to manipulate signals above ≈ 1 GHz with low power and mass constraints, the rapid growth of consumer electronics has made this much easier. Similarly, modulation and coding options for small satellite RF links have grown significantly over the last decade, allowing more efficient use of allocated bandwidth. Powerful forward error correction (FEC, also called channel coding) algorithms can provide up to ten times improvement (i.e., 10 dB) in power consumption or data rate, so this option should always be considered on new designs. Coding and modulation options are discussed further in section "Performance Limits, Modulation, and Coding".

2.2 FSO Payloads

FSO payloads use lasers for inter-satellite links (ISLs) or to provide communications between satellites and ground. Similarly to the RF case, advances in optoelectronics and the large development of terrestrial fiber-based communications have greatly improved the prospects of FSO for small satellites. Most links transmit in the infrared or optical bands, with wavelengths around 1550 nm (as used in most optical fiber) becoming increasingly common. This band is called "eye-safe" as lasers cause less damage to the retina, e.g., (Kaushal and Kaddoum 2017). Other common wavelengths include 1064 and 850 nm. For these payloads the "antenna" is some form of telescope. While the typical transmit power of small satellite RF or FSO payloads is similar (e.g., 0.1 to 10 W), the large difference in data rate arises from the high antenna gain in the FSO case due to the many orders of magnitude change in wavelength. Indeed, at least in the transmit case, it's frequently not possible to use the whole antenna gain from a modest optical aperture on a small satellite, and laser divergence must be increased to make the link acquisition feasible.

Digital functions such as framing and FEC are similar for FSO and RF payloads and are shown by blue signals in Figure 1. The payloads differ more in the red paths, which use either coaxial cable or waveguide for RF and often fiber for optical signals. Given a single antenna, the simplest diplexer in RF systems in a solid-state or mechanical switch, allowing bi-directional communications by a time division multiplex (TDM) approach. In the FSO case, the use of two wavelengths is very common, with the diplexing carried out by dichroic optical components such as mirrors and filters.

Key technology options for FSO payloads include the selection of wavelength (s), optoelectronic device families, modulation method, and antenna pointing options. The simplest FSO LEO downlinks rely on the platform attitude control system (ACS) to steer the laser downlink and simply turn the laser signal on or off to transmit bits of information, i.e., on-off keying (OOK). The detection scheme for these systems is likely to be noncoherent, often called "direct detection" where the received signal is delivered to some type of photodiode. Section "Performance Limits, Modulation, and Coding" explores FSO detection options a little further.

Unfortunately, the pointing accuracy of the small satellite attitude control system (ACS) is not usually sufficient to make efficient use of the laser downlink. For example, suppose the ACS allows the laser to be pointed to an optical GS (OGS) with a standard deviation error of 1/3 of a degree and the laser beam divergence is arranged to be 1 degree, or $\approx$17 milliradians (mrad), giving a 3σ confidence that the laser signal reaches the OGS. In this case the number of photons per bit at 100 Mbit/s, from LEO with 1 W laser power, into a 20 cm OGS aperture is only $\approx$1 (lowsnr.org n.d.).

For this reason, optical payloads normally control their own pointing in order to make use of lasers with smaller divergences (say from 1 mrad to 10 μrad). This pointing control can take many forms. It may use the satellite platform for coarse pointing and implement, say via controlling steering mirrors, a fine pointing system that can direct the laser with suitable precision. If the satellite's knowledge of its absolute pointing is ill-defined relative to the desired laser divergence, it is not sufficient to provide a fine steering method that relies on the performance of the host ACS. Instead it is common to make use of some reference signal, such as an uplink beacon. The optical comms payload may also need to provide its own coarse pointing facility. Bear in mind that in the case of the LEO downlink to OGS, say from an Earth observation satellite, the downlink pointing to a specific OGS will be constantly changing during a pass. In addition the satellite may be subject to transient attitude disturbances due to its own ACS actuators and thrusters. Pointing and tracking are discussed further in sections "Antennas and Pointing" and "PAT Schemes for Small Satellites".

3 Key Issues

This section explores some specific issues related to RF and FSO communications payloads for small satellites. Where possible the similarities and differences between the optical and radio approaches are described.

3.1 Performance Limits, Modulation, and Coding

In the RF case, Shannon determined a number of fundamental performance limits for digital communications. For the last 60 years, there has been steady progress in approaching these limits by the use of FEC. In a digital communication system, the relevant performance metric is called energy per information bit to noise spectral density *(E_b/N_0)*. Most satellite channels have a high free space loss (FSL) due to large link distances and are limited in performance by the thermal noise added at the receiver input, so they can benefit substantially by using FEC methods. Early approaches added parity bits to the information bit stream and thereby increased the overall bandwidth requirements. In the 1970s it was realized that FEC could be applied at the level of modulation symbols and the benefits of error correction (called coding gain) could be obtained without necessarily increasing the RF bandwidth. Given the importance of conserving bandwidth, it is useful to assess the performance of an RF link in terms of the required E_b/N_0 to achieve a required spectral efficiency (i.e., information bits per second per Hz of RF bandwidth).

Figure 2 shows a summary of these fundamental limits, plus some practical examples of actual performance, with FEC (selected DVB-S2 modes, shown with "X" symbols) and without FEC ("+" symbols). The solid curve is the capacity limit derived by Shannon, and the dashed plots illustrate modulation-constrained bounds, up to 16-point constellations. The figure shows the fundamental trade-off between spectral efficiency and E_b/N_0. Good codes are approaching the capacity limits and may provide about 7 to 10 dB improvement compared to uncoded transmission. For comparison, if the standard satcom convolutional code performance is plotted on this figure, it's about halfway between the coded and uncoded examples shown. These results assume coherent detection with ideal (or almost ideal) pulse shaping (achieved through filtering) to minimize bandwidth. Modern radio systems often

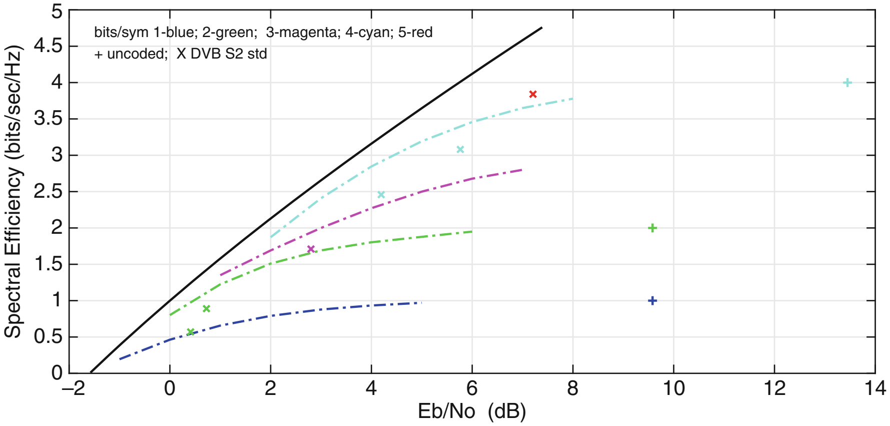


Fig. 2 Spectral efficiency versus E_b/N_0: bounds (solid and dashed lines) and actual performance (symbols)

vary in both the amplitude and phase of the RF carrier wave to carry multiple information bits per transmitted symbol, thereby achieving a higher spectral efficiency. This is called quadrature amplitude modulation (QAM).

Most of the coding gain in Fig. 2 comes from an iterative approach called low-density parity-check (LDPC) codes, or from closely related "turbo" codes. Perhaps the first such code on a small satellite was the turbo code used on "FedSat" in 2002 (eoPortal web pages 2002). Iterative coding methods may be extended to handle some other impairments, e.g., section "RF Payload Using SDR". In space, computational requirements must be considered, but efficient designs are becoming available (e.g., Turbo and LDPC Codec Designs n.d.).

Compared to the RF case, there's a very wide range of modulation and detection options, plus device technologies which are employed in FSO communications. This chapter provides a brief summary, and the reader is referred to (Kaushal and Kaddoum 2017; Aviv 2006; Hemmati and Caplan 2013; Hemmati 2009) for further information. Both noncoherent and coherent approaches are used, although the former are considerably simpler to realize. For example, the incoming light may be simply focused onto a reverse biased diode, whose junction contains an undoped (or intrinsic) layer between the p-type and n-type semiconductor regions. When a photon of sufficient energy falls on the junction, an electron-hole pair is produced which leads to a current pulse. These PIN diode photodetectors have many advantages but suffer from the need for electrical amplification of the tiny output currents, which invariably leads to the addition of significant electrical noise. A related approach relies on an avalanche effect when one or more photons arrive. Avalanche photodiodes (APDs) can avoid most of the electrical noise addition but with lower bandwidth as the gain multiplication increases. Better results can be obtained with these noncoherent (or direct detection methods) by amplification prior to detection, after coupling the received signal into a suitable optical fiber. The amplification can be achieved via semiconductor optical amplifiers or by using doped fiber amplifiers. For example, erbium-doped fiber amplifiers (EDFAs) are widely used in many areas for optical amplification in the region of 1550 nm. By mixing the input signal with a "pumping" laser at a shorter wavelength, it is possible to amplify the input signal by stimulated emission of photons from excited erbium ions in the fiber. This type of device may also be used in FSO transmitters to amplify the output of a small semiconductor laser to the power levels required by the optical link budget.

Coherent optical detection involves the "mixing" of a reference laser with the incoming optical signal. As in the RF case, the mixing process results in the modulated signal being shifted in the frequency domain, either to 0 Hz (homodyne) or to an intermediate frequency (heterodyne), say within radio wavelengths. The coherent approach opens the door to standard RF modulations, such as PSK, and can produce excellent results. Needless to say, the provision of stable optical references, and detection methods that preserve phase information, adds considerable complexity. A somewhat simplified approach is to use differential PSK (DPSK) detection, where a delayed version of the input signal is used as the "reference" signal. For example, this scheme is used in the LCRD (Edwards 2019).

In the optical case, in addition to the impact of additive noise, it may be necessary to take into account statistical fluctuations if a small number of photons are received per bit. This effect is called shot noise. For a given bit rate, the shot noise issue can be mitigated by using pulse position modulation (PPM) with more bits (and more photons) per optical symbol. Section “PAT Schemes for Small Satellites” mentions an example of a “photon-counting” OGS using M-ary PPM, where M represents a large number of possible pulse positions.

Accounting for various noise sources in FSO receivers can be difficult, and approaches used in link budgets vary. A common approach is to use the received photons per bit (PPB) as the key performance metric for satellite communications. A summary of measured PPB results ranging from about one to hundreds may be found in (Caplan 2007; Rohwer et al. 2010). Unamplified direct detection methods, such as PIN diodes, will require thousands of PPB. Direct detection and PPM, either with optical pre-amplification or photon counting, can give excellent results.

3.2 Antennas and Pointing

For RF links, two antenna issues must be addressed. The first is stowage and deployment of the physical antenna, and the second is how to point it in the required direction. As noted above, at lower frequency bands, it is often convenient for LEO satellites to use wire antennas that are released from a stowed configuration via a simple “burn wire” approach. These low-gain antennas largely avoid the need for antenna pointing. Rotation of the electric field vector, caused either by Faraday rotation in the lower frequency bands or antenna misalignment, can add additional loss with linear polarization but can be overcome by CP. Microstrip antennas also offer options for small satellites. Single patch radiators may provide 5 to 7 dBi gain.

Antennas become more demanding as the required gain increases. In general, antenna pointing options include relying on platform attitude control, mechanical steering of antenna structures, and phased array approaches. A classic example of steered RF antennas in LEO was provided by the first-generation Iridium constellation, (Rohwer et al. 2010) which used mechanically steered Ka-Band antennas for cross-link and feeders, plus phased array L-Band antennas, giving spot beams to user terminals. At the time (two decades ago), the multi-beam phased array antenna was a significant advance.

Particularly in CubeSats, the physical volume of the stowed high-gain antenna is an important issue. Whereas the traditional approach in the microwave bands has been parabolic antennas which are unfurled during commissioning, recent innovations include deployable meshes of patch antennas and the “reflectarray” recently used on the Mars CubeSats (see section “High-Gain CubeSat Antennas”).

Antenna deployment is not a problem for optical payloads, but as noted in section “Antennas and Pointing”, pointing is a critical issue. As mentioned above, it’s common to separate the solution into fine pointing and coarse pointing mechanisms. An uplink beacon from the OGS is the most frequent approach to assist fine pointing the satellite downlink. This requires a control system whose input often originates from a “four-quadrant” photodetector that measures the angular offsets in the received uplink beacon. The error signal is used to control actuators to align the transmitted optical signal with the received beacon. Some FSO links operating over paths with significant relative motion have the added complexity that the flight time of the signal is large enough that its transmit laser must be directed to a future receiver position. This is called “point-ahead” tracking.

The design of sensors, actuators, and control loops that can provide the required pointing accuracy, both for initial acquisition and then tracking, is a demanding aspect of the optical communications payload design and requires multidisciplinary expertise. A few aspects of this area are described below, and section “PAT Schemes for Small Satellites” contains examples showing recent progress in this area. As mentioned in section “Communications Payload Overview”, FSO satellite links are usually “full duplex,” i.e., operating in both directions at once, although the data rates may be highly asymmetric, or even zero if a received beacon is only used for transmit pointing. This requires a very high degree of optical isolation (e.g., 140 dB) so that the transmit signal does not “blind” the receiver. Beacon signals are typically modulated in some fashion, possibly with low-rate data, so that they can be separated from background optical signals. The acquisition phase typically needs a larger field of view. After splitting the common optical path into receive and transmit components, it is common to use most of the incoming signal for data reception but extract a portion for acquisition and/or tracking. Imaging arrays can be employed instead of four-quadrant detectors for this function, with trade-offs between extra complexity and better tracking or faster acquisition to be considered. Acquisition requirements will vary widely according to the application scenario. For rapid lock, it’s clearly very desirable that the received signal will be within the acquisition field of view (FOV); otherwise a search strategy must be employed. Acquisition must usually be achieved in two directions before data transmission commences. Searching for the signal at both ends of the link should be avoided! Finally, the bandwidth of pointing control loops depends on the dynamics of the host satellite and the degree of isolation between the platform and the optical payload. Careful simulation of the electromechanical system, using a model of the platform vibrational behavior, is normally undertaken to ensure transmit signal pointing jitter will be (say) within 10% of the beam divergence.

3.3 Fading and Obstruction

Satellite links between space and Earth must consider the effect of various impairments. In the lower frequency bands, the attenuation from the atmosphere is negligible, but mobile devices with low-gain antennas may suffer from fading due to ground reflections and/or signal attenuation caused by path obstruction. For point-to-point RF links, there’s little atmospheric loss below Ku Band. However Ka-Band systems can suffer tens of 10 dBs attenuation due to rain and clouds. Fade statistics depend on frequency, elevation angle, and geographic region. For example, at 20 GHz, with 40 degrees link elevation, attenuation does not exceed 10 dB for more than 1% of the time, or 30 dB for 0.1% of the time in the worst of eight ITU-R rain regions, e.g., (Mitchell 1997). While attenuation due to rain is the main impairment, other weather effects include attenuation by water-bearing clouds, small losses in antenna gain due to wet surfaces, and depolarization effects which degrade the performance of systems using orthogonal polarizations. Above Ka-Band the atmospheric effects increase greatly due to absorption by water vapor or oxygen molecules. For example, the latter attenuates strongly near 60 GHz.

Mitigation approaches for RF fading include increased fade margin, adaptive power control, and adaptive modulation. Satcom systems subject to significant RF attenuation will need to consider system issues such as latency requirements, onboard storage, the number of ground stations, and possible use of ISLs to achieve suitable performance.

The atmosphere is more of a problem for optical links. Clouds and fog may obstruct the signal completely, so the statistics of cloud cover are important when considering OGS locations. For example, using multiple OGSs across Europe can reduce the outage probability to about 10^{-3}, but an intercontinental network can achieve any required availability (Giggenbach et al. 2015). These will require good terrestrial optical fiber connections. Interestingly, rain may only cause modest attenuation in optical links, compared to the higher RF bands. For this reason hybrid RF and FSO systems have been proposed, mainly for terrestrial scenarios, where an adaptive modulation and coding strategy can be used to adjust the relative use of the RF and FSO links depending on weather conditions, to maximize throughput.

Even in clear-sky conditions, FSO links suffer from attenuation and fading issues, e.g., (Kaushal and Kaddoum 2017; Hemmati and Caplan 2013). The wavelength used will lie within an atmospheric “transmission window” where molecular absorption (by water vapor, carbon dioxide, or ozone) will be only a fraction of a dB per km. Rayleigh scattering becomes more significant at shorter wavelengths below 1000 nm. These effects are heavily dependent on the amount of atmosphere traversed, so the OGS height and elevation angle of the optical link can make large differences. While these effects are usually categorized simply as attenuation, a more serious effect is due to slight changes in temperature and pressure of air cells within the optical path. Differences in the refractive indices of these cells cause scintillation effects which are observed as rapid intensity variations over millisecond time scales. These variations result from cancellation or reinforcement of the laser signal as it propagates through multiple cells. This fading can cause serious impairment to FSO links. Figure 3 shows an example of variations that are well modelled by a lognormal distribution.

In addition, for satellite communications these turbulence effects vary depending on whether uplinks or downlinks are considered. In the former case, beam spreading or beam wandering effects due to turbulence occur at the start of the transmission path, so the impact is much worse than in a downlink along the same satellite-ground path. Unsurprisingly, mountain locations are popular for large OGSs as the atmospheric effects are significantly reduced.

Mitigation strategies for fading include spatial diversity (e.g., using a large enough telescope in the OGS to “average out” some of the short-term variations),

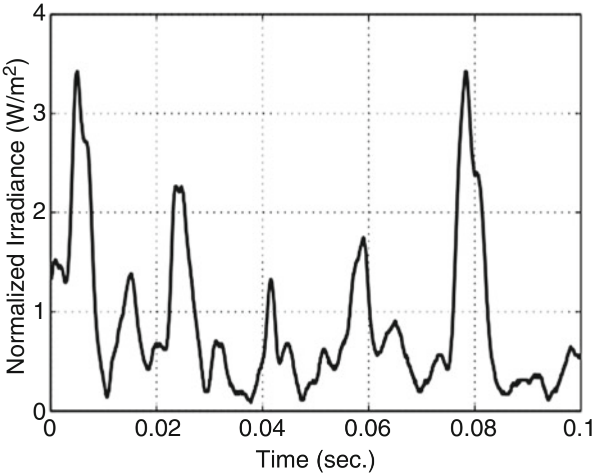


Fig. 3 Example of FSO fading over a 1.5 km 1550 nm horizontal path, using a 13 mm aperture, from (Letzepis et al. 2008)

multiple-input and multiple-output (MIMO) techniques, interleaving combined with FEC and adaptive optics which aims to correct the wave front distortions.

4 Small Satellite Examples

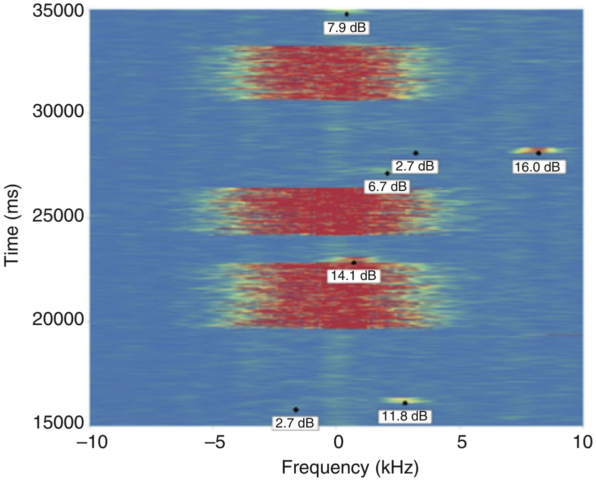
This section considers some specific examples which illustrate recent developments and current status of topics discussed above. See also (NASA n.d.; Gao et al. 2018).

4.1 RF Payload Using SDR

This case illustrates a scenario of uplinking short messages from very large numbers of low-cost ground terminals to a LEO CubeSat constellation. This is ideally handled by VHF or UHF communications where both the terminals and the satellites use low-gain antennas with few pointing requirements and terminals must be very low power.

The application scenario is not new, but the approach used in this example is novel and illustrates the benefits of recent signal processing and coding advances. Based in Adelaide, Myriota is a startup originating from the University of South Australia. The author was involved in early stages of this research several years ago. Given the limited communications capacity of existing "Internet of Things" (IOT) providers, this project set out to maximize the spectral efficiency for the IOT scenario and simplify terminal access requirements. It uses an extension of iterative channel coding approaches to handle short uplink messages that are completely unsynchronized in time and frequency. The resulting system caters for many more

Fig. 4 Reception of weak ground terminal signals from LEO CubeSat



terminals than traditional methods and is much more robust in terms of interference and noise. Figure 4 shows an example spectrogram with seven successfully decoded messages, plus large interferers. The low-SNR messages are ≈1 kHz wide and have a duration of 250 ms. The company has shown it is often possible to decode messages which suffer from significant interference overlap. [See (Haley et al. 2018) for details.]

At present Myriota delivers an uplink-only service to customers by capturing signals in LEO and performing signal processing on the ground. They are migrating some of this processing to a custom CubeSat constellation. Myriota is also able to downlink data to terminals. This is currently used for network management and will be offered for customer data in the future.

4.2 High-Gain CubeSat Antennas

Parabolic antennas have been deployed from large communication and remote sensing satellites for many decades, but their use in CubeSats has only occurred in the last decade. The RainCube (Chahat et al. 2016) project has deployed a Ka-Band mesh reflector from a 6 U CubeSat. This 0.5-m-diameter dish is part of a 35.75 GHz nadir-pointing radar designed to measure precipitation from LEO. This project required a suitably high-gain antenna (≈42 dBi) to achieve the small beamwidth (≈1.2 degrees) to give adequate radar resolution. Achieving the required antenna surface accuracy at Ka-Band from a 1.5 U stowed volume is impressive. A Cassegrain design was used, with a telescoping circular waveguide to the feedhorn. RainCube has been in use since mid-2018. The deployment can be seen at (NASA/JPL n.d.).

Other approaches have shown it is not essential to use a parabolic reflector. An S-Band antenna design using an array of patch antennas is illustrated in (Warren et al. 2015). The patches lie on flexible membranes which are flattened by a tensioning scheme during deployment. This design avoids the need for a feed assembly deployed away from a reflecting surface. It uses under 2 U of stowage space to give an antenna area of 1.53 m^2 and provided a gain of 30.5 dBi at 3.6 GHz during ground tests. The “reflectarray” approach has been successfully used in ISARA and Mars CubeSat (Hodges et al. 2017, 2018) missions. It uses flat panels which reflect the signal transmitted from a feed assembly. By varying the size of square patches on the flat panels to change their phase, this design can form a beam and steer it in a required direction. Furthermore the flat panels can be very conveniently stowed in unused space around the CubeSat before launch. Using this approach the Mars CubeSats, shown in (Hodges et al. 2017; Rohwer et al. 2010), successfully provided X band communications back to Earth during the descent of the Mars lander.

4.3 LEO FSO: OSIRIS

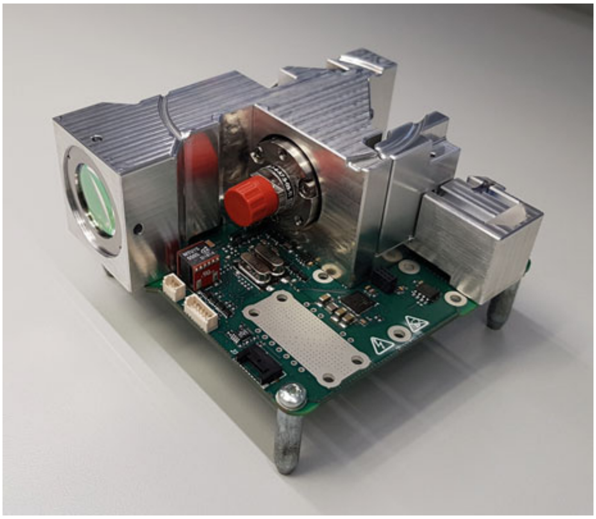
The Institute of Communications and Navigation at DLR has extensive experience in both terrestrial, aeronautical, and satellite FSO communications. They have conducted several FSO trials with international partners, including the author’s university. DLR has recently been developing their own optical payload, called OSIRIS, for small satellites. This section provides a short summary of this work which illustrates a steady evolution in FSO terminal capabilities.

Four versions of the OSIRIS terminal have been developed. The first was flown as a secondary payload on the University of Stuttgart “Flying Laptop” 110 kg satellite launched in 2017. The payload tested two laser sources (100 mW laser diode and 1 W EDFA) and supported data rates up to 200 Mbps. This LEO satellite provided an excellent pointing accuracy of better than 0.5 mrad to an observation target on the ground. The OSIRIS payload uses satellite pointing thereby saving significant complexity and only weighs 1.3 kg. The transmit beam divergence was nominally 1.2 mrad. References (Fuchs et al. 2018, 2019) contain more details of calibration and downlink experiments.

The second version of OSIRIS was launched as a secondary payload on the BiROS satellite. In this case the beam divergence was reduced, aiming for a bit rate of 1 Gbps. With a very small increase in mass, the design includes a sensor that measures the offset in reception of an uplink beacon, with the aim of sending this to the platform ACS to obtain the required pointing accuracy. While most of the payload functions have been demonstrated, at this time it has not been possible to achieve downlink data reception, as the optimization of the satellite ACS to achieve the required accuracy could not be continued due to the primary mission of BiROS.

Two more versions of OSIRIS are in the pipeline. Version 3 is aiming for 10 Gbps and is planning to fly on the ISS in 2020. It includes a coarse pointing assembly (CPA), plus FEC and automatic repeat request (ARQ) in the downlink. Version 4 is designed for CubeSats and was first shown at the IAC of 2018. The target mass is 300 gms, with a data rate of 100 Mbps and output power of 100 mW. It will use the CubeSat ACS for coarse pointing, to an accuracy of +/− 17 mrad and includes fine pointing using an uplink beacon. Figure 5 shows a prototype of this terminal.

Fig. 5 Prototype of the OSIRIS payload, version 4 s



4.4 PAT Schemes for Small Satellites

Section "Antennas and Pointing" introduced issues associated with achieving suitably accurate pointing of FSO satellite terminals. The following examples illustrate recent developments in pointing, acquisition and tracking.

In the Lunar Laser Communications Demonstration (LLCD), NASA and MIT have shown the feasibility of high-rate FSO links over lunar distances. In 2013 the LLCD demonstrated reliable communications at 622 Mbps in the downlink and 20 Mbps uplink on the Lunar Atmosphere and Dust Environment Explorer (LADEE) satellite. This ≈7 kg terminal may be seen in exploded form at (Weatherwax and Doyle 2014; Hemmati et al. 1996). The figure shows a 10 cm reflector telescope in the upper right-hand side. A two-axis gimbal allows coarse pointing over a large angular range. Between these two an inertial reference unit (IRU, shown in blue in the figure) is used to stabilize the telescope and other optical components from satellite vibrations. This approach was developed under a NASA Small Business Innovation Research scheme and has subsequently been used on several FSO projects. Highly sensitive angular rate sensors, based on magnetohydrodynamics, plus digital control systems and voice-coil actuators allow the MIRU to isolate the optics from satellite vibrations above several Hz. Variations at lower frequencies are handled by sensing the received power after nutation of the receive fiber using piezoelectric actuators. The overall scheme was designed to meet the demanding 4.2 urad RMS pointing error requirement. Further details, including a photon-counting OGS, can be found in (Weatherwax and Doyle 2014; Scozzafava et al. 2007; Boroson et al. 2009).

Recent projects from MIT and JPL illustrate further progress in pointing, acquisition, and tracking for small satellite optical payloads over shorter distances.

NASA's TeraByte InfraRed Delivery (TBIRD) demonstrator aims to deliver up to 200 Gbps from a LEO CubeSat, using COTS parts where possible (Chang et al. 2019). Their approach uses a quadrant detector of the uplink beacon signal for both spatial tracking and low-rate communications (e.g., to allow an ARQ system for the high-rate downlink). To minimize payload complexity, this single receive sensor provides pointing feedback to the satellite bus for fine attitude control. The uplink uses 2 PPM with pulse shaping to provide a discrete spectral component which helps the tracking algorithm avoid background perturbations.

TBIRD uses a transmit beam divergence of approximately 130 urads and requires a volume of under 2 U with a mass of slightly over 2 kg. Clearly the approach relies on recent improvements in the ACS of small satellites, especially in the area of star trackers and reaction wheels. After acquisition of the uplink beacon, the FSO payload provides feedback to the TBIRD ACS at 30 Hz. TBIRD is due for demonstration in 2020 and is only one part of NASA's ambitious optical communications program (Edwards 2019; Park et al. 2019). A related recent CubeSat project funded by NASA and developed by The Aerospace Corporation is called the Optical Communications and Sensor Demonstration (OCSD). This resulted in 1.5 U CubeSats that used platform pointing and relied on very good platform ACS, from accurate star trackers, to avoid the use of an uplink beacon. In this case a more powerful 4 W, 1064 nm laser was employed. Over the course of the project, the laser divergence was reduced as the platform ACS accuracy improved (Todd et al. 2019).

An MIT project also aims at low-cost FSO downloads from LEO. The Nano-Satellite Optical Downlink Experiment (NODE) project uses only 200 mW of optical power, to 30 cm "amateur" telescopes in the OGS. With a larger divergence of $\approx$1.3 mrad, they aim for 10 Mbps. The NODE payload is less than 1 kg in a 1.2 U volume (Clements et al. 2016; Cahoy 2018).

5 Summary

RF satcom is progressing well with the use of higher frequencies, better spectral/power efficiencies, low-volume deployable antennas, and further payload miniaturization. Particularly in the last decade, even greater progress has been achieved for FSO payloads, where significant reductions in power, mass, and volume have been achieved. In addition the standardization of FSO, transmission formats are making progress (e.g., Edwards et al. 2017). Scarcer RF spectrum, longer links, and higher throughput will increasingly favor FSO solutions.

6 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System

- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ Small Satellite Antennas
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

References

Analog Devices, *Analog Devices, highly integrated radio frequency transceiver AD9361 IC* (n.d.), https://wiki.analog.com/resources/eval/user-guides/ad-fmcomms2-ebz/ad9361

D.G. Aviv, *Laser Space Communications* (Artech House, Boston, 2006)

D.M. Boroson, J.J. Scozzafava, D.V. Murphy, B.S. Robinson, M.I.T. Lincoln, The lunar laser communications demonstration (LLCD), in *2009 Third IEEE International Conference on Space Mission Challenges for Information Technology*, (2009), pp. 23–28

K. Cahoy, *Laser Communication with CubeSats*. At http://www.bostonphotonics.org/files/seminars/KCahoy-2018.pdf, 2018

D.O. Caplan, Laser communication transmitter and receiver design. J. Opt. Fiber Commun. Rep. **4**, 225–362 (2007)

N. Chahat, R.E. Hodges, J. Sauder, M. Thomson, E. Peral, Y. Rahmat-Samii, CubeSat deployable Ka-band mesh reflector antenna development for earth science missions. IEEE Trans. Antennas Propag. **64**, 2083–2093 (2016)

J. Chang, C. Schieler, K. Riesing, J. Burnside, K. Aquino, B. Robinson, Body pointing, acquisition and tracking for small satellite laser communication, in *Proc. SPIE*, vol. 10910, (2019)

E. Clements et al., Nanosatellite optical downlink experiment: design, simulation, and prototyping. Opt. Eng. **55**(11), 111610 (2016)

B. Edwards, *NASAs Optical Communications Programs*, 2019. Presentation

B.L. Edwards, R. Daddato, K. Schulz, C. Schmidt, J. Hamkins, D. Giggenbach, B. Robinson, L. Braatz, R. Alliss, An update on the CCSDS optical communications working group, in *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, (2017), pp. 1–9

eoPortal web pages, FedSat (Federation Satellite). Available at https://earth.esa.int/web/eoportal/satellite-missions/f/fedsat, 2002

C. Fuchs et al., Optical satellite downlinks and QKD at DLR, in *ESA Scylight Workshop on Optical Communication*, (2018)

C. Fuchs et al., Update on DLR's OSIRIS program and first results of OSIRISv1 on flying laptop, in *SPIE Proceedings Free-Space Laser Communications XXXI*, vol. 10910, (2019)

S. Gao, Y. Rahmat-Samii, R.E. Hodges, X. Yang, Advanced antennas for small satellites. Proc. IEEE **106**, 391–403 (2018)

D. Giggenbach, E. Lutz, J. Poliak, R. Mata-Calvo, C. Fuchs, A high-throughput satellite system for serving whole Europe with fast internet service, employing optical feeder links, in *Broadband Coverage in Germany. 9th ITG Symposium. Proceedings*, (2015), pp. 1–7

D. Haley, A. Beck, A. Pollok, A. Grant, R. McKilliam, Massive scale, long battery life, direct to orbit connectivity for the internet of things. Acta Astronaut. **151**, 318–323 (2018)

H. Hemmati, *Near-Earth Laser Communications* (CRC Press, Boca Raton, 2009)

H. Hemmati, D. Caplan, *Optical Satellite Communications*, ch. 4 (Elsevier, 2013), pp. 121–162

H. Hemmati, K. Wilson, M.K. Sue, L. Harcke, M. Wilhelm, C.-C. Chen, J.R. Lesh, Y. Feria, D. Rascoe, F. Lansing, J.W. Layland, Comparative study of optical and radio-frequency communication Systems for a Deep-Space Mission, in *Telecommunications and Data Acquisition Progress Report*, (NASA, Pasadena, 1996), pp. 42–128

R.E. Hodges, N. Chahat, D.J. Hoppe, J.D. Vacchione, A deployable high-gain antenna bound for Mars: Developing a new folded-panel reflectarray for the first CubeSat mission to Mars. IEEE Antennas Propag. Mag. **59**, 39–49 (2017)

R.E. Hodges, D.K. Lewis, M.J. Radway, A.S. Toorian, F.H. Aguirre, D.J. Hoppe, B.N. Shah, A.A. Gray, The ISARA Mission flight demonstration of a high gain Ka-band antenna for 100Mbps telecom, in *AIAA Conference on Small Satellites, SSC18-VI-03*, (2018)

H. Kaushal, G. Kaddoum, Optical communication in space: Challenges and mitigation techniques. IEEE Commun. Surv. Tutorials **19**, 57–96 (2017). Firstquarter

N. Letzepis, I. Holland, W. Cowley, The Gaussian free space optical MIMO channel with Q-ary pulse position modulation. IEEE Trans. Wirel. Commun. **7**, 1744–1753 (2008)

lowsnr.org, Link Budget Android app (n.d.), https://lowsnrblog.blogspot.com/2017/11/app-and-applet-for-rf-link-budgets.html

W. Mitchell, Rain Fade compensation for Ka-Band communications satellites, Tech. Rep. CR-97-206591, NASA, 1997

NASA, *State of the Art of Small Spacecraft Technology* (n.d.), Available at https://sst-soa.arc.nasa.gov/

NASA/JPL, *RainCube Antenna: Ground Test Deployment* (n.d.), https://www.youtube.com/watch?v=5rCXOOGsfDY

E.A. Park, D. Cornwell, D. Israel, NASA's next generation 100 Gbps optical communications relay, in *2019 IEEE Aerospace Conference*, (2019), pp. 1–9

A.B. Rohwer, D.H. Desrosiers, W. Bach, H. Estavillo, P. Makridakis, R. Hrusovsky, Iridium Main Mission antennas a phased array success story and mission update, in *2010 IEEE International Symposium on Phased Array Systems and Technology*, (2010), pp. 504–511

J.J. Scozzafava, D.M. Boroson, J.W. Burnside, M.L. Glynn, C.E. DeVoe, C.M. DeFranzo, K.B. Doyle, Design of a very small inertially stabilized optical space terminal, in *Proc. SPIE*, vol. 6709, (2007)

SWIFT-KTX, *Tethers Unlimited Data Sheet* (n.d.), http://www.tethers.com/SWIFT.html

S. Todd et al., Optical communications downlink from a 1.5U cubesat: OCSD program (conference presentation), in *SSC18-XI-10*, vol. 10910, (2019)

Turbo and LDPC Codec Designs. *Small World Communications* (n.d.), https://www.sworld.com.au/products/index.html

P. Warren, J. Steinbeck, R. Menelli, C. Mueller, Large, deployable S-band antenna for a 6U Cubesat, in *Proceedings of the Small Satellite Conference, SSC15-VI-5*, (2015)

M.S. Weatherwax, K.B. Doyle, Vibration analysis and testing for the LLST optical module, in *SPIE*, vol. 9192, (2014)

Hosted Payload Packages as a Form of Small Satellite System

Joseph N. Pelton

Contents

Abstract

In recent years there has been an enormous amount of attention that has been given to small satellites. Much of the focus of that publicity has related to very large constellations of small satellites such those proposed by OneWeb, SpaceX, Boeing, Thales Alenia, Planet, Spire, and others. Many of these constellations involve the launch of hundreds or even thousands of satellites. The rapid buildup of these small satellite constellations has to some extent overshadowed another important concept that has been effectively used in recent years as an alternative to free-flying small satellite projects.

This important alternative is known as a "hosted payload." The concept is simply to place a smaller "payload" on board of a satellite platform. This allows a small and typically quite efficient payload to carry out its intended function not as

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_18

a free-flying small satellite but as an adjunct to a larger space platform. In this type of configuration, a hosted payload derives its power, stabilization and orientation, and tracking, telemetry, and command services from its larger host platform. In some cases there might be only one hosted payload on another satellite. In other cases there might even be a number of hosted payloads all flying on a single satellite platform, rather than as free flyers.

Such a hosted payload arrangement can provide a number of advantages that can be derived from such an arrangement. These advantages can include (a) improved launch arrangements and associated improvement in launch costs, reduced regulatory requirements related to frequency coordination, registration of satellite launching notification to the United Nations, etc.; (b) economies of scale and cost reductions associated with the ability to share the power system, thermal controls, TT&C system, and stabilization, pointing, and orientation system of the larger spacecraft platform; (c) reduced operational cost associated with maintaining a small satellite in order or in some cases maintaining a large network of satellites in orbit (Note: this advantage includes not having to be concerned about avoidance of conjunctions with other satellites since this function is carried out by the larger satellite operator); and (d) not having to be concerned with the end-of-life disposal of the hosted payload(s), since these functions will also be carried out by the spacecraft operator that manages the larger satellite or in some cases an entire satellite constellation.

This does not mean that there are only positive benefits derived from carrying out a mission or even providing an ongoing space service by means of a hosted payload approach. If there is a failure (i.e., partial or total) of the host satellite or even a system failure that applies throughout an entire network of the host platform satellites, this is clearly a problem for the hosted payload. This failure of the host satellite or the constellation of host satellites would clearly be a very serious nature. There can be more complex types of problems beyond a host satellite not achieving orbit or total failure. There could be problems such as partial loss of a capability. This might be a problem with the solar arrays that require a cut back or even total loss of power supply to the hosted payload. In the case of a hosted payload mission, it is prudent to anticipate potential problems and seek to spell out in a contractual document an equitable solutions to possible problems before they occur.

The following article seeks to present examples of the various types of ways that hosted payload systems have been used to carry out missions that might have otherwise been undertaken by small satellites. It explains the types of organizations that operate in this area, including the Hosted Payload Alliance, that promotes this approach to governmental and military organizations that have been a frequent adopter of this approach over the past decade. It provides information about the possibility of use of hosted payloads on an entire constellation such is now the case with the Aireon hosted payloads that are currently operational on all 66 of the satellites in the Iridium Next small satellite constellation.

Keywords

Aerion hosted payloads on the Iridium system · ADS-B aeronautical surveillance service · Economics of new launch services · End-of-life deorbit · Hosted payloads · Hosted payloads as part of a constellation · Hosted Payload Alliance (HPA) · Host platforms · Intelsat General · Liability insurance · Lifetime testing · “New Space” · SES World Skies US Government Solutions · Technology verification

1 Introduction

The idea of combining space missions and flying an experimental package on another larger satellite has been implemented in practical ways for many years. In the 1960s NASA combined unrelated experiments that flew on the Applications Test Satellite (ATS-1) Intelsat included a Maritime Communications Satellite (MCS) package in the Intelsat VA satellites that was designed to provide maritime services. This continued to provide services for mobile services in the L-band even after the creation of Inmarsat organization. Likewise the Marisat program that was built and deployed by the Communications Satellite Corporation to provide maritime communications services to the US Navy was designed to provide additional commercial maritime communications services in different frequencies. Thus for many decades, there have been combined missions on satellites to achieve economies in the design, launch, and operation of satellite systems through the use of hosted payloads. Many of the early instances involved governmental agencies or defense agencies.

The last 15 years has seen increasing interest in the efficiencies that hosted payloads can bring to governmental, military, commercial, and experimental space programs. The Hosted Payload Alliance (HPA) is a strong advocate for the use of this approach. The US Government Accountability Office undertook a formal review of Department of Defense hosted payload projects completed and planned and reported its findings as follows: “GAO and others have found that using commercial satellites to host government sensors or communications packages – called payloads – may be one way DOD can achieve on-orbit capability faster and more affordably. Using hosted payloads may also help facilitate a proliferation of payloads on orbit, making it more difficult for an adversary to defeat a capability. Since 2009, DOD has used three commercially hosted payloads, with three more missions planned or underway through 2022” (United States Accountability Office 2018).

Commercial organizations, such as Intelsat General, SES World Skies US Government Solutions, etc., provide particular assistance to use the hosted payload approach for military and governmental agencies. Perhaps most impressive of all has been the deployment of Aerion payloads on all of the Iridium Next satellites to provide a comprehensive global ability to provide Automatic Dependent Surveillance-Broadcast (ADS-B) aeronautical surveillance via these specially equipped systems (Space-Based ADS-B: Making Global Air Traffic Surveillance a Powerful Reality n.d.).

The early experience with hosted payload was most typically just one-off efforts. These were often efforts to provide technology verification of a new space technology or service. This hosted payload approach provided a cost-effective way to provide an in-orbit testing of how this new technology might work. It was found that one way to conduct an in-orbit experiment was to put a package on another larger satellite "host" platform. This was simpler than putting together a complete satellite platform, arranging for its launch, registering the launch with the United Nations, meeting due diligence requirements of the launching state, and perhaps carrying out RF interference coordination negotiations.

Often such add on packages, if they were small enough, could fit within the mass margin available for already contracted launch services. This often proved to be the case for commercial systems deploying a new telecommunications or remote sensing satellite to orbit. This advantage alone could provide a great cost savings. The Maritime Communications Subsystem (MCS) package on the Intelsat VA and the Marisat launches arranged by Comsat for services to the US Navy as well as to provide commercial maritime mobile satellite services may have been the first two times that a hosted payload was designed to provide an ongoing commercial service. This provided a very cost-effective type of approach. Thus designing a "package" that could ride on a host platform was clearly confirmed as viable way to provide commercial space applications even in the 1980s (Pelton et al. 2004).

Today, the 66 operational Aireon packages on Iridium Next, a low Earth orbit (LEO) constellation for mobile satellite communications, represent the largest such network deployed as a hosted payload constellation. The small satellites represented by Iridium Next, with an even smaller hosted payload on board, provide economies of scale to the Aerion system and its operation. This arrangement also provides incremental revenue to the Iridium LLC Enterprise (see Fig. 1).

Of course in some instances, the hosted payload (or payloads) can fly on quite large satellites deployed in orbits that include LEO, MEO, GEO, and even other types of orbits. Such hosted payloads might typically be in the range of 1–50 kg, but the host platform might be a smallsat or even run up to the largest of all satellites such as the Alphasat or Inmarsat XL that is well over 10,000 kg in mass.

2 Hosted Payloads for Technology Verification and Service Verification

The most common use of hosted payloads for many years has been for technology verification. At least for the years 2013–2018, technology verification represented about 20–25% of the reasons for all small satellite launches. Projections for the future suggest that there will be much greater growth in terms of applications and services if use of hosted payloads follows the pattern of overall small satellite usage (Overall Distribution of Small Satellite Launches by Usage n.d.).

In a number of instances, it was a combination of technology verification and in-orbit lifetime testing. In light of the high cost of satellite launches and the difficulty of in-orbit repair or retrofitting, the designers of satellite systems like to

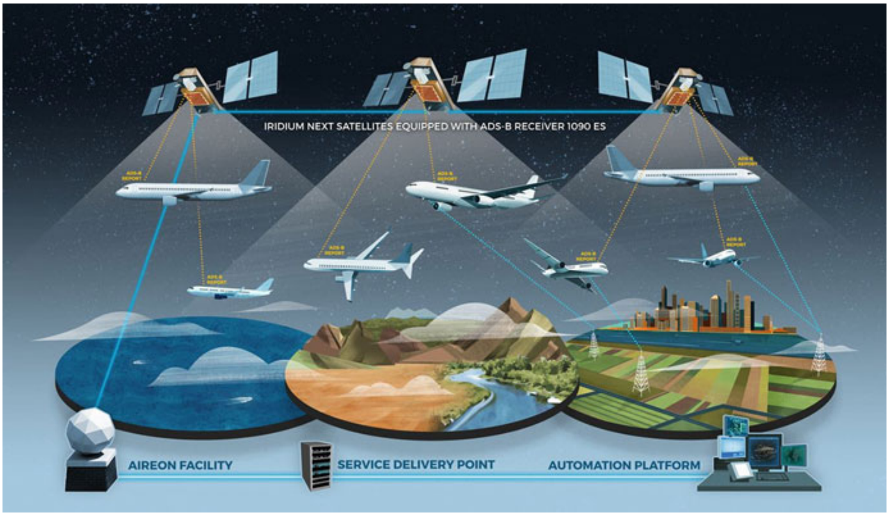


Fig. 1 The Aireon ASD-B hosted payload packages are now providing aeronautical surveillance service to commercial aircraft. (Graphic courtesy of Aireon)

be confident in the viability of all the technologies that are implemented on a spacecraft. Operators of satellite systems such as those that provide telecommunications services have used the current generation of satellite to test next-generation technology.

In one related type of mission, the Intelsat system flew an experimental router developed by Cisco on the Intelsat 14 that was in this case funded by the US Air Force as arranged by Intelsat General. In this case Cisco leased three transponders to conduct experimental with flexible reassignment of capacity using the IRIS router to reallocate capacity to meet needs for video downloads and other high bandwidth requirements. The type of experiment is central to future moves of communications satellite designs to encompass onboard processing and the building of so-called "smart" satellites. Intelsat on an earlier mission has also flown Ka-band packages prior to widespread operational use of this band in the 28 GHz uplink and 18 GHz downlink (Cisco Router Sent Into Space Aboard Intelsat Satellite 2009).

It is not necessarily the case that onboard hosted payloads by commercial telecommunications carriers are related to the future mission of the satellite organization. SES Americom, another satellite communications, signed an agreement with the US Air Force to host an experimental missile warning sensor on a communications satellite launched in January 2011 (Brinton 2009).

The future of telecommunications satellite services may well require exploitation of the Q-band (33–50 GHz), V-band (50–75 GHz), and W-band (75–110 GHz). Currently there is a Q/V experimental package known as TDP5 (named after Italian scientist Aldo ParaBoni) that is flying on the joint Inmarsat and European Space Agency (ESA) spacecraft. This spacecraft is known as Inmarsat XL (but is also known as the European Space Agency's Alphasat). The purpose of the hosted

Fig. 2 The Q/V Aldo Paraboni experiment launched as a hosted payload that rides aboard the Alphasat project by ESA (Graphic courtesy of ESA)

payload experiment was to test telecommunications satellite services using advanced digital multiplexing techniques and precipitation attenuation mitigation techniques in the Q/V bands (Brinton 2009) (see Fig. 2).

This Alphasat and Inmarsat XL satellite joint mission represented one of the world's most complex hosted payload undertakings. This satellite was designed primarily as a high-capacity mobile communications satellite. Yet, under the agreement with ESA, some 20% of the satellite resources were devoted to the four hosted payload experimental packages aboard. The Alphasat part of the joint project first flew for a 3-year period as funded experiments. This was, however, renewed for an additional 3-year period through the end of 2019 (ESA Artes Alphasat programmed to be extended n.d.).

In the case of the even higher satellite transmission frequency experiments undertaken by the Italian Space Agency to testing satellite transmission in the W-band, and known as the WAVE project, a different approach was taken. In this case the decision was taken to launch the experiment as a free-flying nano-satellite rather than taking the hosted payload approach. This experiment lasted only 3 months. Thus it did not have the opportunity of a 6-year in-orbit test which was possible with the Alphasat Q/V hosted payload experiment (Experimental Missions in W-Band: A Small LEO Satellite Approach, Researhgate n.d.).

3 The Hosted Payload Alliance

In April 11, 2011, seven commercial space industries, led by Iridium, formed what is called the Hosted Payload Alliance. The initial members of the Hosted Payload Alliance, who also the formed the steering committee, consisted of the following companies: Boeing Space and Intelligence Systems, Intelsat General Corp., Iridium Communications, Lockheed Martin Space Systems, Orbital Sciences Corp. (now

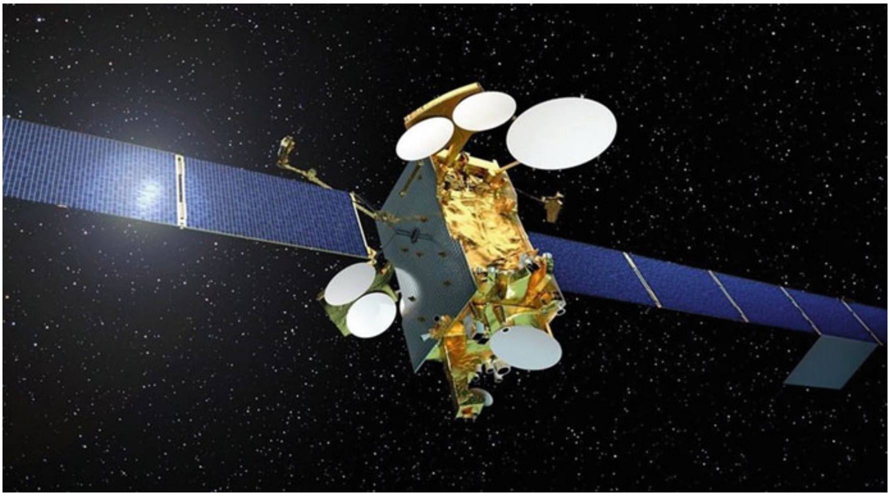


Fig. 3 The SES-14 satellite launched in 2018 with the GOLD hosted payload aboard. (Image provided courtesy of NASA)

Northop Grumman Innovation), SES World Skies US Government Solutions, and Space Systems/Loral (Seven Satellite Firms Form Hosted Payload Alliance 2011).

These aerospace companies had past experience with working with governments as contractors and providing new and sometimes unique solutions to governmental entities. Intelsat formed Intelsat General to work specifically with the US government and the US Department of Defense on providing dual-use facilities to meet special needs and transponder leases for dedicated communications services. This evolved into finding ways of meeting requirements for placing hosted payloads onto Intelsat satellites. The IRIS hosted payload by CISCO that became a hosted payload on the Intelsat 14 and funded by the US Air Force was launched in 2013. SES World Skies US Government Solutions was also formed to accommodate special needs of the US government. This led to the 2015 award to SES World Skies US Government Solutions of a contract for a NASA experiment to fly on the SES-14 satellite.

In this case the technology was not for a practical application but for research as to the effects of solar and thermal radiation on the Earth. This hosted payload experimental package was known as GOLD. This rather contrived acronym stood for Global-scale Observations of the Limb and Disk (GOLD) instrument. This research payload was launched in January 2018 and helped confirm the cost, schedule, and operational efficiency of hosted payload projects (Foust 2018) (see Fig. 3).

The Hosted Payload Alliance (HPA) is not directly involved in the individual arrangements for contracting with commercial contracts to carry research packages into orbit, but this organization has provided useful assistance to the process of bringing such arrangements into the mainstream of thinking of such arrangements by governmental officials. The HPA holds annual conferences that reports on the various projects that have taken place, provides a website and press releases that explains project successes and milestones, and helps share information with regard to contractual language, insurance and liability matters, and procedural and regulatory matters of interest. The Hosted Payload and Small Satellite Summit serves a quite useful forum to bring together potential experimenters and commercial satellite operators that can offer platforms for tests, experiments, demonstrations of technology, and even the opportunity for providing an ongoing space-based services, as is the case with the Aireon hosted payloads.

In the annual summit meeting of the Hosted Payload Alliance and Major James Crane of the US Military's Hosted Payloads Office, he has stated the following conclusions: "Ultimately, the benefits of hosted payloads are staggering. Their ability to increase access to space, slash the cost of military space missions and fundamentally shift the way the military approaches satellite and spacecraft acquisitions is simply too important to let concerns about risk and control keep hosted payloads on the ground" (Presentation of Major James Crane, DOD Hosted Payloads Office n.d.).

Despite these findings by the US Government Accountability Office and the Hosted Payload Office including the approval of "an IDIQ contract called HoPS" (known as the Air Force's Hosted Payload Solutions Program), the number of hosted payload projects has not greatly increased. Some observers have suggested that having programs and projects over which military units retain complete control and involve much larger budgets are still a factor that limits the number of hosted payload undertakings.

4 "NewSpace" and Economics in Launch Services and Spacecraft Design

Another key aspect that will likely control the extent to which the number of hosted payload projects will be undertaken relates to progress that is achieved by so-called "NewSpace" aerospace companies seeking to develop lower-cost launch capabilities. This is particularly the case in the area of new launch services providers and their ability to deliver reliable and easily schedulable launches for small satellite missions at ever lower costs. There have been studies done of various hosted payload projects that have found that the combined costs for developing and launching hosted payload packages run around $250,000 per kilogram. This would equate to about $1,250,000 for a 5 kg project or $12,500,000 for a 50 kg project.

These cost figures are difficult to relate to a free-flying satellite experiment or service providing spacecraft. The lack of comparison comes from the fact that an independent spacecraft must also provide for a power supply, a positioning and orientation system, thermal controls, and a tracking, telemetry, and control system, plus a platform structure and thermal controls. Further there would be additional staffing and operational costs associated with a free-flying satellite.

What is clear is that if the cost of launching a free-flying small satellite were to be significantly reduced, then the relative advantages of hosted payloads would be somewhat diminished. There are now all sorts of ambitious efforts to create much lower-cost launching systems. These newer designs include reusable rockets (i.e., first stages and fairing covers); new types of lower-cost materials for fabricating rocket stages (i.e., Rocket Labs); new use of additive manufacturing for creating rocket launcher engines; lower-cost launching operations from truck-mounted systems or from high-altitude carrier planes; and more. Also some of these new launcher companies are located in countries with lower salary costs such as Argentina, Brazil, China, India, Israel, Russia, etc.

Some of these new commercial launch services companies are estimating that the cost of their commercial launch services for small satellites will drop down to around $40,000 to $50,000 per kilogram or even lower. Even so, these prices will remain well above the capabilities of reusable launchers such as the Falcon 9 rockets at around $10,000 per kg and potentially as low as $5,000 per kg. Others are projecting that the cost of designing and manufacturing spacecraft will also fall. This assumes not only that satellites will be designed and manufactured for less but also that satellites will be designed with increasing skill so as to do more within less mass and volume (Andraschko et al. 2019).

Indeed these economies have already been achieved. Companies such as Blue Origin, SpaceX, Launcher One, Vector, and Rocket Labs are offering lower prices and greater launching rates. There are another 40 new start-up launcher companies that are promising greater economies and better results. Some have suggested that instead of rockets that can be launched repeatedly for 20 times to 30 times, in the future, this could go to repeated launches up to 100 times. If this can be accomplished with lower-cost launching sites, and if the manufactures of these rocket launchers are can be reliably done in countries with lesser labor costs, the prices could continue to fall. In such a price or cost environment, the emphasis toward the use of hosted payloads might shift from cost savings to an emphasis on less orbital debris and less “space junk” to be removed from orbit.

5 Mission Consolidation Efficiencies

The greatest emphasis that is placed on hosted payload projects is on the cost savings that can be achieved. It is logical in that there are clear savings in many ways. There are clear savings in terms of launch costs and all of the paper work and regulatory hurdles associated with a launch. Then there are also demonstrable cost savings associated with the sharing of power systems; tracking, telemetry, and command systems; pointing and stabilization systems; structures; thermal systems; etc. Once the satellite is launched and operational, there are savings due to the fact that the “spacecraft bus” is managed by the platform host operator rather than the organization associated with the host payload sensor or telecommunications package.

The benefits extend beyond the cost savings that can be derived. The additional benefits that should logically be considered include the following: (i) the operator of the host platform is responsible for removal of the satellite for orbit and the proper discharge of batteries or outgassing of fuel tanks to avoid explosions or other such misadventures; (ii) in the case of reliability, lifetime testing, or demonstration of new services, the period of the test can likely be much more extended. In the case of the Q-/V-band, telecommunications services and precipitation attenuation mitigation testing on Alphasat were able to go for 3 years and then extended for another 3 years. In the case of the W-band nanosat free flyer, the test was for only 3 months.

Further the record of dependability or reliability with nanosats and cubesats systems are much worse than that associated with large spacecraft. A reliability assessment of cubesats by NASA scientists and engineers has indicated the reliability problem with cubesats as follows: "There has been an exponential increase in CubeSats launched since 2003. There were only 105 launched from 2003 through 2012, 79 in 2013, and 118 in 2014. Yet mission success rates average, 45 percent and 77 percent for academia and industry, respectively. Missions were deemed a success if the CubeSat operated on orbit for 60 days or longer" (Venturini n.d.).

There are a number of design, manufacture, testing, and launching techniques that have served to increase the reliability of nanosats and cubesats, but nevertheless the success in terms of reliability is far less than with more sophisticated satellite systems, and the time of successful operation is significantly longer. The initial launch of 60 minisats for the SpaceX constellation resulted in 5 satellites that did not properly activate. This results in concerns about the reliability of such smallsats but also in the ability to deorbit smallsats that do not activate and cannot be reached for commands (O'Callaghan 2019).

6 Legal, Regulatory, Liability, and Insurance Considerations

The types of legal, regulatory, liability, and insurance considerations associated with a hosted payload system are clearly different than in the case of a free-flying nanosat or cubesat. For the most part, they tend to be less of an issue because the main operator of the satellite and the associated launching nation have most of the responsibilities for getting the national license to launch, filing the launch notification to the United Nations, and to carry out the technical intersystem coordination under the International Telecommunication Union (ITU). Nevertheless someone seeking to launch a hosted payload has the responsibility to provide the needed technical information required for various filings to the organization that is launching the host payload satellite. If the hosted payload or series of hosted payloads on board a constellation of satellites are providing services to various countries, they still must obtain so-called landing licenses to operate in those countries. In some instances, there will be new regulatory issues to address.

If remote sensing data is obtained by a hosted payload but such data is not downloaded within that country, and processed data is only sold via the Internet, there could be questions as to whether some form of national approval might be required. This is not a question unique to a hosted payload. The fact that such operation is conducted via a hosted payload does not exempt a satellite service provider from national or international regulatory policies.

There are questions about insurance coverage. Can separate launch insurance be obtained for a hosted payload and if so would it be for the cost of replacing such a payload or could it cover the cost of lost revenues from the services it is seeking to provide?

There are a number of possible questions of liability. If the host platform satellite operator partially loses power so that it cannot continue to provide power to the hosted payload, does the guest payload owner have standing to sue the host platform satellite operator to recover from its losses? Does the host platform satellite operator sign an agreement in advance to provide a proportionate part of the remaining power? In the case of the Inmarsat XL-Alphasat project, for instance, Alphasat has claim to 20% of the mission resources. In the case of the International Space Station, each one of the partners in the project signs a "franchise agreement" that spells out each country's rights and claims to resources. What is clear is that legally binding contractual agreements that spells out rights, responsibilities, and proportionate claims on resources should be agreed in advance of a launch of a host platform satellite and the hosted payload.

7 Framework for Hosted Payload Contractual Arrangements

The above discussion indicates both the need for a clear contractual arrangement that would spell out the responsibilities of the host platform satellite owner and/or operator as well as those of any hosted payload. Fortunately there are precedents of such agreements that provide useful models that might be used. This agreement should cover not only what the rights, duties, mutual responsibilities, and sharing of resources under nominal conditions as well as in the case of difficulties and system failures. It should also cover the possible issue of dangers or harm that the satellite in question, including its hosted payload(s), might somehow cause to another satellite or the injured party in the case of a deorbiting accident. Some of these events might seem quite remote or almost impossible to consider ever happening, but mutually protective language in the case of such partnerships seems prudent to address in advance.

8 Conclusion

The popularity of hosted payload agreements seems likely to continue to grow. There are not only the advantages of cost savings related to launch services, satellite manufacturing economies, and operating costs but other clear advantages as well. The development of new launch capabilities and efficiencies, improved forms of satellite design and manufacture, as well as rising concerns with orbital space debris will likely impact the degree to which the use of hosted payload systems will grow in the future.

What is clear is that the so-called "small satellite" revolution has many implications for the future. Small satellites and new launch services have showed the world new ways to exploit space systems and technologies. Some of these new ways include hosted payloads and small missions based on new ways of sharing space resources. Other concepts include the idea of high-altitude platform systems (HAPS) and shifting of services to Internet-optimized networks and fifth-generation broadband cellular services that utilize a range of terrestrial, cellular, HAPS, and satellites deployed at various altitudes.

9 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellite Antennas
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Small Satellites and Structural Design
- ▶ Stability, Pointing, and Orientation

References

M. Andraschko, J. Antol, S. Horan, D. Neil, Commercially hosted governmental payloads: Lessons from recent programs, Researchgate.com, Jun 25, (2019). https://www.researchgate.net/publication/224229171_Commercially_hosted_government_payloads_Lessons_from_recent_programs

T. Brinton, Cisco Views IRIS Experiment as Market Primer for Space Routers Space News, (Nov 27, 2009). https://spacenews.com/cisco-views-iris-experiment-market-primer-space-routers/

Cisco Router Sent Into Space Aboard Intelsat Satellite, Joint Cisco and Intelsat Release (2009) https://www.cisco.com/c/dam/en_us/solutions/industries/docs/gov/Cisco_Intelsat_IRIS_release.pdf

ESA Artes Alphasat programmed to be extended (n.d.), https://artes.esa.int/news/alphasat-hosted-payload-extension

Experimental Missions in W-Band: A Small LEO Satellite Approach, Researhgate (n.d.) https://www.researchgate.net/publication/3481678_Experimental_Missions_in_W-Band_A_Small_LEO_Satellite_Approach (Last accessed July 2019)

J. Foust, NASA science hosted payload ready for launch, *Space News* Jan. 5, (2018) https://spacenews.com/nasa-science-hosted-payload-ready-for-launch/

J. O'Callaghan, 'Not good enough' – SpaceX reveals that 5% of its Starlink satellites have failed in orbit so far, Forbes, June 30, (2019)

Overall Distribution of Small Satellite Launches by Usage, 2019 Report on Small Satellites, North Sky Research (n.d.)

J. N. Pelton, J. Oslund, P. Marshall (eds.), *Satellite Communications: Global Change Agents* (Lawrence Erlbaum Associates, Mahwah, 2004)

Presentation of Major James Crane, DOD Hosted Payloads Office, Hosted payloads and small satellite summit, (n.d.) https://ses-gs.com/hosted-payloads-do-the-benefits-finally-outweigh-the-risks/

Seven Satellite Firms Form Hosted Payload Alliance, Space News April 4, 2011. https://spacenews.com/7-satellite-firms-form-hosted-payload-alliance/

Space-Based ADS-B: Making Global Air Traffic Surveillance a Powerful Reality (n.d.) https://aireon.com/ (Last accessed July 2019)

United States Accountability Office, Military space systems: DOD's use of commercial satellites to host defense payloads would benefit from centralizing data, GAO-18-493, (2018) https://www.gao.gov/assets/700/693481.pdf

C.C. Venturini, Improving mission success of cubesats Aerospace report no. TOR-2017-01689, Released 2017 (n.d.)

High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites

Joseph N. Pelton

Contents

Abstract

The advantages of a high altitude to provide telecommunications, broadcasting, surveillance, remote sensing, and military related services have been known for a long time. For many years the options have largely been limited to ground-based antennas on towers or mounted on top of buildings or mountains or satellite systems. Other options such as balloons, aerostats, or other alternatives such as kites have all

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_19

largely proved to be unreliable. Such systems have not proven reliable in maintaining power and altitude, especially in violent rain and wind storms.

In recent years the idea of an intermediate altitude option to ground based towers or satellites has been re-explored in the form of what have been formally designated by the International Telecommunication Union (ITU) as High Altitude Platform Systems (HAPS). The ITU designated service for radio communications from HAPS has been specified to operate in the altitudes of 20–50 km. The practical uses of the altitudes known as near space or as the "Protozone or "Protospace" (i.e., the stratospheric region from 20 km to 160 km) have in recent years grown from essentially nil to a wide range of new applications.

This range of altitudes, sometimes described as near space, the "Protozone" or "Protospace," is usually referred to as the area above commercial airspace and most military aviation (i.e., 20 km) and below the altitude where one can sustain a satellite in orbit for a long periods (i.e., 160 km). This area has slowly but steadily emerged as an area of interest for many new and innovative uses. These applications of the Protozone include high altitude platform systems (HAPS), dark sky stations, possible use by robotic air freighters, hypersonic missiles, and hypersonic craft performing so-called "space tourism" or even hypersonic transportation systems.

The uses of a reliable high altitude platform system that could maintain a relatively stable platform for a sustained period of time might be used for telecommunications and networking, broadcasting services, stratospheric atmospheric research, remote sensing, surveillance, and other military uses.

This chapter discusses the various efforts that have been undertaken to develop HAPS technologies and systems as well as the various practical, military, and research applications that have been envisioned for so-called "near space" or "protospace" or "the Protozone." A range of different technical approaches have been proposed and tested. These have included flown platforms using both pilots and automated systems (i.e., balloons, airships, dirigibles, and zeppelins, and even powered kites), platforms that are jet powered, platforms that are solar powered and automated, and even platforms that use microwaves transmitted from the ground and converted to electrical power to power such stratospheric platforms for a sustained period of time at a stable altitude and position. Several initiatives have been seriously pursued, and space research organizations such as NASA and JAXA have carried out serious experimental projects in this area. Also some aerospace companies are prepared to offer commercial HAPS capabilities to carry out a number of difference "Protozone-based services."

Such high altitude platform systems (HAPS) are seeking to prove that they can be reliable in service, stabile in their altitude and positions, have adequate power, and be cost competitive with low Earth orbit satellite services. Today billions of dollars are being spent on deploying large scale satellite constellations using small satellites. The question is whether HAPS-based networks can offer viable competitive service? This chapter seeks to provide useful information that might help to answer that question.

Keywords

Aerostat · Broadband telecommunications services · Broadcasting services · Defense-related services · Drone · High Altitude Platform Systems (HAPS) · Hypersonic transportation · Near space · Protospace · Remote sensing · Stratosphere · Surveillance · Unmanned Aerial Vehicles (UAVs) · Unmanned Aerial System (UAS)

1 Introduction

The basic concept of a High Altitude Platform System (HAPS) is relatively straight forward. The idea is to create the equivalent of a geostationary satellite but position it over a 1000 times closer to Earth. This means that when path loss is considered a High Altitude Platform System at 35 km rather than at 35,870 km altitude can concentrate its power, with a comparably designed antenna with the same gain, a million times (i.e., 1000^2 more effectively) than a geostationary satellite. This is a huge advantage in terms of effective power and at 35 km the coverage is enough to cover a country like Cuba or even the island of Hispaniola with high efficiency. Clearly an island country with modest national dimensions could find a high altitude platform system (HAPS) or a so-called Unmanned Aerial System (UAS) or Unmanned Aerial Vehicle (UAV) of interest not only telecommunications, networking, or broadcasting purposes, but for many other purposes. UAVs or HAPS can usefully provide platform higher than a tall building, tower, or mountain top but lower than an orbiting satellite (see Fig. 1).

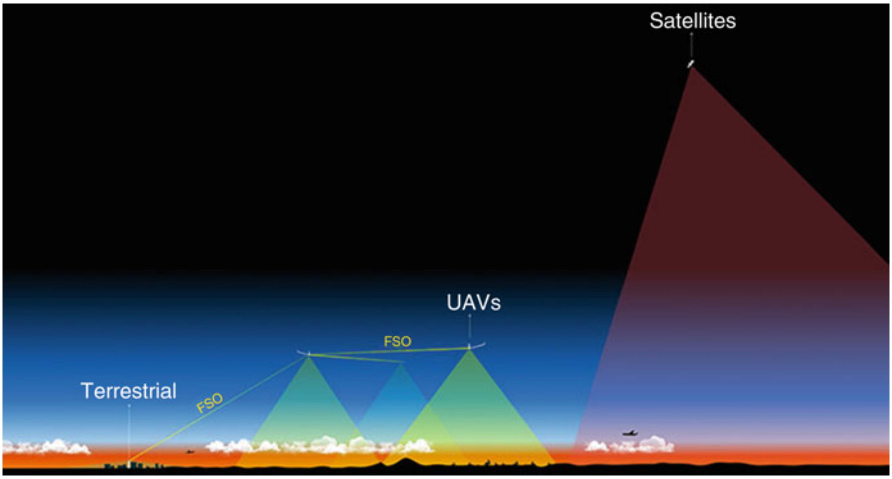
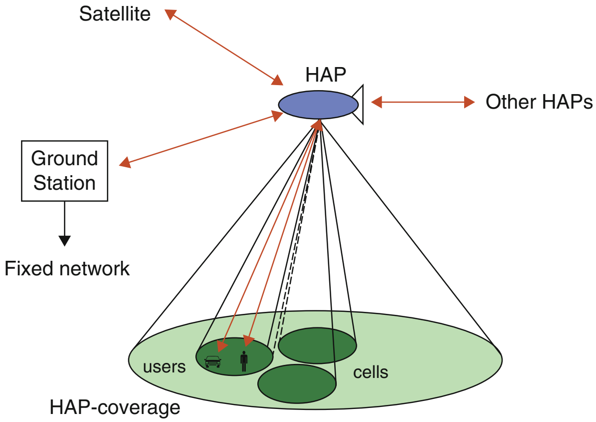


Fig. 1 The gap in coverage that a UAV or HAPS can provide vis a vis terrestrial towers and satellites

Fig. 2 Schematic showing the basic architecture of a High Altitude Platform System (HAPS)



Such a high altitude platform can be used for aerial surveillance for forest fires, agricultural- or forest-related diseases, urban planning, pollution infringements, illegal fishing, or other criminal activities, as well as for a wide range of communications related activities. Today the term of art that is more often used is UAS which stands for Unmanned Aerial System. This is because the UAV is actually just part of an overall system including the ground operations that controls the vehicle and the payloads on the vehicle. In some senses a UAS could be considered a drone, but for the most part a UAS involves more sophisticated automated aircraft that can fly to much higher altitudes and support larger payloads and missions. UAS capabilities such as the Golden Hawk or Predator, for instance, represent very sophisticated pieces or equipment that costs millions of dollars. These types of UAS as developed by the US Defense Advanced Research Projects Agency (DARPA) for military purposes should not be considered the same a "toy drones" costing thousands of times less (UAVs 2019).

And with the proper design a HAP system can connect with satellites, ground stations, other HAPS, and users located in cells to extend coverage that just one HAPS can provide (see Fig. 2).

The concept of a UAV or HAPS in terms of geographic coverage and effective power performance vis a vis a geosynchronous satellite, or even a low Earth orbit (LEO) satellite, is clearly shown in Figs. 1 and 2. The key problem is how does one stabilize a HAPS in a volatile atmosphere in a relatively stabile 3-axis location? Further how is sufficient power, performance, and continuity of service provided over a long term period of operation?

2 History of the Development of Higher Altitude Platforms (HAPS) or Unmanned Aerial Systems (UAS)

2.1 Aerostats

The first attempt at higher altitude platforms were a much lower altitudes and these systems were called aerostats. These were tethered systems that were deployed to provide communications services provide for border security or other forms of

Fig. 3 A docked aerostat not in service that is used primarily for surveillance. (Graphic courtesy of Internet global commons)

policing and armed security systems. These systems have often found to be unstable and strong storms and winds have tended to blow them away from their ground tethers. More recently the concept for aerostats has tend to move to smaller tethered balloon that can carry aloft very small packages such as Ethernet data links or sensor and surveillance equipment, and these smaller systems are easier to maintain in place more reliably. Some aerostats have been equipped with a pumping system that could add or subtract air from the system to control altitude (Aerostat definition 2019). Such aerostats operate at much lower altitudes and are not for activities that would be considered in competition with small satellite constellations. The prime uses of these systems today are for border security and military surveillance (see Fig. 3).

The idea of using UAS or HAPS for telecommunications or remote sensing was in the 1990s and 2000s considered to be a possible major alternative to GEO satellites. This was before the possibilities of large scale constellations of low Earth satellites populated by small satellites that could work to flat panel ground antennas that use phased array electronic beam tracking of satellites. Many different projects were actively undertaken.

2.2 Jet Powered High Altitude Aircraft

There was the Angel Technology Corporation. It studied the possibility of a series of jet propelled craft that would fly in "halo" flight path to provide telecommunications and remote sensing services at very high stratospheric altitudes with a replacement craft cycling up before the other descended. This project had Burt Rutan, the aerospace designer, as the prime craft designer, and also involved Arthur D. Little and Peter Diamandis. It was acquired by Raytheon when it declared bankruptcy.

2.3 Beamed Microwave-Powered High Altitude Platforms

Another project, known as Stationary High Altitude Relay Platform (SHARP), involved plans to create an experimental aircraft that would be powered by microwave energy beamed up from the ground that could be converted to electrical power to maintain this platform at high altitudes for a very long period of time. This project which was initially conceived by had a number of engineers and scientists involved. A commercial version of this system was incorporated to create this system, but it also ended in bankruptcy. This project was not able to solve a number of technical, operational, and cost issues as well as the basic safety issue of transmitting high intensity microwave beams up from the ground with possible danger to airline passengers (Schlesak et al. 1988).

2.4 Solar and Battery Powered HAPS-UAS Platforms

Yet another approach that has been pursued is that of solar powered platforms that uses solar energy to power electric engines to drive propellers to key a platform aloft and which includes batteries to keep the platform operational at night. NASA has developed such a solar powered system in conjunction with Aeroenvironment Inc. In September 11, 2019, a Tokyo company HAPSMobile Inc. (“HAPSMobile”), which is a subsidiary of SoftBank Corp. (TOKYO:9434) and minority-owned by AeroVironment, Inc. was able to complete a successful test flight of a commercial system prototype known as the HAWK30 solar-powered high-altitude platform system (HAPS). This test flight was conducted at the NASA Armstrong Flight Research Center (AFRC) and flew to an altitude sufficient for this platform to provide telecommunications, remote sensing, or surveillance services over an area of many thousands of square kilometers (HAPS Mobile Successfully Completes…., Sept 2019) (see Fig. 4).

Fig. 4 Solar-powered HAPS platform. (Graphics courtesy of NASA)

2.5 Dirigible-Based HAPS Systems

General Al Haig and associates undertook trying to design a US-based network of very large dirigible-based system that would operate at an altitude of around 20 km (13 miles) high that would be able to provide telecommunications, networking, and broadcasting services. This project also failed due to both a lack of overall financing and technical design issues (Mike Miles 1998).

The dirigible-based HAPS program that made it the farthest from concept to implementation was the Japanese HAPS system. The concept was to be a network of 15 dirigibles that would be able to provide complete coverage of Japan for communications services. This project was jointly undertaken by Japanese space specialists at what was then known as the Communications Research Laboratory (CRL) and now known as the National Institute of Information and Communications Technology (NICT) and the National Aerospace Center (About NICT 2019).

There were many issues to address. One of these issues was the annual major wind reversal that would blow the HAPS dirigibles off course and maintaining the network in place would be quite difficult in terms of the very strong change in winds. The ultimate solution found was to let all of the 15 HAPS dirigibles to be blown to a new position and then have the last dirigible be flown around to assume the first position in the national coverage configuration. In Fig. 5, there is an artist graphic image looking down from a satellite to see HAPS dirigibles below.

Another key issue was obtaining frequency allocations for suitable frequencies that could be used for this HAPS system for telecommunications services to Japan. The solution found was a so-called “reverse allocation” of the Ku-band spectrum used for satellite communications. In this case, the up link would be as 12 GHz and the down link would be at 14 GHz. Japanese calculations were that this use of the spectrum could result in about a 6% efficiency penalty for Ku-band satellite services in the region.

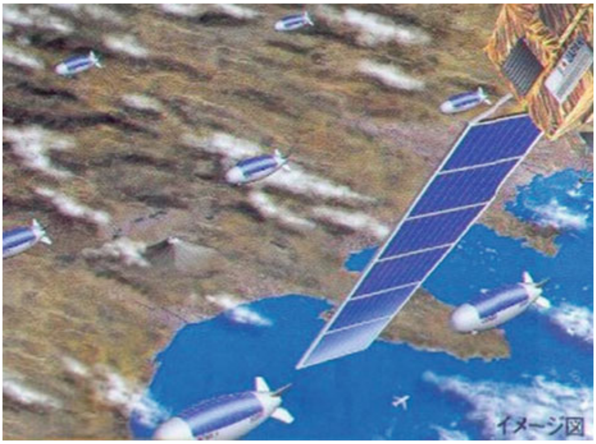


Fig. 5 Artist representation of Japanese 15 HAPS system of a dirigible network that was never deployed. (Graphic courtesy of Japan’s NICT)

After years of planning, design, and initial implementation efforts, it was ultimately decided not to deploy this system for Japan.

3 Cost and Efficiency of HAPS Networks for Communications Service

There are a number of reasons why HAPS systems for telecommunications and broadcasting services have ultimately not been deployed in a systematic way such as been the case for communication satellites. There remain technical design issues, questions of reliability, and resilience of operation. Some of the largest issues have revolved around the cost of building, deployment, sparing, and cost effective operation of these networks. The cost efficiencies of GEO satellites and the new planned LEO small satellite constellations are continuing to increase and the reliability of satellite networks have achieved a 99.999% performance.

The most efficient high throughput satellites in GEO orbit have now achieved up to a 300 Gigabit/second throughput capabilities. The largest of the small satellite will also provide very efficient, reliable, and cost efficient services. There are no specific or reliable numbers for the cost of service or satellite or HAPS system costs at this time, but they can be reasonably closely estimated for purposes of rough order of magnitude assessments. These rough estimates are provided in Table 1.

Although the costs for HAPS service might seem high in the Table 1 chart, it must be noted that the HAPS services would be highly targeted to the needs of say an island country. Further, when it is realized that there are 527,600 minutes in a year, the cost of a very broadband gigabit/second of throughput for a minute drops to about $0.00006 for the highest efficiency GEO satellite, to $0.0003 for a LEO System, and to $0.065 for a HAPS network. It turns out that all three of these transmission media represent a very small part of the cost of an overall telecommunications or broadcasting service. For instance, the cost of a billing, advertising, and marketing program, or other cost elements are likely to be much higher than the cost of any one of these three types of transmission systems. If one figures the cost of a 100 megabit/s data stream on a HAPS network, the per minute cost would drop to $0.0065.

Nevertheless the bottom line is that high throughput GEO satellites or large scale small satellite constellations will for the most part outperform HAPS networks for telecommunications and broadcast services, particularly if there are high throughput broad band services requirements. Further they likely would be able to provide a higher level of service both in terms of bit error rate and continuity of service as well as providing interconnectivity to the rest of world for international services with much greater ease and efficiency.

4 The Future Prospects for HAPS Services

All of the various transmission systems addressed in this Handbook such as GEO, MEO, and LEO satellite system and HAPS or UAS networks are developing new and better technology and certainly the cost and performance figures in Table 1 will

Table 1 Cost efficiencies for satellites and HAPS networks

Rough economic comparisons of the transmission efficiencies the current technologies of GEO, LEO, and HAPS Systems

System type	Estimated system cost	Coverage (Sq. Km)	Beam throughput	Beam performance index
Geo system (3 sats) 200 beams 15 years lifetime	\$1.25 billion	5×10^5 sq. km/ beam Total coverage: 1×10^8 sq. km	1.5 gigabits/s	\$33 for each gigabit/s/km^2 of throughput for each year of lifetime
LEO System (1000 sats) 40 beams 7 years lifetime	\$4 billion	1×10^4 sq. km Total coverage: 1×10^8 sq. km	200 megabits/s	\$170 for each gigabit/s/km^2 of throughput for each per year of lifetime
HAPS (20 beams) 10 years and 10 HAPS	\$50 million	5×10^2 sq. km Total coverage: 1×10^5 sq. km	100 megabit/s	\$37,000 for each gigabit/s/km^2 of through for each year of lifetime

Note: These theoretical comparisons are distorted in many ways by such factors as the fact that satellites cover the entire globe. This includes regions that have no or minimal service requirements (i.e., oceans, deserts, arctic regions). It is likely that global satellite systems provide active revenue services from an area that is less that 10% of the Earth surface. In contrast a HAPS system would be directly targeted to a compact island area which may in many instances have narrowband requirements. This targeting efficiency is not taken into account in the above beam performance index. This analysis was prepared by Joseph Pelton and all rights are reserved. This chart is licensed to Springer for this presentation in the *Handbook of Small Satellites*

likely continue to advance apace. Currently there are stratospheric systems that are being developed to provide for higher efficiencies in terms of altitude stability, improved power systems, and intersystem links between HAPS systems. One such example is the so-called Stratobus HAPS which is designed for providing both telecommunications service to its service area but also to interconnect to other HAPS as pictured in Fig. 6.

5 Applications for HAPS and UAS Systems at Stratospheric Altitudes

The biggest and most successful applications for satellites have been telecommunications and broadcast services and this is likely to be the case for High Altitude Platforms. There are many applications in the age of broadband 5G cellular services, over the top data streaming and other networking services that could well be met by

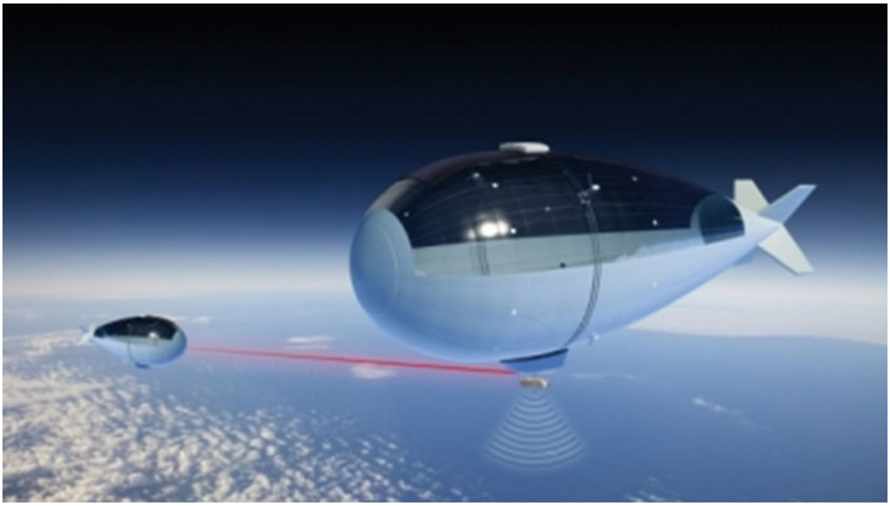


Fig. 6 Stratobus High Altitude Platform System (HAPS). (Graphic courtesy of Thales Alenia)

HAPS/UAS systems – particularly in areas of the world that have limited networking services now in place. There are billions of unserved or underserved people in the world that could utilize these systems to gain access and do so at reduced costs.

But Unmanned Aerial Systems (UAS) and HAPS are a multifunctional type capability that are capable of many diverse applications that go beyond telecommunications, broadcast, Over-The-Top streaming services, and networking services. Some of these applications are discussed below and, indeed in some cases, they are being actively employed in various parts of the world today.

(a) **Border Security**

One of the active uses of HAPS/UAS systems today is border security. Areas where illegal border crossings are at issue and frequently occurring have resorted to deploying UAS with sensing devices, telescopes, telephoto cameras, and other capabilities to detect such crossings. There are companies such as Verus Technology Corporation, Tekever, and Israel Aerospace Industries that are developing and selling such systems around the world for border security and related applications. The IAI system that has been installed in Argentina for border security and includes UAS systems has been described by Major General (Ret) Gadi Shamni, Executive Vice President of Land Systems at IA as follows: ". . ..it is a novel approach to border control and grappling with multiple challenges faced by many countries. IAI's land systems offer a range of strategic and tactical solutions targeting multiple threats. We combine technological expertise, advanced communication solutions and innovative operational concepts into a comprehensive solution (IAI/ELTA, Dec. 20, 2017)."

(b) **Surveillance and Military Operations**

Perhaps the most extensive use of UAS capabilities around the world is for surveillance and military operations. These are primarily sophisticated drone systems that are designed to operate at various altitudes. Northrop Grumman is perhaps the largest manufacturer of systems that can be controlled to obtain imaging of particular areas. This can be simply systems to collect information. Or it can be a system to support logistics for troop operations and alert war fighters of terrain issues or location of hostile forces. Or it can be even be used as a platform from which to fire weapon systems against land or air systems.

(c) **Monitoring of Pollution, Illegal Fishing, Smuggling, and Police Activities, etc.** After border security and military activities, various policing and monitoring operations are now common uses of UAS capabilities. These systems are particularly well suited, of course, for monitoring very wide and vast areas for particular activities. Thus, monitoring of areas for illegal fishing, for smuggling operations, or for spotting polluting activities are very well suited for UAS that are equipped for these activities. Since satellite systems do not typically provide real time imaging and analysis, UAS operations are particularly apt to uses where immediate actionable data can be produced. In some cases, however, information from UAS sensors can be cross indexed with satellite data such as automatic identification systems (AIS). Thus, AIS data from satellites on ship locations could be cross referenced from ships seen from high altitude platforms to spot smugglers or illegal fishing operations.

(d) Remote Sensing
There can from UAS systems be helpful for many purposes related to remote sensing. Again it is possible to combine sensing information from satellites and UAS systems by comparative analysis of older satellite data with real time information from high altitude platforms. Some of the more such applications include smart farming to determining improved data for watering and fertilizing of plants, soil acidity, or basic levels, etc. These systems can also be used for crop and tree disease detection, forest fire spotting, or even analytics of terrain to assist with resource detection for mining or other operations.

6 Stratospheric Tourism

There are some new ways that balloon or dirigible technology can also be employed that may produce innovations that may produce benefits and applications along the lines outlined above. One of the more innovative new concepts is the idea of providing lifts by tourists and even wedding parties to stratospheric altitudes. There are at least two companies that are currently providing this type of offering. These are Worldview and Zero-to-Infinity which are both offering booked high altitude accessions and for much cost less than those now providing so-called space tourism accessions (Zero-to-Infinity, Simplifying Access to Space 2019; Worldview 2019).

The development of these systems has led to some innovations and others will perhaps follow. The dirigible accent systems used by the Worldview enterprise has developed a secondary escape system in the event of a problem with the primary accent system. This is shown in Fig. 7. In the event some of the remote sensing,

Fig. 7 Stratospheric Tourism and new ascent system with escape system. (Graphic Courtesy of Worldview)

surveillance, or monitoring operations should be designed in the future to include human operators these safety features could prove quite important.

7 Dark Sky Stations

Another innovation that is under study and involves new capabilities with balloon or dirigible systems is the so-called dark sky station. This idea is the creation of a balloon buoyed station in the stratospheric that could be used for upper altitude research, Earth observation, and also possibly serve as a platform for ion engine systems to insert nanosats into Earth Orbit. It is an idea that has been championed by such organizations as JP Aerospace (JP Aerospace 2019). This type of capability represents yet one other application for use uses of the Protozone and gives additional urgency to the idea that space traffic management rules and regulations, or at least best practices, include procedures for satellites and space craft in Earth orbit, but would also seek to address who safety systems and traffic controls would apply to the upper stratosphere above commercial air space and military air space (Fig. 8).

8 Space Traffic Management (for Orbital Space and the Protozone)

There are now a growing number of uses that are now occurring or are envisioned for the regions above 20 km and below 160 km that seem to require space traffic management systems to be put in place. This is a matter of both technological

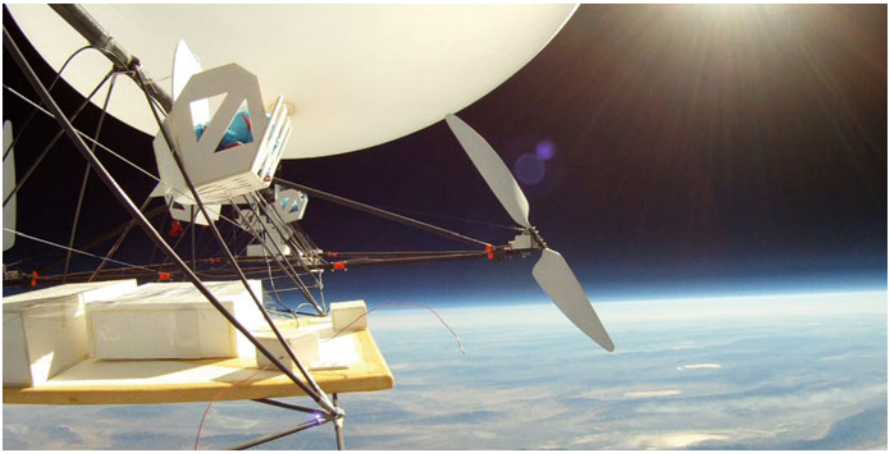


Fig. 8 Dark Sky Station. (Graphic courtesy of JP Aerospace)

capabilities for monitoring of traffic and velocities of things traveling on near space or the protozone and also regulatory controls or at least best practices until actual regulatory systems are put into place. Current uses of this near space region include HAPS or UAS platforms or vehicles, robotic aircraft carriers, dark sky stations, hypersonic space planes for space tourism or in time point to point transport, and a variety of military applications that include surveillance planes, hypersonic missiles, and other types of crafts. To utilize a region of the stratosphere where there are stable platform operating with little or no velocity and hypersonic vehicles operating at say Mach 6 is to invite disaster. Efforts have been undertaken by the UN Office of Outer Space Affairs (OOSA) and by the International Civil Aviation Organization (ICAO), but no specific regulatory processes have been agreed or explicit provisions of international law enacted involving space traffic management for the Protozone. This will be one additional reason to inhibit the development of the use of HAPS or UAS in the upper stratosphere. Thus, most uses will likely be at lower altitudes (i.e., below 20 km) and above national territories, where national aviation regulatory agencies such as the FAA in the USA, EASA in Europe will provide for air safety and traffic regulation.

9 Frequency Allocations and Access to Spectrum

The other key issue that will likely impact the deployment and use of HAPS and UAS is procedures and regulatory process for the allocation of frequencies associated with the control of such systems and the operation of radio signals for telecommunications, networking, broadcasting, platform operational controls, or data relay. For many years, the oversight of the use of radio signals was largely divided between terrestrial, ocean, and air-based regulatory controls and outer space. The addition of the need to control a regulatory process for the Protozone or near space adds yet another level of complexity. Figure 1 at the beginning of the chapter shows that there is a new region of significant size and volume now needs regulatory and safety controls. This need is increasingly being recognized as new applications are developed.

10 Conclusion

The idea of using high altitude platform systems (HAPS) or unmanned aerial systems (UAS) is not a new idea. For nearly 50 years there have been meteorological balloons, aerostats, and high altitude military jets for surveillance purposes. Only in the past decade or two have there been a surge of ideas from space planes and hypersonic transport to dark sky stations and HAPS and UAS for telecommunications and other services (Pelton 2017).

In some ways it may turn out that these stratosphere platforms could provide a competitive option to large scale small satellite constellations, but in many ways it may turn out that these systems might serve as complementary tools to be used in combination with each other. There are a number of economic, technological, operational, and regulatory issues to be addressed and resolved before there will be greatly expanded uses of the so-called Protozone or near space regions about 20 km, but such increased applications now seem quite clear. This chapter sought to provide some historical background, a review of some of the alternative technological approaches, and some brief analysis of regulatory concerns that comes from expanded use of HAPS and UAS for telecommunications, remote sensing, and military applications.

11 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Antennas
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellite Radio Link Fundamentals
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

References

About NICT, https://www.nict.go.jp/en/about/. Last Accessed 9 Dec 2019

Aerostat definition, https://www.thefreedictionary.com/aerostat. Last Accessed 2019

HAPS Mobile Successfully Completes First HAWK30 Solar HAPS Test Flight at NASA Armstrong Flight Test Center, Press release 13 Sept 2019. https://www.suasnews.com/2019/09/hapsmobile-successfully-completes-first-hawk30-solar-haps-test-flight-at-nasa-armstrong-flight-research-center/

IAI/ELTA Completes Delivery of First Secured Border Crossing in Argentina, Press release 20 Dec 2017. https://www.uasvision.com/2017/12/20/iaielta-completes-delivery-of-first-secured-border-crossing-in-argentina/

JP Aerospace, http://jpaerospace.com/. Last Accessed Dec 2019

Mike Miles, Haig floats a high tech trial balloon. Washington Post, April 13, 1998., https://www.washingtonpost.com/archive/business/1998/04/13/haig-floats-a-high-tech-trial-balloon/b7640a27-55ef-40f3-adbc-a9ca79d52897/. Last Accessed 9 Dec 2019

J.N. Pelton, A New Integrated Global Regulatory Regime for Air and Space: The Need for Safety Standards for the “Protozone”, (2017), Manfred Lachs Conference, McGill University Institute of Air and Space Law

J.J. Schlesak, A. Alden, T. Ohno, A Microwave Powered High Altitude Platform. IEEE Spectrum, May 1988. https://ieeexplore.ieee.org/document/22031. Last Accessed 8 Dec 2019

UAVs., https://www.darpa.mil/about-us/timeline/amber-predator-golden-hawk-predator. Last Accessed 9 Dec 2019

Worldview, https://www.worldview.space/. Last Accessed 9 Dec 2019

Zero-to-Infinity, Simplifying Access to Space., http://www.zero2infinity.space/. Last Accessed 9 Dec 2019

Part IV

Launch Systems and Small Satellites

Retrofitting and Redesigning of Conventional Launch Systems for Small Satellites

Joseph N. Pelton and Scott Madry

Contents

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

S. Madry
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_20

Abstract

The small satellite revolution has dominated news in the space industry for the past decade. This change in the space industry has been variously described as the “NewSpace” or “Space 2.0” revolution. Certainly a major aspect of this revolution has come from the popularity that arose from the launch of hundreds of cube satellites as well as other types of micro- and minisatellites. This new way of looking at how to design satellites, miniaturize components, and use off-the-shelf components and even new way to construct satellites on assembly lines and to test their reliability using type approvals has changed the satellite construction industry. Another key part of this Space 2.0 revolution has come in the space launch industry. We have seen the development of new rocket launchers that represent new ways of designing, manufacturing, integrating, and testing of launch vehicles as well. The conventional suppliers of rocket launchers have also reacted by reinventing themselves as well.

This Space 2.0 revolution with regard to launch vehicles has frequently led to innovations as well – both for new entries in the launch industry and for established launch providers. We have seen such changes as use of new materials, new avionics and other subsystems, as well as new construction techniques and testing systems. In some cases there have been efforts to create alternatives to launching from conventional launch facilities such as launching from carrier vehicles or even balloons or air towing systems. This ongoing effort to create new launchers to support the burgeoning market represented by “cubesats”on up to “microsats” and “minisats” for smallsat LEO constellations keeps expanding. In short all launch services providers – new and old – have seen the need for change, innovation, cost reduction, and better performance.

This chapter focuses on how the “conventional suppliers” of launchers have adapted to the changing space industry and have responded as effectively as possible to the challenge represented by new and more entrepreneurial providers of new launch systems.

In short, this chapter focuses on the “conventional” or “established” launch providers and explores some truly important changes that are now afoot. It is clear that the established providers of rocket launchers intend on innovating and responding to the competitive challenges that the “NewSpace” or “Space 2.0” revolution has brought to the launch services industry. Currently there is some “protection” to the “conventional” launch providers offered due to the fact that national launches, particularly those for strategic or defense-related missions, are restricted to national flag industries.

There is now an effort around the world to innovate, to redesign, to reconfigure, and to adapt the space launch process. In some cases, it is a matter of changing existing launch vehicles or upgrading launch system adapters to accommodate the growing need to launch these much smaller craft and to launch many more smallsats at one time. The move is on to reduce costs, accommodate more small satellite launches, and accommodate new types of commercial space systems customers that are new to the world of space and have new types of expectations.

This chapter addresses these creative adaptations, redesigns, or totally new innovations from the established space launcher industry. This creative adaptive process is addressed in three different parts:

(i) The use of large-scale launcher system residual capacity to provide for a piggyback ride for space
(ii) The creation of new launch configurations to create a way to accommodate multiple minisatellites such as smallsats of the 100–500 kg class
(iii) Other innovative launch configurations that range from getting payloads into space via hosted payload systems, multiple smallsat carrier systems that accommodate a number of "smallsats" or even small experiments that fly on board the International Space Station as installed on the NanoRacks experimental station

In addition to the information provided in this chapter and the ones that follow in this section, there is supplemental information on launch systems that can be used for deploying small satellites in Appendix E on Global Launch Systems.

Keywords

Arianespace · Blue Origin · Chinese National Space Agency · Cubesats · ESA · Falcon Launch Vehicle · Indian Polar Satellite Launch Vehicle (PSLV) · International Space Station · JAXA · Long March Launch Vehicle · Microsatellites · Minisatellites · Nanosatellites · NASA · Rocket Labs · Roscosmos · Soyuz · SpaceX · United Launch Alliance · Vega · Virgin Orbit · Vector · Vulcan

1 Introduction

The "smallsat" revolution, as reported in the press, has been about much more than designing and building small satellites. This revolution, which is sometimes known as "NewSpace" or "Space 2.0," is really much broader in scope. It really represents the idea of disruptive technologies that can replace conventional ways of doing things and making things better in every aspect of the aerospace industry.

This can involve inventing new ways of doing things that are either faster; lower in cost; more efficient; easier to design, build, and test for quality and safety; more efficient to operate; or more environmentally sound or sustainable for the future.

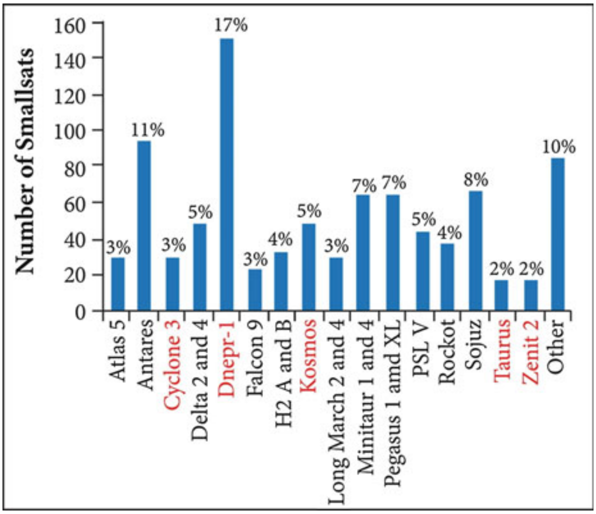
The essence of "disruptive ideas" is to be really creative and not do things that are 2% or 3% better, but 50% or even twice as good as before. It also involved doing things in totally new and "outside the box" ways. The military-industrial complex, the defense department officials, and large-scale aerospace companies have for decades been innovative and managed to incrementally improve technology and designs over time. The conventional approach to improvement in the aerospace industry, however, has been in the form of gradual improvements and incremental change. “NewSpace” or “Space 2.0” has a drive to breakthrough innovation that is disruptive to the status quo approach of doing things.

The thought process that came from Google, Amazon.com, Microsoft, and start-ups from the world of Silicon Valley and other innovators around the world that have come from the computer industry has sought radical change. There has been a push for truly disruptive ways to change the way things are done. The entrepreneurs from the world of computers, IT systems, artificial intelligence, and robotics thought not about small improvements but big changes. The “NewSpace” innovators have thought up ways to shrink satellites by a factor of ten to even a hundred times. They have sought to make them in new and more creative ways, using different materials and production processes. And once this process started, it certainly did not stop there.

Suddenly there was a new breed of thinkers who were not only seeking to improve how satellites were designed and built, but some of the “NewSpace” innovators were examining new and more efficient ways to launch satellites. They even questioned whether rockets had to be launched from expensive ground-based launch facilities. The precise start of “NewSpace” revolution is hard to fix in time, but the establishment of the Ansari X-Prize to create commercially a private space plane was a key milestone in the move to find new, better, faster, and lower-cost ways to launch things into space.

This challenge has now become abundantly clear to the conventional launch industry and to the space agencies of the world. Yet even here the record of small satellite launches up until 2014 has been dominated by conventional launches and proven systems as shown in Fig. 1. It is only in the last 5 years that new launch options have begun to appear. Even in cases where national policy restricts launches to national carriers, changes have occurred. New entrants such as SpaceX, Blue Origin, and others are making inroads.

Fig. 1 The launch record for small satellite through 2014. (Graphic courtesy of the global commons)



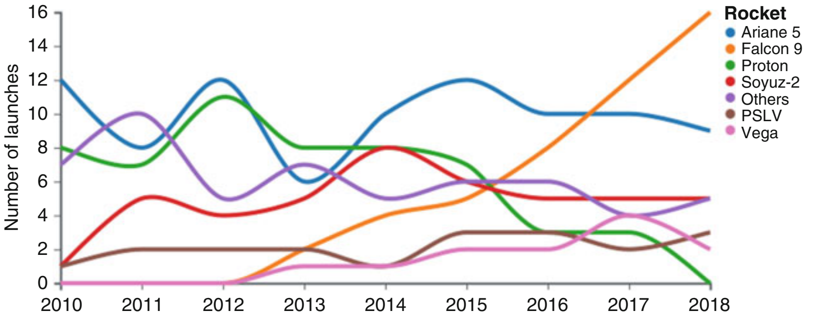
Thus space agencies such as NASA, ESA, JAXA, Roscosmos, the Chinese National Space Agency, and ISRO, among others, recognized that the world of rocket launchers was changing.Likewise, the large aerospace companies such as Arianespace; the Airbus Group; Lockheed Martin; Boeing; the United Launch Alliance (ULA); Northrop Grumman; BAE Systems; Khrunichev, the Russian Proton rocket manufacturer; and the Chinese Long March company have all recognized that the twenty-first century market for rocket launches has significantly changed and is not in their favor. There will be a significant shift from the launch of large spacecraft into GEO into a much more diversified need of many different types of satellites into many different orbits. There will be a significant increase in the launch of various types of small satellites ranging from femtosats, to picosats, to nanosats, to microsats, and to minisats. Meeting such diverse demand for "smallsats," which ranges from under 100 g up to 500 kg, will be difficult. This will be especially true if the demand is to support a very high volume of such small satellite launches. Further, this will be additionally complicated if a resupply of small satellite constellations is required on the order of every 7 years or so. Change, adaptation, and new rocket development will be the name of the game. New concerns with the sustainability of space, orbital debris removal, and cleaner fuels with less particulates will only complicate this adaptation process.

Of the existing set of commercial launchers, only the Indian Space Research Organisation (ISRO) with its Polar Satellite Launch Vehicle (PSLV) seemed to be well positioned to respond to the competition posed by newer and more agile and perhaps significantly more cost-efficient commercial launch providers.

There have been many adjustments in the past decade to accommodate the needs of the changing launch market by the traditional providers of launch services. This has included adjustments in pricing, revamping of launch vehicles and new launch rockets designs, and reconfiguration of the launch and deployment options available to those seeking to launch small satellites.

2 The Changing Launch Market

According to the US FAA Office of Commercial Space Transportation, the global space economy as of the end of 2018 was $245 billion, but global launch services represented only $5.5 billion or only about 2% of the total. It is perhaps even more important to stress that only about one-third of this amount is globally competitive since there are national guidelines and strategic concerns that restrict launch selection to national launch providers. Thus this part of the global space economy is less than 1% of the total, yet this part of the international space launch marketis increasingly subject to competition (FAA-AST). The last decade of this competitive profile is shown in Fig. 1. This shows that the Falcon 9 has ascended (not a pun), while Ariane 5 has lost its predominant role, and the Russian Proton has been the largest loser in this competitive process (Space Launch Market Competition) (See Fig. 2).



Rocket	Origin	First launch	2010	2011	2012	2013	2014	2015	2016	*2017*	*2018*
Vega [c]	Europe	2012	N/A	N/A	0[c]	1	1	2	2	*4*	*2*
Soyuz-2	Russia	2006	1	5	4	5	8	6	5	*5*	*5*
PSLV [b]	India	2007[b]	1	2	2	2	1	3	3	*2*	*3*
Proton-M	Russia	2001	8	7	11	8	8	7	3	*3*	*0[a]*
Others[d]	-	-	7	10	5	7	5	6	6	*4*	*5*
Falcon 9	USA	2010	0	0	0	2	4	5	8	*12*	*16*
Ariane 5	Europe	1996	12	8	12	6	10	12	10	*10*	*9*
Total Market	29	32	34	31	37	41	37	40	41	*40*	*40*

(a) Two commercial launches planned in 2018, Eutelsat and Yamal, were pushed to 2019
(b) First launch of the competitive PSLV-CA and PSLV-XL versions (2007 and 2008)
(c) Maiden flight of Vega was non-commercial
(d) Atlas + Delta excluding U.S. military missions and GPS Related Launches, Dnepr, Rokot, Zenit

Fig. 2 The changing scene of launch providers in the global competitive market (Ibid., Space Launch Market Competition). (Graphic courtesy of the FAA-AST)

The result is a rather chaotic market. The "conventional" launch providers are seeking to adjust, reengineer, and re-envision their launch systems to maintain their dominant positions in the market. This is for at least two primary reasons. The first reason is the new competition from the new launch providers such as SpaceX and their Falcon 9 and Big Falcon Rocket, Blue Horizon, New Glenn, Rocket Labs, LauncherOne, and others are bringing to the competitive launch market. These new entries are forcing a move to provide more cost-effective and responsive launch options. The second reason is that the market is changing and there is a new and expanding market for both quite small satellites (i.e., cubesats, nanosats, and micro-sats) up to 50 kg in size and minisats in the 50–500 kg class. Both of these markets are currently projected to rise sharply in the future.

2.1 Global Competitive Commercial Launcher Market

The market study conducted by SpaceWorks has charted the growth of the smallest satellites in the 1–50 kg range, and they have found a healthy growth in this type of “smallsat,” but they are projecting a rise that will continue to expand and reach perhaps 700 a year in volume by 2024, if the higher end of the projections are correct. This would mean that some 2,600 such nanosats and microsats would be launched between 2019 and 2024 (SpaceWorks) (See Fig. 3).

Studies by Northern Sky Research of minisatellites up to 500 kg in size show a similar rapid increase. These projected launches of new constellations range from a few dozens of satellites on the low end up to SpaceX’s ambitious plans to launch many thousands of satellites on the high end. These satellite constellations are to be launched to support the establishment of large-scale constellations for telecommunications, networking, data collection and analysis, automatic identification services (AIS), remote sensing, and even frequency monitoring and strategic information gathering. Other uses include technology demonstration and component testing, military monitoring and other strategic applications, and scientific experimentation not only in Earth orbit but also in deep space. The Northern Sky Research studies indicate that the theoretical total of satellites launched to support new constellations could add up to 20,000; their more cautious projection is that some 7,000 or so will be launched by 2027 and provide a breakdown for the various purposes for which these small satellites will be launched (See Fig. 4).

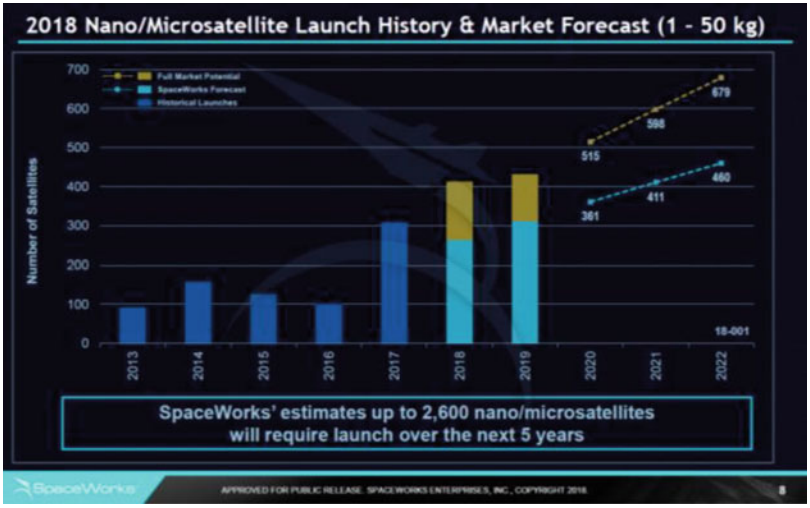


Fig. 3 SpaceWork’s estimates of 2,600 nano-/microsats to be launched by YE 2024. (Graphic courtesy of SpaceWorks)

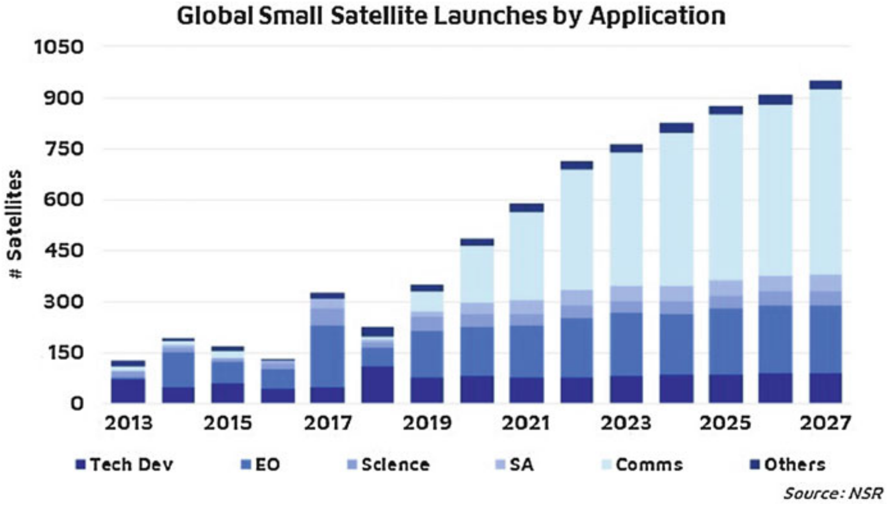


Fig. 4 Northern Sky Research projections of microsat and minisat launches. (Graphic courtesy of Northern Sky Research)

The Northern Sky Research study notes that more than a little amount of caution should be exercised in light of the current "effervescence" in the small satellite market. The satellite market has seen similar enthusiasms in the 1980s when 17 new Ka-band satellites were filed and only 2 were actually built. Also there were multibillion dollar bankruptcies constellations in the late 1990s for the Iridium, Globalstar, Orbcomm, and Teledesic systems. The Northern Sky Research study states their caution in the following manner in their report on small sat markets: "In the past decade, a vast number of new players have entered this space with diverse business models targeting a multitude of applications. Yet the question remains: has the growth in the small satellite market increased beyond sustainable business cases?" (Small Satellite Markets).

Regardless of whether there are 20,000 satellites launched in the next 8 years or 7,000, this is still an enormous number to contemplate. Currently there are only about 1,500 operational satellites in the Earth's orbit. What is sobering is that there are also over 20,000 pieces of space debris larger than the size of a baseball that might potentially collide with all of these new smallsats. Further, almost all of these new satellites are to be deployed in the most congested areas between the altitudes of 400 and 1200 km. Further LEO satellite networks must be resupplied about once in every 7 years. This means we need to consider not only the new deployments but also their replacement satellites as well.

This sharply rising demand to launch "smallsats" in the coming decade ahead very likely means that this demand will be met by both revisions and innovations in conventional deployment systems by conventional launch providers plus new commercial entries into the launch services market as well. The changes that are occurring with regard to the launch of small satellites will be addressed under the four different types of deployment systems that are now evolving within what is called here the conventional commercial launcher companies and instrumentalities.

There is additional information provided in Part 13 on various types of launch vehicles currently available in the global launch vehicle market with regard to conventional launch services providers discussed in this chapter as well as new launch service providers. Also Part 4.3 provides information on new smallsat launch options for cubesats and the new Kaber system that can launch smallsats up to 100 kg in size.

2.1.1 The Use of Large-Scale Launcher System Residual Capacity to Provide for a Piggyback Ride for Space

One of the key strategic issues facing the launch vehicle industry today is what is the best strategy going forward in a rapidly changing market? Is the best way forward to continue to develop large but very cost-efficient launchers that are partially reusable but with "adaptors" that allow a variety of different types and sizes of satellites to be launched? Or should there be a fleet of different types and sizes of launchers that can be more closely fitted to the needs and deadlines for launch for the customers seeking to deploy satellites – especially for large-scale constellations with hundreds or perhaps thousands of small satellites to be launched?

The Indian Space Research Organisation with their PSLV launch in mid-February 2017 deployed a Cartosat-2D Remote Sensing Satellite for India satellites, plus 88 3-unit "cubesats" for Planet Labs, as well as 8 cubesats for SPIRE as well as for other customers. This record-setting launch put some 104 different free-flying satellites into LEO with one PSLV Mark 2 rocket, and it shows that a combination of dispensing and adaptive structures can make larger-scaled rocket systems quite responsive to small satellite operator needs as well as those deploying larger satellites (Foust 2017) (See Fig. 5).

Clearly there are a growing number of "NewSpace" developers of truly small launcher companies such as Virgin Orbit, Rocket Labs, etc. that are tailoring their launchers to deploy small satellites. It seems likely that they can be much more geared to providing customized services and flexibility of schedule while also providing very cost-effective launch services. The question is whether their services will be reliable, responsive, and truly cost-effective in the new launcher market. Further, there are new entries such as SpaceX and Blue Origin that seem to bank on their innovative designs and reusability of first-stage launchers to drive down costs. In short, the best way forward is not certain in today's global launch industry even among established service providers who have been in this business for many decades.

It is these types of questions that are central to the strategic thinking of many of the established rocket launching organizations. The remainder of this section addresses some of the strategies that seem to be emerging from these carriers to the extent that these approaches have become known. These are presented in alphabetic order and not in any order of importance or significance.

Fig. 5 The Indian PSLV Mark 2 launch in February 2017 with a record number of satellites deployed into LEO. (Graphic courtesy of ISRO)

3 Ariane 5 and Ariane 6 by Arianespace

The Ariane 4 and Ariane 5 vehicles were for many years the predominant rocket launching system in the world and provided the majority of commercial launches, particularly for the launch of telecommunications satellites into GEO and for remote sensing satellites into polar orbits. The Ariane vehicles offered many options for smaller satellite piggyback launches with its SPELDA adapter. The high cost of the Ariane 5, currently in the $165 million to $220 million range, is no longer considered cost competitive. The strategy of Arianespace until fairly recently was to develop an Ariane ME launcher that would span the time until the new Ariane 6 could be designed and deployed. More recently it was decided to cancel the development of the Ariane ME and press ahead to develop the solid-fueled Ariane 6 more rapidly. Furthermore, the current focus seems to be to develop the Ariane 6 so that it more or less duplicates the launch capability of the Ariane 5 but to create a new launcher that is significantly less costly to launch and operate so that launch services can be offered at substantially lower cost.

The Ariane 6 will have two versions, the A62 and the A64. The A62 will have two solid boosters and will be capable of launching 5 metric tons to geosynchronous transfer orbit. The larger A64 will have four rocket motors and will be capable of transferring 11 metric tons to geosynchronous transfer orbit. These large boosters will have adapters to accommodate a wide range of satellite sizes and missions (Ariane 6: The Next-Generation Launch Vehicle).

One of the key Ariane 6 design feature is that it has adopted a modular configuration. Thus the Ariane 6 has core stages that are powered by liquid propellant modules. These core stages can be supplemented by either two strap-on solid boosters for the A62 or four strap-on solid boosters for the A64. The other feature that has been used to reduce cost is to utilize what is called a “series production” for its rocket engines. This approach allows a technology-sharing approach for the smaller new Vega C rocket that also uses the P120 engine. This is the same P120 engine that will be used in Ariane 6’s solid strap-on rocket motors. This allows net savings for the Vega C and the Ariane 6 series.

The Ariane User Manual that is currently online indicates that these vehicles can be configured to launch into a variety of orbits that include LEO, highly elliptical orbit (HEO), SSO, MEO, polar orbit, sub GTO, GTO, and escape orbits (Ariane 6 User Manual).

The other key strategic move is that Arianespace has become one of the key investors in the OneWeb constellation, which will perhaps be the first of the large constellations to market. Thus Ariane will be guaranteeing its launch manifest to deploy a large portion of the OneWeb satellites to orbit. The initial OneWeb launches will utilize the Soyuz launcher as arranged by Arianespace. These Soyuz vehicles will utilize the French launch site in Guyana to deploy six of the OrbWeb satellites at a time. Later launches with utilize the Ariane 6 that will deploy a much larger number of the OneWeb satellites with timing and numbers still to be determined.

4 Indian Space Research Organisation (ISRO) Polar Satellite Launch Vehicle (PSLV)

One of the standout space agencies of the world in terms of developing new, reliable, and cost-efficient launching capacity that continues to be highly competitive with regard to “NewSpace” disruptive new launchers is that of the Indian Space Research Organisation (ISRO) and their Polar Satellite Launch Vehicle. This development of a reliable launch vehicle has proceeded steadily by upgrading and enhancing the lift of this vehicle by addition of solid rocket engine boosters and other enhancements.

The first and smallest of the launchers, the PSLV-G, was first launched in September 1993. The PSLV-CA was first launched in April 2007. The PSLV-XL was launched initially in October 2008. Most recently the PSLV-DL was first launched on January 24, 2019. This medium and upper medium launch vehicle represents one of the lowest cost launch options available to the commercial launch market with the price of the PSLV rockets ranging between $21 million and $31 million as of 2019 (Polar Satellite Launch Vehicle).

These PSLV rockets have launched spacecraft to the Moon and to Mars and have also orbited some 50 spacecraft for India out of 43 successful missions with only two launch failures and one partial failure. They have deployed well over three-quarters of their total spacecraft since 1993 for overseas commercial customers. This includes the record launch in February 2017 when they launched an Indian remote sensing satellite and two other Indian small satellites and well over 100 cube satellites that included 88 3-unit cubesats for Planet Labs and 8 3-unit cube satellites for Spire plus some others for overseas customers (India launches).

5 JAXA HII, HIIA, and HIIB

The International Space Station is a project of the United States, Russia, Europe, and Japan and involves a cooperative agreement between these countries space agencies, i.e., NASA, Roscosmos, the European Space Agency (ESA), the Canadian Space Agency (CSA), and JAXA, the Japan Aerospace Exploration Agency. Japan has played a number of key roles in the International Space Station program since the original international agreement was signed in 1988. This participation has included the construction of the Japanese Experimental Module (JEM), known as Kibo, support to the station-keeping of the ISS, via the Japanese Data Relay Test Satellite, and the H Transfer Vehicle (HTV) (Kamigaichi, n.d.).

The most recent launch was the HTV-6 that was launched to the ISS on the HIIB launch vehicle in December 2016 to carry cargo to resupply the ISS. This HTV capsule was the sixth mission to the ISS. This capsule can carry supplies, equipment, and also small satellites (i.e., cubesats and microsatellites) for redeployment via the Japanese Experiment Module, Kibo. With the new agreement to extend the lifetime of the ISS to 2024, Japan has agreed to develop the upgraded HTV-X transfer vehicle that may include a return capsule rather than being incinerated in the Earth's atmosphere (HTV-X Concept (JAXA) 1 (c)) (See Fig. 6).

The continuing problem that applies to Japanese launch vehicles is their high cost. One response that has been made to control costs has been the decision by JAXA and the Japanese government to turn the operation and construction of the HII vehicles over to the Mitsubishi Heavy Industries company and to seek to control the cost of the solid fuel boosters provided by US supplier Northrop Grumman-Orbital ATK (China's Long).

Fig. 6 The conceptual model for the Japanese HTV-X transfer vehicle

6 Long March 1 to Long March 9

Long March vehicles represent a wide range of capabilities from the smallest Long March 1 to the very heavy lift Long March 5, which is currently the largest of the Chinese rocket systems. This vehicle currently serves a largely Chinese market. The many launches associated with Chinese governmental programs are sufficiently large to support a very active domestic space program without major commercial launch services business.

The Chinese top heavy lift launcher, the Long March 5, has a diameter of 5 meters and a height of 57 meters. This vehicle is competitive to the launch capacity of the Ariane 5, Atlas 5, Delta 4, Falcon High Thrust, and Soyuz vehicles.

The July 2017 launch failure of this heavy lift launch vehicle for China has delayed the construction of the Chinese space station and its Chang'e lunar missions. Nevertheless, a redesign of this launch vehicle has been completed. This includes the new liquid oxygen and liquid hydrogen YF-77 engines, two of which power the Long March 5 first stage. This change is believed to be primarily aimed at correcting the turbopump issue that was reported to be the cause of the 2017 failure. China announced early in 2019 via its "Blue Book of China Aerospace Science and Technology Activities" that it would pursue perhaps the world's most active national space program. The ambitious objective was to launch 50 spacecraft through over 30 launches including three Long March 5 missions (Jones).

In addition to the planned ambitious launch agenda for the Long March 5, China has also now developed the Long March 6 and Long March 7 vehicles. These are smaller than the Long March 5. The Long March 6 is optimized to support the launch of 1080 kg to sun-synchronous orbits at an altitude of 700 km that can particularly support remote sensing missions (Archive of Long March 6). The Chinese Long March 7 is designed to lift up to 13,500 kg to low Earth orbit (LEO) (Archives Long March 7 Launch Vehicle).

Finally, the Chinese Academy of Launch Technology has announced plans for the very large capacity super heavy lift Long March 9 rocket as well as less specific plans for the Long March 8 that would be a partially reusable lift system that would recover the first stage and would be designed primarily for launch to sun-synchronous polar orbits.

The new Long March 9 rocket as currently announced would be more or less equivalent in lift capacity to the Saturn V used in the US Apollo program. This rocket would also parallel the lift capacity of the new Space Launch System (SLS) of the United States currently being developed by NASA for planetary missions. The SLS currently has an estimated first launch date around 2021 or 2022. This massive new Chinese launch vehicle is expected to have a weight exceeding 4,000 metric tons and would stand 93 meters high, which is the equivalent of a 30-story building. According to reports from the Chinese Academy of Launch Vehicle Technology (CALT), this rocket will be powered by newly developed 220 ton hydroxyl engines. It will reportedly have a lift capacity of 140 tons to low Earth orbit. With a suitable dispensing system, this type of super heavy lift system could deploy thousands of minisatellites for a low Earth orbit (LEO) constellation with a single launch (Berger).

7 Northrop Grumman Innovation Systems (Formerly Orbital ATK) (Antares, Cygnus Capsule, Minotaur, and Pegasus)

Northrop Grumman, through its subsidiary Northrop Grumman Innovation Systems (formerly Orbital ATK), provides a number of space launch vehicles that are capable of launching small, medium, as well as larger payloads to orbit. The smallest of these launchers is the Pegasus® rocket. This smaller rocket is very cost-efficiently launched from the company's "Stargazer" L-1011 carrier aircraft. The Pegasus has proven to be the industry's small space launch workhorse, having conducted 43 missions from six different locations worldwide since 1990. This launch vehicle launched one of the world's first small satellite constellations, the Orbcomm system for global store-and-forward messaging. Northrop Grumman's Antares space launch vehicle provides medium-class space launch for payloads weighing up to 8,000 kg. Omega™, Northrop Grumman's newest rocket, is currently in development for the US Air Force's Evolved Expendable Launch Vehicle (EELV) program. This is a new class of intermediate- and large-class launch vehicles.

The Minotaur® is a ground-launched rocket. This rocket combines Pegasus upper stages with larger decommissioned Peacekeeper first-stage rocket motors. The Minotaur can be used to boost larger payloads to orbit. Currently active are the Minotaur IV, V, and VI rocket configurations that are available to provide increased lifting capacity for government-sponsored payloads. Minotaur-C is a commercial Minotaur option for NASA and launch nongovernment-sponsored payloads (Space Launch Vehicles). Minotaur II designs also provided stage elements for the Antares launcher development.

The Taurus is yet another option from Northrop Grumman Innovation Systems, but this is being phased out of operation.

8 Rokot

Rokot is a Russian/USSR-developed rocket that derived from a USSR intercontinental ballistic missile that was originally known as the UR-100N (or the S-19 Stiletto). This launcher is marketed by the Eurockot Launch Services GmbH company that is based in Bremen, Germany. This launch vehicle is manufactured at the Khrunichev Space Center. It typically launches a payload of some 1950 kg into 200 km low Earth orbit (LEO).

There were three launches in 2019 of the Rokot (that translates as "Boom" in Russian) from the Plesetsk launch site. These launches were of communications and Earth observation satellites which were larger spacecraft, but the first of these launches of a Gonets-M satellite included piggyback launches of two small satellites that included an amateur radio satellite and an experimental small satellite for Geodesy measurements.

One of the more significant Eurockot launches was the Swarm of three small satellites for the European Space Agency (ESA) in September 2013. This Swarm network is measuring theEarth's magnetic field and the changes to the magnetic poles that may be currently beginning a reversal process. The cost of this launch was approximately $36 million or (27 million euros).

The status of the Rokot launch is currently under redefinition and will likely be redefined for any future missions (Eurokot).

9 Soyuz Launch Vehicle (See also Vega)

The Soyuz rocket system is manufactured by the Progress Rocket Space Center, which was formerly known as TsSKB-Progress. This is a Russian joint-stock company under the jurisdiction of Roscosmos State Corporation responsible for the Russian government space program. It is the developer of the famous Soyuz-FG rocket used for manned space flight, as well as Soyuz-U used for launching unmanned probes. Since 2013, both Soyuz-U and Soyuz-FG are gradually being replaced by the modernized Soyuz-2 launch vehicle (Soyuz) (See Fig. 7).

Soyuz rockets are now the only vehicle being used to ferry crews to and from the International Space Station. In addition, there are now commercial launches being operated from the Arianespace Soyuz CSG launch facilities that have now been

Fig. 7 Soyuz launch vehicle. (Graphic courtesy of the global commons)

Fig. 8 Soyuz with large payload and 3–200 Kg minisats and Vega with 5–200 Kg minisats. (Graphic courtesy of Soyuz)

configured at the Kourou launch center in French Guiana for Soyuz-2 commercial launches. There are also launch facilities at Kourou Launch Center for the new Vega vehicle. Figure 8 shows typical configurations for both Soyuz and Vega launches that include possible ways to provide lift to orbit for various 200 kg small satellites (Soyuz at the Guiana Launch Site).

10 United Launch Alliance (ULA)

United Launch Alliance (ULA) is a US launch provider that largely represents a joint effort of Lockheed Martin and Boeing, but other contractors now contribute to this overall effort. The Boeing-manufactured Delta 4 and Delta 4 Heavy are currently being phased out of service due to high costs. Recently, the marketing of the Atlas 5 has been transferred from Lockheed Martin to (ULA), and that is expected to help lower costs by having a single entity being responsible for marketing and launch arrangements. The main initiative to create a new heavy lift and cost-efficient launch vehicle is the development of the new Vulcan® rocket, with engines developed by Blue Origin, into service with the initial “trial launches” to be offered to commercial customers at reduced rates as it is being flight qualified. This represents a case of “conventional” launch providers, i.e., Lockheed Martin, and new entry companies, i.e., Blue Origin, joining forces (Foust 2018).

One of the objectives of the new Vulcan and Vulcan Centaur is to create a new cost-efficient launch vehicle designed toaccommodate deployment of microsatellites and minisatellites (typically in the 10–500 kg class).

11 Vega Small Launcher

Vega accommodates the launch of small satellites. Specifications related to minisatellites (200–400 kg),microsatellites(50–200 kg),ornanosatellites (<50 kg)have been set forth intheAuxiliary Passengers User's Manual for the Vega. There are many different options now spelled out with regard to auxiliary or "piggyback" launch options. These include the so-called Small Spacecraft Mission System to accommodate cubesats, nanosats, microsats, and minisats. The SSMS includes the PiggyBack HEXA 1, the PiggyBack HEXA 2, as well as other options.The rideshare table for Vega spells out at least six options. Vega C (consolidation) can send up to 2,300 kilograms (5,070 lbs) to low Earth orbit (LEO) – 60% more than Vega. The object of a new Vega Lite that is under study would provide an even smaller launcher. It would be designed to compete with Vector, Virgin Orbit, and Rocket Labs. The Vega C and Vega E configuration is designed to compete with such launch options as Taurus and Taurus XLS, Minotaur IV, Minotaur-C, Rokot, and Soyuz-2-Iv (Elizabeth Howell).

12 Innovative Launch Arrangements from the "Conventional" Launch Industry

The "conventional" satellite industry has sought to respond to the challenge that "NewSpace" launch companies have posed to business models. The high-cost systems such as Delta 4 and Delta 4 Heavy are being phased out, as they cannot be upgraded to make them competitive with SpaceX. Several launch service providers have tried to exploit the cost advantages of proven military missile technologies, such as the Northrop Grumman Innovation Systems, formerly Orbital ATK, has done with the Minotaur and Taurus vehicles.

There have also been efforts to launch from aircraft rather than traditional launch centers, adopting new avionics systems, attempts at more vertical integration, and development of reusable vehicles. There have also been many attempts to create launch configurations and small satellite dispensers. These range from the various configurations discussed above with regard to Ariane, Soyuz, Vega, to the amazing Indian Polar Satellite Launch Vehicle that in February 2017 put over 100 cubesats into LEO orbit. The Vulcan development by ULA even has simply adopted the Blue Origin engines to seek a new competitive pathway forward.

The bottom line is that the small satellite revolution that has demanded new, more creative, and lower-cost launch arrangements has forced the traditional launch companies to make changes by a wide range of innovations in launch design, manufacturing, components, and testing. Indeed, innovation has found ways to use the International Space Station and the Japanese Experiment Module and the Canadarm as innovative ways to deploy cubesats and microsats.

There has also been cooperation and strategic shift involving complicated cooperative arrangements with spacecraft manufacturers. The launch of constellations in LEO or larger satellites in MEO or GEO has now been planned to include hosted payloads so that some of the "new smallsats" are actually piggyback payloads that are riding inside of the satellites to be launched. In other cases, there have been new efforts to develop systems that operate in the stratosphere or what has been called "subspace" or the "protozone" to provide communications, remote sensing, or other services that do not require a launch into orbit at all.

The world of the space launch industry has changed, but not all of the innovations have come from the new entries like SpaceX, Blue Origin, Virgin Orbit, Rocket Labs, Virgin, or the 40 or so start-up companies that are seeking to create new launcher capabilities for small satellites as addressed in a separate chapter in this handbook.

13 Strategic and Risk Elements for the Space Launch Industry

And there is some risk in the space launch industry in becoming overly focused on the immediate challenges of the day. There are creative minds at work to examine new and even breakthrough ideas for the longer-term future. If there are major discontinuities with perhaps on the order of ten thousand small satellites to be launched in a year and then a lull for 7 years, this is clearly a large corporate challenge to face. But there is also the question of what disruptive technologies might come next.

It has been posited that in 50 years, the proposition that putting people and products and cargo on top of a controlled bomb may turn out to be considered odd, foolish, environmentally unsound, or at least un-clever. There are scientists and engineers who are looking into what might be done with rail guns, mass drivers, tether lift systems, and even the so-called space elevators or space funiculars. There are other ideas that involve lighter than air craft and dark sky platforms from which ion engines could fly small satellite systems to orbit.

And the challenge is not just better ways to access orbit, but also there is a need to develop new technologies to get space junk safely down from orbit. The current UN guideline for removal of spacecraft within 25 years of end of life of a satellite seems badly out of step with the idea of multiple mega-constellations of many thousands of satellites with an average lifetime of 7 years. The replenishment of the constellations every 7 years without removing the dead satellites creates untenable situation. The math simply does not work. Clearly, the launch industry of today that is busily innovating to cope with today's challenges must look to longer-term challenges as well.

14 Conclusions

The future of launch vehicle development seems divided into three types of markets. These are (i) launches of large satellites into GEO to support commercial video and global telecommunications and enterprise requirements; (ii) minisatellite constellations with masses typically in the 100–500 kg range for very large constellations in LEO and MEO orbits; and (iii) cube satellite (or nanosat) systems that are typically in the 1–10 kg range.

Exactly how the launch industry might best respond to these different needs is still not clear. The next 5 years, however, should give much definition to what types and range of sizes for launch vehicles will respond to these different needs in terms of launch schedules and types of spacecraft to launch.

The idea of very large high lift launchers that deploy hundreds or thousands of minisatellites might represent one option. The other option could be smaller but highly cost-efficient launchers that could be launched more nimbly. This is the market that many of the new commercial "NewSpace" rockets seemed to be aimed at servicing. "NewSpace" or "Space 2.0" initiatives are forcing the global space launch services industry to change and change quickly. Will the traditional launch providers regroup and win out over the new competition? Or will the disruptive technologies of the newest launch providers that are deploying a wide range of new technologies and systems in a new and powerful ways win out? Or will there be forms of mutual accommodation and thus new ways whereby the new systems will merge with the old? The move by the established United Launch Alliance to integrate the rocket motors being developed by Jeff Bezos' Blue Origin into their new Vulcan rocket seems to be yet another example of the "new" now merging with the "established" launch service providers. Another example might be the One Web System as it emerges from bankruptcy under new financing. This was originally planned to be deployed by a combination of Ariane 5, Soyuz, and LauncherOne vehicle by Virgin Orbit.

15 Cross-References

- ▶ Frequent and Reliable Launch for Small Satellites: Rocket Lab's Electron Launch Vehicle and Photon Spacecraft
- ▶ New Launchers for Small Satellite Systems

References

Archive of Long March 6 Launch Vehicle performance specification, https://archive.is/20150918112832/http://www.spaceflight101.com/long-march-6.html and at: https://en.wikipedia.org/wiki/Long_March_6. Last accessed as of 20 Mar 2019

Archives Long March 7 Launch Vehicle, http://sinodefence.com/cz-7/ and at https://en.wikipedia.org/wiki/Long_March_7. Last accessed 20 Mar 2019

Ariane 6 User Manual, http://www.arianespace.com/wp-content/uploads/2018/04/Mua-6_Issue-1_Revision-0_March-2018.pdf. Last accessed March 2018

Ariane 6: The Next-Generation Launch Vehicle, http://www.arianespace.com/ariane-6/. Last accessed 15 Mar 15 2019

E. Berger, China appears to be accelerating development of a super heavy lift rocket, ArsTechnica.com, September 19, 2019. https://arstechnica.com/science/2018/09/china-appears-to-be-accelerating-development-of-a-super-heavy-lift-rocket/

China's Long March 5 heavy-lift rocket set for crucial July launch, GBTimes, January 30, 2019. https://gbtimes.com/chinas-long-march-5-heavy-lift-rocket-set-for-crucial-july-launch

Elizabeth Howell, Vega: Europe's light launcher, Spaceflight, May 18, 2018. https://www.space.com/40602-vega-rocket.html

Eurokot, https://www.eurockot.com/. Last accessed 28 June 2019

FAA-AST, The annual compendium of commercial space transportation: 2018. https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf. Last accessed on 15 Mar 2019

J. Foust, India sets record with launch of 104 satellites on a single rocket, Space News, February 15, 2017. https://spacenews.com/india-sets-record-with-launch-of-104-satellites-on-a-single-rocket/

J. Foust, ULA to focus more attention on commercial launch market, Space News, March 14, 2018 by Jeff Foust – March 14, 2018. https://spacenews.com/ula-to-focus-more-attention-on-commercial-launch-market/

HTV-X Concept (JAXA) 1 (c), https://www.teslarati.com/spacex-falcon-heavy-eyed-europe-japan-ula-spectacular-delta-heavy-launch/htv-x-concept-jaxa-1c/. Last Accessed 20 March 2019

India launches record 104 satellites in a single mission, BBC.Com News, February 15, 2017. https://www.bbc.com/news/world-asia-india-38977803

A. Jones, China will attempt 30-plus launches in 2019, including crucial Long March 5 missions. January 29, 2019. https://spacenews.com/china-will-attempt-30-plus-launches-in-2019-including-crucial-long-march-5-missions/

S. Kamigaichi, International Cooperation among ISS Partners among ISS Partners and Japan's contribution and activities, June, 2012. http://www.unoosa.org/pdf/pres/copuos2012/tech-18.pdf

Polar Satellite Launch Vehicle, https://www.isro.gov.in/launchers/pslv. Last Accessed 20 Mar 2019

Small Satellite Markets, 5th edn, Northern Sky Research, December 18, 2018. https://www.nsr.com/research/small-satellite-markets-5th-edition/

Soyuz, https://en.wikipedia.org/wiki/Progress_Rocket_Space_Centre. Last accessed 28 June 2019

Soyuz at the Guiana Launch Site, https://en.wikipedia.org/wiki/Soyuz_at_the_Guiana_Space_Centre. Last accessed 28 June 2019

Space Launch Market Competition, https://en.wikipedia.org/wiki/Space_launch_market_competition

Space Launch Vehicles, Northrop Grumman. http://www.northropgrumman.com/Capabilities/SpaceLaunchVehicles/Pages/default.aspx. Last accessed 16 Mar 2019

SpaceWorks announces release of 2018 nano/microsatellite market forecast, January 30, 2018. https://spaceworkseng.com/spaceworks-announces-release-of-2018-nanomicrosatellite-market-forecast/

New Launchers for Small Satellite Systems

Carlos Niederstrasser and Scott Madry

Contents

Abstract

The “smallsat” revolution has created a new and immediate need for additional launch capabilities for a variety of small payloads, ranging from 1-U CubeSats to larger smallsats of various different designs and applications, ranging up to 500 kg or even larger. An important component of this new market is the variety not only of types of satellites and organizations building them but also the new, very large constellations that will be launching hundreds and even many thousands of small satellites that will drive many of the new launcher needs. Part 4.1 has covered the traditional and existing launch capabilities, such as Soyuz, Ariane, Delta, Atlas, the Polar Satellite Launch Vehicle, Long

---

C. Niederstrasser
Northrop Grumman Space Systems, Northrop Grumman Corporation, Dulles, VA, USA
e-mail: Carlos.Niederstrasser@ngc.com

S. Madry (✉)
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_21

March, etc. Other articles in this section also discuss several of the new launch options available and their smallsat capabilities and rideshare options as well. These launch options include (i) the SpaceX Falcon launchers; (ii) Blue Origin and their New Glenn launcher; (iii) the new Vulcan launcher that will be a part of the launch services offered by the United Launch Alliance; and (iv) the Ariane 6. In this chapter, the main objective is to consider the many new entrants into the launch industry in recent years that have specifically targeted this emerging new launch market but, in most cases, have not yet flown. The new launch vehicles that are being proposed and built for small satellite launches and how they will accommodate these many small satellite systems and their launch requirements are discussed.

Keywords

Chinese launchers · CubeSat launches · Electron launch vehicle · Falcon launch vehicle · Launcher markets · Launch vehicle · Minotaur launch vehicle · Pegasus launch vehicle · Smallsat launch arrangements · SpaceX · Taurus launch vehicle · Vector launch vehicle · Conestoga · Convair · Atlas · DARPA Launch Challenge (DLC) · NASA Venture Class Launch Services (VCLS) · Future Launchers Preparatory Programme · Horizon 2020 · Electron · ExSpace · Bloostar · Relativity Space · Additive manufacturing

1 Introduction

The previous chapters have covered the basics of smallsat launchers and the several, existing conventional launchers that provide services for the growing smallsat community. This chapter presents the very large number of new entrants into the smallsat launch market (USU Smallsat Conference website 2019). It is important to remember that the launch market, while the most visible (and loudest) part of space activities, is actually a very small part of the total space business. As shown in Fig. 1, the launch market in 2015 was some US$5.1 billion, and while this is a large number, it is only 1/3 of the satellite manufacturing market, and it is dwarfed by the space services, ground segment, and government operations aspects of the global space business. Launchers get much of the attention and press coverage, but the launch market remains a small part of the overall space market, and even with the several new entrants, this will not substantially change in the near term.

Although there are many kinds and definitions of smallsats, those developing the launchers and payloads must meet all of the regulatory, liability, telecommunications, and frequency requirements imposed on those who launch rockets and satellites into orbit. The regulatory aspect of both launching and operating satellites cannot be underestimated, even as the global space regulatory context changes. Launchers and satellites, no matter how small, must still be properly licensed by their national authorities.

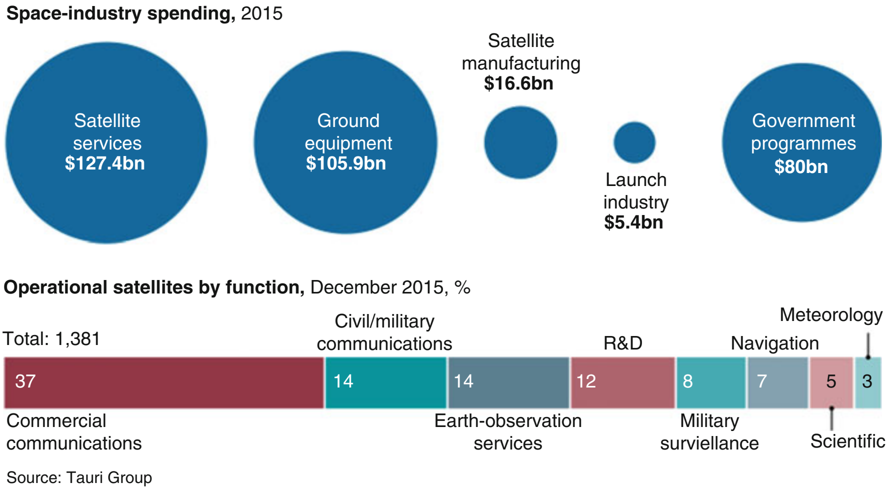


Fig. 1 Space industry spending as of 2015. (Image courtesy: The Tauri Group)

2 New Launch Options for Smallsats

Launching a CubeSat or smallsat into orbit is the single largest item of expenditure for most CubeSat projects. Getting even small amounts of mass into Earth orbit requires a very large amount of energy, and today that is provided by chemical rockets that are very costly and also quite dangerous.

There has been explosive growth in the smallsat market, and this has shown a 23% increase between 2009 and 2018; this trend is seen to continue to grow through 2024 (Space News 2019). Some 322 satellites were placed into orbit in 2018, in a total of 44 individual launches. It is interesting to note that smallsats are made up 69% of these launches, as measured by satellites, while accounting for only 4% of the total launch mass. This is a major change in progress and one that likely will accelerate in the near future. The current generation of space launch vehicles was sized for payloads of several thousand kilograms, as the world moves into an era of ever smaller and smaller satellites.

2.1 The Second Small Launcher Revolution

There are approximately 80 new small satellite constellations that are being proposed for a variety of commercial services in the near future, consisting of thousands of new satellites. These include telecom/data/Internet of Things (IoT) systems, as well as remote sensing and data analytics systems. All of these, as well as the hundreds of other “Silicon Valley” space startups, CubeSat kits, and student projects, will require launch services.

The growth in the smallsat market, combined with the success of SpaceX, has led to a dramatic increase in the number of launch vehicles being developed to service this particular niche. This new trend has been further encouraged by several new government programs such as the European Union's Horizon 2020 and the American DARPA Launch Challenge.

Small launch vehicles are not new. In fact, many of today's heavy launch vehicles – Atlas V, Delta IV, Falcon 9, and Ariane 5 – all trace their origins to smaller rockets. Today's Atlas V has a direct heritage going back to the Convair Atlas SM-65 ICBM designed in the 1950s. This was the first US operational ICBM missile and the origin of the Atlas rocket family. It also was used for the first four American orbital astronaut launches in Project Mercury. It was 23.11 m tall, with a 3-m diameter, and carried a payload of some 1680 kg (Fig. 2).

Fig. 2 Atlas 2E Ballistic Missile on display at the San Diego Aerospace Museum, Gillespie Field, El Cajon, California. (Graphic courtesy of US Air Force)

Before embarking on larger launch vehicles, SpaceX and Arianespace both cut their teeth on smaller launchers like the Falcon 1 and Ariane 1, respectively. As the need for payload performance grew, largely driven by the increasing size and complexity of commercial, GEO telecommunications satellites, so too did size and capability of the rockets. Both governments and private industry found it more economic to field ever-larger launch systems, and satellite developers matched these capabilities with ever-larger designs in a positive feedback loop that led to mighty launchers such as the Ariane 5.

Of the small launchers in the early days of the Space Age, only the Scout has retained its small size. Even as the Scout became obsolete due to aging technology, a small niche remained for vehicles able to lift less than 1000 kg to LEO. In 1995, the Conestoga became the first fully commercially developed rocket to ever be launched; unfortunately its first and only flight resulted in a launch failure (Fig. 3).

Fig. 3 The Conestoga, the first truly commercial space launcher. (Graphic courtesy of Conestoga)

In 1990, Orbital Sciences Corporation deployed the Pegasus rocket, which used a Lockheed L-1011 wide-body airliner as the first stage, getting the Pegasus up to about 10,000 m altitude. Also developed largely on a commercial basis, Pegasus has gone on to become the workhorse of the small launch vehicle market, with 44 flights flown to date. Subsequently Pegasus was joined by Taurus, Athena, and the Minotaur I, which utilizes excess government military ICBM motors, recycled for commercial launch services (see Fig. 4).

The perceived need for small launchers in the 1980s and 1990s, which resulted in the development of Conestoga and Pegasus, was largely driven by new, large LEO telecommunications constellations such as ORBCOMM and Iridium. Ultimately the demand from these constellations and larger constellations like Teledesic failed to materialize, due to a variety of economic and regulatory factors. The resulting low launch rates, and competition from rideshares on larger vehicles, destined this generation of small launchers to high-priced niche markets. This created a significant barrier to low-cost new entrants. Twenty years later, the growth of CubeSats and new constellations such as Planet, OneWeb, and Starlink is creating a perception of new demand for small rockets. Planet is now considered the world's "largest constellation of Earth-imaging satellites" (Planet 2019) with over 400 satellites launched to date. SpaceX has filed an FFC license request for more than 30,000 satellites, and OneWeb has outlined plans for a constellation of more than 2,000 satellites, as described in other chapters in this volume. Others, including Sony, Amazon, and Apple, have recently made statements regarding creating their own satellite constellations.

Traditional rideshare and secondary payload opportunities, discussed elsewhere in this volume, fundamentally force the payload provider to compromise; the primary customer for these rockets controls all mission parameters such as schedule, destination orbit, safety requirements, etc. The smaller satellites simply "tag along" and accept whatever restrictions are placed on them by the primary customer. This lack of flexibility may be acceptable for small technology demonstrations or CubeSat academic projects, but it is not practical when launching an operational asset or fielding a large constellation.

Fig. 4 The Orbital Sciences L-1011 jet aircraft releases the Pegasus rocket carrying the Space Technology 5 spacecraft with its trio of microsatellites (2006). (Graphics courtesy of Northrop Grumman Innovation)

The expected growth in small satellite launch requirements, and the commercial and very visible success of SpaceX, has led to a new wave of proposed vehicles with payload capacities as small as a single 3-U CubeSat (roughly 5 kg) and as big as 1,000 kg, reaching the lower end of today's medium-class commercial launch vehicles. All of these new entrants are looking for an answer to the same "chicken and egg" question that confounded the small rockets of the 1990s – in order to be successful, large constellations need low costs, but costs can only be kept low if the launch rate is high and remains stable over time.

2.2 New Launch Vehicles

Today, there are over 140 different entities worldwide hoping to develop new small launch vehicles. A full review of these is provided annually, and the trends are all pointing toward a robust market (Niederstrasser 2019). Many of these newcomers are driven by purely commercial goals with visions of hundreds, if not thousands, of satellites launched every year. The coming of age of "New Space," friendly capital markets, and the successes of SpaceX and Planet have led many new entrepreneurs to start down the tortuous path of space rocket development. Others, seeing the appeal of government contracts as agencies like NASA, the DoD, and ESA, also have set their eyes on smaller satellites for their operational launch needs.

In the past 10 years, governments have started to encourage this new trend. The US Department of Defense and NASA are funding a variety of small launch vehicles while looking not just for traditional launch services but also for "launch on-demand" capabilities that are not currently offered. US programs like the new DARPA Launch Challenge (DLC) and NASA Venture Class Launch Services (VCLS) aim to provide enough incentive and guidance to these new fledging companies to bring them from PowerPoint presentations to actual launch systems. The DLC mirrors the prizes of the early aviation age and the successful, modern XPrize, with its goal to launch payloads with just a 14-day notice to a previously unspecified orbit. The successful team stands to win a US$2 million reward on the initial launch and US$10 million reward on the second launch within 2 weeks. To many of the small launch vehicle contenders, DARPA's interest makes a lot of sense. "[DARPA's] seeing the same scenarios or requirements that a lot of us are seeing — the need for more responsive access," said John Garvey, president of launch services at Vector, one of the three companies selected as a finalist in the DLC (Masunga 2018) (see Fig. 3). Showing the inherent risk in this endeavor, however, Vector has since entered into a bankruptcy phase due to financial issues (Fig. 5).

Government interest in small launch vehicles is not limited to the United States. ESA's Future Launchers Preparatory Programme or FLPP (ESA 2018) and studies funded through the European Union's Horizon 2020 (Oving et al. 2017) have both contributed the needed investment in the European market. Individual countries have also taken a new interest in small satellites. For instance, the United Kingdom has been actively exploring potential launch sites for many of the new entrants and

Fig. 5 Infographic describing the DARPA Launch Challenge. (Credit: DARPA)

announced the selection of at least four sites across the country to field both vertically and horizontally launched vehicles (Moore 2018).

Another new player in the area of small launch vehicles is China. China has had a robust government launch industry for many years, and in the past few years, they have increased their investment in small launch vehicles. Efforts in this area are led by government organizations, state-owned enterprises, and also new commercial companies claiming to be the first commercial space companies in the country. This is all part of a bigger space effort in China. The Beijing-based consulting firm Future Aerospace stated that there are over 60 private Chinese aerospace firms now in existence (Space Daily 2018), but the exact commercial nature of these is unclear. Commercial Chinese launch systems face a significant policy and regulatory barrier, as US payloads are prohibited by law from utilizing Chinese launch services, but this limitation does not apply to payloads from most other countries. So even if the US launch companies are not in direct competition with Chinese firms for American payload launches, they will see significant competitive pressure from their new Chinese counterparts, if they can demonstrate initial success.

As of October 2019, there are currently eight operational systems with payload capabilities of less than 1000 kg to LEO that are available on a semicommercial or commercial basis. The oldest and most successful of these is the Pegasus XL, originally fielded by Orbital Sciences Corporation, now part of Northrop Grumman. Five of these eight operational systems are Chinese, and although it is expected that they will be offered commercially outside of China, this has not yet happened. The newest non-Chinese rocket in this category is the Electron, developed by Rocket Lab, based in the United States and New Zealand. After a failure on its maiden flight in 2017, Electron has launched eight times with 100% success rate, and has recently added a second launch pad in Virginia, and is adding another second pad to its

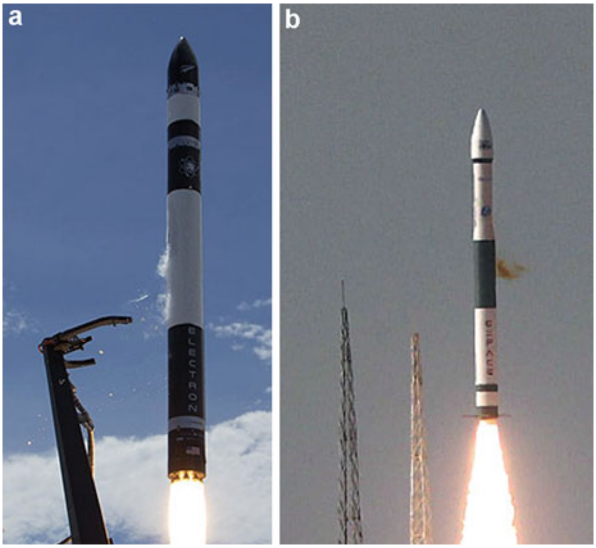


Fig. 6 (**a**) US/New Zealand Electron vehicle from Rocket Lab. (Graphic courtesy of Rocket Labs). (**b**) Chinese Kuaizhou-1A from ExSpace is one of the newest proven small launch vehicles in the world. (Graphic courtesy of ExSpace)

Table 1 The eight current small launch systems in operation. (Credit: Niederstrasser 2019)

Organization	Vehicle name	Country	First launch
Northrop Grumman	Pegasus XL	USA	5-Apr-1990
Northrop Grumman	Minotaur I	USA	27-Jan-2000
China Aerospace Science and Technology Corporation	Chang Zheng 11	China	25-Sept-2015
ExPace	Kuaizhou-1A	China	9-Jan-2017
China Aerospace Science and Technology Corporation	Kaituozhe-2	China	3-Mar-2017
Rocket Lab	Electron	USA/New Zealand	21-Jan-2018
iSpace	Hyperbola-1	China	25-July-2019
China Rocket Co., Ltd.	Jielong 1	China	17-Aug-2019

existing launch facility in New Zealand (see Fig. 6). Other systems like the Israeli Shavit or the Iranian Safir also fall roughly into this performance class, but are not listed in Table 1 due to their limited availability outside of their country of origin.

Beyond these operational systems, there are over a hundred of new systems currently under development worldwide. Some are little more than paper and PowerPoint designs by three people in a garage, while others are well-established startups or subsidiaries of multinational corporations with hundreds of millions of dollars in funding. All of these share the aim to dramatically increase the ease of access to space for small satellites. As has been previously stated, this is a trend that is not limited to the United States. While the United States continues to have the largest share of new vehicles under development, China has a significant number of new entrants as well. Spain and the United Kingdom are also well represented due to significant recent investments in the industry made by their respective governments. Other efforts come from countries as varied as Brazil, India, Singapore, South Korea, Turkey, and many others.

3 Design Developments

With so many vehicles under development, it is not surprising that each new entrant is trying to find a distinguishing characteristic that will allow them to differentiate their products and services from their competitors in what is shaping out to be a very crowded field. One of the key areas of differentiation is the way the rocket is launched. Until 1990, every single space launch rocket ever flown had launched in the same fashion – from a ground-based launch pad somewhere on terra firma. In 1990, Pegasus became the first launch vehicle to be dropped from an airplane, rather than take off from land. At least one commercial Russian launch has been made from a military submarine, in 1998, when a converted submarine ballistic missile was launched in the Barents Sea carrying two small German satellites, TUBSAT-N and TUBSAT-N1 (Space Today Online 2003). In 1999, a Zenit launcher from Sea Launch became the first to take off from a floating, sea-based platform, taking advantage of a launch at the equator. New vehicles under design are still dominated by traditional, land launch-based concepts, but a significant number of them are being designed to be launched from a sea platform or from an airplane first stage. Other previously untried methods, such as balloons and electromagnetic rail guns, are also under consideration.

For example, the Spanish firm Zero 2 Infinity, founded in 2009, proposes utilizing a stratospheric balloon system to lift the rocket (dubbed rockoon) to approximately 30 km altitude, where it would then ignite its engines and commence its ride to orbit. The expected benefit of such an arrangement derives from the rocket being above most of the Earth's atmosphere at ignition, thereby significantly reducing drag and required fuel. Like other air-launched systems, it also offers the benefit that it can be launched from virtually anywhere with limited ground infrastructure and support. This can result in a fundamentally different vehicle configuration. The Zero 2 Infinity Bloostar uses concentric toroidal stages rather than the traditional cylindrical tandem stages (see Fig. 7). A total of 13 methalox engines are arranged in three stages, with engines dropping off in turn in groups similar to traditional staging. The system is designed to place 140 kg into LEO and 75 kg into sun-synchronous polar orbits for remote sensing applications. The company claims multiple launch customers, but the system has not launched at this time.

Even less traditional systems are also under development. A number of systems impart most of the vehicle's kinetic energy at the start of the launch rather than through a traditional chemical rocket system. SpinLaunch is proposing the use of spinning "kinetic energy-based launch system" that would impart initial acceleration to hypersonic speeds. Other companies are looking at electromagnetic rail guns or gas guns to provide the initial acceleration. None of these systems are near production at this time.

Fig. 7 Zero 2 Infinity Bloostar rocket prototype deployed from a stratospheric balloon. (Credit: Zero 2 Infinity)

Beyond the launch method, new entrants are looking at a variety of new technologies and propellants as they develop their systems. Additive manufacturing, or 3D printing as it is colloquially known, is utilized by a large number of the new launch systems. The use of 3D printing of engines can lead to engines that are simpler with a significantly lower number of moving parts and hence could potentially increase vehicle reliability and reduce cost. Some companies, like Relativity Space, are taking this a step further, as they 3D print the bulk of their entire rocket rather than using traditional rolling and welding techniques for tanks and other pressure vessels. The search for safer, more environmentally friendly, or higher-performing propellants has some companies moving away from the traditional chemical rocket propellants to new combinations like hydrogen peroxide and kerosene, fuming nitrous acid and turpentine, and other undisclosed, proprietary propellant mixes.

4 Performance and Cost

Although this chapter addresses small launch vehicles in general, not all new entrants have the same performance. Over half of the new small launch vehicles have payload capabilities in the 150–500 kg to LEO range, similar to what is available with older systems such as the Pegasus or Minotaur I. Other systems are aiming for larger capability of 1000–1500 kg to LEO, bringing them closer to the domain of “medium lift” rockets such as the now retired Delta II. On the other end of the spectrum, several new vehicles are aiming to service the very small market, with some planning to carry under 10 kg to LEO, sufficient for just one or two CubeSats. This broad range of payload capabilities illustrates the uncertainty in the small launch vehicle market. There are widely differing opinions on which class payloads are likely to experience the most growth and will become niche markets.

This market uncertainty is also evident in the proposed launch costs for the new vehicles. Although common wisdom would seem to dictate that lower cost should be the primary goal for a new system, this is not true for the majority of companies trying to enter the market. The primary advantage of dedicated small launchers (compared to traditional rideshares) is operational flexibility. Some have equated this difference to a bus versus a taxi. In a rideshare (bus) service, the secondary payload provider has a very little say on the exact schedule and ultimate orbital destination, being held captive to requirements of the primary payload. With a dedicated (taxi) services, the small satellite is the primary payload and thus has a significantly greater say on operational requirements such as schedule and orbital destination. As a result the cost per kilogram for most of the new small launch vehicle entrants is in the neighborhood of $20 k/kg to $40 k/kg, which is significantly higher than the cost per kilogram on larger rockets such as the Falcon 9 ($2.7 k/kg for the reusable variant). That is not to say that low cost is not important for many of the new providers. Indeed, some of the newer technologies, such as the additive manufacturing discussed previously, are aimed at reducing vehicle costs.

Future cost containment is also important to continued market success of the vehicle, since many efforts in the past have seen their costs grow significantly after the initial launch. To contain cost growth, it will be important for new vehicles to have high flight rates. Many of the new entrants are aiming at 50 flights per year. As a reference, the most prolific launcher in 2018 was the Falcon 9 with 20 launches. This, once again, points to the “chicken and egg” problem previously referenced. To achieve the desired flight rates, the new vehicles will have to rely on the mega-constellations, and for these constellations to be successful, low launch costs will be key. Unfortunately, for small launch vehicles, mega-constellations often have dozens of satellites in the same orbital plane, which makes multiple-satellite launches on large rockets more efficient. The ability to achieve high flight rates is another large market unknown facing the companies and entrepreneurs entering this field.

5 Funding the Revolution

Even amid all these market uncertainties, capital for new rocket developments has been plentiful. With the noted exception of Pegasus, every successful launch system before the 2010s relied almost exclusively on government funding and the promise of government purchases for its development and initial deployment. Today, national governments continue to be an important source of funding, but they are not the only source. Some of the new entrants are entirely founder-funded, relying on the deep pockets of their founders. Others are funded through venture capital, prizes, and other mechanisms. Somewhere between $1.5 billion and $2.5 billion has been invested in the small launch industry over the past 10 years.

The variety of funding available is as broad as the vehicles themselves. In addition to national governments, local governments such as the Gobierno de Aragon (Spain) and government development funds like the Saudi Industrial Development Fund contribute capital as investors in the company. Beyond government entities, private equity is also playing a significant role in the industry, demonstrating a growing investor confidence in this emerging field. Investors range from specialized seed investors, such as Space Angels, to well-known venture capital firms such as Khosla, Huaxing Growth Capital, and Sequoia Capital. Whether traditional venture capitalists are ready for the higher risks and longer development time cycles of launch vehicles remains to be seen. One of the most advanced efforts, Vector Launch, Inc., filed for bankruptcy after Sequoia Capital declined to provide additional funding to the company (Gladstone 2019).

Beyond government and venture capital, some efforts have been funded by billionaires hoping to leave their mark in the growing space industry. Jeff Bezos (Blue Origin) and Elon Musk (SpaceX) are well known for their investments in large launch systems. Other billionaires such as Microsoft founder Paul Allen and Indian actress Deepika Padukone have invested in smaller launchers. Billionaire investment does not come without its pitfalls however. Stratolaunch, an effort to launch rockets from the world's largest airplane, suffered a significant setback when its primary funder, Paul Allen, passed away. The executor's of Mr. Allen's estate did not have the same interest in space ventures as Mr. Allen, and Stratolaunch was sold to other investors and changed its mission from space launch to hypersonic vehicle testing.

Regardless of the funding source, the need for significant amounts of capital is the one constant among launch system development. Rocket Lab is reported to have raised $288 million over several rounds (Foust 2019). This largely mirrors reported development costs for SpaceX's Falcon 1 or Orbital Sciences' Pegasus. The credibility of an organization that states they can develop a new launch system for significantly less than that needs to be assessed carefully. Thus it is not surprising that, even as new players emerge, a number of efforts have already collapsed under the immense technical and financial challenges of developing a new launch system. The aforementioned Vector Launch is only one of several firms that have filed for bankruptcy or ceased operations.

6 Conclusion

The "smallsat" revolution now underway has created a strong requirement for new launch systems that are specifically designed for smaller payloads. There is also an increasing interest in "launch on-demand" services. There is likely to be significant growth in the smallsat launch services market over the next several years. This will be serviced by an interesting mix of new and existing launch providers like SpaceX, Blue Origin, United Launch Alliance, ISRO, Ariane, rideshares on other launchers, deployments from the International Space Station, and new, small launch entrants like the Electron. Indeed there are a very large number of new smallsat entrants, over 140 at this counting, but most of these will not survive to see their first launch. Many more nations are entering this new market, with China taking a large role at present. Small launch vehicles are within the technical capabilities of a wide range of nations, including Brazil, Israel, the United Kingdom, and Iran, among others. There are new and innovative approaches being taken, including launches from balloons and also new fuel types being considered. Additive manufacturing is rapidly maturing and will play an increasingly large role in the construction of both satellites and rockets. The requirement for "launch on-demand" and dedicated smallsat launch options will likely make several new small launch systems successful, but the overall picture remains uncertain and perhaps will not be clear until a decade or so from now.

7 Cross-References

- ▶ Frequent and Reliable Launch for Small Satellites: Rocket Lab's Electron Launch Vehicle and Photon Spacecraft
- ▶ Retrofitting and Redesigning of Conventional Launch Systems for Small Satellites
- ▶ The Evolution of Medium/Heavy-Lift and Reusable Launch Vehicles and Its Implications for Smallsat Access to Space

References

ESA, ESA explores microlaunchers for small satellites. ESA, 8 February 2018 (2018), http://www.esa.int/Our_Activities/Space_Transportation/ESA_explores_microlaunchers_for_small_satellites

J. Foust, Rocket Lab raises an additional $140 million. Space News, 15 November 2018 (2019)

A. Gladstone, Space-Tech Startup Vector Launch files for bankruptcy. Wall Street Journal, 16 December 2019 (2019), https://www.wsj.com/articles/space-tech-startup-vector-launch-files-for-bankruptcy-11576517002

S. Masunga, The Defense Department wants small rockets that can launch satellites at a moment's notice. LA Times, 24 May 2018 (2018)

T. Moore, Four spaceports to be built across UK. Sky News, 16 July 2018 (2018), Web: http://news.sky.com

C. Niederstrasser (2019) Small Launch Vehicles – A 2019 State of the Industry Survey. In: Proceedings of the AIAA/USU Conference on Small Satellites, http://digitalcommons.usu.edu/smallsat/year/all'year'/#/

B. Oving, et al., Small innovative launcher for Europe: achievement of the H2020 project SMILE, in *Proceedings of the 7th European conference for aeronautics and space sciences*, 2017

Planet Our Approach (2019), https://www.planet.com/company/approach/. Accessed 09 Oct 2018

Space Daily, Staff writers. "Sunrise for China's commercial space industry". Space Daily, 14 May 2018 (2018), http://www.spacedaily.com

Space News, Analysis | Are smallsats entering the maturity stage? By Maxime Puteaux and Alexandre Najjar (2019), https://spacenews.com/analysis-are-smallsats-entering-the-maturity-stage/

Space Today Online (2003), http://www.spacetoday.org/Rockets/Plowshares/Submarine.html. Accessed 22 Dec 2019

USU Smallsat Conference Proceedings (2019), https://digitalcommons.usu.edu/smallsat/

Smallsat Rideshares and Launch Aggregators

Scott Madry

Contents

Abstract

The "smallsat" revolution has created a new and immediate need for additional launch capabilities for a variety of small payloads, ranging from 1U cubesats to larger smallsats of various different designs and applications, ranging up to 500 kg, and indeed some definitions even include satellites up to 1,000 kg as "small." An important component of this new market is the wide variety of types of small satellites and the expanding nature of organizations building them. One of the most critical factors in sizing the launch market for small satellites is the rapidly expanding number of the proposed very large constellations. Many of these constellations envision the launching of hundreds and even many thousands of small satellites that will drive the size of launcher market and dominate new launcher offerings. Earlier chapters in this section have covered the traditional and existing launch capabilities and how they might be configured to launch small satellites – particularly for small satellite constellations. Thus, the first chapter in

---

S. Madry (✉)
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_98

this section has considered well-established launchers such as Soyuz, Ariane, Delta, Atlas, the Indian Polar Satellite Launch Vehicle (PSLV), etc. The second chapter in this section covers the new small launch options. In this chapter, the focus is on the several existing and available rideshare launch vehicle options and how they can accommodate small satellite launch needs. It will also consider the new and rapidly evolving business of "smallsat launch aggregators" which provide the service of working with cubesat and other component manufacturer needs for the services of an experienced integrator who can manage all of the regulatory and engineering processes and who will work with the launch provider or even make all of the arrangements for the launch.

Keywords

Ames Nano Launch Adapter System (NLAS) · Cubesat · EELV Secondary Payload Adapter (ESPA) · External Cygnus Deployer (E-NRCSD) · Indian Space Research Organisation (ISRO) · International Space Station (ISS) · ISIS Quadpack Cubesat Deployer · Japan Manned Space Systems Corporation (JAMSS) · JAXA · JEM Small Satellite Orbital Deployer (J-SSOD) · KIBO module · Kosmotras · Launch aggregators · Launch license · Launch market · Microsat · Minisat · NanoRacks · NanoRacks CubeSat Deployer (NRCSD) · Nanosat · NASA · Polar Satellite Launch Vehicle (PSLV) · Rideshare · Safety requirements · Satellite constellation · SHERPA · Smallsat

1 Introduction

The previous chapters have covered the basics of smallsat launchers, the several, existing conventional launchers that provide services for the growing smallsat community, and the many new small launchers in development. In this chapter, the focus is on rideshare options that are currently available and the future expansion of these options as additional launch aggregators emerge. In short, it addresses the new market of smallsat aggregators. It is important to remember that the launch market, while the most visible, and certainly the loudest part of space activities, is actually a very small part of the total space market. As shown in Fig. 1, the launch market is typically on about 2% or so of a $300 billion plus overall space market. It is typically only about a third of the satellite manufacturing market, and it is dwarfed by the space services, ground segment, and government operation aspects of space. Launchers get much of the attention and press coverage, particularly when they fail, but the launch market remains a vital but small part of the space market, and this will not substantially change in the near term as new launcher developments make launchers more cost-efficient and more broadly available for smallsats.

There are many kinds and definitions of smallsats, and the boundaries are shifting as the new industry grows and matures. Smallsats, nanosats, cubesats, microsats, minisats, and more are being produced by more and more entities around the world. The number of proposed large-scale constellations keeps accelerating. All of these

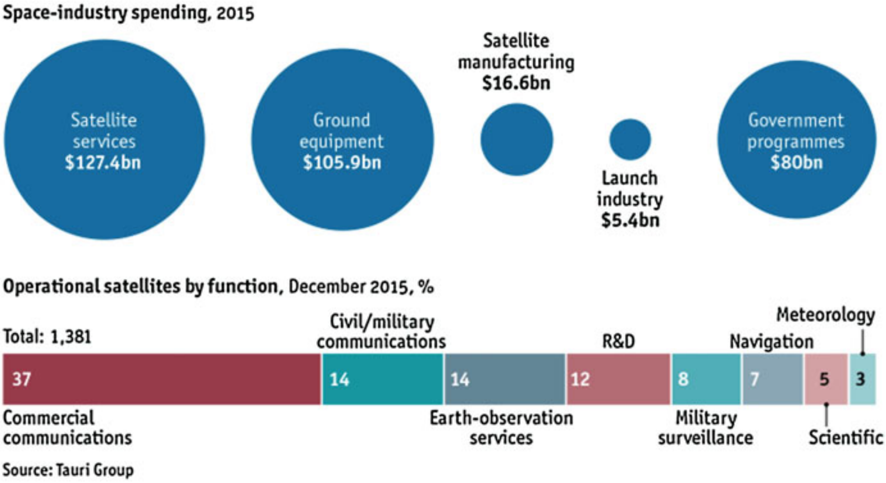


Fig. 1 Overall space industry spending. (Image courtesy Tauri Group/Satellite Industry Association)

ultimately require launchers, and they also must meet all of the regulatory, liability, and telecommunication requirements to be launched into orbit. It is a time of new opportunity but also of some confusion and turmoil.

While we have a very large number of new small launch entrants, there is an equally interesting and active new market consisting of companies who will act as an integrator and provide a middleman service for cubesat and smallsat developers, and these often arrange for smallsat launches. Most university cubesat builders have little to no experience in what is actually required in getting their project launched and have no knowledge of the requirements for integrating a payload into a launch manifest or the regulatory, telecommunications, power, and safety requirements of individual launch providers. This has created the new market of cubesat and smallsat launch aggregators, who provide this service, in addition to arranging the actual launch. The launch can also be the most expensive aspect of a cubesat project, and it requires skills well beyond those needed to build a cubesat at a university or startup. National policy, intellectual property requirements, ITAR restriction, and more place burdens on smallsat developers that can be confusing and smallsat aggregators can provide the needed skills and perspective to navigate this aspect of launch.

The original source of launch services for cubesats and smallsats was piggyback launches and launches provided by decommissioned military ballistic missiles. At first, many cubesats were launched on decommissioned Russian rockets through companies like Eurockot and Kosmotras, and the launch costs were about US$50,000 per single U cube on Kosmotras. Kosmotras was founded back in 1997 to use the Ukrainian Dnepr rocket launch systems, which was based on the SS-18 ICBM rocket that was no longer in military service due to international missile treaties. This vehicle could serve very well as a commercial satellite launch vehicle and did so for many years and at a very low cost. The company was a joint Russian

(90%), Ukraine, and Kazakhstan venture that launched commercial payloads from both the Baikonur Cosmodrome in Kazakhstan and the Yasny facility in Russia. The three-stage system successfully launched 21 commercial missions, including a 2014 flight that launched a total of 33 smallsats, a record at that time. This was the first aggregated smallsat mission, which launched various satellites for commercial and educational customers from 17 countries around the world (https://spaceflightnow.com/2015/02/06/customers-assured-of-dnepr-rockets-nearterm-availability/) (see Fig. 2).

Several successful launches were made, including low-cost smallsat payloads brokered by Kosmotras, but with the deteriorating Russian political and military situation with Ukraine, the venture no longer operates. But it led the way in demonstrating that there is a market for commercial smallsat launchers and for smallsat aggregators.

Eurockot Launch Services, GmbH, was founded in 1995 as a joint venture between the ArianeGroup and the Russian Khrunichev State Research and Production Space Center. It was founded to launch payloads from the Plesetsk Cosmodrome in northern Russia and has provided several commercial launches, starting in 2000, using the Russian Rokot vehicle. Plesetsk is some 800 km north of Moscow and is used primarily for remote sensing payloads launched into

Fig. 2 Dnepr rocket launching the German TanDEM-X satellite from Baikonur. (Image courtesy DLR. https://www.dlr.de/media/en/desktopdefault.aspx/tabid-4986/8423_read-15607/8423_page-2)

polar, Sun-synchronous orbits (SSO). The Rokot is a Russian SS-19 liquid-fueled ICBM, converted to commercial use. There have been 26 successful (out of 28 attempted) launches through 2018, but the venture is now “under redefinition” according to its website and is no longer accepting new missions. These two retired Cold War intercontinental ballistic missile systems, converted to peaceful uses, led the way for others to follow.

2 Cubesat Launches from the International Space Station (ISS)

The ISS has proved to be an excellent point from which to launch cubesats and smallsats, and this has now become a common occurrence. The Japanese Kibo module, because of its external airlock, can be used to launch cubesats, as shown in the images below (see Fig. 3).

The JEM Small Satellite Orbital Deployer (J-SSOD) is a JAXA-developed device that allows cubesats to be loaded on a Japanese HTV-3 ISS replenishment vehicle for deployment from the Kibo airlock. It was the first of such system and was first used in 2012, when 12 cubesats were successfully deployed using this system. It can load six Us at a time per airlock operation. Cubesats are loaded and launched from within the pressurized compartment and can be tested and checked out by the ISS crew before deployment. The Japan Manned Space Systems Corporation (JAMSS) provides smallsat launch services through the ISS and the Japanese H-llA launchers, starting in 2014. They provide all interface coordination, safety requirements and documentation review, logistical services, and technical consulting for cubesats up to microsats up to 50 kg (https://digitalcommons.usu.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=3264&context=smallsat). Over 30 smallsats have been launched so far, dating back a decade to 2009 (Fig. 4).

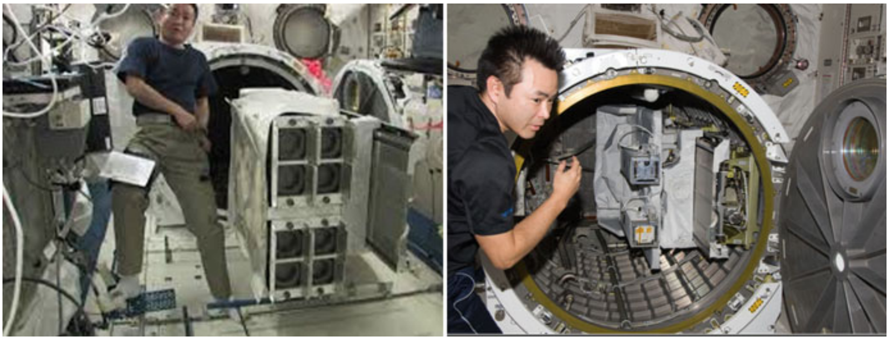


Fig. 3 A rack of eight 3U cubesats in a dispenser, being loaded into the Kibo module airlock for launch from the ISS. (Images courtesy NASA)

Fig. 4 The J-SSOD on the ISS deploying three 1U cubesats. (Images courtesy JAXA)

3 NanoRacks "Concierge to the Stars"

The American company NanoRacks was founded in 2009, and they have developed a variety of commercial capabilities for the ISS. In 2013, after successfully launching a cubesat using the J-SSOD, they requested permission to develop their own commercial cubesat launch capability, and the NanoRacks CubeSat Deployer (NRCSD) was launched to the ISS in January of 2014 on an Orbital Sciences (now Northrop Grumman Innovation) Cygnus vehicle, preloaded with a total of 33 small satellites. This was the first commercial cubesat launch capability on ISS, and it has several advantages, including a larger 48U capacity. It is a self-contained cubesat deployer system that mechanically and electrically isolates cubesats from the ISS, cargo resupply vehicles, and ISS crew, thereby reducing the regulatory and safety complexity and cost of launching from the ISS (http://nanoracks.com/wp-content/uploads/NanoRacks-CubeSat-Deployer-NRCSD-Interface-Definition-Document.pdf). It can be launched from Earth, already loaded with cubesats, by several different vehicles to the ISS, and is then grabbed by the ISS arm and placed in the correct orientation for the remote launch of the satellites by the ISS crew. The smallsats never enter the station's pressurized modules, and so the system is far simpler. NanoRacks acts as the payload integrator and handles all safety

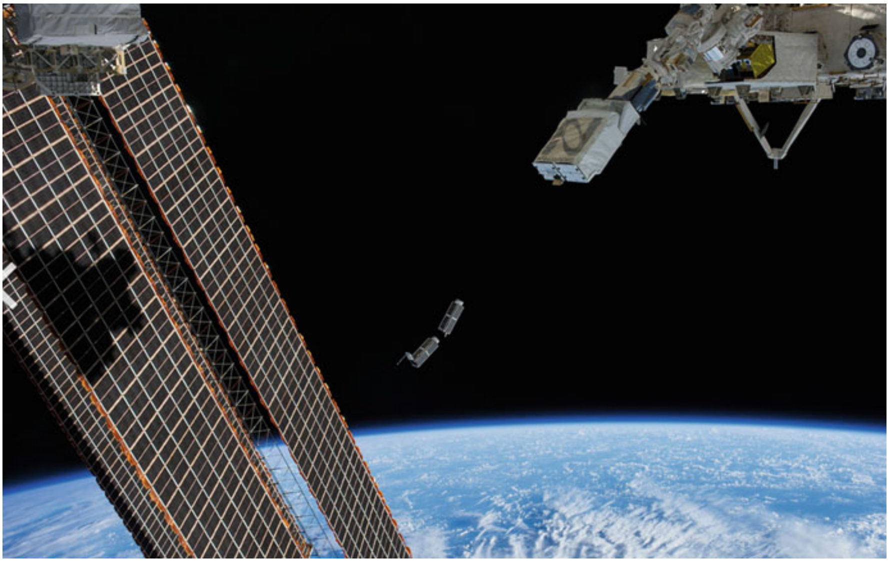


Fig. 5 Two 3U Planet Dove satellites being launched on January 25, 2014, from the ISS by the NanoRacks CubeSat Deployer, attached to the Japanese remote manipulator arm. (Image courtesy NASA)

documentation, regulatory approvals, and NASA requirements for its customers as part of its launch business services. As of this writing, NanoRacks has facilitated over 580 payloads, including many experiments as well as smallsats to the ISS, including the launch of multiple cubesats (Fig. 5).

Cubesats can be launched to the ISS aboard any of the various resupply options and loaded into the Kibo airlock for launch or launched using the NRCSD externally. Of course, this limits the satellites to the ISS orbital inclination and altitude (51.6° and approximately 400 km). Another limitation to using the Kibo airlock is that, because the payloads are taken aboard the living spaces of the ISS, all cubesats must meet the very strict ISS safety and documentation process, which is complex and very detailed, and adds cost and complexity to the cubesat development process. The NanoRacks system avoids this limitation.

NanoRacks is now working with Boeing to develop, launch, and operate a new airlock from the US segment of ISS, providing similar capabilities from the American part of the station specifically for smallsat deployment.

In order to get around the ISS orbital altitude and inclination limitations, NanoRacks has developed the External Cygnus Deployer (E-NRCSD) system. This innovative approach uses an NRCSD, loaded with up to 36U of cubesats, which is launched to ISS on a Cygnus resupply vehicle, and which remains attached to the Cygnus during its stay there. Once the Cygnus is loaded with trash and separates from the ISS, instead of simply deorbiting immediately, it is boosted up to a 500 km orbit, well above the ISS orbit, and the satellites are then deployed

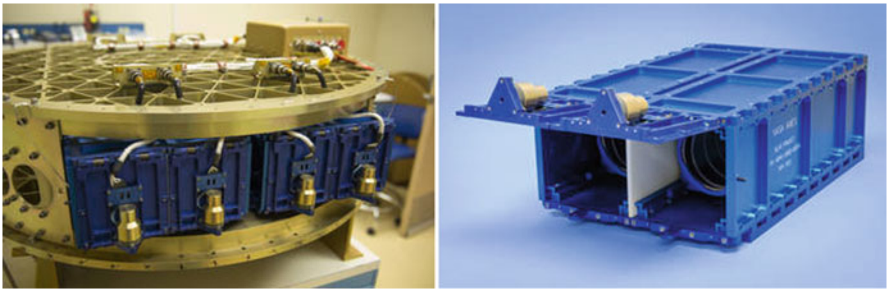


Fig. 6 The NASA Ames NLAS dispenser. (Images courtesy NASA)

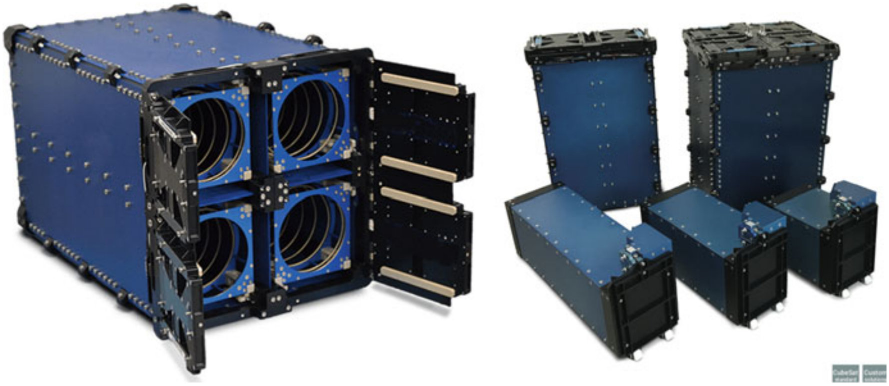


Fig. 7 The ISIS Quadpack CubeSat Deployer in various sizes. (Image courtesy ISIS)

remotely from there. This system has flown three times in 2016 and 2017, successfully launching multiple satellites.

NanoRacks has not stopped at servicing the ISS. They have signed agreements with ISRO of India to provide similar systems to launch into polar, Sun-synchronous orbit from the Indian Polar Satellite Launch Vehicle (PSLV), and they have also signed an agreement with Blue Origin to market microgravity research payload services on the New Shepard suborbital vehicle.

There have been several other cubesat deployment systems developed, including the NASA Ames Nanosatellite Launch Adapter System (NLAS) shown below. The system includes four dispensers for up to 24U, an adapter frame to mate with various launch vehicles, and a sequencer to control the system. It can accommodate from 1U to 6U payloads, and multiple adapters can be mounted on the same vehicle (see Fig. 6).

The Quadpack is an unpowered European 12U cubesat deployment system developed by ISIS in the Netherlands. It is a system develop outside of US-ITAR trade restrictions and so avoids US export limitations. It has flown multiple payloads dating back to 2014 on Falcon 9, Soyuz, Indian PSLV, and Dnepr launch vehicles (see Fig. 7).

3.1 The Payload Orbital Delivery System (PODS)

Space Systems Loral has developed the PODS system to provide frequent and cost-effective access to near GEO for smallsat payloads. This concept uses commercial GEO satellites built by SSL to carry smallsat payloads to near GEO for deployment. It provides power and can accommodate smallsat payloads of up 75 kg.

3.2 Beyond the ISS: Shared Missions

There have been multiple opportunities for smallsat and cubesats to ride as small, parasite, or shared payloads on larger launches with a prime customer. For traditional launch vehicles like Ariane V, Delta, Soyuz, etc., the added mass of a few cubesats is minimal, but there must be an interface system for power, deployment, etc. In the early years, each launch provider developed their own, unique adapter structure, and this was done for the ESA Vega, Ariane V, Delta, and more. What was needed was a standardized adapter system that could be used on multiple vehicles.

3.3 ESPA: The EELV Secondary Payload Adapter

Establishing standard payload interface capabilities has been an important step forward in making commercial, shared launch missions practical. The ESPA adapter was originally developed in the 2000s to launch secondary payloads on US Defense Department space missions from Atlas V and Delta IV Evolved Expendable Launch Vehicles (EELV). The adapter design has become a de facto standard and is now also used for many government and private spacecraft missions as well (https://arc.aiaa.org/doi/abs/10.2514/6.2001-4701) (Fig. 8).

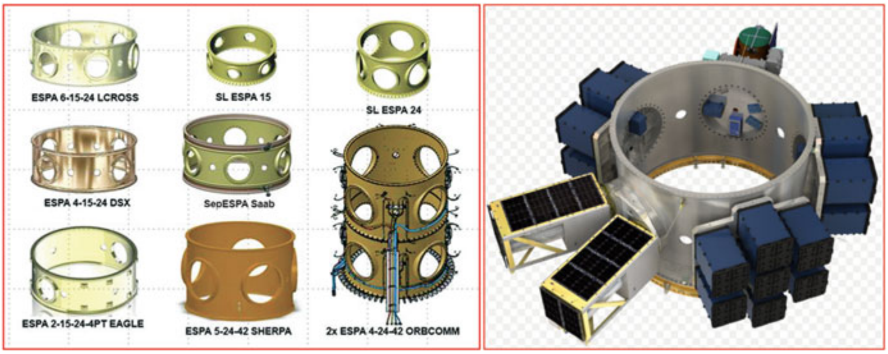


Fig. 8 Multiple ESPA rings were used on a recent launch of the SpaceX Falcon 9 that carried the Orbcomm OG-2 constellation of data networking satellites. (Images courtesy Spaceflight Industries)

3.4 Spaceflight Industries

Seattle, Washington-based Spaceflight Industries was founded in 2010. Its business is to aggregate cubesats and other small, secondary payloads to fly as secondary payloads on various different commercial launchers from around the world. It also operates a geointelligence company, BlackSky, which operates high-resolution remote sensing satellites and provides custom imagery data analytics.

In order to facilitate their rideshare business, Spaceflight has developed its SHERPA system, which provides the structure, power, data, and other required interfaces for multiple satellites. SHERPA is a commercial additional development of the ESPA system but which also contains an optional kick motor to allow for orbital changes and which also provides power for the satellites after separation from the booster rocket. The first SHERPA multi-payload adapter ring was to fly on a test flight aboard a Falcon 9 rocket in 2016, but this was delayed, and it was used to fill a Falcon 9's entire launch capacity on a December 2018 mission. This mission flew a total of 64 individual satellites for 51 customers from 14 countries, all of which flew on a Falcon 9 rocket into a Sun-synchronous orbit. It was the third launch of this Falcon 9. All satellites deployed nominally (see Fig. 9).

There are at least four versions of the SHERPA, either existing or in development, including small, unpowered systems with a small sail to passively decrease the release orbit and a large system with a kick motor designed to put satellites into a Geo Transfer Orbit (GTO). As of this writing, there are no new announced missions for the SHERPA.

European launchers have also kept pace with offering rideshare capabilities, and ESA has the P-POD deployment system for their Soyuz rocket's ASAP-S platform. This can accommodate several small payloads for each mission, and over 50 smallsats have been launched on both the Soyuz and Vega launchers, with more to come. Several of these have been a part of the ESA "Fly Your Satellite" program (https://www.arianespace.com/mission-update/a-trio-of-miniaturized-satellites-are-ready-for-launch-on-arianespaces-next-soyuz-mission/), where students are given the opportunity to build and fly cubesats as a part of their participation in the ESA Academy (Fig. 10).

NASA has a similar program, called the CubeSat Launch Initiative (https://www.nasa.gov/content/about-cubesat-launch-initiative). Since its beginning, some 85 missions have flown on 22 Educational Launch of Nanosatellites (ELaNa) flights on multiple launchers, including from the ISS, with 34 more on the manifest. These have included the first elementary school cubesat and the first built by a tribal college, among others. NASA provides the launch, but does not fund the development or building of the satellites themselves (Figs. 11 and 12).

4 The New SpaceX Rideshare Program

The rapidly evolving world of smallsat launchers like Rocket Lab and smallsat aggregators like Spaceflight Industries were quickly changed in August 2019, when SpaceX Chief Elon Musk announced that SpaceX will now offer monthly "Rideshare"

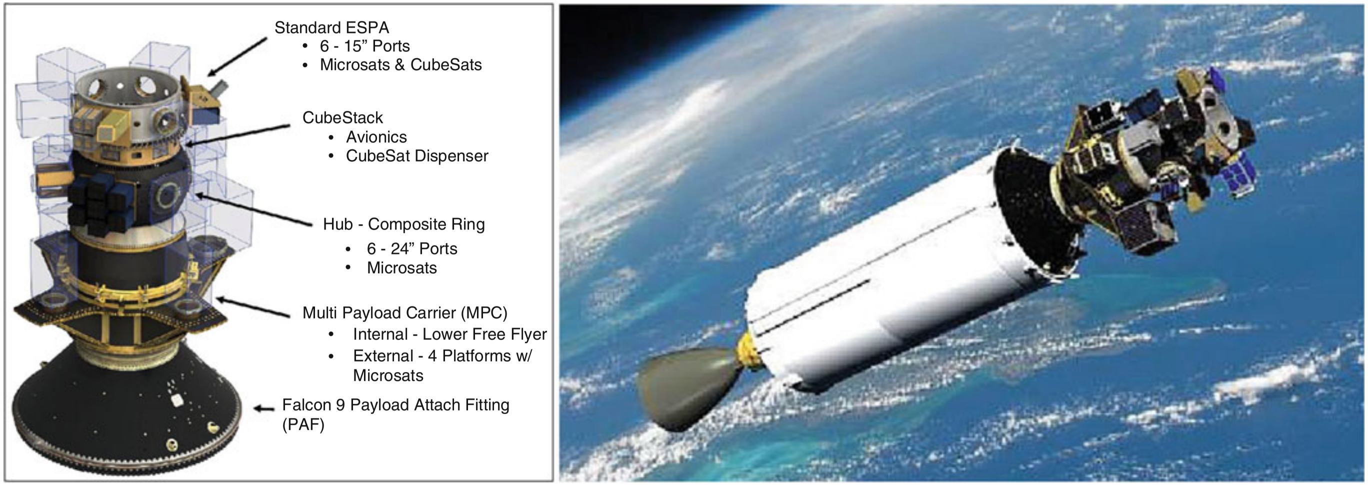


Fig. 9 The Spaceflight SHERPA bus with multiple payloads, attached to the SpaceX Falcon 9 upper stage. (Images courtesy Spaceflight Industries)

Fig. 10 Image of the potential smallsat mass available on the Soyuz and Vega launchers. (Image courtesy Arianespace)

Falcon 9 scheduled smallsat and cubesat launches to Sun-synchronous orbits (https://spacenews.com/spacex-revamps-smallsat-rideshare-program/). Always the disruptor, Musk has decided to take a major share of the smallsat launch market using his existing Falcon 9 launch schedule. He has announced a regularly scheduled, three launches per year offering, from Vandenberg, into polar Sun-synchronous orbit (SSO), that will charge only US$1 million for up to 200 kg, with launches starting in March of 2020. This is less than half of the cost originally stated by SpaceX and is a significant reduction in price over existing operators, at US$5,000 per kg if the full 200 kg is filled or just $10,000 per kg if only half of the 200 kg allocation is filled.

Musk has observed that airlines do not wait to fill an airplane before departing; Musk also announced that the launches would proceed on schedule, even if some customer's payloads were not ready, with those requiring a later launch paying

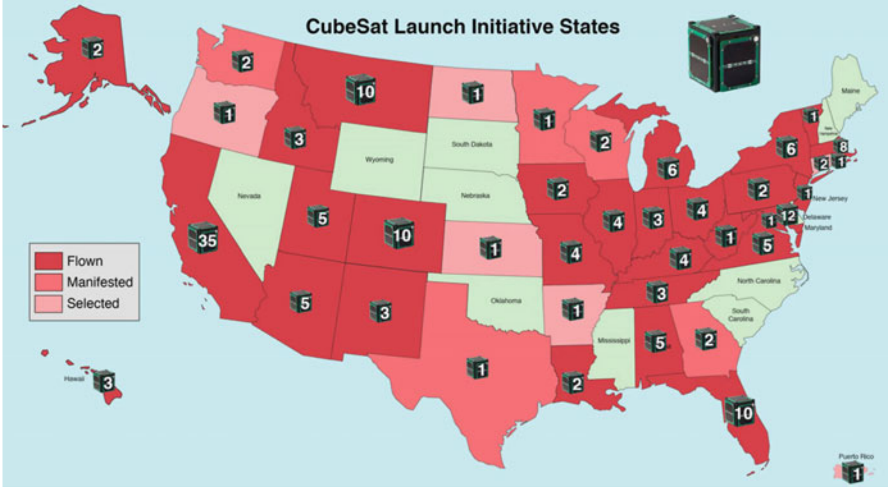


Fig. 11 Number of satellites per state launched by the NASA CubeSat Launch Initiative. (Image courtesy NASA. https://www.nasa.gov/content/about-cubesat-launch-initiative)

a small fee to roll over to the next launch (https://spacenews.com/spacex-says-rideshare-missions-will-launch-on-time-even-if-partly-empty/). The first scheduled launch will be a previously launched Falcon 9 to Sun-synchronous orbit in March of 2020. Launches will proceed on a quarterly basis thereafter. SpaceX will also routinely offer extra space on their many upcoming Starlink LEO launches and on other commercial launches with excess capacity. While SpaceX has said that they intend to continue to work with smallsat aggregators like Spaceflight Industries, this very low-cost and regularly scheduled smallsat launch service is very bad news for the many new, smallsat launch entrants and aggregators. SpaceX will likely command a significant fraction of the smallsat launch market with their proven launchers, regular schedule, and very low cost. They have also recently announced the return of polar Sun-synchronous orbit (SSO) flights out of Cape Canaveral, offering such missions from Florida for the first time in many years.

Arianespace has also entered this market and will offer a Vega smallsat launch in the first quarter of 2020 and also now has longer-term plans for a reusable launcher. Blue Origin likewise is seeking to bring a reusable launcher to market. India is developing a new Small Satellite Launch Vehicle that will be sized for small satellite payloads as well. This will be offering 500 kg to LEO and 300 kg to SSO. This will be a solid rocket design intended to provide very low-cost smallsat services either directly or through aggregators. The problem is that most of the new small launchers, including those by Vector, Virgin, and Rocket Labs, will have prices that are typically in the $30,000–80,000 per kg. With launch price offerings in this range, there may be an ongoing struggle by small satellite launcher organizations as discussed elsewhere in this handbook to be competitive with those who are developing reusable launch systems.

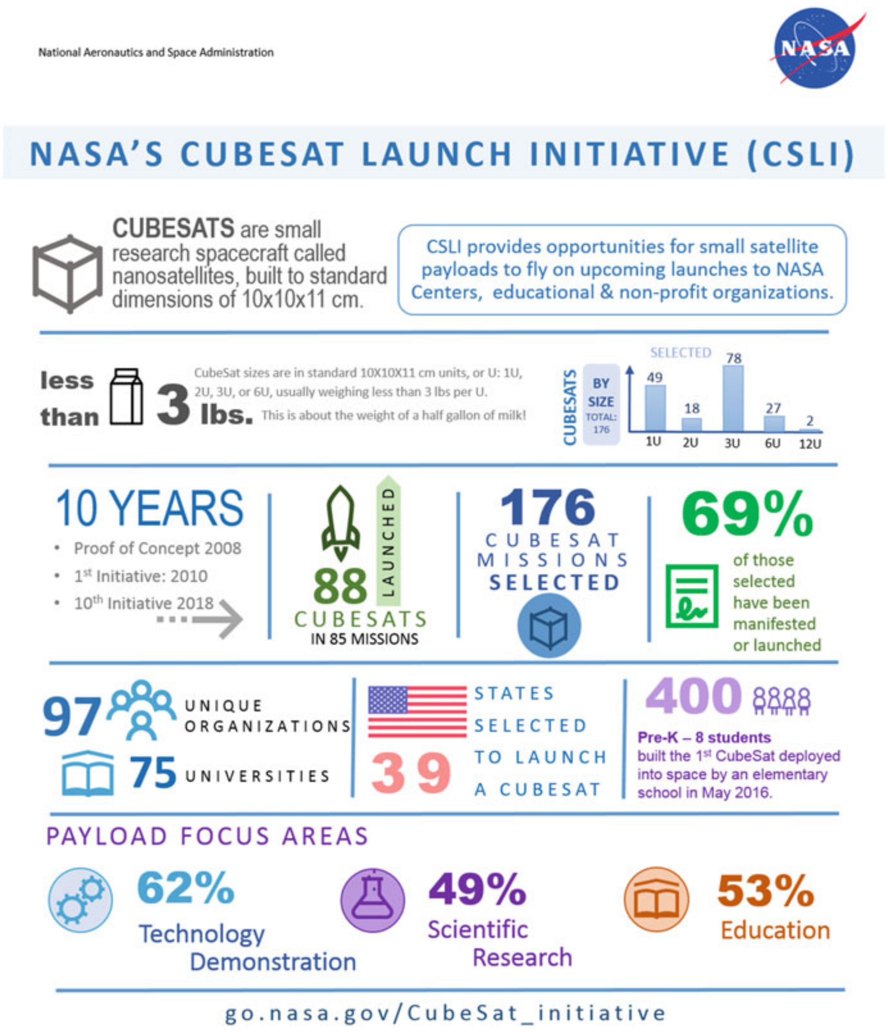


Fig. 12 The NASA CubeSat Launch Initiative. (Image courtesy NASA)

5 Conclusion

There will be explosive growth in the smallsat launch services market over the next several years. This need will be provided by a mix of existing launch providers like SpaceX, Ariane, Rocket Labs, Blue Origin, ISRO, Vector, Virgin, and perhaps many other startups that are seeking to support this market as discussed elsewhere in this handbook. Rideshares on other launchers which are managed by smallsat aggregators and new small launchers are still largely in development. Building a cubesat is quite different from navigating the complex and difficult process of finding a launcher and meeting all of the safety and regulatory requirements. Smallsat aggregators provide a useful service for novice cubesat builders, by providing this expertise, and this market will continue to grow and expand in the future. This is driven by the complex regulatory and documentation requirements for smallsats that most university and startups lack.

Large space agencies like NASA and ESA will continue to make rideshares available as an educational opportunity, but these slots will be limited. The International Space Station will continue to be a launch port for these through existing and new smallsat launch mechanisms. SpaceX has disruptively altered the existing mix by offering regularly scheduled launch opportunities potentially priced as low as US$5,000 per kg. It will be difficult for other providers to match this, with the possible exception of Blue Origin and Ariane, and possibly others, which will also be providing reusable launchers in the future. At this point, one must wait and see how the market continues to develop. No matter who provides these services, there is likely to be a robust and dynamic smallsat aggregator and launch market extending into the future, and even if only a few of the many, new small launch systems in development actually become active, there will be many launch opportunities available.

6 Cross-References

- ▶ Frequent and Reliable Launch for Small Satellites: Rocket Lab's Electron Launch Vehicle and Photon Spacecraft
- ▶ New Launchers for Small Satellite Systems
- ▶ Retrofitting and Redesigning of Conventional Launch Systems for Small Satellites

References

http://nanoracks.com/wp-content/uploads/NanoRacks-CubeSat-Deployer-NRCSD-Interface-Definition-Document.pdf
https://arc.aiaa.org/doi/abs/10.2514/6.2001-4701
https://digitalcommons.usu.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=3264&context=smallsat
https://spaceflightnow.com/2015/02/06/customers-assured-of-dnepr-rockets-nearterm-availability/
https://spacenews.com/spacex-revamps-smallsat-rideshare-program/
https://spacenews.com/spacex-says-rideshare-missions-will-launch-on-time-even-if-partly-empty/
https://www.arianespace.com/mission-update/a-trio-of-miniaturized-satellites-are-ready-for-launch-on-arianespaces-next-soyuz-mission/
https://www.nasa.gov/content/about-cubesat-launch-initiative

Frequent and Reliable Launch for Small Satellites: Rocket Lab's Electron Launch Vehicle and Photon Spacecraft

Morgan Bailey

Contents

Abstract

With frequent orbital launches of the Electron rocket and the successful deployment of customer satellites to orbit, Rocket Lab has established itself as one the key technology innovators of the global small satellite launcher industry. Rocket Lab seeks to address major barriers currently associated with small satellites, including long lead times to launch, reaching of precise orbits, and cost reduction. These are solutions the small satellite industry has been promised for decades, but now they are a reality with Electron and other innovations now being achieved. The Electron launch vehicle is a dedicated small launcher designed to serve the small satellite market with dedicated, high-frequency launch opportunities. Having crossed the threshold into commercial operations, Rocket Lab is well positioned to identify and address the persistent and evolving challenges faced by

---

M. Bailey (✉)
Rocket Lab, Huntington Beach, CA, USA
e-mail: media@rocketlabusa.com; m.bailey@rocketlab.co.nz

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_91

small satellite operators seeking to reach orbit, spanning launch availability, licensing and funding models, and more.

Keywords

Defense Advanced Research Projects Agency · DARPA · Economic launch services · Electron launcher · Federal Aviation Administration (FAA) · Licensing of launches · NASA · On-demand launches · Rocket Lab · Rutherford rocket engine · Small satellite design and manufacture · Small satellite launchers

1 Introduction

Rocket Lab's mission is to make space accessible by delivering a rapid-response orbital launch service for small satellite customers that is both frequent and reliable. Before Rocket Lab began orbital launches in January 2018, commercial and government small satellite operators alike did not have access to timely, cost-effective, and responsive access to orbit. Historically, small satellite operators were forced to choose between infeasibly high costs for a dedicated launch or accept the limitations of flying as a secondary payload on a rideshare launch. The infrequency of launch opportunities also poses a challenge for resiliency in space. All satellites are vulnerable, be it from natural, accidental, or deliberate actions. The ability to deploy new satellites to precise orbits in a matter of hours, not months or years, is critical to government and commercial satellite operators alike. It means uninterrupted weather monitoring, communications, navigation, early warning, and security systems – serving billions of people every day.

Realizing the potential of small satellites, Peter Beck founded Rocket Lab in 2006 to deliver this level of frequent and reliable access to space with the Electron launch vehicle. Following on from orbital launch in January 2018 (see Fig. 1), the Electron launch vehicle has now deployed 47 satellites across seven orbital launches (as at 31 December 2019). Rocket Lab has delivered a 100% mission success rate for small satellite customers.

2 Electron Launch Vehicle Overview

The Electron launch vehicle was designed from the outset for reliability, performance, and a high flight rate. Electron is a two-stage launch vehicle with an additional Kick Stage (see Fig. 2) designed to circularize the orbit of small satellites. Capable of launching payloads of 150 kg (330 lbs) to a nominal 500 km sun-synchronous orbit from a choice of two dedicated Rocket Lab launch sites, Electron provides unrivalled flexibility and launch schedule control for small satellite customers.

Electron's full structure, including propellant tanks, is made from carbon composite for a strong and lightweight flight structure. The all carbon-composite construction of Electron decreases mass by 40%, resulting in enhanced vehicle performance over traditional materials such as aluminum. The payload fairing on Electron is a split clam shell design and includes environmental control for the

Fig. 1 Electron's first orbital launch "Still Testing," 21 January 2018. (Graphic courtesy of Rocket Lab)

payload. The fairing is 2.5 m in length with a 1.2 m diameter and a total mass of 44 kg. It uses a pneumatic locking system and spring separation.

Electron's first stage is powered by nine of Rocket Lab's flagship Rutherford engines, with the second stage powered by a variant of the Rutherford engine which provides improved performance in vacuum conditions (Table 1).

Rocket Lab excels at producing high-performance miniature avionics and flight computer systems. Avionics flight hardware is custom designed by Rocket Lab and includes flight computers and a navigation suite incorporating an initial measurement unit (IMU), GPS receiver, and S band transmitter which transmits telemetry and video to ground operations. Guidance and control algorithms are developed with flexibility in mind, and the combination of flight hardware, software, and guidance and control algorithms is fully tested and validated using Hardware-In-The-Loop (HITL) testing frameworks.

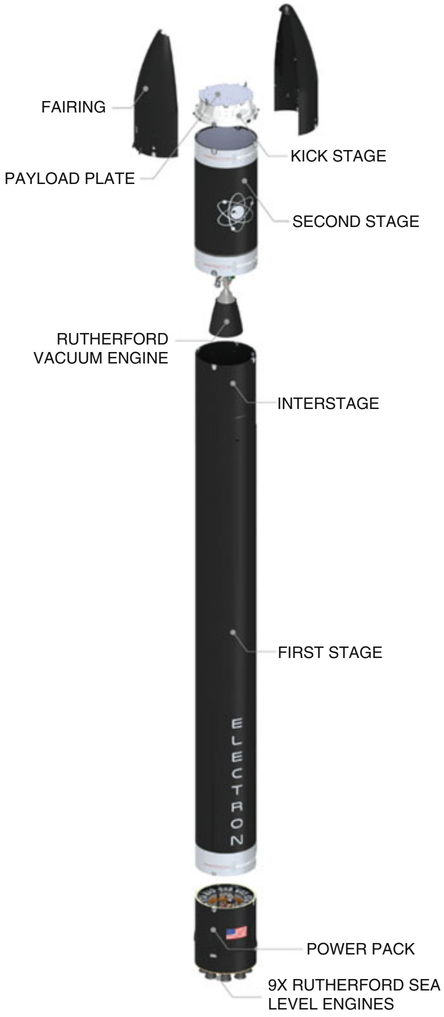
All aspects of the Electron vehicle are designed for ultimate manufacturability to allow for a high launch cadence and to provide an unprecedented frequency of launch opportunities.

3 Rutherford Engine

Rocket Lab's flagship engine, the 4900 lbf Rutherford, is an electric turbo-pumped LOx/RP-1 engine specifically designed for the Electron launch vehicle (see Fig. 3). Rutherford adopts an entirely new electric propulsion cycle, making use of brushless DC electric motors and high-performance lithium polymer batteries to drive its turbo-pumps.

Rutherford is the first oxygen/hydrocarbon engine to use additive manufacturing for all primary components, including the regeneratively cooled thrust chamber, injector pumps, and main propellant valves (see Fig. 4). Additive manufacturing of

Fig. 2 Electron launch vehicle design. (Graphic courtesy of Rocket Lab)



engine components allows for ultimate manufacturability and control. All aspects of the engine are designed, developed, tested, and manufactured in-house at Rocket Lab.

4 The Kick Stage

The small satellite industry is experiencing incredible growth, with more spacecraft operators than ever before demanding frequent access to space. Today large constellations are already taking shape on orbit, with many more planned. With the influx of traffic in low Earth orbit comes the responsibility of small satellite operators

Table 1 Summary of Electron's key technical elements and performance parameters

Specification	Value
Length	17 m
Diameter	1.2 m
Stages	2
Vehicle mass (lift-off)	13,000 kg
Payload mass	150 kg (sun-synchronous orbit)
Payload diameter	1.08 m
Standard orbit	500 km (sun-synchronous orbit)
Propulsion – stage 1	9 × Rutherford engines (LOx/kerosene)
Propulsion – stage 2	1 × Rutherford engine (LOx/kerosene)
Material/structure	Carbon fiber composite
Standard launch site	Mahia, New Zealand

Fig. 3 The Rutherford engine. (Graphic courtesy of Rocket Lab)

and launch providers alike to ensure space remains safe and accessible for the benefit of all on Earth. Rocket Lab plans to launch more frequently than any other launch provider in history, so the company is carefully considering its role in the solution for the sustainable use of space and the reduction of debris in orbit. Traditional launch methods leave large rocket stages on orbit for years and often provide limited control over where a small satellite is deployed, adding unnecessary risk for all satellites.

Rocket Lab's Kick Stage (see Fig. 5) enables a sustainable small satellite launch system and a safer LEO for all. After Electron's second stage reaches an elliptical orbit, the Kick Stage separates (see Fig. 6) and a 3D-printed engine named Curie ignites and circularizes the payload's orbit.

Fig. 4 Electron’s nine first stage Rutherford engines in flight. (Graphic courtesy of Rocket Lab)

Fig. 5 Electron’s Kick Stage during final prelaunch fit-out. (Graphic courtesy of Rocket Lab)

The Kick Stage is capable of delivering multiple payloads to a range of different orbits on the same mission. Thanks to the Curie engine’s ability to reignite in space, the Kick Stage can move to different orbits to deploy multiple satellites to different, precise locations. A cold gas reaction control system supports this further for precision pointing on deployment (see Fig. 7).

Not only does this put satellites in their perfect orbit, but it makes them faster and easier for operators and regulators to identify and catalogue them. Once the payloads are deployed, the Kick Stage can perform a deorbit maneuver to lower its orbit, making it possible to renter the Earth’s atmosphere and burn up in just days, not months or years. This design enables Rocket Lab to launch missions that leave no part of Electron in orbit once payloads are deployed.

Fig. 6 The Kick Stage immediately following separation from Electron's second stage during the "Still Testing" mission in January 2018. (Graphic courtesy of Rocket Lab)

5 Electron Performance Capability

Electron missions are customized to suit customer's individual mission requirements, allowing the flexibility to reach a customer's desired orbit when and where required. Rocket Lab can tailor the vehicle to specific mission requirements including a range of sun-synchronous altitudes in circular or elliptical orbits at inclinations between 39° and 98°.

Electron's performance to various orbits can be seen in Figs. 8 and 9 below.

6 Photon

After establishing itself as the global leader in small satellite launch, Rocket Lab introduced the next evolution of its mission services – the in-house designed and built Photon satellite platform.

Rocket Lab now delivers an all-inclusive spacecraft build and launch service that enables small satellite customers to focus on delivering their service from orbit and generating revenue, rather than building their own satellite hardware. Small satellite customers simply bring their payload or idea and Rocket Lab takes care of the rest, including complete satellite design, build, and launch as a bundled and streamlined experience.

Photon is an advanced and planned evolution of the Rocket Lab Kick Stage (see Fig. 10). Operating a high-powered iteration of the flight-proven 3D-printed Curie propulsion system, Photon can support missions with up to a 5-year on-orbit life span. Equipped with an S-band communication system, a high-fidelity attitude control system, and a robust avionics suite, Photon is the complete spacecraft solution for a range of LEO missions, from constellation development, through to technology demonstrations and hosted payloads. Photon enables small satellite

Fig. 7 13 CubeSats for the NASA ELaNa-19 mission in December 2018 being integrated onto the Kick Stage in preparation for launch. (Graphic courtesy of Rocket Lab)

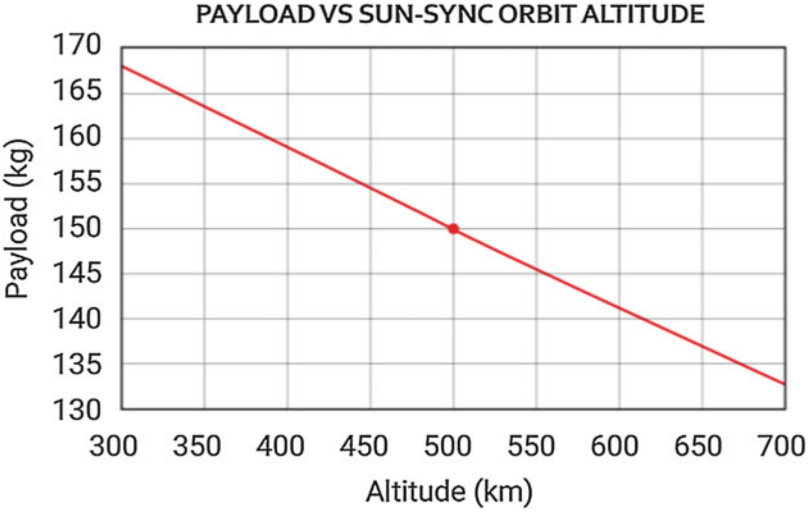


Fig. 8 Performance to circular sun-synchronous orbit

operators to focus on their core purpose – their payload applications – without the needless distraction of developing or procuring a spacecraft.

See Table 2 for full Photon specifications.

7 Launch Sites

Historically, the ability for small satellite operators to access launch frequently and on short notice has been hampered by more than just a lack of launch vehicles. Launch sites are a major contributor to launch queues, slowing the path to orbit for

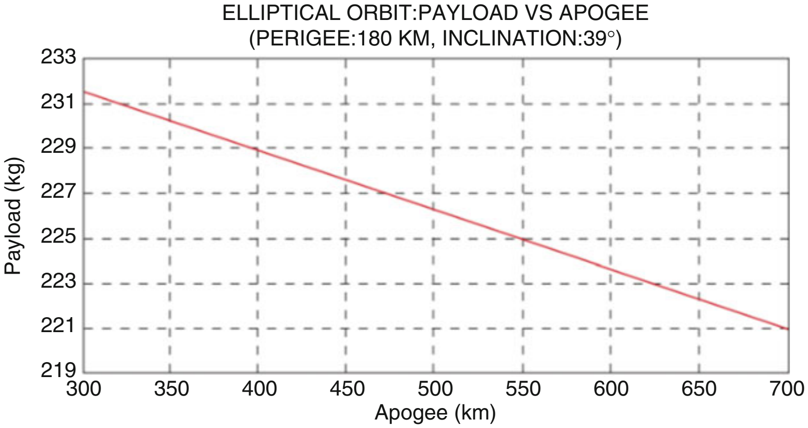


Fig. 9 Performance to a 180 km perigree at 45° inclination elliptical orbit

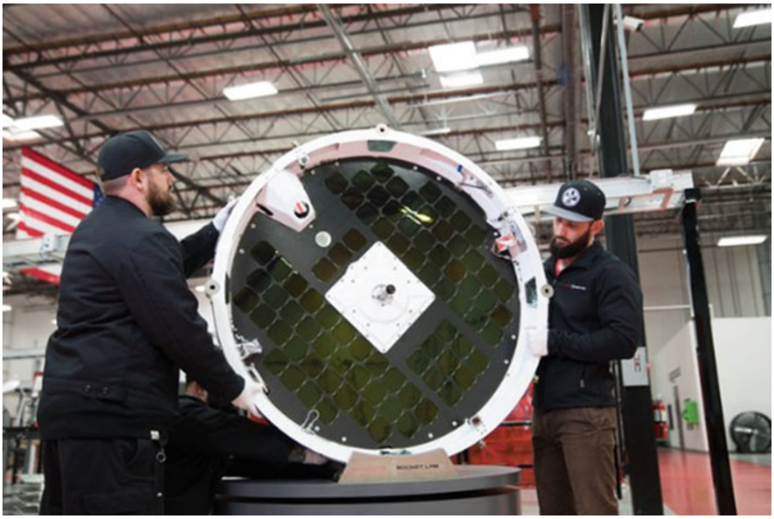


Fig. 10 Photon in production at Rocket Lab's Huntington Beach Headquarters. (Graphic courtesy of Rocket Lab)

satellite customers. Large launch vehicles with dedicated payloads take priority on crowded launch ranges, often forcing smaller missions down the launch schedule. The high volume of air and marine traffic over United States' launch sites also causes friction between launch, sea, and air operators all vying for safe, clear routes. This growing traffic jam also creates increasing challenges for regulatory and licensing authorities such as the Federal Aviation Administration (FAA).

To combat this issue and free small satellite operators from the queue, Rocket Lab operates two dedicated launch sites offering customers unmatched schedule flexibility.

Table 2 Summary of Photon specifications and performance versus the Kick Stage

Specification	Kick Stage	Standard Photon	Performance Photon
Payload mass	Up to 200 kg	Up to 170 kg	Up to 160 kg
Payload volume	Electron payload fairing		
Payload power (peak)	N/A	100 W	TBS variant(s) 1000 W
Payload energy	N/A	TBS	TBS variant(s) 300 Wh
System voltage	N/A	28 V unregulated; regulated options available	
Pointing accuracy	N/A	5°	50 arcsec
Pointing stability	N/A	1°/s	2 arcsec/s
Slew rate	N/A	5°/s	
Specific impulse	220 s		290 s
Payload data interfaces	LVDS, Ethernet, CAN RS422/435 Space Wire		
Payload data storage	N/A	8 GB	32 GB
Communications	N/A	S-band space/ ground	Space-ground via GEO
Telemetry and command data rate	N/A	Up to 512 kbps	S-band: Up to 512 kbps GEO relay: Up to 200 kbps
Payload data rate	N/A	Application-dependent	
Design life time	Hours	LEO >5 years	
Navigation accuracy	5–10 m		

7.1 Launch Complex 1

Established in 2016 and located on New Zealand's Mahia Peninsula, Rocket Lab's Launch Complex 1 is the world's first private orbital launch range (see Fig. 11). This FAA-compliant site can accommodate a launch rate of 120 flights per year. From the site, it is possible to reach orbital inclinations from sun-synchronous through to 39°. This enables a dedicated launch option with a wide spectrum of orbital inclinations. New Zealand's remote island location and low volume of marine and air traffic creates ideal conditions for frequent launch opportunities, enabling the highest possible launch cadence of any pad in the world.

Launch Complex 1 supports on-site payload integration with two separate and secure cleanrooms located in the Integration and Control facility <200 m from the launch pad (see Fig. 12).

Payload integration and encapsulation operations procedures are designed to minimize complexity and increase mission reliability.

Cleanroom specifications:

- Certified ISO 8 cleanliness level (Class 100K)
- Overhead crane for payload integration operations
- Standard 110 V AC @ 60 Hz and 230 V @ 50 Hz Power
- Secure area including 24/7 security guards, building access control, video monitoring, and an area warning system

Fig. 11 Launch Complex 1 on New Zealand's Mahia Peninsula. (Graphic courtesy of Rocket Lab)

Fig. 12 A DARPA payload in the LC-1 cleanroom during integration procedures. (Graphic courtesy of Rocket Lab)

Both cleanrooms offer a private customer viewing area and workspace that looks into the cleanroom during operations, giving customers full oversight of operations while minimizing the number of personnel required in the cleanroom itself (see Fig. 13).

Fig. 13 The dedicated customer room and viewing area that looks directly into the cleanroom. (Graphic courtesy of Rocket Lab)

To date, Launch Complex 1 has been host to eight Electron launches that have deployed small satellite payloads for NASA, DARPA, the Unites States Air Force, and a range of commercial customers.

7.2 Launch Complex 2

In Q4 2019, Rocket Lab will complete construction of Launch Complex 2, the company's second launch site. Located at the Mid-Atlantic Regional Spaceport on Wallops Island, Virginia, LC-2 is tailored specifically for government missions and can support up to 12 launches per year (see Fig. 14).

In addition to the pad itself, Rocket Lab is developing a Launch Vehicle Integration and Assembly Facility in the Wallops Research Park to support the simultaneous integration of up to four Electron vehicles. The facility will also contain a control room with connectivity to LC-2, as well as dedicated customer facilities. This new facility, combined with the purpose-built gantry located at LC-2, will provide significant and dedicated vehicle processing capability and flexibility to meet Rocket Lab's high launch cadence.

8 Responsive Launch Capability

Responsive space launch, the ability to rapidly and frequently deploy satellite infrastructure, is crucial in maintaining strategic, commercial, and scientific advantages in space. The U.S. Space Transportation Policy (2013) clearly states that the

Fig. 14 Launch Complex 2 under construction in September 2019. (Graphic courtesy of Rocket Lab)

United States Government shall "pursue research and technology development activities regarding alternative launch capabilities to improve responsiveness, resiliency, and cost effectiveness for future space launch alternatives."

Responsive space access is of strategic importance for government small satellite operators and commercial constellation operators alike. As reliance on services from small satellite constellations dedicated to internet connectivity, marine tracking, weather, and communications grows, the ability to promptly, accurately, and decisively deploy assets to orbit becomes vital.

Rocket Lab's Electron launch vehicle and Photon satellite bus were designed from the outset to deliver timely spacecraft deployment, restoration, and sustainment in orbit.

Truly responsive space access requires three things – responsive launch vehicles, responsive launch sites, and responsive satellites. With the Electron launch vehicle, two dedicated launch complexes and the configurable Photon satellite platform, Rocket Lab has demonstrated all three aspects.

Rocket Lab's rapid response launch architecture has been designed to support 24-h, on-call launch capability.

The mission flow for a rapid-response launch is a modified and streamlined version of the proven, standard Rocket Lab launch capability.

Preassembled Electron launch vehicles can be stored at Rocket Lab's USA and New Zealand launch complexes ready for call up 24/7 (see Fig. 15). Rapid checkouts and stage mates can be carried out in hours, with vehicle interfaces, fluid, and electrical connections designed for quick connect/disconnect.

Small satellite payloads can be pre-integrated onto Electron's Kick Stage payload plate and stored securely in a flight-ready state at Rocket Lab launch sites, ready for

Fig. 15 A preassembled Electron launch vehicle awaiting launch at LC-1. (Graphic courtesy of Rocket Lab)

deployment at any time. Electron's standardized, modular design sees satellites integrated onto the stand-alone payload plate which can then be mounted to any Electron vehicle, enabling rapid responsive launch capability. Alternatively, Rocket Lab can take urgent delivery of a spacecraft and conduct a rapid spacecraft integration and encapsulation within hours.

Rocket Lab goes one step further with the creation of the common Photon satellite bus. Small satellite operators simply provide their sensor and Rocket Lab looks after satellite build, launch, and ground segments. Photon removes the need for operators to build their own spacecraft and is an end-to-end solution for increasing flexibility for quick-reaction launches without sacrificing reliability.

While payload and vehicle operations are being carried out, concurrent mission delivery analysis and licensing takes place, with trajectories, Monte Carlos, and Hardware-In-The-Loop (HITL) testing carried out by a 24/7 call-up rapid response team.

This mission flow minimizes launch timelines and increases flexibility without significantly increasing technical complexity or cost.

9 Reusability

In an effort to create further efficiencies and increase launch cadence, Rocket Lab has confirmed plans to recover and reuse the first stage of the Electron launch vehicle. Work on Rocket Lab's Electron first stage reuse program began in late 2018 at the end of the company's first year of orbital launches. The plan to reuse Electron's first stage will be implemented in two phases. The first phase will see Rocket Lab attempt to recover a full Electron first stage from the ocean downrange of Launch Complex 1 and have it shipped back to Rocket Lab's Production Complex

Fig. 16 A render of Electron's first stage during reentry. (Graphic courtesy of Rocket Lab)

Fig. 17 A rendering of Electron's first stage with chute deployed for reentry, awaiting air capture by helicopter. (Graphic courtesy of Rocket Lab)

for refurbishment. The second phase will see Electron's first stage captured midair by helicopter before the stage is transported back to Launch Complex 1 for refurbishment and relaunch (see Figs. 16 and 17).

On Rocket Lab's tenth launch, currently scheduled for November 2019, Electron will carry critical instrumentation and experiments to provide data that will inform future recovery efforts; however, Rocket Lab will not attempt to recover the stage on this mission. Rocket Lab plans to begin first stage recovery attempts in 2020.

10 Conclusion

Rocket Lab has brought frequent, reliable, and dedicated launch capability to the global market, freeing small satellite operators from launch queues and rideshare limitations. With the introduction of the Photon satellite platform, the completion of Rocket Lab's Launch Complex 2, and plans to recover Electron's first stage for reuse, Rocket Lab is poised to deliver increasing flexibility and responsiveness to government and commercial customers.

11 Cross-References

- ▶ New Launchers for Small Satellite Systems
- ▶ Retrofitting and Redesigning of Conventional Launch Systems for Small Satellites
- ▶ Smallsat Rideshares and Launch Aggregators

References

National Space Transportation Policy, (21 November 2013), https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/national_space_transportation_policy_11212013.pdf. Accessed 30 Sept 2019

The Evolution of Medium/Heavy-Lift and Reusable Launch Vehicles and Its Implications for Smallsat Access to Space

Clay Mowry and Michael Grasso

Contents

Abstract

The advent of reusable commercial medium−/heavy-lift launch vehicles will drive growth in the small satellite (smallsat) industry by enabling low-cost access to space for constellation operators in geosynchronous orbits (GEO) and non-geosynchronous orbits (NGSO). Innovations in reusability, high-performance engines, and larger payload fairings are changing the economics of launch, providing significant value to smallsat operators. Reusable, medium−/heavy-lift launch vehicles like Blue Origin's New Glenn and SpaceX's Falcon offerings offer smallsat operators affordable access to space and significant value in the form of decreasing time to market, rapid fleet refresh, and solution scalability.

This article describes how the evolution of space launch capabilities will impact the smallsat industry. Specifically, it describes the developments in the launch services market, smallsat operator launch preferences, and the enabling role played by heavy-lift vehicles.

C. Mowry (✉) · M. Grasso
Blue Origin, Washington, DC, USA
e-mail: cmowry@blueorigin.com; MGrasso@blueorigin.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_92

Keywords

Ariane 6 · Blue Origin · Calisto · Delta II · Economics of launch services · European Space Agency (ESA) · Falcon 9 · High-performance engines · Low-cost access to space · Launch aggregators and facilitators · Low Earth orbit (LEO) · Medium−/heavy-lift vehicles · NASA · New Glenn · Non-geosynchronous satellite orbit (NGSO) · Decreasing time to market · Prometheus · Reusable launch vehicles · Rideshare missions · Smallsat industry · Soyuz · SpaceX · Start-up launch service providers · United Launch Alliance · US Government policy

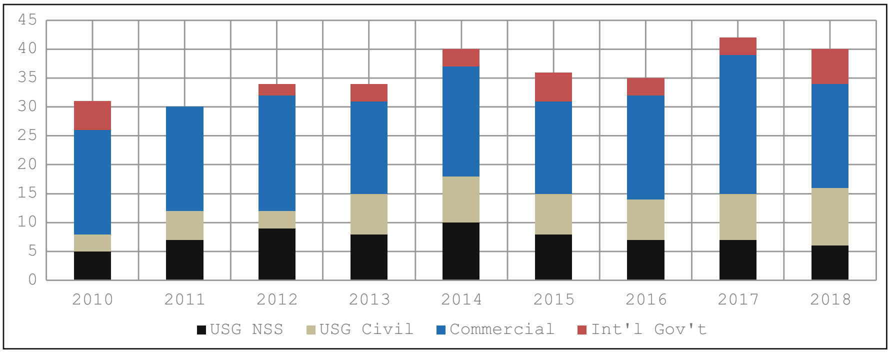
1 Introduction

Demand for commercial launch services has changed considerably from 2010 to 2020. Compared to the prior decade, there were more launches of large high-throughput satellite (HTS) geostationary systems and constellations of smallsats supporting a range of applications from communications to remote sensing. Moreover, several companies announced plans to deploy non-geosynchronous (NGSO) mega constellations of hundreds and, in some cases, thousands of spacecraft to service burgeoning connectivity markets. In fact, in the last 2 years, SES, Iridium, Telesat, OneWeb, and SpaceX deployed test and/or operational spacecraft for their respective NGSO systems. During the same period, changes to US Government policy further added to medium−/heavy-lift launch demand. For example, NASA drove additional demand by outsourcing the delivery of cargo to the International Space Station (ISS), and the US Air Force began competing launch services contracts. These policies increased the size of the addressable market and allowed for greater competition among established providers and new entrants. These shifts in US Government policy coupled with the evolution of commercial satellite architectures have changed the global launch services landscape.

Within the launch market, there are four categories of launch customer verticals addressable by US medium−/heavy-lift providers: (1) commercial, (2) US government civil (USG civil), (3) US government national security space (USG NSS), and (4) international civil/military. From 2010 to 2018, the number of addressable launches for US medium−/heavy-lift providers averaged 36 per year. (Note: Certain Ariane 5 missions to GTO count as dual launches.)

There was modest growth at approximately 3% year-over-year during this period. Growth is attributed to demand from the commercial and USG civil verticals. For reference, the total number of addressable launches to US-based commercial medium−/heavy-lift launch providers comprised about 40% of all global orbital launch events over the last decade. The other 60% of launches include those for governments with their own launch capabilities (e.g., Russia, China, France) and launches on small and light-lift vehicles (e.g., Minotaur, Pegasus).

As shown in Fig. 1, the commercial vertical was the largest in terms of volume of launches, representing roughly half since 2010. This vertical is primarily comprised



Source: Blue Origin

Fig. 1 Launch market for US-based commercial medium−/heavy-lift providers (2010–2018)

of operators of commercial communications satellites that operate in GEO, and each weighs between 3,000 and 6,000 kg.

Launch demand from commercial operators in particular is in the midst of a large transformation that could be defined by the proliferation of non-geosynchronous orbit (NGSO) constellations, primarily in LEO and MEO, and smallsats in GEO. Over the next decade, several companies plan to deploy large constellations of smallsats in LEO to provide global broadband connectivity services. Many of these constellations are so large that they require a significant increase in commercially available launch capacity to ensure that they can to deploy their targeted number of spacecraft to close their business cases and meet regulatory guidance. In fact, the growth of NGSO constellations in the commercial market could ultimately comprise a majority of future launch demand in the 2020s and beyond encompassing initial deployment, evolution, and replacement missions. In 2019 alone 120+ NGSO smallsats belonging to SpaceX and OneWeb were deployed. The numbers for 2020 were projected to increase sharply, but planned deployments were curtained by the effects of the Covid-19 virus and the One Web bankruptcy.

Beyond LEO, operators are moving forward with plans to operate “Micro GEO” satellites weighing 300 to 1,500 kg and targeting niche connectivity applications. Start-up providers like Saturn, Astranis, and Ovzon are seeking to provide service to underserved areas of the world and for smaller national satellite communications projects, using satellite form factors that are 4 to 20 times smaller than traditional GEO satellite platforms and employing software-defined payloads. These spacecraft can offer significant and targeted bandwidth that can meet new and existing customer needs. Astranis’ spacecraft, for example, have ~7.5 gigabits per second of throughput capacity (Via Satellite 2019). These systems will require shared launches on medium−/heavy-lift vehicles to achieve greater cost savings. Micro GEOs may also require much more frequent refresh, especially when compared to large HTS and classical GEO systems, as their lifespans are expected to be about half that of legacy systems (~7 years instead of 15 years). Their size, refresh requirements, and need for fast time to market may ultimately drive demand for new launch approaches, specifically for direct injections into GEO versus more classical transfer orbits. Eliminating electric orbit raising time and extending life on orbit are two major advantages of GEO direct missions, the benefits of which are enhanced given the size and expected lifespan of these small spacecraft.

2 Access to Space for Smallsats

Over the last decade, commercial interest in smallsats increased because they were considered relatively inexpensive, flexible, and easily upgradeable platforms (Avascent 2015). In swarms or constellations, smallsats also offer the advantage of disaggregation to large platforms. This changed operational risks and provided other commercial benefits (e.g., coverage, revisit, redundancy). Smallsat constellations are now viewed as complements to larger satellite systems and, in some cases, as substitutes.

The increasing capability of smallsats coupled with their attractiveness for commercial and government applications has accelerated demand for launch services to accommodate them. This has driven more interest and investment in (1) medium−/heavy-lift launch vehicles with bulk deployment capabilities, (2) small−/light-lift launch vehicles with targeted deployment capabilities, (3) ridesharing systems, and (4) managed services offerings.

These investments have increased the number of launch options available to smallsat operators. Today, they can launch on dedicated and multi-manifested/rideshare missions; they can buy launches directly from service providers or from brokers and third-party aggregators; and they can even outsource the space segment entirely to managed services providers, such as condosat operators like Loft Orbital.

Historically, satellite operators have used medium−/heavy-lift expendable launch systems for the initial deployment of satellite constellations to LEO and MEO orbits (refers to satellite constellation operators whose individual spacecraft have a mass of more than 100 kg). There are operators of satellites that weigh less than 100 kg, such as Planet and Spire, who have used a combination of medium-, light-, and small-lift vehicles to initially deploy, refresh, and augment their constellations. Smallsat constellation operator launch preferences are dictated by their manufacturing throughput, risk posture, time-to-market requirements, fleet size, and spacecraft mass/size (refers to satellite constellation operators with individual spacecraft mass of more than 100 kg).

Iridium, Globalstar, Orbcomm, O3b, and OneWeb all selected medium−/heavy-lift launch vehicles (Soyuz, Delta II, Falcon 9, Zenit, and Ariane 6) as the price per satellite and per gigabit deployed on orbit is lower compared to using small launch systems. Deployment schemes are derived from constellation architectures, including the number of planes, number of satellites per plane, and the mass and volume of the satellites.

With larger mega constellations, the use of larger, reusable heavy-lift vehicles can dramatically reduce capital expenditures for constellation operators by lowering launch costs, typically the largest single cost associated with deploying the broadband satellite system. For example, New Glenn's payload capability of up to 45 metric tons delivered to LEO, combined with a 7 m fairing that is twice the volume of the largest launch system operating today, will reduce per satellite launch costs and lower capital expenditure requirements for constellation operators like Telesat and OneWeb. Telesat's Chief Executive Officer Dan Goldberg stated that they selected the heavy-lift New Glenn because "Blue Origin's powerful New Glenn rocket is a disruptive force in the launch services market which, in turn, will help Telesat disrupt the economics and performance of global broadband connectivity" (Henry 2019).

Moreover, for many operators, time to market with an operational constellation is critical. Deployments that maximize the amount of spacecraft deployed in one launch event will dramatically reduce the time between concept development and commencement of operational services. Time to market for connectivity providers and imagery companies may further drive demand for new launch business models and procurement approaches.

3 Bulk Deployments, Multi-manifesting, and Ridesharing

Access to space for smallsat operators typically involves a trade-off between price and control over schedule/orbit. Many operators, especially those in early stages of system development and financing, sacrifice control over schedule/orbit for inexpensive launch services. This section explores three launch approaches that smallsat operators have adopted to deploy their smallsats and constellations.

3.1 Bulk Deployments

While the Geneva-based International Telecommunication Union's (ITU) 2019 report on global broadband deployment stated that more than 50% of the world's population now has access to the Internet, a large portion of those users are underserved, and more than three billion people remain unconnected. Satellites are a low-cost way to provide service to rural and underserved areas of the world where deploying fiber-optic cable is cost-prohibitive.

Demand to launch the initial population and replenishment of fleets of NGSO broadband constellations is expected to increase dramatically over the next decade to meet the growing demand for Internet connectivity around the world. Bulk deployments are launches that take nearly the entirety of launch vehicle's performance to deliver large quantities of spacecraft. For example, SpaceX is currently bulk deploying its Starlink constellation on Falcon 9, as is Arianespace for OneWeb on Soyuz 2. Satellite operators, particularly those planning to offer broadband services, will require medium−/heavy-lift launchers for bulk deployment of their systems. These commercial operators will need access to low-cost launch systems that have the capability and availability to ensure continuity of coverage and service quality.

These NGSO spacecraft are expected to weigh between 100 kg and 1,000 kg, which necessitate launch systems with the most performance to orbit and fewest volume constraints. NGSO mega constellation operators intend to operate in multiple planes at varying altitudes and inclinations (e.g., mid-inclination LEO, SSO). Some operators will operate their satellites at low altitudes (sub 700 km) to ensure low latency and rapid reentry. While demand for constellation bulk deployments will grow, it could be variable on a year-by-year basis depending on refresh cycles. These operators require medium/heavy commercial launch services that offer low costs, high availability, and sufficient performance (mass/volume) to meet customer needs and regulatory deployment, service, and coverage requirements.

3.2 Multi-manifesting

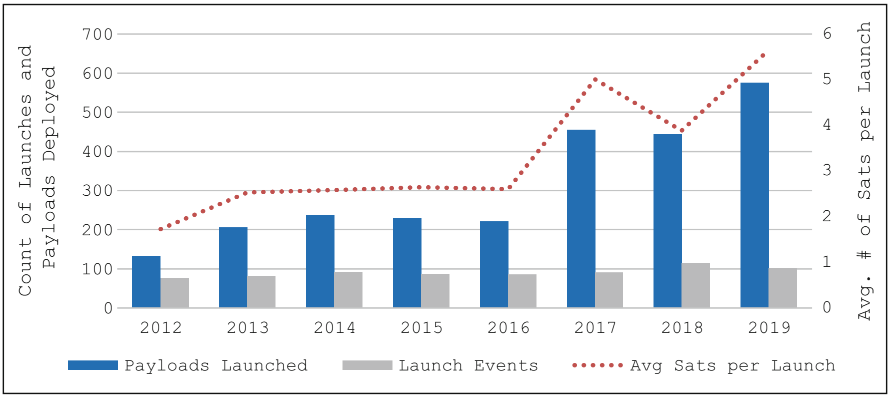
Overall payload mass launched has continued to grow, both in the form of larger satellites and in the form of multi-manifested payloads. The increase in multi-manifested payloads has been influenced primarily by new NGSO satellite constellation launches, the growth in availability of capable smallsat platforms, increasing diversity in GEO broadband spacecraft, and a proliferation of rideshare options on existing and new launch systems.

Satellites planned for GEO will continue to be launched alongside co-passengers. Multi-manifested missions, like those launched on Ariane 5, will continue to be popular means to reaching orbit. In the near future, operators of micro GEO satellites and flexible light GEO spacecraft (FlexLight), which are characterized by their ability to reconfigure in orbit and offer flexible coverage, will seek multi-manifested approaches to reach orbit. Example FlexLight platforms include Thales Alenia Space's Space Inspire, Airbus' OneSat, and Boeing's 702X platforms. (Note: Industry experts also refer to these FlexLight satellites as software-defined satellite (SDS). Such approaches can help ensure low-cost access to space for operators of large and small spacecraft in GEO.

3.3 Ridesharing

The market for rideshare launch services has grown significantly over the last decade. The onset of capable, smallsat form factors and the availability of affordable launch services for auxiliary payloads have increased the number of satellites launched globally. While the number of launches globally experienced modest growth, the number of payloads launched into space annually has increased dramatically. In fact, the annual number of payloads launched has more than doubled over the years 2012 to 2019 (Fig. 2).

Ridesharing capabilities and multi-manifesting are responsible for the democratization of access to space as well as new companies and business models, which is driving an unprecedented expansion in the quantity of satellites deployed over the last decade.



Sources: Blue Origin and Space Activities in 2019, Jonathan McDowell, Rev 1.3

Fig. 2 Launches and count of payloads deployed (2012–2019)

Rideshare is an approach to deploying multiple payloads into orbit on a single launch by leveraging excess capacity. Rideshares are defined as missions for non-primary payloads on a particular launch campaign (ULA 2015). For launch service providers, rideshare is a means of asset utilization.

There are several types of rideshares. There are launches of auxiliary payload rideshares, where one or more secondary payloads share a launch with a primary payload customer. There are dedicated rideshare missions, where there is no single primary payload that has priority rights; under this approach, mission capacity is shared between several satellites. Lastly, there are propulsive rideshares, where an auxiliary platform with propulsion is co-manifest alongside primary payloads. These propulsive systems offer independent orbit-tailoring and dispensing capabilities.

Ridesharing offers many advantages to satellite operators. It gives them access to an abundance of available flight opportunities across multiple vehicles. For certain missions, ridesharing on larger launchers may even enable some degree of weight and volume flexibility over smaller vehicles. But, perhaps most important, there is a perception of affordability versus dedicated launches. This perception is exacerbated when operators compare launches on smaller systems whose price per kg of payload to LEO, for example, can be eight times more expensive than options on medium—/heavy-lift rideshare alternatives.

At the same time, there are drawbacks to ridesharing. Historically, there has been limited price transparency, though SpaceX's SmallSat Rideshare Program has challenged this notion directly by publicly announcing a $1 M per 200 kg price tag for capacity on Falcon 9 to SSO and mid-inclination LEO. There is also less orbit control, meaning satellite operators may need to trade a more optimized orbit that could be achieved on a smaller rocket for a less ideal orbit on a rideshare mission. Again, some companies, such as smallsat propulsion providers and on-orbit transfer companies (e.g., Momentus), those that offer last mile delivery with altitude raising systems, believe this drawback can be solved affordably by adopting their respective products and services. Rideshare missions also have less schedule control, as they tend to be subject to vehicle availability and delays with the primary payload. Lastly, some rideshare missions have relatively inflexible contract terms and conditions, which can prove burdensome to satellite operators.

4 Conclusion

A key market-defining enabler of smallsat launch, whether bulk deployments, multi-manifested missions, or rideshare, is reusable medium−/heavy-lift launch vehicles. These systems offer unparalleled cost savings relative to expendable alternatives and have superior availability, as they are not constrained by manufacturing throughput or ultra-specialized supply chains. Moreover, vehicles with high-performing upper stage engines and large payload fairings will further enable smallsat operators to deploy systems that offer superior services and products to their respective customers.

On November 23, 2015, Blue Origin's New Shepard suborbital rocket became the first launch vehicle to climb above the 100 kilometers Kármán line, the internationally recognized border between the Earth's atmosphere and outer space, then return to safe land vertically. That same New Shepard booster and capsule repeated the achievement four more times with limited maintenance before being retired. SpaceX's Falcon 9 medium-class launch vehicle first flew to space and landed successfully a month later in December 2015. Subsequent Falcon 9 and Falcon Heavy boosters have flown to space and back three times. Blue Origin is now completing design of the New Glenn heavy-lift system, which baselines a minimum of 25 reuses per booster. Following these successes, ESA announced their own reusable rocket engine development program dubbed Prometheus, and the French and German space agencies CNES and DLR have started work on a reusable first stage flight demonstrator named Callisto.

These medium−/heavy-lift reusable boosters were developed with the goal of dramatically lowering the cost of access to space for satellite operators and space agencies, allowing a thriving space economy to grow and flourish. For mega constellations their large architectures require both increased heavy-lift performance and more payload fairing volume to efficiently deploy and replenish constellation planes.

5 Cross-References

- ▶ Frequent and Reliable Launch for Small Satellites: Rocket Lab's Electron Launch Vehicle and Photon Spacecraft
- ▶ New Launchers for Small Satellite Systems
- ▶ Retrofitting and Redesigning of Conventional Launch Systems for Small Satellites
- ▶ Smallsat Rideshares and Launch Aggregators

References

Avascent, *Space Market Disruption: The Smallsat Revolution*. (2015)

C. Henry, “Telesat signs New Glenn multi-launch agreement with Blue Origin for LEO missions”, *Space News.* (January 31, 2019)

J. McDowell, Space Activities in 2019, 12 January 2020, Rev 1.3

United Launch Alliance, *United Launch Alliance Rideshare Capabilities for Providing Low-Cost Access to Space.* (2015)

Via Satellite, *The Software-Defined Future of Satellites.* (2019)

Part V

Design, Engineering, and Manufacture of Small Satellites for Constellations

Kits, Components, and the Design, Manufacture, and Testing of Small Satellites

Joseph N. Pelton and Rene Laufer

Contents

Abstract

The "NewSpace" revolution has changed the world of satellite applications, science, and experimentation. The design, manufacture, testing, and operation of small satellites in the age of "NewSpace" (or "Space 2.0") have altered dramatically – especially so in the past decade. Today is a time when small satellites (i) are still shrinking in size; (ii) are being designed and built more economically; (iii) are being tested more efficiently; (iv) are being subtly upgraded through multiple generations with minor improvements; (v) are being produced at a much more rapid pace: and (vi) are definitely being launched at lower cost. All of these shifting factors that might be called "efficiency factors" make the field of small satellite design and construction fairly dynamic.

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

R. Laufer
University of Cape Town, Cape Town, South Africa

Baylor University, Waco, TX, USA
e-mail: rene.laufer@me.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_23

Nevertheless construction standards for cubesats and now pocketQubes help to acquire smallsat components and structural elements from a competitive global market via the Internet with increased efficiency and competitive costs. There are also Internet sites that provide useful description of qualified suppliers and their products with clarity and useful background information.

Clearly the small satellite market is divided into truly diminutive units (i.e., femtosats, picosats (including pocketQubes), and nanosats (including cubesats)) that are typically for academic experiments and investigations and the larger smallsats for commercial services (3U cubesats and up to microsats and minisats). Although the suppliers of kits, components, and smallsat sensors are largely attuned to academic institutions and student small satellite experiments and proof-of-technical-concept missions, some of these same suppliers can also support commercial market satellite programs as well.

This chapter is focused on providing some advice and guidance on more effective ways to design, obtain key parts and components, integrate, test, and arrange for the launch of what is often called the academic smallsat market. Nevertheless, this chapter may also provide useful information to commercial smallsat programs, especially those whose spacecraft are of the 3U to 6U cubesat variety.

Keywords

Chipsats · Components · Cubesat · Femtosat · Independent verification and validation (IV&V) · Kits · Launch services · Mother ships · Nanosat · Picosat · Qubesat · Resiliency · Smallsat · Smallsat components · Smallsat kits · Swarms of smallsats · Testing and verification

1 Introduction

It might be assumed by some that because a smallsat project involves a very small device, fitted into a standardized unit, it is also simple. The line of logic is that since this smallsat is being designed to accomplish a student's experiment or investigation at the lowest possible cost, this somehow translates into something that is much less "complex" than a full-sized satellite. In short, "small" means less complicated. This is, of course, very far from the truth. The key functionality of a satellite must be shrunk to fit into a very small structure, and thus, if anything, the design, manufacturing, and testing process may be far more demanding.

A small satellite must have a power supply; antennas for communications; sensors for various functions; thermal controls; processors to control the functioning of the satellite and to process signals related to tracking, telemetry and command. It must also have radio telecommunications/data relay capabilities plus the essential; experiment or test of concept that is the prime purpose of the smallsat mission. It must have a structure, wiring, power converters, filters, and other features, such as torquerods and possibly micro-thrusters, fuel, passive deorbit systems, deployment mechanisms for solar arrays, antennas, and other components. The ability to design, build, and test a small satellite is actually a demanding task. Squeezing all of these parts into a very small volume and keeping the mass low are not in any way simple (see Fig. 1).

This project required 3 months to design and construct by well-qualified engineers and technicians at SSTL who worked as volunteers in cooperation with volunteers from Amateur Radio United Kingdom. This project contained an amateur

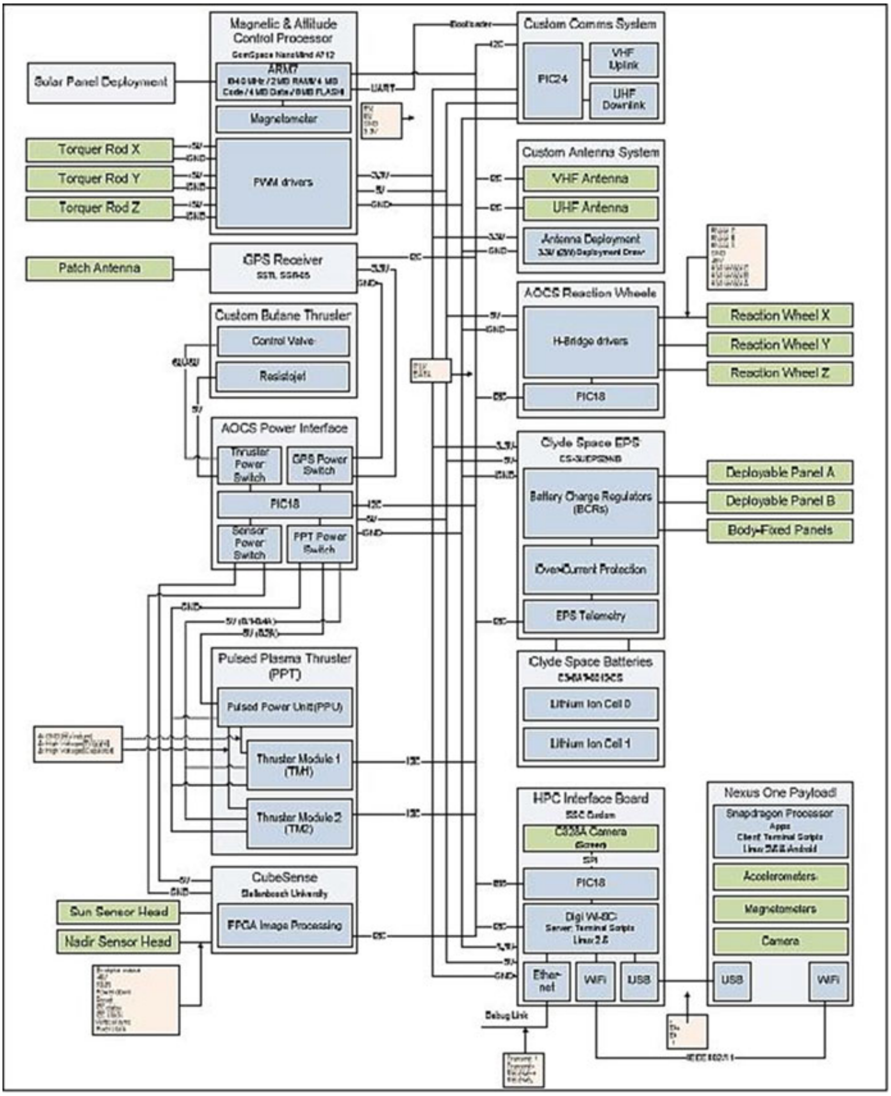


Fig. 1 Schematic diagram of the STRaND-1 3U cubesat designed by SSTL and Amsat-UK (STRaND-1 2019). (Graphic courtesy of SSTL and USSC)

radio AX-25 packet radio downlink that operates in the 437.568 MHz band. In some ways it is like a cell phone in the skies. This project was designed and built at the Surrey Space Technology Limited (SSTL) and launched on an Indian Polar Satellite Launch Vehicle (PSLV-C20). This smallsat project is perhaps somewhat more complex than others in that it did include custom butane and pulsed plasma thrusters and other special features such as both X, Y, and Z axis torquerods and X, Y, and Z axis reaction wheels. In this project a Pumpkin© brand solid chasis, a battery supplied from Clyde, Ltd.©, and a solar cell deployable array from SSTL© were the sources of key components (STRaND-1 Smartphone Cubesat 2019).

The design and assembly of all the key components and integrating them together are no small feat. After the integration is complete, component parts and the overall satellite have to be tested for qualification and readiness for launch (see Fig. 2).

The fact that the task of designing, building, integrating, testing, and launching of cubesat projects around the world has been accomplished many times over provides clear advantage to those embarking on new smallsat projects for the first time. Today’s smallsat experimenters can benefit from those that have gone before, thus providing very useful information. Someone starting a cubesat project does not have to, in effect, reinvent the wheel.

Nor does one have to develop from scratch a 3-axis stabilized free-flyer cubesat as the only way to undertake an experiment in space. One can deploy smaller units such as pocketQubes that are essentially one-eighth in size (i.e., 5 × 5 × 5 cm), and these

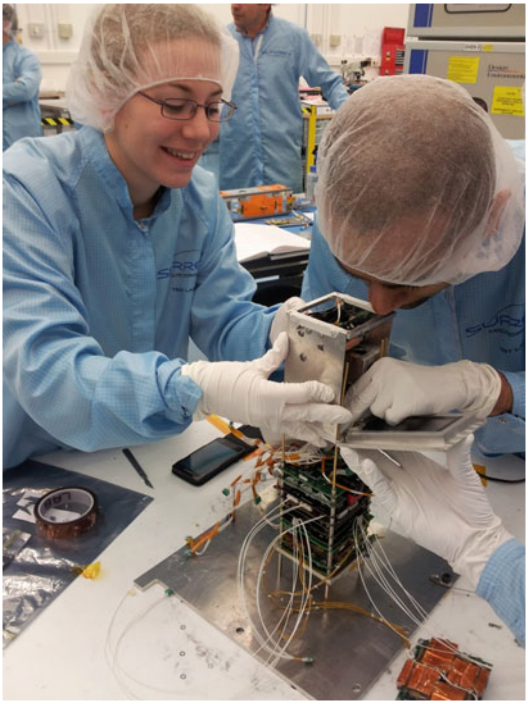


Fig. 2 The assembly and integration of the STRaND-1 smartphone cubesat. (Graphic courtesy of the Surrey Space Center)

do not have to be three-axis stabilized. It is also possible to design experiments that fly on a larger "mothership" that supplies power, stabilization, and telecommunications as well as tracking, telemetry, and command functions.

There are also arrangements that can be made via nanoracks for small orbital experiments to be designed that are flown up to the International Space Station where these mini-projects can be placed in the nanorack experimental bay and never actually launched as free-flyers. Under this approach astronauts can start and stop experiments and even monitor results that can be reported to the ground. This is the type of project sponsored by the National Center for Earth and Space Science Education and the Arthur C. Clarke Institute for Space Science Education. This is the simplest approach by far, and even students at the primary and secondary levels of education can plan and execute space science educational projects of this type.

2 Kits and Components

There are many websites online that are devoted to assist those seeking to undertake smallsat projects or related activities. Perhaps the most notable is the cubesat.org website that features several dozen suppliers of cubesat kits and key components that are accessible via the web in many areas such as structures, batteries, solar cells and solar arrays, sensors, materials and deployment mechanisms, processors, torquerods, reaction wheels, integration services, and assistance with launch services. This website is accessible at http://www.cubesat.org/new-index.

This website describes in one paragraph the offerings of many smallsat-related suppliers and features only companies with a clearly established and creditable track record of quality product and services.

NASA by means of its NASA Ames Research Center has started a program known as SmallSat Parts On Orbit Now (SPOON). This program is seeking responses and updated information with regard to smallsat programs, products, and services from educational organizations, research labs, not-for-profit organizations, and even industry sources via a specific request for information process. The stated purpose of this solicit of information is to assist organizations planning smallsat projects and to promote competition.

NASA has designed its "SPOON" project to seek information that is considered "state-of-the-art" and at what they define as a Technology Readiness Level 5.

This SPOON directory of information is organized into the following specifically defined areas:

> **NASA SPOON Database**: Structures, Materials & Mechanisms; Complete Spacecraft Platforms; Communications; Propulsion; Power; Command and Data Handling; Attitude Determination & Control; Thermal Systems; Software (Architectures, Methodologies); Guidance, Navigation and Control; Spacecraft Integration; Launch and Deployment; Optoelectronics; and Deorbit Mechanisms. (NASA SPOON Database 2018)

The European Space Agency, like NASA, has also been active in the small satellite arena. ESA has sponsored or engaged in a number of small satellite programs. These activities have included the use of small satellites for its "In-Orbit Technology Demonstration" Program. Recent projects have included (i) GOMX3, (ii) GOMX4B, (iii) Simba, (iv) Picasso, (v) Qarman, (vi) Radcube, (vii) Pretty, (viii) AMS-Sat, (ix) Hera, (x) RACE, and (xi) Proba-V cubesats. It has had two pocketQube projects involving telecommunications and networking projects known as Astrocast and Pocketqube. It has also chosen a number of smallsats for its Fly Your Satellite (FYS) Program, and it has included Oufti-1, e-st@r-II, and AAUSat-4 in its first edition program. Also, it has supported the launch in its second edition program of the following smallsats: LEDSAT, EIRSAT-1, CELESTA, 3CAT4, UoS3, and ISTsat-1. Finally it has undertaken five interplanetary small satellite projects (Walker and Hager 2018).

Under the ESA Fly Your Satellite Program, extensive support is offered to university-based student experimental projects that are qualified to meet the program standards. Under this program for qualified projects, ESA offers:

- Direct support from ESA specialists
- Introduction to ESA verification processes and related documentation
- Participation in ESA workshops and training courses
- Access to ESA environmental test facilities
- Training opportunities to get acquainted with ESA standards and best practices (see Roger Walker and Philipp Hager presentation, June 2018)

Other space agencies also have various programs to support small satellite missions that they are undertaking themselves or to support small satellite initiatives by educational institutions or industry projects. This includes those that are seeking to design and build small satellites or to develop new launch systems to support small satellite launches. A search of the sites of these other space agencies is recommended.

3 Testing

The support that is offered involves not only help with the design and construction of small satellites. There is also support with regard to the testing, independent verification and validation, and qualification of small satellites for launch. This "qualification" of cubesats is important to those constructing and launching the small satellites in order to reduce the number of "dead on arrival" missions and to extend their operational lifetime from a few days to months or even years. Careful review of the cubesat and its design and safe configuration is likewise important to avoid accidents involving the launch operations.

There are a number of issues that are of particular concern. Sometimes industrial wiring rather than space-qualified wiring might be used in cubesat projects. The flow of electricity and wiring resistance to electrical current are different in space, and this can lead to the failure of small satellites and could even lead to electrical fires. The NASA and ESA safety reviews, verification testing, and testing documentation can avoid unfortunate design and construction errors. Other areas of particular testing and design review are concerned with the stabilization and pointing systems, batteries, mechanical deployment systems, active and passive thermal controls, any fuels or pyrotechnics that might be included in the cubesat design, and all electronics, electronic switching, power converters, and processor systems.

A significant number of cube missions have been launched via the International Space Station. In this case there is a particular concern with safety and whether the cubesat might represent a fire or other type of hazard. For this reason NASA has created a special unit to review the safety and design of all cubesats to be launched via the International Space Station.

The elements that might be included in a spacecraft can be quite extensive. The following represents a listing of the elements that would normally be included in an independent verification and validation plan that would seek to ensure that a spacecraft would be not only safe to launch but also be as resilient as possible and thus achieve its expected lifetime or operate for its nominal mean time to failure (Table 1).

In the case of femtosats, picosats, and nanosats, the quality, verification, and safety testing may be less exacting. The thought process is that if the small satellite can be designed, built, tested, and launched for a cost that is perhaps hundreds or even thousands of times less than a conventional large spacecraft, then there are practical risks that can be taken into consideration with regard to not undertaking the most expensive and time-consuming thermal/vacuum tests or not manufacturing the smallsats in the most exacting and expensive clean rooms. Thus Planet Inc. manufactures their Dove 3U cubesats in what they call their "clean enough" room and avoids thermal/vacuum testing. Each smallsat project thus tends to be designed, built, and tested according to a strategic business plan that makes judgments as to the degree to which they might use commercial off-the-shelf components with regard to digital processors, battery systems, and solar arrays, as well as to which verification tests they will do and the specifications that they will use for clean room assembly. The key question is whether verification tests are focused on the "payload" or the "bus." Thus is the testing most directed toward the smallsats' mission that is to undertake remote sensing, telecommunications or networking services, weather observation, etc., or is the testing zeroed in on the functional platform which allows the payload to perform its tasks?

There is no single set of guidelines as to how exacting the specifications for components for small satellites must be or to the degree to which components should be assembled and tested in the highest quality clean room. The ability to use small satellite missions to provide proof of concept includes testing the use of lower-cost components or new manufacturing conditions to produce spacecraft at lower cost. In the case of commercial systems where there are hundreds or even thousands of spacecraft being produced, the important question of cost savings in manufacturing and testing programs comes from several key factors. As the volume of production

Table 1 Elements of a spacecraft verification testing program (Bukley et al. 2018)

Elements that are included in a spacecraft test plan
Typical components and subsystems to test
Guidance navigation and control
Propulsion
Attitude control, 3-axis stabilization, and pointing systems
Thermal control system
Communications, telemetry, command system, and data handling
Processors, redundant systems, and switching systems
Power systems
Active and passive thermal control systems
Structure, deployment mechanisms, and control sensors and actuators
Payload components and systems (if there is a standardized and flight-proven bus platform, then more emphasis can be placed here)
Adequacy and reliability of the ground control systems and global access of TTC&M systems to satellite network
Areas of testing and test measurement specifications
Thermal range (heat and cold extremes)
Vibration testing (intense vibration at launch, pogo effects, and low-frequency sinusoidal vibrations)
Acoustical systems
Radiation levels
Reliability, precision, and clean room specification for manufacture and assembly
Design reviews and oversight of manufacturing and testing
Functional elements of test plan
Test objectives, frequency, and locations
Test equipment requirements
Step-by-step procedural detail and process
Test methodology and protocol
Input/output value limits and pass/fail criteria

goes up, these questions become increasingly important. Some of the most key factors are:

- Can various components be used that are off-the-shelf products which have not been flight and/or endurance tested and thus acquired at much lower cost and still produce minimal on-orbit failures?
- Can key components or kit structural elements be acquired at low cost from competent suppliers that have developed smallsat elements and products with demonstrated space flight resilience and yet reasonable cost because of their economies of scale? (This is key for particular projects, experiments, or missions that only involve one or a few spacecraft.)
- Can a “good enough” clean room with technicians that have only modest training and assembly skills be used to produce smallsats for the project in question?

- Can quality, verification, and safety testing be limited to only a relatively small number of tests that can be conducted with equipment that is not greatly expensive and does not require long-term endurance testing?
- Can some of the components requiring high precision and resilience be produced by the use of additive manufacturing (i.e., 3D printing)?

Several of these questions apply not only to those producing smallsats, but going forward, these questions might also apply to those producing and testing large spacecraft and launch vehicles as well. Currently the production of small satellites is expanding into new sectors. Thus smallsats are not only being produced at schools and universities and by startup firms that have invented new approaches to the design, manufacture, and testing of the cubesat-sized spacecraft that they are building but also companies from the well-established aerospace world.

One such example is the SENSE 3U cubesat produced by the Boeing Corporation for the US Air Force and launched in 2013. Indeed it can be a large established aerospace corporation that is producing many of the smallsats currently in production around the world (see Fig. 3).

AirBus plays a key role into the production of OneWeb satellites. Boeing has begun the production of the m-Power MEO satellites for SES that represents the second generation of the O3b constellation. Its subsidiary Argon ST along with Sierra Nevada has built the second generation of the Orbcomm system. Thales has filed to deploy its own large-scale constellation and manufactured the second generation of the Globalstar constellation as well as Iridium Next. Boeing has also filed to deploy its own constellation of small satellites as well. The Sierra Nevada Corporation and SpaceX are not exactly established aerospace corporations, but they are no longer seen as startup firms as well. If SpaceX accomplishes its goal, it will become the largest producer of small satellites as well as the largest manufacturer of satellite transceivers on the ground.

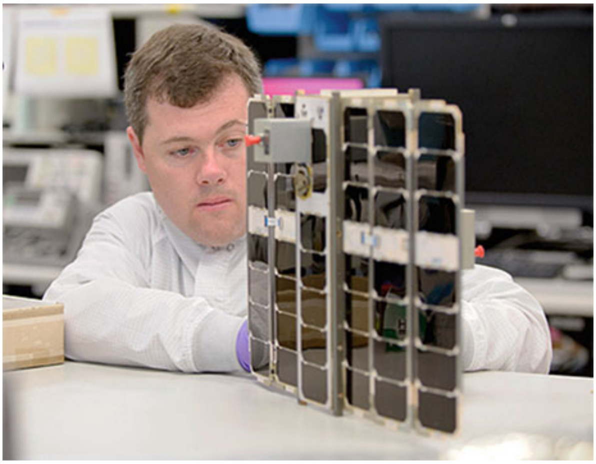


Fig. 3 The SENSE smallsat supplied to the US Air Force by the Boeing Corporation. (Graphic courtesy of the US Army) (Satnews 2019)

What we do know is that way that spacecraft are designed, manufactured, tested and launched have made a dramatic shift in the past decade. The shift to production of smallsats has altered almost every aspect of how to make and deploy satellites, how they are operated, how new generations are deployed, how old satellites deorbited, and how arrangements are made for sparing and reliable operations ensured.

The smallsat was designed to collect meteorological data and transmit it back to Earth via an S-band link to support US Air Force operations and to test the ability of this 4 kg satellite to perform reliably for this purpose in contrast to much larger and more expensive satellites.

4 The Pocketqube Option

The popularity of the cubesat appropriate to experimentation, proof of concept, and other missions that can be achieved with very small satellites has now produced the inevitable result of what is now called the pocketQube.

The pocketQube, as noted elsewhere, is the consequential idea of a picosatellite that is one-eighth of the size of cubesat and is a 5 × 5 × 5 cm cube that can be used to carry out experimentation and proof of concept in even small packages than a cube satellite. The standardization in its volume and a maximum mass of 250 g allows ease of arrangement for launch and also allows kits and components to be developed so that economies of scale can once again be achieved by those that develop key components. These components can be structural frames, batteries, solar arrays, torquerods and other components needed for this new entry into to the smallsat arena.

Alba Orbital, who has pioneered this field, offers a complete kit on the web for the current price of $10,299.00 as of August 2019 and explains its offering in the following terms:

> Satellites have traditionally been expensive with even lower cost solutions like Cubesat costing six figure amounts, limited to those with larger budgets. The PocketQube Kit addresses these problems and widens access to space for smaller budget organisations. The PocketQube Kit is ideal for a wide range of groups who are interested in building a low cost Satellite. For example Science, Technology, Engineering and Maths (or STEM) educators, from K-12, High School up to University. The Kits is also ideal for Governmental customers looking to begin a program. (Alba Orbital 2019)

In the age of miniaturization and microelectronics, no one can truly predict where the process of shrinking of smallsats will end. Today, however, the pocketQube concept has increasingly become a popular idea for student experimentation and low-cost launch arrangements. The Unicorn 2 picosat from Alba Orbital that is now offered via the web is shown in Fig. 4.

Other competitors will offer alternative systems in the future, but Alba Orbital has to date been the prime entry in this area of offering the kit for the complete picosatellite as well as assistance to arrange for launch services. The offerings related

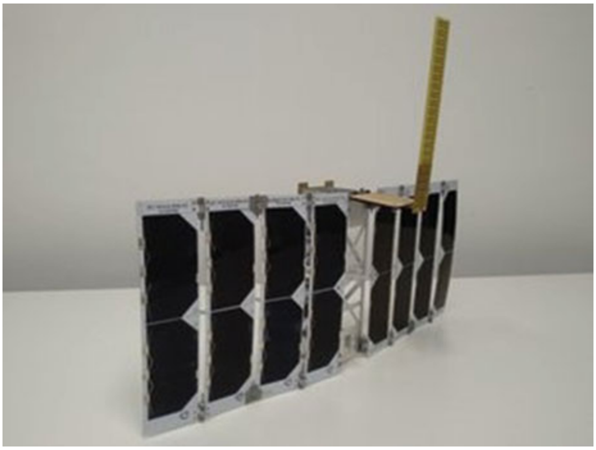


Fig. 4 The Unicorn 2 nanosat of 250 g mass is essentially solar cells and electronics. (Graphic courtesy of Alba Orbital)

to pocketQubes will undoubtedly become even more cost-effective, and perhaps configurations will become even more creative. One of only a few pocketQubes has actually flown into space to date, but dozens are queued for launch. The question that has increased in scope and vigor with regard to cubesats will perhaps reach a crescendo with regard to pocketQubes. There should be an altitude limit attached to tiny smallsats that have no active or passive deorbit mechanism. The idea of restricting nanosats and picosats to a maximum altitude of perhaps 250 km to ensure their return to Earth and safe deorbit is a topic of consideration, and this is likely to receive increased discussion and perhaps international support in the future.

5 Swarm Configurations

The problem with very smallsats is that when they get to be quite small, they lack the power and antenna gain to communicate over long distances. The latest idea centers around extremely small satellites, the size of stickers or even postage stamp. Such small satellites are commonly known as “chipsats.” These can include micro-level sensors that can be deployed to take measurements within a field or dispersed system to take readings and then communicate back to a “mothership” satellite the data that a swarm collects. The data relayed by the chipsats to the mothership can then be communicated back to Earth or a spaceship. Various chipsats are now being developed, and these tiny small satellites (i.e., femtosats) can include sensors able to collect data and report this information as collectively acquired by the swarm (IFL Science 2019; http://www.cubesat.org/new-index).

These types of chipsats are still too experimental to be standardized into kits or uniform components, but in time this seems very likely to be the case. As noted above the problem that would also apply to swarms of chipsats is how are the chipsats recollected and returned to the mothership so as to not leave debris behind (Fig. 5).

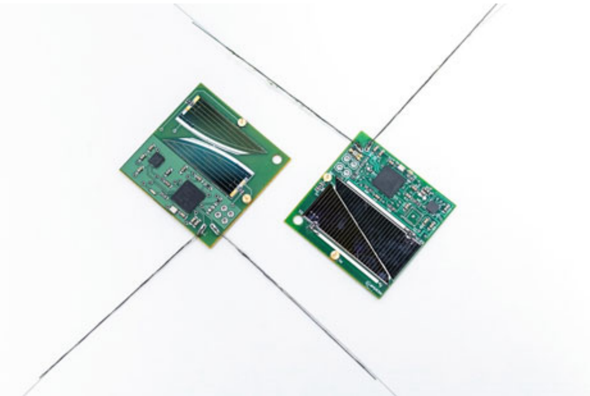


Fig. 5 Stamp-sized "chipsats" that can collect information as a swarm and report data to a "mothership." (Graphic courtesy of Stanford University)

6 Conclusion

The field of small satellites has continued to leap ahead as innovative ideas and new approaches to the design, manufacture, testing, launch, and utilization of small satellites have continued to race ahead. Conferences focused on smallsats, cubesats, and now even pocketQubes and chipsats contribute to the scientific, engineering, and practical knowledge associated with the smallsat field of study.

The whole area of innovation in the field has almost the field of constant innovation and spin-off ideas and creativity. The idea of cubesats for student experimentation, concept development, and learning about spacecraft design has led to a growing number of new ideas. The idea of nanosats and increasingly efficient cubesats has evolved to innovative picosats and pocketQubes. This drive toward increasing efficiency and innovation has in turn led to femto-satellites and even more recently toward chipsats and the idea of swarm systems linked to a "mothership" to collect data and transmit the information back to Earth.

There have also been innovations in terms of testing and verification processes, and as increasing knowledge and manufacturing systems developed, the production efficiencies also have increased. This has now led to a number of commercial ventures that can produce key components and even integrated systems at reduced cost. Today there are a number of smallsat kits and component parts that are accessible through such websites such as www.cubesat.com or pocketQube systems via www.albaorbital.com.

The remarkable development of smallsat technology and systems has made these capabilities available to an ever-widening circle of participants and at ever-decreasing cost. Innovations such as smallsat kits and components can be globally accessed via a growing number of reputable websites. Students at colleges and universities and in schools even down to primary level can be involved in space studies and experimentation. The authors were recently able to see student's space experiments in operation in a public school just outside of Cape Town, South Africa, which was active on the International Space Station.

The more effective use of a variety of smallsat systems and technologies plus improved and more cost-efficient launch systems has opened the doors to many more uses, applications, and scientific inquiries. Space agencies, research institutes, and commercial organizations have found an ever-expanding way to use smallsat efficiencies to explore and probe key areas of space sciences, demonstrate and test new technology and systems, and examine new space applications. This is an important new tool that continues to evolve, improve, and become more capable and cost-efficient.

7 Cross-References

▶ Resiliency, Reliability, and Sparing Approaches to Small Satellite Projects

References

Alba Orbital, Pocketqube kit, http://www.albaorbital.com. Last accessed 22 July 2019

A. Bukley, J. Connolly, T. Kaya, K. Yoshida, Systems and spacecraft (chapter 8), in *The Farthest Shore*, ed. by J. N. Pelton, A. Bukley, 2nd edn., (Apogee Books, Burlington, 2018)

IFL Science, “Sticker-Sized Satellites Will Soon Get to Orbit” IFL Science. https://www.iflscience.com/space/sticker-sized-satellites-will-soon-get-to-orbit/. Last accessed 25 July 2019

NASA SPOON Database, Smallsat parts on-orbit now (SPOON) database, NASA, request for information, solicitation number: NNA17S3VI001 Issued: July 31, 2017 and Modified: July 02, 2018. https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=3ce1bfa346d6459e296aea40632c602a&_cview=0

Satnews, SENSE meteorological Smallsat for U.S. Air Force by Boeing. http://www.satnews.com/cgi-bin/story.cgi?number=789943063. Last accessed 22 July 2019

STRaND-1, Surrey training research and nanosat demonstrator. https://earth.esa.int/web/eoportal/satellite-missions/s/strand-1. Last accessed 21 July 2019

STRaND-1 Smartphone Cubesat. https://amsat-uk.org/satellites/tlm/strand-1/. Last accessed 21 July 2019

R. Walker, P. Hager, “ESA Small Satellite Efforts” ESA presentation, IPPW small satellite course, June 2018. https://www.colorado.edu/event/ippw2018/sites/default/files/attached-files/4_-_ippw_2018_-_esa_small_sat_efforts.pdf

Resiliency, Reliability, and Sparing Approaches to Small Satellite Projects

Joseph N. Pelton

Contents

Abstract

The design, manufacturing, testing, and sparing approaches that have been used in the space industry have been built up over the course of over 60 years of experience. That experience has come largely from two sources, namely, civil and military space agencies and the aerospace industry serving the operators of increasingly sophisticated space application systems primarily for telecommunications, remote sensing/Earth observation, and GNSS networks. These systems largely had in common that they were complex, big-budget programs that were expected to have a long life despite the harsh conditions of outer space and launch operations. This has led to a design and testing process based on the emphasis of high reliability. This included such concepts as in-orbit spares, providing for redundancy of components that

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_27

represent a single point of failure and a very elaborate testing program to qualify all of the subsystems and fully integrated spacecraft against all types of possible flaws that could lead to failure. This approach has led to extensive quality assurance and lifetime testing for each spacecraft and key components. This testing program and the adding of redundancy for key components have extended the manufacturing time for spacecraft. It has also added significantly to the cost. This approach was believed to be necessary because there was no repair capability in space and of the high cost of launches, the expectation of quite long lifetime for spacecraft, plus the need to take this type of approach to obtain launch and operational insurance from underwriters.

The rise in recent years of the “NewSpace” industries, sometimes known as “Space 2.0,” has led to a revolution in how to design, manufacture, and operate spacecraft in Earth orbit. These new players in commercial space have questioned almost everything about commercial spacecraft design, manufacture, deployment, operations, and approach to reliability. They have asked basic questions about the long accepted “conventional approaches” as to how one should design, build, test, and launch spacecraft and even the orbits in which they should operate. Thus there are now a number of new ideas about the architecture of satellite systems and new concepts about how to design, manufacture, undertake quality and lifetime testing, launch, deploy, operate, and provide for operational spares in orbit. When there are hundreds or even thousands of operational spacecraft, the ratio of spares to operational satellites can be greatly reduced down to less than 10%.

The focus on this article is on how small satellites, and especially new small satellite constellations in LEO and MEO orbits, might be designed, built, tested, and deployed with new approaches to resiliency, reliability, and sparing. This approach started in a low-key way when much lower-cost satellites were using off-the-shelf components. This process began with the building of Amsat Oscar satellites and then the efforts of what is now known as Surrey Space Technology Limited. The next stage of thought came with the LEO systems designed by Iridium and Globalstar systems, but the most important breakthroughs came in the era of cubesats and the successful rise of small satellite projects such as those represented by Planet Labs, Spire, Skybox, and other small satellite projects born out of Silicon Valley-based entrepreneurs who have dared to think about satellite design and reliability in totally new ways.

This chapter examines these new ways of thinking and analyzes the pros and cons of these new ways of building and operating spacecraft and assesses how different approaches for different types of systems might still be appropriate. In short there may be more than one approach that can be used for different types of spacecraft that have different goals and aims.

Keywords

Acoustic testing · Additive manufacturing · Clean room specifications · End-of-life deorbit · In-orbit spares · Insurance coverage · Launch services cost · Liability convention · Lifetime testing · Mean time to failure (MTTF) · In-orbit servicing ·

Quality testing · Redundancy · Reliability and assurance testing · Resiliency · Sparing philosophy · Thermal vacuum testing · Vibration testing

1 Introduction

The world of spacecraft design, manufacture, reliability and assurance testing, launch services, and launch insurance for the space industry is in many ways different from most enterprises carried out on Earth. This is true for a number of obvious reasons.

Once a spacecraft is launched, there are no service personnel available to make repairs or to provide new fuel for thrusters or to replace batteries or solar cells that no longer function. Secondly the space environment is challengingly and in many ways quite lethal. The satellite can potentially be heated by the sun or if shielded become quite cold. There is also potentially damaging space weather in the form of solar radiation, coronal mass ejections of high speed ions, or even bombardment by micrometeorites, cosmic radiation, and now even collisions from orbital space debris. Space is a hostile and dangerous environment for satellites and getting more dangerous. Thirdly, for many decades at least the cost of launch services remained quite high with modest improvement in the cost per kilogram to launch a satellite, and reliability and possible launch failure are always a concern. Fourthly most satellites were ordered in limited numbers, and thus these handcrafted spacecrafts were expensive to build and test for reliability.

In sum, the design, production, reliability testing, launch, and operation of each satellite have become increasingly expensive for the conventional satellite industry as these satellites became bigger, more powerful, yet more cost-efficient. Large and more capable satellites represented a challenge to operate as their tracking, telemetry, and command systems grew to require millions of lines of code and launch insurance costs mounted as well. The development of larger, more powerful, and cost-efficient spacecraft, however, always seemed to make sense in that the high-powered beams allowed the ground systems to become ever smaller and less costly. Low-cost VSAT dishes for broadcast satellite services and even handheld transceivers that grew to number in the millions also provided the cost justification for this technology inversion. More technology and power in the sky for a few complex and powerful satellites made sense if there could be millions of low-cost dishes at every home or apartment building, or this allowed millions of handheld satellite phones to be sold at lower cost.

At various times there were questions about this main line thrust of satellite development to design and build bigger, more capable, yet more cost-efficient spacecraft that could also have lifetimes that extended to 15 years or even 18 years. Volunteer scientists built low-cost amateur radio satellites called OSCARs that were launched at low costs. In the 1990s there were various ideas that promoted the ideas of producing capable but smaller satellites that could be produced on manufacturing lines with greater efficiency and lower cost of production and lower cost of testing once the production line had proved a reliable product. The Iridium satellites, largely designed and engineered by the Motorola Corporation (Thomas n.d.), and the Globalstar network, largely designed and engineered by Space Systems/Loral and Qualcomm, had a major impact on how low Earth orbit constellations and small satellite for mobile communications would be designed, engineered, manufactured, launched, and operated (Globalsatr n.d.).

In some ways the so-called Teledesic satellite network that was backed by Bill Gates and Craig McCaw and first organized in 1994 eventually went bankrupt at the turn of millennium. This never-launched system was conceived as a disruptive technology that would re-envisioned many aspects of the conventional model for global satellite communications.

In terms of design, rapid prototyping and manufacture, use of inter-satellite links, reduced transmission latency, large-scale deployment in LEO orbit, and sparing philosophy, the Teledesic system was designed to create a whole new model for how satellite networks were designed, manufactured, tested, deployed, and operated.

In every key aspect including resiliency of design and sparing this system, as conceived some 20 years ago, is almost an exact a model for the large-scale LEO constellations of small satellites now being implemented today. Certainly some design aspects were found in the Globalstar and Iridium mobile satellite systems that were deployed in the late 1990s. Teledesic, in terms of overall design concepts, however was the "true intellectual parent" of the OneWeb and Starlink megaLEO satellite systems that are currently being deployed and will also serve as precursor in many ways of many other systems yet to come (Lloyd's Satellite Constellations-Teledesic n.d.) (Fig. 1).

The design of the Teledesic system was revolutionary in a number of ways. These included several new concepts in terms of resilience and reliability. Teledesic, which was to be a Ka-band system, envisioned assembly line manufacture but also with

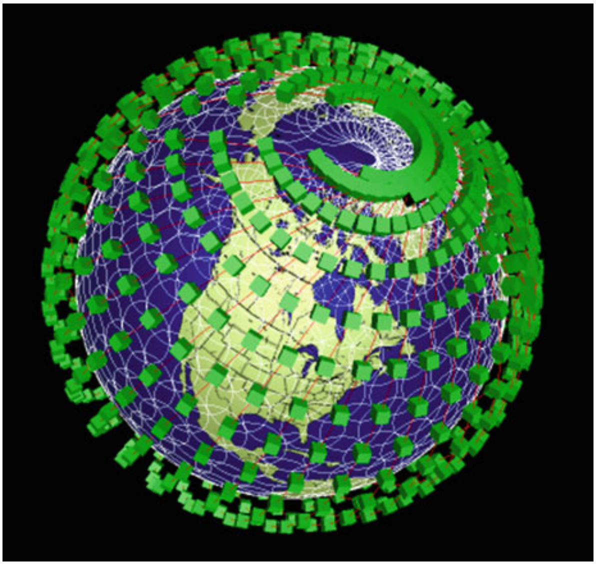


Fig. 1 Proposed 840 Teledesic satellite system plus 80 spare satellites. (Graphic Courtesy of Lloyd's of London)

high levels of reliability. The large number of satellites in the constellation included the idea that the incremental cost of deploying 80 additional satellites as system spares (i.e., 9% of the total) would not be large in proportion to overall cost of manufacturing and launching the overall system. Secondly it envisioned the design would include eight inter-satellite links that could then interconnect to eight adjacent satellites. With this degree of network flexibility, it would not be difficult to work around any satellite failure in the large-scale network. After more system design, studies were done and efforts were made to reduce cost; it was decided in time to reduce the number in the network to 288 satellites. Ultimately the innovative project as first envisioned by Dr. James Stuart as the "calling" telecommunications satellite project was abandoned (Teledesic, Astronautix Encyclopedia n.d.).

The low Earth orbit (LEO) systems that were deployed, namely, the Iridium and Globalstar satellite system for mobile communications and Orbcomm for store and forward data relay services, all thought in terms of putting up spares that could be inserted into operational service. Further, Iridium included the capability of inter-satellite links (ISLs) to increase reliability by working around satellite failures in the network. This feature also greatly reduced the costs in potentially eliminating the need for a large number of TT&C facilities located all over the world. It must be noted that in the case of Iridium, the additional cost to the satellite manufacture of the ISLs largely offsets the cost savings by eliminating the need for a large network of ground-based tracking, telemetry, and command (TT&C) facilities. Thus the main advance was in terms of near instance restoration of services when a satellite might fail.

The final historical note about LEO constellations and reliability comes from what some call the cubesat revolution. The student experimenters that began building small sats in the 1980s and 1990s often did not have huge budgets and then thus tried to find both lower-cost ways to construct their cube satellite experiments, but they also focused on miniaturization of components, sensors, power sources, structures, and antennas to also save on launch costs. These cubesat projects led to commercial start-up ventures that managed to design application satellites that were quite cost-effective.

Thus new commercial ventures such as Planet Labs, Skybox, and Spire found ways to design and build small satellites for a fraction of the cost of commercial operators of more conventional remote sensing and Earth observation companies. In some cases it was lower-cost wiring, batteries, and processors, and in other cases it was miniaturized sensors. These new small satellite system operators conceded that their small satellites were perhaps not as reliable as the larger and more conventional satellites for remote sensing. Their practical answer was to say that they would launch more satellites in their assembly lines that would in essence never shut down. The idea is that they could on their continuous production lines achieve three goals: (i) continuous improvement with frequent new generations of their small satellite measured in weeks or months rather than years; (ii) they would be able to get more frequently updated information for improved analytics; and (iii) they would consider each new small satellite a potential "spare" that would add resiliency to their overall network.

Although small satellites for remote sensing have led the way, the telecommunications satellite industry has followed their lead to pursue small satellite innovations. In this case the motivation has been the pursuit of new markets with low-latency satellites that are better suited for Internet-based services, Internet of Things (IoT) services, broadband 5G services, and better services to rural and remote areas. Another driver is the shift from broadcast satellite service to OTT (over the top) digital streaming via broadband networking. The need for power and antenna gain has not allowed communication satellites the same miniaturization advantages, but the other advantages seem to all apply.

These other gains that apply for small sat networking satellites include more efficient high-volume manufacturing, additive manufacturing techniques, more efficient deployment of small satellites from new reusable launch vehicles, and new sparing concepts used in all of the very large-scale constellations.

This change in satellite system design has happened quite quickly over the past 10 years. There are now three main types of satellite systems that are now available for the largest space systems market of telecommunications including broadcasting and networking. There are high-throughput satellites (HTS) with extraordinary data streaming and broadcasting efficiency deployed in GEO orbit such as operated by Intelsat, EchoStar, Eutelsat, and Telesat.

There are the MEO orbit satellite networks as represented by SES's O3b and its latest mPower network that is being manufactured by Boeing (Henry 2017) (See Fig. 2). And then there are the high- to medium-speed LEO constellations that vary everywhere from the Kepler and Capella true small sat constellations to the much larger mini-satellite LEO systems such as those currently being launched such as OneWeb, SpaceX's Starlink, and others to be deployed.

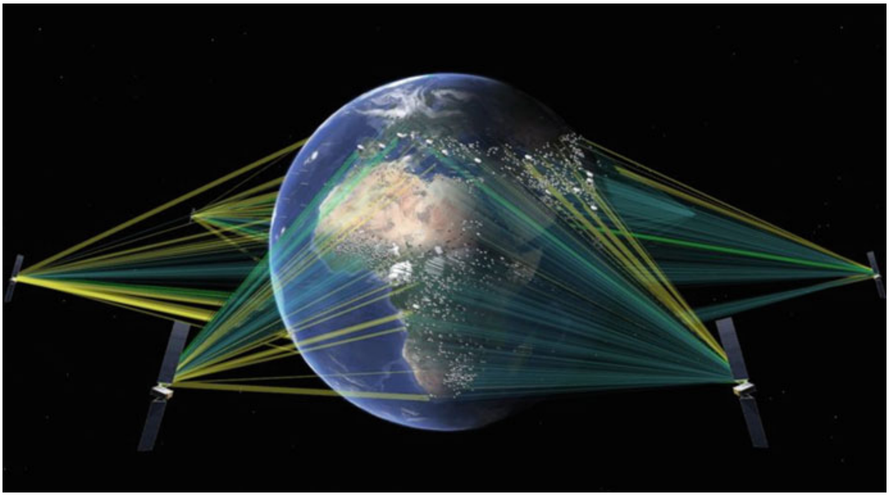


Fig. 2 The new O3b MEO "mPower" network with fiber-like throughput speeds. (Graphic courtesy of SES)

What is important to note, in terms of reliability and resilience, is that these various types of satellite systems entail different approaches to coping with risk and spacecraft or system control failures. Nevertheless each has a technical logic and business and economic viability to them. The strategies for GEO and MEO systems are closely aligned with the conventional approaches to quality and mission assurance, while the LEO systems largely represent a new approach of letting the large number of satellites in the constellation to be the protective margin for service reliability. This may or may not also be augmented with inter-satellite links designed to provide additional protective margins for systems control and network redundancy.

Each of these approaches will be discussed below. In addition the added complication of orbital debris and debris removal, especially in the large-scale LEO constellations, will be discussed as an additional element of risk.

2 Reliability and Resilience for GEO and MEO Networks

The traditional approach to providing for the reliability and resilience largely continues to apply to GEO and MEO systems. This is because the number of satellites that are procured at one time, for such networks, continues to be a rather small number that is typically in the range of 4–10 spacecrafts. This limited number of procurement limits the ability to take advantage of the economies of large production runs and achieving a number of spare satellites at the incremental cost of last satellites in the production run and economies of scale achieved at the end of a production run and the economies associated with launching a number of satellites together to low Earth orbit (LEO).

There are efficiencies of production and benefits of proven efficiencies that can be realized by manufacturers creating standardized platforms that have proven reliability. Thus manufacturers tend to create three-axis stabilized spacecraft platforms often optimized for satellites of a particular size, mass, and power performance. Thus a satellite operator might be purchasing say four, six, or eight spacecrafts at a time, but the payload may be integrated with a proven platform bus that has been successfully flown on scores of other missions. Thus the specialized remote sensors or telecommunications antenna system for a particular mission may fly on a proven bus that has performed reliably on many previous missions. This provides both a cost bonus and risk reduction benefit.

There is a need for reliability testing for the new payload and for the payload as integrated with the platform to ensure that the risk of an in-orbit failure is as low as possible. The testing process breaks down into what systems and subsystems that are to be tested, the type of testing that is to be done, and when and where this test evolves into a test plan for the satellites. The key components and subsystems that are typically to be tested, the types of tests, and test plan components are noted in Table 1 (Bukley et al. 2018).

The reliability, performance, sophistication, and operation of satellites in Clarke orbit (GEO orbit) and MEO orbits are in many ways quite similar. These typically are high-performance satellites with sophisticated instrumentation, relatively high-power systems with high-performance sensors or telecommunications antenna capable of supporting high-precision spot beams designed to achieve very high levels of frequency reuse. Thus all of the testing procedures and quality and mission assurance tests noted in Table 1 above would be all likely included in acceptance testing for both MEO and LEO satellites. Nevertheless there are some differences that are worthy of note.

Radiation level testing: The satellites in MEO orbit are more likely to be subjected to much higher levels of radiation. GEO satellites are generally above the highest levels of radiation exposure from the Van Allen belt. GEO satellites still have to be concerned about radiation flares from the sun that occasionally occur, but radiation from the upper Van Allen belt is more or less a pattern of a continuous

Table 1 Key elements in a test plan, types of tests, and component tests

Elements that are included in a spacecraft test plan
Typical components and subsystems to test
Guidance navigation and control
Propulsion
Attitude control, three-axis stabilization, and pointing systems
Thermal control system
Communications, telemetry, command system, and data handling
Processors, redundant systems, and switching systems
Power systems
Active and passive thermal control systems
Structure, deployment mechanisms, and control sensors and actuators
Payload components and systems (if there is a standardized and flight-proven bus platform, then more emphasis can be placed here)
Adequacy and reliability of the ground control systems and global access of TTC&M Systems to satellite network
Types of tests and manufacturing specifications
Thermal range (heat and cold extremes)
Vibration testing (intense vibration at launch, pogo effects, and low-frequency sinusoidal vibrations)
Acoustical
Radiation levels
Reliability, precision, and clean room specification for manufacture and assembly
Design reviews and oversight of manufacturing and testing
Test plan components
Test objectives, frequency, and locations
Test equipment requirements
Step by step procedural detail and process
Test methodology and protocol
Input/output value limits and pass/fail criteria

degree of exposure. Thus the design of MEO satellites will typically include more of a glass-like coating of the photoelectric cells in the solar array to extend lifetime. The electronics and circuit breakers and switches will need to be designed to protect against high levels of radiation exposure.

Thus the exact orbit and its nearness to the Van Allen belts and the need for protective shielding or precautions against high level of radiation from high energy protons in these belts must be taken into consideration.

The inner belt is shaped like a toroid (i.e., like a doughnut). This first belt is largely concentrated between 960 and 6000 km or (600–3700 mi). The outer belt (another toroid) is largely concentrated between 15,000 and 20,000 km (or 9300 and 12,400 miles) above the planet. In short radiation from the Van Allen belts is highly concentrated and can be quite harsh at some altitudes and much more benign in other regions (see Fig. 3).

Thus LEO satellites are often deployed at altitudes under 1000 km, and MEO satellites tend to be orbited in the range between 6000 and 15,000 km. If they are deployed in the range between 15,000 and 20,000 km such as the case with the NAVSTAR GPS satellite system, additional radiation protection and shielding for the solar arrays and the electronics are highly advisable.

Further digital processing chips and electronic components should be tested against higher radiation levels. Of course the added shielding increases spacecraft mass and thus boosts launch costs (Howell 2018).

Deorbit requirements: There is another mass penalty associated with MEO satellites that is actually much larger than that represented by shielding to protect solar cells, electronic components, switches, and processors. This penalty comes from the fact that MEO orbits create a real challenge for deorbiting at the end of life. LEO satellites are easiest to bring down to splash in the oceans or more likely burn

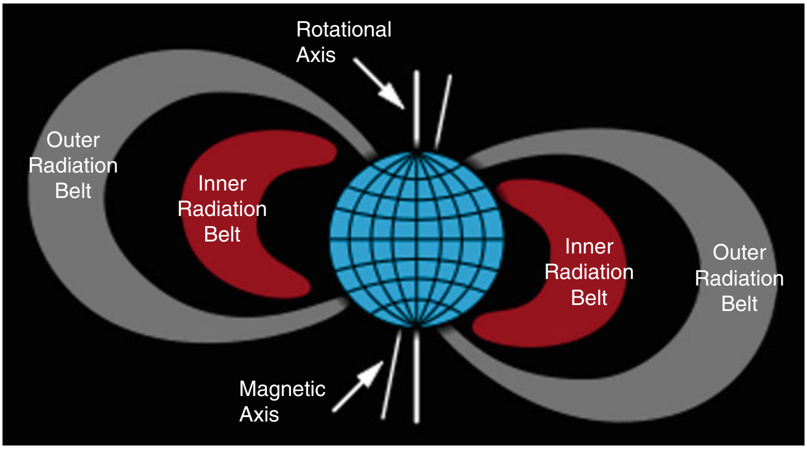


Fig. 3 The Van Allen belts represent high-radiation areas and a threat to spacecraft. (Graphic courtesy of NASA)

up in the atmosphere. GEO satellites can be raised to a higher parking or “graveyard” orbit where they can remain for literally millions of years.

MEO satellites, however, must add quite a bit of additional fuel (about 40% additional to that provided for regular station-keeping) in order to actively deorbit them. These types of spacecraft in terms of their orbital configuration are in the reverse of a “Goldilocks” orbit in that they are either too high to deorbit back toward Earth or too low to go into a graveyard orbit above geosynchronous orbit. In terms of number of satellites to create a global network (i.e., about 15–20) or altitude that does not to have too much path loss or latency, MEOs were first thought of the perfect compromise between extremes, but in terms of excess fuel to achieve deorbit, these types of satellites represent the extreme example. If strict new regulations are enacted for mandatory deorbit guidelines, it will be MEO orbit satellites that will have the greatest challenge to meet without there being a large financial and operational challenge.

3 Testing Apparatus

One area where MEO orbit satellites can have an advantage over GEO satellites is that they can often be much more compact than GEO orbit satellites. These satellites because they are twice to even four times closer to Earth can have the equivalent of 4–16 times the effective antenna gain or sensor performance of a GEO satellite. This means that the satellite can be less massive and have smaller solar arrays or smaller antennas than a larger GEO satellite. This means that smaller and less costly thermal vacuum chambers can often be used for testing. In general verification and validation assessments, lifetime or stress testing or performance can be done at lower costs.

4 Reliability and Resilience for Small Satellite Networks

The “NewSpace” revolution has been disruptive to many aspects of how spacecraft systems are designed, manufactured, launched, and operated. Core to these changes is the idea of small satellites that are less costly to design and built with components that sometimes include off-the-shelf components and are manufactured via such techniques as additive manufacturing. They also might be less extensively verification and validation testing after the manufacturing process has been proven to be precise and completely consistent against proven standards. This small satellite production in large quantities for constellation numbering in the hundreds or thousands allows the paradigm to shift from a few satellites elaborately tested for absolutely highest of standards of reliability and resilience to a process of having a large array of satellite serving to verify system reliability.

5 Small Satellite Constellation Design as Self-Sparing Network

The predominant approach to satellite applications for many years was to have a limited number of operational satellites and an even more limited number of designated in-orbit or possibly on-ground spares ready for launch. The idea of large-scale constellations includes a sufficient number of satellites that the entire constellation represents a sparing capability for itself. The Iridium and Globalstar mobile satellite system did deploy satellites intended as in-orbit spares but leveraged the capability of these spares in various ways. The Iridium system introduced the concept of inter-satellite links (ISLs) so that adjacent satellites could work around the "hole" created by any satellite failure until the replacement satellite was maneuvered to the correct orbital position. Further it developed a system of deploying spare satellites in a slightly lower orbit that could efficiently be lifted to the proper position and thus reduce fuel expenditure and increase the speed of restoration of full service capability.

The shift from LEO constellations with 50–70 satellites to megaconstellations with many hundreds and potentially thousands of satellites creates a large enough network that individual satellites are no longer of great consequence. Particularly in networks for remote sensing such as Planet Labs, the idea of reliability is geared simply to such measures as moving up the regular deployment of satellites. The existing large number of satellites will respond to any satellite failure. There is no longer any scarcity of spare capacity since the entire constellation is the spare.

This approach has been summarized in the following manner: "For this type of alternative design architecture, the replacement of failed satellites with a ready supply of spares [within the existing network] is the key to achieving system reliability. This approach is seen as the alternative to stringent testing and flight-qualified components with proven long-life capabilities in a stringent space environment"(Pelton 2018).

In networks such as SpaceX's Starlink that envisions the ultimate launch of around 12,500 spacecraft, there will be more or less a constant deployment of satellites including spare satellite capacity. When there is a campaign of launching 60 satellites at a time that only represents 0.5% of the entire network, the calculus of sparing dramatically changes.

6 Inter-satellite Links (ISLs) to Augment Reliability

Of course networks such as Starlink represent the extreme for large LEO networks. Another strategy that was introduced by Iridium and was proposed by Teledesic was the use of inter-satellite links (ISLs) to work around satellite failures that might create a gap in complete global network coverage.

The addition of inter-satellite links to large-scale LEO networks is clearly a way of extending the reliability of a large satellite network. If adjacent satellites either to the side or with regard to leading or lagging orbits can connect to users, then the outage would not be apparent to the user community. If there is a spare satellite in a slightly lower orbit that can be raised to the orbital location where the failure occurs within hours of the failure, the problem would be seamlessly addressed. The biggest problem might be finding a way to deorbit the failed satellite.

7 Radiation and Space Weather Concerns

There is always a concern with spacecraft being exposed to solar flares and coronal mass ejections (CMEs). Fortunately for LEO systems, these are best protected by the Van Allen radiation belts and the Earth's natural electromagnetic protective fields. Thus while there should be some concern for shielding and protection against a high-level CME event, this is not a key concern for LEO constellations deployed below 1000 km. For constellations that are launched in orbits about 1000 km, perhaps more concern should be given to radiation testing.

8 Lifetime Concerns

Spacecraft that are deployed in LEO orbits tend to have shorter lifetimes than satellites deployed in GEO or MEO orbits. This is because of their nearness to the Earth's atmospheric drag; high orbital speed; strict mass budgets that limits redundancy for key components, subsystems, or vital components; and no allowance for additional fuel, batteries, or other expendables. Mean time to failure in the range of 6–8 years might be a typical expectation. This shorter lifetime can be seen as an advantage in terms of being reasonably able to use more off-the-shelf components, processors, batteries, and structural elements that are lower in cost yet still have a reasonable lifetime expectations.

On the other hand, the shorter lifetime for quite large constellations, particularly those that might have thousands of spacecraft deployed in a network, represents a disadvantage. If satellites have a lifetime of 6–8 years before they need to be replenished with new satellites, it is a major if it takes up 1–2 years before the launch campaign is finished. GEO and MEO systems can be quickly deployed, and lifetimes in the 12–18 years range are common. The full lifetime of the GEO and MEO networks can be realized and exploited, but for megaLEO systems the deployment period eats into the period of useful system exploitation.

9 Deorbit Concerns

The deorbiting issue of satellites at the end of their practical life that is well synchronized with the deployment of the next generation of upgraded satellite represents a number of practical, technical, economic, and reliability and resilience concerns. The number of crucial questions that are concerned here includes:

How long can a system operator extend the operational lifetime of retiring satellites without risking the possibility of collision between retiring spacecraft and the new generation of satellites?

Are the deployment approaches now being used to launch large number of small satellites such as the spinning release of 60 satellites at a time (in the case of a Falcon launch vehicle for the Starlink system) sufficiently safe in the case of a replenishment of a LEO network, or is a controlled dispenser needed?

Are the current voluntary guidelines from the IADC for deorbit of satellites some 25 years after end of life now obsolete and perhaps highly dangerous in light of the likely replenishment schedules of LEO constellations occurring every 6–8 years and launch campaigns that might take 1–2 years to complete?

10 Concerns About Orbit Space Debris

The concerns of the new very large-scale constellations and the accelerated chances of orbital collisions continue to rise. Current estimates of the likelihood orbital collision between two space objects as developed by NASA and ESA estimate the current odds are now between once every 5 years and once in every 10 years. These assessments were developed prior to the latest plans to launch perhaps over 20,000 new spacecraft in the next few years with a high concentration in low Earth orbit (LEO).

The Aerospace Corporation has undertaken an analysis of the additional concern that a deorbiting spacecraft from one of the new LEO constellations might possibly hit an aircraft. This assessment found that there was indeed a finite possibility that such a collision could occur with a greater than 1% per year in the event that all of the proposed constellations were deployed as now envisioned.

11 Conclusion

The world of “NewSpace,” “Space 2.0,” and the so-called small satellite revolution has brought many changes to the space industry. These new approaches to designing, manufacture, launch, and operation of application satellites have been disruptive in many ways. One of the many significant changes has come in how the resilience and reliability of space systems are planned for and implemented. The new manufacturing and testing methods associated with small satellites including the use of more off-the-shelf components and large production runs with automated processes have tended toward satellites with lesser standards of reliability being launched, but the sheer volume of the spacecraft that are planned for launch is seen as a means of increasing the reliability of the overall networks that have significantly larger elements to ensure continuity of service.

There are several aspects of small satellite design and manufacture that can assist with reliability and rapid restoration of services. The elements include (i) inter-satellite links (ISLs) that can allow routing of service around failed satellites, particularly in the case of telecommunications and networking services; (ii) additive manufacturing techniques that can increase reliability of component parts; and (iii) super redundancy of satellites deployed in megaLEO constellations in order to allow the "network to be the spare" rather than designated spare satellites.

These new approaches to sparing and reliability of small satellite constellations have tended to shift the emphasis of concern from "sparing philosophy" to concerns about space traffic management, space situational awareness, and the prevention of collisions between the large number of satellites that are being deployed into huge constellations. The particular concern is the disposition of satellites in large constellations at the end of life and the new deployment of spacecraft for the next generation of satellites. In the age of GEO and MEO constellations, this was a relatively straightforward and not particularly high-risk type of operation. The experiences with the Globalstar, Iridium, and Orbcomm networks have already shown that deorbit operations involve risk elements that raise significant concern. The move to large-scale constellations with thousands of spacecraft raises a new level of concern about the deorbit and replacement process and the risk of collisions occurring.

There are also concerns about the reliability of command and control systems and systematic control of such networks without spacecraft conjunctions and potentially catastrophic collisions occurring. The resiliency of TT&C networks and the ability to execute commands on a continuous and uninterrupted basis represent a concern that is perhaps not fully addressed.

Some of these concerns can and will be addressed through improved technology and artificial intelligence in satellite control systems. Other aspects of the concerns for orbital safety and the long-term sustainability of outer space activities will need to be addressed in new regulatory guidelines and processes. These might be by means of bottom-up development of best practices. In time these safety measures will likely require new processes associated with internationally agreed methods of space traffic management and perhaps globally mandated methods for orbital debris removal and improved systems to achieve sustainability of space services and operations in Earth orbit – particularly in low Earth orbit.

12 Cross-References

▶ Kits, Components, and the Design, Manufacture, and Testing of Small Satellites

References

A. Bukley, J. Connolly, T. Kaya, K. Yoshida, "Systems and spacecraft" chapter 8, in *The Farthest Shore*, ed. by J. N. Pelton, A. Bukley, 2nd edn., (Apogee Books, Burlington, 2018)

Globalsatr, (n.d.). http://sslmda.com/downloads/products/gblstar.pdf (Last accessed Jun 30, 2019)

C. Henry, "SES building a 10 terabit 03b 'mPower' constellation space news, (2017). http://www.astronautix.com/t/teledesic.html

E. Howell, The Van Allen radiation belts: Facts and figures, (2018). https://www.space.com/33948-van-allen-radiation-belts.html

Lloyd's Satellite Constellations-Teledesic, (n.d.). http://personal.ee.surrey.ac.uk/Personal/L.Wood/constellations/teledesic.html (Last accessed June 30, 2019)

J.N. Pelton, *"Lifetime Testing, Redundancy, Reliability, and Mean Time to Failure" Handbook of Satellite Applications*, 2nd edn. (Springer Press, Switzerland, 2018), p. 1326

Teledesic, Astronautix Encyclopedia, (n.d.). http://www.astronautix.com/t/teledesic.html (Last accessed June 28, 2019)

J. Thomas, Low Earth orbit satellites: An overview of the Iridium satellite system (n.d.). https://pdfs.semanticscholar.org/38eb/002e16a2fb7975fe106341cc77a31e219bcf.pdf

Part VI

Ground Systems and Small Satellites

Evolution of Satellite Networks and Antenna Markets

Arunas G. Slekys and Safieddin (Ali) Safavi-Naeini

Contents

Abstract

The VSAT (very small aperture terminal) was first developed for commercial use by Hughes Network Systems in the mid-1980s and implemented on the first commercial satellite network for Wal-Mart, operating over a GEO (geostationary) Ku-band satellite. In over 30 years since, there have been dramatic advances in satellite, networking and ground system technologies, solutions, and services, the scope of which go well beyond what can be addressed in this Handbook. The modest objective of this chapter is to provide key insights into the evolution of satellite networks and associated ground systems that today serve all global

---

A. G. Slekys (✉)
Corporate Marketing, Hughes Network Systems, Germantown, MD, USA
e-mail: Arunas.Slekys@hughes.com

S. A. Safavi-Naeini
Department of Electrical and Computer Engineering, University of Waterloo,
Waterloo, ON, Canada
e-mail: safavi@uwaterloo.ca

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_32

market sectors. It identifies applications for which the transformative potential of electronically steerable phased arrays (described in chapter ▶ "Electronic Beam-Scanning Technology for Small Satellite Communication Systems and Their Future Development") is poised to displace mechanically steered parabolic antennas as large-scale, small satellite constellations are launched. The net result will be an expansion of global satellite markets and diversification of ground systems, as VSATs and flat panel, phased array solutions supplement each other to fuel the expansion.

The world of small satellite constellations in LEO and MEO orbits will extend the reach of satellite communications, particularly in underserved portions of the world. By eliminating mechanical steering, flat panel antennas with electronic tracking will open up new addressable mobility markets through lower cost and compact packaging, whether for airborne, maritime, train, or land vehicle applications. This is not a matter of ground satellite systems being replaced, but supplemented in a very significant way.

Keywords

VSAT (very small aperture terminal) · Satellite networks · Ground systems · Global market sectors · Geostationary (GEO) satellites · Low Earth orbit (LEO) constellations · Medium Earth orbit (MEO) constellations · Mechanically steered parabolic antennas · Phased array antennas · Flat panel antennas

1 Introduction

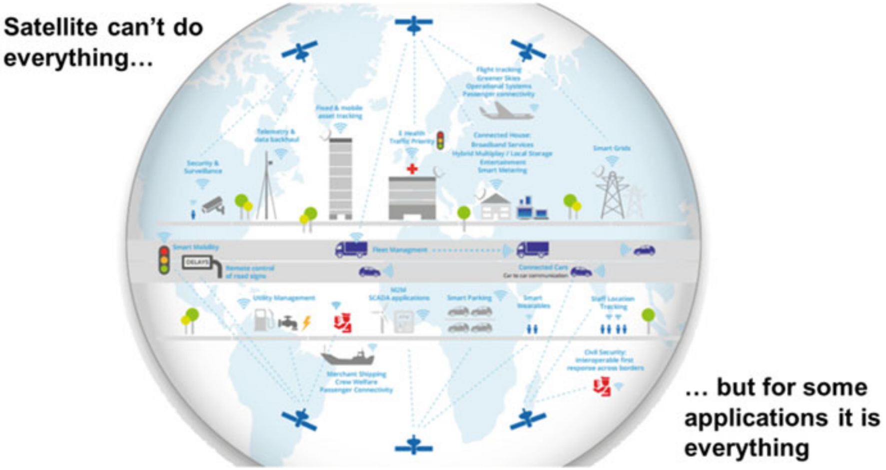
That decision to implement the first enterprise satellite network by Walmart was hailed by Fortune magazine (Fortune 2005) as "one of 20 most strategic business decisions of the twentieth century" because it gave them an "informational competitive advantage." In particular, it gave Sam Walton, the owner of Walmart, the ability to review progress of his many distributed stores by utilizing the then new medium of video-conferencing with his management team, including sharing up-to-date sales, marketing, and inventory information. Only satellites could reach all of his locations across the country, mostly in rural America, and unlike terrestrial technologies, offering uniform quality of service delivery at costs that are independent of location.

Fast forward more than three decades and these core benefits of satellite networks remain as key drivers in enterprise and government markets globally. Most significantly, advances in satellite architectures and technologies have lowered cost per bit of high-speed service delivery to be competitive with terrestrial, thereby expanding addressable markets to include the billions of consumers unconnected worldwide. Latest market data (Northern Sky Research 2019) shows the total installed base of VSATs globally is approaching seven million sites, with approximately four million being consumer and the aggregate growing at almost 15% CAGR. Today's largest consumer satellite Internet service, on just one VSAT system, i.e., HughesNet™, spans the Americas with over 1.4 million subscribers.

Invention of the VSAT began the transition from when only large corporations or broadcast networks could afford the large dishes and the extensive real estate required to receive signals from the early C-band and Ku-band GEOs, to today's world of multi-spot beam, Ka-band, high-throughput satellites (HTS) in which everyday consumers can enjoy the benefits of high-speed Internet access at affordable costs. For example, in the mid-1960s, Intelsat I (http://www.boeing.com/defense-space/space/bss/factsheets/376/earlybird/ebird.html) required a 30-meter Standard A parabolic antenna to receive one TV signal. Just two decades later, this had dramatically changed. The first VSAT emerged as a large briefcase-size box weighing several kilos connected to an external 1.5- to 2-meter fixed parabolic antenna, providing typically a maximum user uplink data rate of 9.6 kbps and costing approximately $10,000.

Today's GEO satellites can transmit over 200 TV channels into a half meter parabolic antenna and receiver or deliver up to 1 Gbps of two-way Internet data throughput via the latest generations of compact VSAT installations, including modems/routers and a range of fixed/mobile/transportable antennas, virtually all being mechanically steerable parabolics.

As illustrated in Fig. 1, today's burgeoning multi-billion dollar satellite industry is a core part of a rapidly evolving networking architecture that connects people, enterprises, and things worldwide, delivering video, voice, and Internet access/data services to millions of locations.



- Consumers
- Service providers
- Large and small enterprises across all verticals: Oil and gas, utilities, retail, news, lotteries, hospitality, banking, film production, forestry, sporting events, insurance
- Government and defense: Border patrol, NASA, FEMA, EPA, FBI, NATO
- Emergency services organizations, police, fire, medical

Fig. 1 A world of satellite markets. (Graphic courtesy of Hughes Network Systems)

2 Satellites Enable High Availability Connectivity

By virtue of operating over wireless channels in space, satellite networks uniquely provide a robust alternative path to terrestrial links, whether fixed (fiber, cable, landlines) or wireless/cellular. High availability, fault-tolerant solutions result when both networking categories are configured together, with either as primary or backup, making them critically important when disasters strike for both emergency preparedness/response and maintaining enterprise or government operations. As a case in point, during the aftermath of Hurricane Maria which hit Puerto Rico and the US Virgin Islands in November 2017, satellite connectivity proved invaluable in recovery operations as terrestrial infrastructure was devastated (Fig. 2).

Hughes and partner, Response Force 1, supported the San Cristobal Hospital in Ponce by deploying VSATs and solar generators, helping to keep it operational and enabling leadership teams to order supplies and medications as well as evacuate patients in critical condition. They also supported businesses, such as wholesalers, pharmacies, retailers, and others to ensure operations could continue, including processing insurance claims, credit card payments, and government-issued food stamp (debit card) purchases – which was critical as cash was difficult to come by following the storms. And not to mention working with federal agencies to reconnect airports in St. Croix, St. Thomas, and San Juan in order to schedule first responder flight cycles to the islands (Fig. 3).

3 Mobility Solutions: From Emergency Response to Telemedecine, Mobile Education, and Banking

In virtually all the application areas illustrated, VSATs and related satellite systems/gateways from the earliest versions to the most advanced have employed primarily parabolic, mechanically steerable antennas operating over Ka or Ku band GEOs, in either fixed, transportable, or mobile configurations. Figure 4 illustrates just one example (C-COM Satellite Systems 2019) of a transportable antenna offering, a category that evolved to serve a wide range of markets by virtue of rapid, self-pointing capability, typically 90 seconds or less, and not requiring specially trained experts – in this case with solar panels and battery backup for rapid deployment virtually anywhere.

Transportable configurations span a wide range of applications globally, from satellite newsgathering, to mobile telemedicine, remote oil/gas and military field operations, cellular towers on wheels, and more, which the reader may find at various vendor websites. Figure 5 shows examples from various countries of mobile clinics configured for different categories of medical care, from basic checkups and nutritional guidance to breast cancer screening – bringing much needed telemedicine services to the public living outside urban areas.

Mobility applications as opposed to transportable have proven extremely challenging when employing mechanically steerable antennas, and all require some form of movable and stabilized platform, including accurate GPS and gyro positioning.

Fig. 2 Terrestrial infrastructure can struggle to withstand the forces of nature. (Graphic courtesy of Hughes Network Systems)

Fig. 3 Satellite connectivity at the airfield of San Juan Airport. (Graphic courtesy of Hughes Network Systems)

- Portable and scalable
- Transportable case includes battery, 2-4 foldable solar panels (125W)
- Single sealed lead acid battery holding up to 100Amp/Hr, expandable
- Direct AC (110 or 220VAC) and DC (12VDC) outlets
- Recharged via solar panels, vehicle DC or AC;
  can operate for 2 days: typical load(Antenna+Ctlr+modem+BUC+IPphone+laptop)

Fig. 4 Example of transportable self-pointing parabolic antenna. (Courtesy of C-COM Satellite Systems)

Fig. 5 Examples of mobile telemedicine vehicles. (Graphic courtesy of C-Com Satellite Systems)

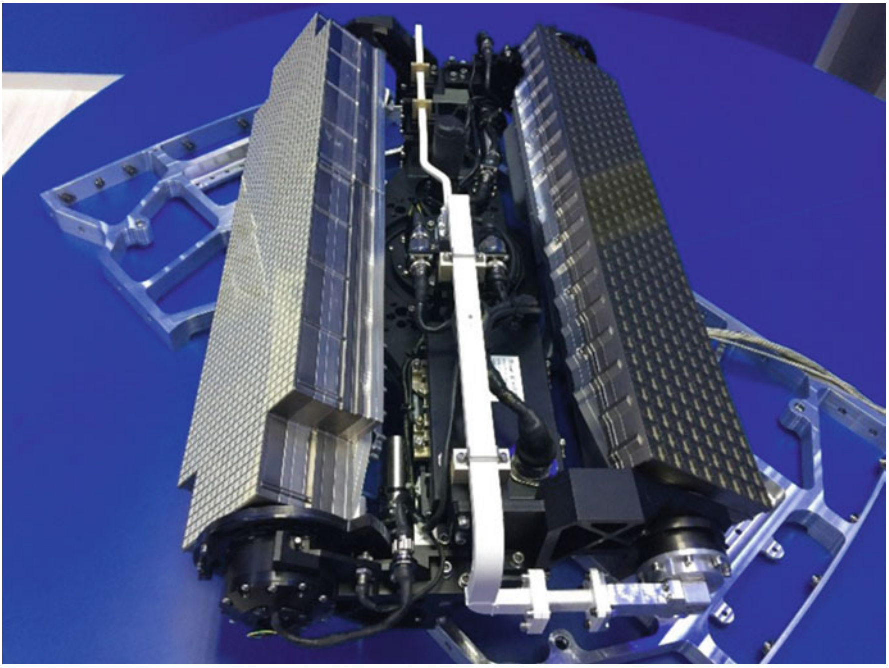
Whether operating over GEOs, MEOs, or LEOs, and whether for airborne, maritime, or train services, such configurations are bulky and relatively expensive, on the order of 100 thousand or more US dollars, and as a result have been limited to low volume commercial and military markets.

Figure 6 shows an example of an airborne, mechanically steerable Ku/Ka dual-band antenna designed for commercial aircraft. Besides the high cost of retrofit, the relatively large radomes to house such antennas increase flight drag and add to fuel costs. Despite these barriers, the market demand is unabated, and Euroconsult estimates that more than 23,000 commercial aircraft will offer connectivity to passengers by 2027 (up from 7,400 aircraft in 2017).

A discussion of electronically steerable phased arrays as a game-changing alternative to the mechanically steerable parabolic follows in chapter ▶ "Electronic Beam-Scanning Technology for Small Satellite Communication Systems and Their Future Development," highlighting its advantages in reducing size, weight and power requirements and with lower cost. This is especially important for airborne applications through reduced radome sizes and hence corresponding drag, not to mention opening up the potential for personal vehicle applications.

4 Emerging Hybrid Architecture: From GEOs, MEOs, to LEOs, SmallSats, and 5G Wireless

Today, with over 7 billion wireless and over 4 billion Internet subscribers, we are on the brink of creating a truly interconnected global society with unprecedented opportunities to advance social and economic development in all nations. But to



Receive frequency [GHz]	10.7–12.75	17.8–18.8, 18.3–19.3, 19.7–20.2
Transmit frequency [GHz]	13.75–14.5	29.25–30
Polarization RX/TXSelectable via A791 AMIP	Linear VP/HP	Circular LHCP/RHCP
Receive G/T (at 30° elevation)*	11.6 dB/K @ 12.75 GHz (cruise level)	15.4 dB/K @ 20.2 GHz (cruise level)
Transmit EIRP [dBW]*	43 dBW @ 14.5 GHz	48 dBW @ 30GHz
Transmit antenna patterns	FCC 25.209	FCC 25.209
EIRP spectral density	FCC part 25.222 and 25.227ETSI EN 302 186	FCC Part 25.138,ETSI EN 303 978
IF input (TX)	950–1700 MHz	
IF input (RX)	950–2150 MHz	
Antenna to Modman interfacefor configuration, control, and monitoring	ARINC A791 AMIP	
Antenna to inertial reference unit (IRU)	Supporting ARNIC A429	
Power consumption (antenna only)	240W (average)	

Fig. 6 Dual-band Ku/Ka airborne antenna. (Courtesy Hughes Network Systems and Gilat)

realize this dream, the most pressing question now is how can we create the best delivery ecosystem on a planet-wide scale to realize the greatest promise of the Internet itself: To be always available, easy to use, affordable, and transparent to users? The answer lies in marrying new generations of satellite with both terrestrial fixed and wireless technologies such as 5G. This is already happening in the marketplace – and rapidly advancing beyond GEOs to include MEOs, LEOs, and an emerging plethora of SmallSat constellations. Figure 7 summarizes Euroconsults' forecast of total satellites of all types to be built and launched by 2026, approaching 3000 and representing approximately $300B of investment. The latest filings and

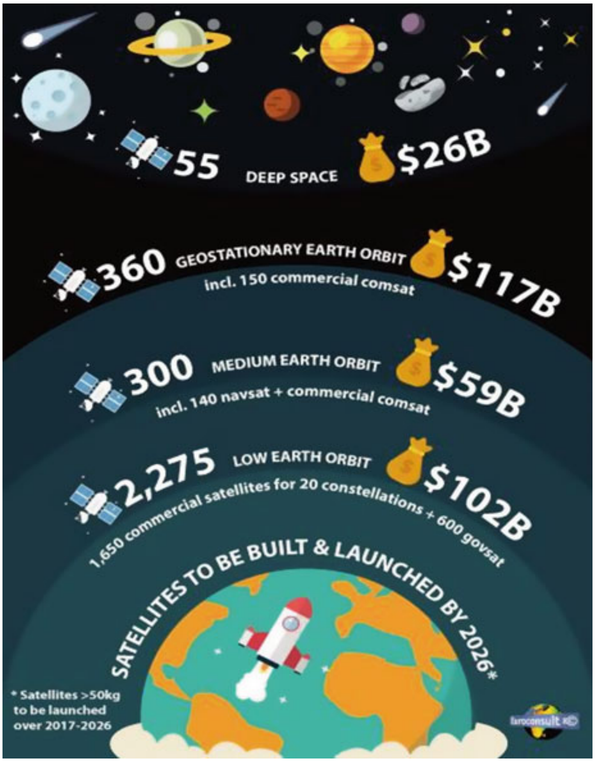


Fig. 7 Satellite launch forecast. (Courtesy of Euroconsult)

launch schedules may actually change substantially due to new small satellite constellation launches on the plus side or Covid-19 virus impacts on the negative side. According to Researchandmarkets.com, the overall global supply of satellite capacity – including GEO, MEO, and LEO constellations – will grow from 1.3 Tbps in 2017 to almost 10 Tbps by 2022, an eightfold increase in just 5 years.

No visionary could predict these advances, not even Arthur C. Clarke, who in 1945 had postulated that geostationary orbiting platforms could provide all types of services to mankind everywhere, with receiving parabolic antennas of about 1 foot in diameter! Indeed, the communications satellite is a machine that has changed the world for the better – one of the major engineering achievements of the twentieth century.

4.1 The Affordability Challenge

In countries and regions where individual subscriptions to satellite service are too expensive for the average resident, hybrid solutions of wireless and satellite technologies are emerging to power community Wi-Fi hotspots and shared VSAT services that make access affordable. The main advantage of these solutions is that people can use their own devices, usually handheld mobile phones, a category today that accounts for 48% of web page views worldwide (https://www.statista.com/topics/779/mobile-internet/). This simple example of marrying cellular and satellite technologies has helped bring connectivity to numerous "mobile first" markets in Asia and Africa, providing cellular operators a cost-effective path to expand their addressable markets beyond higher density urban areas. It's estimated that by 2022 nearly 12% of global mobile traffic will be via the emerging 5G wireless technologies (https://www.nsr.com/geo-vs-non-geo-who-wins-the-90-billion-consumer-broadband-opportunity/?utm_source=NSR+Email+List&utm_campaign=509a5de80e-VBSM18.BL1&utm_medium=email&utm_term=0_524993cda3-509a5de80e-259555657), which in ex-urban and rural regions with limited or no terrestrial services will undoubtedly include combined sat/cell hybrid approaches.

At the satellite systems level, the industry has advanced from single CONUS-coverage Ku-band GEO satellites with a few Gigabits of capacity, to multi-spot beam GEO architectures with from tens to 100s of Gigabits of capacity – so-called high-throughput satellites (HTS) – and on the near horizon, numerous constellations of MEOs, LEOs, and the newest category of SmallSats or Microsats. Table 1 summarizes the key variables of GEO/MEO and LEO satellites extracted from Reference (Architectures for Next Generation High-Throughput Satellite Systems 2014), which is an excellent treatise on the subject of satellite architectures.

This architectural evolution has led to new designs for systems, gateways, and a plethora of high-speed user terminals which are beyond the scope of this handbook. The reader may reference any number of manufacturer's websites to learn about their respective system and service offerings, including advancements such as wideband channels with DVB-S2x modulation, high-density gateways with lights-out operation, web acceleration/caching, advanced compression, and hardware security – which all taken together result in more efficient management of satellite bandwidth and, hence, low OPEX/CAPEX for operators, greater flexibility in creating competitive service plans, and a media-rich customer experience.

4.2 The Internet of Things (IoT) Explosion

On the immediate horizon is the Internet of Things (IoT) and its associated cellular/wireless 5G technology, arguably one of the most exciting and revolutionary technological developments of the Internet age. IoT is a network of cyber-physical devices comprising embedded electronics, sensors/actuators, software, and connectivity, enabling such devices to collect and exchange data over the Internet. These devices interact with physical environments, whether in homes/offices or externally on land, sea, or airborne, and their data collected by sensors are processed intelligently in order to derive useful inferences and enable controlling them. For example, an actuator is a device that is used to effect a change in the environment, such as adjusting the temperature controller of an air conditioner, which could be on an airplane, in cruise ship, or in an apartment.

Table 1 Satellite system parameters

			LEO		MEO		GEO	
			Up to 20 deg elevation	Over 400 km wide nadir cell	Up to 20 deg elevation	Over 400 km wide nadir cell	Up to 20 deg elevation	Over 400 km wide nadir cell
User elevation	β	Deg	20.00	74.86	20.00	87.64	20.00	87.88
Beta		RAD	0.35	1.31	0.35	1.53	0.35	1.53
Orbit height	H	Km	840		20,200		35,786	
Earth radius	R_a	Km	6378.00	6378.00	6378.00	6378.00	6378.00	6378.00
Orbit radius	R_o	Km	7218.00	7218.00	26578.00	26578.00	42164.00	42164.00
Path distance	d	Km	1840.93	866.52	23712.03	20204.13	39554.46	35789.69
SAT centric		RAD	0.98	0.23	0.23	0.01	0.14	0.01
SAT centric angle	θ	Deg	56.13	13.34	13.03	0.57	8.17	0.32
Earth centric		RAD	0.24	0.03	0.99	0.03	1.08	0.03
Earth centric angle	ϕ	Deg	13.87	1.80	56.97	1.80	61.83	1.80
Total angle		Deg	90.00	90.00	90.00	90.00	90.00	90.00
Radius in satellite UV plane	r_{uv}	Deg	47.57	13.22	12.92	0.57	8.14	0.32
Number of cells	N_{cell}		1.00	13.00	1.00	520.00	1.00	648.00
Nadir cell diameter	D_e	Km	3087.23	400.00	12682.95	400.00	13765.04	400.00
Coverage area	Asat	Km^2	7449137.889	125653.4071	116266137.8	125653.4093	134922687.6	125653.7499
Area normalized to GEO coverage			0.06		0.86		1	

IoT applications are essentially unlimited, spanning industrial processes, logistics, eco-sustainability, energy efficiency, remote assistance, and environmental monitoring, with estimates of as many as 50 billion devices by 2025. As for any networks, performance indicators, such as scalability, reliability, data throughput, latency, and energy consumption are important system design considerations. In particular for IoT – representing networks of networks – the range of metric values is especially wide, given there will be literally billions of devices which can each be served timely with very low data rates, while aggregations can require substantial capacity.

Introduction of 5G wireless links will provide for high data rates with low end-to-end latency, which are particularly important properties for such time – critical applications as autonomous cars and intelligent transportation systems. Coverage of 5G networks will in the foreseeable future be limited to urban and higher density areas, due to cost constraints of terrestrial buildout. This presents the opportunity to marry satellite and 5G terrestrial wireless networks to create a unified framework for seamless IoT coverage as illustrated in Fig. 8.

Such an architecture is rapidly evolving and with the following advantages:

(i) **Global Coverage**: Constellations of GEO (Geo-stationary) satellites employing Ka-band spot beam technology are rapidly covering the globe and already delivering high speed, affordable Internet access to millions of subscribers either unserved or underserved by terrestrial broadband technologies,

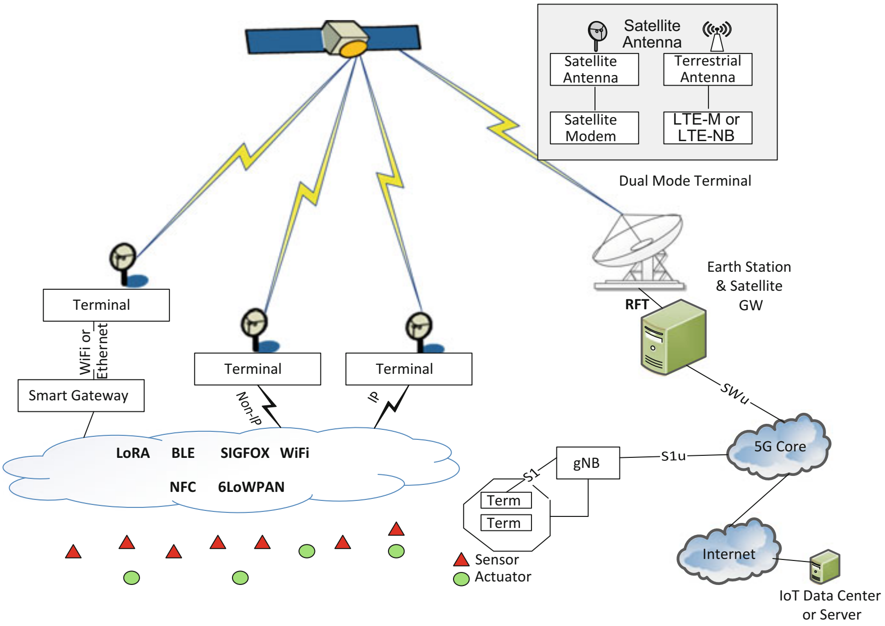


Fig. 8 Hybrid satellite and 5G architecture. (Graphic courtesy of Hughes Network Systems)

whether fiber, DSL, cable, or wireless. Soon to be launched LEO (low –earth –orbiting) satellites such as by OneWeb, Telesat, and Amazon will augment capacity globally in the next few years, and orbiting at approx. 1000 km result in much lower latency than GEO's at 40,000 km.

(ii) **High Reliability/Availability**: The high reliability of satellites is well proven, with service quality levels typically at or above 99.9% and with in-orbit operational lifetimes of 15 years as the norm, meaning IoT networks can be readily configured as a combination of terrestrial 5G and satellite with either providing primary or backup connectivity or as a hybrid simultaneous cellular-satellite solution.

(iii) **Longevity**: As already noted, satellite network operational lifecycles today are typically 15 years, and since all of these constellations are expected to be backward compatible, technology life cycles of 20+ years in future can be anticipated.

(iv) **Deployment Flexibility**: Besides ubiquity, satellite coverage can be targeted and dimensioned via spot beams much like terrestrial cell sites to deliver a specified capacity to serve a given collection of sensors. Furthermore, low power/low data rate sensors can be easily deployed and operate using solar power options in rural or remote areas. For higher-throughput control or aggregation applications, such as backhauling of cellular traffic, VSAT terminals with up to 1 Gbps can be rapidly deployed at a low cost that's distance insensitive, unlike terrestrial options requiring middle and last mile physical infrastructure.

(v) **Isolation**: The fifth value proposition comes from a satellite IoT network generally being offered as a proprietary, closed system, enhancing reliability, and offering greater security.

(vi) **Multicasting**: The final benefit is multi-casting. This refers to broadcasting a message to a group or subgroup of subscribers as a single billable event. Multicasting of a single broadcast to reach multiple units when combined with satellite's flexible coverage and capacity dimensioned beam sizes yields the most cost-effective network designs, mitigating overall capital, and operating costs (CAPEX and OPEX).

Given the ubiquity and capacity of space-based communications, satellite technology will play a critical role in supporting the development of the IoT sector and realizing the full potential of interconnected devices, having created a broadband superhighway in space – easily handling the potential billions of forecasted IoT devices.

5 Conclusion

As the above examples show, incredible progress has been made by the satellite industry in just a few short decades, and yet we find ourselves in a sense "back to the future," at the dawn of yet a larger and more profound era. And nobody, not even

Arthur C. Clarke, could have predicted the significant scale of satellite markets growing and expanding as new satellite technology in space and on the ground is deployed. The one certainty is that there will be progress, fueled by the combined creativity and partnerships of people and businesses across the expanding spectrum of technologies – terrestrial and satellite alike – to make these advances happen.

In particular, the following article in ▶ "Electronic Beam-Scanning Technology for Small Satellite Communication Systems and Their Future Development" on phased arrays and related market opportunities describes the disruptive potential of these new generation antenna systems that are poised to displace parabolic, mechanically steerable technology as large-scale small satellite constellations become deployed in the 2020s.

6 Cross-References

▶ Economic and Market Trends for Ground Systems to Support New and Future Small Satellite Systems
▶ Electronic Beam-Scanning Technology for Small Satellite Communication Systems and Their Future Development
▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas
▶ Small Satellites and Innovations in Terminal and Teleport Design, Deployment, and Operation

References

Architectures for Next Generation High-Throughput Satellite Systems. *BenAmmar, Gopal et al Int. J. Satell. Commun. Network*. 2014; 00: 35
C-COM Satellite Systems. Nov 2019. http://www.c-comsat.com
Fortune, *20 That Made History*, p. 45, June 27, 2005
Northern Sky Research, *VSAT and broadband Satellite markets*. p. 18, Nov. 2019

Electronic Beam-Scanning Technology for Small Satellite Communication Systems and Their Future Development

Safieddin (Ali) Safavi-Naeini and Arunas G. Slekys

Contents

Abstract

The rapid development of a new antenna technology known as electronic beam-scanning systems, phased arrays, flat panels, and other phraseologies has opened up new vistas for antenna solutions of twenty-first-century satellite communications. This technology has the potential to be applied in the deployment and use of MEO, LEO, and small satellite constellations, in addition to supporting ground

---

S. A. Safavi-Naeini (✉)
Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada
e-mail: safavi@uwaterloo.ca

A. G. Slekys
Corporate Marketing, Hughes Network Systems, Germantown, MD, USA
e-mail: Arunas.Slekys@hughes.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_30

systems of GEO/MEO/LEO satellite networks. In particular, it holds the promise of expanding the addressable market for mobility applications of satellite networks by virtue of reducing size, weight, power, and cost compared to mechanically steered antennas. Development of this technology for space antennas and ground systems is still evolving. This chapter describes the nature of electronic beam-scanning antennas, the technology challenges, their applications, and state-of-the-art solutions.

Keywords

Electronic beam-scanning antennas · GEO satellite systems · Integrated Space and Terrestrial Networks (ISTN) · Low earth orbit (LEO) satellites · Medium earth orbit (MEO) satellites · Modular and scalable phased-array architecture

1 Introduction

Satellite communications (SATCOM) is uniquely positioned to extend the global digital economy to every corner of the world, in the ocean, high in the sky, and to the remotest villages, including the 60% of the world's population that still does not have access to the Internet. Unlimited demand for ubiquitous access to information and connectivity everywhere and anytime for the widest variety of applications – ranging from commercial and personal communication to environmental monitoring (remote sensing), navigation, science, and defense – has stimulated significant innovation and growth in satellite communications systems, components, and network technologies.

As noted in Part 6.1, GEO systems have been the main industry drivers to date, with associated antenna solutions based primarily on mechanically steerable parabolic technology, i.e., high gain reflector and dual-reflector antennas with focal plane arrays having multi-beam radiation capability. The largest volume applications have been for fixed configurations, with mobility versions limited to transportable or on-the-pause kits, which are assembled in the field and typically employ rapid, self-pointing functionality. But they are not usually mobile in the context of handheld cellphones, although Inmarsat and Thuraya have managed to offer this type service from GEO platforms in L- and S-bands. Mobility applications in the much higher-frequency Ku- and Ka-bands in particular have proven extremely challenging, requiring some form of movable and stabilized platform, including accurate GPS and gyro positioning. Hence, whether operating over GEOs, MEOs, or LEOs, and whether for airborne, maritime, train, or other land mobility services, such configurations have typically been bulky and relatively expensive, i.e., on the order of tens to hundreds of thousands of US dollars, and have been limited to low volume commercial markets. Nor are such large antenna systems suitable for small satellite systems because of their significant size, weight, and power consumption requirements.

Enter the opportunity for flat panel, phased-array antenna solutions, which are poised to revolutionize the industry – no matter if it's for GEOs, MEOs, and LEOs or for small satellites in low earth orbits (typically 500 km to 1,200 km, etc.) and even for lower altitude applications such as high-altitude platform systems.

2 General Characteristics of Antenna Systems for Small Satellite Constellations

With remarkable advances in low-cost and lightweight structures, including the miniaturization of RF/microwave electronics and component technologies, small satellites (mini-, micro-, nano-, pico-, and femto-satellites) with ranges of weight from less than 100 g to around 500 kg have become the fastest-growing new sector of the industry. By virtue of their low-cost, small mass, and much easier launch requirements, they are being rapidly deployed in an increasing number of applications from earth science to geo-mapping, as well as a wide range of data communications in support of the exploding world of Internet of Things (IoT)/5G broadband cellular devices. Smaller members of this family, namely, CubeSats, are being increasingly used for remote sensing, earth observation, and scientific research. Microsatellites and minisatellites are being introduced in mega-constellations (SpaceX, Telesat, OneWeb) to deliver broadband Internet access worldwide.

As a case in point from SpaceX (May 15, 2019): "Each of the Starlink satellites weighs around 500 pounds (227 kilograms). Stacked together inside the payload shroud of a Falcon 9 rocket, the 60 satellites weigh 15 tons (13,620 kilograms), making the cargo for the May 2019 launch the heaviest ever lofted into orbit by SpaceX" (https://spaceflightnow.com/2019/05/15/spacex-releases-new-details-on-starlink-satellite-design/).

Antennas are key elements of all satellite systems, providing the necessary RF communication links between the satellite and the ground stations for both command/control and telemetry, navigation, and payload. Inter-satellite links (ISL) have also become quite important for small satellite networking, allowing for more accurate orbital placement and maintenance of moving satellites and requiring high gain antennas with low SWaP (size, weight, and power), and, above all, beam-forming and tracking.

Small satellites have traditionally been used for disaster monitoring, scientific and technology demonstrations, earth observation, and search and rescue missions. Telecommand, telemetry, and tracking systems typically use narrow band signals at VHF/UHF, S-, X-, Ku-, and Ka-bands. These antennas should cover a wide angular range (often a full hemisphere or very broad beam) in a reliable manner: monopoles, helices, patches, complex slots, and deployable systems (Gao et al. 2018).

Antennas for broadband communications should be high gain and with narrow beams directed toward the ground station. Although high-precision Attitude

Determination and Control Systems (ADCS) are becoming available for small satellites; currently the only viable solution is to lower the gain and to widen the beam. A number of deployable, inflatable, and foldable structures have been proposed and developed (Gao et al. 2018; Rahmat-Samii et al. 2017).

Emerging LEO mega-constellations and convergence of space and terrestrial communications (Integrated Space and Terrestrial Network or ISTN) are having significant impact on radio communication requirements of small satellites and their ground segment. Several mega-constellations are in the formation stages, with their primary goals to provide both mobile and stationary users on land, sea, and in the air with broadband Internet access. The 5G rollout has started with promises of extreme bandwidth, connectivity, low latency, and reliability. However to extend its reach to all corners of the world, it must use space communication as a truly ubiquitous infrastructure. Depicted in Fig. 1, realization of the ISTN (Integrated Space and Terrestrial Network) concept and architecture as the next major evolution of global network topology depends on highly intelligent radio links and antenna technologies with agile beam-forming capability. Antenna array technology with built-in intelligence is the only viable solution to materialize such a vision.

Almost all current small satellite antennas are fixed beam systems, which are obviously not optimal for many emerging and future applications. For low-frequency, low-speed telemetry and telecommond functions, fixed antenna with appropriate pattern may have an acceptable performance. However, as mentioned before, the increasing complexity of operational scenarios while both ends of the link are mobile requires fast beam-forming and tracking capability. To address serious constraints on the size and weight of the antenna for small satellite systems, multifunctional design approaches with integrated radio front-end appear to yield highly promising solutions.

Based on the aforementioned facts, to meet the requirements of future missions, small satellite antennas must have agile beam-forming/tracking capability with the following characteristics:

- Light weight
- Small size and conformal geometry
- Low power consumption
- Stable performance over a wide range of temperature and other environmental factor variations
- Material and fabrication methods should resist launch condition and be qualified for space applications
- Low-cost

3 Phased-Array Antenna Systems for Small Satellite Communications

As mentioned earlier, communications between the satellite and ground networks and satellite-to-satellite links underpin the worldwide ISTN network. Extremely high data throughput of all classes of satellites, including the smallest, requires

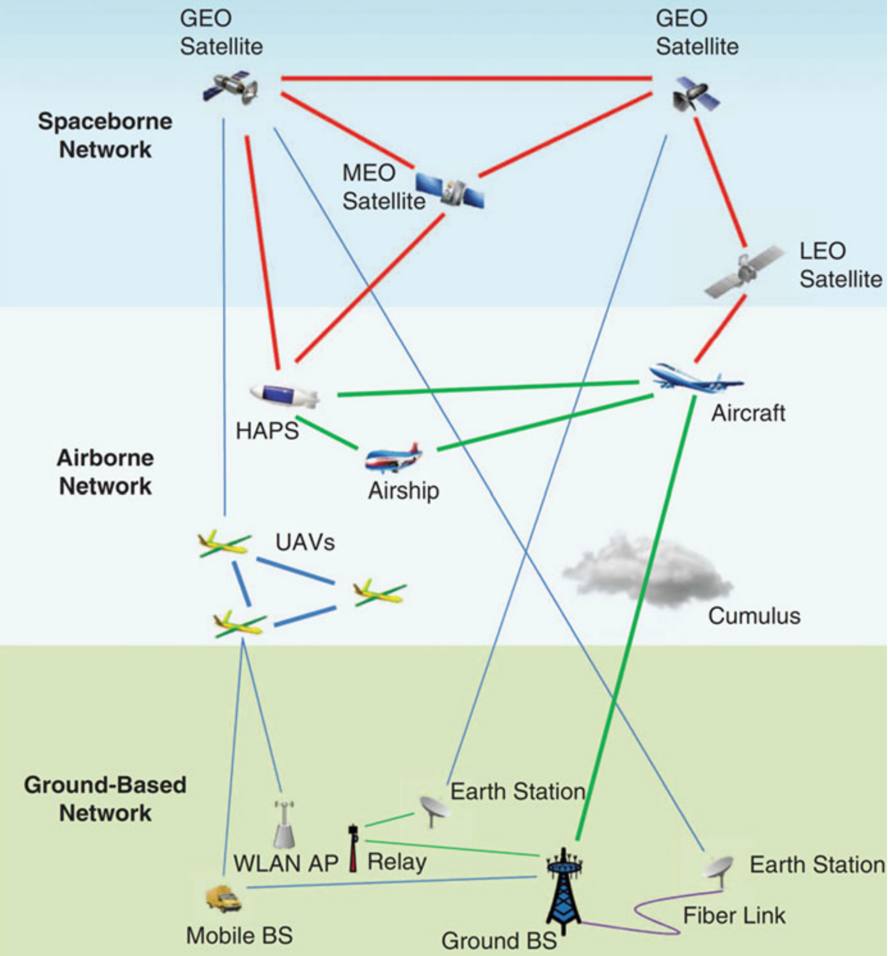


Fig. 1 Integration of space and terrestrial networks: evolution toward Integrated Space and Terrestrial Network (ISTN). (Courtesy of X. Huang et al. 2019)

wideband antenna systems with high gain and beam-steering capability over the hemisphere, in low-profile (conformal) configurations, with low weight and power.

Mechanically steered reflector antennas (Imbriale et al. 2012), which are still most widely used in satellite systems, are large and heavy structures with complex gimbal mechanisms, which are slow and consume considerable power. Vibration generated by mechanical rotation of the antenna induces error in high-precision sensors and can change the location and orientation of the satellite.

Phased-array antenna with electronic beam control capability has attracted considerable attention as the most promising technology for a wide range of applications including satellite to ground, aircraft to satellite (aeronautical satellite communication), and inter-satellite links.

By adaptive antenna beam-steering using intelligent electronics and signal processing schemes, phased-array technology will eliminate the need for motorized, mechanical steering systems, thereby realizing considerable savings in antenna size, weight, and power consumption. These specifications are critical to airborne and fast-moving, vehicle-mount SATCOM terminals for which flat/low-profile and lightweight antennas are desirable for reducing vehicular/aircraft drag and increasing radio communication efficiency. Indeed, connected mobility applications are expected to be the primary demand drivers for flat panel antennas, accounting for 92% of their estimated cumulative global revenues (est. $9.1B) by 2026 (Northern Sky Research 2017).

Migration toward high-throughput systems is not limited to large satellites and GEO links. There is a growing trend toward broadband data communication in smaller satellites down to nanosats (King et al. 2012), operating at Ku-band (18 to 27 GHz) and Ka-band (27 to 40 GHz).

3.1 Challenges

Despite all the unique advantages of millimeter-wave (mmW) technology, such as extreme communications bandwidth and measurement resolution (angular, distance, and time), commercial (mass market) exploitation of this spectrum is still quite limited due to current device technology cost, complexity, and performance limitations (limited signal power and noise performance). High propagation and scattering losses (Sulyman et al. 2014) as well as considerable mmW attenuation in typical operational environments (man-made objects, foliage, etc.) cause severe signal decay and dispersion in this range of frequencies.

3.2 Solution

To deal with the aforementioned radio link impairments and active device performance limitations, intelligent multi-antenna systems – such as phased arrays with integrated beam-forming devices for phase/amplitude control – have become the most promising solutions (Roh et al. 2014) to deliver enough signal power at the receiving point and to provide sufficient quality of communications. Phased arrays are still quite costly and complex structures and until very recently have been primarily and almost exclusively developed for defense and scientific (space) systems. Aggressive CMOS and SiGe technology scaling and progress in commercial high-density multifunctional integrated circuits and ASIC technology in mmW (Roh et al. 2014; Jeon et al. 2008; Tabarani et al. 2018), however, coupled with advances in high-precision multilayer circuit and packaging technologies (Meniconi et al. 2013; Litschke et al. 2005; Chen et al. 2006), are rapidly removing these barriers and opening new and exciting possibilities. During the last decade (Han et al. 2015; Gu et al. 2015; Vaccaro et al. 2010; Hong et al. 2014), there has been significant growth in worldwide efforts by research organizations and companies targeting low-cost commercial technologies for mmW multi-antenna beam-forming.

Mobile SATCOM terminals, in addition to cost/complexity constraints, should also meet a number of additional requirements such as size, weight, and power consumption or so-called SWaP, which require unique solutions. Mobile SATCOM has become a driving market force behind the commercialization of high-performance, phased-array technology.

Antenna arrays with beam-forming capabilities for mobile SATCOM, mainly in Ku-band (12/14GHz), have been proposed and developed by research institutes (Baggen et al. 2013; Mousavi et al. 2008; Schippers et al. 2008; Hoehn et al. 2013) and industries (Johnson et al. 2015; GILAT 2014; Henderson and Milroy 2005; ThinKom 2014; Phasor Soluions 2015) over the last decade. A comprehensive European Ka-band phased-array initiative (Baggen et al. 2013) resulted in active sub-array modules. Although the modules are still somewhat complex and expensive for mass market applications, recent progress in semiconductor technologies, digital systems, and multilayer planar technologies will undoubtedly reduce the cost. A number of Ku-band, phased-array development activities have been reported by industries over the last 5 years. The technical details and the achieved performances have not been reported in details. However, some general remarks can be made based on their published data and patents.

The existing industrial developments can be broadly divided into two approaches: (1) RF beam-forming and (2) digital beam-forming. A Ku-band phased-array with digital beam-forming has been reported in (Phasor Soluions 2015). Each antenna element is connected to its own transceiver chip, which down-converts the signal to bits. Although the signal combining at bit level is simpler than that at RF level, the overall system architecture is quite complex, and extension to very broadband applications is quite difficult. A Ku-band reconfigurable holographic beam-former has been reported in (Johnson et al. 2015), using originally MEMS and then liquid crystal to control the transmission properties of a metasurface. The technical details and specifications have not been reported yet. The developed system has a medium bandwidth.

The beam-scanning and phase adjustment can also be performed by a mechanical movement based on Variable Inclination Continuous Transverse Stub Array (VICTS) (Henderson and Milroy 2005) idea. A Ka-band beam-scanning array has been developed based on this idea (ThinKom 2014). Although VICTS is a mechanically steering system (not an electronic scanning array), the physical motion of the aperture is limited to the rotation of three plates (feed, aperture, and polarizer) around a common vertical axis inside the fixed system package. Therefore the structure is fairly low profile, and the antenna structure as whole does not have any apparent mechanical movement. The system has been deployed in commercial applications by Gogo Inc.

Extensive research activities and industrial efforts in three sub-areas, (a) phased-array antenna in microwave band, (b) mmW multilayer antenna elements and small arrays (Baggen et al. 2013; Mousavi et al. 2008; Lier and Melcher 2009; Ehyaie and Mortazawi 2010), and (c) advanced single- and multi-channel mmW front-end integrated circuits (Tabarani et al. 2018; Hashemi et al. 2005; Koh and Rebeiz 2008; Jeon et al. 2008) with beam control capabilities, are gradually reducing the cost and complexity of phased arrays and will eventually result in the rapid deployment of this technology in price-sensitive commercial applications. As the most promising approach, the modular and scalable system architectures can significantly reduce the cost and complexity of the overall system. This approach is further described in the next section.

4 A Cost-Effective, Modular, and Scalable Phased-Array Architecture

In this section, after a quick review of phased-array theory and its main characteristics, a modular and scalable phased-array technology as the most cost-effective solution for intelligent antenna and radio system is described.

4.1 Review of Phased-Array Theory: Choice of Antenna Element and Array Configuration

The choices of the antenna element and the array configuration are intertwined, and both are linked with the general specifications of the system. The total radiated field, $\mathbf{E}(\mathbf{r})$, from an array made of M identical and identically oriented antenna elements with the far field, $\mathbf{E}_e(\mathbf{r})$ (assuming that the element radiated power = 1 W), is given by:

$$\begin{aligned} \mathbf{E}(\mathbf{r}) &= \mathbf{E}_e(\mathbf{r}) \sum_{m=1}^{M} |I_m| \exp(j\psi_m) \exp\left(j\widehat{\mathbf{k}} \cdot \mathbf{r_m}\right) \\ \widehat{\mathbf{k}} &= \widehat{\mathbf{x}} \sin\theta \cos\varphi + \widehat{\mathbf{y}} \sin\theta \sin\varphi + \widehat{\mathbf{z}} \cos\theta \end{aligned} \tag{1}$$

where $|I_m|$ exp $(j\psi_m)$is the relative excitation amplitude and phase of the element number "m," located at $\mathbf{r_m}$. The unit vector $\widehat{\mathbf{k}}$ is along the direction of radiation (look angle: polar angle θ and azimuth angle φ). It is obvious from (1) that the radiation and circuit properties of an array system depend on the element as well as the configuration of the elements and the feed circuit. Polarization of the far field, to a large extent, is determined by the element pattern, $\mathbf{E}_e(\mathbf{r})$. However, special arrangement (e.g., "sequential rotation" method) of the elements in the array can improve the polarization of the array beyond that of the element.

The antenna elements should have sufficient (impedance/gain/axial-ratio) bandwidth, good polarization purity (polarization can be improved over the scan range by complex excitation of the element orthogonal ports), and high radiation efficiency.

It is important to maximize the isolation (minimize the coupling) between the elements. A quick analysis reveals this. The so-called active impedance of the antenna element, which is the input impedance of the antenna in an array environment, is different from that of the same element in isolation. The active impedance of the element number "q" is given by:

$$Z_{a,q}\left(\widehat{\mathbf{k}}\right) = Z_{qq} + \sum_{m=1,\, m\neq q}^{m=M} Z_{qm}\left|\frac{I_m}{I_q}\right| \exp\left[j\left(\psi_m - \psi_q\right)\right] \tag{2}$$

where $Z_{a,q}\left(\widehat{\mathbf{k}}\right)$ is the active impedance of the antenna number "q" when the beam is scanned to the direction $\widehat{\mathbf{k}}$ and Z_{qm}s are the mutual impedances between various elements. The key point here is the dependence of the active impedance on the scan angle. To see this, note that to move the beam toward the direction $\widehat{\mathbf{k}}$, the phase of each element should be set to:

$$\psi_m = -\widehat{\mathbf{k}} \cdot \mathbf{r_m} \pm 2N\pi \tag{3}$$

where N is an integer. Therefore as the beam is scanned to new direction, $\widehat{\mathbf{k}}$ and consequently ψ_m will change (see Eq. 2), and as it is obvious from (2), the active impedance of each element will change accordingly. This change, in general, has a negative impact on the performance of the active feed circuits, which are often optimized for a particular load (antenna) impedance. However, if the couplings between the antenna elements (Z_{qm}) are small, the active impedance variation, which is generated from the summation term in (2), can be neglected. There are a number of methods, which can be used to minimize coupling between the array elements. The easiest way is to increase the element spacing. However, half-wavelength spacing is the most common choice. Larger spacing decreases the coupling but limits the scan range.

The same array may be required to work at two different frequency bands. The elements should work at two disjoint frequency bands. The element spacing (in the case of array with regular grid) is chosen such that grating lobes are suppressed over the scan range. This usually leads to choosing the element spacing equal to half-wavelength at higher-frequency band (smaller wavelength).

Choice of the most optimal array configuration for a given set of requirements is a major initial step in development of a cost-effective electronic beam-scanning system. Referring to (1), this includes determination of the minimum of number of the antenna elements, M, and their locations $\{\mathbf{r_m},\quad m = 1, 2, \cdots M\}$, and the element normalized (with respect to the current required for unit power radiation by each element) excitations $\{|I_m| \exp\,(j\psi_m);\quad m = 1, 2, \cdots M\}$, which would provide the required EIRP (transmit side) and G/T (gain divide by the system noise temperature of the receiver array) over the scan range, while meeting the standard (e.g., FCC or IUT) radiation spectral density mask, over the entire range of operational frequencies. Certain level of polarization purity is to be maintained over the same range of frequencies and scan angles.

The transmitter array's most important performance characteristic is EIRP $(\widehat{\mathbf{k}})$ [Watts or dBW]:

$$\text{EIRP}\left(\widehat{\mathbf{k}}\right) = \left[\text{Gain of the Array}\left(\widehat{\mathbf{k}}\right) \times \text{Total Radiated Power}\right] \tag{4}$$

$$\text{Gain of the Array}\left(\widehat{\mathbf{k}}\right) = \text{Gain of the Element}\left(\widehat{\mathbf{k}}\right)\frac{\left|\sum_{m=1}^{M}|I_m|\exp\left(j\psi_m\right)\exp\left(j\widehat{\mathbf{k}}\cdot\mathbf{r_m}\right)\right|^2}{\text{Total Radiated Power}} \tag{5}$$

as a function of radiation direction $(\widehat{\mathbf{k}})$. In the case of active array, the element excitations, $\{|I_m|\exp(j\psi_m);\quad m=1,2,\cdots M\}$, can be controlled by a beam-forming MMIC (containing variable gain amplifiers and tunable phase shifters).The excitation coefficients should be optimized to maximize EIRP without violating the radiation mask over the entire scan range.

On receive side, to determine G/T, G, or gain of the receiving array can be calculated by (5), but $\{|I_m|\exp(j\psi_m);\quad m=1,2,\cdots M\}$, should now be replaced by the normalized complex gain and phase of the low-noise amplifier and tunable phase shifter of the receiver front-end MMIC. Furthermore, all the feed line losses up to the point where G/T is calculated or "referred to," which is often the input of the low-noise amplifier, should subtracted from G. The system noise temperature, T, is the sum of the effective antenna noise temperature, T_a [°K], and the receiver system noise temperature, T_{rcvr} [°K], or:

$$T = T_a + T_{rcvr}\quad\left[{}^\circ\text{K}\right] \tag{6}$$

Effective antenna noise temperature depends on the external noise sources (often represented by their brightness temperature) around the receiving antenna, the receiving antenna pattern $G\left(\widehat{\mathbf{k}}\right)$ as a function of look angle, antenna physical temperature, and the insertion loss of the transmission line between the antenna element and the low-noise amplifier. The dependence of T_a [°K]on the external noise sources is given by:

$$\frac{\int_{4\pi} T_B\left(\widehat{\mathbf{k}}\right)G\left(\widehat{\mathbf{k}}\right)d_2\widehat{\mathbf{k}}}{\int_{4\pi} G\left(\widehat{\mathbf{k}}\right)d_2\widehat{\mathbf{k}}} \tag{7}$$

where $T_B\left(\widehat{\mathbf{k}}\right)$ is the brightness temperature around the antenna. It is quite interesting to note that the part of the antenna noise temperature given by (7) actually changes with the scan angle because of change in the antenna receiver beam and gain$G\left(\widehat{\mathbf{k}}\right)$. The fact that by proper shaping of the receiver antenna beam, $G\left(\widehat{\mathbf{k}}\right)$ (reducing side-lobe levels toward the warm ground or other sources of noise or interference), the effective antenna noise temperature and therefore the total system noise can be reduced. This simply points to another important advantage of phased array as compared to fixed beam systems.

The receiver system noise temperature, T_{rcvr} [°K], is mainly determined by the noise figure of the receiver front-end. Therefore *G/T* is essentially a measure of SNR (signal-to-noise ratio) at the receiver front-end.

An example of an optimal array (square grid) of half-wavelength-spaced microstrip patch elements, optimized for 40 dB gain (boresight), and satisfying FCC mask is shown in Fig. 2. Note the loss of gain (aperture efficiency) due to tapering and also gain reduction as the beam scanned to off-boresight angles. The array can be implemented in a modular fashion (2 × 2 or 4 × 4 sub-arrays).

Regarding the antenna array configuration, there are a number of optimal nonperiodic (irregular) array geometries, which result in less number of the antenna elements and are most often used for fixed beam system. The optimal array topology for a wide-scan beam, which can satisfy radiation mask, is still an open research question (Haupt 2007; Rocca et al. 2014; Chirikov et al. 2013). Most of the existing optimization efforts lead to non-modular topologies, which are obviously not cost-effective and therefore of no interest to mass market applications. Although so far the most feasible module geometries are square/rectangle and triangular/hexagonal, nonuniform sub-arraying and non-regular shape modules (polyomino tiling) are also being investigated as possible alternatives for further reduction of the number of elements.

Although separate transmitter array and receiver array provide highest performance in terms of transmit/receive channel isolation (full duplex communication systems), impedance/gain bandwidth, pattern/polarization, and angular scan, there are cases where transmitter array and the receiver array must share the same aperture. Two important approaches to achieve this are (1) interleaved array configuration, wherein the transmitting and receiving array elements are placed between each other, and (2) dual-band transceiver arrays, consisting of multi-band radiating elements. Although interleaved array with fixed beam, particularly for half-duplex communications, has been demonstrated successfully, high-performance full-duplex phased array with wide-angle beam-scanning capability at higher microwave and millimeter-wave range of frequencies is quite costly and complex.

4.2 Cost-Effectiveness of Modular Architectures

As compared to a non-modular structure, modular architecture has a significant production cost advantage. Fabrication of a large array of few thousands of antenna elements at millimeter-wave, incorporating beam-forming active devices in one batch, with high positioning and alignment accuracy in the range of tens of micrometers (microns), at a reasonable cost for commercial applications is quite challenging. However, providing such level of accuracy for smaller modules (a small number of antenna elements) over small areas (few cm square) is quite feasible.

Furthermore, embedding tens of thousands of active and passive devices in complex, large-area multilayer circuits and antenna structures with high precision is another formidable task. A third problem with the conventional non-modular approach is its inherent lack of flexibility. Very often, any change in the current

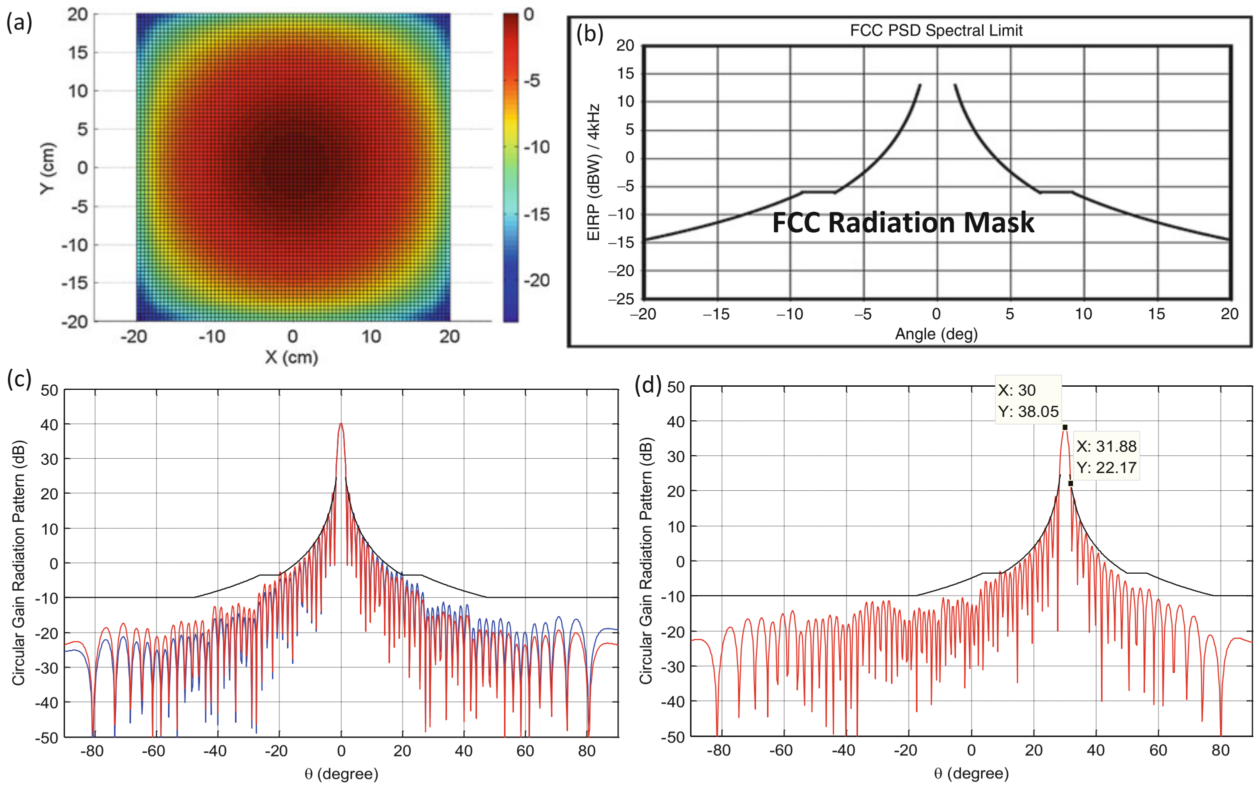


Fig. 2 (**a**) Amplitude distribution of an 80 × 80 array of half-wavelength spaced patch elements, (**b**) FCC radiation spectral density mask, (**c**) gain pattern at boresight, and (**d**) gain pattern at 30° scan angle. (Courtesy of University of Waterloo-CIARS (Centre for Intelligent Antenna and Radio Systems))

design parameters (array size, configuration, number of elements) for a new market will require a complete redesign of the entire array system and a new costly and time-consuming development cycle. This usually results in the considerable modification of the beam-forming algorithm and calibration as well, thereby with significant increase in the production cost.

In a modular architecture however, the entire phased array is built from a number of small and identical modules (small sub-arrays) or building blocks, allowing for the aforementioned challenges to be overcome in a convenient manner. The low-profile Ku-band receiving phased-array system (Fig. 3) reported about a decade ago (Mousavi et al. 2008; Fakharzadeh et al. 2009; Bolandhemmat et al. 2009) was one of the first modular systems developed for commercial mobile SATCOM. The entire phased array (1,000 elements) consisted of a few tens of sub-arrays, each passing the combined signal to one low-noise amplifier and an electronically controlled phase shifter (RF beam-forming). The system uses low-cost devices and fabrication methods and does not require any factory calibration. A highly intelligent algorithm performs calibration (removing phase/amplitude unbalance between the channels) and beam-forming, without any initial knowledge of device and antenna characteristics ("Zero Knowledge" algorithm (Mousavi et al. 2008)). The combination of low-cost but tunable sub-array modules and a highly intelligent algorithm results in a very cost-effective approach.

The Ku-band transceiver phased array reported in (Phasor Soluions 2015) follows a modular approach, but using digital beam-forming and much larger modules. A 256-element Ka-band phased array for mobile SATCOM is reported in Low et al.

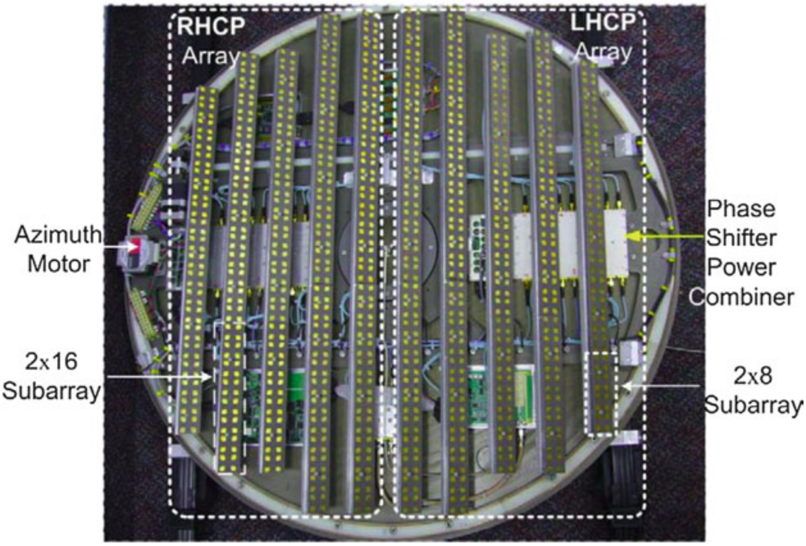


Fig. 3 Ku-band phased-array developed by the University of Waterloo-CIARS. (Courtesy of Intelwaves Technologies (Mousavi et al. 2008))

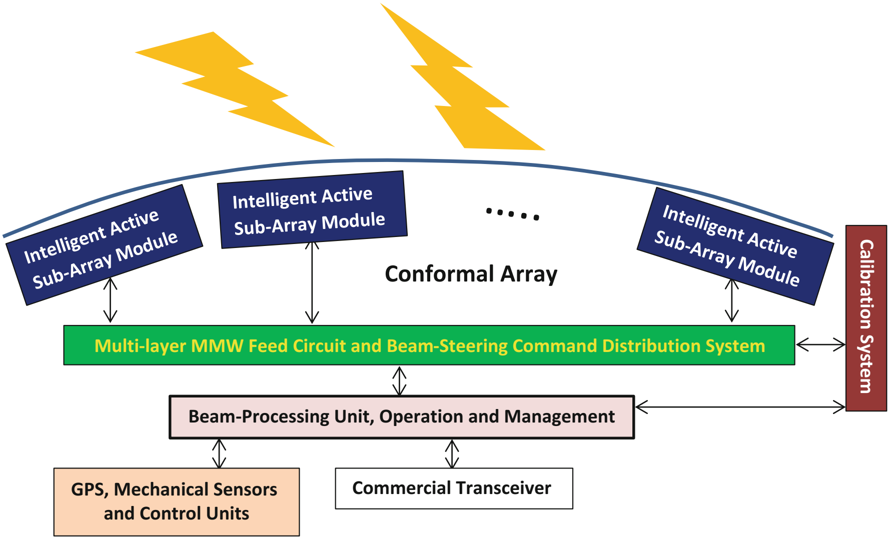


Fig. 4 A modular and scalable system architecture for intelligent antenna/radio system. (Courtesy of UW-CIARS (Abdel-Wahab et al. 2019))

(2019). The array has a 3-dB beamwidth of 7° and 34.5 dBW EIRP at broadside. The design concept can be extended to a larger array. A highly modular architecture presented in Abdel-Wahab et al. (2019) uses highly intelligent and small sub-array modules, incorporating active beam-forming devices with built-in intelligence, as a building block for a wide range of phased-array systems with different numbers of elements and configurations. The system architecture is shown in Fig. 4.

Each intelligent sub-array module (building block) consists of a small number of elements (2 × 2, 4 × 4, or 8 × 8) together with their beam-forming devices and a local beam-forming processor and memory which stores calibration data related to a particular building block or sub-array module.

A peculiar feature of the modular architecture of Fig. 4 is that the antenna beam-forming algorithm can be implemented in a distributed manner. Built-in intelligence and the local processing power of each module allow for parallelizing the beam-processing algorithm in such a way that a significant part of the beam-steering process can be carried out in the module local processor. Therefore, modularity extends to the beam-forming algorithm as well. This architecture significantly simplifies the beam-steering command distribution network, which constitutes one of the challenges in large-scale, high-performance phased-array systems.

The same architecture can be implemented in beam-steering reflect-array and transmit-array configurations.

The architecture illustrated in Fig. 4 is highly cost-effective. Intelligent active sub-array modules can be considered as autonomous RF beam-forming modules, with fully software definable functions, which can be used for almost all communications or sensing applications within its operational range of frequencies. The

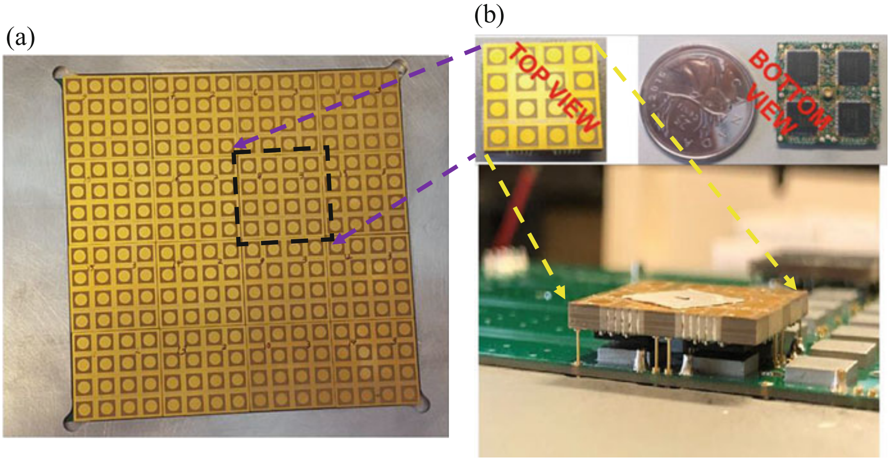


Fig. 5 (**a**) A modular architecture for 256-element Ka-band phased array made of 16 intelligent sub-array modules (4 × 4), (**b**) LEGO-like assembly process. (Courtesy of UW-CIARS, C-COM Satellite Systems)

modules are therefore standard "agnostic." The fundamental production cost advantage of such a modular approach as compared to conventional non-modular technologies stems from the flexibility/programmability of the modules, which can be used for a large number of applications and therefore can be mass-produced. Modules constitute more than 70–75% of the system cost and hence present economies of scale to bring down the cost significantly. The only part of the system which should be customized for various applications is a passive backplane feed circuit, which either distributes the RF signal among the modules (in transmit mode) or collects RF signals (in receive mode).

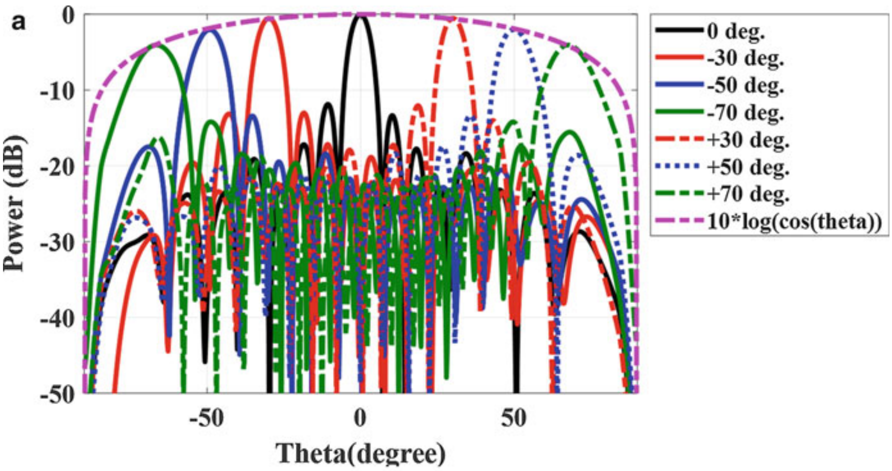
A highly modular array architecture and its LEGO-like assembly process are shown in Fig. 5.

The radiation pattern as the beam is scanned, EIRP, and *G/T* of the 256 element array is shown in Fig. 6.

4.3 Feed Circuit and System Integration Technologies

In this subsection, phased arrays with RF beam-forming are considered due to their lower cost and complexity, which are of paramount importance for small SATCOM applications.

To enhance system radiation efficiency and bandwidth, the insertion loss and dispersion of the feed circuit must be minimized. Although metallic waveguides have significantly lower insertion loss as compared to planar lines (strip line, microstrip line, coplanar waveguides, etc.), their cost, complexity, volume, and weight are not acceptable for many commercial mobile applications. On the other



b

	Scan Loss (dB)						
Scan angle (deg.)	-70	-50	-30	0	+30	+50	+70
Theory	- 4.70	- 1.92	- 0.62	0	-0.62	-1.92	-4.70
Meas.	- 4.10	- 2.0	- 0.54	0	-0.54	-2.0	-4.10

Antenna Array Directivity, D (dBic)	Noise Figure, NF	EIRP (dBW)	G/T (dB/°K)
28.8	5.0	34.50	-1.0

Fig. 6 (**a**) Radiation pattern of 256-element phased array of Fig. 5 at different scan angles, (**b**) transmitter array EIRP and the receiver array G/T as a function of scan angles. (Courtesy of UW-CIARS)

hand, the printed planar lines, which are the most popular type of signal transmission technology for small circuits, become quite lossy in large-scale feed circuits at millimeter-wave frequency bands of interest in HTS systems. A promising solution which combines the advantage of the two methods is substrate integrated waveguide (SIW) (Li and Luk 2015; Xu et al. 2010; Abdel-Wahab et al. 2011, 2015), which can also be considered as a planar waveguide technique. Figure 7 illustrates an 8 × 8 40 GHz dielectric resonator antenna array fed by an SIW.

For large-scale system integration, a multilevel (hybrid) scheme combining various types of feed techniques, such as the three aforementioned technologies, is a highly efficient approach. Shown in Fig. 8 is a typical hybrid scheme, where the first level (intelligent 4 × 4 or 8 × 8 sub-array modules) is implemented in a multilayer planar technology (polymer based, LTCC, or MCM). These are the essential building blocks of the entire system. The second level is an SIW signal

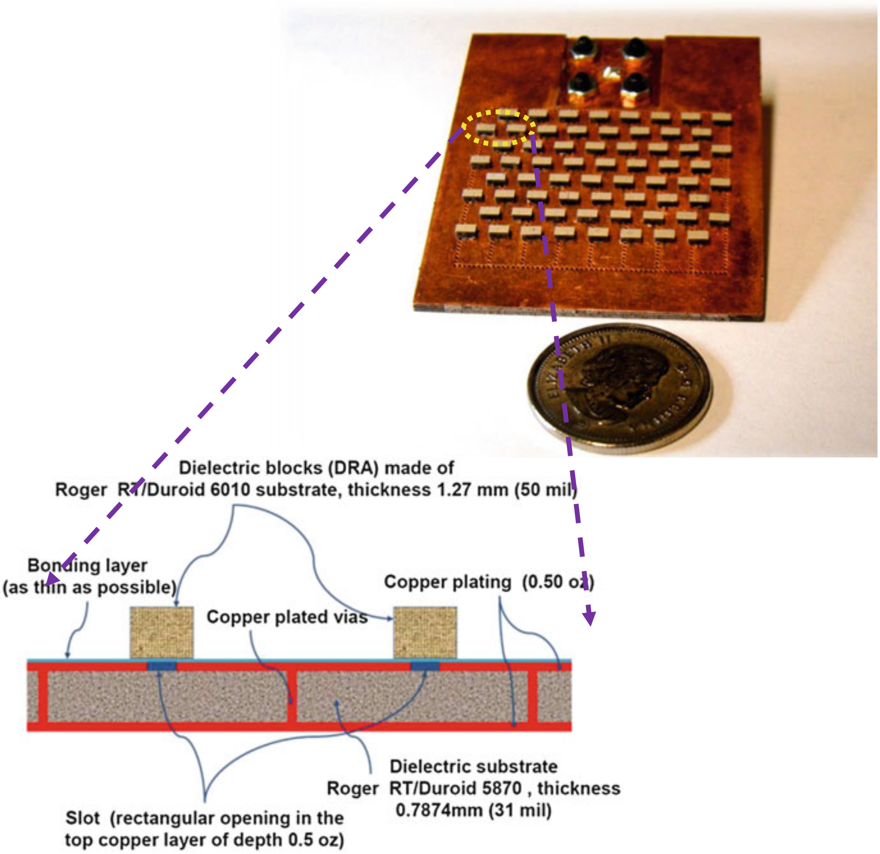
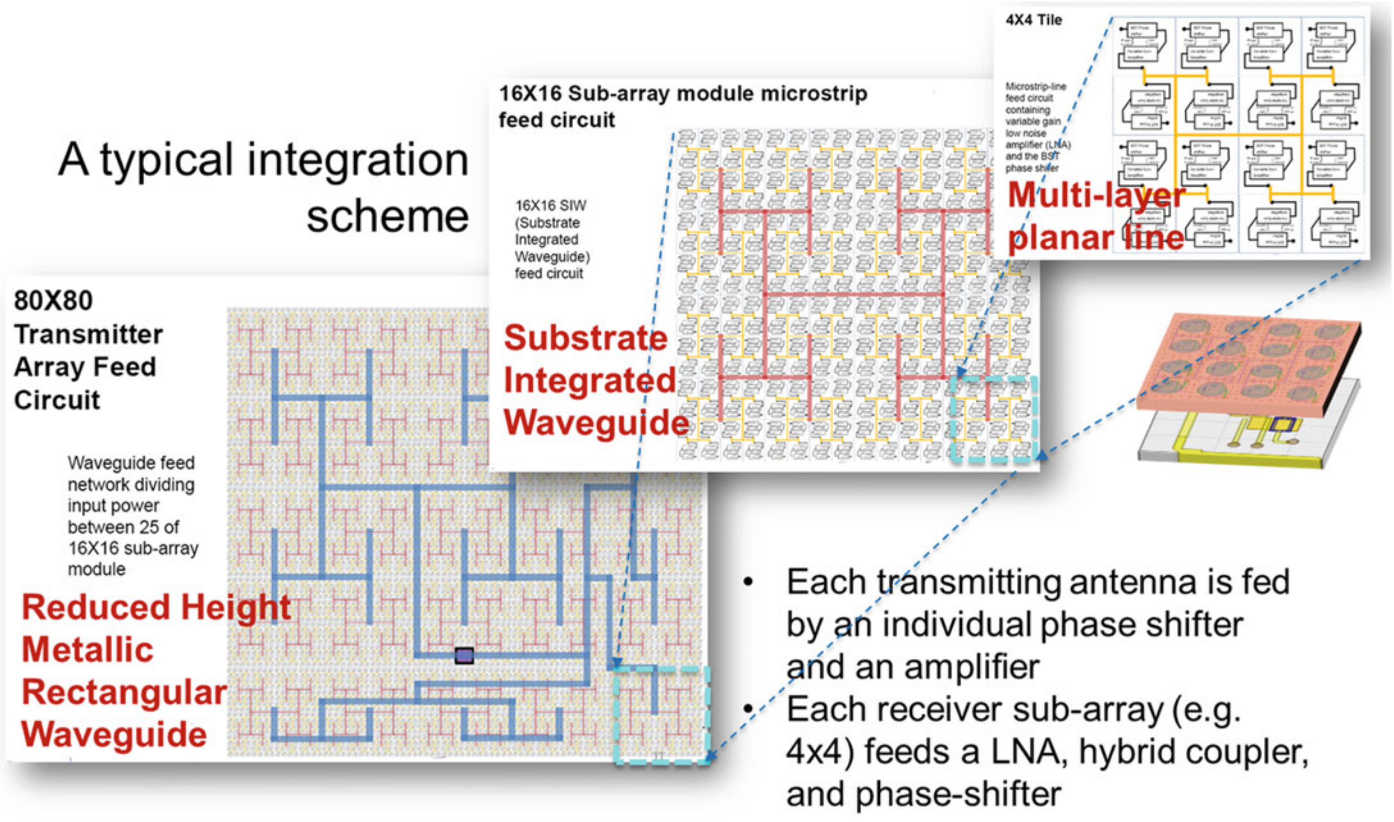


Fig. 7 An 8 × 8 40 GHz dielectric resonator antenna array fed by SIW

splitter (transmitter array) or a signal combiner (receiver array), which splits/combines the signals between/from a certain number (e.g., 4, 6, or 8) of intelligent modules. The choice of SIW is dictated by its lower insertion loss as compared to planar lines for long feed circuits in higher microwave and millimeter-wave range of frequencies. In lower frequencies (L-/S-/C-bands), low-loss planar lines such as air-filled strip lines can also be used in place of SIW for the second level of the feed circuit. For large-scale arrays (few thousands of elements), a third-level feed circuit is needed, which contains the longest segments of the feed lines located between the SIW (second-level feed) and the system RF input/output. Such long feed lines should be realized by the lowest insertion loss technologies. A possible choice is reduced height metallic waveguide. To reduce height, weight, and eventually production cost of air-filled metallic waveguide, metallic 3D printing offers new possibilities and may soon provide a viable alternative to planar circuits at higher microwave and millimeter-wave range of frequencies.



A typical integration scheme

80X80 Transmitter Array Feed Circuit

Waveguide feed network dividing input power between 25 of 16X16 sub-array module

Reduced Height Metallic Rectangular Waveguide

16X16 Sub-array module microstrip feed circuit

16X16 SIW (Substrate Integrated Waveguide) feed circuit

Substrate Integrated Waveguide

4X4 Tile

Microstrip-line feed circuit containing variable gain low noise amplifier (LNA) and the BST phase shifter

Multi-layer planar line

- Each transmitting antenna is fed by an individual phase shifter and an amplifier
- Each receiver sub-array (e.g. 4x4) feeds a LNA, hybrid coupler, and phase-shifter

Fig. 8 A multilevel hybrid scheme for the feed system of large scale high-performance phased arrays

4.4 Active Beam-Forming Device Technology

Active cost-effective beam-forming techniques commonly use multi-channel Si-based MMIC devices, with phase shifting, amplification, and polarization switching capabilities. To maximize the performance within the acceptable target cost range, MMIC architecture should be optimized for the particular active sub-array module configurations.

Commercially available nano-metric CMOS and SiGe processes like 65 nm CMOS and 130 nm SiGe are currently among the most optimal options for implementing microwave/millimeter-wave active beam-forming architecture such as the one shown in Fig. 9.

The MMIC front-end architecture needs to be compatible with the system functions and performance requirements and fully scalable in order to meet the requirements for various scales of the phased-array systems. A number of MMIC architectures for phased-array transmitter/receiver on the chip and wafer (Jeon et al. 2008; Hashemi et al. 2005; Koh and Rebeiz 2008; Jeon et al. 2008; Natarajan et al. 2011; Cohen et al. 2013) have been presented for 8−/16−/32- and 256-element arrays.

The system SWaP (size, weight, and power consumption) requirement is determined, to a large extent, by MMIC power consumption and RF efficiency particular on transmit size. Recent advances in microwave/millimeter-wave power MMIC technologies and downward trend in the power consumption per channel have allowed for effective thermal management of medium-size to large-size active arrays using state-of-the-art, well-designed thermal structures. Worldwide efforts aiming at thermal management of high-power electronics have resulted in a number of highly efficient and low-profile heat transfer and thermal dissipaters using forced air, liquid cooling, and more recently miniaturized heat pipes (Ababneh et al. 2019). Thermal management is a critical issue which should be taken into consideration from the early design stage.

Large-volume microwave/millimeter-wave component testing (on-wafer and packaged) is quite costly, complex, and often not reliable. Production time and cost must be minimized. This problem has been subject to intensive research recently (Kissinger et al. 2010; Kim et al. 2013).

On-chip/off-chip built-in and self-test concepts as described by above researchers not only help with minimizing the MMIC factory level testing/verification but also assist with improving the performance of MMIC in the system, where the work environment of MMIC can be quite different from that of the factory or test lab.

Choice of circuit topology for each MMIC circuit block has to take overall cost/complexity and power consumption requirements into consideration while meeting the performance requirements. As an example, if the system contains an internal calibration system, then given the fact that a robust intelligent calibration algorithm can effectively correct the errors in an analog circuit, a simple analog phase shifter can be considered a good option instead of a digital phase shifter, minimizing cost, complexity, and power consumption.

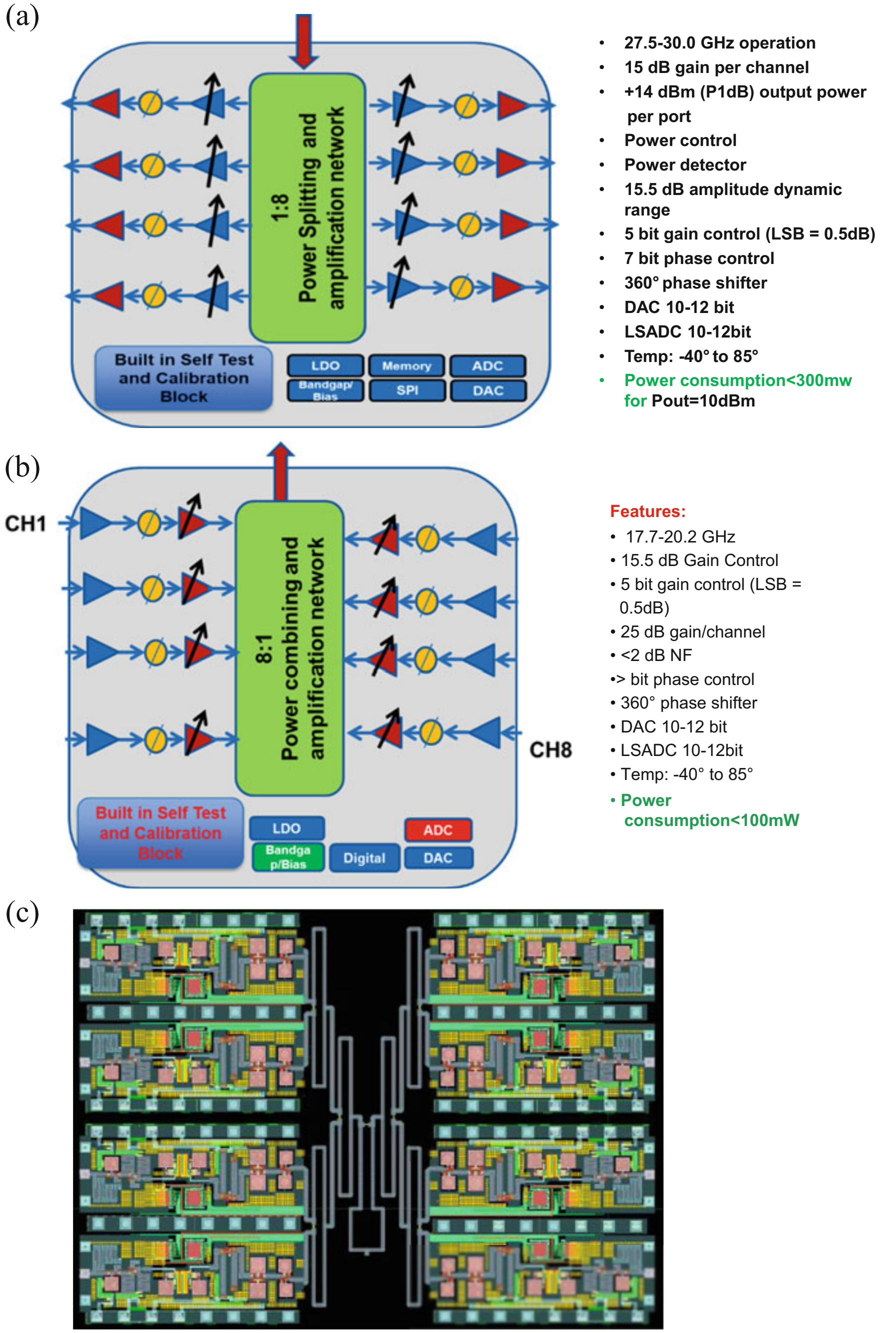


Fig. 9 Typical Ka-/K-band transmitter and receiver 8-channel MMIC architecture: (**a**) transmitter MMIC, (**b**) receiver MMIC, (**c**) 8-channel MMIC layout. (Courtesy of UW-CIARS)

The number of beam-former channels (phase shifter/amplifier) that can be implemented on one MMIC is another important design decision. Given the level of maturity of a certain semiconductor fabrication process, increasing the number of channels beyond a certain point makes the fabrication process more error-prone, reduces the yield, and increases the power consumption and the generated heat per die. Ease of interconnecting the MMIC inputs/outputs to the module feed circuit is another important consideration, which will relate to the type of the feed circuit technology and MMIC packaging technique. These show interplay between various subsystem designs/development.

Similar considerations apply to design of the receiver MMIC. The same approach can be applied to receiver intelligent modules (sub-array building blocks) which are required for active phased-array systems. The most essential system goal on the receive side is to maximize *G/T*. The array gain (*G*) is determined by the size of the array. *T* is the system noise temperature and, as described earlier, is contributed by antenna noise, losses preceding the first stage of the low-noise amplification (antenna radiation efficiency and the insertion loss of the feed circuit between the antenna element and MMIC ports), and the electronic noise generated by the MMIC and other circuit elements (noise figure of the low-noise front-end). In the absence of external noise sources, the dominant factors are often the feed circuit loss and the MMIC noise figure. The feed circuit loss can be minimized by minimizing the length of transmission line between the antenna input and MMIC. The MMIC noise figure depends on the technology minimum noise figure, the low-noise amplifier design, and the antenna active impedance presented to the MMIC. Very often the MMIC noise figure sets the lower bound to the system temperature. For example, with a typical required *G/T* greater than 12 or 14 dB, and the phased-array physical area constraints dictated by major Ka-band application markets, then a noise figure often less than 3 dB or even 2 dB is required for the K-band receiver front-end MMIC, which is fortunately quite within reach of the current state of the art. For some highly critical applications where a much better noise performance is required, a hybrid approach is adopted, wherein the low-cost (CMOS or SiGe) front-end MMIC can be assisted by an additional stage of an ultra-low-noise amplifier using discrete devices such as pHEMT. A unique advantage of a fully active array is the inherent capability to generate pure polarization at any scan angle. The radiated field polarization of any antenna element will change with look angle. In the case of critical applications where a pure polarization is needed at any arbitrary beam pointing direction, each antenna array element can be fed at two orthogonal radiation mode feeding points ("orthogonal ports"). By proper choice of the phases and the amplitudes of the two MMIC channels which excite these two orthogonal ports, any polarization at any scan angle can be generated. The excitation phases/amplitudes are a function of the scan angle. Therefore the polarization and the radiation beam direction essentially become software definable.

A number of techniques to deal with the scan angle dependence on the antenna active impedance have been developed recently. Proper antenna design methods call for choice of the orientation of the neighboring elements and enhancing the isolation between neighboring elements through parasitic structures; engineered surfaces and defect ground plane; and MMIC built-in intelligence and reconfigurable architectures. All have been successfully applied to this problem.

4.5 Passive Phased-Array Technologies

Passive phased arrays, wherein the phase shifting and amplitude control are realized by passive tunable structures, are attractive solutions for low-cost communications and sensing applications where the EIRP and *G/T* requirements and radiation beam characteristics are less demanding. Cost, complexity, and power consumption of active phased-array systems can be significantly reduced if the active beam control circuits could be replaced by reasonably low insertion loss passive phase shifters, whose insertion loss does not change with the phase shift. A number of passive millimeter-wave phase shifters (MEMS-based (Chakraborty and Gupta 2016) and ferroelectric-based structures, liquid-crystal (LC) phase shifters (Strunck et al. 2015), MMIC phase shifters (Yang and Yang 2011; Ellinger et al. 2010), photonic-based phase shifters (Yi et al. 2011; Zhang and Pan 2018), and more recently, high-dielectric movable slab phase shifters (Abdellatif et al. 2014)) have been proposed and developed in recent years. Among these, MMIC phase shifters and moving, high-dielectric constant (such as BLT) slab phase shifters can be considered as feasible approaches for low-cost, large phased-array systems. To date, none of the other approaches can meet the insertion loss requirement (both average loss and phase shift-dependent loss variation) or size constraints (the phase shifter structure footprint must fit underneath the array element or one unit cell of a 2D phased array at higher microwave or millimeter-wave frequencies), in a cost-effective manner. MMIC phase shifters, due to their cost and complexity, are often used in active phased-array systems. The new BLT phase shifter (Abdellatif et al. 2014; Al-Saedi et al. 2018) appears to be an interesting solution for modular passive phased-array applications. BLT (barium lanthanum titanate) is an exceptional material with very high-dielectric constant but very low loss tangent. This technology can potentially result in a low-cost, miniaturized, and low-insertion loss phase shifter with very low phase shift loss dependence for high-performance phased-array systems.

4.6 Internal (On-Board) Calibration

An important advantage of active phased-array systems, as compared to fixed beam antenna systems, is their inherent capability to effectively deal with phase/amplitude imbalances, component failures, and/or large variation in component characteristics over time, through well-designed internal or on-board AI-based calibration and diagnosis techniques. Phased arrays are highly resilient (fault-tolerant) structures and can continue to work, with reduced performance, even if a large number of their active beam-forming devices fail (graceful degradation).

Responses of both active devices and passive components will necessarily change with temperature, mechanical deformation, and other unpredictable environmental factors. Robust and intelligent (AI-based) beam-forming and system identification algorithms can deal with these changes as long as they can be estimated in a timely manner.

On-chip microwave and millimeter wave self-test techniques, as mentioned before, can be extended to real-time monitoring of MMIC critical performance measures. One approach is to measure amplitude and phase of the high frequency signal at critical points of the beam-forming MMICs to assess the chip performance and model its behavior. MMICs for phased-array applications commonly include temperature sensors for reporting the junction temperature, which is used to adjust MMIC parameters and to maintain its performance over a wide range of temperatures. Loop-back test strategies and built-in self-test are other strategies currently being implemented to adaptively control the performance of a MMIC.

Maintaining phase/time synchronism between intelligent modules is another major challenge. A backplane feed network (signal splitter in the case of transmit-array and signal combiner in the case of the receiver array) collects or distributes module RF signals over a large area (tens of cm). Low-cost production processes do not provide the tens of microns range of positioning accuracy or tight angular tolerance needed in millimeter-wave phased arrays. The inevitable phase/amplitude imbalances between the mmW signal paths from the input to the system of each individual antenna should be compensated for. The phase/amplitude balancing is particularly critical for the transmit array, which must satisfy the radiation spectral density mask. A number of statistical methods, orthogonal code-based techniques (Silverstein 1997), and external (remote or on-board) sources (Lier et al. 2000; Fadamiro et al. 2018) have been proposed for calibration of phased-array systems. These methods often require either far field or highly complex near-field measurements, which are not feasible for mobile satellite communication.

A promising approach followed by a number of research groups is to integrate electromagnetic field probes (small test antennas) either in the feed circuit (see SANTANA project (Baggen et al. 2013)) or in the radiating aperture, or at some small distance from the aperture. Using field probes integrated into the aperture offers the most cost-effective approach with minimal or almost no impact on the feed circuit. In a typical scheme shown in Fig. 10, the probe can pick up the near-field aperture signal directly. When the array elements are excited individually or in particularly formed groups, the detector probe near field can be used to accurately estimate the element amplitude/phase imbalances generated by all errors and uncertainties from the input to the system to the radiating aperture. Such techniques can be used not only to fully calibrate the phased-array system but also to characterize each MMIC active channel (amplifier/phase shifter chain connected to a particular antenna element input) inside the array environment. By using such an internal (on-board) calibration technique, the impact of the beam-scanning and the array environment on the gain and phase response of each MMIC can be measured and accounted for in the beam-forming and polarization adjustment during the system operation.

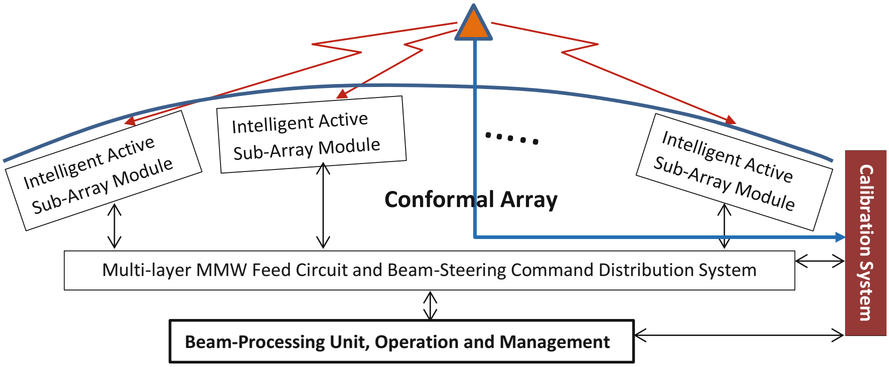


Fig. 10 Integrated calibration system using electromagnetic field probes close to aperture or embedded in the feed circuit

5 Conclusions

The rapid development of new phased-array or electronic beam-scanning technology is changing the landscape of radio and antenna solutions for all satellite communication systems, whether GEO, MEO, LEO, or future small satellites. Recent advances in low-cost, multilayer circuit/antenna technologies, microwave/millimeter-wave integrated circuits, low-cost powerful digital systems, and highly intelligent beam-forming and system identification/calibration algorithms are paving the way for the next evolution toward integration of space, air, and terrestrial networks. The development of low-cost active and passive phased-array ground systems for 5G/6G cellular and small satellite constellations will offer many opportunities for new satellite services, particularly in the under-served regions of the world. The new large-scale small satellite constellations that are being deployed will be heavily dependent on this new ground segment capability to provide their data-based and 5G/6G-oriented broadband cellular services. It is hoped that the technical background provided in this chapter can assist in the understanding of the expanding market for ground antenna systems and particularly for flat panel antennas that will support the rapid increase in small satellite constellations.

6 Cross-References

- ▶ Economic and Market Trends for Ground Systems to Support New and Future Small Satellite Systems
- ▶ Evolution of Satellite Networks and Antenna Markets
- ▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas
- ▶ Small Satellites and Innovations in Terminal and Teleport Design, Deployment, and Operation

References

M.T. Ababneh, C. Tarau, W.G. Anderson, High temperature lightweight heat pipes for solid-state power amplifier (SSPA) thermal management, in *2019 18th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)* (IEEE, 2019), pp. 656–665

A.S. Abdellatif, M. Faraji-Dana, N. Ranjkesh, A. Taeb, M. Fahimnia, S. Gigoyan, S. Safavi-Naeini, Low loss, wideband, and compact CPW-based phase shifter for millimeter-wave applications. IEEE Trans. Microwave Theory Tech. **62**(12), 3403–3413 (2014)

W.M. Abdel-Wahab, D. Busuioc, S. Safavi-Naeini, Millimeter-wave high radiation efficiency planar waveguide series-fed dielectric resonator antenna (DRA) array: Analysis, design, and measurements. IEEE Trans. Antennas Propag. **59**(8), 2834–2843 (2011)

W.M. Abdel-Wahab, Y. Wang, S. Safavi-Naeini, SIW hybrid feeding network-integrated 2-D DRA array: simulations and experiments. IEEE Antennas Wirel. Propag. Lett. **15**, 548–551 (2015)

W.M. Abdel-Wahab, H. Al-Saedi, E.H.M. Alian, M. Raeis-Zadeh, A. Ehsandar, A. Palizban, S. Safavi-Naeini, A modular architecture for wide scan angle phased array antenna for K/Ka mobile SATCOM, in *2019 IEEE MTT-S International Microwave Symposium (IMS)* (IEEE, 2019), pp. 1076–1079)

H. Al-Saedi, S. Gigoyan, W.M. Abdel-Wahab, A. Palizban, A. Taeb, A. Ehsandar, S. Safavi-Naeini, A low-cost Ka-band circularly polarized passive phased-array antenna for mobile satellite applications. IEEE Trans. Antennas Propag. **67**(1), 221–231 (2018)

L. Baggen, M. Böttcher, S. Otto, O. Litschke, R. Gieron, S. Holzwarth, Phased array technology by IMST: a comprehensive overview, in *2013 IEEE International Symposium on Phased Array Systems and Technology* (IEEE, 2013), pp. 21–28

H. Bolandhemmat, M. Fakharzadeh, P. Mousavi, S.H. Jamali, G.Z. Rafi, S. Safavi-Naeini, Active stabilization of vehicle-mounted phased-array antennas. IEEE Trans. Veh. Technol. **58**(6), 2638–2650 (2009)

A. Chakraborty, B. Gupta, Paradigm phase shift: RF MEMS phase shifters: an overview. IEEE Microw. Mag. **18**(1), 22–41 (2016)

M. Chen, A.V. Pham, C. Kapusta, J. Iannotti, W. Kornrumpf, N. Evers, … N. Karabudak, Development of multilayer organic modules for hermetic packaging of RF MEMS circuits, in *2006 IEEE MTT-S International Microwave Symposium Digest* (IEEE, 2006), pp. 271–274

R. Chirikov, P. Rocca, L. Manica, S. Santarelli, R.J. Mailloux, A. Massa, Innovative GA-based strategy for polyomino tiling in phased array design. In *2013 7th European Conference on Antennas and Propagation (EuCAP)* (IEEE, 2013), pp. 2216–2219

E. Cohen, M. Ruberto, M. Cohen, O. Degani, S. Ravid, D. Ritter, A CMOS bidirectional 32-element phased-array transceiver at 60 GHz with LTCC antenna. IEEE Trans. Microwave Theory Tech. **61**(3), 1359–1375 (2013)

D. Ehyaie, A. Mortazawi, A new approach to design low cost, low complexity phased arrays, in *2010 IEEE MTT-S International Microwave Symposium* (IEEE, 2010), pp. 1270–1273

F. Ellinger, U. Mayer, M. Wickert, N. Joram, J. Wagner, R. Eickhoff, … R. Kraemer, Integrated adjustable phase shifters. IEEE Microw. Mag. **11**(6), 97–108 (2010)

A.O. Fadamiro, O.J. Famoriji, R. Kashif, M.S. Ali, F. Lin, An improved calibration algorithm for active phased array antenna, in *2018 IEEE International Conference on Computational Electromagnetics (ICCEM)* (IEEE, 2018), pp. 1–3

M. Fakharzadeh, S.H. Jamali, P. Mousavi, S. Safavi-Naeini, Fast beamforming for mobile satellite receiver phased arrays: Theory and experiment. IEEE Trans. Antennas Propag. **57**(6), 1645–1654 (2009)

S. Gao, Y. Rahmat-Samii, R.E. Hodges, X.X. Yang, Advanced antennas for small satellites. Proc. IEEE **106**(3), 391–403 (2018)

GILAT, in *RaySat EagleRay 5000, Pioneering Ka-band SOTM for Defense and Security Applications* (GILAT, 2014)

X. Gu, A. Valdes-Garcia, A. Natarajan, B. Sadhu, D. Liu, S.K. Reynolds, W-band scalable phased arrays for imaging and communications. IEEE Commun. Mag. **53**(4), 196–204 (2015)

S. Han, I. Chih-Lin, Z. Xu, C. Rowell, Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G. IEEE Commun. Mag. **53**(1), 186–194 (2015)

H. Hashemi, X. Guan, A. Komijani, A. Hajimiri, A 24-GHz SiGe phased-array receiver-LO phase-shifting approach. IEEE Trans. Microwave Theory Tech. **53**(2), 614–626 (2005)

R.L. Haupt, Optimized weighting of uniform subarrays of unequal sizes. IEEE Trans. Antennas Propag. **55**(4), 1207–1210 (2007)

W.H. Henderson, W.W. Milroy, Wireless communication applications of the continuous transverse stub (CTS) array at microwave and millimeter wave frequencies, in *IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics, 2005* (IEEE, 2005), pp. 253–256

A. Hoehn, P.B. Hager, J.T. Harder, Design characterization of an electronic steerable Ka-band antenna using liquid crystal phase shifters, in *2013 IEEE Aerospace Conference* (IEEE, 2013), pp. 1–14

W. Hong, K.H. Baek, Y. Lee, Y. Kim, S.T. Ko, Study and prototyping of practically large-scale mmWave antenna systems for 5G cellular devices. IEEE Commun. Mag. **52**(9), 63–69 (2014)

X. Huang, J.A. Zhang, R.P. Liu, Y.J. Guo, L. Hanzo, Airplane-aided integrated networking for 6G wireless: Will it work? IEEE Veh. Technol. Mag. **14**(3), 84–91 (2019)

W.A. Imbriale, S.S. Gao, L. Boccia, *Space Antenna Handbook* (Wiley, New York, 2012)

S. Jeon, Y.J. Wang, H. Wang, F. Bohn, A. Natarajan, A. Babakhani, A. Hajimiri, A scalable 6-to-18 GHz concurrent dual-band quad-beam phased-array receiver in CMOS. IEEE J. Solid State Circuits **43**(12), 2660–2673 (2008)

M.C. Johnson, S.L. Brunton, N.B. Kundtz, J.N. Kutz, Sidelobe canceling for reconfigurable holographic metamaterial antenna. IEEE Trans. Antennas Propag. **63**(4), 1881–1886 (2015)

S.Y. Kim, O. Inac, C.Y. Kim, D. Shin, G.M. Rebeiz, A 76–84-GHz 16-element phased-array receiver with a chip-level built-in self-test system. IEEE Trans. Microwave Theory Tech. **61**(8), 3083–3098 (2013)

J. King, J. Ness, G. Bonin, M. Brett, D. Faber, Nanosat Ka-band communications-A paradigm shift in small satellite data throughput (2012), https://digitalcommons.usu.edu/smallsat/2012/all2012/54/

D. Kissinger, B. Laemmle, L. Maurer, R. Weigel, Integrated test for silicon front ends. IEEE Microw. Mag. **11**(3), 87–94 (2010)

K.J. Koh, G.M. Rebeiz, An X-and Ku-band 8-element phased-Array receiver in 0.18-μm SiGe BiCMOS technology. IEEE J. Solid State Circuits **43**(6), 1360–1371 (2008)

Y. Li, K.M. Luk, 60-GHz substrate integrated waveguide fed cavity-backed aperture-coupled microstrip patch antenna arrays. IEEE Trans. Antennas Propag. **63**(3), 1075–1085 (2015)

E. Lier, R. Melcher, A modular and lightweight multibeam active phased receiving array for satellite applications: Design and ground testing. IEEE Antennas Propag. Mag. **51**(1), 80–90 (2009)

E. Lier, D. Purdy, J. Ashe, G. Kautz, An on-board integrated beam conditioning system for active phased array satellite antennas, in *Proceedings 2000 IEEE International Conference on Phased Array Systems and Technology (Cat. No. 00TH8510)* (IEEE, 2000), pp. 509–512

O. Litschke, W. Simon, S. Holzwarth, A 30 GHz highly integrated LTCC antenna element for digital beam forming arrays, in *2005 IEEE Antennas and Propagation Society International Symposium*, vol 3 (IEEE, 2005), pp. 297–300

K.K.W. Low, A. Nafe, S. Zihir, T. Kanar, G.M.A Rebeiz, Scalable circularly-polarized 256-element Ka-band phased-array SATCOM transmitter with±60 beam scanning and 34.5 dBW EIRP, in *2019 IEEE MTT-S International Microwave Symposium (IMS)* (IEEE, 2019), pp. 1064–1067

E. Meniconi, V. Ziegler, R. Sorrentino, T. Chaloun, 3D integration technologies for a planar dual band active array in Ka-band, in *2013 European Microwave Conference* (IEEE, 2013), pp. 215–218

P. Mousavi, M. Fakharzadeh, S.H. Jamali, K. Narimani, M. Hossu, H. Bolandhemmat, … S. Safavi-Naeini, A low-cost ultra low profile phased array system for mobile satellite reception using zero-knowledge beamforming algorithm. IEEE Trans. Antennas Propag. **56**(12), 3667–3679 (2008)

A. Natarajan, S. K. Reynolds, M.D. Tsai, S.T. Nicolson, J.H.C. Zhan, D.G. Kam, ... B.A. Floyd, A fully-integrated 16-element phased-array receiver in SiGe BiCMOS for 60-GHz communications. IEEE J. Solid State Circuits **46**(5), 1059–1075 (2011)

Northern Sky Research, *It's a mobile world for flat panel antennas* (2017). [Online]. http://www.nsr.com/news-resources/nsr-in-the-press/nsr-press-releases/its-a-mobile-world-for-flat-panel-antennas/

Phasor Soluions, *COMMS on the Move* (2015)

Y. Rahmat-Samii, V. Manohar, J.M. Kovitz, For satellites, think small, dream big: A review of recent antenna developments for CubeSats. IEEE Antennas Propag. Mag. **59**(2), 22–30 (2017)

P. Rocca, R.J. Mailloux, G. Toso, GA-based optimization of irregular subarray layouts for wideband phased arrays design. IEEE Antennas Wirel. Propag. Lett. **14**, 131–134 (2014)

W. Roh, J.Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, ... F. Aryanfar, Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results. IEEE Commun. Mag. **52**(2), 106–113 (2014)

H. Schippers, J. Verpoorte, P. Jorna, A. Hulzinga, A. Meijerink, C. Roeloffzen, ... M. Wintels, Conformal phased array with beam forming for airborne satellite communication, in *2008 International ITG Workshop on Smart Antennas* (IEEE, 2008), pp. 343–350

S.D. Silverstein, Application of orthogonal codes to the calibration of active phased array antennas for communication satellites. IEEE Trans. Signal Process. **45**(1), 206–218 (1997)

S. Strunck, A. Gaebler, O.H. Karabey, A. Heunisch, B. Schulz, T. Rabe, ... R. Jakoby, Reliability study of a tunable Ka-band SIW-phase shifter based on liquid crystal in LTCC-technology. Int. J. Microw. Wirel. Technol. **7**(5), 521–527 (2015)

A.I. Sulyman, A.T. Nassar, M.K. Samimi, G.R. MacCartney, T.S. Rappaport, A. Alsanie, Radio propagation path loss models for 5G cellular networks in the 28 GHz and 38 GHz millimeter-wave bands. IEEE Commun. Mag. **52**(9), 78–86 (2014)

F. Tabarani, L. Boccia, T. Purtova, A. Shamsafar, H. Schumacher, G. Amendola, 0.25-μm BiCMOS system-on-Chip for K-/Ka-band satellite communication transmit–receive active phased arrays. IEEE Trans. Microw. Theory Tech. **66**(5), 2325–2339 (2018)

ThinKom, *ThinAir Falcon-Ka-2517, Office-in-the-Air-Connectivity* (ThinKom Global Connectivity, 2014)

S. Vaccaro, D.L. del Río, R.T. Sánchez, R. Baggen, Low cost phased array for mobile Ku-band satellite terminal, in *Proceedings of the Fourth European Conference on Antennas and Propagation* (IEEE, 2010), pp. 1–5

J. Xu, Z.N. Chen, X. Qing, W. Hong, Bandwidth enhancement for a 60 GHz substrate integrated waveguide fed cavity array antenna on LTCC. IEEE Trans. Antennas Propag. **59**(3), 826–832 (2010)

J.G. Yang, K. Yang, Ka-band 5-bit MMIC phase shifter using InGaAs PIN switching diodes. IEEE Microwave Wireless Compon Lett. **21**(3), 151–153 (2011)

X. Yi, T.X. Huang, R.A. Minasian, Photonic beamforming based on programmable phase shifters with amplitude and phase control. IEEE Photon. Technol. Lett. **23**(18), 1286–1288 (2011)

Y. Zhang, S. Pan, Broadband microwave signal processing enabled by polarization-based photonic microwave phase shifters. IEEE J. Quantum Electron. **54**(4), 1–12 (2018)

Ground Systems to Connect Small-Satellite Constellations to Underserved Areas

Christoffel J. Kotze

Contents

Abstract

Access to broadband Internet is increasingly becoming compulsory in order to participate in many aspects of modern economic systems. Currently more than a third of the global population does not have access to any form of Internet connection and thus by default is excluded from any activity for which it is a prerequisite. One of the primary reasons for the exclusion of any population from Internet access is the lack of available communication infrastructure; this is particularly relevant in remote societies. Satellite technology by its very nature is not geographically constrained making it ideal to deliver broadband

---

C. J. Kotze (✉)
NOEZ Consulting & Design, Yzerfontein, South Africa
e-mail: chris@noez.co.za

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_31

to remote communities. Opportunity presents itself with the recent announcement of mega-constellations featuring hundreds or even thousands of small satellites, which significantly bolster not only the available bandwidth but also the ability to provide it at low latency as it will operate in lower orbits.

In the world of satellite services, the focus tends to be on the space systems in orbit, but in the case of large-scale LEO constellations, the design and implementation of the ground systems will be of critical importance. The purpose of this chapter is to investigate what is practically required at ground level to allow a remote community to successfully engage small-satellite broadband Internet in a reliable, cost-effective, and technically and operationally feasible manner.

Keywords

Broadband apparatus for remote communities (BARC) · Broadband · Digital divide · Electrical power supplies · Flat-panel antennas · Last-mile problem · Mega-satellite constellations · Small satellites · Technical assistance · Electronic tracking antennas · Wi-Fi access

1 Introduction

The Fourth Industrial Revolution (4IR) is a term used to describe the collective effect on society by rapid simultaneous developments across diverse fields. The new capabilities of this cyber revolution serve as a driver of novel innovation with the potential to positively affect virtually all aspects of society (Schwab). In addition to drivers such as the evolution of cloud technology, connected sensors, and advanced data analytics, it is the sustainable and cost-effective availability of broadband Internet that glues all the components together and enables technology convergence. Though there has been an encouraging acceleration in Internet penetration in recent years, a significant percentage of the global population has still not been connected. Data released in June 2019 indicates that out of an estimated world population of just over 7.7 billion, Internet global penetration is less than 53%. If this estimate is correct, this still leaves 3.3 billion people unconnected (InternetWorldStats 2019). Currently not one of the global macro regions has complete Internet penetration, though in most cases the connected portion of the population is significantly higher than the unconnected; Africa represents the only regional exception (Fig. 1). A 2014 study identified four primary conditions that need to be met before a user will adopt a broadband Internet, namely, it is readily available, accessible, affordable, and relevant to the community or the individual concerned.

Considered the primary preventative factor for adoption of broadband is the “availability” of an Internet service to the target population. The availability of the necessary infrastructure to create the end user community to the connection mesh, often referred to as the so-called last-mile challenge, is the first step in achieving connectivity. In addition to the communication infrastructure, practical use of the Internet also requires ancillary services such as electricity and the necessary

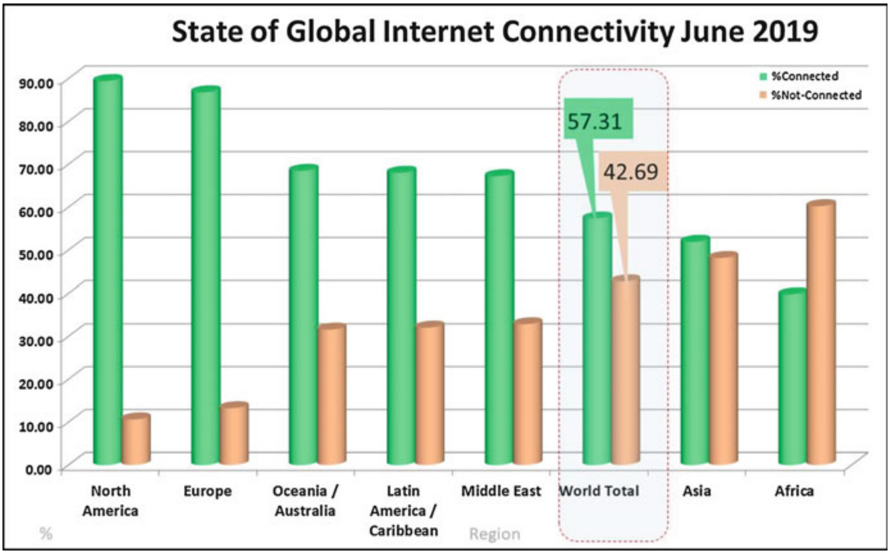


Fig. 1 Regional Internet connectivity expressed as % of the population. (Graphic courtesy of the author)

hardware to engage the service if it is available. A World Economic Forum study indicates the absence of infrastructure as the primary reason for Internet access exclusion of more than a third of the global population, citing 31% not having 3G coverage with 15% without electricity (Biggs 2018a). This chapter aims to explore some of the challenges faced by remote rural communities when it comes to the implementation of broadband Internet and how it can be mitigated.

The term “digital divide” is used to generally differentiate between two groups; on the one side, there are the “haves.” This population generally has access to the best of digital technology and is largely equipped with the relevant skills to use the equipment. The “have nots” represent the other group with limited or no access of any of the “digital privileges” of the other. This phenomenon has been studied extensively for many years. The primary causative factors have been found to be a combination of socioeconomic and spatial demographics. A 2016 World Bank report (World Bank Group 2016) defined the “digital divide” in terms of a user demographic indicating it is particularly skewed toward poor, rural communities as indicated by Fig. 2.

2 The Challenges of the Digital Divide

The “digital divide” though is a multifaceted concept involving not a single but rather a bouquet of digital technologies. One might today, however, argue that it is the availability of the Internet which serves as the standard metric by which to gauge the presence of the digital divide for a specific demographic group. If a community is

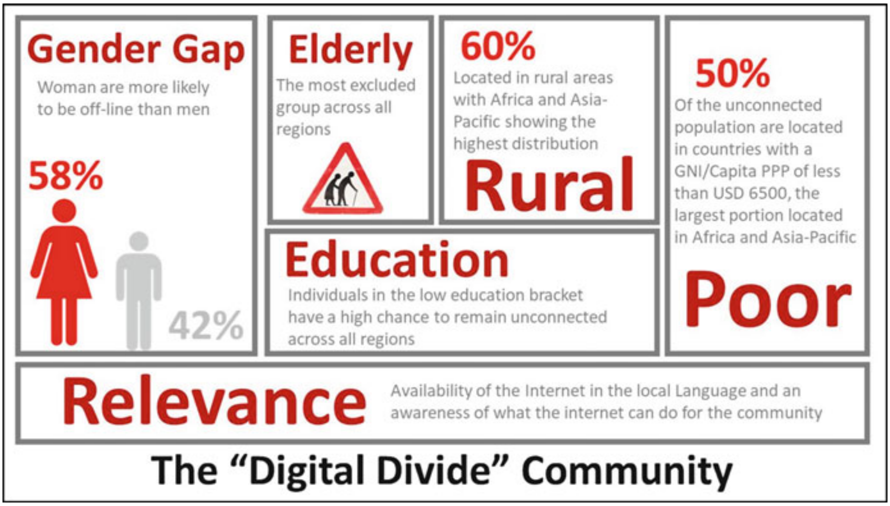


Fig. 2 Demographic profile of the unconnected. (Graphic courtesy of the author)

on the wrong side of the digital divide, it typically means automatic exclusion from the e-commerce economy. According to the last UNCTAD Information Economy report, it had already grown to a 25-trillion USD industry as of year-end 2015 (UNCTAD 2017).

The digital divide at a macro level can eventually impair trade between countries with high levels of digital penetration and those with very low levels of digital integration. As alluded to earlier, the basic availability of infrastructure is the primary exclusion factor for unconnected communities worldwide and thus the primary driver of the "digital divide." Yet, even after the infrastructure problem is resolved, there are still additional barriers to overcome before a user community can productively engage in broadband Internet services. An International Telecommunication Union (ITU) study concluded that in addition to a broadband service being physically available, the following three factors need to be satisfied to determine successful adoption (Biggs 2018b):

- **Cost** – Is the service affordable to the users? An estimated 57% of the global population could not afford Internet access in 2017.
- **Capability** – Do users have the means to access the service, i.e., skill and hardware?
- **Relevance** – Does the user community see a benefit in using the service? Is it applicable from a cultural and language perspective?

Clearly the mitigation of the challenges surrounding infrastructure is key. Yet it is important to note that all relevant factors need to be satisfied for the installation to have a chance of success.

3 The Remote Community Communication Challenge

As illustrated in the previous section, a person living in a rural area has a much higher chance not to be connected to the Internet than one residing in an urban setting. Sub-Saharan Africa where 63% of the population is based in rural areas has the lowest Internet penetration as opposed to the European Union characterized by a very high broadband penetration where only 26% of the population resides in rural areas. In sociology the “Matthew effect” (Rigney 2010), a term coined by Robert K. Merton, refers to a situation where advantage propagates further advantage, and vice versa this can be applied to Internet access. In short, the more you have, the more you can do with it. Rural areas with little to no access thus will, according to the Matthew effect, fall increasingly behind urban areas in activities surrounding “connected” living.

Rural areas have got unique challenges when it comes to the rollout of basic infrastructure which can make these areas more likely not to be included in new technology rollouts. Typically it is the product of a number of causative factors. Yet the strongest factors relate to large distances or difficult terrain that needs to be navigated in order to reach these areas. To investigate the unique challenges faced by rural communities, a study was commissioned by the European Union (EU) in 2008. The study identified four main categories of problems plaguing rural areas (Bertolini et al. 2008):

- **Demography** – rural areas are typically inhabited by a population overrepresented by older people, with a diminishing young populace often leading to an underperforming local economy.
- **Remoteness** – this makes it more difficult to provide and maintain good infrastructure, compounded with an underperforming economy, motivating urban migration consequently acting as inhibitor to an incentive of improving infrastructure.
- **Education** – typically of a lower level among the rural populace, a causative factor in a number of problems experienced by such areas, e.g., lower employment and economic opportunity and increased poverty. Due to a lack of infrastructure, the chance to obtain a better education is diminished.
- **Labor market** – the confluence of the other three factors described limits employment opportunities for residents in rural areas; consequently skilled people leave the area as there is no opportunity, which prevents investment in the area due to a lack of a capable available labor force.

Though the study was done on developed countries within the EU and European Economic Area and therefore is not necessarily applicable directly to developing countries, it does serve as a point of departure to approach challenges affecting rural development in the developing world. Included in one of the many challenges faced by rural areas unfortunately is the ready and cost-effective availability of communication systems.

4 Internet Access Challenges in Remote Areas

For a user to interact with the Internet, a number of primary components must all be available in one place to facilitate the process, namely:

- A communication service to connect the end user to the Internet or the so-called last mile
- Hardware and software to facilitate the connection and allow the user to engage the Internet
- Available electricity to power the Internet-enabling equipment

The requirement to connect to the Internet for a user in a city is in principal the same for an end user in a remote rural setting; however the availability electricity and "last-mile" options typically can be a real constraint.

4.1 The "Last-Mile" Issue

The term "last mile" is a figurative term used in the telecommunications industry used to describe the link between the primary telecoms infrastructure and the end user, e.g., the cable between the telephone and a house or a "Wi-Fi" hotspot. Bridging the "last mile" remains the principal problem preventing the mass rollout of broadband Internet services; the more remote the area, the smaller the probability of a traditional fixed-line connection. In remote areas it is quite often not economically viable to lay cable infrastructure such as fiber optics; quite often it is not even physically possible. Remoteness also impacts the rollout of mobile phone technology where mass rollout is challenged by accessibility maintenance and security issues. Cell phone base stations are increasingly the target of opportunistic theft as thieves target the air-conditioning units, copper wire, and especially the backup batteries; remote isolated towers are especially vulnerable to this kind of theft. An Internet service provider (ISP) typically is a profit-driven commercial enterprise which typically will not willingly deploy to an area where no financial incentive exists or an area where the infrastructure would be difficult to maintain. Satellite technology is particularly well suited to act as the "last-mile" link as it is not bound by physical accessibility, having the ability to connect virtually any area on earth. Yet there is still the challenge of how the consumer achieves connection to the satellite system. This is the key aspect addressed in this chapter.

4.2 Satellite Broadband

Satellite technology by its very nature has to have many layers of redundancy built-in due to the fact that maintenance for the spacecraft is virtually impossible, which practically translates into a highly reliable service. Traditionally satellite broadband delivered by geosynchronous spacecraft has been plagued by cost, capacity, and particularly the problem of latency issues. In recent years technological development across the space industry has benefited the satellite industry. High-throughput GEO satellites can provide a cost-effective broadband service able to compete with terrestrial broadband services in terms of capacity and cost. New standards now include the use of spoofing techniques and larger delay windows to avoid GEO delay not to be mistaken for system congestion. These adjustments and new standard to address GEO satellite latency concerns have increased the ability of these systems to support networked services. Yet latency remains an issue.

Latency is largely determined by the round-trip distance the signal has to travel between source and destination. There can be other factors such as processing times. The transmission round-trip distance will be primarily determined by the orbit the satellite orbits in, which is one aspect that in some cases serves as an exclusion factor for broadband services using geosynchronous earth orbit (GEO). Broadband satellites using GEO orbits have the distinct advantage that it can use a stationary antenna at the user end as opposed to low (LEO) and medium earth orbit (MEO) where tracking is required. However this comes at the price of high latency. The lower orbit constellations can produce very competitive latency performance albeit with the requirement for more sophisticated user antenna tracking arrangement which comes at a cost. Substantial reduction in cost per unit has made satellite broadband increasingly affordable and is expected to continue as additional capacity is added especially in view of a number of small-satellite-based mega-constellations that have been announced and with many now being implemented. Unlocking the true potential of these new mega-constellations which will be operating in the lower orbit segments will depend how well the market can develop the ground equipment necessary to optimally connect to these constellations.

4.3 Smallsats

In the past decade, rapid development in the information and communication technology (ICT) sphere has led to significant increases in the capability and capacity of hardware and the software able to exploit it. These developments have filtered down into all aspects of modern industry including satellite development in the form of small satellites commonly known as “smallsats.” These are highly capable functional units featuring a small footprint and are relatively cheap to produce and less costly to launch. This emerging class of satellites can range from very small “cubesats” (weighing as little as 1 kg) to larger units with a mass typically in the 150–500 kg range. The lesser weight translates into lower launch costs, coupled with the availability of cheaper launch option now becoming available. Between 2008 and 2018, more than 1200 “smallsats” have already been launched, a figure dwarfed by the many thousands of additional units planned for launch by 2028.

The increasing market for spaced-based services to provide communication and remote sensing is expected to continue to drive demand upward for low earth orbit (LEO)-based services leading to increased competition and a decrease in cost for these services and the space and ground systems. Decreased launch costs make shorter technology cycles of space-based assets feasibly relative to terrestrial providers. “Smallsats” are particularly well suited for broadband provision, and as such a number of “smallsats” mega-constellations are now being implemented such as the OneWeb (Dean) network backed in part by Google and the Starlink (Coldewey 2019) system backed by SpaceX; many systems have been announced such as Amazon’s “Kuiper” (Henry 2019). The large number of small-satellite constellations to provide broadband networking services and remote sensing services – now exceeding over 20,000 of such new types of satellites – has raised concerned about a glut of such types of satellite services, large price wars, and serious concerns about orbital debris.

4.4 Electricity

Without the availability of electricity at an end user’s location, the availability of a satellite broadband signal will not mean much as all digital devices need a certain amount of electricity to drive its components. Though the minimum power requirement of the end user hardware is normally quite minimal, it still needs to be available to enable a practical engagement with the Internet (see Table 1).

For urban users the availability of electricity normally is not a problem in most areas of the world where, on average, 96.4% of the urban population has access, as opposed to 73% of the rural population across the globe (SE4ALL 2018). On a regional scale, the difference between urban and rural can be much more pronounced. One such example is sub-Saharan Africa, the region with the fastest growing population in the world. This region which will by 2035 also have the youngest population in the world has a pronounced difference in electricity penetration, where 79% of urban dwellers has access and less than 23% of the rural population has such access (Bello-Schünemann 2017).

5 Broadband Access for Remote Underserved or Unserved Communities

With technological development making satellite broadband an increasingly viable solution for mass rollout, the question is how can it and other emerging technology be utilized to make broadband rollout a practical solution for the unconnected in remote areas. A product that can bridge the “last mile” while also providing the ability to address the other barriers of broadband adoption to effectively present

Table 1 User-end broadband power requirement (Energy Use Calculator 2018)

Broadband “user-end” power requirement					
Access device	“Feature phone”	Notebook	PC	Smartphone	Tablet
Consumption	2–6 W	20–100 W	90–350 W	2–6 W	2–6 W

Table 2 Features, advantages, and benefits of a broadband apparatus for remote communities (BARC)

Broadband access for remote communities (BARC) (Features, advantages, and benefits (FAB) analysis)	
Features	Self-contained broadband Internet system, using satellite communication and renewable energy technology, with the ability to provide additional wireless services such as Wi-Fi connectivity to villages
Advantages	Can be deployed in most remote areas, not dependent on any existing infrastructure, and provide all required supporting services for practical broadband Internet use
Benefits	Allows the community to benefit by being able to use broadband Internet in a practical and costeffective manner

broadband is presented and analyzed here. This is called for this discussion and analysis a broadband apparatus for remote communities (BARC). Such a BARC must have the ability to deliver broadband Internet to any remote community without the need for power or additional communication infrastructure to be already available at the proposed site. Ideally such a product should be designed to be integrated into the daily lives of the user population in such a way that full acceptance of the technology is achieved to the maximum benefit of all stakeholders. Table 2 presents the basic expected features, advantages, and benefits (FAB) of such a product.

The features, advantages, and benefits (FAB) of such a product can further be translated into requirements to define it more clearly as presented below.

A successful product in one way or another is the result of a sound requirement analysis, which can be based on information obtained from various sources and on observed trend data and recommendations and ideally should include some degree of user consultation. This process is generally known as the requirements definition, and arguably the most important phase of the product lifecycle, literally being the first make-or-break point (Daniels 2000). Requirements are typically split into functional and nonfunctional requirements. Functional requirements are based on “feature” or “what” the product must achieve typically described as single requirement. Non-functional requirements are the criteria used to assess the system, i.e., the “how.” Defining “how” the system should deliver the “what” is also referred to as the “quality requirements” and will typically include a set of “acceptance criteria.”

In the case of a product that will serve the remote underserviced market, the basic requirements are determined to a large degree by an acceptance model based on the criteria of availability, accessibility, affordability, and applicability. Such an acceptance model is based on research by various international institutions such as the International Telecommunications Union (ITU), the United Nations (UN), and the World Bank Group among others. Product requirement thus must have as its primary goal the elimination of these four barriers preventing the successful adoption of broadband services in unconnected communities. A product deployed in a remote area where access is not easy nor necessarily guaranteed will also have to offer a very high degree of reliability.

Low-maintenance requirements augmented by a robust remote management and monitoring abilities constitute important considerations. It is also desirable to involve a degree of training to establish a certain community knowledge base to carry out basic maintenance and building community ownership. To ensure additional "buy-in" into the use of the product by the local community, it might be beneficial to add extra features to the product which falls outside of just communications device. Such additional features could be a direct service, i.e., provide light at night in an area where electricity is not available or collect data to serve the community indirectly down-the-line.

The quality requirements can be split into two main groupings, namely, the basic user acceptance requirements and performance requirements. Typical requirements falling under the ambit of performance requirements will relate to product performance, reliability, supportability, and usability. The four generic conformance criteria for community acceptance of broadband serve as the "acceptance criteria." These are very important design considerations as they will determine the product's acceptance rate (Sprague et al. 2014).

These acceptance requirements must importantly include a component to create a "desire" in the target user to "want to" use the product which in turn can be influenced by the design.

6 The Basic Broadband Apparatus for Remote Communities (BARC)

In its basic form, a BARC needs to deliver the means to practically engage broadband Internet to a user in an underserviced remote community anywhere in the world. To achieve this it needs to perform four "foundation" functions, namely, engage two-way communication with a broadband constellation, generate and store electricity, and provide a practical user interface – all delivered in a single unit. This section explores the basic architecture with some notes on enabling technology.

6.1 Architecture

The foundation architecture required to deliver the basic purpose can be viewed as an interrelationship between four integrated functional modules, namely, structure, power, communications, and user interface. In this configuration the product should be able to provide all that is required for an end user to engage a space-based broadband signal. The architecture can be modelled analogously to the concept of a "biological cell," where the environment for all functional components to interact and enable the cell to function as a single unit is created within the boundaries of a "cell wall" – in this model represented by M1 the "Structure Module" (see Fig. 3).

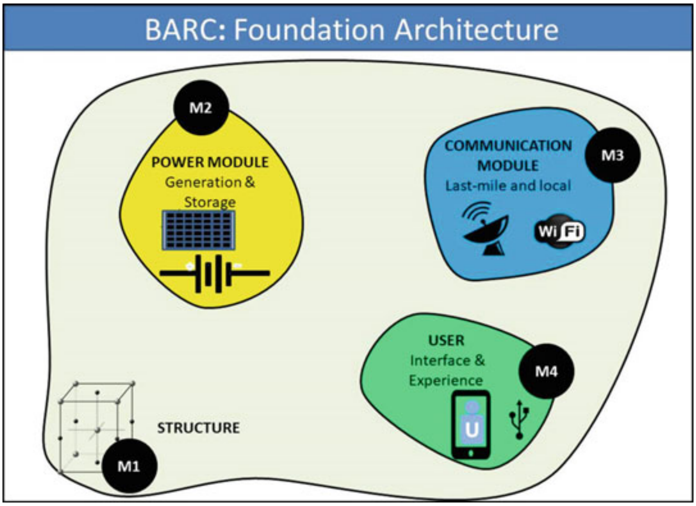


Fig. 3 BARC foundation architecture. (Graphic courtesy of the author)

6.1.1 Structure Module (M1)

This module not only provides the physical structure to anchor all the necessary equipment but also provides the means to integrate and control all the modules into a single workable unit. As the "heart of the system," it is the central point of failure for the system, and the design should be robust enough to minimize risk of failure. Typically it will contain at least the following functionalities:

- Anchor points
- Central control distribution and connections
- Power distribution and connections
- Physical structure to accommodate all required hardware and software
- Reticulation conduits and connectors
- Telemetry

6.1.2 Power Module (M2)

This module is responsible for the generation and storage of electrical power for the BARC system. It will need to utilize a form of renewable energy appropriate to the area of deployment, e.g., photovoltaic panels, which is then stored in batteries. Power generation for any device in a remote area will have to rely on a type of renewable energy which can easily be integrated into a BARC, currently dominated by two types, namely:

- **Photovoltaic (PV) technology** generates electricity through the interaction of a semiconductor material and sunlight. PV is widely used in multiple applications in diverse settings, from powering satellites in space to the pumping of water in the desert and powering of a plethora of personal equipment (NREL 2018). New technology using non-silicon-based materials allow for ever-increasing application allowing PV materials to be directly applied on different shapes and surfaces (Energy.gov). PV technology is by far the most popular technology for rapid rollout of power at underserviced areas and is widely used to power equipment in marine craft such as sail yachts.

- **Wind** power, arguably the oldest form of renewable energy, started out propelling boats in ancient Egypt then gradually evolved into more sophisticated applications with wind-powered water pumps believed to be in use in China as early as 200 BCE (USEIA). Generating electricity by converting the rotational force of wind has therefore been a logical evolution with large windfarms already producing 597 GW by the end of 2018 (WWEA). Small wind generators (SWGs) are less efficient albeit not as complicated as the large commercial systems but can be deployed effectively in remote areas with frequent windy conditions. Compact SWGs have become a popular proven technology and can often be seen on gantries with security cameras and on most oceangoing sail yachts.

Table 3 provides an overview of the key choice considerations for deployment of PV or SWG.

Albeit lesser known than solar and wind and not currently quite a practical consideration yet for a BARC are fuel cells (Kurtz 2016), yet worthy of a mention as potential future power generator for a remote setting. Generating electricity using the electrochemical reaction between oxygen and hydrogen, an extremely energy-efficient process (80–95%) and only producing water as effluent, it presents an attractive prospect. An additional advantage of the technology is that, it being essentially a battery running on “fuel,” it does not require the major storage overhead in the form of batteries normally associated with small-scale PV and SMG. Current virtually all portable versions need recharging of its fuel source which might not be a practical arrangement for remote communities where distance plays a role. Globally a number of commercial initiatives are driving fuel cell development, for example, the platinum mining sector, in search of additional applications for

Table 3 Renewable energy PV and SWT (Fong)

Solar cells – photovoltaic (PV)				
Advantages	Very low eco-impact	Low operational expense	Ease of use	Portability
Disadvantages	Limited power supply	High capital expense	Day only – needs storage system	Efficiency determined by environment
Small wind turbine (SWT)				
Advantages	Cost-effective – depending on location	Can produce power as long as the wind blows	Relatively portable	Small installation footprint
Disadvantages	High operational expense	Mechanical failure	Spare part availability in rural areas	Efficiency determined by environment

its product, which may ultimately lead a practical unit for remote communities (Minerals Council South Africa).

In the future a combination of photovoltaic (PV) cells, small wind generators (SWGs), and fuel cell each complementing the other might be the best option, and in reality it has already been practically demonstrated by the Energy Observer (Stewart) an oceangoing catamaran which uses all three technologies to power its planned 6-year odyssey around the globe.

In the case of any renewable power, the issue of storage always needs to be taken into account to ensure a consistent power supply when the renewable source is not available, i.e., the sun sets or the wind does not blow. Lithium-ion battery technology is currently the preferred choice as the source of backup power for electronic signal equipment, for example, cell phone base stations, where deep-cycle lithium-ion units have been proven as a reliable choice. With low internal resistance (Battery University), high cycle life, low charge time, self-discharge protection, low toxicity, low mass, compactness, and virtually maintenance-free, it is the best current option for a BARC. On the downside it is still relatively expensive although costs have been pushed down driven by the development in mobile electronics and recently increasingly the electric car market. The technology relies on a flammable non-water-based electrolyte, a potential fire hazard (Ribière et al. 2012), which can be mitigated by building a suppressant system capable of dealing with lithium-ion fires into the design especially important in remote locations (Maloney 2013). Redundancy is an important consideration in any battery installation that the design should also accommodate.

6.1.3 Communication Module (M3)

Functionally this module is responsible for all communication services; practically it serves two distinct purposes, namely, taking care of the "last mile" via a suitable antenna and serving as portal to local users via a medium, e.g., Wi-Fi.

Key to this module is the use of satellite ground antennas to communicate to the chosen constellation. The ubiquitous fixed parabolic antennas are universally associated with satellite communications and as with the writing of this chapter still remain the most popular option to provide broadband Internet in remote areas. Fixed parabolic antennas by its nature receive service from GEO satellites and are suitable for broadband applications where latency is not an issue, and therefore currently it is the most widely rollout technology to provide satellite broadband to remote areas. Successfully engaging a broadband constellation operating in lower orbits – where the individual satellites will travel faster and cover a much smaller area than is the case with GEO constellations – a fixed parabolic system will not suffice necessitating the use of a user-end antenna capable of "tracking" the constellation.

A new generation of flat-panel antennas (FPAs) with no moving parts using electronic "steering" with the ability to engage LEO, MEO, and GEO constellations has entered the market already albeit still on the high-end of the market. Incorporating technology such as phased array allows communications tracking by using a RF beam focused at the target constellation using software controlling antenna emissions. Technological advances in a variety of fields have allowed companies to overcome traditional challenges relating to cost and performance to produce antennas feasible for the mass market. Cost is of particular importance when considering penetrating a market dominated by low-income consumers for which an estimate of USD 100 for a complete kit is considered the target “affordability” price point for the “poor” demographic (Werner 2017). It is important to note that tariffs and installation costs can easily double when antennas are actually put in place.

FPAs do have an added design advantage as they offer more freedom to be integrated into a BARC design as they do not have the design constraints that comes with a parabolic antenna.

Since Apple, the first major mainstream manufacturer to adopt the technology into its product lineup, introduced Wi-Fi in its “AirPort” in 1999 (Apple 1999), Wi-Fi has become the “face” of pervasive wireless connectivity, with over nine billion (WorldWiFiDay) devices shipped as of the end of 2017. Providing ease of use, this well proven technology is easy to integrate into virtually any design. Typical considerations are coverage area, distance, capacity, and security. Security is increasingly an important factor in relation to cybercrime and privacy issues. Introduced into the market in 2018, WPA3(Wi-Fi Alliance WPA3™) offers compliance to more strict data security requirements with stronger cryptographic strength while at the same time allows the use of less complex passwords.

6.1.4 User Interface Module (M4)

The purpose of this module is to provide the end user with the utility to translate the available services into a practical reality. In unserviced remote areas, end users will need to have the means to charge the intended access device such as a tablet computer provided to them. The interface must provide an easy-to-use physical interface, providing utility in the form of charge points featuring a variety of industry standard connectors, e.g., USB 3. It might also be used to house biometric authentication devices if so required. At face value it is not as technically complex as the other modules; it is however the most crucial from the perspective of the end user. As design consideration it is the only truly user-facing component with direct physical user engagement, i.e., the “face” of the product. Should it fail to serve the user community, it will render the BARC practically useless to its intended user base; therefore it should be robust enough to survive the rigors of daily use in a challenging environment and should offer a high degree of redundancy all translating into a very low mean time to failure.

6.2 Augmented BARC

Though the basic BARC design will achieve the goal of connecting the “unconnected,” a design that allows to easily add additional features, beneficial to different types of communities, will present a distinct advantage. Different communities might identify different additional needs, and a design that will also allow for new features to be added with relative ease in the future will be highly desirable.

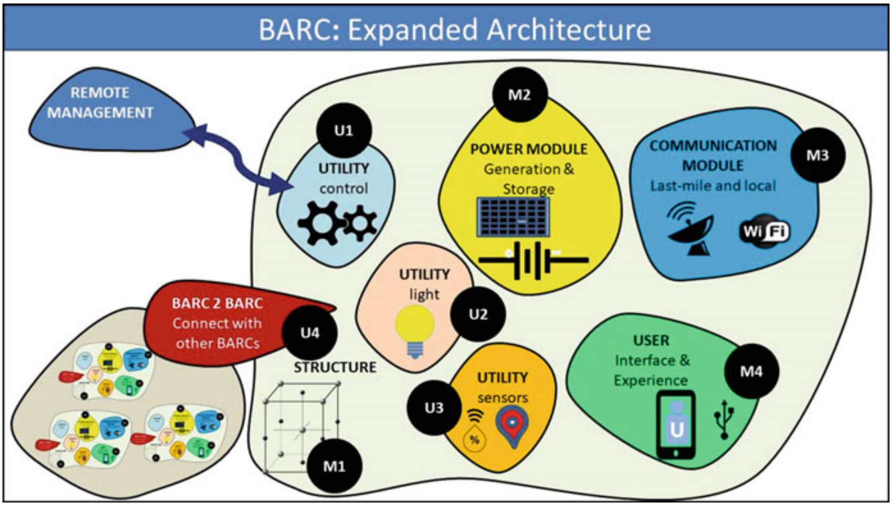


Fig. 4 Expanded BARC architecture model. (Graphic courtesy of the author)

This section presents a number of modules that will not only enhance the utility of the BARC for on-site users but also present the BARC to be of value to other nonlocal stakeholders. Figure 4 presents an expanded model of the BARC; in addition to the four basic modules, an additional four utility modules marked U1–U4 are shown. These are modules accommodated by the structure module (M1) in a similar fashion to the foundation modules (M2–M4) and may use features of these modules as required.

6.2.1 Utility Control Module (U1)

The purpose of this module is twofold: firstly it should provide a unique identity token (UIT) to the BARC, and secondly it must provide the means for remote management. The UIT token can be used among others for remote management and data encryption. Remote monitoring and management of a BARC can be used to proactively identify impending problems, conduct routine maintenance, and apply upgrades among others. Where the BARC is part of a third-party sponsored system, it can also serve as an asset control mechanism.

6.2.2 Light (U2)

The purpose of this module is to provide light and alleviate “light poverty,” a term used to describe communities without the benefit of “decent light” at night. Typically this problem is a function of not having access to electricity; it introduces a number of constraints to the community after dark including but not limited to movement, productivity, and security. Globally an estimated 17% of the population spends up to 1000 times more money on a “unit of light” than their “on-grid” compatriots. The situation impacts the environment as the “light poor” are forced to burn fuel to provide light which is estimated to be equal to the greenhouse gas emissions of

30 million (Mills) cars. LED technology comes in a variety of forms and is easy to integrate into any design and provides high lumens output at a low power consumption. Coupled with low cost and a superior longevity compared with other lighting technologies, LED illumination is ideal as a supplementary utility service of a BARC.

6.2.3 Sensor (U3)

The purpose of this module is to host a number of sensors which can be used for collection of data and meta-data for a variety of reasons. It is said that the Fourth Industrial Revolution is "powered by data," data collected from "new" areas such as the intended deployment of BARC might be of particular value which could be monetized to assist the community. In remote unserviced communities, such collection of data may thus be of benefit to any number of stakeholders. A vast variety of sensors are already available on the market in the form micro-electromechanical systems (MEMS) (MEMSnet) which can be used for reliable data acquisition for virtually any mainstream application. This module can also be used to encrypt the collected data using the BARC UIT (refer U1) which can be deployed as part of an attribute-based encryption scheme (ABE) (Sahai and Waters 2005). The module can also collect meta-data; the communications module (M3) will be used to transfer the encrypted data to its destination.

6.2.4 BARC-2-BARC (U4)

This utility module enables additional BARC units to be added at a location should the need arise to expand the coverage of the system or for redundancy purposes.

7 Form as Consideration

Whereas not the only, "uncertainty" is cited as one of the main reasons people will resist the change typically associated with the introduction of a new product into a chosen demographic. Severe resistance to change can result in the complete failure of a novel product introduced into an environment where the purpose is not clearly understood (Sørensen 2013). Rosabeth Kanter (2012) stated that a target demographic will often "remain mired in misery than to head toward an unknown," when faced with the "excess uncertainty" introduced by a novel product. The product ideally therefore needs to overcome inherent resistance to change, by clearly presenting itself in a beneficial way to the intended demographic, i.e., a product that is perceived useable, useful, and "desirable to use." When planning Disneyland originally the question "How will it provide the customer with a magical experience?" (Thomke and Reinertsen 2012) was used with great success in order to make the eventual product desirable from a user perspective. The more intuitively the design can accomplish this, the greater the chance of success. Product desirability must be achieved within the constraints of what is possible and what is affordable. The ideal product design can be illustrated as a virtual "point" where product desirability, feasibility, and viability intersect while satisfying the basic generic acceptance

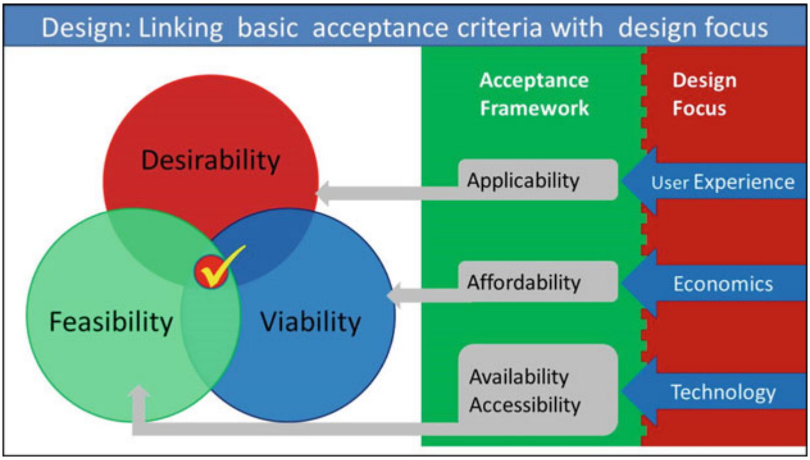


Fig. 5 Conceptual design framework linking basic acceptance criteria with design focus. (Graphic courtesy of the author)

requirements (refer to Fig. 5). This needs to be created within all relevant constraints which could take many forms be it cultural, economic, regulatory, or technological.

Introducing broadband Internet into an unconnected community that does not necessarily perceive a benefit with regards to Internet use, will have to follow a different strategy than engaging one with an existing desire to use broadband Internet. This could be achieved through using the form of the design to offer the user community some obvious other function that the community will find of "immediate value" and as such will accept the presence of a BARC.

A BARC integrated into a functional form such as a structure providing shelter during the day from sun and rain and at night providing illumination to the area might have a better chance of being accepted than an abstract structure dedicated to just providing a broadband signal. Another example could be to integrate the BARC into a water tank, as water plays such an important role in any community, in the developing world especially. According to data from UNICEF (2016), daily more than 200 million hours per day is spent in collecting water mostly by women. Providing a facility to store water locally while providing light at night might be valuable for communities where such a facility does not exist (refer to Fig. 6).

This concept can be explored further as discussed by way of the following three examples exploring three basic themes starting with the idea presented above, a water tank.

The design (Fig. 7) is dominated by a large water tank acting as center piece, with three distinct flat trapezoidal roof frame sections extending outward from the tank. As with the aforementioned design concepts, the roof sections feature PV material on the outside and LED for the ground-facing part. A FPA and sensor pack are mounted on top of the tank; additional sensors are mounted in a utility "ring" mounted lower on the tank also containing the Wi-Fi. A round utility base surrounds the tank, in which the batteries are housed.

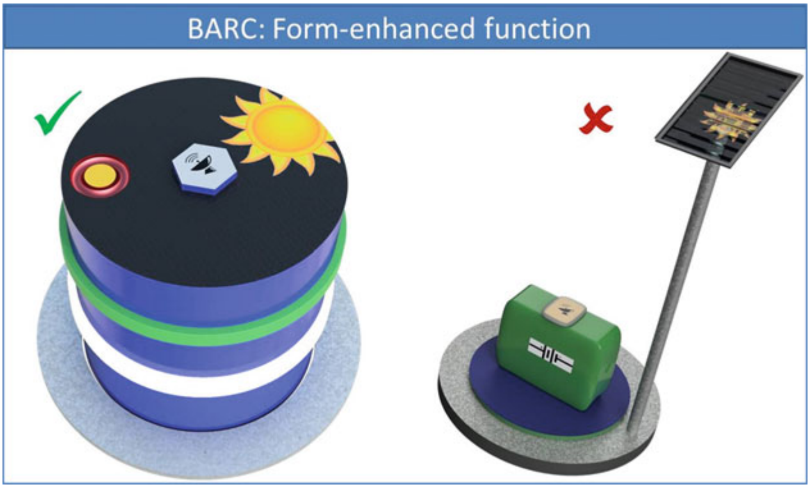


Fig. 6 Function augmented through form. (Graphic courtesy of the author). Copyrighted by the author and licensed to the publisher for this publication

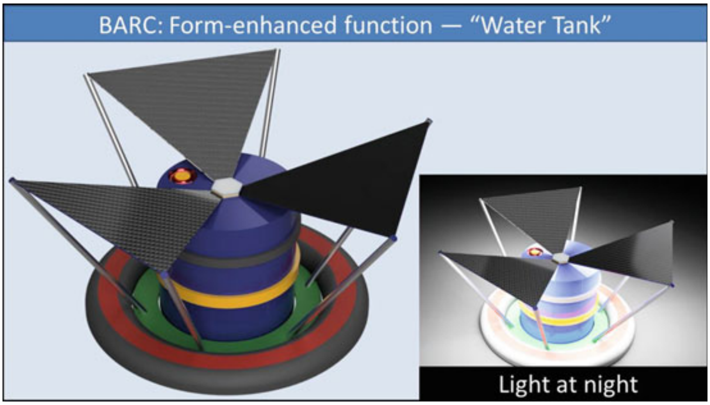


Fig. 7 BARC modules using water tank for enhanced function. (Graphic courtesy of the author). Copyrighted by the author and licensed to the publisher for this publication

Featuring shelter as a central design theme, the second design concept (Fig. 8) aims to provide the end users a shelter to use where they can charge their access devices sheltered from the sun. The roof is clad with material featuring integrated PV collectors; the inside roof ceiling is in turn clad with material featuring integrated ultrathin LED providing light at night. The design is dominated by a conical roof structure with a FPA mounted at the apex, supported by a number of pillars which apart from their obvious structural duty also host the additional BARC functional modules, housing batteries, housing data collection sensors, and providing integrated charge points.

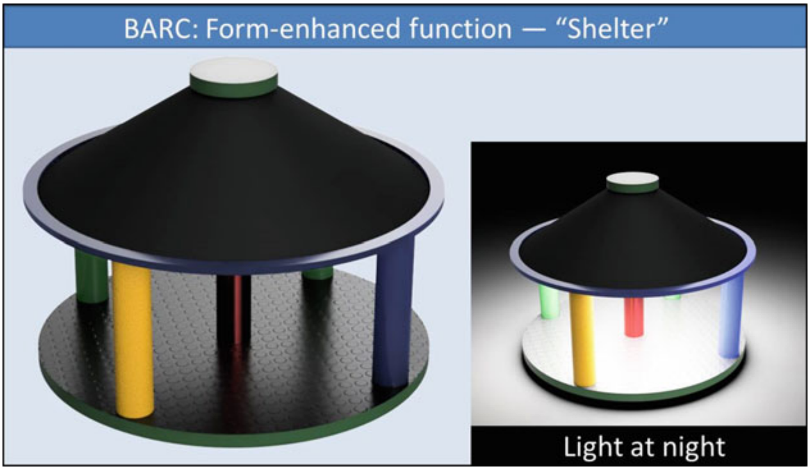


Fig. 8 BARC modules featuring shelter as the enhanced function. (Graphic courtesy of the author). Copyrighted by the author and licensed to the publisher for this publication

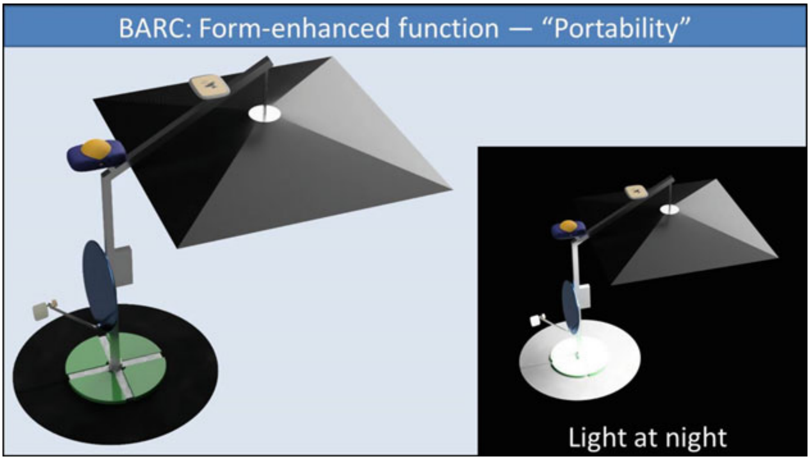


Fig. 9 BARC modules integrated into a collapsible design. (Graphic courtesy of the author). Copyrighted by the author and licensed to the publisher for this publication

The third featured concept (Fig. 9) resembles a cantilever garden umbrella. This concept places emphasis on portability; this could be of particular use to remote communities leading a nomadic existence. Center to the design is a collapsible roof suspended from a cantilever frame anchored to a modular base housing the battery packs. The collapsible roof is made from a material with integrated PV on the top "sun-facing" layer with the inside layer of the "umbrella" featuring flexible LED materials. This design features both a FPA and parabolic satellite antennas. Sensors and Wi-Fi components are housed in a weatherproof enclosure mounted on the top of the frame and the charge points integrated into the frame.

In addition to the immediate acceptance, practical value demonstration of broadband will have to be demonstrated to enhance community acceptance of the product and willingness to explore the potential of the broadband service. The evolution of satellite navigation as a product is a good example; in 1997, very few people saw the value of a handheld GPS receiver providing the user navigation information in the form of numerical coordinates. Yet the same information is still used today; the difference is that it is presented in a practical way. Take a person using a map-based navigation system on a smartphone, the software takes the same information that was presented in 1997 from essentially the same service; the difference is now it comes in a converged form, the user association is not with the coordinates but rather with finding their destination, i.e., the "what" as opposed to the "how."

The design needs to be augmented by a suite of applications relevant to the target community which is "readily available" to be rolled out and installed. Thus there is a need for easy-to-use applications that allow farmers' access to market information in a practical way. This needs to keep into account skill levels and accessibility in native languages. These features will have an immediate impact. The users must be equipped and trained with the relevant skills to practically use these applications. In organizations the ability of the user pool to recognize the value of new external information, assimilate it, and then find ways to apply it to the benefit of the user community is known as the "absorptive capacity" (Tsai 2001). In the long run the true benefit of deployment such as BARC will lie in the ability of the user community to identify new opportunities the broadband ecosystem can bring to their immediate socioeconomic environment which is bound to resonate further up the value chain.

8 Conclusion

The aim of this chapter was to provide a brief overview of practical approaches to provide broadband Internet delivery systems to remote unserviced areas by use of integrated functional modules, i.e., BARCs. The motivation to develop such a product is fairly straightforward; in 2019, more than three billion people globally are still unconnected, a large portion of which is due to the lack of infrastructure. Opportunity is presenting itself through a very large number of small-satellite-based broadband constellations which will present a significant increase in available bandwidth in the next couple of years. The technology to construct such a product is available in the market in the form of flat-panel antennas, renewable energy, and reliable storage systems.

Broadband can only be of benefit to a community if it leads to some improvement in the socioeconomic status quo. Key to this process is getting the community to use the service and importantly to continue using the service; acceptance of the product by the user community is as important as the product itself, and care must be taken to "up-skill" the potential users adequately. True economic benefit can be achieved by broadband implementation into a community. This is possible only when the recipient community has the capacity to fully exploit the capabilities offered by the service, leading to increased use of the system and a widening circle of benefits achieved.

There is a tendency to focus on the satellite technology and even the satellite ground systems, but to provide effective connection to rural and remote areas and the entire system that links the end users and address their needs must be considered. An end-to-end capability that meets local consumer needs is essential to success.

9 Cross-References

▶ Economic and Market Trends for Ground Systems to Support New and Future Small Satellite Systems

References

Apple, About Your AirPort Card (1999) [cited 20 July 2019]

Battery University, BU-107: Comparison Table of Secondary Batteries. https://batteryuniversity.com/index.php/learn/article/secondary_batteries [cited 22 July 2019]

J. Bello-Schünemann, Africa's population boom: burden or opportunity (2017). https://issafrica.org/iss-today/africas-population-boom-burden-or-opportunity [cited 17 June 2019]

P. Bertolini, M. Montanari, V. Peragine, *Poverty and Social Exclusion in Rural Areas. Final Study Report* European Commission DG Employment and Social Affairs based in Brussels, Belgium, (2008)

P. Biggs, *The State of Broadband 2018: Broadband Catalyzing Sustainable Development*, 1st edn. (UN Broadband Commission, Geneva, 2018a)

P. Biggs (ed.), *The State of Broadband 2018: Broadband Catalyzing Sustainable Development* (UN Broadband Commission, Geneva, 2018b). ISBN 978-92-61-26431-4 (electronic version)

D. Coldewey, SpaceX reveals more Starlink info after launch of first 60 satellites. May 24 (2019). https://techcrunch.com/2019/05/24/spacex-reveals-more-starlink-info-after-launch-of-first-60-satellites [cited 5 August 2019]

L. Daniels, *Managing the Product Requirements Definition Process*, Project Management Institute Annual Seminars & Symposium, Project Management Institute, Housten, 2000

J. Dean, OneWeb Satellites breaks ground at KSC's Exploration Park factory. June 27. http://www.floridatoday.com/story/tech/science/space/2017/03/16/oneweb-satellites-breaks-ground-explortion-park-factory/98545074/ [cited 20 June 2019]

Energy.gov, Estimating Appliance and Home Electronic Energy Use (2018) https://www.energy.gov/energysaver/save-electricity-and-fuel/appliances-and-electronics/estimating-appliance-and-home [cited 25 July 2019]

Energy.gov, Solar Photovoltaic Cell Basics. https://www.energy.gov/eere/solar/articles/solar-photovoltaic-cell-basics [cited 12 December 2016]

D. Fong, Global Network Institute – Sustainable energy solutions for rural areas and application for groundwater extraction. http://www.geni.org/globalenergy/research/sustainable-energy-solutions-for-ruralareas-and-application-for-groundwater-extraction/Sustainable-Energy-for-Rural-Areasand-Groundwater-Extraction-D.Fong.pdf [cited 14 July 2017]

C. Henry, Amazon lays out constellation service goals, deployment and deorbit plans to FCC. July 8 (2019). https://spacenews.com/amazon-lays-out-constellation-service-goals-deployment-and-deorbit-plans-to-fcc/ [cited 22 July 2019]

InternetWorldStats, The Internet Big Picture. World Internet Users and 2019 Population Stats. June 30 (2019). https://www.Internetworldstats.com/stats.htm [cited 27 July 2019]

R.M. Kanter, Ten reasons people resist change, Harv. Bus. Rev. (2012) https://hbr.org/2012/09/ten-reasons-people-resist-chang

J. Kurtz, *Hydrogen and Fuel Cells for IT Equipment*. NREL/PR-5400-66610 (NREL – National Renewable Energy Laboratory, Golden, 2016)

T. Maloney, *Extinguishing Agents for Lithium-Ion Batteries* (FAA, Washington DC, 2013)

MEMSnet, Information Portal for MEMS and Nanotechnology community. http://www.memsnet.org/mems/what_is.html [cited 20 June 2019]

E. Mills, Can technology free developing countries from light poverty? https://www.theguardian.com/global-development-professionals-network/2015/jul/30/can-technology-free-developing-countries-from-light-poverty [cited 19 July 2017]

Minerals Council South Africa, Powered by Platinum – Factsheet 2017. http://chamberofmines.org.za/industry-news/publications/fact-sheets/send/3-fact-sheets/381-chamber-of-mines-fuel-cell [cited 13 January 2018]

NREL, Copper Indium Gallium Diselenide Solar Cells (2018)

P. Ribière, S. Grugeon, M. Morcrette, Investigation on the fire-induced hazards of Li-ion battery cells by fire calorimetry. Energy Environ. Sci. **5**(1), 5271–5280 (2012)

D. Rigney, *The Matthew Effect* (Columbia University Press, New York, 2010)

A. Sahai, B. Waters, Fuzzy identity-based encryption, in *Annual International Conference on the Theory and Applications of Cryptographic Techniques*, (Springer, Berlin, 2005), pp. 457–473

K. Schwab, The Fourth Industrial Revolution. https://www.britannica.com/topic/The-Fourth-Industrial-Revolution-2119734 [cited 13 June 2019]

SE4ALL, Sustainable Energy for All (2018). https://datacatalog.worldbank.org/dataset/sustainable-energy-all

J. Sørensen, *The Simple Reason Products Fail: Consumers Don't Understand What They Do* (Quartz, 2013)

K. Sprague, F. Grijpink, J. Manyika, L. Moodley, B. Chappuis, K. Pattabiraman. J. Bughin, *Offline and Falling Behind: Barriers to Internet Adoption* (McKinsey & Company, 2014) New York, USA.

J. Stewart, The Funky Boat Circling the Planet on Renewable Energy and Hydrogen Gas. https://www.wired.com/story/energy-observer-renewable-energy-voyage/ [cited 25 July 2019]

S. Thomke, D. Reinertsen, Six myths of product development. Harv. Bus. Rev. **90**(5), 84 (2012)

W. Tsai, Knowledge transfer in intraorganizational networks: effects of network position and absorptive capacity on business unit innovation and performance. Acad. Manag. J. **44**(5), 996–1004 (2001)

UNCTAD, *Information Economy Report 2017 -Digitalization, Trade and Development* (United Nations, Geneva, 2017)

UNICEF, UNICEF: collecting water is often a colossal waste of time for women and girls (2016). https://www.unicef.org/media/media_92690.html [cited 12 May 2018]

USEIA, People have been using wind energy for thousands of years. https://www.eia.gov/energyexplained/index.php?page=wind_history [cited 25 July 2019]

D. Werner, Cheap satellite terminals key to bridging digital divide, execs say. *Space News* (2017)

Wi-Fi Alliance WPA3™, Wi-Fi Alliance® introduces Wi-Fi CERTIFIED WPA3™ security. https://www.wi-fi.org/news-events/newsroom/wi-fi-alliance-introduces-wi-fi-certified-wpa3-security [cited 20 July 2018]

World Bank Group, *World Development Report 2016: Digital Dividends* (World Bank Publications, Washington, DC, 2016)

WorldWiFiDay, Facts and Stats. https://worldwifiday.com/about-us/facts/ [cited 20 July 2019]

WWEA, Wind Power Capacity Worldwide Reaches 597 GW. https://wwindea.org/information-2/information/ [cited 25 July 2019]

Economic and Market Trends for Ground Systems to Support New and Future Small Satellite Systems

Bernardo Schneiderman and Joseph N. Pelton

Contents

Abstract

The history of space applications and especially satellite communications has been significantly focused on the deployment of spacecraft in geosynchronous orbit, as first proposed by Arthur C. Clarke. This special orbit uniquely allows ground antennas to be constantly pointed to satellites in GEO orbit that appear to hover constantly overhead. This feature allows the ground stations to be simple in design and, once installed, actually require a minimum of maintenance. This has been a particularly attractive feature for applications such as direct broadcast

---

B. Schneiderman (✉)
Telematics Bus. Consultants, Irvine, CA, USA
e-mail: bhstbc@gmail.com

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_33

satellite radio and television services where many hundreds of millions of users are receiving programming from the skies.

The concept of using much lower orbiting satellite clearly could have advantages if there were a low cost and efficient way of tracking such satellites as they passed overhead from horizon to horizon. These advantages include reduced latency or transmission delay, less signal spreading or so-called path loss, and higher-efficiency spot beams that allow more efficient use of spectrum by means of frequency reuse. These new types of satellite systems, in theory, might be able to more closely approximate the effectiveness of cellular telecommunications services.

In short, the choice of GEO systems over MEO or LEO satellite constellations has been driven most powerfully by the cost, technical design complexity, and operational difficulties of ground antenna systems needed for these MEO and LEO satellite systems that require rapid track of spacecraft in these lower orbits as they traverse the skies.

The recent breakthroughs in the design of satellite ground antennas that can be designed to track satellites via electronic means rather than physical tracking processes have been the key to the small satellite constellations. The design of cost-effective flat panel satellite antennas is seen as the answer to ground systems being too expensive because of the need for rapidly moving satellites in LEO orbit. In short these new flat panel systems with electronically steered antenna systems that can be deployed in remote areas and operate reliably will be key to the success of the new smallsat LEO constellations. These new ground systems can be designed to support telecommunications, Internet broadband networking, cellular backhaul, and other services such as IoT messaging, machine to machine (M2M) services, and possibly even broadband Over-the-Top video streaming for news and movie/radio entertainment.

This chapter explores the changes that have come and will evolve in terms of the economics and market trends related to the production and use of ground stations that can electronically track small satellite constellations in LEO and MEO orbits. It examines not only the market for these new type of ground systems but also looks briefly at the many suppliers that are developing the ability to produce these new types of antennas. It also explores some of the emerging strategic partnerships between the operators of these new small satellite constellations and the manufacturers of these flat panel satellite antennas – also known as conformal shaped antennas. It notes that some traditional suppliers of parabolic dishes are adapting to produce these new types of antennas.

Clearly there are many new start-ups that are now also entering this new market. The billions of dollars that are being spent on new small satellite constellations are clearly creating a new market opportunity for a new billion-dollar market for flat panel satellite antennas or what are also called electronically steered antennas with auto signal acquisition. Other conventional antenna suppliers are focused on creating larger units for tracking, telemetry, and control of these large networks, but this will generally not require new technology. Some estimates have placed the market for new flat panel satellite antennas to be as large as $11 billion by 2028. This chapter explores the many factors that might influence the growth of this new market and the companies that are seeking to

respond to this new market demand. It also seeks to provide some preliminary information about the strategic partnership between small satellite constellation operators and the suppliers of electronically steered antennas. Some of the biggest operators of small satellite constellations in LEO and MEO systems, however, might seek to build, deploy, and license their own ground systems.

Keywords

Additive manufacturing · Application-specific integrated circuits (ASIC) · Auto signal acquisition · Cellular backhaul · Electronically steerable antennas (ESA) · Electronic tracking · Flat panel antennas (FPAs) · Flat panel satellite antennas (FPSAs),Ground systems · Link budget · Market trends · Mobile satellite services (MSS) · Over-the-Top (OTT) video streaming services · Price sensitivity · Small satellite constellation · High-throughput satellites (HTS)

1 Introduction

The history of most types of satellite applications has often revolved around ways to simplify the ground segment so that more users can access and use the satellite in a lower cost and more widely distributed basis. The initial steps involved creating higher-powered and more sophisticated GEO satellites with high-gain antennas that could operate effectively to smaller and increasingly low-cost parabolic dish antennas on the ground. These antennas were lower in cost, in part, because they did not have to track the GEO satellites that appeared to hover in a fixed location in their special orbit.

These geosynchronous orbiting satellites, because they were so distant from the Earth – almost a tenth of the way out to lunar orbit – were subject to significant transmission delay and also major path loss as the signal from the satellite spread out in an ever widening circled as they traveled between the ground and the satellite.

When thought was given to the idea of creating satellite systems for mobile satellite services, the idea of using low Earth orbit (LEO) satellites in a constellation was given serious consideration. Since the mobile users would be moving, the key advantage of constantly pointing user antennas to a GEO satellite was no longer there. Further, a LEO satellite, since it would be on the order of 30–40 times closer to Earth, would experience much less path loss. This could allow the user antennas to operate with lower gain. This could help make user antennas, or transceivers, smaller and less costly and even allow handheld units for satellite links. Also there would be less latency or transmission delay. The quarter of a second delay for a signal to go to GEO orbit and return had always created some concern when providing a voice or interactive service.

The two commercial satellite systems that were designed for mobile voice services, Iridium and Globalstar, and the one for data messaging, Orbcomm, all chose to operate in LEO orbits for these reasons. They sought to devise new designs for user devices that could be small enough to be handheld and could receive signals

360° across the azimuth from horizon to horizon. This was an enormous technical challenge. There were efforts to create antenna designs that were capable of receiving signal above the horizon and to create deployable antennas in order to achieve higher gain when extended for use. The main technical advance that was critical to these new satellite telephones was the development of application-specific integrated circuits (ASIC) that allowed advanced digital processing of the transmitted signals between the satellite and user transceivers. There were also advancements in the design of the satellite antennas to create narrower beams using phased array antennas. This allowed computer electronics to form the beam shapes electronically.

The initial designs of these phased array antennas were quite expensive to fabricate. Thus the use of electronic beam formation by means of phased array antennas was initially restricted to the satellites and not applied to ground systems. In short, phased array antennas, which are also referred to as flat panel antennas, were not considered economically viable for user antennas on the ground. The experience with the phased array antennas used on the first- and second-generation Iridium satellites and on the second-generation Globalstar satellites provided useful and important developmental advances of this technology that could be in some senses transferred to research related to the ground transceivers.

The latest evolution in thought about the delivery of satellite services has been to seek ways to provide broadband digital services with a minimum of delay (or latency) at high-throughput speeds that are comparable to terrestrial laser systems using fiber optics. This concept was first originated by the so-called Teledesic mega-LEO system that proposed the deployment of some 840 high-throughput LEO satellites plus 80 spares that could blanket Earth with a digital network operating with high-speed services operating in the Ka-band.

This proposed network of the 1990s lacked the technological and advanced production techniques to deploy such breakthrough technology (neither for the satellites or perhaps especially for the ground systems). This innovative Teledesic satellite system that was backed by Cellular service entrepreneur Gregg McCaw and Microsoft founder Bill Gates ultimately declared bankruptcy. This possible future vision of a new type of satellite system was important to the future evolution of satellite system design. This trailblazing design foreshadowed the LEO and MEO systems of the 2020s that envisioned improved satellite services that could cover the world and provide comprehensive access to rural and remote areas. The experience from Iridium, Globalstar, Orbcomm, and Teledesic opened the door to thinking about small satellite constellations in LEO and MEO orbit. The new vision was new types of satellite networks that could deliver broadband, high-throughput and low latency services comparable to fiber-optic networks. The technical challenges were many. The greatest challenge was developing ground systems capable of electronic tracking of broadband satellites in a LEO or MEO constellation.

Today a large number of so-called mega-LEO networks and some in medium Earth orbit (MEO) are in various stages of deployment. The ability to design, engineer, and manufacture the high-performance small satellites for large constellations is now relatively well established, but the ability to make low-cost flat panel antennas with electronic steering is another matter. The costs of these types of user terminals remain too high. There are estimates from the Northern Sky Research 4th Report on Flat Panel Satellite Antennas, 4th edition, that the market for these new type of antennas will grow rapidly in the next decade (Northern Sky Research 2019). The NSR market analysis, however, suggests that the use of these types of antennas will be predominantly targeted in the nearer term for mobility applications (i.e., cellular backhaul and aircraft, ships, trucks, buses, and even self-driving cars) (i.e., 94%). Thus the NSR market analysis for flat panel satellite antennas associated with the new smallsat constellations and ground systems for these networks might represent only 6% of the total market – at least for the nearer term. The latest projection by the Northern Sky Research has anticipated that the global market might reach some 1.5 million units being shipped in that year with revenues totalling $11 billion per year by around 2028 (see Fig. 1) (Northern Sky Research 2019).

Yet these estimates are based on several key assumptions. Thus, critical factors in the market projections are as follows: (i) the rate of breakthrough in design and production, particularly with regard to how quickly there will be reductions in the cost of designing, fabricating, and installing flat panel antennas; (ii) the overall demand for flat panel antennas/electronically steerable antennas to support 4G and 5G cellular backhaul services and other so-called mobility markets; (iii) the success of new smallsat constellations for broadband networking; and (iv) and the extent of the eventual demand for flat panel satellite antennas to support GEO satellite systems and related high-throughput satellite markets as the cost of flat panel satellite antennas drop over time.

Some market estimates, as the Northern Sky Research study noted above, suggest that the demand for flat panel antennas will be almost entirely driven by demand for these units for 4G and 5G cellular, aeronautical, and other mobility services and that satellite-based demand for such aspects as broadband LEO and MEO constellations will perhaps be much smaller in the next 5 years through 2024. Some have said that the demand for flat panel satellite antennas represent the “tail” of the dog, that is, this larger and more significant market that will be installing flat panel antennas on aircraft, ships, trucks, trains, and buses and for military-related mobile services.

Some have said that the largest market may be for self-driving cars that have to be instantly updated via 5G cellular systems and satellite connections to avoid collisions. Even more mundane requirements associated Wi-Fi/Wi-Max systems and IoT or SCADA messaging may drive the overall flat panel antenna market at least in terms of volume of units sold. One of the biggest variables might relate to the volume of the market related to military systems and retrofitting of aircraft and ships, and this assessment is beyond the scope of this article.

At the Paris World Satellite Business Week Conference held in early September 2019, leading satellite experts concurred that flat panel antennas will have a dramatic and profound impact on satellite communications services market. This will likely start with mobility services (including cellular related applications) and Internet of Things (IoT) satellite services and then expand to support all forms of satellite services as performance increases and production costs fall.

Pradman Kaul, CEO and President of Hughes Network Systems, stated the view that broadband satellite services from constellations in low or medium Earth orbits

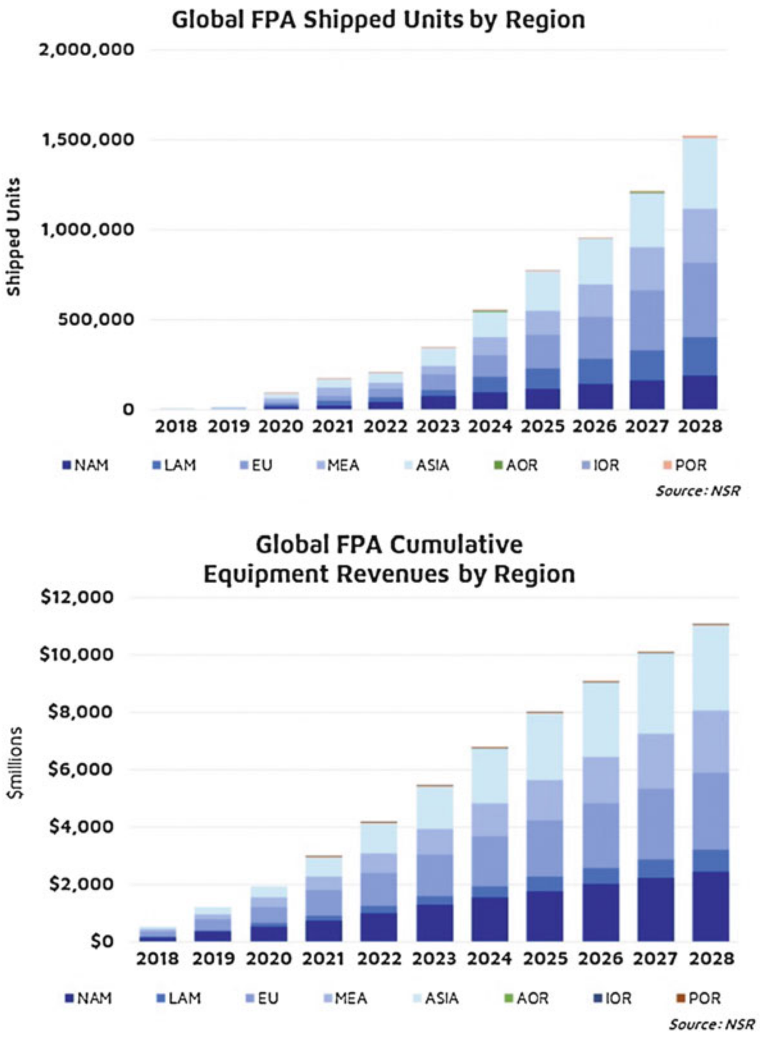


Fig. 1 Northern Sky Research (NSR) projections of market demand for flat panel satellite antennas. (Graphic courtesy of NSR). Code: *NAM* North America, *LAM* Latin America, *EU* Europe, MEA Middle East-Africa Asia, *AOR* Atlantic Ocean region, *IOR* Indian Ocean region, *POR* Pacific Ocean region

required inexpensive flat panel antennas to be successful. He declared this was a “critical” need but we were not there yet. He added, “That is the biggest application today that we can’t address because we don’t have a low-cost, electronic array-based flat-antennas (Werner 2019).”

iDirect CEO Kevin Steen added that demand for satellite connectivity to provide global Internet of Things (IoT) services was another area where low-gain flat panel satellite antennas were a key to the future. He suggested small electronically steerable antennas, i.e., flat panel antennas, will be a "game changer" for increasing the role satellites play in this area. "It changes the economics when you look at the installation (Werner 2019)."

In the maritime market, the picture is more mixed. Some believe that offshore drilling rigs and the largest cruise ships and freighters will keep higher-gain conventional dishes, but smaller vessels with lower-throughput rates will go to flat panel antennas sooner. Aircraft and backhaul for 5G cellular are also seen as prime markets for these electronically steerable antennas.

Opinions differ on some aspects of the flat panel antenna market as to where usage will be quickly adopted. Some believe that cruise ships will continue to rely on large antennas working to high-throughput larger GEO satellites. Others believe that high-throughput but smaller satellites in MEO orbit such as the m-Power network can respond to this market. SpeedCast CEO Pierre-Jean Beylier, who spoke to the issue of cruise ship markets presented the view that this industry needed high throughput and video services and thus required ". . .. . . hundred of megabits and highly efficient antennas. We are not going to get there with flat-panel antennas (Werner 2019)."

The bottom line is that the flat panel antennas and the small satellite constellation market do not perfectly line up. Some believe that highly cost-efficient flat panel satellite antennas will also work to GEO satellites. Further the flat panel antennas for aircraft, ships, and military aircraft and ships will be different in cost and performance. Further the flat panel antennas for messaging, low data rates, Internet of Things, and machine to machine (M2M)-type applications will be different than other broadband and cellular backhaul services. In short there is not a single future flat panel satellite market, but a series of them.

Clearly there are many remaining unknowns for flat panel satellite antennas. It is unclear as to how much market demand will actually develop for the large constellations being deployed for global networking and broadband services.

In particular, it is uncertain as to which of all the now proposed, nearly 20 small satellite constellations for broadband services and another 12 for messaging and (IoT) networks will succeed and which will fail. It is clearly uncertain as to what will be the market demand for the so-called mobility market that is now leading demand. The market demand for military communications and commercial systems appear to be different. Further, the flat panel satellite antennas (FPSAs) that will serve the LEO-based broadband small satellite constellations for commercial aircraft and ships will be different than the antennas used for military mobile services. Finally, it is not clear how quickly the demand for flat panel satellite antennas associated with GEO-based satellite systems will develop. Answers to these market demand characteristics will likely hinge on the most cost-efficient systems. In short, the future of flat panel satellite antennas will be highly price-dependent vis-a-vis traditional dish-based antennas. Technical, operational, and maintenance performance factors will also be highly relevant.

It would seem that there could be substantial demand for flat panel satellite antennas if the cost were to go low enough to support GEO systems. Here the service could be for fixed satellite services (FSS), for mobile satellite services (MSS), and even broadcast satellite services (BSS) if the cost for these antennas fall to competitive levels with conventional dish antennas. The new systems being developed by Isotropic Systems that use optical processing seems to have a good shot at truly cost-efficient systems with the prospect of $300–$600 units, but this will have to be proven, and it is still early days in the development of FPA/ESA systems. There has also been good progress for those developing credit card or deck of playing card systems for IoT messaging. Again it is still early days.

And on top of all these uncertainties, there are questions as to which companies that are planning to deploy LEO or MEO small satellite constellations might manufacture these new type antennas on their own. Further it seems that for a number of reasons related to national security concerns, protective regulations, and particular specification, the development of the FPSA systems will this divide into the two areas of commercial FPSAs and defense related FPSAs as well as broadband versus narrow band services?

Further it seems that, it does appear that there are a number of suppliers for defense systems and particularly for aircraft and ships and their communications that may seek to provide flat panel satellite antennas for defense-related mobility where special specifications are applicable. In this regard, suppliers such as Lockheed Martin, Boeing, General Dynamics, Cobham Plc, and Airbus Defence and Space may serve to be suppliers to military requirements but may not serve as major suppliers for commercial networks. The one exception might be Boeing, if it ultimately decides to deploy a commercial LEO small satellite constellation. The uncertainty noted above are thus good reason to be cautious in accepting any market projection that might be made at this time, although the NSR market profile seems to be the most carefully researched (Flat Panel Satellite Antenna 2019).

It appears that both Amazon and SpaceX are now planning to develop their own FPSAs for their LEO smallsat constellations. The design and fabrication processes for these antennas, in order to get costs down to an acceptable level, is a significant undertaking. SpaceX has filed with the US government a document indicating that they will seek to deploy one million of these flat panel satellite antennas and have their licensing approved. Amazon/Kuiper Satellite Network have indicated plans that they will build their own ground antenna systems as well.

Amazon and SpaceX are perhaps the two largest small satellite constellations that are now planned to be deployed. If both SpaceX and Amazon/Kuiper go the route of vertical integration and end up manufacturing their own antennas, this will clearly affect the potential market size for those that are focused entirely on developing and manufacturing flat panel antennas/electronically steerable antennas.

Today the Northern Sky Research study of flat panel antennas has identified over 20 companies either now providing or actively engaged in their development. The companies that are pursuing this market as producers and/or integrators include the following: ALCAN Systems, Anoki Systems, Ball Aerospace, Boeing, C-Com, GetSat, Gilat Satellite Networks, Kymeta, HiSky, Honeywell, Hughes Network Systems, Isotropic Systems, Omni Wave, Phasor Systems, Satixfy, StarWin, Thinkom, Tianyi Satcom Company, Toshiba, and Viasat (NSR Press Release). In addition it appears that SpaceX and Amazon/Kuiper might be self-suppliers (see the Appendix at the end of this article to learn more about these companies and the status of these development efforts).

Many of these companies are currently focused on the aviation and shipping mobility market for both commercial operators and military systems. As the new smallsat constellations are deployed, the market can be expected to shift.

What must be kept in mind throughout this analysis of the market demand for flat panel satellite antennas (FPSAs) is that currently the biggest market demand is for 4G and 5G cellular and mobility market and not units to support small satellite constellations. This could just be a sideline for the largest suppliers of flat panel antennas.

The rapid success (or not) in the build out of a number of the large LEO constellations such as those of One Web, SpaceX, Amazon (Kuiper Network), Telesat, Carousel, Comstellation, Thales, Boeing, SES/O3b m-Power, and others now planned systems will be key to the ultimate success of the Flat Panel Satellite Antenna market in the next decade.

This chapter explores the various companies seeking to develop and market lower-cost flat panel antennas, analyze their marketing strategy, and ultimately assess what the market potential is for these new types of ground antenna systems.

2 Assessing the Market Potential of the Companies Seeking to Provide Their Own Flat Panel Antennas

Only a few manufacturers of flat panel antennas/electronically steerable antennas (FPAs/ESAs) have come to market, and even those manufacturers are not providing detailed pricing information since costs and pricing are still in a high period of development. Especially when production goes to a very high level, then significant reductions in both cost and pricing can be expected.

Essentially the market in satellite antenna production seems to be separated into the following categories: (i) developers of mega-LEO or new MEO systems that opt to design and manufacture their own FPA/ESA units (at this stage, this seems to be SpaceX and Amazon/Kuiper and possibly several others); (ii) developers that are seeking to develop and supply FPA/ESAs to serve the needs of 4G and 5G backhaul and broadband Internet services; (iii) developers that are seeking to design and manufacture ground systems to support narrow band data messaging services; and (iv) established producers of ground system equipment that will seek to meet demand for satellite ground systems with conventional fixed dish antennas, and mechanically steerable dish antennas, or other conventional antenna systems such as helix antenna or omni antennas. It is assumed in this analysis the conventional dish offerings will tend to phase out and not be other than a very modest part of the market by 2028. This amounts to saying that the options that will be pursued are fairly complex. There are many ways that the lines of the division between satellite developer, satellite operator, ground segment supplier, and investors in these various systems and equipment developers may be divided. After another decade of experience, the roles will likely become much clearer.

An assessment of these suppliers and their current market and technology conditions and projections of market conditions are provided in the section that follows.

3 Smallsat Constellation Developers Seeking Vertical Integration and the Production of Their Own Electrical Steering Antenna

At this stage there seem to be only two companies that have clearly indicated their intention to produce their own FPA/ESAs for their large-scale LEO smallsat constellations. These are Amazon and SpaceX. It is possible that several other companies that are planning large-scale constellations may follow suit. These companies might particularly include those that have worked with phased array technology in the past such as Boeing and Thales Alenia. On the other hand, it is possible that either Amazon or SpaceX might for various reasons reverse direction and seek ground equipment from other suppliers at a future date.

If Amazon and SpaceX plus other providers of large-scale small satellite constellations do proceed to produce their own ground equipment, this will have a clear impact on the market. Just in the case of SpaceX, they have filed plans with the FCC and the iTU to deploy a total of over 12,000 satellites. They have also indicated plans to produce a total of one million FPA/ESA units. In the case of Amazon/Kuiper Network, they have indicated plans to deploy over 3200 satellites and an unspecified number of ground segment units. If indeed other providers of large-scale small satellite constellations for telecommunications and networking services decide to follow suit and produce their own ground systems, this will restrict the market for new suppliers of FPA/ESA equipment.

At this stage, only a few of the small satellite constellation operators have indicated their plans to work strategically with companies specializing in the production of FPA/ESA equipment. These include OneWeb (assuming successful refinancing). SES/O3b m-Power, and Telesat which intends to deploy a smaller constellation. The following provides the latest information about the planning by Amazon/Kuiper Network and SpaceX. It is recommended that one go to the websites of these companies for the latest updates.

Amazon/Kuiper Constellation: Amazon has filed to deploy a LEO constellation of 3236 broadband satellites in Ka-band. Amazon during july 2019 announced that Kuiper System will rely on a user-terminal mix of comprised of flat, electronically steered, phased-array antennas and mechanically steered dish antennas. Amazon has experience with developing complex electronic products for a mass market such as its Alexa device. In order to make its global digital satellite constellation feasible, it needs to be able to have a very large number of antennas on the ground to use this system at low cost. A FPSA product that could be sold via Amazon to access the Kuiper satellite network to buy products and services from Amazon could also be used to get access to entertainment, the Internet, health and educational information, and more. Amazon has experience with advanced electronics, application-specific integrated circuits, and global marketing of its products.

In some ways the Amazon Alexa system has some comparable experience. This is not only technological expertise but also includes experience dealing with tariffs and local taxation and permitting requirements. No specifics are currently available as to actual design or costing of the Amazon/Kuiper networking ground systems.

SpaceX has plans for a Ka-band network of over 4500 satellites operating in the Ka-band, as well as a Q/V band network that would have over 7500 satellites. This huge investment of over $10 billion for these networks is dependent on being able to allow consumers to access these systems at relatively low cost. The filing for up to one million ground antennas that SpaceX has made with the FCC was made with few specifics. The business philosophy that Elon Musk has used in other business ventures such as Tesla electric autos and SpaceX rockets has consistently been based on the principle of vertical integration, or creating as much of a product in-house without depending on suppliers of parts and component – to the maximum extent possible. Thus creating ground systems to operate with the SpaceX large- scale global constellations would be consistent with past practices.

4 New Suppliers of FPA/ESA Equipment

There are only a few suppliers that are currently offering FPA/ESA but a growing number of potential suppliers who have product under development and who are now actively marketing the product they hope to offer within a short period of time. The number which are expected to provide flat panel antennas (FPA) to support the new small satellite constellations is currently around 20, but the prospects of others joining the effort to produce new flat panel satellite antennas appears to be growing steadily. If the market does reach $11 billion per year as of 2028, that number will have undoubtedly increased from those reported on in Table 1.

SES of Luxembourg now owns and operates the O3b MEO constellation. SES is planning to deploy the next generation of MEO-based satellites known as the m-Power constellation. It has announced strategic partnerships in the deployment of the ground systems for their new system. This new m-Power network has promised the capability to provide speeds sufficient to meet the networking and enterprise service needs of large multinational companies. This suggests the m-Power will seek to serve the same market as the LEOSAT network as well as provide new networking capabilities to rural and remote parts of the world in a dual-pronged campaign to serve more than a single market.

The announced partners include ALCAN Systems, Isotropic Systems and Viasat. Reportedly these three companies are being asked by SES under contract to develop “smart” high-throughput terminal solutions. Thus these high-throughput ground antenna systems are different in design, performance, and cost than ground systems designed for individual consumers or remote communities. These high-throughput systems thus would have much greater capability than simpler, lower gain systems

Table 1 Currently active companies involved in FPA/ESA for commercial small satellites

Name of company	Profile and headquarters location	Web site
ALCAN Systems	**ALCAN Systems** of Darmstadt, Germany. It is developing a new class of innovative smart antennas that will use ultrathin flat panel technology, and with very low power usage, and able to adjust its beam electronically without any moving parts	https://www.alcansystems.com
Amazon/ Kuiper Systems	The **Amazon/Kuiper System** is US based and a system application for 3236 satellites in a low Earth orbit constellation, and it is apparently the case that Amazon/Kuiper System is intending to manufacture and install a large number of consumer flat panel antennas around the world for use of this system. No strategic partnerships for antennas have been announced. Location for any FPA production not yet known	https://www.space.com/amazon-plans-3236-satellite-constellation-for-internet.html There is no current corporate site by Amazon Kuiper Systems website, but FCC filing is available
Anoki Wave	**Anoki Wave is** focused primarily on developing antennas for the much larger 5G cellular equipment market. It has developed silicon-based and integrated circuit flat panel antennas for satellite communications in the K-band, Ku-band, and Ka-band	https://www.anokiwave.com/products/index.html
Ball Aerospace	**Ball Aerospace** has five US locations. These include plants and facilities in New Mexico, Colorado, Missouri, Ohio, and Virginia. Ball Aerospace has developed and tested phased array applications for communications, radar, space, and electronic warfare applications**.** This includes S-band and geodesic dome phased array antennas. To keep costs low, Ball Aerospace has sought to leverage commercial off-the-shelf technologies, software, and processes	https://www.ball.com/aerospace/markets-capabilities/markets/defense-intelligence/antenna-systems
Boeing	**Boeing,** headquartered in the United States, has developed its flat panel antennas initially for installation on military jets. It is possible that if they deploy their proposed LEO small satellite constellation that they might seek to produce FPA/ESA for use with this network. Decision to deploy such a system is currently on hold. Boeing has also received a $1.6 million contract to design satellite communications phased array **antennas** for navy submarines	https://boeing.mediaroom.com/1999-11-08-Boeing-Receives-Contract-To-Design-Prototype-Communication-Phased-Array-Antennas-For-Navy-Submarines

(continued)

Table 1 (continued)

Name of company	Profile and headquarters location	Web site
C-Com Satellite System Inc.	**C-Com Satellite Systems Inc**. of Ottawa, Canada has successfully tested its 16 × 16 subarray phased array antenna using 4 × 4 Transmit and receive building block modules. The panels were developed and tested at the Centre for Intelligent Antenna and Radio Systems (CIARS) at the University of Waterloo	http://www.c-comsat.com/news/c-com-announces-successful-test-ka-band-phased-array-mobile-satellite-antenna/
GetSat	**GetSat** of Rehovot, Israel, and GRC of Hereford, UK, have announced a strategic partnership for the production of conformal and flat panel antennas for military aircraft and ground and maritime communications	https://www.getsat.com/news/get-sat-and-u-k-s-grc-create-strategic-cooperation-relationship/
Gilat Satellite Networks	**Gilat Satellite Networks** of Israel has developed the RaySat SR300 phased array as a flat panel antenna. This includes the 300-M system which is a compact, MIL-STD compliant antenna. This is a two-way antenna system that enables real-time broadband satellite communications, primarily for voice and data services. This can include both “on-the-move” or “on-the-pause” services. RaySat SR300 antennas are based on a flat panel array. This covers transmit and receive bands. The antenna features multiple onboard tracking sensors, which enable accurate tracking, short initial acquisition, and instantaneous reacquisition in the case of signal loss	https://www.gilat.com/technology/sr300-m/
HiSky	**HiSky**, based in Tel Aviv, Israel, is in a strategic partnership with Hispasat to provide flat panel antenna to provide low data rate mobile satellite services and Internet of Things (IoT) messaging services. There is an intent to expand this effort to use the Hispasat Arizonas 5 satellite to provide similar type services to Latin America, Portugal, Spain, and northern Africa. This service involves GEO satellites, but the flat panel antenna technology could potentially be applied to LEO smallsat constellations	https://www.hiskysat.com/2019/04/30/hispasat-and-hisky-to-offer-iot-and-mss-in-mexico-through-small-portable-terminals/
Honeywell	**Honeywell** and **Kymeta** (both of the United States) and **Inmarsat** (based in the United Kingdom) have a strategic partnership. Kymeta has a contract to send its flat panel antenna to Honeywell for testing and integration so that it can be used	https://www.satellitetoday.com/telecom/2015/04/15/honeywell-inmarsat-kymeta-to-develop-antenna-for-advanced-ifc-system/

(continued)

Table 1 (continued)

Name of company	Profile and headquarters location	Web site
	with Inmarsat GX systems. This partnership is in support of flat panel antennas to be used in partnership with GEO satellites, but this type of technology could also be adapted to use with LEO broadband small satellite constellations	
Hughes Network Systems	**HNS,** an Echostar Company located in Germantown, Maryland, US, has noted the importance of flat panel antennas but has not released specific information about development plans for flat panel antennas. They currently have a large back order for conventional VSAT antennas to support demand to communicate to GEO high-throughput satellites including their own Jupiter System	http://www.hns.com/
Intellian	**Intellian** is a strategic partner with Kymeta that is integrating Kymeta m-Kymeta antenna into maritime communications systems	https://www.intelliantech.com/News/pressrelease/view/185
Kymeta Systems	**Kymeta** and **OneWeb**, of the United States and the United Kingdom, respectively, announced in 2018 that they were working together to deploy flat panel satellite antennas. Kymeta's flat panel antennas with fast tracking of LEO smallsat constellation are one of the first to market and can be deployed in units that are modular to allow increased gain and throughput. It has the special feature of being partially financed by Microsoft founder Bill Gates	http://www.kymetacorp.com
Omni Access	See Phasor Solutions. **Omni Access** is a strategic partner with Phasor Solutions in the installation of Phasor Solution flat panel satellite antennas on luxury yachts and other maritime vehicles/ships	https://www.omniaccess.com/omniaccess-teams-up-with-phasor-inc-to-showcase-first-maritime-ku-band-digital-flat-panel-antenna/
Phasor Solutions	**Phasor Solutions**, based in Washington, DC area, is designing modular flat panel or conformal shaped units with an emphasis on aeronautical and maritime usage. Phasor has strategically partnered with Omni Access for installation of their FPSAs on yachts and ships	www.phasorsolutions.com
SatixFy	**SatixFy UK Limited**, of the United Kingdom, has introduced what it has described as the world's first ESMA (electronically steered multi-beam array) Ku-band 256 element array antenna as of	http://www.satixfy.com/news/satixfy-launches-worlds-first-silicon-based-electronically-steered-multi-beam-array-antenna/

(continued)

Table 1 (continued)

Name of company	Profile and headquarters location	Web site
	February 2019. This antenna uses fully digital beam forming technology array which can use all 256 element to create complex antenna patterns. Costing not available	
SpaceX	**SpaceX** Space X has filed with the FCC for licensing approval of the small flat panel antennas that it intends to deploy a million flat panel antennas with it Starlink system. How and where these FPAs will be fabricated is not yet announced. It would seem that it is also intended that it would also design and fabricate the V band FPAs/ ESAs as well	https://techcrunch.com/2019/05/24/spacex-reveals-more-starlink-info-after-launch-of-first-60-satellites/
Star Win	**Star Win Science and Technology Ltd**. which is based in China has been a provider of VSAT and larger dish antennas but is now developing flat panel satellite antennas. The characteristics of these electronically steerable antennas include high efficiency ≥90%; simple structure and low-cost maintenance, fully automatic and high accuracy targeting of satellite and compact and low weight, and portable	http://www.starwincom.com/
Thinkom	**Thinkom** Thinkom which is based in California, US, has a proved phased array conformal antenna system is currently in use on 15 airlines and some 1300 aircraft is one of a few providers with a proven ability to provide service installed on airlines. It has also claimed that its technology could serve to aid in the replacement of antenna farms which are expensive and also requires a great deal of room	www.Thinkom.com
Tianyi Satcom	Shaanxi-Tianyi Satcom of China is a manufacturer of satellite communications antenna. They are developing flat panel satellite antenna technology for Satcom on-the-move and internet access	http://satcom-sys.com/vendors/shaanxi-tianyi-antenna-co.,-ltd.html
Toshiba	**Toshiba** of Japan has developed flat panel antennas for X-band radar services and could extend this technology in the future for small satellite constellation services at a future date	www.toshiba.com

(continued)

Table 1 (continued)

Name of company	Profile and headquarters location	Web site
Viasat	**Viasat**, based in San Diego, California, is designing and building an all-electronic dual-beam flat panel antenna system to meet the requirements of the O3b mPower next-generation MEO satellite fleet. The Viasat antenna is based on proprietary flat panel core technology, a new radio-frequency (RF) integrated circuit and a modular approach that will enable multiple types of user terminals to keep pace with growing broadband connectivity demands	www.viasat.com

that would operate a much lower speed. The exact specifications and performance requirements for these systems are not clear and perhaps have not even been set. Presumably these would be at least in the 100 megabit/sec up to multiple gigabit/sec throughput capabilities. The direct connection to corporate sites via the m-Power MEO sat constellation would presumably be at least three times faster than GEO systems, but still have greater latency than the mega-LEO networks. Presumably scaled-down versions of these ground systems might be created to support rural and remote areas.

The following represents a brief report on the capabilities and design and production capabilities of the strategic partners that are supporting the SES m-Power MEO constellation.

- **ALCAN Systems GmbH** is based in Darmstadt, Germany. In August 2017, it announced that it had raised 7.5 million euros to design, engineer, and manufacture its new type of "smart" antennas to support the latest broadband cellular services as well as broadband connection to new satellite constellations. The three main funders were SPC, SES, and Merck. ALCAN Systems is reportedly now developing a new "smart antenna" that is a flat panel design and would presumably have no moving parts or mechanical components. The beam steering would be controlled by an integrated circuit designed for this purpose. In most cases, this would be an application-specific integrated circuit (ASIC). The design is intended to be mountable on airplanes, ships, buses, trains, and even self-driving cars to support 5G sensors needed to maintain instantaneous control and avoidance of collisions. Thus this type of unit would have an electronic beam steering capability to support satellite and cellular network needs. Most market assessments suggest that the predominant market would be for cellular and mobile applications and satellite systems would be the secondary market. The design would be intended to support GEO, MEO, and LEO satellite networks.

  The ALCAN Systems design would primarily consist of mass-produced liquid crystal panels and integrated circuits that could control the desired beam forming. The concept would be to produce these units for different applications at high volume. Once a high degree of automation is achieved, the liquid crystal panels could be proceeded at a much lower cost and rapid production rate achieved through robotic assembly line manufacturing (ALCAN Systems 2017).

- **Isotropic Systems**, of London, United Kingdom, and Lithicum, Maryland, was founded in 2013. It is developing a low-cost, low-power multi-service antenna capability. This is not a flat panel satellite antenna per se. Rather it is a multi-beam antenna that is scalable in size and service capabilities to reach from the smallest consumer-use capabilities to high-throughput service needs. The patented Isotropic Systems design is seeking to provide instantaneous bandwidth, to create an optical-based, multi-beam electronically steerable terminal that can transmit and receive high-bandwidth signals within the a modular, and thus scalable aperture.

  Isotropic Systems describes its capabilities in the following manner: "Isotropic Systems is developing the world's first multi-service, high-bandwidth, low power, fully integrated range of high throughput terminals designed to support the satellite industry to 'reach beyond' traditional markets (Isotropic Systems 2019).

  Isotropic Systems claims that their antennas can be scaled up from consumer-use antennas to provide multiple types of higher rate services. Thus they indicate that increased performance antennas using the optical-based beam forming can provide electronic connectivity for aeronautical uses, coaches and buses, trains, ships, cellular backhaul, and defense-related com-on-the-move services. The essence of their design is enabled by their optical-based beam former module. This design reduces the circuitry needed for multi-beam formation and reduces costs in an exponential basis. The claim is that this can provide Ku- and Ka-band antennas with multi-beam forming antennas that are 70% to even 95% lower than phased array or flat panel antennas currently on the market (Isotropic Systems 2019).

  In a recent interview, John Finney, the Founder and CEO of Isotropic Systems, has explained the claim of low-cost systems as follows: "We can produce a terminal, certainly in Ku-[band], that is lower than $300. . .. A Ka-band terminal would be sub-$450 (Henry 2019)."

  In addition the Isotropic Systems design is also geared to increase continuity of service and resilience against dropped connectivity during handover of service when switching from one beam to another.

  > The capability of this design includes so-called 'make-before-break'; of a beam hand-over of service from a satellite operating to a single terminal. This capability can also support link aggregation, path diversity, additional on-demand capacity, and greater resiliency of service. (Henry 2019).

  These innovations have served to win Isotropic Systems several awards for design innovation. These accomplishments have led to new levels of investment, including most recently the Boeing company through its Boeing Horizon X investment arm that has made a $14 million investment. Inmarsat has also become a strategic partner and customer for Isotropic Systems antennas where

Fig. 2 A graphic showing an Isotropic Systems antenna and the modular format underneath (Graphic courtesy of Isotropic Systems)

it has indicated a plan to use these innovative antennas to extend its Inmarsat Express services around the world (PR Newswire 2019).

Although the Isotropic Systems product is not a phased array flat panel antenna as normally understood, its surface is indeed flat. What is below the surface is different than what either ALCAN or other flat panel antenna manufacturers are providing (see Fig. 2).

- **Viasat** is designing and building an all-electronic dual-beam flat panel antenna system to meet the requirements of the SES/O3b mPower next-generation MEO satellite fleet. The Viasat antenna is based on proprietary flat panel core technology, a new radio-frequency (RF) integrated circuit and a modular approach that will enable multiple types of user terminals to keep pace with growing broadband connectivity demands.
- **Thinkom** announced early in 2019 that it has already tested their antenna with Telesat LEO satellite.
- **Kymeta** and OneWeb announced in 2018 that they were working together to deploy flat panel satellite antennas. These are one of the first to market and can be deployed in units that are modular to increase gain and throughput (Fig. 3).

5 The Overall Field of Companies Who Are Seeking to Develop Flat Panel Satellite (FPSA) Systems

The previous section discussed the companies that have capabilities in the FPSA field and are working as strategic partners with those deploying broadband smallsat constellations. In this section, there is an attempt to summarize all of the known commercial enterprises seeking to bring this new technology to market. Some of these may have already have working relations with small satellite constellation providers, but these have not yet publicly announced or these relationships have not been discovered in the authors' research to date.

Just as is the case with those designing and manufacturing small satellites, those seeking to launch these growing number of smallsats, the number of organizations

Fig. 3 The Kymeta flat panel satellite antenna is now available on the global market. (Graphic courtesy of Kymeta)

who have sought to enter the new flat panel antenna/electronically steerable antenna field, are volatile and fast changing. If commercial organizations that are seeking to develop this type of new antenna has been overlooked, this has been unintentional. There undoubtedly will be new entries that will continue to appear around the world as this new market continues to evolve.

Those companies that have been profiled in the previous section are not repeated in this section. Those companies that have existing strategic partnerships with small satellite constellations should not be interpreted to mean that their products are superior in technology, reliability, or price. Indeed some of those listed in this section may already have developed relationships that were not obvious or publically announced at the time this chapter was published. Finally, the development of flat panel antennas to support military and defense needs for aircraft, ships, and other military vehicles is largely not covered since much of these market transactions are not publicly available. Further many of these efforts involve non-satellite antennas that involve ground communications for aircraft and not satellite communications. This is clearly a part of the new and growing market, but not explicitly covered here except to note some of the suppliers as noted earlier.

The number of companies that are currently involved in developing FPA/ESA systems is provided below (Table 1). Any omissions from this list are not intentional. Clearly more companies will be joining this field of suppliers in the future.

6 Conclusion

This field of electronically steerable antennas for satellite communications and networking is an exciting new market. This new market for satellite ground equipment is largely an outgrowth that comes from the needs of the so-called mobility market that requires conformal antennas and electronic beam forming.

The flat panel satellite antennas are crucial to the new small satellite constellation industry and the new services that they will develop. These will range from the very small antennas the size of credit cards and cigarette packages for low data rate IoT messaging and machine to machine (M2M) services to the very high broadband services to support enterprise networks for large corporations with offices around the world.

The development will vary from region to region and will spread from mobility markets to fixed satellite services. The huge amount investment that are now pending in new LEO and MEO small satellite network will translate into future investment in flat panel satellite antennas that will first perhaps be on aircraft, on ships, on military vehicles, and then spread to other types of services. The utility of these new systems are to support broadband Internet to rural and remote areas, to support cellular network backhaul, and to enable satellite-based Internet of Things (IoT) data relay and M2M messaging.

The formula that has been used in satellite systems engineering that says that suggests that investments in satellites and ground control systems for the space segment should more or less equal the investment in user terminals that access the satellites. Today there are more than $20 billion in planned investment in small satellite constellations with some $10 billion related to the two SpaceX networks. The $11 billion per year of ground segment investment for users of these networks as projected by NSR for 2018 today seems very aggressive. Yet the wide range of new applications and services that can be unlocked with these new systems, seem to make such projections credible.

The one very serious concern that weighs against these projections are very much related to the issue of space safety, and the very real threat of orbital space debris. The single factor that could have a major negative impact on the growth and level of demand for smallsat LEO constellations, the services they provide, and the demand for user terminals – especially flat panel satellite antennas – would be one or more serious collisions that endanger the continued safe operation of these LEO and MEO constellations populated by as many as 20,000 satellites. Currently NSR has projected that only 7000 of the projected 20,000 smallsats will actually be launched. Even this number of satellites appears to raise substantially the risk of one or more orbital space collisions that could endanger the entire future of this new type of satellite constellation and the electronically steerable antennas that would support these new smallsat networks.

7 Cross-References

▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas

References

ALCAN Systems, A German smart-antenna start-up raises 7.5 Million Euro to manufacture flat panel phased-array antennas, August 18, 2017. https://www.alcansystems.com/press-release-alcan-a-german-smart-antenna-start-up-raises-eur-7-5-million-to-manufacture-flat-panel-phased-array-antennas/

Flat Panel Satellite Antenna Market Overview, Growth and analysis report 2019–2024. Last accessed 18 Sept 2019. https://instanewsletters.com/flat-panel-satellite-antenna-market-overview-growth-and-analysis-report-2019-2024-airbus-defence-and-space-france-honeywell-nternational-us-general-dynamics-corporation/36671/

C. Henry, Isotropic systems gains Boeing as investor, partner on satellite user terminals'. Space News, Jan 19, 2019. https://spacenews.com/isotropic-systems-gains-boeing-as-investor-partner-on-satellite-user-terminals/

http://satcom-sys.com/vendors/shaanxi-tianyi-antenna-co.,-ltd.html

http://www.c-comsat.com/news/c-com-announces-successful-test-ka-band-phased-array-mobile-satellite-antenna/

http://www.hns.com/

http://www.kymetacorp.com

http://www.satixfy.com/news/satixfy-launches-worlds-first-silicon-based-electronically-steered-multi-beam-array-antenna/

http://www.starwincom.com/

https://boeing.mediaroom.com/1999-11-08-Boeing-Receives-Contract-To-Design-Prototype-Communication-Phased-Array-Antennas-For-Navy-Submarines

https://techcrunch.com/2019/05/24/spacex-reveals-more-starlink-info-after-launch-of-first-60-satellites/

https://www.alcansystems.com

https://www.anokiwave.com/products/index.html

https://www.ball.com/aerospace/markets-capabilities/markets/defense-intelligence/antenna-systems

https://www.getsat.com/news/get-sat-and-u-k-s-grc-create-strategic-cooperation-relationship/

https://www.gilat.com/technology/sr300-m/

https://www.hiskysat.com/2019/04/30/hispasat-and-hisky-to-offer-iot-and-mss-in-mexico-through-small-portable-terminals/

https://www.intelliantech.com/News/pressrelease/view/185

https://www.omniaccess.com/omniaccess-teams-up-with-phasor-inc-to-showcase-first-maritime-ku-band-digital-flat-panel-antenna/

https://www.satellitetoday.com/telecom/2015/04/15/honeywell-inmarsat-kymeta-to-develop-antenna-for-advanced-ifc-system/

https://www.space.com/amazon-plans-3236-satellite-constellation-for-internet.html

Isotropic Systems. https://www.isotropicsystems.com/. Last accessed 16 Sept 2019

Northern Sky Research, in *Flat Panel Satellite Antennas,* 4th edn. February 2019. https://www.nsr.com/research/flat-panel-satellite-antennas-4th-edition/

NSR Press Release, Satellite flat panel antennas as a 11 billion opportunity by 2028. https://www.nsr.com/satellite-flat-panel-antennas-an-11-billion-opportunity-by-2028/

PR Newswire, Successful Texting of Ka-band Optical Devices Paves the Way to be The First Solution of its Kind to Market. https://www.prnewswire.com/news-releases/isotropic-systems-successful-testing-of-its-ka-band-optical-devices-paves-the-way-to-be-the-first-solution-of-its-kind-to-market-300. May 8, 2019

D. Werner, Inexpensive flat-panel antennas will be a 'game-changer'. Space News, September 10, 2019. https://spacenews.com/wsbw-2019-flat-panel/

www.phasorsolutions.com

www.viasat.com

Small Satellites and Innovations in Terminal and Teleport Design, Deployment, and Operation

Martin Jarrold and David Meltzer

Contents

Abstract

Bridging the gap between innovation and implementation is at the very heart of *NewSpace*, and the emergence of the small satellite ecosystem, a new era for the space and satellite industry, heralds great promise for the global economy, for society, and for development. Among other themes, this chapter will explore:

M. Jarrold (✉) · D. Meltzer
GVF, London, UK
e-mail: martin.jarrold@gvf.org; david.meltzer@gvf.org

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_103

- The current trends in the “smallsats” ecosystem
- The game-changing developments in the antenna/terminal ground segment
- The importance of the mobility markets
- The competing “state-of-the-art” solutions in the flat panel antenna market and associated forecasts and trends to 2028
- Drivers other than just technology
- Teleports transitioning to data center centric models
- The changing interrelationship of the satcoms and Earth observation environments
- The responsibilities of the operators of the emerging mega-constellations to maintain the sustainability of the operational environment of low Earth orbit

Keywords

5G · Actionable intelligence · Active debris removal (ADR) · Active electronically scanned array (AESA) · Antenna/terminal · Aperture performance · Applications · Application-specific integrated circuits (ASICs) · Auto-acquisition · Autonomous decommissioning · Beam forming · Big data analytics · CAPEX · Cloud · Commercialization of space · CubeSat · Data centers · Data communications · Development cycles · Device-to-device · Digitizing · Distributed resiliency · Earth observation · Earth stations in motion (ESIMs) · Electronically steered antenna (ESA) · Entrepreneurially oriented · Femtosatellites · Fixed phased array · Flat panel antenna (FPA) · Footprint · Form factor · Fronthaul · Geospatial analytics · Geostationary orbit (GEO) · Global digital ecosystem · Ground segment · High-bandwidth efficiency · High-throughput satellite (HTS) · Holographic beam · Industrial Internet of Things (IIoT) · Industrialization of space · Infrastructure · Innovations · Internet of Things (IoT) · Ka-band · Ku-band · Latency · Low Earth orbit · Low profile · Machine learning · Mass production · Mechanically steered antenna (MSA) · Medium Earth orbit (MEO) · Mega-constellation · Metamaterials · Microsatellites · Millimeter-wave band · Miniaturization technologies · Minisatellites · Mission success · Mobile backhaul · Mobile communications · Mobile satellite service (MSS) · Multi-axis gimbal · Nanosatellites · Network of networks · New space race · NewSpace · Non-geostationary orbits (NGSO) · Off-the-shelf components · Operational environment · OPEX · Optical beam forming · Optical observation · Orbital debris · Parabolic reflector · Paradigm shift · Passive electronically scanned array (PESA) · Picosatellites · Pointing accuracy · Predictive analytics · Radome · Satcoms · Satcoms-on-the-move (SOTM) · Satellite end-of-life · Satellite operator · Small satellite · Smallsats · Space debris · Space situational awareness · Spin-offs · Start-ups · Sun-synchronous orbit (SSO) · Sustainability · Synthetic aperture radar (SAR) · Teleport · Tracking antennas · Virtualized · Volumes of scale

1 Introduction

NewSpace is big, but not in the same way as the now decade-long history of the business of launching satellites to Earth orbit. Before *NewSpace*, the "big" in satellite essentially related to the physical size and mass of spacecraft – for commercial communications, for Earth observation and imaging, for weather forecasting, for defining military strategies and tactical objectives, for government intelligence gathering and surveillance, and for numerous other applications – and to the scale of the commercial sector and government sector budgets which funded their design, construction, launch, and in-orbit operations.

NewSpace, the overall context within which the "smallsats" developmental phenomenon is evolving, while it is not, at least yet, replacing or supplanting the established "models" of commercial and government space activity, is a radical departure from those "models." In addition, *NewSpace* entails a tremendously accelerated growth cycle that has been described as the "industrialization of space" and a phenomenon that bridges the gap between innovation and implementation.

The *NewSpace* phenomenon is not only about space segment, however. It is having a multifaceted impact on ground segment infrastructure, with innovation in satellite antennas/terminals and in teleport, design, deployment, and operation.

Affecting the former, the ground segment, to the extent that the long-anticipated paradigm shifts in antenna technology from parabolic – and multi-axis gimbal mounted in the case, for example, of maritime antennas/terminals – to flat panel designs is about to be realized. Affecting the latter, teleports, to the extent that the traditional notion of the teleport – as a substantial physical infrastructure and numbering relatively few – is of declining contemporary applicability and relevance as software comes to dominate and the number of teleports is likely to increase well into the hundreds, worldwide.

2 The GVF Perspective

GVF perspectives, as presented in this chapter, arise out of the ever-widening remit of GVF. Founded in 1997, GVF continues to be headquartered in London and registered in the UK (http://www.satelliteevolutiongroup.com. Last date of access 6th January 2020). One of a very few global nonprofit associations of the satellite industry, GVF, brings together organizations from around the world representing the satellite ecosystem that are engaged in the development and delivery of satellite technologies and services for consumers, commercial, and government organizations worldwide. Its aim is to facilitate expanded access to satellite-based connectivity solutions globally, achieved through regulatory, policy, and spectrum advocacy; training and certification; product quality assurance; and collaboration with user groups and other satellite stakeholders.

Over the decades, satellite connectivity has provided the communications foundation and requirements of many commercial and government vertical markets, but now satellite is increasingly trending to center stage for applications and users right across the economic and social spectrum. Satellite is no longer regarded by the wider sphere of communications solution provisioning as being stage left, no longer regarded as a niche market-only technology, and no longer a solution of last or remote resort. All of this is reflected in the emergence and growth of *NewSpace* and of the "smallsats" revolution – in respect of both space segment and ground segment – as part of it.

So, What Is Different About *NewSpace*? The business of getting to space and applications using space are endeavors undergoing change, moving from domains dominated by governments and by big satellite manufacturing, satellite launcher, and satellite operator companies to a more affordable and entrepreneurially oriented domain populated by many small-scale start-ups and spin-offs from academia.

A plethora of satellite launch companies and launch aggregating service companies now complement the emergence of a myriad of spacecraft manufacturers, building satellites to serve a wide range of applications. This manufacture – featuring shorter development cycles, smaller development teams, off-the-shelf components, miniaturization technologies, mass-production construction techniques, and standardized form factors – is based on a low-cost per unit of functional capability with easier and cheaper launch vehicle integration. In some instances, these techniques are akin to factory production lines. These processes are wholly distinct from the traditional way of building commercial or government satellites, involving a bespoke multi-metric tonne spacecraft design and construction taking several years and absorbing hundreds of millions of dollars.

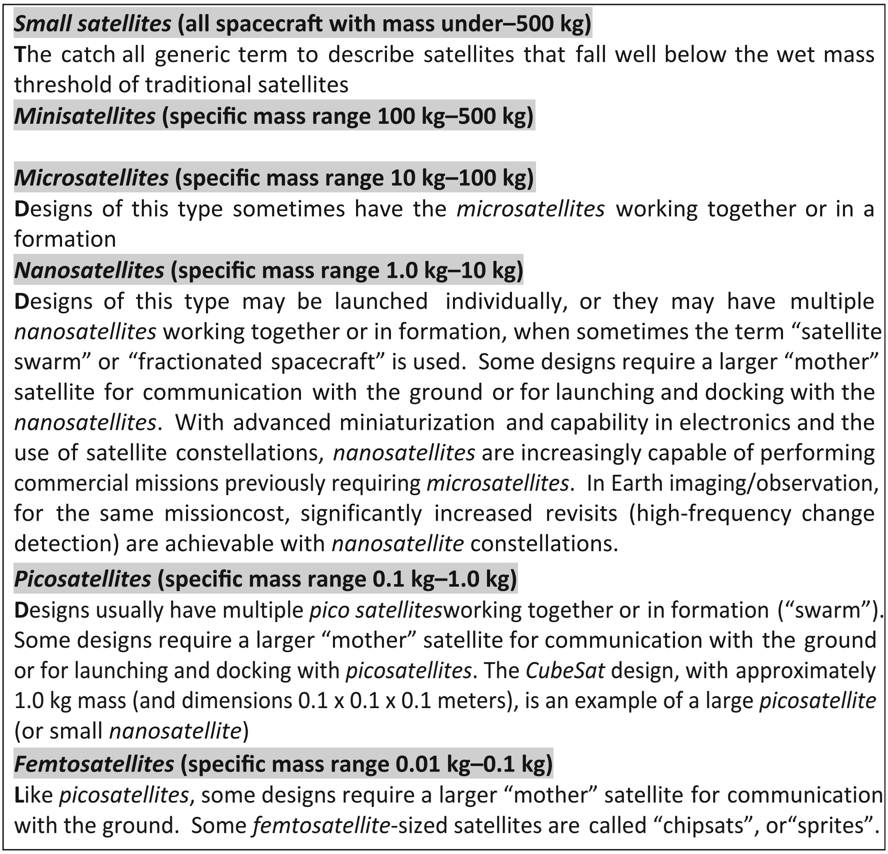
Investors range from well-known business persona such as Jeff Bezos, Elon Musk, and Richard Branson to iconic companies such as the Coca Cola Company and Google. All are driven by the commercial opportunities created by satellites. They are channeling funding into this revolutionary expansion in the commercialization of space, and this is happening in a widening range of countries, not only in the more traditional space nations but in many smaller and developing nations.

3 Small Satellites

While this label is useful as a general catchall term for this new field of commercial space activity, it is more accurately used within a defining grouping or range of spacecraft size classifications. The following tabulation (Fig. 1), *Small satellites: an overview*, reflects the widely recognized terminological conventions:

The full realization of that part of the *NewSpace* revolution that is the technology of small satellites will be across three principal segments:

- ***Communications*** including connectivity for the Internet of Things/Industrial Internet of Things (IoT/IIoT) and machine-to-machine (M2M) applications as well as the emerging broader 5G environment
- ***Earth imaging/observation*** including situational awareness as well as imagery-based intelligence



***Small satellites* (all spacecraft with mass under–500 kg)**

The catch all generic term to describe satellites that fall well below the wet mass threshold of traditional satellites

***Minisatellites* (specific mass range 100 kg–500 kg)**

***Microsatellites* (specific mass range 10 kg–100 kg)**

Designs of this type sometimes have the *microsatellites* working together or in a formation

***Nanosatellites* (specific mass range 1.0 kg–10 kg)**

Designs of this type may be launched individually, or they may have multiple *nanosatellites* working together or in formation, when sometimes the term “satellite swarm” or “fractionated spacecraft” is used. Some designs require a larger “mother” satellite for communication with the ground or for launching and docking with the *nanosatellites*. With advanced miniaturization and capability in electronics and the use of satellite constellations, *nanosatellites* are increasingly capable of performing commercial missions previously requiring *microsatellites*. In Earth imaging/observation, for the same missioncost, significantly increased revisits (high-frequency change detection) are achievable with *nanosatellite* constellations.

***Picosatellites* (specific mass range 0.1 kg–1.0 kg)**

Designs usually have multiple *pico satellites*working together or in formation (“swarm”). Some designs require a larger “mother” satellite for communication with the ground or for launching and docking with *picosatellites*. The *CubeSat* design, with approximately 1.0 kg mass (and dimensions 0.1 x 0.1 x 0.1 meters), is an example of a large *picosatellite* (or small *nanosatellite*)

***Femtosatellites* (specific mass range 0.01 kg–0.1 kg)**

Like *picosatellites*, some designs require a larger “mother” satellite for communication with the ground. Some *femtosatellite*-sized satellites are called “chipsats”, or“sprites”.

Fig. 1 Small satellites: an overview

- ***Scientific/technological***

As scientific and technology demonstration applications lay beyond the remit of GVF, the focus here is, primarily, on communications and, secondarily, on Earth imaging/observation applications.

4 Trends in the Small Satellite Ecosystem

Since 2012, activity in the small satellite industry has grown as entrepreneurs, and nations alike have joined a new space race. Fueling the new space race have two factors. First, the capabilities of satellites are growing due to technological innovations. Second, the costs of “smallsats” are falling due to innovations in spacecraft manufacture, increased data processing capabilities, the ubiquitous presence of GPS enabling location and attitude determination, improvements in ground system costs, and signal processing capabilities. Together, the increased capabilities and falling costs are facilitating market expansion. The global consulting firm, Euroconsult, predicts that approximately seven times more "smallsats" will be launched during the 2018–2027 period compared to the prior 10-year period (i.e., 7,000 vs. less than 1,000) (Euroconsult 2019).

Of note, small communications satellites, whether part of communications mega-constellations or single Earth imaging spacecraft, operate in non-geostationary orbits (NGSO), that is, low Earth orbit (LEO). This orbit enables higher performing *link budgets* (https://www.tutorialspoint.com/satellite_communication/satellite_communication_link_budget.htm. Last date of access 6th January 2020) and reduced transmission latency while having the coverage of higher altitude orbits. Small Earth imaging/observation satellites operate in Sun-synchronous orbit (SSO) – a LEO variant – which reduces revisit times or increases revisit frequencies (high-frequency change detection) for the same Earth surface territory.

5 A Game-Changing Ground Segment

NewSpace is bringing change to the ground segment – the infrastructure of antennas/terminals and teleports which transmit and receive today's IP-based data and which facilitate management of satellite networks.

6 Terminals/Antennas

An increasing range of Earth imaging/observation applications, such as high-resolution and full-color ports/docks surveillance, maritime routing, and sea-lanes security monitoring, are real time from LEO or SSO. This means they have more in common with data communications than with more traditional Earth observation techniques. This also means that to stay in permanent contact with ground segment infrastructures, the antennas – unlike the fixed satellite service (FSS) installations in geostationary satellite links – have to point and then have to move to track a given satellite and then constantly change the satellite to which they are pointing as the successive elements of a constellation traverse the sky.

7 Mobility, Mobility, Mobility

Today's mobile communications paradigm is very familiar. Readers of this chapter, consumers of all sorts of broadband-based applications, accessed via various types of devices over cellular networks and private and public Wi-Fi, expect no limitation on exactly where to get access to the Internet – including on buses and trains (and cars), on ships at sea, and at 12,000 m above the oceans.

The deployment of satcoms-on-the-move (SOTM) solutions across transportation networks is a key fact of *NewSpace*. Satellite-based maritime communications have been around for years in the mobile satellite service (MSS), or L-band, arena. More recently, however, the shipping industry has been transitioning to VSAT-based broadband systems in the fixed satellite service (FSS) of GEO spacecraft with shipboard installations known as Earth stations in motion (ESIMs).

ESIMs enable container vessel captains to maintain their links into company corporate networks and to enable the functioning of a ship's bridge as an office at sea. ESIMs give cruise line passengers a broadband experience, and they provide globe-trotting senior executives and super-entrepreneurs aboard their mega-yachts the kind of connectivity necessary to stay in touch with the global financial markets.

In the commercial airliner environment, ESIMs enable broadband access for passengers who comprise a new type of airline customer, a customer whose choice of airline is influenced by the availability and quality of inflight connectivity. ESIMs are vital for the airline too (aircraft systems monitoring, aircraft fleet management, cabin crew-passenger communications, etc.), for jet engine manufacturers (engine performance monitoring), and for air traffic management infrastructures at the national, continental, and global level.

With the advent of constellations of communications "*smallsats*," ESIMs – on ships and on planes – will need to have moving terminal antennas continually pointed at moving LEO and medium Earth orbit (MEO) satellites tracking from horizon to horizon. This has, of course, long been achieved with reference to the GEO satellite environment. Such traditional tracking antennas – the familiar tri-axis gimbal-mounted parabolic reflector that has long been the very icon of satellite communications – maintain satellite links as the platform on which they are mounted undergoes the pitch, roll, and yaw movements of the sea-going vessel or the aircraft in flight. Of course, there are other considerations that impact the relative performance of gimbal-mounted parabolic antennas as the vehicular platform on which they are mounted moves around the geography of the Earth. Two such considerations are "skew" and "scanning." In this chapter, it is not intended to engage in a detailed technical appraisal of these issues.

The physical footprint and physical positioning of an antenna (and the radome necessary to protect it from harsh weather and other atmospheric conditions) aboard a ship, or another maritime platform such as a jack-up or floating oil rig, are often an installation and operational challenge in terms of available deck space and the avoidance of superstructure obstacles to clear line-of-sight between antenna and satellite. With the arrival of passenger broadband access provision aboard commercial airliners, the footprint (and weight) of antennas and the overall size of fuselage-mounted antenna radome "bubbles" – which is an atmospheric drag and fuel budget-related issue for airlines – are additional concerns.

Satellite antennas have improved in aperture performance (https://en.wikipedia.org/wiki/Antenna_aperture#Aperture_efficiency. Last date of access 6th January 2020), pointing accuracy and form factor by leaps and bounds in recent years. The continuation to even smaller form factors – and reduced weight in the case of airlines – in antenna technology will be a significant step forward for these user market sectors.

While, as noted above, SOTM is not really *NewSpace*, the long and keenly awaited arrival of flat panel antennas (FPAs) is a part of *NewSpace* because these new antenna technologies will help enable the revolution.

8 Antenna Revolution (But They Don’t Move, Do They?)

FPAs are broadly anticipated to make a major contribution to revolutionizing the entire communications sector. With such defining attributes as low aperture, high reliability and pointing accuracy, small form factor, and low weight, they are the imperative solution for the mobility markets and for those facets of the IoT, including, as a subset, the IIoT that includes such developments as connected cars and trucks, the emergence of the “Smart City,” and industrial process and utility monitoring.

However, it is not as simple or straightforward as that, and much like the classification of types of small satellites in the *NewSpace* space segment, it is important to note the technology-type subsets of FPAs of the *NewSpace* ground segment. This will be explored below.

9 FPAs: What Is the “State of the Art”?

A multitude of companies in today’s FPA market all offer their own respective “state-of-the-art” solutions. Currently, more than 20 antenna manufacturers are in various stages of development and deployment of FPA solutions. These companies are attracted by a market potential that (Northern Sky Research 2019a) is predicted to bring cumulative FPA equipment sales to approximately US$11 billion by 2028. This is a market that has many orders of magnitude above the historical positioning of FPAs.

FPAs have for long been a niche alternative to parabolic antennas. FPAs of the fixed phased array type have been in use since the 1950s and have progressed significantly since then – beginning with mechanically steered units and moving to the greater efficiency and reliability of electrically steered technology. But, due to high costs and variable performance, market potential has been limited, until now. Now, just the right combination of factors has created a “Goldilocks Zone,” a coincidence of new demand from evolving and expanding markets, radical technologies, advanced engineering techniques and manufacturing processes, and opportunities for scale which is expected to finally address the issue of unit costs.

The FPA market is benefiting from partnerships up and down the industry value chain, with operators, service providers, and ground equipment manufacturers forming relationships to drive advances in antenna ecosystem development and achieve the right mix between performance and price. These partnerships have resulted from the widespread recognition that the satellite industry is in a state of fundamental transformation, where falling capacity prices are signaling major technology-shift dynamics. The impact of high-throughput satellite (HTS) technologies has required a concomitant response and rebalancing reaction from the ground segment to build on a long-held expectation that all the necessary pieces of the satcoms jigsaw will come together. Perhaps, there will soon be limited distinction between fixed, inclined, MEO, and LEO satellites from the perspective of the antenna/terminal.

There is no single FPA solution that is a best fit for all current, and potential future, markets. The solutions from the many companies referenced above take different technology paths but tend to be one of the two principal FPA technology types – the *mechanically* steered antenna (MSA) and the *electronically* steered antenna (ESA).

MSAs – which currently dominate the FPA market, at 95.5% of all shipped units (Northern Sky Research 2019a) – have enjoyed a first-to-market advantage in the aeronautical vertical. This has been at least partially achieved by leveraging the actual and existing mechanical advantage which satisfies the rigorous antenna performance requirements, regulations, and barriers to entry in this user segment.

A commercially available FPA of the MSA type on today's market offers a Ku-band solution with two beam-forming antennas, transmit and receive. The antennas create beams by mechanically rotating a series of internal disks/plates which amplify and direct signals in a specific way. Although the internal disks/plates are moved mechanically, unlike a gimbal antenna, the entire antenna face is not pointed directly at the satellite, and instead small changes in plate position are used to adjust the elevation and azimuth scan angle. This technology is capable of achieving data rates up to 70 Megabits per second (Mbps) down and 15 Mbps up; however, this is expected to increase to as high as 100 Mbps as new spot-beam satellites become more available.

As noted above, MSAs are currently dominating in the aeronautical sector. Dividing this sector into commercial and government user segments, NSR expects the MSA lead in shipped units – at 76% and 95%, respectively – to continue until 2028, partly due to factors already noted and additionally due to momentum generated by value chain dynamics, partnerships, and norms in respect of installation costs and timing (Northern Sky Research 2019a).

The land mobile sector is similarly divided into government and commercial user segments, with the latter split into the train and bus markets, as well as the connected car market. However, the connected car market is not expected to be realized until much later than the train and bus markets. Again, according to NSR, government segment users are currently caught between the reliability and ruggedness of MSAs and the anticipation of next-generation terminal capabilities. The segment will only slightly favor ESAs by 2028, with 55% of shipped units at that time. In the interim, government requirements on testing and certification will lead to legacy MSA predominance. Favoring ruggedness and reliability is the connected train market which provides the principal commercial land mobile opportunity, followed by the connected bus market. However, given that both markets also want physically low-profile installations, ESAs will eventually come to the fore, by 2028 taking up 82% (Northern Sky Research 2019a).

10 "2028" Vision: A New Era for the Antenna/Terminal

The expectation is that the FPA market will transition, medium term. While, in the view of NSR, FPAs with low-profiles and high-bandwidth efficiency characteristics are those that are generally advancing the technology and bringing business changes in the satellite industry, thus advancing the possibility of new applications, it is the electronically steered FPA technology on which the future of satcoms is principally dependent. Indeed, the NSR forecast puts ESAs as accounting for 97% of FPA shipments in 2028 (Northern Sky Research 2019a).

ESA technology is still developing, and today it remains expensive to engineer, thereby making the current per unit cost of manufacture too high to secure mass market interest and penetration. However, the market for ESA technology is not entirely closed as some companies are selling actual product, albeit on a limited scale. While this should change as more of the LEO constellations start to orbit their first satellites, the likely scenario will not be one of the wholesale replacements of MSA deployments by ESAs but by competition between, and customer choice of, the two technologies.

Unit prices coming down will not change the fact that ESAs are complex high-tech devices. There is, as noted above, not a single ESA technology, and different manufacturers claim their own "state-of-the-art" ESA. However, all ESAs – in order to ensure precise satellite pointing in the most demanding of circumstances where the antenna/ESIM platform is moving and the target satellite is also moving in its LEO or MEO orbit and the target satellite must continually change as one spacecraft hands-off to another – have to be able to make thousands of tiny, individually tuned elements work together as one, unified antenna. This process must operate for long periods of time, covering extreme temperature ranges, with power to actively control high-demand phase shifter components and amplifiers. However, having noted this broad definition, other technological approaches to how satellites are tracked, how the beam is pointed, and how quickly the beam can be moved to another satellite are available!

The most currently competitive rival technology to the gimbal-mounted antenna is the type of FPA known as phased array, of which there are two basic designs – the passive electronically scanned array and the active electronically scanned array. Phased array antennas have numerous radiating elements, tiny, fixed antennas, each with a phase shifter to form a beam, or beams, by shifting the phase of the signal emitted. This creates a constructive/destructive interference which may be used to steer the beam, or beams.

Beam(s) can be pointed instantaneously in any direction, tracking the movement of a satellite in the sky, regardless of the movement of the vehicle mounted ESIM. These antennas usually have a very low profile, no external moving parts, and although exact designs vary, high reliability. This high reliability results from the fact that in the event of an antenna element failure, the remaining elements continue to function and the collective pattern of the whole is modified slightly to overcome the loss.

Passive electronically scanned array (PESA) systems have elements connected to a single transmitter and/or receiver and are the most common type. In active electronically scanned arrays (AESA), each antenna element has an individual transmitter/receiver unit, controlled by a computer. AESAs can radiate multiple beams of radio waves in different directions, at multiple frequencies, at the same time.

Electronic beam-steering performance – similar to phased array technology but without the same power-hungry characteristics – is also possible without expensive phase shifters, amplifiers, etc. The absence of phase shifters means that this technology is, rather paradoxically, deemed to be “passive” even though advanced capabilities mean dynamic creation and correction of phase and amplitude distribution to form the most focused beam possible. In the absence of active RF components, and despite many more elements than a typical phased array antenna, there are no power amplifiers to create excess heat and thus no need for a cooling system. Overall power consumption amounts to only a few watts, a significant contrast to the 1,000+ watts for a typical phased array antenna.

One example of an electronically steered, low-profile, high-throughput phased array antenna takes all the supporting electronics like block upconverters (BUCs) and amplifiers and compresses them into application-specific integrated circuits (ASICs) with the objective of reducing costs through manufacturing efficiency and high volumes. In place of phase shifters, this solution uses a large number of ASICs, each of which is connected to a small patch antenna.

The ASICs allow satellite signals to be separated from background signal noise, and microprocessors in the electronics dynamically control signal phases of all individual elements, combining and steering transmit or receive beams in any direction. No moving parts equate to a compact and reliable system which is also very thin.

Rows of ASICs on the underside of the antenna board are connected to rows of element patch antennas on top. Multiple control/antenna boards can be combined to increase capacity, and importantly, boards may be shaped to conform to curved surfaces, reducing atmospheric drag (important for aircraft) and enabling scanning for and links to satellites low on the horizon.

Another technological approach avoids the use of large numbers of phase shifters and amplifiers or the fitting of separate BUCs and low-noise block downconverters (LNBs) into ASICs for each antenna element. This approach uses a single LNB and BUC, similar to antennas across the satellite industry. The antenna itself is passive, with no mechanical parts and no requirement for rows of actively controlled phase shifters.

The antenna provides for satellite auto-acquisition and tracking, with transmit and receive using a single aperture, offering a wide-angle scanning to the horizon. RF beam steering, beam forming, polarization selection, and angle pointing control are all electronic and software defined. A metamaterial-based approach enables the formation of a holographic beam, with very low-level power requirements, to transmit and receive satellite signals. The elements of the antenna act together like “pixels” to create the holographic beam. Using software to change the pattern, the antenna can be pointed in the correct direction using no moving parts, internal or external. The design lends itself well to mass production, which will drive costs down with increased manufacturing volumes of scale.

11 “Graceful Degradation” and Millimeter Wave

A feature of the drive toward fully passive phased array technology, sometimes described as the “Holy Grail” of the intelligent antenna community, and one alluded to above, is phase-shift independent insertion loss where, even with some antenna elements turned off, the unit still delivers an acceptable radiation pattern without significant performance degradation. Preparation in the phased array technology environment for operational extension into the higher millimeter-wave band is another important development in anticipation of wider rollout of next-generation 5G mobile cellular.

12 Optical Beam Forming

It is arguable that *the* general major issue with the FPA/phased array technology ecosystem is that a lot of circuitry is needed to create a single beam, or satellite link, in any given direction for optimal connectivity. This functionality is power-hungry, expensive, and not radio efficient. There is another alternative technology on its way to market, a cutting-edge field known as optical beam forming.

This approach begins by noting the simplicity and high efficiency of parabolic antennas with their geometric structure focusing energy into a single feed source. In between the antenna parabolic geometry and the feed source, there is only air, creating a simple and highly efficient system but non-scanning. Beam-forming optics take legacy technology together with FPA technology and use the best features of both, in as much as a beam’s energy is directed to a single feed source, going passively through air and avoiding aberrations and losses prior to signal processing.

Engineered for Ku- and Ka-band terminals, the structure features multiple beam-forming sources, each of which can support an individual beam. When not in use, individual sources can be switched off, reducing power requirements – compared with current FPAs and phased array antennas – by as much as 80%. Design flexibility is such that if scanning range is reduced, the electronics can be reduced, configuring to include only the electronics needed to support a given application. The final product is an integrated solution that includes modem, BUC, and LNB components in a single package. The solution avoids the limitations of phase shifters, enabling it to handle GHz of instantaneous bandwidth, ensuring that the terminal is never the bottleneck, and supporting any commercial carrier size currently available.

While it is very clear that maximizing the benefits to be derived from the satcoms future does depend on the coming era of electronically steered FPAs, the antenna, or terminal, is not the only evolving piece of an increasingly complex industry puzzle.

13 New Technology, Not the Only Driver

The actual *adoption and deployment* of the new technology that is the very fabric of the *NewSpace* industry environment is not only driven by the coming into existence of said space and ground segment technologies. There is now taking place an entrepreneurially driven “industrialization of space,” wherein entrepreneurs are launching cheap – US$1 million - satellites to last for just a few years. This reflects change in the industry risk dynamic and change to a mindset which is very different to that of operators of expensive communications satellites which are the product of a lengthy design and manufacturing cycle and which are planned to have an orbital life of 15–17 years. *NewSpace* technologies are now brought into operation in months, not years.

14 5G and IoT/IIoT

The 5G standard specification is not yet finalized by the 3GPP – the 3rd Generation Partnership Project, the standards organization which develops protocols for mobile telephony. However, it is clear that small satellite constellations will have to be a vital contributing element to the success of the emerging IoT and Industrial IoT world and of the global 5G mobile broadband communications future as a whole.

5G will be a quantum leap from the person-to-person communications focus of current and earlier generations of mobile to a device-to-device focus, with devices on the network achieving speeds between 1 and 10 Gigabits per second (Gbps), together with practically unlimited capacity. This quantum leap goes way beyond the realms of the maturing, and still expanding, M2M connectivity environment which has an already long-standing dependency on, and synergy with, satellite communications links.

The 5G networked world of IoT/IIoT, and manifold-related applications, will require that every device is connected wherever it happens to be, and while Wi-Fi, Bluetooth, and today’s terrestrial wireless network connections are able to support many IoT/IIoT applications, these technologies are not ubiquitous and seamless.

IoT/IIoT coverage, to be truly global in scope – in terms of both urban device density and remote device deployment – will require wholesale integration of the terrestrial network with the ubiquity and seamlessness that only satellite networks can provide. These satellite networks will increasingly include small satellite constellations. The world of IoT/IIoT will be built on a connectivity foundation which will comprise a highly integrated functionality of, and between, terrestrial broadband wireless platforms and broadband satellite platforms.

Thus, small satellite constellations will develop as a core element of *NewSpace.* As referenced by the 3GPP, satellite will no longer merely be an “interfacing” technology and service, with a secondary role in the “network,” but an “integrated” technology and service, fully part of an evolving and complex “network of networks.”

Mobile backhaul, and cellular base station networking, has long been an important business driver for satellite and for teleport operators, and IoT/IIoT is already now becoming an additional market driver for these sectors. With this as backdrop, rollout of 5G mobile services has the potential to vastly accelerate growth in this business, given that supporting the “network of networks” will lead to a very significant growth in the mobile backhaul requirement.

In the 5G world, communications with objects in motion, currently a satellite specialty, will increase demand, likely driven in large measure from a massive increase in video to mobile devices. The economics suggest that caching video files at the edge could become a major business for teleports. Additionally, features already being deployed in existing 4G/LTE networks encourage mobile operators to concentrate heavy-duty processing in data centers linked to remote base stations, creating a market for “fronthaul” that is currently provided by fiber but is very likely to need satellite in the 5G future.

This is one reason, among others, why now it can be argued that it makes sense for satellite teleports to be considered as data centers – or, on the flipside – data centers to be considered teleports. More on the other reasons follow below.

15 In Transition: Teleports, Data Centers, and Emerging “X as a Service” Business Models

As these developments become more clearly in evidence, a number of important points should be recognized. Firstly, just as it is understood that 5G is an architecture that will have a massive impact on how the whole world communicates, the satellite industry must recognize that the mobile industry wants to finalize the 5G standard to match its own commercially exclusive interests and in doing so potentially push back on facilitating the necessary enabling environment for the satellite component to be entirely realized. Accordingly, the satellite and teleport industries must apply pressure to ensure a share in the investment that 5G will create over its deployment.

Until very recently it would have been true to say that satellite teleports have not really changed very much in 20 years, usually consisting of 19-in. racks of hardware, and being relatively few in number. However, teleports are now changing with one development being the teleport-data center dichotomy and the other having its focal point outside of *NewSpace* but that is nevertheless adjunct to *NewSpace*, and will contribute to its growth.

In this latter connection, more and more of the satellite industry’s traditional and long-standing end-user customers, often operating in remote and sometimes mobile contexts such as oil and gas, shipping, and more recently mining and farming, are rapidly digitizing their internal commercial and industrial processes. These commercial enterprises want their remote IoT/IIoT, and other sourced data resources, to be accessible from multiple originating locations and transmitted, via big data analytics infrastructure, on to decision-making centers.

For such enterprises, the development and creation of the necessary analytics infrastructure are just the means to the end of dealing with influxes of big data in order to extract core information and key insights for decision-making processes and devising solutions to actual problems. This "means to an end" is CAPEX intensive. Increasingly, an OPEX-oriented enterprise world has been turning to the *Cloud*, having recognized that data analytics offerings on virtual systems – perhaps in the public *Cloud* as opposed to private *Cloud* servers – offer many advantages. These advantages run from lower costs to being able to leverage service offerings that integrate the function of the "virtualized" data center (potentially including artificial intelligence and machine learning) with the function of the teleport.

Ground infrastructure companies which provide hardware and software for teleports increasingly recognize the greater efficiencies that can be achieved by relying on *Cloud* servers to virtualize network functions, as well as the big data analytics.

The development of "Managed Platform as a Service" (MPaaS) solutions – a facet of the "X as a Service" *Cloud* environment within which IaaS (Infrastructure as a Service), PaaS (Platform as a Service), and SaaS (Software as a Service) were the early primary elements – can combine satellite hubs, teleport/data center uplinks, and terrestrial networking contributions, enabling easy deployment of high-throughput connectivity in vertical market user customer locations across the globe. The addition of new GEO HTS generations, expanding MEO constellation capacity, and upgraded and new LEO mega-constellations, many of them comprising small satellites, will bring vast additional bandwidth capability to orbit which will further facilitate the rise of fully managed satcom services.

Given this, and the perspectives cited earlier, the reason for satellite teleports now to be considered as data centers or, on the flipside, data centers now to be considered teleports gains additional traction.

What is the next step for the data center? Some satellites currently in orbit already function analogously to mini-data centers, receiving data from Earth, processing and storing information, and transmitting back to Earth. Small satellite constellations in LEO – as well as the altitude of the orbit itself offering the advantage for some, time-sensitive, applications of reduced latency – provide for greater amounts of in-orbit data processing, storage, and transmission, as well as resiliency in the form of a multiple redundancy of nodes that is akin to the distributed resiliency strategies used by *Cloud* platforms. A LEO system could potentially geospatially distribute and replicate information around the constellation to prevent data outage or loss. Additionally, a secondary group of satellites could provide another data backup.

16 Teleports as Data Centers: Earth Observation Small Satellite Ecosystem

The "industrialization of space" is not only about satcoms. Manifestations of the *NewSpace* race can be more clearly seen, and at a considerably more advanced stage of development, in the Earth observation (EO) arena, within which the most advanced optical observation constellations are nearing completion of their first generational iteration. Other platforms with nonoptical sensors are emerging – i.e., synthetic aperture radar and hyperspectral imaging – but relatively few have so far progressed as far as launch.

Today, enormous volumes of EO data are generated each day. Various flavors of small satellites, launched to Sun-synchronous orbit (SSO), have rapid revisit times/ frequencies (high-frequency change detection) for the same part of Earth's surface, generating many thousands of images, vast quantities of imagery-based geospatial analytics, and information to feed into geospatial information systems (GIS) applications. Combining this with IoT/IIoT sensor-based applications (with hundreds of zettabytes of data generated each year by billions of devices), it is possible to comprehend the magnitude of the big data analytics environment into which the evolving teleport functional dynamic is migrating.

Differences in business models are evident in the EO ecosystem, models defined by a range of variables (including type of application) determining the associated degree of resolution required, the use of visual or other spectrum wavelengths, geographic imaging dimension parameter requirements (e.g., width of swath), frequency, and speed of data downlinks. Added to the modeling equation are such factors as the cost-effectiveness of different platform design iterations, often employing combinations of CubeSat units, together with build lead times that feed into as short as possible time-to-orbit.

EO business models also often feature the development of strategic partnerships which pairs EO with the global communications infrastructure providers in the satellite space segment. This reflects the continued blurring of the boundaries between communications and EO that has been engendered by the "smallsat" phenomenon within *NewSpace* and the fact that EO data – and the actionable intelligence derived from it via predictive analytics and machine learning – needs to be quickly, efficiently, and cost-effectively distributed to customers and stakeholders.

While there are very many examples of current optical-based EO missions, one decade-long program has been amply demonstrating that a low-cost "smallsat" (technically microsatellites, weighing-in at 90 kg) approach can provide solutions that have a medium resolution (i.e., between 6 m and 30 m) requirement is the Disaster Monitoring Constellation (DMC). The optical payload of the constellation's microsatellites – each of which is the product of one of the DMC's international consortium of entities – generates a total of approximately 500 images per day, covering equatorial sites daily and more frequently at higher latitudes.

EO originated big data will only increase in volume as optical imaging sources are increasingly complemented by the launch and operation of other sensor technology payloads, for example, synthetic aperture radar (SAR). SAR has some operational advantages over optical imaging, but it is only comparative recently that SAR missions have, like optical missions, come to be applications-driven rather than being driven by performance characteristics.

Not the least of SAR's operational advantages is its ability to penetrate through cloud cover and to continue to generate imaging data when the Earth's surface is in darkness. Despite this, it is only now that SAR technology is moving from a large budget, institutional mission, environment – one within which priority is given to all imaging parameters (resolution, swath, sensitivity) being fully technologically optimized – and taking the same evolutionary step in satellite design which is not at odds with low cost and is fully applications-driven. That is the very step that has enabled numerous optical EO programs to become affordable to a widening customer user base.

Thus, as various commercial SAR EO missions come to maturity, the microwave region of the spectrum will also come to be driven by an orientation to serving a broad range of actual applications. Such applications include agricultural crop assessment, coastal and maritime (ship detection, oil spill monitoring, maritime safety, defense/security), disaster management and monitoring, flood monitoring, forestry management and monitoring, land use mapping, etc.

17 Store-and-Forward Data Delivery and "Smallsats" Networks

One of the pioneer companies in the field of nanosatellite telecommunications solutions, together with a market-leading provider of radio and satellite communications solutions (Kepler Communications and Cobham SATCOM), have quite recently announced a strategic partnership aimed at facilitating the elimination of barriers to the adoption of high capacity data services over the pioneer's currently orbiting nanosatellites, the first few of an as yet still under construction LEO constellation.

The partnership's offering – defined as a "User Terminal-as-a-Service" (UTaaS) – centers on the use of proven, reliable ground segment, and budgeting for equipment costs (installation, technical support, terminal maintenance) and future capabilities for add-on services as a monthly operational fee (OPEX) rather than a more traditional onetime capital expense (CAPEX), the level of which would otherwise be significantly determined by the still high cost of today's tracking antennas. This business model also includes "airtime," permitting the customer a day-to-day frictionless experience and enabling the customer to maintain focus on their application with the advantage of economic transmission of gigabytes of data, to and from the end user's location. The solution – based on a store-and-forward technology model – is suited for delay-tolerable data such as large multimedia files, high-resolution videos and imagery, and other bandwidth-intensive data within, for example, the maritime and oil and gas sectors.

18 Small Satellites: Maturity? Operator Responsibility!

The “industrialization of space” is an entirely apt metaphor for *NewSpace* in many ways, for many reasons, but three, in particular, stand out:

1. NewSpace, like the industrial revolution of the nineteenth and twentieth centuries, will suffer from the ups and downs and uncertainties of innovation, difficult to predict dynamics which can easily be misinterpreted, obscured, or glossed over in the course of the understandable enthusiasm and excitement surrounding the opportunities created by any (r)evolutionary change.
2. In relation to the importance of not making the same mistakes as in the period of Earth-bound industrialization, which is understood to have come to compromise the *sustainability* of Earth’s current environmental equilibrium through fossil fuel emissions induced climate change, the keyword here is *sustainability.*
3. In ensuring the continued *sustainability* of space operations which, as well as being important for the satellite industry itself, will be the key enabling factor in the application of imaging and detection/measuring technologies that together with various other “frontier technologies” will contribute to the building of a global digital ecosystem to support socioeconomic development objectives.

As noted at the beginning of this chapter, the “smallsats” environment is at the beginning of a tremendously accelerated growth cycle. Euroconsult sees the market as being full of uncertainties as growth gives way to a more stable pace of maintenance and replenishment of satellites in large constellations by 2025 (Euroconsult 2019). This report anticipates the rolling 5-year growth rate for “smallsats” to peak in 2024 at 48%, following which market size should stabilize until second-generation mega-constellations begin to launch. Euroconsult projects that in the period 2019–2028, more than 8,500 satellites will be launched, half of which will be in broadband constellations. The report cautions, however, that market acceptance of the mega-constellations has yet to be validated and that the availability of a new generation of low-cost terminals and efficient distribution networks will be key success factors for them. Despite the justified celebration of the technology gains, in the years to come, it will be the market that will drive the value of propositions and determine whether “smallsats” are now reaching a maturity threshold or if radical and quick changes are now part of the industry as a whole.

The overall growth of the “smallsat” market is a boom time, a massive expansion in the space economy. Barriers to entry have been lowered, new applications are constantly emerging, and established applications are being supported in more effective ways, and substantial new revenue streams are a near-term prospect. The key question must be, “Is all this sustainable?”

NSR estimates that 39% of all “smallsats” launched over the next 10 years will be of <10 kg mass, that is, nanosatellites, and notes the growing trend in picosatellite (<1 kg) launches. This impacts on the sustainability issue (Northern Sky Research 2019b). Over the years the issue of space, or orbital, debris has been acknowledged as a major problem. Current space situational awareness (SSA) capabilities cannot accurately and precisely track objects of size less than 10 cm, which makes some small satellites – as well as small pieces of debris generated by a host of causes over decades of space activity – almost impossible to track. This can only add to the pre-existing problem which encompasses debris that ranges in scale from spent launcher stages down to a rogue nut and bolt and now also includes the consequences of anti-satellite actions by state actors. Even without the Kessler syndrome, orbital collisions are almost inevitable, given the sheer number of satellites comprising multiple mega-constellations. But, of course, it's not only collisions that matter; it's the sheer number of satellites that, given relatively short time from launch to end-of-life, must be disposed. GEOs, after 15 or, perhaps, 17 years, can be parked in a graveyard orbit out of harm's way. In contrast, LEOs should/must be deorbited in Earth's atmosphere where they are expected to meet a fiery end.

Some of the mega-constellation operators have designed their satellites with onboard independent and autonomous decommissioning systems to be used for orbit clearance at satellite end-of-life. This strategy makes obvious business sense and addresses the concerns of governments and many other stakeholders regarding sustainable space operations.

The SSA "industry" is reaching beyond just debris tracking and Earth-bound collision avoidance methods and is initiating efforts to tidy-up Earth's orbital backyard. There are varied approaches to this, such as "active debris removal" (ADR) missions using, for example, a specialized platform equipped with cameras and laser-ranging Lidar to track, characterize, target, and capture orbital debris (e.g., an out of control or drifting satellite), using a harpoon plus a net and a "dragsail" membrane which unfurls to hasten its atmospheric reentry and destruction, along with the captured "space junk." In another ADR approach, a debris removal vehicle, akin to a "tow truck," will use robotic arms to capture a target body and then engage in powered deorbiting maneuvers. In yet other approaches, "smallsats" (though not the very smallest variants) might be refueled or otherwise maintained in orbit by robotic space tugs, although any future availability of refueling technology should not remove from "smallsat" operators the responsibility for ensuring that satellite end-of-life is managed by clear protocols.

In relation to the debris issue, there is an apparent change in the measure of "mission success" in the *NewSpace* world. Mission success used to be an "all-or-nothing" matter, but this is no longer the case. Orbiting tens of satellites in a single launch, yet losing a few of them to technical failure, is still deemed a success. Multiple mega-constellations experiencing a failure rate of just a few percent will result in hundreds of nonoperational satellites occupying otherwise viable orbital positions, increasing operational costs for the remaining satellites in the constellation and potentially increasing collision risks.

19 Conclusion

The fundamental conclusion here must be that the technology innovation that is the small satellite is bringing about a qualitatively and quantitatively different space economy and one that might, at long last, even bridge the world's *digital divide*. Equally, "smallsats" will be able to deliver solutions for the other long sought-after next step – universal, unrestricted, and low-cost broadband connectivity that is mobile. The final aspect of this conclusion relates to an expression of hope in what NewSpace can deliver for the future. Of course, finally bridging the *digital divide* will itself contribute to equalizing the great differences in socioeconomic development around the world, but that is not enough – the world needs a "global digital ecosystem."

In a UN paper of 2019 – a product of the Development and Environment programs, UNDP, and UNEP – Jillian Campbell and David E. Jensen discussed the building of such an ecosystem.

In 2015, the UN adopted 17 Sustainable Development Goals as part of *Agenda 2030* to achieve a better future for all humanity. Radio communications, including satellites, have a key supporting role in achieving the 17 SDGs. This is all the more evident when noting, as does the UNDP, that 68% of the 93 environmental SDG indicators cannot currently be measured due to lack of data. This is the other "digital divide" which must be bridged, enabling us to acquire and deploy data sets to build a digital ecosystem for the entire planet which will allow data flows to be eventually transformed into insights for sustainable decision-making. This will require contributions from the various "frontier technologies" alluded to above – e.g., *Cloud* and edge computing, AI and machine learning, IoT/IIoT, and distributed databases, with the addition of the recent news from Google on quantum computing – but also from small satellite and related communications technologies. The context for this is, again as noted above, the continued blurring of the boundaries between communications and EO that has been engendered by the "smallsat" phenomenon of *NewSpace*.

This chapter includes text drawn from original GVF material, material originally authored by GVF for publication by Satellite Evolution, and material published by BusinessCom Networks, with permission.

20 Cross-References

- ▶ Economic and Market Trends for Ground Systems to Support New and Future Small Satellite Systems
- ▶ Electronic Beam-Scanning Technology for Small Satellite Communication Systems and Their Future Development
- ▶ Evolution of Satellite Networks and Antenna Markets
- ▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas

References

Euroconsult, *Prospects for the Small Satellite Market*, 2019 edition (August 2019)
Kepler Communications and Cobham SATCOM
Northern Sky Research, *Flat Panel Satellite Antennas*, 4th edn. (February 2019a)
Northern Sky Research, *Small Satellite Markets*, 5th edn. (February 2019b)
http://www.bcsatellite.net. Last date of access 6th January 2020

Part VII

Experimental and Technology Demonstration Smallsats

Student Experiments, Education, and Training with Small Satellites

Scott Madry and Joseph N. Pelton

Contents

S. Madry (✉)
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_34

Abstract

The use of small satellites as a tool for education, training, and recruitment of new talent for engineers and scientists in the field space applications and space science has grown enormously in the past two decades. Perhaps the most significant event in this regard was the defining of the cubesat standard and then the subsequent definition of the pocketqube standard that has followed more recently. Indeed the development of concepts of the femtosat, picosat, and nanosat have allowed the development of ways to undertake student experiments in much more cost-effective ways for student experimenters to undertake projects within the resources of colleges, universities, and even students at the pre-university level. Projects to undertake mini-experiments that can be carried out on-board the International Space Station (ISS) or other spacecraft designed to carry out space experiments have broaden the scope of student space experiments in scores of countries around the world, broadening the scope and extent of space education.

There are now multiple groups, organizations, and foundations, plus most space agencies, providing active support, training sessions, and contract awards to universities to foster and encourage these new initiatives for students and university researchers. These sponsors, among numerous others, include institutions and nonprofits that sponsor STEM educational initiatives and space agencies such as NASA, ESA, Canadian Space Agency, CNES (French Space Agency), and JAXA, the Japanese Space Agency. These organizations, foundations, institutes and space agencies provide new opportunities for cubesat training and actual projects, provide research grants, offer assistance with regard to technological and safety screening, provide relevant research grants and contracts, and assist with regard to launch arrangements – all to facilitate student smallsat tests and experiments.

This article describes the types of space experiments that are now possible with various types of smallsats. It provides background with regard to the most commonly used standards that are employed for these experiments and how to arrange for these smallsat experiments to be launched into space. This covers primarily nanosats (or cubesats) and picosats (such as pocketqubes). There is even some discussion of femtosats, at the very smallest end, and microsats at higher end of such programs. In the case of microsats of up to 100 kg, this most typically would be a developing country with a smallsat project leading an activity but perhaps one or more national university assisting in the satellite definition or assisting in training related to the operation of the microsat. There are today a wide range of universities, colleges, institutes, schools, foundations, organizations, and space agencies all seeking to promote smallsat space experimentation, technology verification, and proof of concept. There are also an increasing number of projects where university projects are actually seeking to verify smallsat systems for practical commercial projects. In the majority of cases, such projects are a means of providing training for young people and to excite their interest into the world of aerospace engineering and space applications.

Finally there is a discussion in this article about two subjects of particular concern. One issue is the reliability issue (or failure rate) concerning academic and student-related small satellite projects. The other is about concerns related to the longer-term sustainability of space and how student experimentation can be conducted so as to minimize the creation of space debris and space objects that remain in orbit.

Keywords

Arthur C. Clarke Institute for Space Science Education (ACCISSE) · Cubesats · Digital imaging · Earth observation · European Space Agency (ESA) · Femtosats · NASA · National Center for Earth and Space Science Education (NCESSE) · Picosats · Pocketqubes · Remote sensing · Smallsat · Telecommunications

1 Introduction

The 10 cm cube "cubesat" as a type of satellite designed for student experimentation has now grown significantly in importance. The smallsat as an educational and training tool and as a way to demonstrate new technology is now a key factor in the satellite industry. In short, it has many implications beyond its first intended purposes of simple and inexpensive student education and training. This standard not only opened the door to student experimentation, but it also led to many useful developments as well that have begun to permeate the aerospace industry. The "smallsat" has, for instance, also helped to show how satellites for commercial use could be designed to be better, faster, and more cost-effective. The smallsat revolution has helped to demonstrate how satellites might be much smaller in size while performing the same task. They have helped to show instances where it also might be possible to use many off-the-shelf components to reduce cost. Smallsats, due to their smaller mass, also obviously help to reduce launch costs.

Today there are many commercial systems that are using 3 unit cube satellites within commercial constellations such as Planet Inc. for remote sensing, and Spire for remote sensing, environmental measurement, and automatic identification service (AIS). These and other smallsat ventures started off as student initiatives and developed from designs that evolved from university-based experimental programs. The later evolution of new standards such as pocketqube that is one eighth the size of a cubesat, namely, 5 cm × 5 cm × 5 cm (i.e., picosats) and even femtosats (10 to 100 g) have opened the door to even more cost-effective ways to undertake student experiments and demonstrate new satellite technologies.

The 1 Unit CubeSat "standard" (i.e., a 10 cm × 10 cm × 10 cm cube with a mass of no more than 1.33 kg) was first started in 1999 as a cooperative effort between two US universities, Professor Jordi Puig-Suari of California Polytechnic State University (Cal Poly) and Professor Robert Twiggs of Stanford University's Space Systems Development Laboratory. They sought to create a new approach to satellite design on a scale suited to student experimentation and university and school budgets.

At that time, satellite programs were largely undertaken by civilian space agencies, military space programs, and large aerospace corporations that were typically working for governmental space programs. The original intent of the project was to offer a lower-cost access to space for the university science and engineering programs, so that the cost of designing and building the satellite and getting it launched might be such that a university or school might be able to undertake such a project. The speed of development was also a benefit. Indeed such projects could be conducted while a group of students were in school together. The fact that there have now been hundreds of cubesats launched as student experiments in the last 20 years shows just how successful this concept has proven to be.

Cubesat projects have now been successful not only by students at large universities but also smaller universities and schools at all levels of study even down to secondary and primary levels of education. New standards such as the pocketqube (5 cm cubes and up to 250 g of mass) and even femto-satellites (10 to 100 g) in size keep opening new doors to new and innovative smallsat experiments. Each new innovation has opened the door wider to a broader base of training and educational opportunity for a broader range of students in developing countries as well. New options such as ever smaller smallsats and projects that can be quickly built and launched at lower cost of these options open the door to students to devise and conduct space experiments in a better way.

These small satellite projects also can be a very effective way to train new entrants into the space industry how to design, test, and build satellites and learn key lessons in space safety. Even projects that fail can help expose new information about types of failures that can occur, and other key thing that can go wrong (such as incompatible standards). New designs, new materials, and new manufacturing techniques might lead to new levels of cost efficiencies (Cubesat 101 Basic Concepts). This experience has shown that a great diversity of designs, antennas, solar arrays, remote sensing cameras, and sensors, plus very strong processing power can be encapsulated with a 1 unit cubesat as it is deployed in outer space. Even capabilities that can be packed into a 1-meter cube now equal things that once involved satellites that were six to ten times larger. (See Fig. 1).

This article describes some of the prime instruments, standards, and approaches that can now be employed for student experiments. It explores some of the means of assistance that might be sought as well as some of the issues and concerns that arise

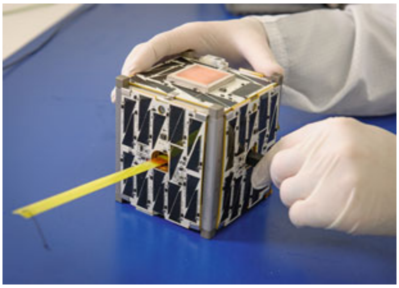


Fig. 1 PhoneSat 2.5, a CubeSat built at NASA's Ames Research Center in 2013. (Graphic Courtesy NASA. https://www.nasa.gov/content/goddard/nasas-science-mission-directorate-cubesat-initiative)

from the student projects. These concerns includes such areas reliability, frequency of failure within a month or two of launch, and rising concerns about orbit space debris and debris removal or avoidance.

2 Cube Satellite Programs

The number of cubesats that have been launched over the last 20 years has grown from a handful per year at first to a growing stream of cubesats. The cubesat assistance programs that NASA and the European Space Agency (ESA) have undertaken to encourage the launch of small satellites have certainly contributed to this increase. NASA has provided an advisory and technical review unit to help in the design of cubesats. This has aided in avoiding possible mistakes in the design of these units and to avoid the use of wiring that does not safely operate in space, as well as other common errors.

Despite the assistance provided, the success rate with cube satellites has not been particularly high. The overall success rate has been about 40% for academic programs and about 77% for commercial cubesat programs.

There are now dozens of professional training courses and seminars at various locations around the world or that are offered on-line. These courses can be taken to assist in the proper design, engineering, and manufacture of cubesats as well as to acquire expertise as to how they should be deployed in space. Such courses and the knowledge that are acquired from these courses are perhaps valuable as the assemblage of the cubesate itself. Such course can certainly be a key part of the overall learning process. There are also tutorials that are available free online such as the courses that are available from NASA known as “Cubesat 101: Basic Concepts” which is designed to impart fundamental knowledge and useful knowledge to those wishing to take on a cubsesat project.

The key elements which will likely be found in most other comparable training programs are outlined below, as they are set forth for the Teaching Science and Technology Inc. Ascend program. In this case, the program is organized into five separate short courses, as described below. Other program will tend to be consolidated into more integrated and somewhat shorter programs. Space Agencies and other institutions in some cases even provide free training programs to cover many of these elements. (See Fig. 2). (Ascend Cubesat Training 2019).

“The Ascend 5 Part Course on Cubesats

- **Solve** technical problems in orbital mechanics and space system design;
- **Describe** the inputs, processes and outputs of a space system verification and validation program including the unique requirements for environmental testing.

(continued)

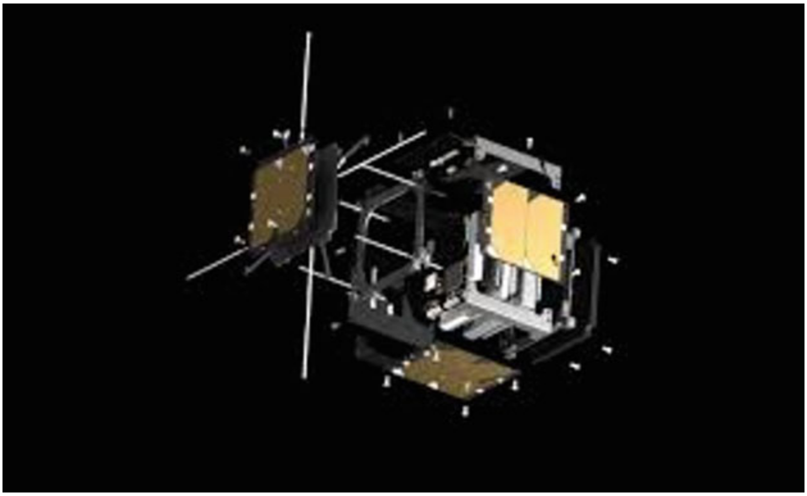


Fig. 2 A Cubesat with its deployable antenna extended. (Graphic courtesy of global commons)

- **Define** the planning, execution and support requirements for real-time space mission operations.
- **Apply** space systems engineering processes and system design principles, along with software tools to develop a conceptual design for a space mission.
- **Synthesize** all tools and techniques learned in the program during end-to-end concurrent mission design workshop. Given a real-world set of mission goals and objectives, along with a set of integrated design tools, design, develop, build, integrate and test a bench-top payload into a non-flight educational satellite system.
- **Take the next crucial step** up the space development ladder to embrace NANOBED and other tools to develop space payloads and undertake serious discussion with hardware vendors and explore launch and deployment option."
- Ascend Cubesat Training course by TSTI https://www.tsti.net/ascend/

Today, the starting point for undertaking nanosatellite projects for universities or even schools with a STEM (Science, Technology, Education, and Math) focus is much easier than a few years ago. There are many organizations that offer training programs and support obtaining or even fully integrated and designed cubesat systems. There are also websites that are available to help find specific components, structural elements, sensors, payload instruments, and so. There are omnibus websites such as "Cubesat.com" that can be very helpful. Such a website provides helpful listings of companies and their capabilities. These listings are broken down into companies that provide cubesat components, testing equipment, buses/chasses, and assistance with launch arrangements (Cubesat.com 2019).

3 Pocketqube

The small compact nature of cubesats offered a viable means for student experiments, but the cost of cubesat launches was still too expensive for many student projects, so an even smaller standard seemed to be a good idea. Thus scientists and engineers at Morehouse State University and the Kentucky Space Grant Consortium in 2009 pooled their resources to come up with the idea of a pocketqube. (See Fig. 3).

This was a 5 cm × 5 cm × 5 cm cube that would allow eight student experiments to be packaged within the volume represented by a cubesat. The name is derived from the idea that the satellite could fit in your pocket. As miniaturization of electronic components, sensors, and other components continue to shrink, the idea of a pocketqube has now come to have growing appeal, and the ability to obtain pocketqube-sized kits and components is continuing to grow as well. The first four pocketqube were launched on November 11, 2013, packaged within the so-called mothership known as Unisat-5 (The Group of Astrodynamics for the Use of Space Systems UNISAT-5 Mission 2019). Three of these were 1P units and the largest of these, known as T-Logicqube, was the size of a 2.5 P satellite. Currently there are over 20 pocketqube projects under development with P satellite projects now coming from around the world.

The idea of an even smaller than a Cubesat standard with a mass of no more than 250 g that can be provided as a kit has thus started to catch on around the world. The idea has continued to be developed and is now a powerful means to save costs and allow the experimenters to focus on the payload and experimental efficiency for student space projects. The latest launch for pocketqube missions was on a Vector-R, a small launcher using Alba Cluster 1 that occurred in 2019, and the number of launch opportunities will continue to grow (Zack et al. 2013).

One of the means that have been used to develop new information as well as support for pocketqube projects has been a series of workshops. In April 2014, NASA hosted the first of the pocketqube workshops. This consisted of a workshop at Ames Research Center in California and a session in Florida at the Kennedy Space

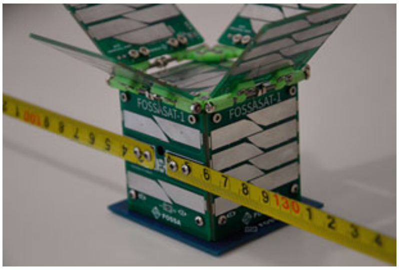


Fig. 3 FossSat-1 A Pocketqube satellite. (Graphic Courtesy of Julian Fernandez)

Center. It was not until March of 2017 that the second workshop was held at the Technical University of Delft that has evolved into an annual event to learn about the latest projects and advances in components design and the latest knowledge about launch arrangements and integration (Poxkwrqube 2019).

The number of pocketqube missions now in development is over 20 in number and will continue to grow each year. Interest in these very small launch systems will be driven forward by the development of practical information about to design, build, and launch a pocketqube continues to grow. Currently the two organizations offering the ability to provide launch integration services for pocketqubes are Alta Orbital and Gauss Srl (Pocketqube 2019).

4 Femto Satellites

The idea of small satellites for student experimentation and training has even gone beyond the limits of cubesats and pocketqube systems down to so-called femto-satellite level. This is q satellite that is in the range of 10–100 g. This diminutive satellite has an upper limit of about 4 ounces. This means that the mission must be truly limited in its scope with current technologies. At this scale, one approach is to have an experiment that is not a free flyer but is designed to carry out a test program, not as a free flyer, but simply as being in a test-bed that can fly on the International Space University (ISU) or on other space platforms deployed by China, or even private space stations such as the Bigelow Genesis or other future private space station systems. In such arrangements, the experiment, or the test results can be returned to Earth, or even more simply the experimental results might be relayed directly to the ground from the space station's telecommunications system. In this instance, an astronaut might be able to activate the experiment and take readings or otherwise assist with the experimental exercise.

Clearly, the very small size of 10–100 g for a Femtosat experimental project imposes exacting limits. Such a diminutive unit will not be able to have a payload large enough to test something such as an electronic sensor or a biological system and still have room for a large enough telecommunications capacity and antenna to relay communications back to Earth. Thus the solution is to be able to relay communications a short distance to a space station data relay system or operate within a "mothership" that can relay a signal to Earth of the test results.

5 International Cubesat and Small Sat Initiatives and University Relationships

Many beginning international satellite projects start out at universities and involve designing and building cubesat or small satellite projects that can be adapted effectively to commercial services. In some cases, the relationship with universities stems from participating in the annual small satellite conference hosted by academic institutions. These particularly include Utah State University in the United States, the annual conference at the Technical University of Delft, or international cubesat meetings such as those started in Peru. The complete records of all the papers presented at the Utah State University Program since its beginning are available online as open source documents. This database alone is a truly invaluable source of information for anyone seeking to embark on a new cubesat academic project.

In other cases, the keys are university-based technical assistance or consulting programs that provide valuable design, technical services, or key training on new satellite systems and ground systems (which are sometimes unfortunately overlooked yet are still vital).

The program that started at the University of Surrey and is now represented by the Surrey Space Technology Ltd. (SSTL) in the United Kingdom represents perhaps the best example in this category. Particularly in the 20-year period from 1995 to 2015, the University of Surrey program in small satellites helped the developing and emerging nations to expand their space programs and projects to get smallsat projects off the ground. Indeed, they provided key support to smallsat programs where local universities were able to play a key role in helping entirely new space initiatives get off the ground.

Indeed dozens of such new international small satellite projects have begun in this matter. Just some of the international cooperative programs between SSTL and small satellite projects in developing countries have included programs involving Thailand, Malaysia, Algeria, Taiwan, Korea, China, Kazakhstan, Turkey, etc. come to fruition. In some cases, Surrey engineers and scientist played a predominant role, but in other cases, the help was just in training or advising university faculty, students, and national expertise create their own capability. The following examples of Surrey Sat projects are summarized below.

6 Thailand: Thai-Paht (TMSat): Launched in1998

Thai-Paht was the first Thai microsatellite. It was a cooperative project with the Mahanikon University, which is located in Bangkok, Thailand. This small satellite was designed for multispectral Earth observation. It also used data storage and advanced onboard processing and communications to download the remote sensing data it acquired. It had a mass of 55 kg. It was launched on July 10, 1998 on a Zenit launcher from the Baikonur launch center. This small satellite project was completed with a team of 12 engineers from the University under a transfer program. Training of these engineers was accomplished in the UK at the SSTL (Surrey Space Technology Ltd 2019).

7 Malaysia: TiungSat-1: Launched in 2000

The TiungSat-1 satellite was Malaysia’s first operational satellite and it contained both operational units and technology demonstration elements. It was built under contract with Malaysia and was launched in 2000. As was typical of these developmental contracts, this arrangement also included a training provision. This allowed a team of Malaysian space engineers to operate the satellite for Earth Observation and space science experiments. It covered training on how to operate the high capacity data storage and store and forward downloading of the information at Malaysian terrestrial sites.

8 Algeria: ALSAT-1: Launched 2002

ALSAT-1 represented Algeria's first national satellite that was a free flyer satellite, although it leased capacity for domestic telecommunications and video services from Intelsat many decades previously. This experimental satellite was designed and constructed in collaboration with the Algerian Centre National des Techniques Spatiales (CNTS).

ALSAT-1 was designed to carry out Earth observation data collection. The ALSAT-2 experimental satellite provided moderate levels of resolution. Its imaging cameras only provided 32-meters resolution, but operated across three spectral bands, namely, green, red, and near Infra-red. This was one of first satellites to be activated to participate in the Disaster Monitoring Constellation.

9 Turkey: BILSAT-1: Launched in 2003

This satellite, known as BILSAT-1, represented the first Turkish Scientific Earth Observation satellite. This satellite contained a number of advanced features. This included, GPS assisted navigation and an experimental package to multiband remote sensing. This was a cooperative program between TUBITAK-BILTEN and the Surrey Space Technology Ltd. Team. It also included onboard propulsion, an advanced Control Moment Gryoscope, and high precision solid-state data recorders and star trackers. Its remote sensing payload included five cameras that operated in the near-infrared, red, green, and blue bands plus one panchromatic (i.e., black and white) camera.

10 Nigeria: NigeriaSat-1: Launched in 2003

This 100 kg experimental minisat was built for the Nigeria Space Research & Development Agency. It was able to provide 32 m multispectral imaging across a 600 km wide coverage path which allowed frequent updating on a global basis. It had a special capability to provide a read-out known as a Normalized Differential Vegetative Index (NDVI). This feature allowed a rapid alert with regard to possible environmental blights. This capability and other images were unexpectedly used to produce the very first Earth observation satellite images of the Hurricane Katrina disaster in New Orleans. This was discontinued in service in 2012 after 8 years of service.

11 China: Beijing-1: Launched in 2005

Beijing-1 was an improved Earth Observation (EO) satellite with one of two cameras having a much higher resolution imaging capability. This spacecraft thus carried two digital imaging payloads. One was the 4 m black and white quite high resolution imaging camera for a small satellite, while the color imaging camera had a 32 m resolution camera that tracked a 600 km wide path. Support was provided for the platform and the sensors for this project.

Beijing-1 was able to provide rapid updates on Chinese issues such as water resources, agricultural yields, urban growth patterns, environment pollution, and disaster monitoring throughout China. This new capability was also used to generate new digital maps of China as a whole and precision maps of cities and urban areas.

12 NigeriaSat-2: Launched 2011

This was the second small satellite that SSTL collaborated with Nigeria on in terms of design, manufacture, and deployment. The NigeriaSat-2 Earth, like NigeriaSat-1 is an Earth observation satellite that is based on the standardized Surrey Space Technology Ltd.'s SSTL-300 platform. The satellite gathers data that is utilized by both the Nigerian National Space Research and Development Agency (NASRDA) and the Disaster Monitoring Constellation. This satellite carries a 2.5 m resolution digital camera for black and white imaging and a 5 m resolution camera for multispectral imaging. This satellite records images that follow imaging swaths that are 24 km in width (See Fig. 4).

13 Kazakhstan: KazEOSat-2: Launched in 2014

Kazakhstan decided to collaborate with Surrey Space Technology limited on its KazEOSat-2 satellite. This spacecraft is designed to deliver medium resolution images with a 6.5 m GSD and a 77 km swath. Under the contract SSTL also provided 6 months hands-on training for 19 customer engineers and Managers. KazEOSAT-2 medium resolution imagery is utilized for mapping, agricultural monitoring, and resource management.

14 Formosat-7 Launched in 2019

In this cooperative program with Taiwan, SSTL has supplied six satellite platforms. As part of the formosat-7/Cosmic-2 program, these satellites are used for meteorological and ionosphere readings and observations and also part of a climate change investigation. This system is intended to replace the current Formosat-7 cosmic 2 constellation. SSTL has supplied 6 spacecraft platforms for the FORMOSAT-7/

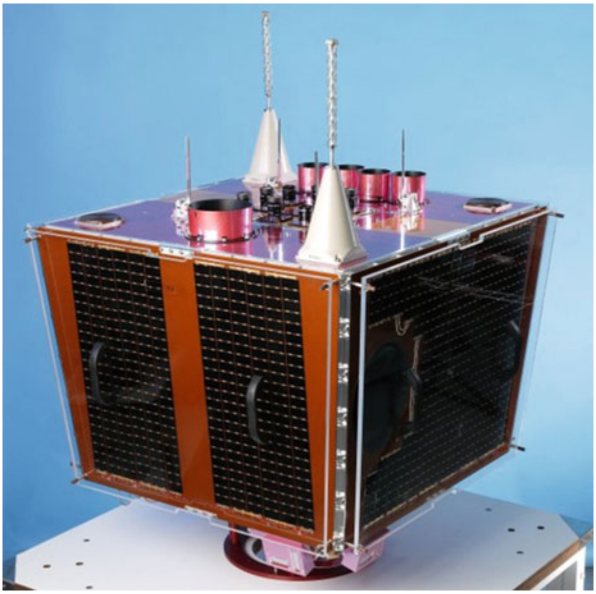


Fig. 4 NigeriaSat-2 Small Satellite for Higher Resolution imaging. (Graphics courtesy of surrey space technology center)

COSMIC-2 Program. This was less of a developmental and shared learning project and more of an equipment supply transaction.

15 NigeriaSat-X: Launched 2011

The NigeriaSat-X Earth observation satellite provides the Nigerian National Space Research and Development Agency (NASRDA) and the Disaster Monitoring Constellation with 22 m imaging capability. The spacecraft delivers 22 m GSD across a 600 km swath width.

NigeriaSat-X was used as a Training Model spacecraft for the team of Nigerian engineers who participated in SSTL's training and development program. Over a period of 18 months, the Nigerian engineers were based at SSTL in the UK and were involved in the design, manufacture, and test phases of the NigeriaSat-X spacecraft in a controlled real project, real engineering environment. After launch, NigeriaSat-X was commissioned in orbit by the Nigerian engineers.

Today there are such opportunities for exchanges between and among universities about advances in the design and building of cubesat project such as at the International Conference on Cubesat Technology. This conference held in Peru in October 2018. At these sessions, there were presentations on cubesat initiatives that were being undertaken by the Universidad Catolica San Pablo, Arequiba, Peru, by INPE of Brazil, and universities and national space initiatives from all over South America, as well as from Japan, Canada, the USA, and Mexico (International Conference on Cubesat Technology 2018).

One example is the Chasqui 1 cube satellite project of Peru. This 1 kg cubesatellite is designed to take visible and infrared images of Earth. It was notable for its unusual launch when it was tossed into space by a Russian cosmonaut during a spacewalk from the International Space Station (ISS) (Kramer 2014).

Peru then quickly moved forward from this modest cubesat project to a high-definition remote sensing satellite known as PeruSat-1. This was procured from the Airbus, and built in their new "Projects Factory" that is designed to produce satellites more quickly and at reduced cost using the latest manufacturing techniques. In this case, Peru purchased not only the spacecraft, which was manufactured in 2 years, but also obtained ground equipment and training in the analysis of the remote sensing data that PeruSat-1 will produce (PeruSat-1 by AirBus 2019). (See Fig. 5).

This rapid transition from the Casqui-1 cubesat project launched by a cosmonaut tossing it into orbit from outside the ISS to the 2016 launch of the minisat PeruSat-1 that has hundreds times more massive was a large leap forward by Peru's space program. This project also involved extensive training and the creation of a sophisticated ground receiving station and development of a processing team to analyze the remote sensing data. These large steps forwards were accomplished through contracted services from Airbus. A part of the reason that this rapid progress was possible was the small satellite revolution that has helped to manufacture small satellites, from cubesats, microsats, and even minisatellites in the 100–1000 kg class much more rapidly and with greatly reduced cost.

Another key source of support is the many organizations that help to sponsor student smallsat projects. Sometimes these are only very small experiments that can be entirely on the International Space Station and sometimes these can be as large as cubesat projects. Some of these programs are sponsored by Arthur C. Clarke Institute for Space Sciences Education (Arthur 2019), IGOSat (2019), and

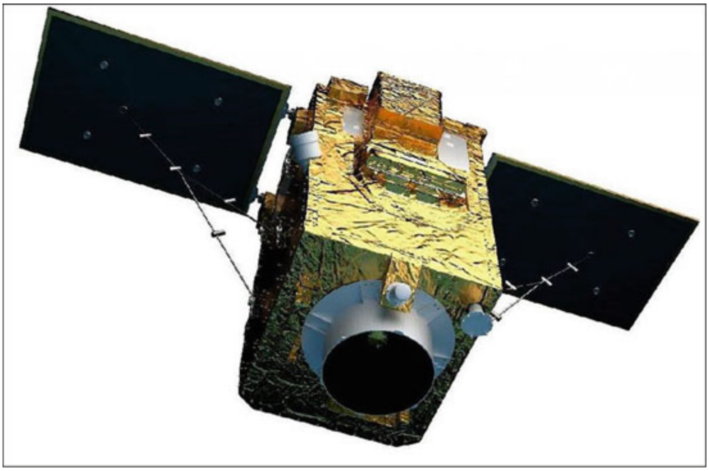


Fig. 5 The PeruSat-1 satellite for high-definition remote sensing. (Graphic courtesy of Airbus)

PolyOrbite (2019). These are only some examples. There are many others that can be located by on-line searches.

16 Concerns Related to Reliability

The reliability of cubesats and other types of small satellites is a particular area of concern. The experience to date has actually been problematic. Up through 2017, the reliability statistics (i.e., successful operation of satellite for at least 2 months) of academic small satellites has only been about 40%, and even with commercial small satellites, the reliability of operation has only been a 77%. Although these success rates are low, it can be argued that these results are still acceptable in terms of the cost efficiency of such projects when compared to larger satellites. Nevertheless, there needs to be a concerted effort to understand why the failure rate is so high and to seek ways to improve the reliability of small satellites and particularly academic and student projects which are quite low. The failure of satellites, however, must be seen not only in an economic sense but in an environmental sense as well. The implications of too many satellites left in orbit and thereby posing a risk of a major collision that proliferates orbit debris is a key concern that increases as more and more small satellites are deployed.

17 Concerns Related to Orbital Debris

The launch of small satellites of all types continues to rise. With it has come the fear of runaway orbital debris. For years it seemed that one could responsibly ignore the possibility of the orbital debris problem and note that natural hazards from small meteors and space dust far outnumbered man-made debris. In the 1970s and 1980s, few thought there was a little possibility that the orbital debris problem could spiral out of control. In particular, the forecast of a Carrington Syndrome, i.e., a runaway avalanche of space debris created by humans, was not taken very seriously. Yet today, there is a real possibility that the buildup of 22,000 trackable space debris objects and 500,000 debris elements in millimeter range could continue to multiply in the next decade. There is real concern that more and more collisions will occur as more satellites are deployed in orbit – for commercial, governmental, military, scientific discovery, technology verification, and academic experimentation. Recent studies carried out by the Aerospace Corporation of the problem of deploying and deorbiting satellites from large constellations without risking collisions underscore these concerns.

Certainly cubesats, picosats, and femtosats built for experimental purposes are not the main problem. Nevertheless they do contribute to the overall buildup of small debris, and they are a very visible and new component of space. The hundreds of small satellite projects undertaken by students for tests, demonstrations, and experimental purposes that are launched into orbits above 300 km take a long time to naturally decay and return to Earth. If student-based satellites had some form of system to aid deorbit such as a passive system that would inflate to create drag or an active thruster system to help reentry into the Earth's atmosphere this would help, but would also be difficult given the size, weight, and cost constraints of small academic space projects. Further, consolidated systems that might fly a number of student systems aboard a mothership and then actively deorbit on a controlled basis this would also help to alleviate the space debris problem.

A new international guideline would be beneficial. This might be in the form of guidance that would specify that student projects, especially those without active space deorbit control systems, should be launched into orbits below 300 km, or perhaps even better be limited to below 250 km. Such an orbital altitude limit would be a clear step forward to help ensure that student small satellite tests, demonstrations, or experimental investigations would not contribute to the overall space debris problem.

This restriction would limit the use of the International Space Station (ISS) to dispense student cubesats for experimental, demonstration, and technology verification, unless there were some special orbital launch system devised that would create an orbit that had an apogee at the ISS and a perigee at perhaps 200 km or even lower.

18 Conclusion

The development of the cubesat standard represented a breakthrough in the ability of students to participate directly in the process of designing, texting, building, integrating, and launching of spacecraft into orbit. This process has had many unexpected benefits. It has turned out to be an excellent training tool for young engineers who wanted to enter the field of aerospace and space manufacturing and design. It has been a useful tool for entrepreneurial students who have funded cubesat experimental projects via Kickstarter and crowd sourced funding mechanisms and then went on to use successful demonstrator small satellite projects to move to venture capital funding and startup of new commercial space businesses. This was the case for the startup of the Planet Labs effort – now simply known as Planet. It was also the case for Spire that used its cubesat experimental test and demonstration project as a means to get financing for its now operational Spire systems that is now backed by a billion dollar contract from ESA for environmental data.

Perhaps the most profound aspect of student developed cubesatellite projects has been its contribution to what is now commonly known as "NewSpace" or "Space 2.0." The various university-based cubesat initiatives have helped to show how more can be done with less. Some of the most successful new commercial satellite constellations, such as the Planet and Spire 3-unit cubesat constellations mentioned above. Both of these commercial ventures grew out of student initiatives and proof-of-concept student projects. Thus, the cubesat initiative that started as a teaching and learning experience has shown more ambitious results. There is solid evidence that student and university-based activities centered around cubesat projects have helped to create successful new satellite ventures that have embraced the new and highly innovative design techniques and concepts at the heart of cubesat projects.

This is actually in some ways history repeating itself. The first small satellite activities dating back three decades ago came from Surrey University in the United Kingdom that designed the first Surrey Sats. Today Surrey Space Technology Limited (SSTL), now owned by Airbus is a key designer and producer of small satellites that range from cubesats up to minisats. The Oscar satellites for amateur radio were built by volunteers from industry and academia. Today, countries seeking design, build and launch their first satellites often start with cubesat projects and turn to organizations such as SSTL, still located on the Campus of the University of Surrey or to Utah State University that host the annual Small Satellite Conference for assistance.

The European Space Agency has characterized student-based cubesat initiatives in the following way: “CubeSats offer students a true hands-on experience in designing, developing, testing, and operating a real spacecraft system and its ground segment. Lately, CubeSats have also started to show an increasing potential for commercial use, and are recognized as one of the current top trends in space activities” (Fly Your Satellite Programme: Cubesats and Education 2019).

Thus there are new ways of design, manufacturing, testing, and deploying commercial application satellites and satellites for governmental military or other programs that have benefitted from new ways of thinking about what a small or smaller satellite might be able to do as well as its size, functionality, and overall design.

19 Cross-References

- ▶ Scientific Discovery and Geomagnetic Monitoring in Earth Orbit using Small Satellite Systems
- ▶ Small Satellites and Hosted Payloads for Technology Verification

References

C. Arthur, Clarke Institute for Space Science Education.

Ascend Cubesat Training course by TSTI, https://www.tsti.net/ascend/. Last accessed 18 July 2019

Cubesat.com. http://www.cubesat.org/descriptions. Last accessed 15 July 2019

Fly Your Satellite Programme: Cubesats and Education. https://m.esa.int/Education/CubeSats_and_Education_the_Fly_Your_Satellite!_programme. Last accessed 15 July 2019. https://www.nasa.gov/content/goddard/nasas-science-mission-directorate-cubesat-initiative

IGOSat. http://igosat.in2p3.fr/en/news/. Last accessed 19 Aug 2019

International Conference on Cubesat Technology, Arequipa, Peru, 23–27 Oct 2018. http://ucsp.edu.pe/ic2t/EN/

M. Kramer, Spacewalking cosmonaut tosses tiny satellite into orbit for Peru” Space.com, 18 Aug 2014. https://www.space.com/26841-spacewalking-cosmonaut-launches-peru-satellite-video.html

PeruSat-1 by AirBus. https://directory.eoportal.org/web/eoportal/satellite-missions/p/perusat-1. Last accessed 18 July 2019

Pocketqube. https://en.wikipedia.org/wiki/PocketQube/www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf. Last accessed 15 July 2019

PolyOrbite. https://polyorbite.ca/. Last accessed 15 July 2019

Poxkwrqube. https://en.wikipedia.org/wiki/PocketQube. Last accessed 18 July 2019

Surrey Space Technology Ltd, Launched Missions https://www.sstl.co.uk/space-portfolio/launched-missions. Last accessed 16 July 2019

The Group of Astrodynamics for the Use of Space Systems UNISAT-5 Mission. https://www.gaussteam.com/satellites/gauss-latest-satellites/unisat-5/. Accessed 15 July 2019

K. Zack, J. Garrett Jernigan, L. Cominsky, The development of a 3P PocketQube. Bull. Am. Phys. Soc. **58** (2013) 21

Scientific Discovery and Geomagnetic Monitoring in Earth Orbit Using Small Satellite Systems

James Green, David Draper, Helen Grant, and Jonathan Rall

Contents

Abstract

The field of SmallSats and CubeSats is evolving very rapidly, making this short review of how they are used in geomagnetic monitoring only a snapshot in time. The desire for shorter development times, lower launch costs, and the opportunity to provide a teaching, hands-on environment will keep the momentum for this type of platform going well into the future. It is important to note that SmallSats and CubeSats cannot address all important science objectives and are not a low cost substitute for every application, such as needing large apertures, but where they can produce major results is in simple well focused science, requirements of multipoint observations, or in short duration missions that can be executed under low cost constraints. In particular, these missions are generally within the mass constraints of 1.33 kg per CubeSat unit, e.g., a 3U CubeSat could have a mass of up to 4 kg, up to a maximum of 180 kg for a SmallSat. Despite their smaller mass,

J. Green (✉) · D. Draper · H. Grant · J. Rall
NASA Headquarters, Washington, DC, USA
e-mail: james.green@nasa.gov; david.draper@nasa.gov; helen.grant@nasa.gov; jonathan.rall@nasa.gov

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_35

volumen, and launch costs they are able to achieve significant scientific results. The quality of experimental space missions is not measured in how large the satellites are but rather the quality of the derived data and their significant contributions to scientific knowledge. This overview will not be a comprehensive list of geomagnetic monitoring missions, also called heliophysics missions, but will discuss a representative set in various development and operational phases.

Keywords

SmallSats · CubeSats · Multipoint Observations · Heliophysics · Magnetic fields · Plasma measurements · Polar orbit · Sun-synchronous orbit

1 Introduction

In the early days of space exploration, satellites were restricted by the technology and launch vehicle capabilities of the time. The first artificial satellite, Sputnik, launched by the former Soviet Union on 4 October 1957, was 58 cm in diameter and weighed only 83.6 kg (NASA 2019a). Soon after Sputnik, Dr. James Van Allen of the University of Iowa provided a cosmic ray detector as the only science instrument for the first satellite launched by the United States, called Explorer 1. This mission was launched 31 January 1958. The cosmic ray detector was designed to investigate the flux of these high energy particles with altitude but it also measured the particles trapped in Earth's magnetic field, later named the Van Allen belts. Explorer 1 weighed 14 kg and was operational until 23 May 1958 (NASA 2019b).

Explorer 1 ushered in a multidecade era of small satellites that made significant contributions to space sciences. As technology and launch vehicle payload capacity improved, the research community exploited this capability, building ever larger and more capable satellites until they became the norm. Large scientific spacecraft such as the Hubble Space Telescope (HST) and James Webb Space Telescope (JWST) take advantage of this increased capacity to develop large, complex spacecraft with more sophisticated instrumentation. In the case of HST, the life of the mission could be extended by upgrades and maintenance performed by visiting astronauts. This trend continues even today.

NASA science is strategically defined by a set of fundamental science questions and associated missions that are delineated in National Academy of Sciences (NAS) reports that are referred to as "decadal surveys" since they are issued in each science discipline that NASA supports (Earth Science, Heliophysics, Planetary Science, Astrophysics, and Life Science & Microgravity) once per decade. Over time, decadal missions involved an ever increasing difficulty in making critical measurements that continued to lead to larger and larger missions.

In recent years, however, advances in miniaturization and a desire to develop lower cost missions have led to an increase in interest in smaller spacecraft. Initially used as technology demonstration missions or as an avenue to provide students hands on experience in designing and building spacecraft, the small satellite also holds promise as a full-fledged research platform. Simply stated, these new types of smaller missions leveraging new technologies began to show characteristics of disruptive innovations that needed to be further studied (e.g., Shkolnik 2018; Mercer 2019). As a result, NASA and the National Science Foundation asked the NAS to establish an ad hoc committee to examine the potential use of CubeSats to obtain high priority decadal level science. The result was the report, *Achieving Science with CubeSats* (NAS 2016).

In just a few short years, SmallSats and CubeSats have become a mainstream activity for a number of Space Agencies and are showing up in NAS decadal reports. Fig. 1 is an overview of the NASA SmallSat and CubeSat missions that are currently operating, under development, or in formulation. Not shown are the extensive number of missions that are currently under study. The missions in Fig. 1 span the areas of technology development, Earth science, Heliophysics, Planetary Science, and Astrophysics with the future missions shown in bold.

Currently, NASA has multiple activities designed to support the use of small satellites that demonstrate a benefit to NASA's missions. Since access to space is a critical concern, the CubeSat Launch Initiative is designed to connect NASA supported CubeSat developers, as well as educational institutions and nonprofit organizations with launch providers (NASA 2019c). In addition, NASA's Space Technology Mission Directorate (STMD) sponsors the Small Spacecraft Technology Program to identify technologies and use SmallSats as a flight test and demonstration platform (NASA 2019d). NASA also sponsors the Small Spacecraft Systems Virtual Institute (S3VI) that provides information useful to small satellite developers

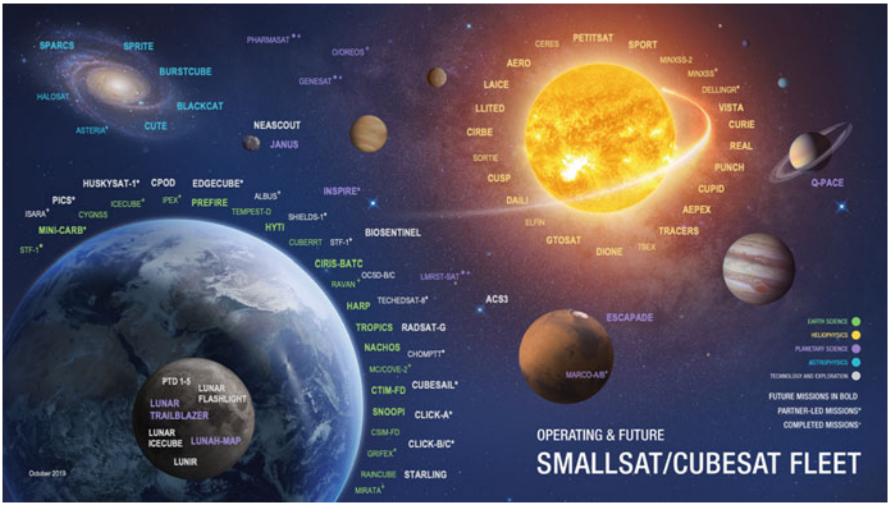


Fig 1 All operating and future SmallSat and CubeSat missions covering Earth and space science as well as technology demonstrations

including design tools and information about upcoming NASA solicitations (NASA 2019e).

2 NASA Smallsats and CubeSats: A Snapshot in Time

Briefly described here, the growing fleet of NASA-sponsored SmallSats and CubeSats intended to study the Sun and Earth's magnetosphere. Although some of these missions are intended primarily to demonstrate technologies for later use, all of them include significant contributions to advancing knowledge in Heliophysics. Table 1 summarizes the missions described here in four subsections: those in preformulation (i.e., pre-Phase A), those selected for flight and in formulation (Phase A), those selected for flight and in design or production (Phases B through D), and those currently operating (Phase E).

2.1 Selected Missions in Preformulation

These are concept studies awarded by NASA to principal investigator (PI) led mission teams. Concept studies are typically for approximately 1 year of work to develop the mission concept in such a way that it would be competitive in an eventual call for flight proposals. Concept study selection does not assure selection for flight. The preformulation concept studies were awarded in the 2018–2019 timeframe.

2.1.1 Aeronomy at Earth: Tools for Heliophysics Exploration and Research (AETHER)

The AETHER concept proposes to characterize how geomagnetic storms affect the ionosphere-thermosphere system using instrumentation aboard the International Space Station. These observations would be complemented by ground-based data on electrons in the same region. AETHER would constrain complex processes of space weather by measuring interactions between charged particles in the ionosphere and the neutral, terrestrial-weather-driven thermosphere. AETHER would launch no later than 2024; the lead institution is the University of New Hampshire in Durham, NH.

2.1.2 COronal Spectrographic Imager in the Extreme ultraviolet (COSIE)

The COSIE concept would mount a solar-observing instrument onto the International Space Station to acquire wide field images of the corona and full Sun spectral images with high sensitivity and rapid cadence. These data would constrain the global field topology and track coronal mass ejections from the disk through the inner heliosphere and contribute to space weather. These constraints would in turn allow determination of the magnetic connectivity between the lower and outer corona where the transition between open and closed magnetic fields occur. In this

Table 1 Summary of NASA-sponsored heliophysics smallsats

Mission name	Host institution(s)	Anticipated launch date	Science objectives
In pre-formulation (pre-Phase A)			
AETHER	University of New Hampshire	NLT 2024	Measurements of how the thermosphere interacts with the ionosphere's charged particles
COSIE	Smithsonian Astrophysical Observatory	tbd	Constrain the global field topology, track coronal mass ejections from the disk through the inner heliosphere
CURIE	University of California Berkeley	tbd	To study radio burst emissions from solar eruptive events in the inner heliosphere
EUVST	Naval Research Lab	NLT 2025	Measure interplay between solar plasma and geomagnetic fields
EZIE	Johns Hopkins University Applied Physics Laboratory	NLT 2024	Measurements of auroral electrojet
MEME-X	NASA GSFC	tbd	Measuring atmosphere mass flux and loss through the upper atmosphere to space
SETH	NASA GSFC	tbd	Energetic neutral atom detections of signatures of major solar eruptions
Solar Cruiser	NASA MSFC	tbd	Simultaneous measurements of magnetic field structure and velocity of CMEs; tech demo for solar sail
In formulation (Phase A)			
AERO	Massachusetts Institute of Technology Haystack	2022	Test a novel "Vector Sensor" radio capable of sampling low radio frequencies from orbit in the Earth's auroral zones
AWE	Utah State University, NASA GSFC	Aug 2022	To investigate how atmospheric gravity waves impact transport of energy and momentum into space
CIRBE	University of Colorado LASP	2021	To study the formation, source, intensity, and dynamic variations of inner Van Allen radiation belt electrons
CuPID	Boston University	2020	Miniaturized X-ray camera to study Earth's magnetic cusps via solar-wind soft X-rays
GLIDE	University of Illinois Urbana-Champaign	Oct 2024	Lyman-alpha measurements and images of geocorona from outside the exosphere
MUSE	Lockheed Martin	2022	Measurements of mechanisms of energy release in the corona and the dynamics of the solar atmosphere
REAL	Dartmouth University	2021	To characterize physical mechanisms that scatter radiation belt electrons into the atmosphere

(continued)

Table 1 (continued)

Mission name	Host institution(s)	Anticipated launch date	Science objectives
SunRISE	University of Michigan	tbd	Synthetic aperture radio telescope to assess how solar energetic particles are accelerated and released into interplanetary space
THOR-US	University of New Hampshire	NET 2025	US contributions to European Space Agency's Turbulence Heating ObserveR M-class candidate mission
TRACERS	University of Iowa	NLT Aug 2022	To study global variability in magnetopause reconnection with targeted set of new and unique in situ measurements
VISTA	Massachusetts Institute of Technology Haystack	2022	To operate with AERO, yielding vector interferometry to study wave emissions in the Earth's auroral zone
In design or production (Phases B-D)			
B: DAILI	Aerospace Corporation	2021	To provide density and compositional data for atmospheric models used in calculating precise orbits and understanding propagation of radio signals
B: GTOSat	NASA GSFC	2021	To detect very high energy particles for understanding acceleration and loss of relativistic electrons in Earth's outer radiation belt
B: LLITED	Aerospace Corporation	2021	To investigate equatorial temperature, wind, and ionization anomalies in the neutral atmosphere or in the region containing charged particles
B: PetitSat	NASA GSFC	2021	To study density irregularities in mid-/low-latitude ionospheric plasma to better understand irregularities in long-distance radio communication
B: PUNCH	Southwest Research Institute	NLT Aug 2022	To study how coronal structures fuel ambient solar wind with mass and energy, and dynamic evolution of transient solar wind structures
C: CuSP	Southwest Research Institute, NASA GSFC	tbd	To serve as a "space weather station" to measure particles and magnetic fields in space
C: SPORT	Instituto Tecnológico de Aeronáutica (Brazil), NASA MSFC	2020	To observe scintillation structures and plasma bubbles in order to predict their behavior and assess ways to mitigate their effects
D: LAICE	University of Illinois Urbana-Champaign	2019	To make in situ measurements of wave perturbations in the ionosphere and remote sensing of the middle atmosphere

(continued)

Table 1 (continued)

Mission name	Host institution(s)	Anticipated launch date	Science objectives
Operational or closed out (Phases E-F)			
ASTERIA (Astro IR&D tech demo)	Massachusetts Institute of Technology, NASA JPL	Nov 2017	Precision photometry to study stellar activity, transiting exoplanets, and other astrophysical phenomena
CeREs	NASA Science Mission Directorate	Dec 2018	Measuring how electrons are energized and how are they lost from the Earth's radiation belts, and how solar flare electrons are energized
Dellingr (Helio IR&D tech demo)	NASA GSFC	Aug 2017	Measure magnetic fluctuations and molecular changes in upper atmosphere to determine baseline conditions and observe space weather impacts
ELFIN	University of California Los Angeles	Sep 2018	Measure the angle and energy distribution of precipitating relativistic electrons within and near the loss cone
E-TBEx	NASA GSFC	Jun 2019	Explore bubbles in the electrically charged layers of Earth's upper atmosphere, which can disrupt key communications and GPS signals
FOXSI-3	NASA GSFC	Sep 2018	Hard X-ray telescope to detect hot plasma and energetic electrons near energy release sites in solar corona
MinXSS-2	Colorado University LASP	Dec 2018	Measurement of soft X-ray flare energetics over the solar cycle
SORTIE	ASTRA LLC, University of New Mexico, COSMIAC	May 2018	SORTIE measures wave perturbations, electric fields, and observations of the irregularities in plasma density which result from instability growth
SWARM	European Space Agency	Nov 2013	Most precise and highest-resolution measurements of Earth's vector magnetic field

GSFC Goddard Space Flight Center, *JPL* Jet Propulsion Laboratory, *MSFC* Marshall Space Flight Center

way, COSIE would provide a "missing link" between the physics of the low corona and that of the heliosphere. COSIE is hosted at the Smithsonian Institution/ Smithsonian Astrophysical Observatory in Cambridge, Massachusetts.

2.1.3 Cubesat Radio Interferometry Experiment (CURIE)

The CURIE concept is a pathfinder for developing future low-frequency (0.1–40 MHz) interferometry observatories. It would fly a pair of CubeSats in low Earth orbit separated by a distance between 1 and 3 km. The CubeSats would be launched in a 6 U configuration and separate on orbit to two 3 U satellites. The primary science objective is to make radio interferomic observations of radio bursts that arise from coronal mass ejections (so-called Type II bursts) and from solar flares (Type III bursts). Secondary objectives achievable with the same dataset include in situ measurements of temperature and electron density in the ionosphere and producing a map of the "radio sky" at frequencies below which ground-based observations are not possible (the ionospheric cutoff). Only space-based measurements can accomplish these goals. CURIE would set the stage for additional CubeSats added to the array to enable better characterization of transient events and even to place them in cis-lunar space to make observations from the lunar farside on the early universe's epoch of re-ionization. CURIE would be operated at the Space Science Laboratory at the University of California in Berkeley, California.

2.1.4 Extreme Ultraviolet High-Throughput Spectroscopic Telescope (EUVST)

The primary goal of the EUVST concept is to make the first simultaneous observations of interactions between magnetic fields and solar plasma to understand how these interactions drive solar activity and eruptions, such as solar flares and coronal mass ejections. These observations would constrain how the two systems affect solar atmospheric dynamics. EUVST is conceived to launch with the Japan Aerospace Exploration Agency's Solar-C mission, planned for 2025. The lead institution for EUVST is the US Naval Research Laboratory in Washington, D.C.

2.1.5 Electrojet Zeeman Imaging Explorer (EZIE)

The EZIE concept would study an electric current known as the auroral electrojet, which traverses Earth's polar atmosphere at ~60–90 miles elevation and can cause disruptive geomagnetic storms. The concept is for three SmallSats to measure magnetic fields and observe electrojet structure and evolution, with a view toward ultimately deriving predictive models for these types of storms. EZIE would launch no later than 2024. The lead institution for EZIE is the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland.

2.1.6 Mechanisms of Energetic Mass Ejection – eXplorer (MEME-X)

MEME-X would constrain the physical processes that control mass flux to space through Earth's upper atmosphere. MEME-X data will improve (in a potentially far-reaching way) understanding of how planetary atmosphere loss operates both from solar and local influences. The host institution for MEME-X is NASA's Goddard Space Flight Center in Greenbelt, Maryland, and the team includes members from NASA Marshall Spaceflight Center in Huntsville, Alabama.

2.1.7 Science-Enabling Technologies for Heliophysics (SETH)

SETH is primarily a technology demonstration concept for two enabling technologies. The first is less-complex small- and CubeSat optical communications hardware that could yield major increases in data rates, while reducing the burden on NASA's Deep Space Network. This type of advance has obvious applications to enabling future refinements for smallsats (including fleets of satellites operating in tandem) requiring communications at high data rates. The second is technology to detect energetic neutral atoms in the solar wind along with other solar particles and waves. This improvement would be useful for generating early warning of potential threats to astronauts from energetic solar events. SETH, along with the Solar Cruiser concept (see below), is a candidate to fly as a secondary payload on NASA's Interstellar Mapping and Acceleration Probe, currently slated to launch in October 2024. Only one of these two missions will be included as secondary payload after concept studies are complete. The lead institution for SETH is NASA's Goddard Space Flight Center in Greenbelt, Maryland.

2.1.8 Solar Cruiser

The Solar Cruiser concept would also demonstrate two technologies. The first is a "solar sail," a more than 1670-m^2 sail, in the spacecraft's polar orbit around the Sun. If successful, it would enable the use of solar radiation as a propulsion system. The second is a coronagraph that would acquire simultaneous measurements of the structure of the Sun's magnetic field and the velocity of coronal mass ejections, which are potentially harmful to terrestrial electronic infrastructure. As in the case for SETH, it would improve the ability to provide advance warning of potential solar disturbances before their effects arrive at Earth. Solar Cruiser, along with the SETH concept (see above), is a candidate to fly as a secondary payload on NASA's Interstellar Mapping and Acceleration Probe, currently slated to launch in October 2024. Only one of these two missions will be included as secondary payload after concept studies are complete. Solar Cruiser's host institution is NASA's Marshall Space Flight Center in Huntsville, Alabama.

2.2 Selected Missions in Formulation (Phase A)

These missions have been at least provisionally selected for flight and are currently in formulation. Phase A studies are typically for approximately 1 year, and after review a key decision point will determine whether each mission concept advances to later development Phases for design and fabrication.

2.2.1 Auroral Emissions Radio Observer (AERO)

AERO is a one-year 3 U CubeSat mission that will determine if auroral kilometric radio emissions extend into the lower atmosphere. Scheduled for launch in 2022, it will test a novel "Vector Sensor" radio capable of sampling low radio frequencies from a polar orbit in the Earth's auroral zones above the ionospheric peak. The CubeSat will measure the direction of arrival of auroral radio emissions, making it capable of imaging their source regions. It will also have auxiliary sensors including a magnetometer and optical aurora sensor. These activities will address fundamental questions about nonthermal emission mechanisms and the structure of the ionosphere. The host institution for AERO is the Haystack Observatory of the Massachusetts Institute of Technology, with partnerships including MIT's Lincoln Laboratory, Morehead State University, Dartmouth University, and Merrimack College.

2.2.2 Atmospheric Waves Experiment (AWE)

The AWE concept would deploy a high-resolution infrared imager on the International Space Station to make measurements of temperatures using the 87-km altitude OH nightglow emission. These data would then be used to resolve gravity waves on a nearly global scale in terms of momentum and energy fluxes. These data will be modeled at high-resolution to assess the interplay of controlling factors in causing gravity-wave spatial and temporal variability. AWE is hosted at the Utah State University Research Foundation in Logan, Utah.

2.2.3 CubeSat: Inner Radiation Belt Experiment (CIRBE)

CIRBE's primary objective is to constrain the formation and decay of inner belt electrons ($>$100 keV to $>$ 1 MeV) and to determine the intensity and dynamic variations of these electrons. The mission will use a miniaturized version of an instrument that flew on NASA's Van Allen Probes, on a CubeSat in a steeply inclined low-Earth orbit. Even heavily shielded instruments on the Van Allen Probes have suffered degradation from the penetration of highly energetic protons. To make these determinations on inner belt electrons, particularly those with energy close to 1 MeV and higher, low-Earth orbital measurements with more refined energy resolution are needed. The orbital inclination allows the avoidance of trapped highly energetic protons, which are detectable only when the spacecraft goes through the South Atlantic Anomaly region. The host institution for CIRBE is the University of Colorado at Boulder, CO.

2.2.4 Cusp Plasma Imaging Detector (CuPID)

The CuPID Cubesat Observatory is a 6 U design intended to test competing models of solar wind-magnetosphere coupling. CuPID will carry a first-of-its-kind wide field-of-view soft X-ray telescope that will measure soft X-rays emitted during charge-exchange when solar-wind plasma collides with neutral atoms in Earth's atmosphere. The primary observations will be spatial and temporal patterns of X-ray images collected by the telescope. The project is a collaboration between Boston University, Drexel University, NASA Goddard Space Flight Center, Johns Hopkins University, Merrimack College, Adcole Maryland Aerospace, Aerospace Corporation, and the University of Alaska, Fairbanks.

2.2.5 Global Lyman-alpha Imagers of the Dynamic Exosphere (GLIDE)

The GLIDE mission would track, on a global scale, far ultraviolet light emitted from hydrogen as a constraint on the uppermost region of Earth's atmosphere. Only a few such observations have been made from outside the atmosphere previously. Exospheric responses to solar and terrestrial influences can interfere with radio communications in space, and these results should help lessen (or mitigate) these impacts. GLIDE is run out of the University of Illinois, Champaign-Urbana, IL.

2.2.6 Multislit Solar Explorer (MUSE)

MUSE would improve high resolution extreme ultraviolet (EUV) imaging and spectroscopy of the solar corona. It features a multislit EUV spectrograph combined with an imager. MUSE would yield detailed measurements, at far better resolution than those made previously, of the dynamics of the corona and transition region. These dynamics are integral to the heating the solar corona, driving solar wind, and energetic eruptions. The MUSE data will be treated using state of the art numerical modeling. The MUSE team is led by Lockheed Martin's Solar and Astrophysics Laboratory, Palo Alto, CA, with contributions from the Smithsonian Astrophysical Observatory, Michigan State University, the University of California Berkeley, the Norwegian Institute for Theoretical Astrophysics (Oslo), and NASA Goddard and Marshall Spaceflight Centers.

2.2.7 Relativistic Electron Atmospheric Loss (REAL)

REAL aims to improve understanding of the physical mechanisms that scatter radiation belt electrons into the atmosphere by addressing three main science questions. When and where do diffusion, strong diffusion, and nonlinear scattering precipitation loss modes occur? How do these loss modes depend on energy? What are the relative contributions of these loss modes on electron scattering in the radiation belts? The REAL mission will use a 3 U CubeSat in low-Earth orbit to characterize the different loss modes via high time resolution measurements of the electron pitch angle and energy distributions over a wide energy range (keV to MeV). Low-Earth orbit, where the atmospheric loss cone is ~60°, is better suited for these measurements than at the equatorial plane where the loss cone is only a few degrees. The pitch angle-resolved measurements will also enable precipitating, quasi-trapped, and trapped populations of electrons to be distinguished to best quantify the electron loss rate from the radiation belts. REAL is hosted by Dartmouth College in Hanover, NH, with a partnership with Montana State University in Bozeman, Montana.

2.2.8 Sun Radio Interferometer Space Experiment (SunRISE)

SunRISE would provide a constellation of CubeSats operating as a synthetic aperture radio telescope and would be the first of its kind. Flying in a 10 km diameter formation, it would address how solar energetic particles are accelerated and released into interplanetary space. SunRISE will measure coherent Type II and III radio bursts produced during coronal mass ejections and solar flares. These bursts are detectable from space before major arrivals of energetic solar particles, but they cannot be seen from Earth because of absorption by the ionosphere. The host institution for SunRISE is the University of Michigan in Ann Arbor.

2.2.9 US Contributions to the THOR Mission (THOR-US)

The Turbulence Heating ObserveR (THOR) mission is one of four proposed missions currently under consideration by the European Space Agency (ESA). A Partner Mission of Opportunity proposal, THOR-US, has been selected for analysis for three in situ secondary payload instruments. Work will begin on implementation of THOR-US only if THOR is selected.

THOR-US would investigate how kinetic processes heat and accelerate plasma by the dissipation of turbulent fluctuations. The concept study for THOR-US was conducted prior to its selection for NASA's Explorer Program, so the team is prepared for the detailed design phase if ESA selects THOR. The THOR-US team is led by the University of New Hampshire in Durham, New Hampshire.

2.2.10 Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS)

TRACERS is expected to be launched as a secondary payload with PUNCH (see section below) and will observe particles and fields in the region of Earth's northern magnetic cusp. This area encompasses Earth's pole, where magnetic field lines curve down toward the surface. As a consequence, particles from the boundary between Earth's magnetic field and interplanetary space are guided down into the atmosphere, particularly during magnetic reconnection events. TRACERS will characterize this process in the cusp with two matching spacecraft, permitting simultaneous reconnection measurements near Earth. The host institution for TRACERS is the University of Iowa in Iowa City, Iowa.

2.2.11 Vector Interferometry Space Technology Using AERO (VISTA)

VISTA is designed to work in tandem with the AERO mission (described above) targeting Earth's radio aurorae. It is a 3 U twin to AERO, launching and deploying with it into a polar orbit. VISTA will demonstrate vector sensor interferometry in space, use that technique to take measurements of the radio aurora, and characterize radio-frequency interference at high frequencies in low-Earth orbit. The missions will demonstrate whether interferometric arrays of vector sensors will maintain sensitivity in the presence of terrestrial interference. If so, low frequency interferometers could be placed in low-Earth orbit, reducing cost and increasing data volume. AERO and VISTA should have 90 day nominal mission lifetimes. Like AERO, VISTA is hosted by the Haystack Observatory of the Massachusetts Institute of Technology, with partnerships including MIT's Lincoln Laboratory, Morehead State University, Dartmouth University, and Merrimack College.

2.3 Selected Missions in Final Design or Construction (Phases B-D)

Missions in these Phases have cleared key decision points and design reviews and have been approved to advance to the next phase eventually leading to flight. Each mission must still pass a critical design review before being finally selected for flight.

2.3.1 Phase B (Preliminary Design, Technology Completion)

Daily Atmospheric Ionospheric Limb Imager (DAILI)

DAILI is a 6 U CubeSat intended to characterize dynamical changes in the composition of Earth's atmosphere in the approximate altitude range of 140–290 km (the so-called thermosphere gap). It will measure, on a daily basis, the absolute O_2 density at mid- and low latitudes (there are few existing measurements in this regime). It will characterize the variability of tides and planetary waves from 140–180 km and determine the extent of neutral O_2 transport during geomagnetically active periods as functions of latitude and altitude. It will also measure electron density profile variations in the F-region above 200 km that arise from tides and planetary waves. These observations will be made via images of Earth's limb acquired over a 6° field of view. DAILI is expected to be launched from the International Space Station using the NanoRacks CubeSat Deployer, resulting in a nominal 51° inclination orbit at 400 km altitude. DAILI is designed to last at least 1 year, but anticipated to last up to three. The mission is run by The Aerospace Corporation, headquartered in El Segundo, California.

Geosynchronous Transfer Orbit to Study Radiation Belt Dynamics (GTOSat)
GTOSat is a 6 U CubeSat envisioned as a pathfinder for new radiation-tolerant technologies of potential use to smallsats operating above low-Earth orbit. GTOSat will be launched into a highly elliptical geosynchronous transfer orbit commonly used in deploying communications satellites to geostationary orbit. It will use a more robust version of the NASA-developed Dellingr spacecraft bus known as Dellingr-X. GTOSat will measure very high energy particles to constrain the acceleration and loss of relativistic electrons in Earth's outer radiation belts. At the same time, it is intended to measure electron spectra and pitch angles of both the seed and the energized electron populations using a high-heritage instrumentation similar to those flown on NASA missions such as Juno, Parker Solar Probe, and the Van Allen Probes. The mission is being developed by NASA's Goddard Space Flight Center in Greenbelt, MD.

Low-Latitude Ionosphere/Thermosphere Enhancements in Density (LLITED)
The goal of the LLITED mission is to characterize two important interactions in the low-latitude dusk-side ionosphere and thermosphere, the Equatorial Ionization Anomaly (EIA) and the Equatorial Temperature and Wind Anomaly (ETWA). It will determine ETWA variability as a function of season, longitude, and latitude and constrain its role in EIA heating. It will characterize whether and how neutral winds interact with the EIA zonal structure and investigate small-scale wave fluctuations in neutral atmosphere quantities for comparison with features of ionospheric density. To do this, it will fly two 1.5 U CubeSats with their payloads, separated by ~30° of latitude, in a low-inclination orbit. The spacecraft are anticipated to be launched from the International Space Station. The mission is run by The Aerospace Corporation, headquartered in El Segundo, CA.

Plasma Enhancements in The Ionosphere-Thermosphere Satellite (PetitSat)
PetitSat is a 6 U CubeSat in development to study ionospheric density irregularities in the mid- and low-latitudes, including depletions, enhancements, and small-scale scintillation. All of these can distort the propagation of radio waves in the ionosphere. PetitSat will provide in situ measurements of plasma density, ion drift in three dimensions, and plasma composition in terms of ion and neutral species. The instrument suite will measure plasma fluctuations and changes in the neutral profile.

PetitSat is to be based on the Dellingr design (see section 3.1.4 below) and anticipated to be deployed from the International Space Station into a 51° inclination orbit at 400 km altitude. The lead institution for the mission is NASA’s Goddard Spaceflight Center in Greenbelt, Maryland.

Polarimeter to Unify the Corona and Heliosphere (PUNCH)

PUNCH will study the Sun’s corona and how it produces the solar wind. Composed of four small satellites, PUNCH will record the solar wind as it leaves the Sun as well as track coronal mass ejections to constrain their evolution and improve the ability to predict such eruptions. Through polarized Thomson-scatter imaging of the transition from corona to heliosphere, PUNCH will advance understanding of how coronal structures drive the ambient solar wind and of the dynamic evolution of transient structures in the solar wind near the source surface. These measurements will complement other NASA missions such as Parker Solar Probe, and the upcoming European Space Agency/NASA Solar Orbiter, due to launch in 2020. PUNCH will be able to image the solar atmospheric structures encountered by these missions by blocking out the Sun’s bright light, enabling examination of the much fainter atmosphere. PUNCH is intended to complement the TRACERS smallsat mission (see below) as well. PUNCH is hosted at the Southwest Research institute in Boulder, Colorado.

2.3.2 Phase C (Final Design and Fabrication)

CubeSat for Solar Particles (CuSP)

CuSP is planned as a 6 U CubeSat secondary payload on the first flight of NASA’s Space Launch System in the early 2020s and is intended as a “space weather station” to measure particles and magnetic fields in interplanetary space. It will occupy a trans-lunar heliocentric orbit at 1 AU with a nominal lifetime of 3 months, although it is anticipated to last for over 2 years. Its science payload consists of a suprathermal ion spectrograph, a vector helium magnetometer, and a miniaturized electron and proton telescope. The mission is hosted by Southwest Research Institute in San Antonio, Texas, with contributions from NASA’s Jet Propulsion Laboratory in Pasadena, California, and Goddard Spaceflight Center in Greenbelt, Maryland.

Scintillation Prediction Observations Research Task (SPORT)

SPORT is a 6 U CubeSat mission to address the conditions leading to the formation of equatorial plasma bubbles. To augment descriptions in the scientific literature, most of which have resulted from observations at a single site in Peru, SPORT will systematically study prebubble conditions at all longitudes. Science objectives include improved predictions of ionospheric disturbances that affect radio propagation of telecommunication signals, which will be accomplished by combining satellite observations from a nearly circular, middle inclination orbit with extensive ground based observations from South America near the magnetic equator. SPORT is an international partnership between NASA, the Brazilian National Institute for

Space Research, and the Technical Aeronautics Institute under the Brazilian Air Force Command Department.

2.3.3 Phase D (System Assembly, Integration, Testing, and Launch)

Lower Atmosphere/Ionosphere Coupling Experiment (LAICE)

LAICE seeks to study atmospheric gravity waves via in situ measurements of perturbations in the ionosphere and remote sensing of the middle atmosphere. These measurements will then be correlated with weather maps of the lower atmosphere, allowing for atmospheric coupling studies over a wide altitude range. The initial concept was funded by the US National Science Foundation, making LAICE the first publicly funded (and university-constructed) 6 U satellite. Its goals include demonstrating a unique magnetic torqueing altitude control system that constrains the satellite in a fixed altitude, acquiring measurements of neutral and ion density properties in the 150–325 km altitude range, and to remotely sense wave parameters between 90 and 100 km as the waves propagate from the lower atmosphere into the ionosphere. The mission is run by the University of Illinois in Urbana-Champaign, in partnership with Virginia Tech in Blacksburg, Virginia.

2.4 Selected Missions in Operation (Phase E)

Missions in Phase E are operating in flight. Missions that have ceased operations or otherwise reached the end of their life cycle are closed out during Phase F and are not described here.

2.4.1 Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA)

ASTERIA is primarily a technology demonstration mission to establish fine-pointing capability through arcsec-level line of sight pointing error and highly stable focal plane temperature control. ASTERIA is a 12 kg 6 U CubeSat operating in Low Earth Orbit and has a payload consisting of a lens and baffle assembly, a CMOS imager, and a two-axis piezoelectric positioning stage on which the focal plane is mounted. ASTERIA was launched on 14 Aug 2017 on the SpaceX CRS-12 Dragon flight to the International Space Station on a Falcon-9 launch vehicle and was deployed from the ISS on 21 November 2017. It operates in a near circular orbit with an altitude of ~400 km and an inclination of 51.6°. ASTERIA is a collaboration between the Massachusetts Institute of Technology and NASA's Jet Propulsion Laboratory, with JPL handling the program management and mission operations.

2.4.2 Compact Radiation Belt Explorer (CeREs)

The primary science goal of CeREs is to make rapid, high-resolution energy spectra measurements of electrons over a broad energy range to improve understanding of radiation belt electron energization and loss processes. CeREs is a 3 U CubeSat in a high inclination low-Earth orbit. CeREs will examine how radiation belt electrons are energized and lost, particularly during microbursts. The mission also characterizes high-energy solar wind particles. The spacecraft bus and the payload were developed, tested, and integrated at NASA's Goddard Spaceflight Center, Greenbelt, MD, with contributions from the Southwest Research Institute in San Antonio, TX. The project also involved graduate students from the Catholic University of America in Washington, DC, and the University of Texas, San Antonio. CeREs was one of ten CubeSats on the 19th Educational Launch of NanoSatellites (ELaNa) mission through NASA's CubeSat Launch Initiative.

2.4.3 Dellingr

Dellingr is a 6 U CubeSat that carries three fluxgate magnetometers for space weather measurements and a spectrometer to measure upper atmosphere ion and neutral particles. These in situ measurements of atmospheric composition and density are useful both for understanding atmospheric dynamics and to define the steady state background conditions. Two magnetometers were body-mounted, with the third on the end of a 55 cm boom to allow comparison of data from the two regimes. Dellingr helped establish baseline estimates of magnetic variation and particle fluxes in the exosphere. Its deployment and operations were highly challenging but ultimately successful (NASA 2019f). Dellingr is managed by NASA Goddard Spaceflight Center in Greenbelt, Maryland.

2.4.4 Electron Losses and Fields Investigation (ELFIN)

ELFIN is a dual, 3 U CubeSat system designed to study one of the processes that allows energetic electrons to escape the Van Allen Belts and fall to Earth. ELFIN launched from the Vandenburg Air Force Base in California on 15 September 2018. The primary objective of the mission is to understand mechanisms by which relativistic electrons in the radiation belts are lost via measurements of the full energy distribution and pitch angle resolution of precipitating electrons. A secondary science objective is to identify the source locations in the magnetosphere of ionospheric field aligned currents in relation to dipole region magnetotail boundaries via measurements of multiple 100–500 keV ion and 0.5–5 MeV electron isotropy boundaries. ELFIN includes a 3-axis Fluxgate Magnetometer to detect electromagnetic ion cyclotron waves. ELFIN is a largely student-operated project run out of the University of California in Los Angeles, CA.

2.4.5 Enhanced Tandem Beacon Experiment (E-TBEx)

E-TBEx is designed to investigate bubbles in Earth's ionosphere, whose evolution is unpredictable and difficult to characterize from the ground. It consists of a pair of 3 U CubeSats in near-identical, low-inclination orbits, each carrying tri-frequency radio beacons, that are complemented by ground-based diagnostic sensors in the Central Pacific. E-TBEx seeks to understand how lower-atmosphere forcing acts through plasma-neutral coupling processes to yield local, regional, and global-scale structures and dynamics in Earth's exosphere. It characterizes the development of plasma structure, including equatorial plasma bubbles (EPBs) by sending signals to these receiving stations, some of which pass through the EPBs. In this way, the total density of any ionospheric bubbles in the signal paths can be deduced. E-TBEx was launched in June 2019 aboard a SpaceX Falcon Heavy launch vehicle, and the mission is run out of NASA's Goddard Spaceflight Center in Greenbelt, Maryland.

2.4.6 Focusing Optics X-ray Solar Imager (FOXSI-3)

FOXSI-3 is the third experiment in a series intended to refine hard x-ray telescopes for imaging of the Sun. To focus X-rays, FOXSI uses 7 iridium-coated optics modules, each containing nested X-ray mirrors. Photons are imaged using energy sensitive detectors made of Si and CdTe. The team includes contributions from NASA Marshall Spaceflight Center, the University of Minnesota, the Japanese Aerospace Exploration Agency, and the lead institution is NASA Goddard Spaceflight Center.

2.4.7 Miniature X-Ray Solar Spectrometer 2 (MinXSS-2)

The MinXSS 2 mission flies a duplicate of the MinXSS 1 CubeSat that launched in 2015 and operated for two years, and is intended to investigate study solar flares, active regions, the quiescent Sun, and their impact on Earth's upper atmosphere. It launched on 3 December 2018 from a SpaceX Falcon-9 and is in a polar and sun-synchronous orbit at approximately 575 km altitude, with a mission life anticipated to have a duration of approximately 4 years. MinXSS 2 observes the Sun's soft X-ray energy distribution, improving upon the first mission with upgraded versions of the X-ray spectrometer and attitude control systems, and took advantage of advances in low-mass silicon drift detectors between the first and second missions. The mission utilizes a Sun Position Sensor and X-ray Photometer to provide independent, fine-pointing knowledge of the solar position and broadband X-ray comparisons for use in science processing. The mission is run out of the University of Colorado in Boulder, Colorado.

2.4.8 Scintillation Observations and Response of the Ionosphere to Electrodynamics (SORTIE)

The overall goal of the SORTIE mission is to understand wave-like plasma perturbations in the ionosphere, which can result from a variety of causes. It was launched on 21 May 2018 aboard an Antares/Cygnus rocket and consists of a 6 U CubeSat configuration to measure electric fields from which the growth rate of instabilities near plasma bubbles can be determined. SORTIE also provides initial observations of plasma density irregularities that result from the growth of these instabilities. The mission is led by ASTRA LLC (Atmospheric and Space Technology Research Associates) of Boulder, Colorado, the Air Force Research Laboratory of Kirtland Air Force Base, NM, the University of New Mexico in Albuquerque, New Mexico, the University of Texas at Dallas, COSMIAC (Configurable Space Microsystems Innovations & Applications Center) of Albuquerque, Minnesota, and Boston College of Boston, Massachusetts. The UNM team were the integrators of the CubeSat, and COSMIAC built the satellite and collects the data from it.

2.4.9 SWARM

SWARM is an ESA mission comprising three, near-polar orbiting satellites, two of which fly side-by-side in identical circular orbits (290 mi, inclination 87.4°), and a third in a higher circular orbit (330 mi, inclination 88°). The objective of the mission is to make the most precise measurements of the Earth's magnetic field ever taken resulting in a survey of the overall geomagnetic field and how it evolves over time. SWARM makes high-precision, high-resolution measurements of the vector magnetic field, that is, both the strength and direction of the field. The instrument suite on each spacecraft consists of fluxgate vector magnetometer to make the field measurements, a scalar magnetometer to calibrate the vector magnetometer, an electric field instrument to measure ion density, drift velocity, and electric field, an accelerometer to eliminate atmospheric drag, and a laser retro-reflector for precise, ground-based laser range measurements. The majority of the science objectives relate to inferring dynamic processes in Earth's interior but the mission also measures currents flowing in the magnetosphere and ionosphere, and quantification of magnetic forcing in the upper atmosphere. The mission was launched in 2013 and is still operating.

3 Conclusion

The "process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up market, eventually displacing established competitors" was the definition used by Clayton Christensen as a disruptive innovation (Christensen 2019). SmallSats and CubeSats, aided by major advances in miniaturization and launch vehicles with multispacecraft deployers, are becoming more mainstream. Despite their small mass, volume, and launch costs they are able to achieve significant scientific results. Successful experimental space missions are not measured in how large the satellites are but rather the quality of the data returned nad their impact to advancing scientific knowledge. CubeSats were introduced in ~2000 but obtained a significant boost in 2008 when US government funding began primarily for technology development and instrument maturation in addition to training objectives (NAS 2016). Since that time the funding has continued to increase until these types of missions are becoming, once again, critical ways to obtaining decadal level science. Today, SmallSats and CubeSats are the disruptive innovation that many hoped they would be.

4 Cross-References

- ▶ French Space Programs for Cubesats and Small Scientific Research Probes to Deep Space
- ▶ Small Satellites and Hosted Payloads for Technology Verification
- ▶ Student Experiments, Education, and Training with Small Satellites

References

C. Christensen, Disruptive innovation (2019), http://www.claytonchristensen.com/key-concepts. Accessed 27 Nov 2019

C. Mercer, Small satellite missions for planetary science, in *33rd Annual AIAA/USU Conference on Small Satellites*, (2019). https://digitalcommons.usu.edu/smallsat/2019/all2019/102/. Accessed 27 Nov 2019

NASA, Sputnik and the dawn of the space age (2019a), https://history.nasa.gov/sputnik. Accessed 27 Nov 2019

NASA, Explorer 1 overview (2019b), https://www.nasa.gov/mission_pages/explorer/explorer-overview.html. Accessed 27 Nov 2019

NASA, CubeSat launch initiative (2019c), https://www.nasa.gov/directorates/heo/home/CubeSats_initiative. Accessed 27 Nov 2019

NASA, STMD: small spacecraft technology (2019d), https://www.nasa.gov/directorates/spacetech/small_spacecraft/smallsat_overview.html. Accessed 27 Nov 2019

NASA, Small Spacecraft Virtual Institute (2019e), https://www.nasa.gov/smallsat-institute. Accessed 27 Nov 2019

NASA, Dellingr: the little CubeSat that could (2019f), https://www.nasa.gov/feature/goddard/2018/dellingr-the-little-cubesat-that-could. Accessed 27 Nov 2019

National Academy of Sciences (NAS), Achieving science with CubeSats (2016)

E. Shkolnik, On the verge of an astronomy revolution. Nat. Astron. **2**, 374–378 (2018)

Small Satellites for Science

Peter Martinez

Contents

P. Martinez (✉)
Secure World Foundation, Broomfield, CO, USA
e-mail: pmartinez@swfound.org

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_36

Abstract

This chapter examines the current state and scientific potential of CubeSats through a series of representative examples drawn from several fields. The aim is not to provide an exhaustive catalogue of smallsat science missions, but rather to give a flavor of the rich diversity of scientific applications of smallsats.

The rapid growth of CubeSat-based projects developed by the scientific community has been enabled by low entry cost barriers, access to frequent, affordable launch opportunities, open standard interfaces for subsystems, the ready availability of commercial off-the-shelf components for the non-scientific, mission-specific spacecraft subsystems, and a growing user community that openly shares its experiences and knowledge. This makes smallsats ideal platforms for a short-cycle "fly-learn-refly" approach to carrying out scientific missions. The chapter ends with some remarks on the importance of utilizing these new possibilities offered by nanosats in a responsible manner.

Keywords

Constellation · CubeSat · Educational Launch of Nanosatellites (ELaNa) · Explorer 1 and 3 · Fly-learn-refly · Launch licensing · NASA · Radio frequency allocations · Responsible behavior in space · Smallsat · Space Grant Consortium · Sputnik 1

1 Introduction

The use of small satellites for scientific investigation is nothing new. Sputnik 1, launched by the Soviet Union on 4 October 1957, had a mass of 83 kg and was equipped with temperature and pressure sensors that transmitted their readings from space. This first satellite was what would be termed in today's lexicon a small satellite, or "smallsat." The motion of the satellite provided information about the density of the Earth's upper atmosphere, while its radio signals were used to map out the electron distribution in the ionosphere. The satellite itself was also a meteor detector. Since the spacecraft was pressurized with a nitrogen atmosphere, any breaches or punctures would be noticed by its onboard barometer and transmitted back to Earth (although no such events were recorded during the 3-week mission of Sputnik 1).

Soon after, the United States launched its first satellite, Explorer 1, on January 31, 1958 (Fig. 1). This satellite had a mass of 14 kg and contained several scientific payloads. These included a cosmic ray detector, five thermal sensors (one internal, three external, and one on the nose cone), an acoustic sensor, and a wire-grid sensor to detect micrometeoric impacts (Fig. 2). Data from Explorer 1 and the nearly identical Explorer 3 (launched on March 26, 1958) were used by James Van Allen and his colleagues at the University of Iowa to detect the existence of charged

Fig. 1 A life-size replica of the Explorer 1 satellite, held aloft by Dr. William H. Pickering, former director of JPL, which built and operated the satellite, Dr. James A. Van Allen, of the State University of Iowa, who designed and built the instrument on Explorer 1 that discovered the radiation belts, and Dr. Wernher von Braun, leader of the Army's Redstone Arsenal team, which built the first stage Redstone rocket that launched Explorer 1. (Image courtesy of NASA)

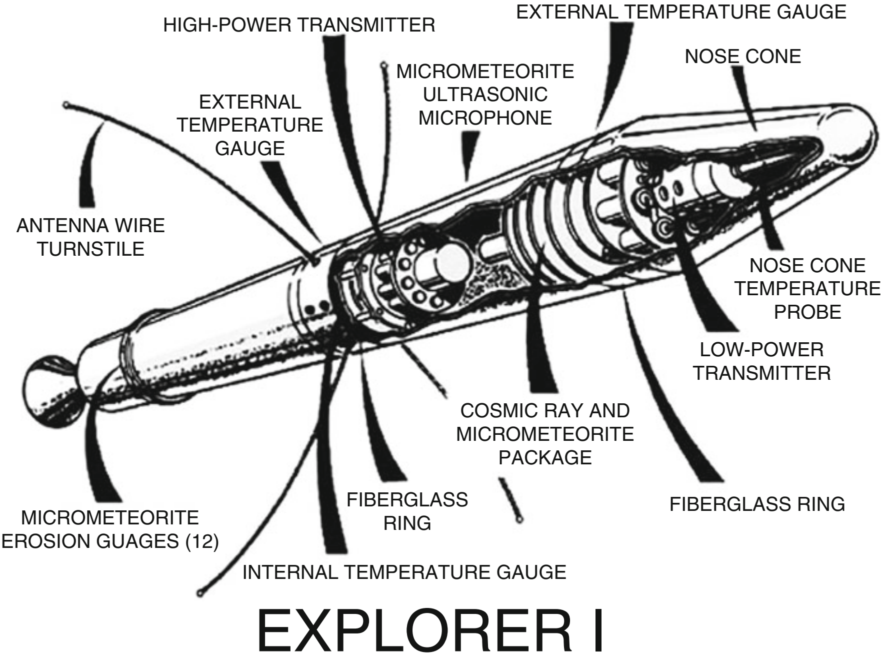


Fig. 2 Cutaway view of Explorer 1 showing its various scientific instruments. (Image courtesy of NASA)

particle radiation trapped by Earth's magnetic field – now known as the inner Van Allen radiation belt.

While Sputnik 1's 83 kg mass would place it in the category of a microsatellite in modern parlance, the 14 kg mass of Explorer 1 approximates the mass of a 6 U CubeSat, so for the purposes of the missions to be discussed in this chapter, a maximum spacecraft size of 6 U for the missions will be considered. The size of Explorer 1 is a good benchmark to illustrate just how much space technology has advanced in the past 60 years, and how much more capability we can pack into a given volume of spacecraft nowadays than was possible in 1958.

In November 2011, Montana State University launched a 1 U CubeSat to repeat the Explorer 1 observations on the 50th anniversary of the discovery of the Van Allen belts. The satellite, named Explorer 1 PRIME-2 (E1P-2), was launched from Vandenberg Airforce Base in California on 28 October 2011 as part of the ELaNa-III mission (Fig. 3). ELaNa refers to a NASA initiative titled Educational Launch of Nanosatellites that aims to attract and retain students in the science, technology, engineering, and mathematics disciplines through providing opportunities for these students to build, launch, and operate their own satellites. Each ELaNa launch typically places anywhere from three to a dozen or more nanosats in space at a

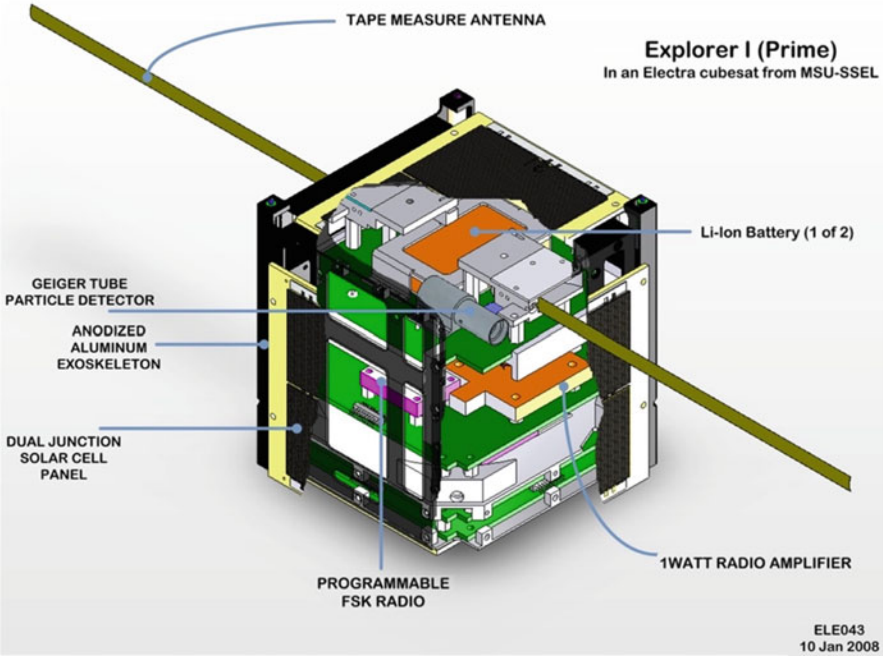


Fig. 3 Cutaway view of the Explorer 1 PRIME-2/HRBE spacecraft, a 1 U CubeSat built by students at the University of Montana to commemorate the discovery of the Van Allen radiation belts in 1958. The spacecraft contained a Geiger counter donated by Dr Van Allen. (Image courtesy of NASA)

time. As of this writing, 28 ELaNa launches have been conducted, and several more are planned.

The Explorer 1 PRIME-2 (E1P-2) satellite was placed in a sun-synchronous, near-circular polar orbit at an altitude of 824 km and an inclination of 98.7°. E1P-2 carried a miniature Geiger tube donated by Dr. Van Allen to measure the intensity and variability of ionospheric electrons from low Earth orbit. A passive magnetic attitude control system was used to align the Geiger tube perpendicular to the local magnetic field.

Shortly after launch, the E1P-2 mission was renamed the Hiscock Radiation Belt Explorer (HRBE), in honor of Dr. William A. Hiscock, the founder and former director of the Montana Space Grant Consortium. By mid-February 2012, the CubeSat had completed over 1500 orbits in LEO and had collected data for 111 days (Fig. 4), surpassing the entire 111-day mission of its history-making predecessor, Explorer 1. This is a demonstration of how CubeSats have become robust platforms for science in space.

When Explorer 1 was launched, it was the sole payload riding atop its Redstone rocket. E1P-2/HRBE was one of six secondary payloads launched together with NASA's NPOESS Preparatory Project spacecraft on a Delta-2 launch vehicle. This illustrates how much the capacity per launch to loft more payloads into space has increased in the past 60 years.

In the next few sections of this chapter, the scientific applications of smallsats of size 12 U and under are illustrated in a variety of scientific applications. CubeSats are particularly useful when one needs a distributed network of sensors to obtain either simultaneous measurements or an uninterrupted time series of measurements. Examples of smallsats used in individual missions and in networks of distributed sensors, where they come into a class of their own, will be discussed.

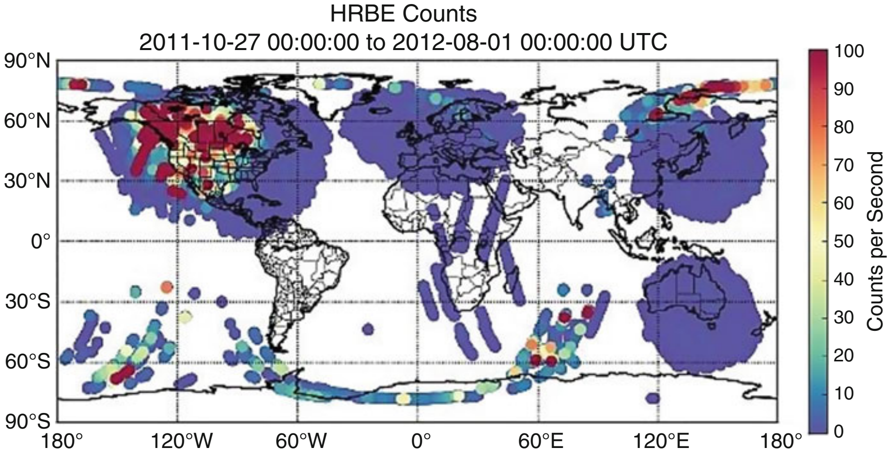


Fig. 4 Geiger counter measurements recorded by the HRBE satellite at different points in its orbit. (Image courtesy of NASA)

2 QB50: A CubeSat Constellation to Study the Earth's Thermosphere

The thermosphere is a layer of the Earth's atmosphere, so named because temperature increases with altitude in this region. It extends from about 90 km to about 500–1000 km above the Earth and is the layer in which the aurorae (Northern Lights and Southern Lights) mostly occur. At the base of the thermosphere, the air density is too low to sustain aerodynamic flight, but the residual atmospheric drag is also too high to sustain long-duration orbital flight. This boundary is referred to as the Kármán line, named after Theodore von Kármán (1881–1963), who sought to define the air/space boundary as that layer of the atmosphere that delineates the transition from aeronautics to astronautics. Sounding rockets can be launched to provide vertical profiles of atmospheric conditions in the thermosphere, but provide at most a few minutes of data at one location and at one time. Because of this characteristic, it is not surprising that this layer of the atmosphere has not been widely explored with in situ sensors. The QB50 mission was designed to provide the first multipoint measurements of the density, composition and conductivity of the thermosphere using a distributed constellation of sensors on board CubeSats. The small size and low mass of CubeSats make them ideal for a low-cost distributed sensor network that can provide new scientific data over wide regions of the thermosphere for a short period of time.

The QB50 project was conceived by the Von Karman Institute (VKI) in Belgium and supported financially by the European Commission under the FP7 framework at the level of just under €8 million. The idea of the QB50 project was to use a constellation of CubeSats launched into relatively short-lived orbits to study the middle and lower thermosphere, and also to perform re-entry research. It goes without saying that an improved knowledge of the density of the thermosphere and its properties will greatly improve reentry models and help to mitigate the risks posed by space objects reentering the atmosphere. The constellation would be allowed to fall under drag from an initial deployment altitude of around 420 km down to 200 km in 1 year, observing the chemistry and other properties of the thermosphere as it did so. Additional objectives of QB50 were European industrial development, student training, and workforce development.

2.1 The QB50 Satellites and Their Scientific Instruments

Most of the QB50 satellites were 2 U CubeSats equipped with a QB50 sensor. In addition, many of them also carried additional payloads developed by their respective university or organization. The satellites typically used body-mounted solar cells, had a navigation means such as GPS, had attitude control capability, and communicated in the UHF and VHF radio amateur frequency range.

The QB50 consortium agreed on three different types of sensors, which were provided to the participating institutions for incorporation in their CubeSats:

- Ion and Neutral Mass Spectrometers (INMS), supplied by the Mullard Space Science Laboratory (MSSL), to probe the major chemical species such as O, O_2, NO, and N_2 and possibly others.
- Flux Ion Probe Experiment (FIPEX) sensors, supplied by the Technical University of Dresden (TUD), to measure atomic and molecular oxygen by means of two separate solid electrolyte sensors.
- multi-Needle Langmuir Probe (mNLP) sensors, supplied by the University of Oslo (UiO), to probe electron density and other electron characteristics of the thermosphere.

Each participating institution was asked to incorporate one of these sensors and a thermistor/thermocouple in their CubeSat. They were free to utilize the remaining volume, mass, and power budget to incorporate whatever additional payloads they could fit within the volume/mass/power envelope of their spacecraft.

2.2 Development of the Constellation

VKI was selected as the project leader and coordinated the work of 33 partner institutions from 24 countries on 5 continents. The process of designing and building the QB50 CubeSats lasted 6 years. One of the main benefits of the QB50 project was the experience gained by the many teams who participated in this project under the leadership of VKI. Although initially planned, as the name QB50 suggests, to have 50 or more CubeSats, in the end 36 were actually launched, which is still a very impressive accomplishment.

It is instructive to describe how this widely distributed consortium of partners with different levels of technical capabilities and spaceflight experience in 24 countries managed itself to design, build, launch, and operate the constellation. As several of the VKI partners had limited experience in the design and construction of satellites, VKI and the QB50 consortium provided technical guidance for CubeSat development through the definition of technical requirements, support for meeting technical requirements (such as sensor alignment), advice (such as standards), and support for participating in milestone reviews (such as templates for the technical documents that had to be submitted for these reviews). Formal acceptance of each QB50 spacecraft was agreed by the QB50 consortium at the Flight Readiness Review, following which ISIS handled the final integration of each satellite with its science instrument, transportation of the integrated CubeSats to the launch site and their installation in a launch deployer.

VKI also supported the participating teams by obtaining all necessary legal permits for launch. The satellites were registered by VKI with the government of

Belgium. VKI also supported the QB50 partners with radio frequency allocations by carrying out frequency coordination with AMSAT and IARU, the Belgian Institute for Postal sevices and Telecommunications (BIPT) and the ITU. This approach allowed the QB50 partner teams to focus on their own national regulatory requirements for carrying out a space activity and related issues, such as export/import regulations. Despite being registered in Belgium, each satellite remained the property of the organization that developed it and it was under the control of that institution from its own ground station.

2.3 Deployment

Two precursor satellites were launched on a Kosmotras Dnepr rocket 19 June 2014 from Yasni, Orenburg Oblast, Russia, into a 630 km circular, 98° inclination orbit. The orbit of the precursor satellites was chosen to be at a higher altitude than the operational satellites to allow for longer mission operation time for troubleshooting, gaining operational experience and operations training for the partners.

The first 28 CubeSats of the full constellation were deployed from the International Space Station during the period 16–26 May 2017 into a 415 km, 51.6° ISS inclination orbit. The deployment was managed by Nanoracks (Fig. 5). Another 8 QB50 satellites were launched on 23 June 2017 on an Indian PSLV rocket into a

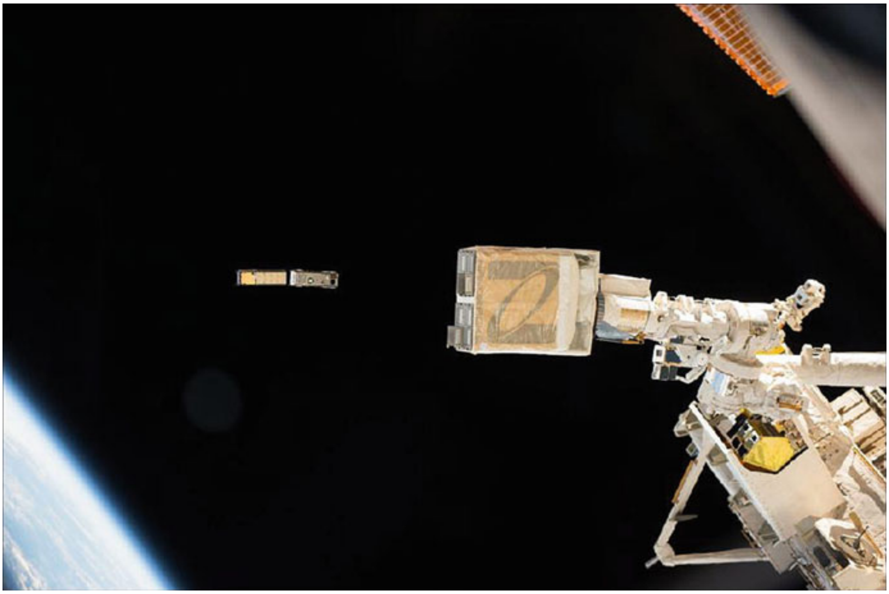


Fig. 5 This image shows deployment of nanosatellites from the ISS by NanoRacks on 16/17 May 2017. The two satellites pictured here are not QB50 satellites, which were released on the same day. (Image courtesy of NASA)

Table 1 Basic information on the QB50 satellites. The light blue part of the table lists the satellites launched from the ISS. The light green part lists the satellites launched on an Indian PSLV launcher. (Source: QB50/VKI)

QB50 ID	Satellite Name	Lead Institute	Country	Launch	Deployment date/time (UTC)	Size	QB50 sensor
AU01	SUSat	University of Adelaide	Australia	ISS via Atlas-V	25/05/17, 11:55	2U	INMS
AU02	UNSW-ECO	University of New South Wales	Australia	ISS via Atlas-V	25/05/17, 5:25	2U	INMS
AU03	i-INSPIRE II	University of Sydney	Australia	ISS via Atlas-V	26/05/17, 04:00	2U	mNLP
AZ01	ZA-AEROSAT	Stellenbosch University	South Africa	ISS via Atlas-V	18/05/17, 01:00	2U	FIPEX
AZ02	nSIGHT	SCS-SPACE	South Africa	ISS via Atlas-V	25/05/17, 08:45	2U	FIPEX
CA03	ExAlta-1	U of Alberta	Canada	ISS via Atlas-V	26/05/17, 08:55	3U	mNLP
BE02	LilacSat-1	Harbin Institute of Technology (HIT)	Belgium	ISS via Atlas-V	25/05/17, 08:45	2U	INMS
BE03	NJUST-1	Nanjing University of Science and Technology	Belgium	ISS via Atlas-V	25/05/17, 5:25	2U	FIPEX
BE04	Ao Xiang-1	NPU	Belgium	ISS via Atlas-V	26/05/17, 12:15	2U	INMS
DE02	SOMP2	TU Dresden	Germany	ISS via Atlas-V	16/05/17, 08:25	2U	FIPEX
ES01	QBITO	E-USOC, ETSIA, Universidad Politécnica de Madrid (UPM)	Spain	ISS via Atlas-V	25/05/17, 11:55	2U	INMS
FI01	Aalto-2	Aalto University	Finland	ISS via Atlas-V	25/05/17, 11:55	2U	mNLP
FR01	X-CubeSat	Ecole Polytechnique	France	ISS via Atlas-V	17/05/17, 01:45	2U	FIPEX
FR05	SpaceCube	École des Mines Paristech	France	ISS via Atlas-V	18/05/17, 08:25	2U	FIPEX
GR01	DUTHSat	Democritus University of Thrace	Greece	ISS via Atlas-V	25/05/17, 08:45	2U	mNLP
GR02	UPSat	University of Patras and Libre Space Foundation	Greece	ISS via Atlas-V	18/05/17, 08:25	2U	mNLP
IL01	Hoopoe	Herzliya Science Center	Israel	ISS via Atlas-V	18/05/17, 08:25	2U	mNLP
KR01	LINK	KAIST	South Korea	ISS via Atlas-V	18/05/17, 01:00	2U	INMS
KR02	SNUSAT-1	Seoul National University	Korea	ISS via Atlas-V	26/05/17, 04:00	2U	FIPEX
KR03	SNUSAT-1b	Seoul National University	Korea	ISS via Atlas-V	25/05/17, 23:40	2U	FIPEX
SE01	qbee	Open Cosmos Ltd. & LuleaUniversity of Technology	Sweeden	ISS via Atlas-V	17/05/17, 01:45	2U	FIPEX
TR01	BEEAGLESAT	Istanbul Technical University	Turkey	ISS via Atlas-V	26/05/17, 12:15	2U	mNLP
TR02	HAVELSAT	Havelsan	Turkey	ISS via Atlas-V	16/05/17, 08:25	2U	mNLP
TW01	PHOENIX	NCKU	Chinese Taipei	ISS via Atlas-V	17/05/17, 01:45	2U	INMS
UA01	PolyITAN-2-SAU	National Technical University of Ukraine & shenyang Aerospace University	Ukraine	ISS via Atlas-V	26/05/17, 04:00	2U	FIPEX
US01	Challenger	University of Colorado	USA	ISS via Atlas-V	25/05/17, 5:25	2U	INMS
US02	Atlantis	University of Michigan	USA	ISS via Atlas-V	26/05/17, 12:15	2U	FIPEX
US04	Columbia	University of Michigan	USA	ISS via Atlas-V	16/05/17, 08:25	2U	FIPEX
AT03	PEGASUS	FHWN	Austria	PSLV	26/06/17, 03:59	2U	mNLP
BE06	NUDTSat	National University of Defence Technology	Belgium	PSLV	26/06/17, 03:59	2U	INMS
CZ02	VZLUSAT1	VZLU	Czech Republic	PSLV	26/06/17, 03:59	2U	FIPEX
DE04	DragSail-CubeSat	FH Aachen, University of Applied Sciences	Germany	PSLV	26/06/17, 03:59	3U	N/A
GB03	UCLsat	UCL	Belgium (made in UK)	PSLV	26/06/17, 03:59	2U	INMS
GB06	InflateSail	University of Surrey	Belgium (made in UK)	PSLV	26/06/17, 03:59	3U	N/A
IT02	URSA MAIOR	Sapienza University of Rome	Italy	PSLV	26/06/17, 03:59	3U	mNLP
LT01	LituanicaSAT-2	Vilnius University	Lituania	PSLV	26/06/17, 03:59	3U	FIPEX

500 km, 97.1° polar orbit. However, 10 of those 36 satellites were dead on arrival in orbit or failed soon after, so in the end there was a 72% success rate, which is higher than the historical success rate for CubeSats. The final, as-launched constellation (Table 1) comprised 10 Ion and Neutral Mass Spectrometers (INMS), 14 Flux Probe Experiments (FIPEX), and 10 multi-Needle Langmuir Probes (mNLP). Two of the satellites had drag augmentation payloads only.

2.4 Operations

The science data downloaded from the satellites comprised the data obtained by the QB50 Science Unit along with its respective orbital information, such as position and time of acquisition. The ground segment for QB50 was distributed among all the partners around the world and allowed a high coverage of communication. Typically, the partners had access to a radio amateur ground station with UHF and VHF capabilities; some also had access to S-band communications. Satellite control software developed by the École Polytechnique Fédérale de Lausanne (EPFL) was made available to other partners, which relieved them of the burden of developing or procuring such software. It also facilitated data submission to the central server located at VKI, which functioned as the heart of the QB50 ground segment, allowing central collection of all the data obtained by the CubeSats, and interfacing to all ground stations at the QB50 participating institutions.

2.5 Results

The official report of the QB50 project (Von Karman Institute 2017) contains an interesting account of how the project was managed and the lessons learnt by the various academic and industry participants. From a purely scientific perspective, the QB50 project did not meet its scientific goals. The mission did not yield any major new insights on the physical processes in the thermosphere. Nevertheless, it was a boldly conceived project, and many lessons were learnt.

Apart from the scientific data generated by the QB50 constellation, there were numerous other benefits. QB50 involved more than 50 professors and 300 students from 24 countries, all of whom now share a common experience of having designed, built, integrated, tested, launched, and operated a satellite, and who have practical experience in international space cooperation. The project also provided development opportunities for the NewSpace industry, not only in developed countries but also in developing countries. For example, the South African company CubeSpace provided the attitude determination and control systems for 15 of the satellites in the constellation.

Hence, bearing in mind that this was the first time anyone had tried to place a nanosat-based scientific network in space, one may conclude that the QB50 project was a worthwhile experience that paved the way for placing similar, more robust distributed scientific networks of sensors in space in the future.

3 Bright(-Star) Target Explorer (BRITE) – A Nanosat Constellation for Astronomy

Astronomical objects display changes in their observable properties (such as brightness, polarization, spectrum) that serve as important clues to their physical nature. These changes occur on timescales ranging from milliseconds to millennia. In the twentieth century, with the advent of electronic sensors, astronomers started discovering and studying rapid light fluctuations in several types of stars. Our Sun, for example, oscillates with a 5-min period and studies of these oscillations have yielded a great deal of information about the interior structure and dynamics of the Sun, and even shed light on a long-standing mystery of fundamental particle physics, known as the solar neutrino problem. The study of solar surface oscillations to yield information about the interior of the Sun is termed *helioseismology*, and is an extension of the application of the basic techniques of *seismology*, the study of Earthquakes and the propagation of elastic waves through the Earth's interior to study its interior structure. In the last few decades of the twentieth century, astronomers discovered rapid oscillations in other stars, and the field of *asteroseismology* was born.

With time, astronomers have become able to study ever-smaller amplitude changes in the light emitted by stars, ranging from several parts in a thousand to several parts in a million. In order to study these extremely low-amplitude temporal variations, astronomers need to accumulate time series of observations – often very long ones to achieve the necessary signal-to-noise ratios. Ground-based astronomers work under several limitations, such as inclement weather, the day/night cycle and limited target accessibility imposed by fixed viewing locations. These limitations introduce gaps in the time series data that can mask the very subtle signals from the stars.

Astronomers have devised several ways to minimize the gaps in their time series data. One common method is for astronomers around the world to collaborate in observing the same star, so that as the star sets at one observatory, it is rising at the next. Of course, such multisite observations are still subject to the vagaries of the weather and optical distortions introduced by the atmosphere. The advent of the Space Age provided an opportunity for astronomers to loft their telescopes up above the distortions of the atmosphere and no longer be subject to interruptions in their observations caused by cloudy nights.

Space telescopes in low Earth orbit, like the Hubble Space Telescope, are only able to observe a target for part of the orbit when the target is not obscured by the Earth. With multiple telescopes in orbit, it is possible to achieve continuous coverage as one telescope takes over from another that is about to lose sight of a given target. Of course, space telescopes like the Hubble Space Telescope and its even larger successor, the James Webb Telescope, are extremely expensive to build and operate, which is why there isn't a fleet of such telescopes in space. This is where small satellites can fill a scientifically valuable niche.

The BRITE constellation comprises five nanosatellites operated by a consortium of universities in Austria, Canada, and Poland. BRITE stands for Bright(-star) Target Explorer and its purpose is to conduct time-series observations of the brightest stars in the sky. Since each BRITE satellite is a nanosatellite of size $20 \times 20 \times 20$ cm^3, the telescope aperture is necessarily small (only 30 mm in diameter), which means that it can only be used to study very bright stars (see Figs. 6 and 7). In this sense, it complements beautifully the excellent asteroseismic data produced by the Kepler mission (Molnár et al. 2016), which has a much larger telescope with a diameter of 1.4 m. In its search for planetary transits, which is Kepler's main mission, Kepler has discovered and observed many thousands of variable stars, but these tend to be quite faint and may not be suitable targets for other more precise follow-up observations.

3.1 Constellation Design and Development

The BRITE satellites were designed by the Institute for Aerospace Studies at the University of Toronto under the Canadian Advanced Nanospace eXperiment (CANX)

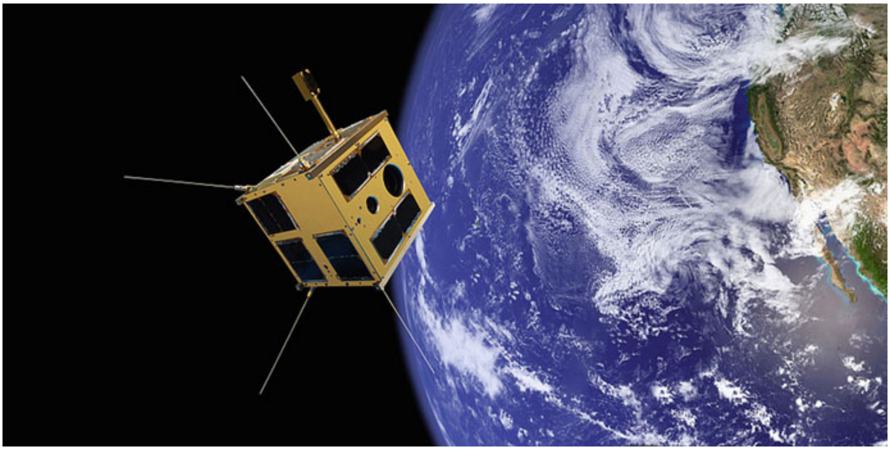


Fig. 6 Artist's conception of the BRITE-Austria satellite in space. (Image courtesy of the BRITE consortium)

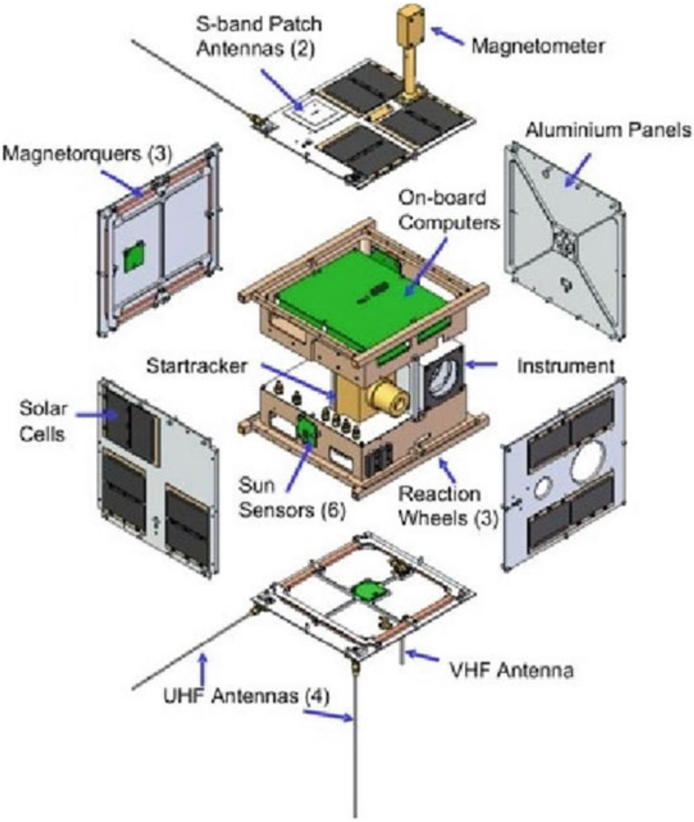


Fig. 7 Exploded view of the BRITE-Austria satellite. (Image courtesy of the BRITE consortium)

Program. Each satellite is a cube-shaped spacecraft with sides of 20 cm and a mass of 7 kg. Thin antennas and a magnetometer boom extend from the bus (see Figs. 6 and 7).

Since accurate pointing is a critical capability for targeted astronomy observations, each BRITE satellite has three orthogonal reaction wheels and three orthogonal vacuum-core magnetorquers for three-axis pointing and momentum dumping. This system provides pointing stability with rms of approximately 1–1.5 arcmin (corresponding to 2–3 pixels on the CCD).

Each satellite has three computers: a main onboard computer; an attitude determination and control system computer; and an instrument control computer. These three computers have the same design, built around an ARM7 processor operating at 40 MHz.

The satellites have six body-mounted solar cells on each face, except for the face with the telescope and star tracker apertures, which has only four cells. These solar cells give a maximum instantaneous power generation capacity of about 10 W, with a worst-case minimum power generation of 5.4 W.

The command uplink to the satellite is handled onboard by a UHF receiver. An S-band transmitter provides the primary downlink for data and telemetry. It uses two 5.5 cm × 5.5 cm patch antennas installed on opposite sides of the spacecraft to provide a nearly omnidirectional radiation pattern.

The science instrument on the BRITE satellites consists of a small refracting (i.e., lens-based) telescope and an uncooled CCD detector. The telescope objective has an aperture of 30 mm and effective focal length of 70 mm. The BRITE CCD detector is a 35.3 mm × 25.7 mm chip with 11 million 9 μm × 9 μm square 14-bit pixels. The CCD is not actively cooled, but there is a heater to provide thermal stabilization, if needed. The BRITE constellation collects data in two optical passbands (red and blue). As the optics on each satellite were optimized for either the red or blue filters, this means that each satellite observes in only one passband. Therefore, each of the BRITE partner countries (Austria, Canada, and Poland) contributed two BRITE satellites, one optimized for the blue wavelengths and the other optimized for the red wavelengths. Thus, two BRITE satellites must observe a given astronomical target simultaneously in order to acquire blue and red passband data. Table 2 shows the basic information for the BRITE satellites.

The two Austrian satellites were developed in a collaboration of the Space Flight Lab (SFL) at the University of Toronto Institute of Aerospace Studies (UTIAS), the

Table 2 Basic parameters of the satellites in the BRITE constellation

Satellite	Country	Filter	Perigee Apogee (km)	Inclination (deg)	Period (min)	Launch date	Launcher
BRITE-Austria	Austria	Blue	767–783	98.47	100.34	2013-02-25	PSLV
UniBRITE	Austria	Red	768–782	98.47	100.35	2013-02-25	PSLV
BRITE-PL1 Lem	Poland	Blue	590–880	97.80	99.51	2013-11-21	DNEPR
BRITE-PL2 Heweliusz	Poland	Red	604–627	97.90	97.00	2014-08-19	CZ-4B
BRITE-CA1 Toronto	Canada	Red	611–733	97.73	98.19	2014-06-19	DNEPR

Institute of Communication Networks and Satellite Communications (IKS) at the Technical University of Graz (TUG), and the Institute for Astronomy of the University of Vienna. The Polish BRITE satellites were developed by the Space Research Centre of the Polish Academy of Sciences and the Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences. The two Canadian BRITE satellites were developed by the Space Flight Lab (SFL) at the University of Toronto Institute of Aerospace Studies (UTIAS) under contract to the Canadian Space Agency.

3.2 Launching the Constellation

The BRITE satellites were launched as secondary payloads on a number of different launches. The two Austrian BRITE satellites were launched on 25 February 2013 from Sriharikota on an Indian Space Research Organization (ISRO) PSLV launcher. The first Polish BRITE satellite, BRITE-Lem, was launched on 21 November 2013, from Yasni, Russia, on a DNEPR launcher. The second Polish satellite, BRITE-Heweliusz, was launched from China on 19 August 2014 on a Chinese CZ-4B launcher. The two Canadian satellites, BRITE-Toronto and BRITE-Montreal, were launched together on a Russian Dnepr launcher on 19 June 2014, from Yasni in Russia. Unfortunately, BRITE-Montreal did not separate properly from the upper stage of the rocket and failed. Hence the final constellation has only five operational satellites (Table 2).

3.3 Operations

The BRITE satellites complete 14 orbits per day, yielding 6–7 passes per ground station. The operation and control of each individual BRITE satellite is the responsibility of each institution that receives funding from their respective national funding agency for their participation in the BRITE consortium. The BRITE constellation has ground stations in Graz (BRITE-Austria and UniBRITE), Warsaw (BRITE-Lem and BRITE-Heweliusz), and Toronto (BRITE-Toronto), which control and download the data from their national BRITE satellites, and they can also act as backups for each other.

Each BRITE satellite collects photometric data of stars in a $24^\circ \times 19^\circ$ field of view. The wide FOV ensures that there will almost always be several suitable on-chip comparison stars for differential photometry of the target stars. Since the start of operations in February 2013, BRITE has taken over 3.5 million measurements of some 500 stars. These observations have yielded new insights into the structure and evolution of stars.

The BRITE consortium is managed by the BRITE Executive Science Team (BEST), which oversees the evaluation of target proposals, generation of observing schedules, data analysis and archiving, and other aspects related to the overall management and control of the project. The BRITE constellation data archive is located at the Copernicus Astronomical Center in Warsaw. Although the BRITE constellation is currently funded and operated by Austria, Canada, and Poland, participation in the scientific activities of the consortium has been open the broader international scientific community from the outset to encourage the best scientific return from the project. In early 2020, the consortium announced that all data would henceforth be made publicly available immediately after acquisition, without any proprietary period through the BRITE data archive.

3.4 Scientific Results

Since the start of operations in February 2013, the BRITE satellites have acquired over 3.5 million high-precision photometric measurements of some 500 stars in two colors (red and blue) to study micropulsation, wind phenomena, and other forms of stellar variability. These BRITE observations are contributing to our understanding of stellar structure and evolution of the brightest and most massive stars in the galaxy and their interaction with their local environment. These massive BRITE target stars are important places for producing the chemical elements in our universe and recycling them in winds and supernovae.

The BRITE science community comprises over 60 scientists from Austria, Canada, and Poland, as well as other countries. The consortium has published over 70 conference papers and peer-reviewed papers. Preliminary science results have been summarized by Handler et al. (2017). The constellation is expected to continue to operate and provide scientifically valuable data beyond 2020, demonstrating that small, inexpensive nanosats can successfully carry out multiyear astronomy missions in space.

3.5 Lessons Learned

As the first operational nanosatellite-based space astronomy constellation, BRITE has encountered and overcome a number of challenges, such as unexpected radiation damage of its CCD detectors, radio interference issues impeding the communication between the satellites and the European-based ground stations, and systematic errors in the BRITE light curves. All of these challenges have been overcome, demonstrating that small, inexpensive spacecraft can serve as useful platforms for small telescopes in space to complement the scientific capabilities of the much larger telescopes in orbit.

4 Firefly: A CubeSat Mission for Atmospheric Lightning Research

Firefly is a 3 U CubeSat mission that was developed by Goddard Spaceflight Center and Sienna College under sponsorship of the U.S. National Science Foundation to study VLF, optical and gamma ray emission from lightning flashes in the Earth's atmosphere. The overall aim of the mission was to study the relationship between lightning and Terrestrial Gamma-ray Flashes (TGFs), which are sudden energetic bursts in the upper atmosphere. The TGF phenomenon was first reported in the open civilian scientific literature from data acquired by NASA's Compton Gamma Ray Observatory mission in 1994, but the origin of the flashes was unknown at the time. A subsequent study by Stanford University in 1996 linked a TGF to an individual lightning strike occurring within a few milliseconds of the TGF, suggesting a causal link between lightning flashes and TGFs.

It is thought that TGFs are produced by beams of very energetic electrons, which are accelerated in the intense electric fields generated by large thunderstorm systems. The objective of Firefly was to explore the link between lightning and TGFs and to determine which types of lightning produce these electron beams and the associated TGFs. To confirm the connection of TGFs with lighting, the Firefly mission was designed to observe lightning strikes simultaneously in the optical, radio and gamma-ray wavelengths (Fig. 8). This was the first time that such simultaneous multiwavelength measurements of lightning storms were collected from space.

4.1 Firefly Design

The Firefly was a 3 U nanosatellite, designed to be deployed by a P-POD deployer. The spacecraft was attitude controlled to point within 20° of nadir using a 3-meter-long gravity gradient boom that also served as a monopole antenna element for the

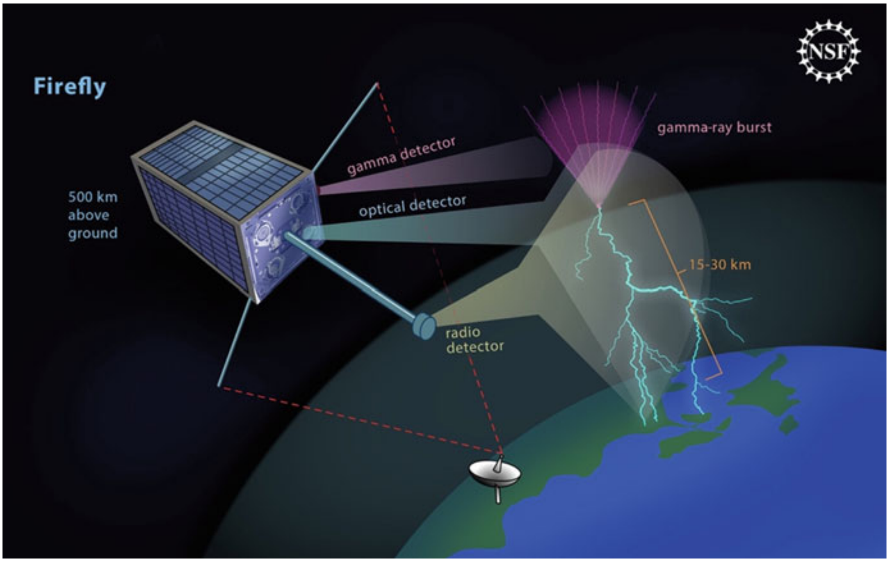


Fig. 8 Schematic representation of Firefly's observation and data relay functions. (Image courtesy of Zina Deretsky, National Science Foundation)

VLF radio receiver system. The optical photometers and gamma ray detector were on the nadir-facing end of the spacecraft. The communication antennas were also on the nadir side of the spacecraft. The zenith facing end of the spacecraft contained most of the spacecraft bus components, such as the flight computer, radio, electrical power system, batteries, GPS receiver, GPS antenna, magnetometer, as well as the power switching and detector interface circuitry. The sides of the spacecraft had either 6 or 7 body mounted solar cells, depending on the side. Figure 9 shows a schematic view of how the various subsystems in the spacecraft were arranged.

4.2 Launch and Operations of Firefly

The Firefly nanosatellite was launched from Wallops Island on 19 November 2013 on an Orbital Sciences Corporation Minotaur-1 rocket as a secondary payload on the ORS-3 (Operationally Responsive Space-3) mission of the U.S. Department of Defense.

First contact with the satellite was achieved on 6 January 2014. The data showed that the spacecraft was healthy and transmitting a strong signal. Not surprisingly, the data volumes on the spacecraft had been filled, as expected, given that the spacecraft had been acquiring data from its onboard sensors since shortly after launch on 19 November 2013.

The Firefly satellite captured over 60 high time resolution measurements of lightning and gamma ray activity, contributing to our improved understanding of lightning physics and the link between electron acceleration in lightning strikes and Terrestrial Gamma Ray Flashes.

With no propulsive capability of its own, Firefly was unable to maintain its altitude and its orbit decayed. Firefly reentered the atmosphere on 1 November 2017. At the time of reentry, the satellite was still operational. In addition to its scientific contributions, the Firefly project also had several educational outcomes. Some 30 undergraduate students were involved in the project, either at universities or as interns at NASA's Goddard Space Flight Center.

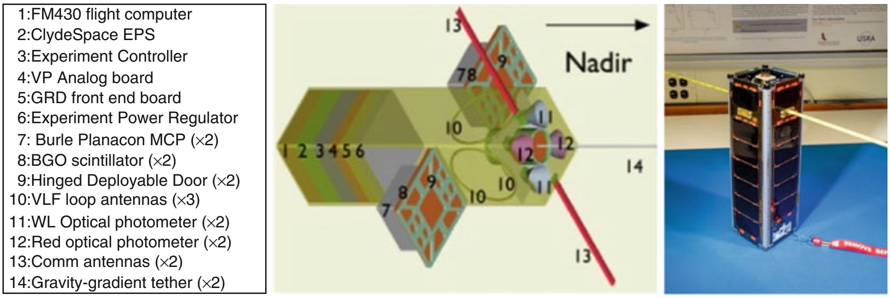


Fig. 9 Design of the 3 U Firefly nanosatellite and lab-bench image of the satellite. (Images courtesy of NASA and NSF)

5 CubeSats in the Life Sciences: Thinking Inside the Box

Satellites have been used as research platforms by the space life sciences community from the earliest days of the Space Age. The first microbiological experiments were carried out in 1960 using *E. coli* onboard the Soviet Korabel-Sputnik-2 satellite (sometimes referred to as Sputnik 5) and *Clostridium sporogenes* onboard the United States' Discoverer 17 satellite (the life science experiments provided the scientific cover for the real mission of this satellite, which was reconnaissance). Subsequent experiments on microorganisms in space were performed using the uncrewed Russian Foton capsules and the European Retrievable Carrier (EURECA), or crewed spacecraft, such as the space shuttles, and space stations, such as Skylab, Mir, and the International Space Station, which allowed possibilities for the return of samples for further post-flight study on Earth. These early experiments have been described by Dickson (1991) and Zea et al. (2014).

In all such cases, the life science experiments were secondary to the main purpose of the mission, meaning that the experiments had to be designed around the main mission. The advent of CubeSats has allowed the spacecraft to be designed around an experiment's scientific objectives, and not the other way around. The leader in using CubeSats for microbiological research is NASA's Ames Research Center, which has built and flown several life science missions in the CubeSat form factor, demonstrating that CubeSats are viable, cost-effective platforms for certain kinds of life science research in space.

5.1 GeneSat-1

The first CubeSat-based life science experiment to fly in space was GeneSat-1, a 3 U CubeSat with a mass of 6.8 kg, which was launched on 16 December 2006. GeneSat-1's scientific objective was to characterize bacterial growth and metabolics using *E. coli* as the model organism. This required creating a controlled environment onboard the satellite to allow bacteria to grow in space. In terms of payload requirements, this meant a microfluidic payload comprising a well plate that had to be operated in microgravity, with temperature regulated to within 0.5 °C of the set point temperature of 34 °C. The payload contained a growth medium and illumination source to excite fluorescence in the microorganisms in 100 μl wells in the well plate. There were also optical sensors required to measure gene expression in the test subjects. Observations of the ratio of fluorescence to scattering in the microorganisms allowed scientists to quantify gene expression in those organisms. In addition to the life science payload, there was also a secondary STEM mission which used a radio beacon operating in the amateur band. GeneSat-1 was designed, built, and operated as a technology demonstrator to prove that it is possible to conduct biological research on a small satellite. In this regard, the mission was to pave the way for other CubeSat-based life science missions that followed.

5.2 PharamaSat

PharmaSat was the first nanosatellite to host a competitively peer-reviewed bioscience experiment. The scientific goal of the mission was to study the effects of microgravity on growth and metabolism of the yeast *S. cerevisiae*. The experiment also investigated the efficacy of antifungal agents under microgravity conditions. The scientific payload comprised a well plate to accommodate the specimens. It needed the capability to provide nutrients for growth and to introduce antifungal agents into the wells in the well plate. This required a miniaturized microfluidics system with pumps and valves. It also needed sensors to measure the optical density in the wells to determine culture growth and it needed to transmit the payload conditions and observations back to Earth.

The 3 U PharmaSat had a mass of 5.1 kg and made use of the 1 U bus developed for GeneSat-1. The attitude determination and control system (ADCS) was based on magnetotorquer rods that aligned the antenna to point to Earth and damped wobble. The data was transmitted in S-band at a rate of 960 bps. The science payload was contained within a pressurized and heated 1.2 l volume. Two 2 W heaters maintained the temperature of the fluidics card within 0.3 °C of 27 °C.

PharmaSat was launched as a secondary payload on a Minotaur 1 rocket 19 May 2009 from Wallops Flight Facility and placed in a 410 km, 40° inclination circular orbit. The satellite reentered on 4 August 2010; it was still operational at that time. The PharmaSat mission revealed that yeast grew more slowly in microgravity conditions than controls on Earth, but also suggested that yeast could continue to have limited metabolic activity at higher antifungal concentrations in space than on Earth. This finding could have could have significant implications for the treatment of fungal infections in microgravity conditions. The scientific findings of the mission were published by Ricco et al. (2020).

5.3 *E. coli* AntiMicrobial Satellite (EcAMSat)

With several space agencies contemplating a return to the Moon and onward exploration of Mars, maintaining the health of astronauts during long-duration space missions will be paramount. Crews will be exposed to a number of pathogens, and it is important to understand whether these pathogens behave differently in microgravity conditions in space than they do on Earth. Previous space experiments have reported increased virulence and antibiotic resistance of microorganisms under such conditions. This, combined with a depressed immune response observed in astronauts, suggests that there may be an increased risk of opportunistic bacterial infections in space.

The EcAMSat mission is a 6 U mission that was launched in 2015 to study the effects of microgravity on the antibiotic resistance of *E. coli*, a bacterial pathogen that is common in humans and animals. EcAMSat was developed jointly by NASA's

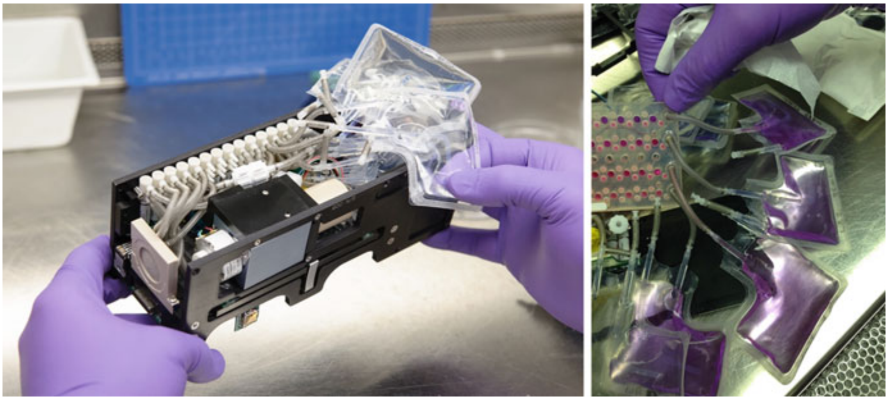


Fig. 10 The experimental module in EcAMSat (left). Bags containing nutrients are connected to a microfluidics card (right), where samples of *E. coli* are cultured in 48 small wells. The card is sandwiched between two heaters to maintain the temperature in the wells to within one degree of 37 °C. (Images courtesy of NASA/Ames Research Center)

Ames Research Center and the Stanford University School of Medicine. The satellite was launched on the ELaNa-13 mission on 11 November 2017 on board the Cygnus CRS-8 uncrewed resupply craft to the ISS, where it was deployed via the JEM airlock on 20 November 2017.

EcAMSat's payload (Fig. 10) contained a 48-microwell fluidic card that allowed study of bacterial cultures at constant temperature. A fluid-delivery system provided a growth medium and predefined concentrations of the antibiotic gentamicin, a common treatment for urinary tract infections (which have been reported in astronauts). Measurements of optical absorbance by the cell suspensions were made at three wavelengths for each microwell. These measurements provided an indication of cell growth in each well (Matin et al. 2017).

The experiment began with elevating the temperature of the well plate to 37 °C. Once the temperature was stabilized, one-sixth strength Luria broth (a nutritionally rich growth medium) was added to all the microwells to initiate the experiments. The cells remained in the concentration of Luria broth for 48 h. Their growth was monitored by measuring the optical transmission through the wells. The cells were then challenged for at least 46 h with three different doses of gentamicin (Gm); zero Gm served as a control. The redox-based indicator alamar Blue was then added and its reduction was followed to measure the effect of the antibiotic on cell metabolic activity. Optical measurements were recorded every 15 min at red, green, and blue wavelengths for each well over the course of the 156.5-h experiment. The experiments showed that the two strains of *E. coli* investigated both exhibited slower metabolism in microgravity, consistent with results from earlier smallsat missions. The results also showed that microgravity did *not* enhance uropathogenic *E. coli* resistance to gentamicin; in fact, both strains were more susceptible to gentamicin in microgravity. Full results have been reported by Padgen et al. (2020).

6 Mars Cube One (MarCO)

CubeSats have also been proposed for a variety of lunar, deep space, and planetary exploration missions, though only two have actually flown as of this writing. Mars Cube One (MarCO) is the first CubeSat form-factor spacecraft to operate successfully beyond Earth orbit in a deep space mission; actually, it was a *pair* of spacecraft.

The mission concept was to use a pair of CubeSats to support the atmospheric entry, descent and landing phases of NASA's InSight Mars lander. Both spacecraft were 6 U CubeSats, each with a mass of 13.5 kg, and the mission was to test new miniaturized communications and navigation technologies developed at JPL. These were the first CubeSats to operate beyond Earth orbit, and aside from their communications relay function, they also tested the endurance of CubeSats in deep space.

The two CubeSats, dubbed MarCO-A and MarCO-B, were launched on 5 May 2018, together with the InSight Mars lander. Shortly after launch, the two MarCO spacecraft were separated to fly on their own trajectory to Mars in order to demonstrate the CubeSats' endurance and navigation capabilities in deep space. During the cruise phase, the two MarCO spacecraft were kept about 10,000 km away from InSight. This distance was reduced as the three spacecraft approached Mars. The closest flyby distance to Mars was 3,500 km on 26 November 2018.

During their Mars flyby, the two MarCO spacecraft provided a real-time communications link to Earth for InSight during its entry, descent, and landing (EDL) phase. This relay was vital, because the EDL of InSight occurred on the side of Mars that was out of line of sight from the Earth at that time. The EDL information from InSight was transmitted in the UHF band at 8 kbit/s to the CubeSats, which then relayed the data in X-band to Earth at 8 kbit/s. The MarCO spacecraft used a deployable solar panel for power, but because of the limitations in solar panel efficiency, the power for the X-band frequency was only about 5 watts.

For the CubeSats to relay the information to Earth, they needed a high-gain (i.e., highly directional) antenna that would be reliable, meet the low mass specifications, have low complexity, and be affordable to build. Three possible types were assessed: a standard microstrip patch antenna, a reflectarray, and a mesh reflector. With the small, flat, antenna size required for the CubeSats, MarCO's design engineers chose a reflectarray antenna made up of three folded panels connected to the body of the CubeSat. Figure 11 shows the general layout of the two MarCO spacecraft.

In addition to its communications payload, each MarCO spacecraft carried a miniature wide-angle camera that was used to verify deployments. Figure 12 shows an image taken by one of the MarCO spacecraft during its Mars flyby on 26 November 2018.

The MarCO spacecraft had a propulsion system with eight cold gas thrusters for providing desaturations for reaction wheel momentum buildup and thrusting to change the spacecraft trajectory. Prior to the Mars encounter the propulsion system made five small corrections to ensure the two small spacecraft were on the correct trajectory to support the Insight Lander during its EDL phase.

The MarCO spacecraft retransmitted the InSight lander's telemetry during the landing, which demonstrated the new relay system and technology for future use in

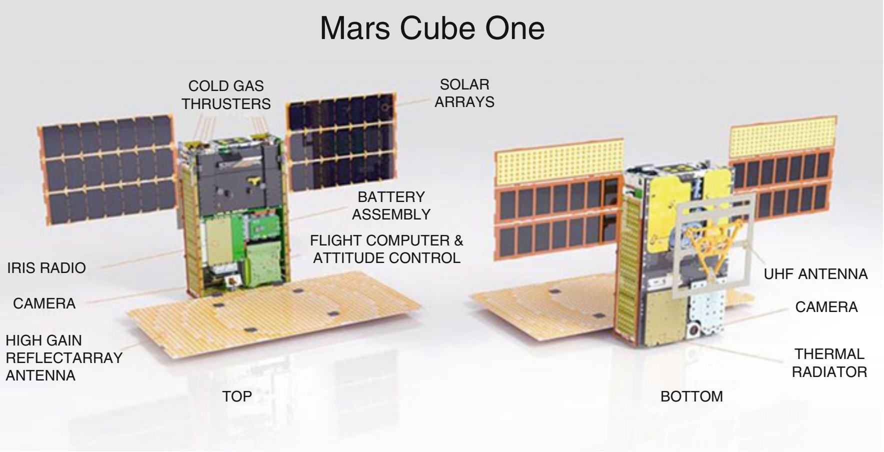


Fig. 11 The MarsCubeOne (MarCO) spacecraft are a pair of 6 U nanosatellites, each with a mass of 13.5 kg. (Image courtesy of NASA JPL)

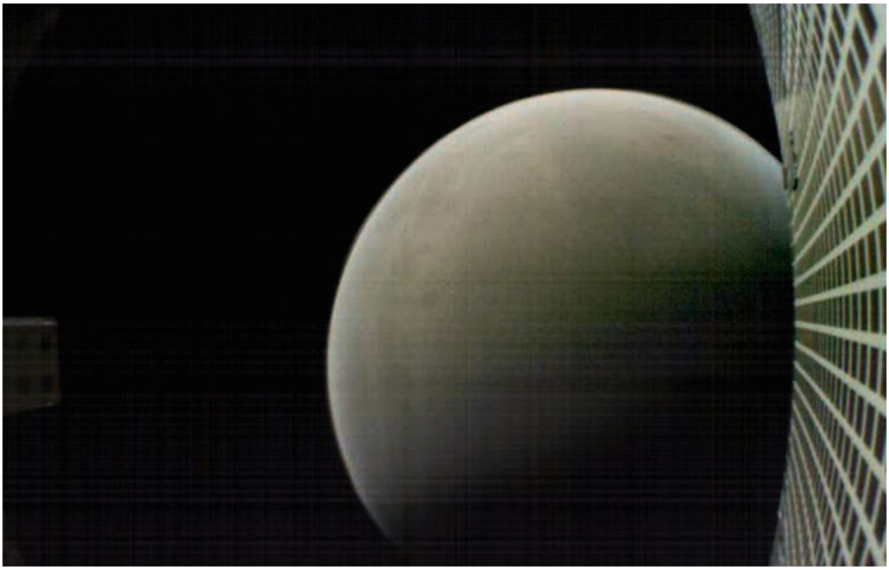


Fig. 12 Image of Mars taken by MarCO-B during its flyby of the planet on 26 November 2018. The spacecraft was at a distance of 6,000 km from the Red Planet when this image was taken at about 12:10 p.m. PST while MarCO-B was flying away from the planet, after InSight had touched down on the planet's surface. (Image courtesy of NASA/JPL)

missions to other Solar System bodies. This provided an alternative to orbiters for relaying information and achieved a smallsat technology development milestone. Having completed their primary mission, the MarCO spacecraft continued in their elliptical orbits around the Sun. The last transmission received from the CubeSats was on 5 January 2019.

The success the MarCO CubeSats achieved in relaying telemetry from NASA's InSight Mars lander demonstrates that such small spacecraft can play important roles in future deep space missions. Indeed, a number of CubeSat missions are planned for cis-lunar space and beyond. The Artemis 1 mission to the Moon, currently scheduled to launch some time in 2021, will carry a dozen or more CubeSats as secondary payloads. Each CubeSat is being developed by a different team, with different scientific goals. Among these will be CubeSats with the Moon and near-Earth asteroids as their destinations. CubeSats, with their inherent power, data, and propulsion limitations, will not replace the larger, more capable spacecraft for deep space exploration, but they have a place in supporting space exploration, such as providing complementary vantage points for simultaneous observations. As such, they can be a cost-effective way of enhancing the scientific return of deep space and planetary exploration missions.

7 Conclusion

In this chapter, it has been shown how smallsats can be useful platforms for scientific research. Although they can be used individually, smallsats come into a class of their own when used in numbers to address problems that require distributed simultaneous observations. The smallsat missions discussed in this chapter have all flown in space and show that smallsats can be effective platforms to perform useful scientific observations and experiments in space. As with any new technology, the early adopters of these smallsat platforms for science are encountering unanticipated technical problems and challenges, but the scientists confronting these challenges today are paving the way for others that will follow in the not too distant future with more capable smallsat missions for scientific research in space.

Traditionally, participation in space exploration has been the preserve of national space agencies, large aerospace corporations, and a few prestigious universities. Smallsats are lowering the technological and financial entry barriers to participation in space exploration, allowing many more universities and nongovernmental entities to participate in exploration endeavors. While a greater and more diverse number of space actors engaging in space exploration is good for science in general, their activities must be carried out in a responsible manner to avoid creating space debris, causing interference with the space activities of other space actors, posing risks to spaceflight safety, or causing biological contamination of the surfaces of other celestial bodies.

There have already been two well-documented instances of deliberate, irresponsible behavior by new space actors that have raised numerous questions about how to promote and ensure responsible behavior and chain of custody, jurisdiction, and control of objects launched into outer space (Henry 2018; Johnson et al. 2019a, b, c).

Regulators will have to balance the interests of the new space actors in space exploration with their obligations under applicable domestic regulations and international law. The regulatory processes for short duration missions as addressed elsewhere in this Handbook provides useful guidelines for scientific missions of this type.

Scientists who make use of the new capabilities offered by nanosatellites to carry out scientific research in space would be well advised to acquaint themselves with the international and domestic regulatory frameworks for conducting space activities and the norms of behavior to promote the sustainable exploration and use of outer space, which are contained in international standards, best practices, and guidelines. The *Handbook for New Actors in Space*, published by Secure World Foundation (2017), provides a very accessible introduction to these issues for a general audience.

8 Cross-References

- ▶ French Space Programs for Cubesats and Small Scientific Research Probes to Deep Space
- ▶ Scientific Discovery and Geomagnetic Monitoring in Earth Orbit Using Small Satellite Systems
- ▶ Small Satellites and Hosted Payloads for Technology Verification
- ▶ Student Experiments, Education, and Training with Small Satellites

References

K.J. Dickson, Summary of biological spaceflight experiments with cells. Am Soc Gravit Space Biol Bull **4**(2), 151–260 (1991)

G. Handler, A. Pigulski, W.W. Weiss et al., The BRITE-constellation nanosatellite space mission and its first scientific results. Published in Proceedings of “Seismology of the Sun and the Distant Stars II”, EPJ web of conferences 160, 01001 (2017), https://doi.org/10.1051/epjconf/201716001001

C. Henry, FCC fines Swarm $900,000 for unauthorized smallsat launch. Space News, 20 December 2018 (2018). Available online at: https://spacenews.com/fcc-fines-swarm-900000-for-unauthorized-smallsat-launch/

C.D. Johnson, D. Porras, C.M. Hearsey, S. O’Sullivan, The curious case of the transgressing tardigrades (part 1). The Space Review, 26 Aug 2019 (2019a)

C.D. Johnson, D. Porras, C.M. Hearsey, S. O’Sullivan, M. Vidaurri, The curious case of the transgressing tardigrades (part 2). The Space Review, 3 Sept 2019 (2019b)

C.D. Johnson, D. Porras, C.M. Hearsey, S. O’Sullivan, M. Vidaurri, The curious case of the transgressing tardigrades (part 2). The Space Review, 16 Sept 2019 (2019c)

A.C. Matin, J.-H. Wang, M. Keyhan, et al., Payload hardware and experimental protocol development to enable future testing of the effect of space microgravity on the resistance to gentamicin of uropathogenic Escherichia coli and its σs-deficient mutant. Life Sci Space Res **15**, 1–10 (2017). https://doi.org/10.1016/j.lssr.2017.05.001. http://www.sciencedirect.com/science/article/pii/S2214552417300251

L. Molnár, R. Szabó, E. Plachy, Variable stars with the Kepler space telescope. J Am Assoc Var Star Obs **44**(2), 168–178 (2016)

M.R. Padgen, M.P. Lera, M.P. Parra, et al., EcAMSat spaceflight measurements of the role of σs in antibiotic resistance of stationary phase Escherichia coli in microgravity. Life Sci Space Res **24**, 18–24 (2020). https://doi.org/10.1016/j.lssr.2019.10.007. http://www.sciencedirect.com/science/article/pii/S2214552419301257

A. Ricco, M. Parra, M. Piccini et al., PharmaSat: Drug dose dependence results from an autonomous microsystem-based small satellite in low Earth orbit (2020). Available online at https://www.researchgate.net/publication/266521190_PharmaSat_Drug_dose_dependence_results_from_an_autonomous_microsystem-based_small_satellite_in_low_Earth_orbit

Secure World Foundation, in *Handbook for new actors in space*, ed. by C.D. Johnson (2017) 144 p., ISBN 978–0–692-45413-8. Available online at https://swfound.org/handbook/

Von Karman Institute, *Final report summary – QB50 (An international network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere and re-entry research)* (2017). Available online at https://cordis.europa.eu/project/id/284427/reporting

L. Zea, L. Stodieck, D. Klaus, The First Fifty Years of Bacterial Growth and Antibiotic Effectiveness Research in Space. American Society for Gravitational and Space Research (ASGSR) Conference, Pasadena, 22–26 Oct 2014 (2014). Available online at https://www.colorado.edu/faculty/zea-luis/sites/default/files/attached-files/poster_-_the_first_50_years_vindesign.pdf

Small Satellites and Hosted Payloads for Technology Verification

Joseph N. Pelton

Contents

Abstract

The early days of satellite applications often began with the development of a half or even full-scale engineering models for the purpose of technology verification. These engineering models were fabricated and tested with many key components designed, tested, and subjected to full-scale design reviews before production satellites were developed. In some cases various renditions of prototype models or full-scale subsystems were even flown in orbit to prove the reliability or functionality of such new components of the new generation of satellites. This technology verification was, of course, quite expensive. In the case of geosynchronous satellites, where there were only limited orders for perhaps four to six operational satellites, the result was that some 40% of the cost was invested in R&D and nonrecurrent development and technology verification costs.

Today, in the case of development and manufacturing for large-scale small satellite constellations, the approach can be quite different. The approach

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_37

to technology verification and manufacturing of reliable small satellites for large-scale constellations can be much different in several ways. This is particularly true in the case of constellations involving significant production runs in the range of hundreds to even many thousands of satellites.

One Web, a year prior to their bankruptcy proceedings, launched six of this first run of “pre-operational” satellites to test their performance technically as well as operationally. In such cases these early test operations not only prove and verify the payload and spacecraft bus capabilities but also allow tests of the ability to avoid interference to geosynchronous satellite networks.

Another newer option is to use the hosted payload systems to carry out performance testing of components or the launch of several CubeSat test satellites as a cluster of technology verification flights. This can be more cost-effective than a separate experimental satellite flight.

The use of small satellites and hosted payloads allows a totally different approach, and more cost-effective approach to research, development, technology verification, and in-orbit test of very small components such as application-specific integrated circuits and electronic switching systems or routers. These new options can allow in-orbit verification tests at much more modest cost.

In short, small satellites as well as hosted payloads offer a range of new possibilities. These various options allow for low-cost test of new technology, verification of components, and use of hosted payloads or small satellites to prove, in-orbit, key new technology. There are now programs specifically designed to use hosted payload systems to carry out verification of new systems or in-orbit lifetime testing. New launch offerings including deployment of CubeSats and almost up to 1 m^3 satellites from the International Space Station have contributed to the cost-efficiencies of such test flights.

This chapter thus outlines the many ways that small satellites and hosted payloads can offer important improvements for the design of satellites to achieve improved performance, longer life, and lower costs. These new options improve the ability to provide for quality testing and verification in the design and manufacture of not only for the entire small satellite and its design but also allow assessment of the performance of components in hosted payload packages and even allow for improvements in the design and reliability of larger-scale MEO and GEO satellites. Small satellite testing can thus aid large satellite design, manufacture, reliability, and performance for all types of satellites – large and small.

Keywords

Alphasat · Cisco · Experimental payload · Geosynchronous Earth orbit (GEO) · Hosted payloads · Hosted Payload Alliance · Independent verification and validation · Inmarsat · Intelsat General · Internet Routing in Space (IRIS) · Lifetime testing · Low Earth orbit (LEO) constellation · Medium Earth orbit (MEO) · Technology verification

1 Introduction

The uses of small satellites are diverse and continue to grow as the utility and cost-efficiency of this type of spacecraft continue to expand. There are useful ways to use small satellites and small packages on large satellites to demonstrate the validity of new technology and systems as well as to carry out effective experiments and lower cost. The past historical experience of the satellite industry is highly relevant. The first needs of the global market for international telecommunications dictated very rapid growth and the expanded use of GEO systems and lower cost ground systems, but as the commercial demand began to peak and the need for mobile services emerged, new patterns of use and spacecraft design emerged. Thus this chapter begins by reviewing this history.

2 Historical Background

The evolution of commercial satellite technology moved quite rapidly in its earliest years. One example of this rapid increase in spacecraft performance can be shown in the improved throughput capability of Intelsat satellites in terms of telephone circuit capacity and television capacity between 1965 and 1986. This expansion of throughput capability by a factor of some 250 times in only two decades is shown in the following table (see Table 1) (Pelton et al. 2004).

In this rapid growth environment, worldwide demand soared as the cost of international telecommunications services plummeted. The demand was met with larger and more sophisticated satellites that were higher in power and included higher gain antennas and extensive reuse of radiofrequency spectrum. This increase in satellite size, technology, and performance allowed the cost of user terminals to drop rapidly. Indeed, this so-called technology inversion allowed ground stations

Table 1 The rapid increase of Intelsat satellite service capacity between 1965 and 1986

Satellite type	Year first deployed	Throughput capacity	Key new technologies
Intelsat 1 and 2	1965 and 1967	240 voice circuits	GEO-squinted beam antenna
Intelsat 3	1968	1200 voice circuits plus 2 TV channels	Spin-stabilized platform, conical higher-performance antenna
Intelsat 4 **Intelsat 4A**	1972 1976	4000 voice circuits plus 2 TV channels/6000 voice circuits plus 2 TV channels	Improved spin-stabilized platform, more transponders, higher gain antenna
Intelsat V	1981	12,000 voice circuits plus 2 TV channels	Three-axis body-stabilized platform, much higher gain antennas, spot beams
Intelsat VI	1986	60,000 voice circuits Plus 2 TV channels	Higher gain antennas, TDMA digital technology, improved spot beams

to decrease from 30 m dishes weighing over 20 t (and staffed with a crew of some 60–70 people) down to VSAT terminals 1 m in size and with no full-time staff required. The abrupt increase to more and more sophisticated satellite technology involved risks as to possible satellite failures due to unproven systems. The Intelsat III “despun” antenna, for instance, froze. This new type of antenna assembly rotated at about 60 rpm as the spinning satellite body spun in the opposite direction at 60 rpm. This arrangement allowed constant pointing of a higher gain antenna to the Earth below with increased accuracy. Rapid reengineering of the antenna bearings had to be undertaken, and the tolerance and lubricant for these satellites “despun mechanism” were changed. This rapid recovery was a success, but in this period of incredible growth, there was no timetable to allow in-orbit tests of the bearing structure (Pelton and Snow 1977).

When the Intelsat V satellite was being first designed, there were two conflicting designs. One anticipated a modest doubling in capacity through higher gain antennas and spot beam designs. The other was for a much more dramatic increase in technology with satellite spot beam and use of more complex switching technology known as the Harrington V – after the Vice President of Technology at Comsat at the time. This more ambitious approach was predicated on the creation of an experimental test satellite that would prove the viability of all the new technologies envisioned in such a new satellite design. The memory of the stuck “despun” Intelsat III remained with the Comsat engineers and Intelsat management committee. Ultimately it was decided that the Harrington V with an experimental test satellite and a series of new technologies represented too high of a risk. The lower-risk design for the Intelsat V was chosen. This approach did not require in-orbit experiments and technology verification. This decision was seen as the right commercial decision. At the time small satellite technology, small satellite constellations, and even small satellite experiments were not even considered an option. GEO satellites in Clarke orbit for telecommunications and radio and TV broadcasting were the predominant commercial satellite applications model. They were predominant because they could work in tandem with very low-cost dishes that could be constantly pointed to satellites without tracking. As the number of satellite dishes that could work to GEO satellites expanded into millions, this approach to commercial satellite services became a solidly entrenched paradigm. No viable design for low-cost tracking ground stations capable of working to LEO satellite networks existed.

The first significant change in how to design, test, verify, and manufacture application satellites for a global commercial market came with the small satellite constellations designed for low Earth orbit services that came in the 1990s. These low Earth orbit (LEO) systems included Iridium, Globalstar, and ICO, all of which were designed to provide new mobile satellite communications services to handheld units. In addition there were also the Orbcomm smallsat network for storing and forwarding data relay or machine-to-machine (M2M) communications. In the case of these services, the ground systems had to be able to track the LEO satellites or provide some form of an omni-antenna for system users that could receive the signal at all angles as it moved across the sky.

The key to these new services was the design of user antennas or transceivers to be used on the ground. What was important to the design of satellite hand phones that could talk to orbiting small satellites in LEO constellations were application-specific integrated circuit (ASIC) chips. These computer chips were vital to the improved performance of these new user devices in terms of performance and reduced costs. This new ground antenna technology enabled the performance of the various small satellite constellations that were deployed in LEO orbits beginning in the late 1990s. The design of such networks with 50–70 satellites in a constellation changed many aspects of how to design, verify performance, manufacture, and test the satellites for these new types of satellite systems.

It should be noted that this was not entirely new in that the US Department of Defense did deploy an Initial Defense Satellite Communications System (IDSCS) in 1965, but this was abandoned in favor of GEO systems after the success of the Intelsat system was also demonstrated in 1965. Also the Amateur Radio League did deploy its OSCAR satellites in LEO orbit, but these and other examples were the exception to the main thrust of commercial satellite applications.

In many ways the Iridium system was the technological leader in this effort to deploy LEO constellation for commercial satellite services. Its design was different in many ways. Instead of spot beams formed by a large reflector, the Iridium system used phased array antennas to form 37 beams (i.e., 12 beams formed with 3 different phase array systems plus a further beam directly downward). The Iridium network also included inter-satellite links (ISLs) that were key to the sparing philosophy for the system. This approach also reduced the cost of ground based network for tracking, telemetry, and command (TT&C).

Instead of launching experimental small satellites to test and verify performance of satellites for the Iridium system, it was decided to manufacture 100 satellites for the 66 satellite constellation with the idea that the earliest satellites for the constellation would test the performance and reliability of the network's design. The plan was that if flaws were detected with earlier satellite deployed, that adjustment could be made to satellites in the later production runs as needed. The 34 satellites beyond the 66 satellites needed for populating the full constellation could be built at modest incremental cost.

It was anticipated that some design upgrades could be made, modifications might be possible to extend lifetime, and most importantly the longer production run could provide for sparing if earlier satellites should fail. This philosophy was generally successful in that the network was first conceived of having a 7-year lifetime from 1997–1998 to 2004–2005, but the initial constellation lifetime extended to 2017–2018 or an amazing 20 years.

The thought was that any satellites not required could always not be launched to save on the total system cost.

Later LEO constellation satellite systems that were designed and deployed starting over a decade later such as the 3-unit CubeSats known as "Doves," as deployed by Planet Labs, in many ways perfected this approach. The first of the "Doves" were seen as prototypes and launched in small numbers, often as piggyback launches one or two at a time. When the design and performance were considered improved, then the shift was made to launching a large number at a time. This culminated in the launch of 88 “Doves” that were placed into orbit on an Indian Polar Satellite Launch Vehicle on February 14, 2017 (Graham 2017).

The price of the launch of experimental or technology verification missions is sufficiently costly that the number of such launches is limited. Nevertheless the history of the last 7 years and projections for the future as proved by Northern Sky Research shows that there have been a fairly constant number of such launches. Further projections for the future suggest that this level will likely continue for the future as more and more satellites are launched for Earth observation, communications, scientific, and other purposes. The dark blue (Technology Development) as indicated in Fig. 1 shows this forecast for the future.

The high cost of experimental satellite launches to test performance and verify new technology has limited this approach for the commercial satellite industry. The approach that has proven quite feasible and has come into more and more frequency use has been to put experimental packages and developmental performance or lifetime testing subsystems on board large missions as hosted payloads. Intelsat carried a router experiment known as IRIS (Internet Routing in Space) on one of its satellites as an experiment for the US Department of Defense that flew in 2009. Inmarsat developed the Alphasat hosted payloads set of experiments that was launched in 2013. The Hosted Payload Alliance has grown and matured since its formation a decade ago. One of prime functions of hosted payload missions has proved to be the test of new technology, regardless of whether these packages have been to test technology for small satellites or perhaps for larger satellites in MEO or GEO.

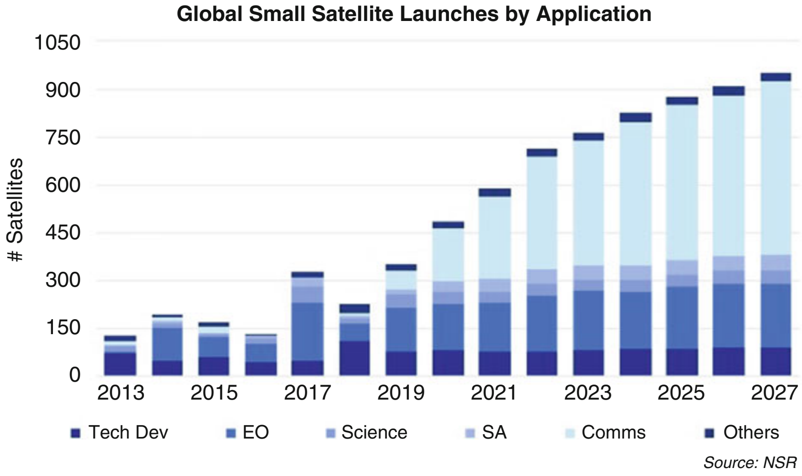


Fig. 1 Northern Sky Research projections of small satellite launches by function. (Source: Courtesy of Northern Sky Research)

3 IRIS Router on Intelsat

One of the early uses of a hosted payload onboard a satellite was to test a key new technology in an experiment known as the Internet Routing in Space (IRIS) as developed by Cisco and then flown as a package attached to the Intelsat 14 satellite. The purpose was to test the viability of onboard routers in order to prove the viability of "smart capability" on a satellite and in particular to assess the value of onboard frequency allocation. This thus became a low-cost way to provide a test of onboard signal regeneration and routing of signals to respond to changing demand. This test was the first instance of the US Department of Defense's Joint Capabilities Technology Demonstration (JCTD) providing a grant to commercial organizations to develop new technology and have it demonstrated in orbit on a commercial satellite (Cisco 2009).

Don Brown, then Vice President of Intelsat General for Hosted Payload, was quoted saying: "IRIS is another example of how hosted payloads allow rapid demonstrations and introductions of powerful new space technologies. This project took less than 3 years from start to launch, showing that the government can evaluate a pivotal new technology in space within a very short period." (ibid.) (see Fig. 2).

There were a number of other hosted payload experiments that preceded and followed on to the IRIS experiment. These included (i) the X-band communications package that flew on the Anik G1 satellite; (ii) the Wide Area Augmentation Service (WAAS) package designed to augment the accuracy of GNSS services provided by GPS Navstar satellites that flew on the Galaxy 15 satellite; and (iii) the UHF package that is flying on the Intelsat 22 satellite. These various hosted payload flights are all examples of technology verification flights (Pelton and Madry 2018).

Fig. 2 The quite large Intelsat 14 epic satellite with small hosted payload IRIS technical verification package aboard. (Graphic Courtesy of Intelsat)

4 ESA's Alphasat Project (Also Known as Inmarsat 4A-F4 or Inmarsat XL)

Alphasat was launched into geosynchronous orbit at 25° East on July 25, 2013. This launch occurred from the European Spaceport in Kourou, on an Ariane V ECA which is the latest configuration of this heavy-lift launcher. The prime mission for this very large and complex satellite with a mass of 6649 kg (14,659 lb) was to provide mobile communications satellite services for the European, Middle Eastern, and African regions of the world and to supplement the capabilities of the other series of four Inmarsat satellites. This was one of the largest satellites ever launched into GEO and is at the opposite extreme of what might be called a small satellite.

Yet the Alphasat part of the mission, as funded by the European Space Agency, was designed to offer a number of opportunities for hosted payloads to undertake technology verification for new smaller satellite space programs to be tested during the 2013–2016 period designated for these ESA-fund experiments.

This Alphasat experimental undertaking proved to be quite successful for the initial 3-year in-orbit demonstration period. This program jointly administered by ESA and Inmarsat and carried out under a public-private partnership agreement was extended for an additional 3 years that began on January 1, 1917 and ended on December 31, 2019 (https://artes.esa.int/news/alphasat-hosted-payload-extension).

The four extended verification tests that were conducted on the ESA-funded Alphasat programs were as follows (Alphasat I):

- **DP1**: This hosted payload package was developed to test a further evolution of an advanced design for an advanced LCT (Laser Communication Terminal). This test of laser inter-satellite links (ISLs) and laser communications terminal (LCT) design constitutes a continuing development of already existing flight hardware that ESA has funded and tested. Thus this latest LCT experiment is an extension of the developments associated with the TerraSAR-X, NFIRE, and TanDEM-X tests. All of these tests were designed to create a reliable and high-performance data link via laser communications to connect satellites in GEO and low Earth orbit. The objective of these high-data rate transmissions was to test optical links operating at 1064 nanometers with data speeds of up to 1.8 gigabit per second. This test is also used for comparative purposes of inter-satellite link operating in the extremely high frequency via Ka-band ISL developed by Tesat-Spacecom (Germany). The payload was funded by DLR, the German Space Agency.
- **TDP5**: This experimental package tested the transmission reliability of two experimental Q/V-band communications transponders. In particular it examines the sustainability of service during heavy rain rate conditions and the precipitation attenuation mitigation techniques. This type of testing will continue to be the key for many of the new small satellite constellations for communications and networking that are intended to operate in these extremely high-frequency bands such as the Starlink constellation and others planning to operate in the Q/V-band. This technology verification and demonstration package was developed by TAS-I and space engineering of Italy.

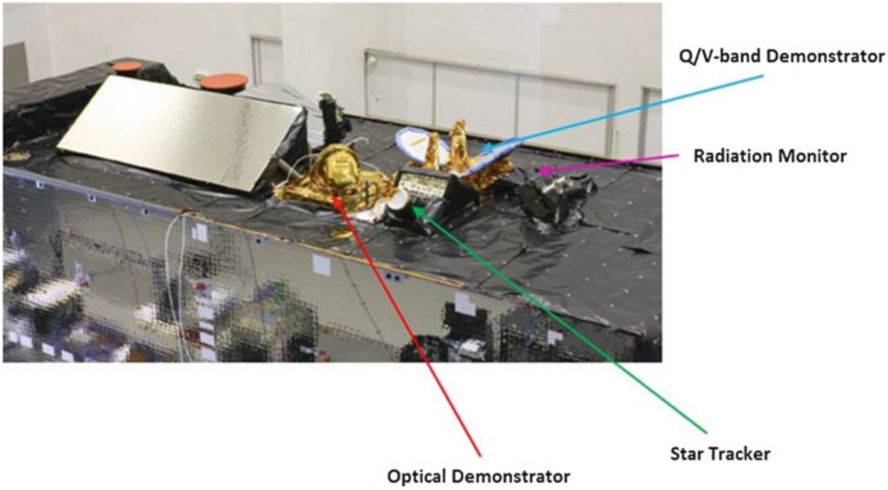


Fig. 3 The massive Alphasat/Inmarsat XL spacecraft under construction with location of the four hosted payloads identified. (Graphic Courtesy of the European Space Agency)

- **TDP6**: The hosted payload project was designed to demonstrate the performance of an advanced Star Tracker with and new type of active pixel detector. This experimental package was developed and built by Jenoptik of Germany.
- **TDP8**: This hosted payload project undertook to demonstrate the performance of an environment effects facility. The purpose of this project was to monitor the GEO radiation environment and its effects on electronic components and sensors. The results of these extended experiments can be useful in the future to the design of both commercial and scientific satellites. This hosted payload experiment was developed by Effacec of Portugal.

These various experiments in the form of hosted payloads are examples of how hosted payloads can provide cost effective technology verification programs. Such an approach allows a form of small satellite mission without the need for separate launches and separate operational control of in-orbit satellites and also allows shared access to common source of energy and a stable three-axis platform. The graphic below shows the four experimental packages for technology verification on the massive Inmarsat XL platform (see Fig. 3).

5 Cost Associated with Hosted Payload Missions

Although the costs associated with a hosted payload can be considered to be lower than a dedicated mission which entails a dedicated arrangement for launch services and other costs associated with launch insurance and operating costs, there are still substantial costs involved. The results of a study carried out by NASA engineers of

Langley Research Center sought to assess the costs and benefits of such a hosted payload approach to experimental packages came up with the assessment of five different projects. The conclusion from their study assessment as to total implementation costs except for operational costs varied from $6.6 million at the low end and up to $15 million for a projected 50 Kg payload. The projects that were evaluated included (i) two L-band experiments launched in 2005 on Telesat and Intelsat satellites; (ii) a VHF communications package on an Orbcomm satellite to validate the ability to provide automatic identification services in 2008; (iii) the IRIS router on the Intelsat 14 in 2009; (iv) an infrared sensor on an AGS satellite in GEO; and (v) a UHF package that flew on an Intelsat satellite in 2012 (Andraschko et al. 2019) (see Table 2).

What is significant with regard to the data collected in this comparative study of hosted payloads undertaken to demonstrate and verify technology with regard to new types of satellite services and key technical systems is the similarity of the costs per kilogram for these various experimental packages. The cost per mass of these technology verification missions did not vary significantly across these five packages. Thus even though there were different governmental agencies conducting the experiments, different suppliers of the payloads, different spacecraft system operators, and different providers of the launch services. The results on the cost of hosted payload were summarized by the NASA analysts in this way:

> The model indicates that the payload hosting costs increase by about $0.175M per kilogram. The result is that the model estimates a cost of $15M to host a notional 50 kg payload. (ibid.)

The advantages that hosted payloads provide, however, would seem to decrease as the cost of launching payloads decrease as new and more cost-efficient launchers optimized for small satellites come online. New providers such as Vector, Rocket Labs, and LauncherOne by Virgin Orbit and nearly a dozen new start-up companies are delivering or promising launch capabilities in $150,000 per kilogram down to around $60,000 per kilogram. Those promising the lowest costs have yet to deliver on their cost projections nor a track record of reliable launch operations.

6 Smallsat Launchers and Technology Verification and Experimental Projects

Certainly another key to the viability of experimental small satellites and test and verification missions comes with reliable smallsat launchers. Many of those seeking to deploy large-scale constellations with a network of small satellites begin by the launch of experimental spacecraft to test the design of these systems. One of the first of these was the TinTin experimental satellites launched for initial test of the SpaceX system and spacecraft design. The test satellites demonstrated that lower orbits might be effectively used and transmission efficiency might be greater than first anticipated by network designers (Wall 2018) (see Fig. 4).

Table 2 Comparative chart of five hosted payload programs with governmental and commercial industry participation

Comparative assessment of different technology verification missions							
Payload	Payload type	Customer	Owner/ operator	Spacecraft Provider Boeing	Payload provider	Launch vehicle	Launch date
WAAS to augment GPS	L-band communications	US Federal Aviation Admin.	Telesat and Intelsat	EAS Astrium and &Orbital Sciences	Lockheed Martin	Proton (Telesat) ArianeV (Intelsat)	Sept. 2005 Oct. 2005
Automatic Identification Service (AIS)	VHF Communications	US Coast Guard	Orbcomm	Polyot	Orbital Sciences	Cosmos	June 2008
Internet Router in Space-IRIS	IP Router	Dept. of Defense	Intelsat 14	Space Systems/Loral	Cisco	Atlas V	Nov. 2009
CHIRP	Infrared sensor	US Air Force	AGS	Orbital Sciences	SAIC	Ariane	3rd quarter 2011
ADF UHF	UHF communications	ADF	Intelsat 22	Boeing	Boeing	Proton	June 2012

This chart depicts the date provided in the NASA Langley Research Study referenced below

Fig. 4 The TinTin prototype satellite for technology verification for the Starlink constellation. (Graphic Courtesy of SpaceX)

Reliable and low-cost small launchers provide another option for small satellite development, proof of concept flights, and even operational deployment. There are many new smallsat launcher companies promising the possibility of reliable operations, flexible on-demand scheduling, and low-cost launches.

Rocket Labs, for instance, successfully launched three experimental satellites for the US Air Force in May 5, 2019, from its New Zealand launch facility. This launch, plus another in late March 2019, was contracted by the US Department of Defense. The recent record of launch by the Electron vehicle by Rocket Labs provides a confirmation of both consistency of reliable launch operations and low cost for insertion into LEO orbit for small satellites.

The total payload for the May 2019 mission was 180 kilograms. Both of the CubeSat missions were to prove the feasibility of the technology. The Falcon Orbital Debris Experiment (Falcon ODE) was designed to help researchers evaluate the effectiveness of ground-based systems for tracking space junk and possibly diverting space debris from the ground to avert collisions. The other CubeSat known as the Space Plug-and-Play Architecture Research CubeSat-1 (SPARC-1) was designed to test in low Earth orbit the performance and accuracy of super small avionics gear and other electronic components (Wall 2019).

There are currently about 40 smallsat launch companies, beyond those already mentioned, that are seeking to bring their new low-cost launch capabilities to the fore. Many of these start-ups are presented in Part 13.3 of this handbook. These start-ups include such firms as ABL Space Systems, Aphelion Orbitals, Bagaveev Corporation, bspace, Celestia Aerospace, Cloud IX, CONAE, CubeCab, CTA of Brazil, Gilmour Space Technologies, Horizon Space Technologies, iSpace, Israel Aerospace Industries, Landspace, Launcher Inc., LEO Aerospace, Link Space Aerospace Technology, Naro Space Center (together with GKNPT Khrunichev), NADA, One Space Technology (Zero One Space), Orbex, Orbital Access, PLD Space, Reaction Engines Ltd., Relativity, Rocket Crafters Inc., Rocket Star, Skyrora Space Technologies, Space Ops, Spaceflight Industries, Space Launch Services, SpinLaunch, Stofield Aerospace, UP Aerospace, and Valt Enterprises.

Clearly not all of these new firms will succeed. There has been speculation in the press as to which of these firms will be able to raise the capital, develop the technology, establish a record of launch success, and acquire the customer-based sufficient to establish themselves as a player in the market. The closely related question is whether this stabilized market will produce a more or less stabilized price for launch services in the range between $50,000 and $100,000 per kilogram. Only some of these 40 firms can succeed. The outcomes that will be clear by the mid-2020s will impact small satellite launch costs and the feasibility and frequency of in-orbit tests of new technology (Foust 2019).

7 Conclusion

The evolution of the space industry and the increasing sophistication in the design, engineering, manufacturing, qualification testing, deployment, operation, and deorbiting of spacecraft at the end of life can be demonstrated in many ways. Perhaps the most important question for system designers is what is the best way to design a small satellite constellation so that it uses the best technology in the most cost effective way and also operates reliably for its full lifetime.

There is now a wealth of knowledge and new expertise in how this might be accomplished. The various ideas and methods about how this might be combined together in an overall design and implementation plan can now draw upon a great deal of knowledge built up on basis of how both large and small satellites are designed, tested, manufactured, and deployed. The number of questions that need to be asked and answered is today quite interesting and indeed almost intriguing. Some of these questions include:

(a) How many satellites are optimum to design and build not only to populate a small satellite constellation but also to provide for prototype technical and operational testing, in-orbit spares, and on-the-ground spares?
(b) Should there be a test of key technologies for reliability verification or sustainability of service (such as in the case of high rates of precipitation attenuation in the case of extremely high-frequency spectrum such as in the q/v or even w bands)?
(c) If there is a need for such technology verification, how might this be best conducted? Should this be through orbital tests, and if so should this be via hosted payload tests that can be flown on a larger satellite mission or via a consolidated series of experiments combined in a single launch or some other process?
(d) Should the early prototype satellites in a large-scale LEO smallsat constellation be considered as verification missions for the satellite design, performance, and operational methods and ground antenna systems.

(e) If the early prototype launches are test systems, what flexibility is there to modify the design for later production runs? Are test parameters related to orbital characteristics, digital processors, software-defined services, phased array antenna design, sensor functionality and/or resolution, interference mitigation techniques, power system design, or other design characteristics?

(f) If design parameters are changed and required that later production models of smallsats to have greater mass or volume, are launch arrangements sufficient to accommodate such changes?

(g) Should in-orbit tests and design modifications be limited to software upgrades or are changes to the physical design of the spacecraft considered viable?

(h) Are there particular volumes of satellite production runs that achieve particularly significant levels of scale economies? Are there methodologies to determine where such economies of scale are possible?

(i) Which particular components or subsystems or operational procedures are most in need of quality or lifetime testing, in-orbit test, or technology verification?

(j) What are the particular concerns related to sparing, replacement of a failed satellite, end-of-life deorbit, or elimination of RF interference, and can these be addressed via in-orbit testings?

(k) Can the experience of small satellite system operators be effectively used to address any of the above questions, and can reliance on this experience replace the needs for in-orbit testing and technology verification?

(l) Can the use of artificial intelligence (AI) spacecraft system management systems assist in creating improved "fail-safe" management systems that can assist with avoiding orbital collisions or near conjunctions, or allow more efficient operations associated with end-of-life spacecraft removal, or replacement of failed satellites? If so how can such systems be tested and introduced into satellite constellation management?

(m) Should a small satellite command and control system be encrypted against possible hacker attacks and should tests be undertaken to access the potential vulnerability of a network's TT&C system be vulnerable to attack (Foust 2018)?

These are only some of the questions that need to be addressed with regard to the design and implementation of a new small satellite constellation. In many cases the key question is whether some sort of in-orbit testing is needed to assist in answering many of these questions. The most difficult and challenging question is whether the cost and time delay associated with such possible tests are considered sufficiently beneficial to the successful operation of a small satellite constellation and whether computer simulations or other methods can eliminate the need for in-orbit tests.

8 Cross-References

- ▶ Scientific Discovery and Geomagnetic Monitoring in Earth Orbit using Small Satellite Systems
- ▶ Student Experiments, Education, and Training with Small Satellites

References

Alphasat I / Inmarsat-XL (Inmarsat-Extended L-band Payload), InmarSat-4A F4. Last accessed 28 June 2019. https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/alphasat

M. Andraschko, J. Antol, S. Horan, D. Neil, Commercially Hosted Governmental Payloads: Lessons from Recent Programs. *Researchgate.com*, June 25, 2019. https://www.researchgate.net/publication/224229171_Commercially_hosted_government_payloads_Lessons_from_recent_programs

Cisco, Cisco Router Sent Into Space Aboard Intelsat Satellite, Nov 23, 2009. https://www.cisco.com/c/dam/en_us/solutions/industries/docs/gov/Cisco_Intelsat_IRIS_release.pdf

J. Foust, No Encryption, no Fly" Rule Proposed for Smallsats. *Space News*, Aug 9, 2018. https://spacenews.com/no-encryption-no-fly-rule-proposed-for-smallsats/

J. Foust, Smallsat Industry Faces New Challenges to Growth. *Space News*, Feb 5, 2019. https://spacenews.com/smallsat-industry-faces-new-challenges-to-growth/

W. Graham, India's PSLV Launch Vehicle Launches a Record 104 Satellites. *NASA Spaceflight.com*, Feb 14, 2017. https://www.nasaspaceflight.com/2017/02/indias-pslv-record-104-satellites/

https://artes.esa.int/news/alphasat-hosted-payload-extension. Last accessed 28 June 2019

J.N. Pelton, S. Madry, Innovations in hosted payload satellite services, in *Handbook of Satellite Applications*, vol. 2, (Springer Press, Switerzerland, 2018), pp. 1223–1230

J.N. Pelton, M. Snow, *Economics and Politics in Satellite Telecommunications* (Praeger Special Studies, New York, 1977)

J. N. Pelton, J. Oslund, P. Marshall (eds.), *Satellite Communications: Global Change Agents* (Lawrence Erlbaum Associates, Mahwah, 2004)

M. Wall, SpaceX's Prototype Internet Satellites are Up and Running. *Space.com*, Feb 22, 2018. https://www.space.com/39785-spacex-internet-satellites-starlink-constellation.html

M. Wall, Rocket Lab Launches 3 Experimental Satellites for the Air Force. *Spaceflight*, May 5, 2019. https://www.space.com/rocket-lab-launches-air-force-satellites.html

French Space Programs for CubeSats and Small Scientific Research Probes to Deep Space

Pierre Bousquet

Contents

Abstract

French involvement in affordable deep space missions has been illustrated over the last few years by the accomplishments of the Philae lander in 2014 and by the mission of the MASCOT lander, developed with DLR, which was delivered on October 3, 2018, by JAXA's Hayabusa2 probe on asteroid Ryugu. The value of CNES dedicated engineering skills, such as mission analysis for the descent to small bodies, and of French laboratories' know-how in the development of high-performance miniaturized instruments has been demonstrated on both missions. It will be put into practice again through CNES' contribution to JAXA's MMX mission to Phobos in 2024, and more mission concepts are also being defined in partnership with major space agencies. In addition, CNES is also in

---

P. Bousquet (✉)
Science project Department, French Space Agency, CNES, Toulouse, France
e-mail: Pierre.Bousquet@cnes.fr

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_102

charge of deep space instrument operations, notably at the moment for two NASA's Mars missions, the Curiosity rover and the InSight lander. This general background will be elaborated in this article, together with French early microsatellite achievements through the Myriade family and with recent CubeSat development that culminated on December 18, 2019, with the simultaneous launch of the ANGELS 12 U Argos NEO demonstrator and of the EyeSat 3 U student astronomy spacecraft.

The second part of the presentation will elaborate on mission architectures for the most promising concepts that CNES has studied or been associated to where CubeSat class probes offer an advantage in terms of affordability, efficiency, and capacity to take risks. In some cases, typically between Venus and Mars, the small probes can operate as stand-alone missions of their own within the inner solar system. Alternatively, they can also augment larger missions to the most remote and challenging destinations in the solar system.

While microsatellites are affordable, and increasingly more capable, they should not be considered as a replacement for more traditional missions that require multiple coordinated measurements to accomplish their science investigation goal. Additionally, larger spacecraft remain far more powerful and can go to more remote locations and survive longer-duration missions and challenging deep space environments. Under many circumstances, however, large spacecraft can benefit greatly from the risk capacity provided by small probes that can be added on and from the multipoint capacity that they can provide.

Keywords

CubeSat · Small probes · Landers · Deep space · Planetology · Space exploration · Instrumentation · Miniaturization · Heliophysics · Magnetophysics

1 Introduction

By necessity, the size of several historical missions to deep space was very restricted. In 1959, the 278 kg Soviet Luna 3 was the first ever spacecraft to photograph the far side of the Moon. Earlier in the same year, the first probe of the United States to escape from the Earth's gravity, Pioneer 4, at 6.1 kg, would be called a nanosatellite with today's terminology. At the end of the 1960s, the Pioneer 6–9 probes successfully investigated the solar wind and cosmic rays with a fleet of 62 kg spacecraft in heliocentric orbit. Telemetry contact was still achieved with Pioneer 6 in 2000, 35 years after its launch. In the 1970s, the Pioneer 10 and 11 probes, 260 kg each, were the first probes to pass the asteroid belt and to send back close-up images of Jupiter and Saturn. All these early examples have demonstrated that small probes can contribute greatly to deep space exploration. However, with the increase of launcher performance and the availability of high-performance – resource-demanding – instruments, the general trend of planetary missions until recent times has relied more and more on sophisticated spacecraft, in general of metric ton weight or above.

The success of the little Sojourner rover of the Mars Pathfinder mission in 1997 can be considered as a turning point toward using miniaturized robots for modern deep space endeavors. It corresponds to a period when miniaturization of technologies has started to progress tremendously and when computation capacities have become available for little onboard resources. More recently, the last decade has seen the emergence of CubeSats based on 1 kg–1 liter standardized units, notably from new space actors such as universities. The availability of cheap ultraminiaturized technologies brought by the very dynamic progress of CubeSats opens the way to innovative solutions for planetary missions, notwithstanding their specific – highly demanding – requirements. This has been illustrated over the last year through the various deployments of several auxiliary landers and of a free-flying camera within the frame of JAXA's Hayabusa2 mission around asteroid Ryugu (Yano 2019) and through the tremendous coverage and data relay of the Mars entry of the InSight lander by JPL's pair of MarCO CubeSats (Klesh 2019).

In collaboration with the very dynamic French research institutes in planetology, as a major actor in solar system exploration, CNES participates to all the missions of the European Space Agency in this field and has the privilege to cooperate with the main space agencies who send probes to deep space (NASA, Roscosmos, JAXA, and CNSA). CNES' contributions are mostly instrumental, but it also takes responsibility of operations, notably at the moment for two Mars assets, the Curiosity rover and the InSight lander. In line with operations, CNES provides regularly its expertise in space mechanics, in particular in the area of small bodies. CNES was among the pioneers in small deep space probes through the development of the MASCOT lander in cooperation with DLR, which was delivered to the surface of asteroid Ryugu by JAXA's Hayabusa2 probe on October 3, 2018. CNES considers that miniaturized technologies open new perspectives and valuable mission schemes for solar system exploration and is determined to diversify French contributions and optimize the scientific benefit of future missions. After identifying critical technologies, this article will elaborate some promising mission concepts where CubeSat-sized devices offer an advantage in terms of affordability, efficiency, and capacity to take risks. The spacecraft that will be discussed encompass orbiters and non-orbiting probes, lander, rovers, and the large variety of autonomous robots that can contribute to the exploration of distant objects.

2 Background

2.1 Small Satellites at CNES Before CubeSat Days (Landiech and Rodrigues 2010)

The development of the Myriade microsatellite line of product was initiated by CNES at the end of the 1990s, in partnership with Thales Alenia Space and Airbus Defence and Space. Since 2004, 18 microsatellites built around CNES' Myriade spacecraft bus have been placed into Earth orbit. Their mass range was from 100 to 200 kg. They aimed at low-cost, fast-track development while preserving high performance for a wide range of scientific, military, technological, and commercial purposes. Most of these satellites were launched to LEO, but two were also delivered to GTO.

The track record of the Myriade family is excellent. All 18 satellites launched so far have exceeded their specified lifetime. In addition, through this deployment, CNES also worked closely with Arianespace toward launcher interface solutions for auxiliary passengers which have been implemented on Ariane 5, Soyuz, and Vega and will be the basis of future offers on Ariane 6. CNES also gained customer experience of launching as a secondary payload. Within the frame of Myriade, CNES also provided partners and customers with a ground segment for in-orbit satellite command and control and developed high-efficiency operational schemes. One of the last members of the Myriade family, the TARANIS scientific satellite, will be launched in 2020 on Soyuz from the Guiana Space Centre (Bastien-Thiry and Privat 2019).

2.2 Ongoing CubeSat Developments

CNES is actively involved in this segment, reflected in projects such as the ANGELS demonstrator, with a view to structuring a nanosatellite ecosystem, and JANUS, which supports the development of CubeSats by students.

ANGELS (Argos Neo on a Generic Economical and Light Satellite) is the first nanosatellite designed and developed by French industry with support from CNES. Thus 25 kg – 12 U – CubeSat carries Argos Neo, an instrument ten times smaller and consuming three times less power than the generation of Argos data collection instruments previously in orbit. CNES and French firm HEMERIA have co-funded and developed ANGELS with a resolutely New Space approach to governance, design, development, and testing, systematically employing miniaturized commercial off-the-shelf (COTS) components. This approach comes with a certain degree of risk, but enables big reductions in costs and lead times. ANGELS (Fig. 1) has been delivered to its LEO orbit on a Soyuz launcher on December 18, 2019, from the Guiana Space Centre. HEMERIA is now ready to offer a whole range of nanosatellites in the 10-to-50-kg category for scientific and operational missions such as data collection and location from transmitters, maritime surveillance, radio-frequency spectrum surveillance, and Earth observation.

The JANUS program, initiated by CNES in 2012, aims to engage students in universities and engineering schools and get them interested in space by helping them to develop their own very instrumented CubeSats tipping the scales at 1 to 10 kilograms. EyeSat has been developed by CNES for the Janus program. This 3 U CubeSat equipped with a small space telescope called IRIS is designed to study the zodiacal light and the Milky Way. The mission has a threefold objective of acquiring science data, demonstrating new satellite technologies, and readying students for careers in space engineering. EyeSat has been launched on December 18, 2019, together with ANGELS. It has demonstrated soon after reaching its orbit a pointing


© CNES/ESA/Arianespace/Optique Vidéo CSG/JM Guillon, 2019

Fig. 1 Integration of ANGELS on Soyuz auxiliary payload structure

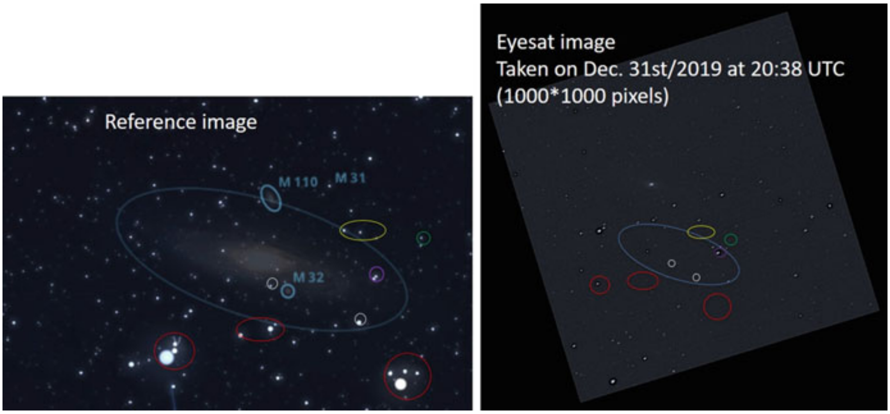


Fig. 2 Andromeda (M31) imaged by EyeSat – credit CNES

knowledge and stability of less than 0.1°. Its first picture of the sky, Andromeda (M31), is shown in Fig. 2.

2.3 Small Probes to Deep Space Realized or Underdevelopment

After the huge success of the Rosetta mission and the Philae landing on comet Churyumov-Gerasimenko, the small lander MASCOT (Mobile Asteroid surface SCOuT) has been developed by the German Aerospace Center (DLR) in cooperation with CNES. Its main objective was to perform in situ investigations of the surface of asteroid Ryugu and to support the sampling site selection for its mother spacecraft, JAXA's Hayabusa2 sample return spacecraft. After a 4-year cruise and more than 1 year around asteroid Ryugu, it was delivered by Hayabusa2 on October 3, 2018. It went through a free fall of ~ 6 minutes (Fig. 3) and a bouncing phase of ~ 11 minutes

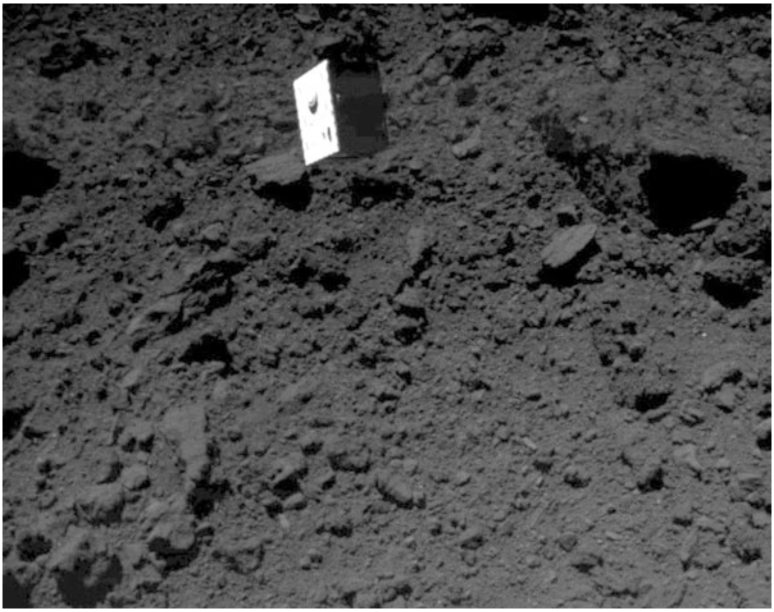


Fig. 3 An image taken during descent by the camera MASCam © JAXA, University of Tokyo

before it finally came to rest at its first settlement point where it entered into its on-surface operational mode. The lander was able to perform science measurements with its payload suite at three locations on Ryugu. After about 17 hours of operations, exceeding its target lifetime, the MASCOT mission terminated with the last communication contact (Tra-Mi et al. n.d.).

DLR was responsible for developing the MASCOT lander and ground segment and was in charge of planning and conducting lander joint operations from MUSC. CNES supplied antennae and power system, provided a support to operations, and was in charge of the flight dynamics aspects of the mission (Moussi et al. 2018). Asteroid surface science is obtained by four experiments: MicrOmega, a near-IR hyperspectral microscope provided by IAS; MASCAM, a wide-angle Si CMOS camera with multicolor LED illumination unit; MARA, a multichannel thermal infrared radiometer; and MASMAG, a magnetometer provided by the Technical University of Braunschweig. The MASCOT lander includes an internal mobility mechanism, a GNC sensor package, and an onboard autonomy software that enable MASCOT to self-right itself and to perform relocation leaps on the asteroid surface. A redundant onboard computer (OBC) provides autonomous control, command and data handling, and preprocessing power. Power is supplied by primary battery via a redundant power sub-system (PCDU). Even though it was not built on the basis of standard CubeSat units, with a 9.8 kg mass (including its 3 kg payload) and a volume of 0.28 × 0.29 × 0.21 m^3, MASCOT fits within the format of CubeSat (Fig. 4). In fact, since its development started in 2010, it can be considered, together with

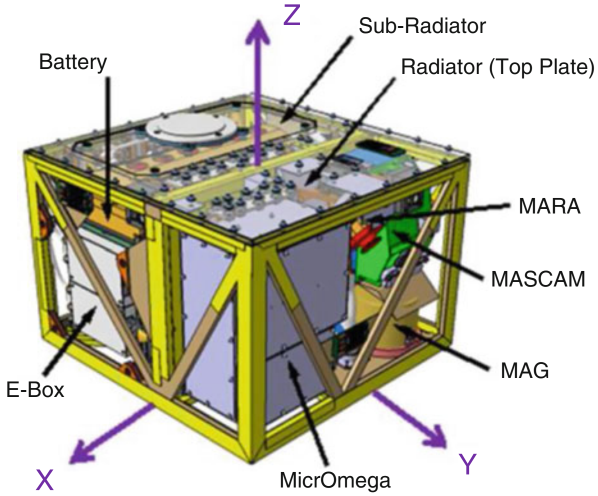


Fig. 4 Schematic of MASCOT lander – credit DLR

JAXA's small MINERVA rovers (that were also part of Hayabusa2) and JPL's Mars relay spacecraft MarCO, as one of the precursors of small deep space probes.

With the same partners as for MASCOT, CNES has started with DLR in late 2019 the phase B of the development of a small-wheeled rover that will be delivered in 2026 to the surface of Mars' moon Phobos by JAXA's sample return mission MMX (Tardivel and Lange 2019). This low-cost and lightweight rover – 25 kg in a 40 × 37 × 23 cm volume – again corresponds to the format of large CubeSats and will use extensively avionics developed for CubeSats. Jettisoned to the surface of Phobos from a low altitude, the rover will autonomously upright and deploy itself from a stowed position. Then, over the course of 3 months, it will carry out its technical and scientific objectives. First, it acts as a scout, experiencing Phobos soil before MMX, de-risking its landing and sampling operations. Second, it is a full-fledged science explorer, with payloads designed to complement or reinforce MMX scientific investigations. Figures 5 and 6 provide an overview of the rover's subsystems and of their provider (CNES or DLR).

2.4 Instrumentation and Onboard Technologies

In collaboration with French planetology, exobiology, and heliophysics/magnetophysics laboratories, CNES has provided an extensive range of scientific instruments for deep space missions over the last years. For future CubeSat applications, a non-exhaustive list of the most relevant families of instrument that are already miniaturized or will be through future R&D efforts can be elaborated:

- Optical camera, in particular the CASPEX color CMOS Camera that will be on board SuperCam on Mars 2020 and on the MMX rover and is proposed on the TeamIndus Moon rover (Virmontois et al. 2019).

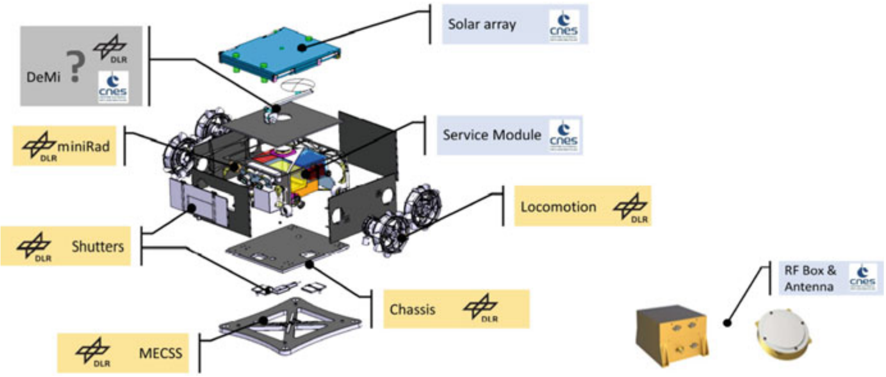


Fig. 5 MMX rover inventory and sharing of sub-systems – top level – credit CNES

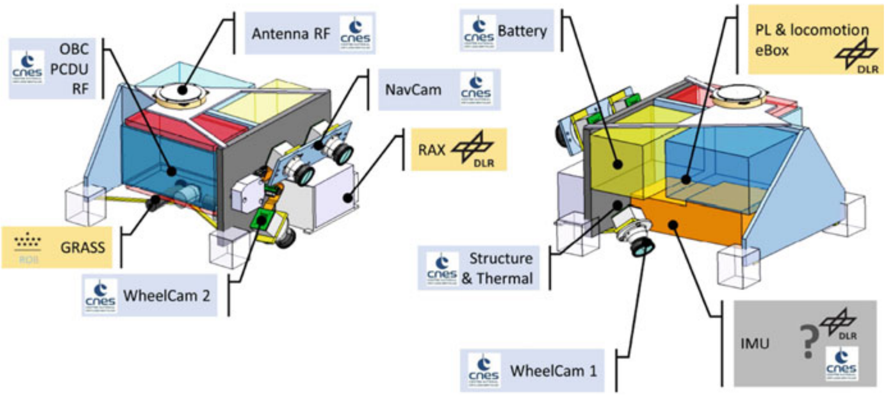


Fig. 6 MMX rover inventory and sharing of sub-systems – service module – credit CNES

- LIBS and Raman spectrometers, where CNES has accumulated an extensive know-how for the Curiosity, Mars 2020, and ExoMars rovers and is considering the development of miniaturized versions (Wiens et al. 2016).
- Hyperspectral infrared microscope (already flown on MASCOT and ready for flight on ExoMars' rover) and spectrometers (will be on board MMX spacecraft) (Royer et al. 2019).
- Chromatography columns for high-resolution mass spectrometers (flown on Curiosity and ready for flight on ExoMars' rover (Buch et al. 2015)), which are currently being miniaturized with MEMS technology.
- High-resolution mass spectrometer based on Orbitrap © technology (Briois et al. 2016).
- Seismometers, with extremely high accuracy solutions such as the SEIS instrument used on Mars for the InSight mission, or coarser sensors such as miniature geophones that can be used for active seismology on small bodies (Murdoch et al. 2017).

- For magnetic measurements, in addition to a wide range of AC and DC sensors, the magnetic cleanliness issue will be solved through measuring the disturbances produced by the CubeSat and setting the sensors at the end of a boom currently developed in CNES' R&D program.
- Langmuir probes, ion and electron spectrometers, and mutual impedance probes are also available: French laboratories will actually provide the electron spectrometer and the plasma sensor of the Comet Interceptor mission (Jones 2019). The development of a miniaturized version of the mutual impedance probe has recently started at R&D level.

In addition, through its extensive experience in Earth observation missions, CNES has developed a very broad image processing expertise which can be highly beneficial to exploration with small probes. These missions need to be autonomous and are generally restricted in terms of telemetry rate: autonomous target choice, onboard image processing and selection, and high-performance compression will be crucial assets that CNES is currently working on.

For spacecraft technologies, CNES' plan is to build upon the solutions developed for ANGELS and for the Janus program, with specific adaptations required by the deep space conditions and mission configuration. In the short-medium term, CubeSats can provide efficient stand-alone solutions for deep space missions between Venus and Mars (including the Moon and near-Earth objects), and the range of critical technologies (qualification to radiations, low-thrust propulsion, communications) shall be extended accordingly. For more distant targets, CubeSats will generally be used under a daughtership/mothership scheme; CNES focuses in this respect on the relative navigation issue and on high-performance inter-satellite link equipment that will be compatible with radio science.

2.5 Flight Dynamics and Operations

As can be seen in the next section, mission concepts using small probes are regularly proposed for the exploration of small bodies or small moons such as for the MMX rover (Virmontois et al. 2019). Orbiting around and landing on these bodies is very challenging, due to the low-gravity environment, the irregular shapes, and the modelling uncertainties of the forces in the close vicinity of the target body. CNES' Flight Dynamics department has acquired a tremendous experience in this area through its responsibility in the preparation and execution of Philae's landing on Churyumov-Gerasimenko and of MASCOT's landing on asteroid Ryugu. It will now be in charge of the landing of the MMX rover on Phobos and support JAXA in the flight mechanic analyses of the MMX mothership for its quasi-orbiting operations around Phobos and its sample collection sequences at the surface (Lorda et al. 2019). French support to the flight dynamic studies of the CubeSats that will orbit the Didymoon asteroid under the frame of the HERA planetary defense mission (Carnelli et al. 2019) is also under consideration. CNES is determined to keep consolidating its position as a major partner in flight dynamics support for future deep space and exploration missions by proposing its expertise, notably for small body applications.

As far as operations are concerned, CNES has an extensive record in operating Earth orbit satellites of all categories, in contributing to ISS operations, and since 2012 in operating instruments at the surface of Mars within the frame of the Curiosity and InSight projects in cooperation with NASA, and it has contributed to Philae and MASCOT operations (Barde and Jocteur 2017). The next logical step should be to operate small deep space probes in the recently created French Operations Centre for Science and Exploration (FOCSE), and CNES is determined to do so in the next decade.

3 Mission Concepts

Examples of mission architectures, studied by CNES independently or in collaboration with potential partner, are associated below to a spectrum of microsatellite and nanosatellite mission “classes” that range from enhancing to enabling and present a definitive advantage in terms of affordability. It can be observed that in some cases, the small probes can operate as stand-alone missions of their own within the inner solar system. Alternatively, they can also augment larger missions to the most remote and challenging destinations in the solar system.

3.1 Technological Demonstration

Two types of demonstrations that could be performed by small spacecraft and be extremely beneficial for future major Mars exploration missions will be emphasized here.

The Mars Sample Return (MSR) Mission currently planned toward the end of this decade requires the detection, localization, and capture of a free-flying orbital sample container: following the ascent of the Mars Ascent Vehicle from the Martian surface, an orbital sample will be released in Mars orbit. At a long relative distance, the MSR Earth Return Orbiter will perform search and detection, approach to rendezvous with and capture the orbiting sample. The search and detection phase, in particular, is very challenging and requires the use of a long-range optical detection by a narrow-angle camera. The early realization of this critical phase by a CubeSat in low Earth orbit would be very valuable to prepare, and ESA has emitted an invitation to tender for such a project at the end of 2019 (Cubesat n.d.).

Aerocapture could valuably be demonstrated at Earth or ideally at Mars by a probe in the range of 100–200 kg, either as an add-on to a larger mission or stand-alone (Sudars and Regnier n.d.). In the frame of the technology development for human Mars exploration, the aerocapture of a vehicle in Mars’ environment needs to be demonstrated. The aerocapture technology is considered as critical to insert heavy vehicles in Mars’ orbit.

The demonstration objectives are:

- To execute an aerocapture in a fully relevant environment and to test specific guidance navigation control techniques and algorithms in a realistic environment
- To contribute to the precise data acquisition of the Martian atmosphere
- To get a better understanding of the parietal heat flux during the Martian atmospheric entry, particularly at the back of the vehicle

3.2 Small Body Reconnaissance and Characterization

The relative accessibility of some near-Earth objects makes them reachable by stand-alone CubeSats, particularly for flybys. CNES has participated in 2019 to a study performed by the University of Strathclyde that showed that pairs of 12 U nano-satellites using low-thrust propulsions could travel together on multi-target flyby trajectories and be designed to be flexible to suit many different target sets (Walker et al. 2019). The primary scientific goal of each spacecraft is to improve the knowledge of visited near-Earth objects in terms of their orbital elements and physical features and properties, in the context of planetary defense. The payload is based on a visible camera and a miniaturized Lidar for ranging. Trajectories aim to maximize the number of visited objects per launch (balanced with favoring larger asteroids).

Along the same line, the Observatory of Paris investigates a concept called BIRDY based on interplanetary CubeSats visiting small solar system bodies and probing their interior (Hestroffer et al. 2019). The aim is to derive the size and shape through imaging, and the mass and bulk density of the small body (asteroid, comet, satellite) through radio-science experiment, making use of a mother craft-daughter craft (or between pairs of stand-alone CubeSats) inter-satellite link. Such CubeSat will rely on low-velocity and close-distance flybys dedicated to the radio-science experiment.

The Comet Interceptor mission (Jones 2019) recently selected for ESA's new Cosmic Vision Class F program is another great example that highlights the great potential of microsats for small body characterization. As mentioned in the instrumentation paragraph above, CNES will provide two instruments to this exciting mission which is based on a mothership with two auxiliary spacecraft and will be launched to the L2 Sun-Earth Lagrange point in 2028. Launch will be shared with the Ariel mission dedicated to exoplanet characterization. From L2, it will wait for the discovery of a comet entering the inner solar system for the first time or even possibly of an interstellar object originating at another star. It will then perform a propulsive ΔV to achieve a flyby of its pristine target. The purpose of the two smaller spacecraft is to venture closer to the target, carrying complementary instrument payloads, to build up a 3D picture of the comet. Figure 7 illustrates this flyby configuration.

This approach will also enable a combination of a low risk and guaranteed baseline science return from the more distant mothership with higher-risk but high-gain sampling of the inner coma by the releasable probes, which do not necessarily need to survive the full encounter for mission success. This mission

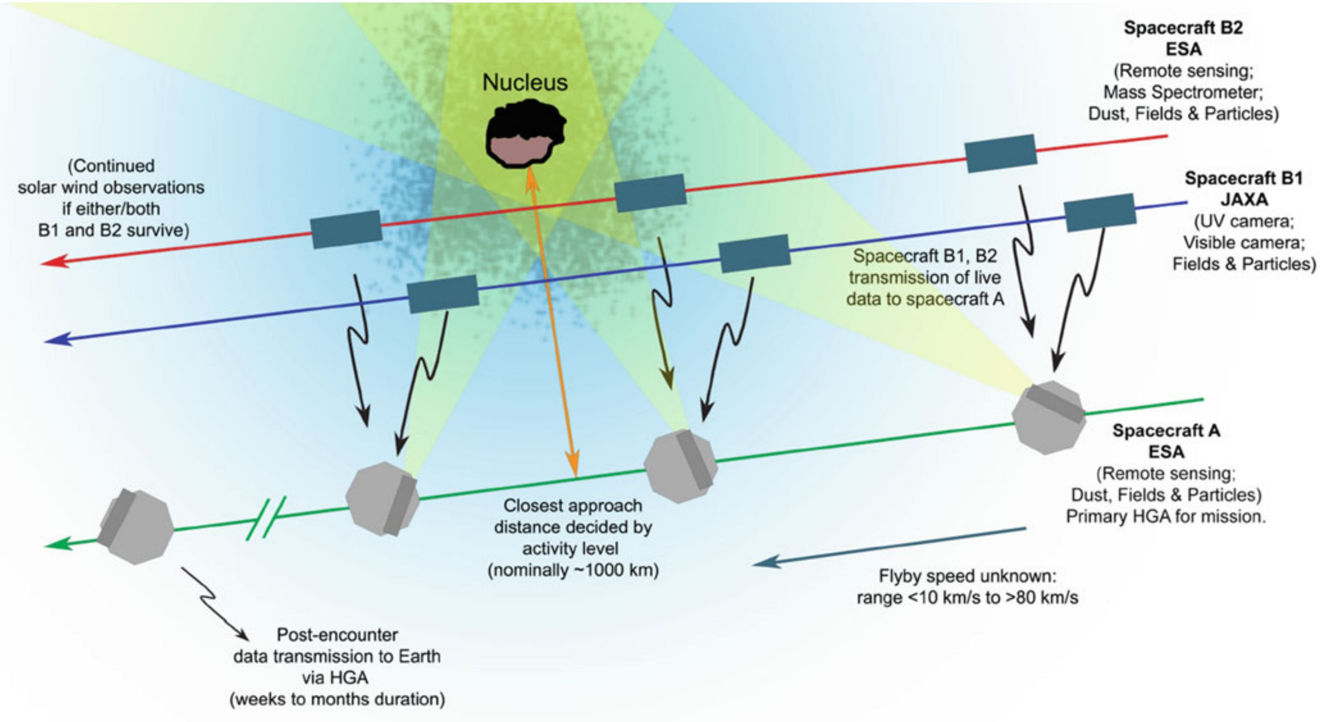


Fig. 7 Flyby configuration of Comet Interceptor – credit UCL Mullard Space Science Laboratory, UK

exhibits two typical features of auxiliary probes for exploration: they can take higher risks than their mothership, and they make multipoint measurements affordable.

The HERA mission (Carnelli et al. 2019) also recently decided by ESA within its planetary defense program is another great example of a mission to a small body that combines CubeSats with a mothership. In this case the set of spacecraft will orbit around the secondary body, Didymoon, of the Didymos binary system. One of the CubeSats, called Juventas, will measure the gravity field as well as the internal structure of the smaller asteroid. In close orbit around Didymoon, Juventas will line up with Hera mothership to perform inter-satellite radio-science experiments and carry out a low-frequency radar survey of the asteroid interior, with an instrumental concept inherited from the concert radar from Rosetta and Philae developed by the French laboratory IPAG. CNES will be in charge of flight dynamics for both CubeSats.

3.3 Multipoint Measurements at Mars or Venus

In the early 2000s, CNES carried the pre-development of a network of four geophysics Mars stations up to phase B. The major goal of this mission, called Netlander (Marsal et al. 2002), was to perform simultaneous seismic and environmental measurements in order to study the internal structure of Mars, its subsurface, and its atmosphere. Each station was deployed by an individual capsule which had a 65 kg mass at entry. It is now generally acknowledged that after the InSight mission which is performing very accurate seismic measurements with a single station on Mars, a network similar in principle to Netlander should be envisioned for a second-generation geological campaign.

Orbital networks are also envisioned around Mars or Venus to characterize the interaction between their upper atmosphere and the solar wind and their magnetosphere. Such a mission is given a lot of attention in the Mars road map elaborated in 2016 by a selection of French scientists (Montmessin et al. 2016). Under the scientific leadership of the LATMOS laboratory, CNES has run a phase 0 study of a mission NETSSEM that would combine a mothership with three CubeSats to investigate Mars' magnetosphere (Leblanc et al. 2019). This generic concept would also apply to Venus (Fig. 8).

3.4 High Risk Enhancement of a Large Mission

Thanks to their low mass and low cost, nanosatellites or microsatellites may fit within the resource margins of large missions to augment their science return. They could allow mixing low- and high-risk investigations, for example, by matching a robust mothership that acquires the primary science and smaller deployables that investigate other aspects of the target, increasing investigation time during a fast flyby, or being deployed during cruise for a different purpose. Galileo and Rosetta have both approached opportunistically several asteroids during their long cruise toward their final target. For future missions of this type, under the same

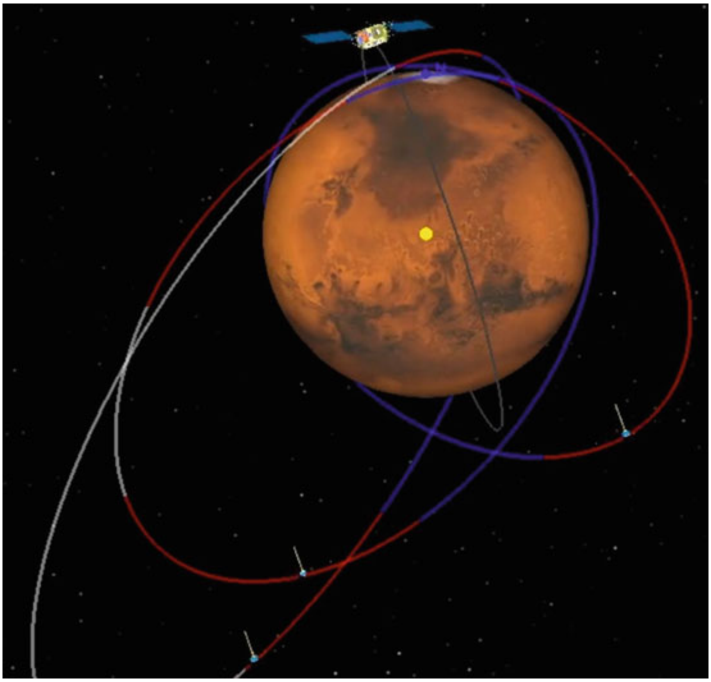


Fig. 8 NETSSEM mission architecture – credit CNES

circumstances, having disposable short-leaved CubeSats on board that could be literally thrown toward the object that the main spacecraft is flying by would add a lot of scientific value by procuring close-up images and measurements (Bousquet et al. n.d.).

Another spectacular possibility of complementary measurements has been associated to the incoming missions to the Europa Jupiter moon. Several short-leaved CubeSat designs, from 3 U to 12 U, have been proposed in France (Gaudin et al. 2017) and in the USA to characterize in situ the plume released by Europe (Fig. 9).

4 Conclusion

Small planetary probes have become a reality, as illustrated by JPL's recent MarCO mission and by JAXA's Hayabusa2 mission where CNES had the privilege to contribute to the MASCOT lander. The amazing current growth of CubeSat launches to Earth orbit and the huge number of conceptual studies based on small spacecraft undertaken over the last couple of years let anticipate that small sat applications to deep space are poised to expand. CNES definitely wants to participate to that trend building up on its CubeSat capacities, on its high

Fig. 9 Europa plume characterization mission architecture – credit IRAP

expertise in flight dynamics, and on its long history of instrument development and operation for planetary science. CNES is very familiar with international cooperation for deep space exploration, and the emergence of dedicated small probe programs in the US (SIMPLEX) and at ESA (Cosmic Vision class F) should boost up opportunities.

CNES can propose a wide range of miniaturized – high-performance – instruments, and the technology is already at reach for daughter spacecraft types of mission architecture. Areas of technological developments that will incrementally enlarge the scope and enhance the scientific output of independent stand-alone small sats, between Venus and Mars as a first step, have been identified.

Microsatellites and nanosatellites can provide a number of unique functions that are both enabling and enhancing to planetary science missions. As shown in the previous section of this article, a broad spectrum of mission architecture based on small probes can contribute to fulfil ambitious scientific objectives, or in some cases provide the only meaningful solution. Yet, while microsatellites are affordable (even though they will undoubtedly be more expensive for deep space than for the more common low Earth orbit applications), and increasingly more capable, they are not a replacement for more traditional missions that require multiple coordinated measurements to accomplish their science investigation goal. Additionally, larger spacecraft remain far more powerful and can go to more remote locations and survive longer-duration missions and challenging deep space environments. Under many circumstances, however, large spacecraft can benefit greatly from the risk capacity provided by small probes that can be added on and from the multipoint capacity that they can provide. In this respect, the combination of small probes with mother crafts will ultimately make it possible to reach further into the solar system and explore new destinations in depth.

5 Cross-References

- ▶ Scientific Discovery and Geomagnetic Monitoring in Earth Orbit Using Small Satellite Systems
- ▶ Small Satellites and Hosted Payloads for Technology Verification
- ▶ Student Experiments, Education, and Training with Small Satellites

References

S. Barde, F. Jocteur, Science & Exploration Ground segments: New challenges seen from CNES, presented at the ESA/ESO SCIOPS Workshop 2017 in Madrid

C. Bastien-Thiry, L. Privat, Taranis mission, presented at the 4th COSPAR symposium on Small satellites for sustainable science and development, Herzliya, Israel – November 4–8, 2019

P.W. Bousquet, G. Vane, J. Baker, J. Castillo-Rogez, C. Raymond, Planetary cubesats: Mission architectures, IAC-17-A3.1.7

C. Briois et al., Orbitrap mass analyzer for in situ characterization of planetary environments: Performance evaluation of a laboratory prototype. Planet. Space Sci. **131**, 33–45 (2016)

A. Buch, V.T. Pinnick, C. Szopa, N. Grand et al., MOMA Gas Chromatograph-Mass Spectrometer onboard the 2018 ExoMars Mission: prototype results and performance, 46th Lunar and Planetary Science Conference (2015)

I. Carnelli, P. Michel, M. Küppers, P. Martino, Hera: European Component of the Asteroid Impact & Deflection Assessment (AIDA) Mission to the Binary Asteroid Didymos, presented at the 13th IAA Low Cost Planetary Mission Conference, Toulouse, France – June 3–5, 2019

Cubesat in support of MSR/MSR pathfinder concept in LEO, ESA Open Invitation To Tender AO9916

D. Gaudin et al., Preliminary design of a CubeSat for plume sampling and imaging at Europa, 6th Interplanetary CubeSat Workshop, Cambridge, United Kingdom, 30–31 May 2017

D. Hestroffer et al., BIRDY: An interplanetary CubeSat to Small Solar System Bodies, iCUBESAT conference, Milano, May 28–29, 2019

G. Jones, Comet Interceptor: A proposed ESA Mission to a Dynamically New Comet, presented at the 13th IAA Low Cost Planetary Mission Conference, Toulouse, France – June 3–5, 2019

A. Klesh, MarCO – Trailblazing Interplanetary Small Science, presented at the 4th COSPAR symposium on Small satellites for sustainable science and development, Herzliya, Israel – November 4–8, 2019

P. Landiech, P. Rodrigues, *Overview on CNES Micro Satellites Missions: In Flight, Under Development and Next*, ed. by R. Sandau et al. Small Satellite Missions for Earth Observation, https://doi.org/10.1007/978-3-642-03501-2_1, (C©Springer-Verlag Berlin Heidelberg 2010)

F. Leblanc et al., Network of small satellites for the exploration of planetary Magnetosphere (NETSSEM), presented at the 13th IAA Low Cost Planetary Mission Conference, Toulouse, France – June 3–5, 2019

L. Lorda, E. Canalias, T. Martin, R. Garmier, A. Moussi, An Overview of the CNES Expertise in Flight Dynamics Analyses For Landing on Small Bodies, presented at the 13th IAA Low Cost Planetary Mission Conference, Toulouse, France – June 3–5, 2019

O. Marsal et al., The Netlander geophysical network on the surface of Mars: General mission description and technical design status. Acta Astronaut. **51**(1–9), 379–386 (2002)

F. Montmessin et al, Roadmap Mars, Solar System French Working Group report presented to CNES, 2016

A. Moussi et al., CNES support to HAYABUSA2-MASCOT operations, SpaceOps Conference, Marseille, France, May 28 – June 1, 2018

N. Murdoch, S. Hempel, S.L. Pou, A. Cadu, R. Garcia, et al., Probing the internal structure of the asteroid Didymoon with a passive seismic investigation. Planet. Space Sci. Elsevier, **144**, 89–105 (2017). https://doi.org/10.1016/j.pss.2017.05.005. hal-01593477

C. Royer, J.P. Bibring et al., The MacrOmega Instrument On-Board MMX, an Ultra-Compact NIR Hyperspectral Imager Based on AOTF Technology: Preliminary Tests on a Breadboard, 50th Lunar and Planetary Science Conference 2019 (LPI Contrib. No. 2132)

M. Sudars, M. Regnier, IRENA Flight Demonstrators, deliverable 2.2 of the IRENA project funded by the European Union's Horizon 2020 research and innovation program, Ref. Ares(2016) 1643756 – 07/04/2016

S. Tardivel, C. Lange, The MMX Rover: An Innovative Design Enabling Phobos In-Situ Exploration, presented at the 13th IAA Low Cost Planetary Mission Conference, Toulouse, France – June 3–5, 2019

H. Tra-Mi et al., The landing and in-situ observation of (162173) Ryugu by the MASCOT lander, 70th International Astronautical Congress, Washington DC, IAC-19-A3.4A.6

C. Virmontois et al., A Micro-Class Lunar Rover Mission To Image Imbrium Lava Flows, presented at the 13th IAA Low Cost Planetary Mission Conference, Toulouse, France – June 3–5, 2019

L. Walker et al., Nanospacecraft Exploration of Asteroids by Collision and flyby Reconnaissance (NEACORE), presented at the 13th IAA Low Cost Planetary Mission Conference, Toulouse, France – June 3–5, 2019

R.C. Wiens, S. Maurice et al., The Supercam Remote Sensing Instrument Suite For Mars 2020, 47th Lunar and Planetary Science Conference (2016)

H. Yano, Hayabusa 2 as a Low Cost Planetary Mission Enhanced by Micro-sat/rover Contributions, invited presentation to the 13th IAA Low Cost Planetary Mission Conference, Toulouse, France – June 3–5, 2019

Part VIII

Small Satellites and Commercial Satellite Applications

Mobile Satellite Communications and Small Satellites

Amit Maitra and Joseph N. Pelton

Contents

Abstract

The mobile satellite service is in many ways one of the most suited to being provided by a network or constellation of small satellites in low Earth orbit. This type of service requires by far the greatest link margin in order to maintain service

---

A. Maitra (✉)
The Foundation for Emerging Solutions Inc., Oakton, VA, USA
e-mail: amaitra@emerging-solutions.us

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_38

continuity because of obstacles that can block a clear line of sight between the satellite and the user's transceiver. Also the processing time and need for storage and buffering of the MSS digital signals associated with maintaining a mobile satellite signal because of possible interruptions, such as tunnels, forests and trees, billboards, and buildings and skyscrapers, mean that delay associated with a GEO satellite compounds the problem of resiliency of service. A LEO system, because of its lower latency and less path loss due to being some 30 to 40 times closer to the ground, has an advantage over a MEO and especially a GEO system.

For a variety of reasons, the first small satellite constellations for voice, data, and machine-to-machine (M2M) services that included Iridium, Globalstar, ICO, and ORBCOMM all had to be reorganized out of bankruptcy. Yet now all of these systems are going enterprises and other new systems are being deployed. Some of these are for new L-band-based data relay and M2M services. These systems are providing such new applications as automatic identification services (AIS) and Internet of Things (IoT) data relay, and others are being deployed to support 5G-based data relay and other advanced applications related to driverless cars.

This chapter describes the design of small satellite networks to support mobile services and augmentation of broadband cellular networks as well as global voice and data services. It explains the challenges that exist to deploy and operate these types of satellite systems as well as the regulatory, standards, and spectrum allocation issues associated with the development, deployment, and future growth of these networks in the future.

Keywords

Application-specific integrated circuits (ASIC) · Automatic identification service · Broadcast satellite services (BSS) · exactEarth · 5G cellular service · Fixed-satellite services (FSS) · Flat panel antenna · Globalstar · ICO · Inmarsat · Internet of Things (IoT) · Iridium · Latency · Ligado · Link margin · Machine-to-machine (M2M) services · Mobile satellite services (MSS) · ORBCOMM · Satellite constellations · Satellite phones · Spire · Thuraya · User transceivers

1 Introduction

The development of satellite communications came in a series of stages. First came the development of commercial fixed-satellite services (FSS) that began with the deployment of networks by Intelsat, Eutelsat, and a series of domestic satellite systems that started with the Canadian Telesat Anik system. This was followed by a series of competitive systems for international services. The initial satellite services for voice, data, and television relay were followed by the development of direct-to-the-home television services that used high-powered FSS satellites. This then transitioned to true broadcast satellite services (BSS) that provided direct-to-consumer radio and television services. But all of these satellite systems of the 1960s, 1970s, and 1980s were largely deployed in the geosynchronous orbit. This is because these satellites appeared to remain stationary in their orbit above the equator. This allowed ground stations to point constantly to the same location above the equatorial orbital arc. The main exception was the Russian Molniya communications satellite that deployed three satellites in highly elliptical 12 h orbits. This highly Northern-biased configuration allowed effective coverage of all of Russia. At least one of the three satellites was clearly accessible for at least 8 h in each of the three orbits. These satellites, however, had to have a tracking capability for all of the user Earth stations on the ground below since they did move across the sky. Since they were moving in a slow arc as they approach their orbit's apogee, this did not require fast tracking.

The last of the major commercial telecommunications satellite services to develop as a significant source of revenues was that of the mobile satellite services (MSS). This satellite service developed later for both technical and market-based reasons.

The rapid evolution of geosynchronous satellite services for fixed-satellite services (FSS) and broadcast satellite services (BSS) was quite logical because these satellites could work to low-cost dish antennas that did not have to track the "apparently stationary" satellite overhead. The FSS and BSS market expanded rapidly because of the large demand for these services and the ease of expanding service by adding new ground-based antennas that were always located in a fixed location and always with a stable pointing orientation.

The idea of communications to mobile systems was a different matter. The ground antennas required by users – whether located on an aircraft, a ship, a vehicle on the ground, or even people on the move – automatically implied the need to accommodate movement. Even so, the first mobile satellite systems were still deployed in GEO, and the ground, ship, or even aircraft had to either have active tracking or alternatively have antennas that could receive signals in all directions above the horizon. The huge path loss associated with the GEO satellites and the low gain associated with user transceivers on the ground, on ships, or on aircraft suggested that perhaps low Earth orbit satellites that were 30 to 40 times closer to ground could perhaps present a better option. Arthur C. Clarke, who first conceived of using geosynchronous satellites for global communications, and published the first articles on this subject in 1945, even wrote about LEO satellites and their possible future use as well.

Since the signal from the antennas of a spacecraft in GEO spreads out in a circle, the effective difference in the satellite signal's effective power is not represented by its distance away but rather by the square of the differences in altitude. Thus a LEO satellite that was 30 times closer than a GEO satellite would have a $(30)^2$ effective power advantage or to seem 900 times more powerful. And if 40 times closer, there would be an effective power advantage of 1600 times. But there was also a price to pay by operating satellites at much lower altitudes. One needs a constellation of 50–60 satellites to effectively cover entire Earth. Three satellites in GEO can cover virtually all the Earth except the polar region. About 12–18 satellites can cover the world with medium Earth orbit (MEO) satellites, but a LEO satellite can only see a limited area so much more have to be launched to get universal coverage. In fact satellites are much like a very, very high microwave tower. Since it is not possible to build towers many thousands of kilometers high, the GEO satellite was a cunning substitute.

The case of mobile satellite was different. This is because the ground stations would also be moving in any event. Thus, the idea of smaller satellites in a low Earth orbit (LEO) constellation might be considered a useful option in designing a mobile satellite system. The much lower path loss could be used to advantage in such a mobile satellite system. Instead of having to build larger, more powerful satellites with larger and larger space antennas, then smaller satellites much closer to Earth might provide more effective mobile satellite services and also would greatly reduce the problem of transmission delay that was considered a problem for voice services in particular. More power, less delay, and smaller satellites to launch were all advantages that led designers of the LEO mobile communication satellites to look seriously at these designs.

The challenge was to find a way to design small user antennas that could either track the fast-moving small satellites overhead or find a way to design ground units that could capture signals from satellites at virtually all angles overhead – but with very low gain.

The other reason that mobile satellite services also developed more slowly is that the market was essentially smaller. The Inmarsat system was created in the 1980s to provide essential international mobile satellite services to ships at sea. It expanded to provide services to aircraft as well. The various satellites at the outset were all GEO systems. These include the Marisat system developed by the Comsat Corporation, the maritime package that flew on some of the Intelsat V GEO satellites, and the Marecs satellites developed by the European Satellite Agency. All these systems were combined into the initial Inmarsat system.

This was largely seen as a relatively small market, and only those willing to pay a rate as high as $10 a minute for a telephone call were foreseen as customers plus ship navigators and captains seeking to achieve the best safest sea routes or to avoid large storms. All of these first maritime satellite systems envisioned very large and very powerful GEO satellites to provide these services, and the key was to develop ground transceivers with digital processing sufficient to get a voice signal and not be too large.

The bottom line was that commercial mobile satellite services using small satellites in constellations thus only began to be developed in the 1990s in parallel with the development of terrestrial cell phone development. Prior to the 1990s, people expected to receive their telephone calls in their homes or office. Unless they were cab drivers or police or military personnel, very few people could afford a car radio telephone. But the cell phone revolution began to change expectation.

People did not expect to reach the Internet via cell phones either since there was no Internet. A large-scale consumer market for mobile communications did not really develop until the age of broadband terrestrial wireless services until the 1990s as the terrestrial cellphone build-out began in earnest.

2 The History of Small Satellite Constellations for Mobile Services

In short, the concept of private ventures that might deploy mobile satellite services (MSS) at the domestic or global level did not begin to emerge until the demand for cellular service really began to catch on. The various mobile satellite services (MSS) that envisioned using low Earth orbit small constellations began in earnest in the early 1990s. At the time link budgets for terrestrial cell phone service was minimal, and the build-out was largely in only big cities and urban areas. It was hard to call inside of homes and cars. In the 5 years that followed, the build-out was fast and furious, and the power of cell towers kept going up and up to provide better and more resilient service.

When the various systems such as Iridium and Globalstar began to offer LEO-based satellite cellphone service in 1997 and 1998, they found the terrestrial cell phone market had changed greatly. The power levels had gone up, and the number of cell towers had multiplied many times over, and the size of cell phones had shrunk greatly. The satellite service had difficulties of high rates; dropped calls; problems of connecting from inside of buildings, homes, or cars; and satphones that receive the unwelcome nickname of “bricks.” The market of millions of subscribers that consultants had predicted simply did not materialize (Pelton 2001).

The systems like Iridium and Globalstar for mobile satphone service deployed in the late part of the 1990s ended up almost immediate bankruptcies. ICO that had likewise planned to deploy a mobile satphone system also folded as did the ORBCOMM store-and-forward data relay network. Yet another system named Teledesic was planned to provide fixed-satellite services (FSS) in the Ka-band. This new and unorthodox system became known as a “megaLEO” satellite system. It was to include a constellation of 840 smallsats plus 80 spares or 920 satellites. This innovative project that was backed by Microsoft founder Bill Gates and cell phone entrepreneur Greg McCaw was also cancelled at that time as essentially being too expensive to build and deploy without having an established revenue stream and large-scale base of customers.

The market for Iridium and Globalstar had largely shrunk to areas where cellular service was simply not available. The high price of these early LEO-based mobile satellite services was a key issue indeed. There had been at least a two orders of magnitude overestimation as of the global demand for the satellite service by telecommunication market analysts. This was in part because the prices consumers ultimately had to pay were much higher than market researchers had projected. The providers of these networks found out too late that they had to split their revenues with national governments in order to obtain what are called “landing rights.” Such agreements were needed in order to operate in countries around the world.

This series of misunderstandings, miscalculations, and technical difficulties with the services drove up the cost of the new MSS offerings and lowered the revenues needed to pay off the multi-billion dollar debts incurred to build these new systems. The cumulative effect of these various factors ended up in across the board bankruptcies and in a very short period of service. The ICO network that was a spinoff of the Inmarsat system was not deployed, but it too also filed for bankruptcy.

The restructured and reorganized entities that bought out the satellite assets from the bankrupt companies were able to re-enter the mobile satellite business. They were able to recover from these large financial failures and multi-billion dollar losses. These first-generation satellites in some instances lasted as operating systems for over 20 years despite earlier estimates of 5–7 years.

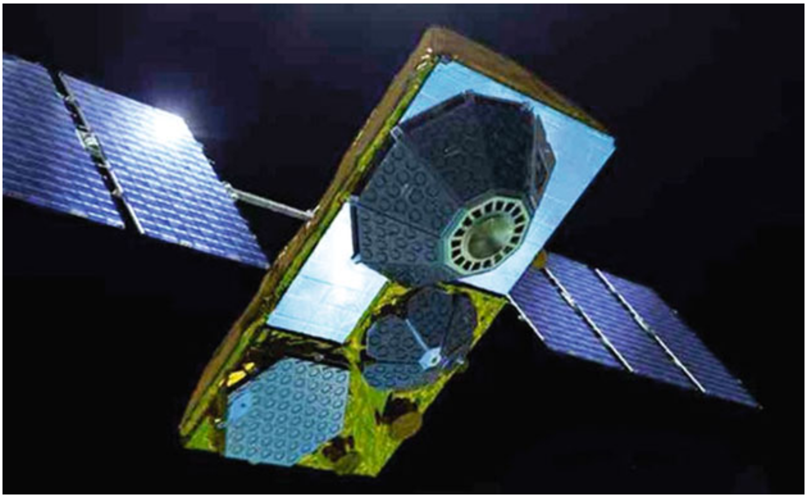


Fig. 1 The Globalstar second generation of satellite with phased array antenna. (Graphic courtesy of Globalstar)

Today, these new iterations of Iridium, Globalstar, and ORBCOMM have deployed new generations of satellites and have recovered from the financially disruptive start of their operations (see Fig. 1 the new generation of Globalstar satellites).

The experience gained has been important. These LEO-based mobile communications satellites operators have improved their offerings in many ways. There are new, smaller, and better user transceivers for consumers. There have been some renegotiation of the landing license requirements and other regulatory challenges met (i.e., such as coordinating frequencies with radio telescope operators around the world). They have learned to make better market forecast and grow their customer base steadily in the past two decades. The new owners and operators were able to learn from past experiences and benefit from much improved technology in space and particularly on the ground.

The second-generation satellites were more powerful and more capable, offered new services, were able to extend and improve landing license agreements, and were able to forecast demand based on real traffic levels and past patterns of growth. The user transceivers and ground equipment are much improved.

3 New Iridium and Globalstar Mobile Satellite Service (MSS) Constellations

The key to success of the small satellites for mobile services has been not only to learn from the past experience but to develop their ability to respond to the needs of the user community with much better-tailored service offerings. The additional power and phased array antenna design on the latest version of the Iridium and

Globalstar satellites that achieve more efficient frequency reuse allow these LEO mobile satellite service satellites to provide broaderband services.

These services compete with the GEO satellite services provided by Inmarsat and Thuraya. The range of users include those involved in sailing, outdoor sports such as cross-country skiing and mountain climbing, those involved in trucking and transport services and mining, those working on offshore oilrigs, prospectors, law enforcement officers, and especially those engaged in military operations or providing emergency aid services in remote areas (Satellite Service).

Both the Globalstar and Iridium satellite systems offer a newer feature. This is a Wi-Fi hotspot that accesses the satellite more efficiently and allows multiple users to access the satellite. Currently for Globalstar there are 8 users and for Iridium there are 5 users.

In the case of Globalstar, this is called a “Sat-Fi system.” This is, in effect, a Wi-Fi hotspot system that allows a regular smartphone to access the satellite without the purchase of a satellite phone. This new mobile satellite voice service and new Sat-Fi hotspot equipment is available for under $1000 and is deployable anywhere it is locally authorized and can be recharged. This allows compatible smartphone to access the Sat-Fi box for voice and data services. This is currently available at subscription rates that are as low as 50 cents to 65 cents per minute in the United States with a minimum usage per month of 150 to 200 min. Another desirable feature is that ordinary country code dialing is possible without using the specific country code number assigned to mobile satellite systems. Its direct connection service rates on a mobile satellite phone are significantly higher (Globalstar SatFi Service).

Iridium Next service has also added new consumer options that are quite parallel to those of Globalstar for both its hotspot type service and its direct to the satellite service via satphone connections. The Iridium service with a mobile hotspot unit is known as “Iridium Go” and is generally comparable to Globalstar Wi-Fi-based service offerings except for allowing five interconnecting smartphones at once rather than up to eight (Iridium Go).

Voice service operations for both of the voice-based satellites directly via satphone currently tend to be more in the range of $1.25 to $2.00 per minute with a requirement of an annual contract to start with and an enrollment fee and early determination fee. Incoming short messaging service (SMS) and voice calls, however, are generally free of charge subject to certain restrictions. Calls to other satellite systems have a high premium charge (2019 Top Iridium Monthly and Yearly Plans).

The key to the success of these smallsat mobile satellite services can be attributed to the following factors as shown below.

4 Success Factors for Small Satellite MSS Networks Providing Voice and Data Services

- Buildup of governmental, corporate, and organization anchor clients over time
- Increased performance of the satellites, user handsets, and Wi-Fi hotspots in terms of capacity, resilience, beam-to-beam handoff, and link budgets to sustain service
- Advances in digital processing, encoding, ASIC chips, and phased array antennas

- Lower latency of LEO constellation versus competitive GEO satellite systems
- New features such as Wi-Fi-satellite hotspots and improved/more compact phones
- Improved agreements with governments for landing licenses
- Shaping the marketing of services to the special needs and requirements to a wide range of potential users so the value of LEO MSS services is better understood

Despite the success of the Iridium and Globalstar networks, there is a constant challenge for these networks to be successful in light of competitive challenges and the new service offerings that can be offered by new entrants into the field of mobile services. There has been competition with satellite systems providing machine-to-machine (M2M) or business-to-business (B2B) messaging services that has come from ORBCOMM, Spire, and others that are also providing automatic identification services for lower-end messaging and other types of lower-cost services such as IoT connectivity. The GEO-based MSS system that are providing voice-based services and broadband data have also challenged the LEO-based MSS smallsat constellations.

In the case of Globalstar and ORBCOMM, they have made a mutual service exchange agreement to meet consumer demand for messaging and identification services. The growing demand for automatic identification services (AIS) for the shipping and transportation industry and other new IoT and 5G-related M2M services have given rise to a greatly expanded number of small satellite networks to provide messaging services of all types. These new requirements and the various new systems that are now being deployed or planned for these types of data and messaging services are discussed in the new section.

5 Small Satellite Constellations for Messaging Services

The ORBCOMM satellite network was deployed at the same time as the original Iridium and Globalstar MSS systems for voice communications. Although ORBCOMM was a much smaller and lower-cost-type satellite that involved much lower capital investment, its mission was to provide store-and-forward data relay, and it also experienced a rapid financial crisis and bankruptcy at essentially the same time. The near simultaneous bankruptcies of Iridium, Globalstar, and ORBCOMM – as well as the fixed-satellite services Teledesic – created major concerns in the financial markets about small satellite constellations in LEO. It required over a decade before investors were willing to consider backing these types of satellite systems again. Technological advances in the satellites, new user antennas on the ground, improved launch vehicles that cost much less, and the confidence that came from the financial and market success of the reorganized Iridium, Globalstar, and ORBCOMM satellites all helped. Thus it was possible to find the support needed for the financing of the second generation of the Iridium, Globalstar, and ORBCOMM systems and also allow new systems to provide data relay and messaging services to emerge in the last few years.

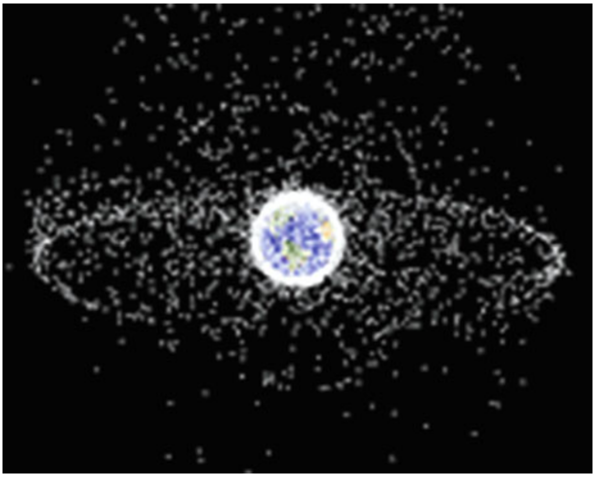


Fig. 2 The mounting orbit debris conditions in GEO and LEO. (Graphic courtesy of NASA)

The current surge in interest to deployment of satellites in LEO networks has now reached a current total of some 20,000 satellites to be deployed in the LEO orbital region between 300km and 1600 km altitudes if they were somehow actually all deployed in coming years. There is a particularly high concentration of new small satellites now proposed for the region between 700 km and 1200 km, with a critical concentration with a peak around 900 km. It is within this altitude band where most mobile satellite constellations are operating or proposed. This raises yet another concern as to the problem of orbital space debris and the threat of orbital collisions that could pose a risk to all types of LEO space operations and the longer-term sustainability of all types of space activities.

The graphic in Fig. 2 shows NASA precise simulation of existing space debris in Earth orbit with the outer ring representing the GEO and the dense inner ring surrounding Earth, shown as a virtually complete white ring, depicting the density of LEO orbital debris as it exists today. Indeed about 45% of the mass represented by orbital debris is crammed into the limited area represented by low Earth orbit (LEO), and with all of the proposed additional launches, it will become much worse.

6 Messaging Services and New Satellite Applications for LEO Smallsat Constellation AIS

The first store-and-forward satellites were the OSCAR 1 AMSAT satellite as built by volunteers and the University of Surrey (UOS) satellites. These early small satellites were constructed by making effective use of miniaturized electronic components and sensors and off-the-shelf parts. These early projects increasingly were able to show that a small satellite could deliver some impressive performance – for both data messaging and remote sensing. The UOS-2 that was launched in 1984 demonstrated that smallsats were not only real but cost-effective and capable of performing such tasks as reasonably fast and effective data relay (Surrey Launched Missions) (see Fig. 3).

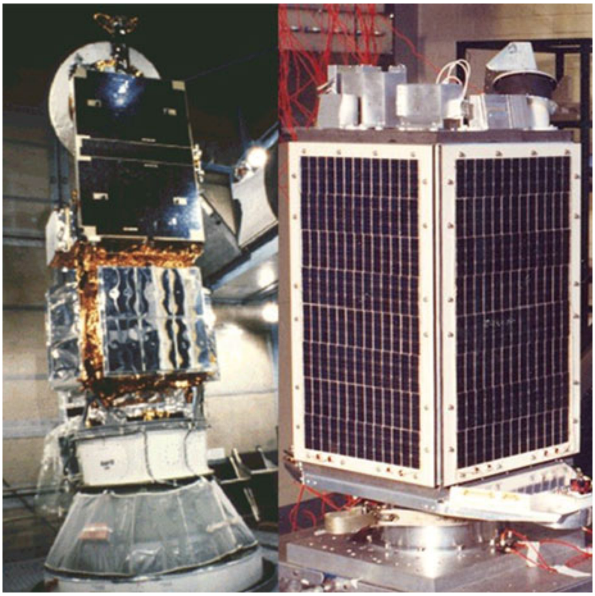


Fig. 3 The UOS-2 store-and-forward 3-unit cube satellite launched in 1984. (Graphic courtesy of the SSTL)

This type of early demonstration of what was possible with small satellites as small as a 3-unit cube satellite in terms of data processing and reasonably high-speed store-and-forward data relay sets the stage for what was to come in the 1990s with the ORBCOMM constellation.

The first commercial small satellite network was the ORBCOMM constellation that Orbital Sciences was bold enough to launch and operate. This was a quite small and compact small satellite that when arranged in a launch configuration could allow over a dozen ORBCOMM satellites to be launched at a time. ORBCOMM manufactured these small satellites and launched them as well. As cost-effective as the manufacture and launch of these small satellites were, there was a difficulty in developing a totally new commercial market that was sufficiently robust to cover the capital and operating costs associated with this startup network. The innovative gravity gradient stabilization design and novel launcher system were not sufficient to save the system from bankruptcy (see Fig. 4).

Yet well over a decade later, the reorganized, restructured, and refinanced ORBCOMM network was able to launch a new constellation of ORBCOMM 2 satellites that had sufficient power, antenna gain, and improved user antennas to support the second generation's sustained operations economically. The new satellite had twice the mass and much higher performance in every regard, but most importantly it had an established and sustained level of customer usage from a wide range of industries, organizations, and governmental customers. This satellite also had a higher-power L-band package that was designed to provide automatic identification services (AIS) to identify ships at sea to help avoid collisions and improve naval operations and safety (Networks: Satellite AIS). This service can also be used for long-distance trucks, buses, and even shipping containers (see Fig. 5).

The market that at one time did not exist when ORBCOMM was created is today quickly evolving as the world of digital communications services has continued to

Fig. 4 The first generation of ORBCOMM. (Graphic courtesy of ORBCOMM)

Fig. 5 The OG2 ORBCOMM satellite with an L-band package for messaging services. (Graphic courtesy of ORBCOMM)

expand in the age of the Internet of Things (IoT) and 5G applications to monitor many mobile functions that vary from sensors on driverless cars to operation of drones. The number of small satellites that are providing functions that include automatic identification services (AIS) to remote data pickup from ocean buoys to store-and-forward or machine-to-machine communications to IoT devices continues to expand. Today, ORBCOMM, an L-band package on Globalstar, Spire, exactEarth, and the international backed ARGOS scientific message relay networks are providing remote data relay services and messaging and also typically supporting AIS applications, but the prospect of providing remote communications to billions of IoT units is attracting a wide range of new smallsat constellations to provide data services.

There is the French-backed Kineis 20 nanosat constellation planned for 2021 that is to replace the long serving ARGOS network. This network currently is using packages on governmentally operated satellites from ISRO, NOAA, and EUMETSAT (ARGOS System). Alexandre Tisserant, Kineis Project Leader, has described this new system as having a laser-like focus on the emerging global satellite-connective IoT market as follows: “Kineis is a satellite operator that will provide unique, universal connectivity fully dedicated to the IoT industry. Any object fitted with a Kineis modem can be located and transmit data wherever it is, whatever the conditions. Kineis connectivity is simple to integrate into third-party devices, consumes very little power and is reliable. All this will be available at a very competitive price, making it accessible to as many people as possible, so Kineis will very soon be locating and collecting data from several million connected objects, in real or near-real time” (Mohney 2018). Of course most of the IoT devices equipped with a modem will be stationary but many will also be mobile. And Kineis is only one of many new systems entering the M2M market with the view to serving the explosively expanding IoT market. Other entries are the Eutelsat-backed ELO (which stands for Eutelsat LEO Objects) and the Else constellation, with perhaps more still to come (Satellite-Based Automatic Identification Market 2025). At this stage, it is hard to forecast how large this market will be and how many of these nanosat-based constellations will succeed.

In summary, the mobile voice and broadband satellite market is today thus divided into GEO-mobile satellite services (i.e., Inmarsat, Thuraya, and Ligado that operates in the United States) and LEO-based constellations Iridium and Globalstar.

The L-band-based smallsat constellations that utilize much smaller and typically nanosats include ORBCOMM, Spire, exactEarth, ARGOS (to be replaced by Kineis), ELO, and Else. New manufacturing techniques and new technology in space and particularly in ground systems have also been key. Finally, demand for new services such as AIS, IoT data relay, and 5G-related demand can all contribute to growth for messaging satellites.

It is important not only to consider the various satellite systems that are providing mobile satellite services and their service characteristics but also to consider in more details of some of the technology that has aided the growth of the larger more capable small satellite constellations, namely, Iridium and Globalstar, as well as the nanosats and microsats that are designed for providing messaging, machine-to-machine (M2M), as well as the newer AIS-, 5G-, and IoT-related services.

7 New Technical Features

A number of technical innovations have aided in the design, engineering, and manufacture of the various types of smallsats used for mobile satellite service (MSS). The following innovations have been key in this regard.

7.1 Additive Manufacturing and Advanced Manufacturing and Testing Techniques

The design, engineering, and testing of the Iridium and Globalstar satellites for their first generations served to transform many aspects of satellite production, especially for smallsats in high-volume production. The production of these satellites used a variety of accelerated production and testing innovations to produce these smallsats at the end of their manufacturing process in under a week rather than in a matter of years as had been the case with large satellites produced in units of just a handful or two at a time. The key was to create and test a satellite's design and manufacturing process so that it could be produced quickly with high quality and reliability. The Iridium and Globalstar first-generation satellites proved to be highly reliable, and these networks lived well past their projected meantime to failure and in most cases two to three times longer than originally projected.

And there were also significant innovations in the design and manufacture of satellite phones. These breakthroughs utilized new design and manufacturing improvements in the production of transceivers with application-specific integrated circuits (ASICs) so that the quality, speed of production, and resilience of these devices produced better and better products. These improvements in user satphone transceivers, of course, were applied to improved consumer products to use with both LEO smallsats and large and powerful GEO sats. Most recently, there has been considerable innovation in the design of ground antennas to relay data and messaging from IoT devices to connect with LEO small satellites. The most recent of these IoT relay antennas are essentially as small as credit cards. Most of these IoT data relay antennas are at fixed locations, but some of these are on mobile platforms or vehicles.

The next step forward in satellite design, engineering, and manufacture has come with additive manufacturing or so-called 3-D printing. Today, a number of key components for satellite manufacture as well as for rockets, including even rocket motors, utilize additive manufacturing production. This not only aids the speed of production as well as the quality and also reduces the costs.

Finally, the miniaturization of computer chips, sensors, and other components has also been added by robotic production that allows these very small units to be produced in a faster, cheaper, and often better way.

7.2 Phased Array Antenna and Intersatellite Links

Another area where mobile satellite systems have led the way in terms of innovation has been in the area of phased array antennas. The phased array antennas on the Iridium satellite were the first time that these types of antennas had been used on commercial satellites, and they allowed efficient beam forming for a maximum amount of frequency reuse to be achieved. These systems performed well and had a very extended lifetime.

The use of intersatellite links was another technical development that came with commercial mobile satellite systems with small satellites operating in low Earth orbit. This innovation allowed for much more efficient operations but required as few as only two command centers for tracking, telemetry, and command which allowed savings in capital investment but over the years substantial savings in operating expenses as well. These were important technical innovations that came with smallsat constellations that operated in low Earth orbit.

7.3 Hosted Payloads and L-Band Packages

The other type of innovation that blossomed with the deployment of mobile satellite constellations involves hosted payloads. Hosted payloads have flown on large satellite for decades, but this has largely been in the form of technology demonstrations. The Intelsat V network flew three maritime packages, and there have been cases of dual-use satellites such as the Marisat satellites that had one payload for US navy communications and another for commercial maritime services. The Iridium Next™ satellites are carrying over 60 Aireon™ hosted payloads to create the world's largest network that operates from a carrier satellite system. Thus the latest Iridium system is also hosting the global network in the form of a package that will be carrying out automatic dependent surveillance-broadcast (ADS-B) services. These innovative services will be the first test of global ADS-B services to allow precision air navigation (Kaul 2019). It can be anticipated that if this large-scale global network functions well the use of ADS-B technology will continue to expand and provide navigation services in all areas of the world not covered by ground-based radar systems.

7.4 Compact Stacking for Launch

Yet another innovation that came with the ORBCOMM system was to design the satellites to be especially compact so that the satellites could be super efficiently stacked to that a number of satellite units could be accommodated in a launch vehicle and placed in orbit in a single launch. The flat phased array antennas that are used in the latest version of the Iridium and Globalstar satellites continue the practice of efficient storage for launch and multiple satellites being accommodated in a single launch operation.

7.5 New Launcher Options

Another key innovation that supports the growth of mobile satellite services is cost-efficient launch options to get the various voice, broadband, and messaging mobile satellite systems into LEO at low cost. The advent of new highly cost-efficient launchers in their latest editions such as the Falcon, New Glenn, Vulcan, Vector, Rocket Labs, Indian Polar Satellite Launch Vehicle, and other new options makes these new mobile satellite networks more affordable. New dispensers and new ways to deploy small satellites such as SpaceX direct insertion from a spinning upper stage represent other launch economies.

8 Conclusions

The small satellites in low Earth orbit (LEO) constellations that were first designed to support new mobile satellite services (MSS) have been a consistent and quite innovative source of many key new ways to design, engineer, manufacture, launch, and operate smallsat networks. The start of this activity came from amateur projects such as the volunteers that built the OSCAR 1 amateur radio store-and-forward small satellites. The Surrey Space Centre and Surrey Space Technology Ltd. began making store-and-forward satellites that could provide messaging and machine-to-machine relay in the 1980s. It was not until the 1990s that there were commercial ventures that designed, built, launched, and operated small satellite constellations in low Earth orbit to provide voice and data relay services. Unfortunately, all of these efforts that included Iridium, Globalstar, ICO, and ORBCOMM all experience a lack of initial sufficient traffic and market and technical issues that led to their bankruptcy.

The revived version of the Iridium, Globalstar, and ORBCOMM satellite networks have all developed a viable traffic base and are now deploying innovative and higher-performance second-generation satellite systems. This has included ever more efficient and higher-performance user transceivers that include the latest in application-specific integrated circuits (ASIC). These systems today (i.e., Iridium Next, Globalstar OG 2, and the current ORBCOMM network) compete with mobile satellite service networks deployed in GEO that include Inmarsat, Thuraya, and Ligado in the United States.

In addition to the voice and broaderband networks, there are new messaging small satellite systems that operate in LEO as constellations and compete with the ORBCOMM network. These systems that most typically are deploying 3-unit cubesats in their constellations include Spire, exactEarth, Eutelsat's ELO, Kineis which is designed to replace the ARGOS space segment (which is a collection of governmentally oriented environmental satellites), and Else. The key to these new smallsat constellations seems to be new types of electronic monitoring and messaging services such as automatic identification services (AIS), IoT messaging services, and 5G-related messaging. The IoT messaging services, in particular, are expected to fuel growth in this area.

9 Cross-References

- ▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas
- ▶ Messaging, Internet of Things, and Positioning Determination Services via Small Satellite Constellations
- ▶ Radio-Frequency Geo-location and Small Satellite Constellations
- ▶ Remote Sensing Applications and Innovations via Small Satellite Constellations
- ▶ Small Satellite Constellations Versus Geosynchronous Satellites for Fixed Satellite Services and Network Services

References

2019 Top Iridium Monthly and Yearly Plans, https://satellitephonestore.com/iridium-services?matchtype=p&network=g&device=c&adposition=1t1&keyword=iridium&campaign=926495263&adgroup=49123895707&keyword=iridium&gclid=Cj0KCQjw4s7qBRCzARIsAImcAxYvgTO61F0HLwsL6kdyLjJmaplkEnF-4qUIpImKj7b_gBjD9sov12YaAgm3EALw_wcB. Last accessed 15 Aug 2019

ARGOS System, https://en.wikipedia.org/wiki/Argos_system. Last accessed 20 Aug 2019

Globalstar SatFi Service, https://www.globalstar.com/en-us/products/personnel-safety/sat-fi. Last accessed 14 Aug 2019

Iridium Go!. https://www.iridium.com/products/iridium-go/. Last accessed 15 Aug 2019

S. Kaul, Integrating air and near space traffic management for aviation and near space. J. Air Space Saf. Eng. **6**(2), 150–155 (2019)

D Mohney, Kineis – Another satellite IoT play, but French aerospace backing. SpaceITBridge, September 10, 2018., https://www.spaceitbridge.com/kineis-another-satellite-iot-play-but-french-aerospace-backing.htm

Networks: Satellite AIS, https://www.orbcomm.com/en/networks/satellite-ais. Last accessed 15 Aug 2019

J.N. Pelton, *Satellite Communications: The Transition to Mass Consumer Markets and Services* (International Engineering Consortium, Chicago, 2001)

Satellite Service, https://satellitephonestore.com/services/satelliteService?CASLID=120312440000001318&CAPCID=358197427381&CADEVICE=c&KWDID=kwd-297232427913&AGID=49123895707&matchtype=p&network=g&device=c&adposition=1t1&keyword=iridium&campaign=926495263&adgroup=49123895707&keyword=iridium&gclid=Cj0KCQjw4s7qBRCzARIsAImcAxbo64b95mTC0zGT8tDRLZYqcYNX3SuXUe2-wyBiXqtg3Rw_JHkKeP8aAmlEEALw_wcB. Last accessed 14 Aug 2019

Satellite-Based Automatic Identification Market 2025, Insight Partners, https://www.theinsightpartners.com/reports/satellite-based-automatic-identification-systems-market. Last accessed 8 July 2019

Surrey Launched Missions, https://www.sstl.co.uk/space-portfolio/launched-missions. Last accessed 15 Aug 2019

Small Satellite Constellations Versus Geosynchronous Satellites for Fixed Satellite Services and Network Services

Joseph N. Pelton

Contents

Abstract

For 50 years GEO satellite systems have dominated the field of satellite communications, and low-cost satellite dishes optimized to work to satellites in the Clarke orbit have dramatically spread across the world. So-called VSATs (very small aperture terminals) have grown by the millions around the globe to provide direct broadcast satellite TV and radio services to homes, offices, condos, and apartments. This type of satellite service has particularly serve to provide connectivity to rural and remote areas of the world. These GEO systems have also support global data networking known as enterprise networks for many large companies. Of all the application satellites providing commercial services to the world well, over 90% of the total revenues come from GEO satellites.

But the world of commercial satellite services seems to be in flux. The birth of "NewSpace" technologies has allowed the faster and more cost-efficient manufacture and reliability testing of small satellites. The new lower-cost launchers have also allowed large constellations of these small satellites to be deployed in lower orbit with greater effectiveness. Finally new types of Earth stations have been developed that can electronically track fast-moving satellites. The new

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_39

capabilities when combined have allowed the new constellations to function with greater effectiveness. These "NewSpace" systems have now completed the trifecta of new capabilities (i.e., lower cost and more capable small sats, lower-cost launch services, and new electronic-tracking ground systems). All are needed for these new systems to work.

There is concern about just how many of these new small satellite constellations in lower orbit can be cost-effectively and viably deployed in a short period of time. Is there sufficient market to sustain the current plans to launch dozens of these new systems that comprise a total of over 20,000 small satellites? Thus this rapid change to go from about 2000 operational satellites as of 2019 to perhaps over 20,000 satellites as of 2024 represents a series of concerns. Thus there are concerns about space situational awareness (SSA) and tracking, about space traffic management (STM), about market viability, and about the long-term sustainability of space and the near-Earth orbit. This article focuses mainly on the global commercial space market and how quickly it will change and who the winners and losers might be as the world of commercial satellite services undergoes a major transition.

Certainly the so-called NewSpace capabilities have come together quickly – especially in the past 5 years. The aerospace world has been confronted by innovation that has burst forth from Silicon Valley and the World of Google, computer systems, and networking systems. We have seen new ways of thinking, new business models, and new ways of raising capital. We have certainly seen much more rapid evolution of design and a willingness to innovate and provide space services and systems in total new ways. This has started to impact the conventional way of doing business that has ruled the world of aerospace for the past 60–70 years that was largely born of research processes and ways to undertake aerospace innovation born out of World War II.

The new entrepreneurially fueled aerospace initiatives have challenged the models of innovation that have come from the traditional aerospace world and R&D concepts born of the so-called military-industrial complex. New initiatives such as SpaceX, Blue Origin, Planet, O3b, OneWeb, and new enterprise that are designing and building small satellites and ground antenna systems are accordingly opening up new opportunities in the satellite world. Some have questioned whether GEO satellites can survive this new challenge as many new operators have emerged seeking to deploy these lower orbit systems that are well suited for IP-based networking and could help deploy new 5G broadband networks and extended Internet-related services in the least served regions of the world. Others have suggested that the real contest might be those deploying new high-throughput satellites that are ten to a hundred times more capable and cost-effective than those using much more conventional satellite system design that are not cost-competitive.

Another complicating part of this analysis is that a number of the established satellite communications service providers such as SES and Telesat plus others now seem posed to move to provide both GEO satellite and new small satellite constellations in the future. Many of the traditional providers of launch services

such as Arianespace and United Launch Alliance have also embraced significant change in how they design and build new launch vehicles. Many well-established companies that have been around for a long time are adjusting to the new technology and finding new ways to compete in the changing market conditions. This article seeks to look at the markets that GEO, MEO, and LEO satellites might serve in the future and to examine whether both types of services and satellite technology might continue to serve different market demands and find new synergies in the years ahead. Further, some consideration will be given to how changes in the launch services industries and those that are designing and building ground antenna systems will affect the future of satellite communication markets in the coming years. The one thing that is clear is that rapid changes to the world of commercial satellite services will come at an ever faster pace. This means more innovation, lower costs and prices for satellite services, and a fairly chaotic market for at least a decade as rapid progress and technological innovation lead to both lower costs and more market failures.

Keywords

5G broadband wireless communications · Intelsat · IP over satellite (IPoS) · Kepler small sat constellation · Launch vehicle economics · LEO small sat constellations · MEO constellation · O3b constellation · OneWeb constellation · Orbital debris removal · Rural and remote access · Satellite communication · SES · SpaceX constellation · Telesat · Spire

1 Introduction

The world of satellite communications has been largely dependent on geosynchronous satellite systems for nearly 50 years. The GEO satellite revolution began with the Syncom 2 and Syncom 3 technical demonstration satellites built by Hughes Communications in 1963. This was quickly followed by the Early Bird satellite which was deployed in 1965 by Intelsat. After this success a string of GEO satellites were launched, and the communications satellite industry increasingly relied on geosynchronous satellites. The GEO satellite designs became more and more capable in terms of having more power and with higher gain antennas that could work to smaller and smaller ground antennas. Spot beams that could be constantly pointed to precise locations on Earth and other technology such as polarization discrimination made more spectrum available to use. Digital encoding has allowed higher throughput.

All of these technological advances allowed ground antennas to become lower in cost and more and more widely distributed. In short technology inversion occurred. The satellites were larger and more powerful and more costly, but the ground antennas became smaller, simpler, and less costly. Accordingly the number of user antennas increased in numbers exponentially and became more closely connected to end users. This has now resulted in the ability of users in homes and apartment buildings and condos to access hundreds of television and radio channels from direct broadcast satellites using dish antennas under one meter in size. They can also receive data and download software from high-power satellites using digital standards such as Digital Video Broadcast-Return Channel Service (DVB-RCS) and Data Over Cable Service Interface Specification (DOCSIS).

The growth and development of the Internet and Enterprise data networks have presented a challenge to GEO satellite transmissions. The latency or transmission delay associated with the signal travelling to and from GEO satellites along a pathway of well over 70,000 km creates over a quarter of a second delay.

There are problems with the delay being perceived as system congestion. There are also other transmission difficulties such as headers being stripped off of transmission packet headers. Today there are a number of standards that have sought to work around IP network difficulties and allow more efficient IP transmission over satellites. These include: (i) increasing the window for detecting network delay; (ii) various spoofing techniques to be used at each end of a satellite transmission; (iii) changes to IP Security (IP SEC) processes to better adapt to satellite transmission; and (iv) improved use of virtual private networking in the satellite usage domain (see Fig. 1).

Advocates of low latency transmission systems such as fiber-optic or coaxial cable networks, broadband wireless terrestrial networks, and high-altitude platform systems (HAPS) and now LEO and MEO satellite systems have sometimes suggested that GEO-based systems are no longer up to the task of supporting the needs of a broadband IP world. This idea of using smaller satellites in lower orbit

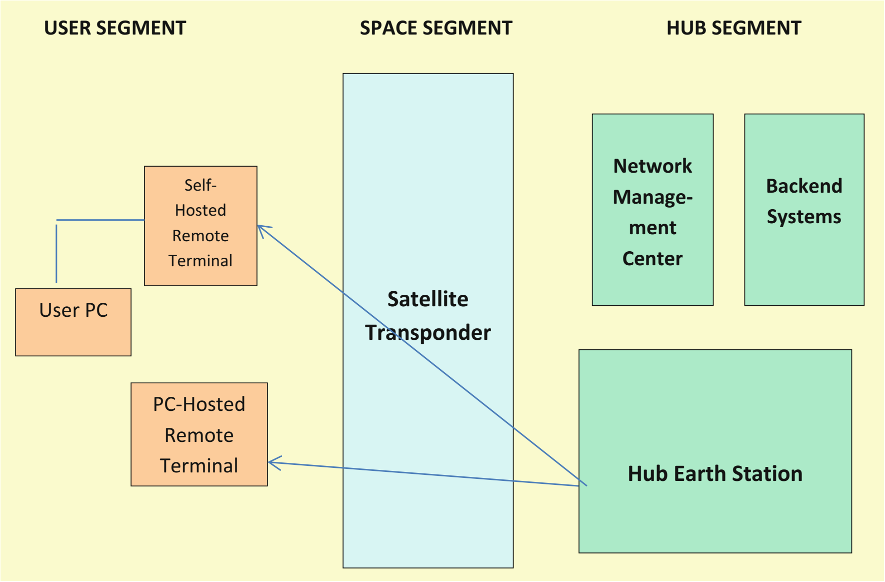


Fig. 1 Diagram showing the application of IP over satellite (IPoS) standards, including IIA Standard 1008, IPoS, TSI Standard TS 102354, and TSS-B

with less transmission delay or latency has in the last 5 years created a groundswell of interest in the deployment of non-geosynchronous satellite networks. The bankruptcies of the Iridium, Globalstar, ICO, Orbcomm, and Teledesic satellite systems of the late 1990s have seemingly been forgotten. While the success of the O3b medium Earth orbit satellite in partnership with SES that now controls this system has rebuilt confidence in such non-GEO systems.

The designers of the new systems feel confident that they can design, build, launch, and operate these new systems that can operate at speeds comparable to that of fiber-optic networks. They feel that they can largely eliminate the latency problems associated with GEO satellite systems. Further they feel the efficiencies of manufacturing satellites using the latest additive manufacturing techniques, accelerated testing and quality assurance techniques, and reduced launching costs associated with reusable launcher systems, and other launcher services innovation have opened up a whole new approach to the cost-efficient delivery of satellite services. What has sometimes seemed to have been overlooked is the need to deploy massive amounts of new low-cost user terminals with terrestrial connectivity that can meet demand for new systems and to complications of deploying these systems globally along with associated licensing and regulatory approvals.

The idea of deploying new satellite systems that are designed to provide new broadband services to the areas of the world where access to the Internet and broadband networking is generally lacking has been the key focus of many of these new initiatives. Clearly there is potential here. Yet there are key challenges to be faced. Deploying of these systems in a timely manner and resolving all of the licensing and tariffing issues clearly and quickly may prove a larger problem than some of the new satellite systems currently envision (Pelton 2017). The earlier bankruptcies of earlier NGSO systems such as Iridium were based on a combination of technical performance, competitive challenges, regulatory constraints related to landing licensing, and revenue-sharing demands and tariffing issues (Pelton 2002).

Greg Wyler was the primary force behind the development and deployment of the medium Earth orbit (MEO) satellite constellation known as O3b. He first examined the idea of deploying terrestrial cable or fiber networks in African countries and then abandoned such efforts as completely uneconomic. Instead he became the entrepreneur leader of an effort to bring new means of connectivity to the Internet in the underserved equatorial regions of the world. He named the O3b satellite system to stand for the “other three billion” people in the world with limited access to data communications. He saw the O3b effort as a means of testing where a lower latency satellite system could better respond to the networking needs of an underserved region of the world. He created a partnership with Luxembourg-based SES and other investors that included Google, HSBC, Liberty Global, Allen & Company, North Bridge Venture Partners, Soroof International, Development Bank of Southern Africa, Sofina, and Satya Capital that financed the new MEO system. In 2016, however, SES exercised its options, increased its ownership share to 50.5%, and then bought out its co-investors (Ownership of the O3b satellite network).

The feasibility of operating lower orbit satellite to provide communications systems had been demonstrated many times in the past. The Initial Defense Satellite

Communication System (IDSCS) had even shown this to be possible as early as 1965, and the Iridium, Globalstar, and Orbcomm systems had shown the technical feasibility of low Earth orbit (LEO) satellite systems again in the late 1990s. The question was whether the O3b satellite system could prove or disprove was market viability. In short, could a non-geosynchronous system, equipped with ground antennas capable of operating with fast-moving satellites, attract enough paying customers to operate in the black? Indeed, the various commercial non-geostationary satellite systems that had gone before, which included Iridium, Globalstar, ICO, Teledesic, and Orbcomm, had also undergone bankruptcy. The first stages of the system were deployed starting in 2013, and by midyear 2016, SES concluded that this service was succeeding in the global marketplace and that the low latency links were attractive from a service perspective.

The backers of O3b that included SES, Google, Liberty Global, Northbridge, and a number of investment banks were largely not testing whether such a system would work, but whether it could gain enough market traction to succeed. In the case of Greg Wyler, the success of O3b propelled him to take not the next step forward but rather a headlong plunge into what he saw as the future of global satellite telecommunications and networking services geared to the world of the Internet and the three billion people who remained largely interconnected to broadband IP data streaming. He with two partners and a small team of people began a project known as WorldVu that evolved into a satellite system known today as OneWeb. The vision was no less that to change the shape and technological vision of what satellite communications meant, especially in the most rural and remote parts of the world that were largely cut off from affordable access to global communications and digital communications.

The idea was to move beyond testing MEO networks with a smaller group of satellites in MEO and to deploy a very large network of small and low-cost satellites in LEO orbit to bring truly broadband services at low cost to the underserved portion of the world and do so at low cost. The vision was in many ways quite similar to that of the designers of the so-called Teledesic satellite network as conceived in the late 1990s.

The question is whether the new LEO systems will succeed in the marketplace by creating new market demand from a pent-up need for services in rural and remote areas of the world where Internet access is limited? Or will new satellite services such as cellular back-haul, Internet of Things (IoTs) messaging, or broader band Internet-based entertainment create totally new market demand? Only time will tell. The problem is that the only market demand that is proven is almost universally carried on GEO satellites. This service is noted in Table 1. Much of this traffic today is on GEO satellites where longer-term contracts are in place to obtain favorable rates. The last few years has seen a loss of subscribers for pay TV satellite distribution in the USA, Japan, and Europe as some users have shifted to so-called over-the-top (OTT) streaming services, but so far this has been a few percentage points and not yet an erosion, and this has been from satellite subscription to terrestrial steaming services. The question thus remains not only whether we are going to see a major shift in market demand for different types of satellite communications networks but also a shift in consumer behavior to move from satellite-based subscription to streaming services. This issue is considered in the next section.

2 The Satellite Communication Service Businesses: How Will It Change?

The business world of satellite communication services is today still heavily focused on GEO orbit satellite networks. This is quite logical in that it is GEO satellites and the satellite service providers who still represent the predominant source of revenue dollars despite some modest revenue declines that have occurred largely in the pay television satellite markets and revenues gain in the launch services, satellite manufacturing, and ground equipment manufacturing sectors.

Well over 90% of those revenues come from GEO satellite networks. Table 1 shows that the satellite services industry and especially pay television service providers are responsible for the lion share of revenues for the global satellite industry (Satellite Industry Association 2019). Table 2 puts the revenues for satellite service providers in better context by showing how significantly satellite service revenues relate to the totals for the overall global space industry. This becomes even clearer when one notes that the ground segment supplier revenues are essentially for GNSS space navigation equipment (i.e., largely application-specific integrated circuit (ASIC) chips in smart phones) or ground equipment for consumers to access communication satellites (Satellite Industry Association 2019).

Although overall satellite service revenues are down in the past 2 years as satellite subscribers for pay TV and radio have shifted to cable television-based over-the-top (OTT) streaming services, this is still the predominant revenue stream. As this trend is expected to continue, it is thought that this will be more than made up by expansion of broadband services in support of 5G service expansion plus other services related to the Internet of Thing (IoT), etc.

The first step to analyzing satellite markets is to realize satellite communication markets are now divided into segments that include broadcast satellite services (BSS), mobile satellite services (BSS), and fixed satellite services (FSS). These broad service categories, and particularly FSS, are now divided into subparts such as broadband, Internet of Things, 5G connectivity, and Automatic Identification System (AIS).

The predominance of broadcast services for direct-to-home and pay television and radio subscription is largely driven by the fact that it is a paid retail service and

Table 1 The commercial satellite service revenues for 2018 broken down by service category

The breakdown of satellite service revenues on a global basis (2018)	
Broadcast (pay television) satellite services	$94.3 billion
Broadcast (pay radio) satellite services	$5.8 billion
Broadband	$2.4 billion
Fixed satellite services	$17.9 billion
Mobile	$4.1 billion
Remote sensing	$2.1 billion
Total satellite services	$126.5 billion

Data derived from the SIA “State of the Satellite Industry” Report, 2019

Table 2 Breakout of revenues for 2018 of key sectors in the global space industry

The key revenue components of the worldwide space industry	
Satellite manufacturing	$19.5 billion
Ground segment equipment	$126.2 billion
Launch services	$6.2 billion
Governmental space and commercial human space flight	$ 82.6 billion
Commercial satellite services	$126.5 billion
Total satellite industry worldwide	$ 360 billion

not a wholesale service as are most of the other satellite services. In the value chain of sales, pay subscription satellite services is able to command both a larger revenue stream and a higher net profitability.

The softening demand for broadcast satellite services and pay satellite services is changing quickly due to the new options that are becoming available by broadband Internet. The global availability of streaming entertainment services, known as over-the-top (OTT) services, is now being offered by NetFlix, Amazon Prime, Hulu, YouTube TV, and others. As these service offerings expand, it is going to have a shrinking effect on revenues for satellite pay TV service providers such as DirecTV, Dish/EchoStar, etc. Indeed Dish and Conviva have formed a partnership some 5 years ago to upgrade its Dish Anywhere and Dish World Digital streaming services (Conviva Swings TVE Deal With EchoStar). AT&T that now owns DirecTV, at an acquisition cost of over $48 billion, is moving toward an all OTT-type service. It is no longer installing direct broadcast dishes but instead mailing consumers a thin “Osprey” box to obtain its OTT digital streaming service via the Internet. John Stevens, an AT&T executive, said recently: “End-users will ‘hook the box into a broadband line’ from AT&T or another service provider in lieu of having a satellite dish installed by AT&T technicians.” Analysts have said that this next iteration of DirecTV, i.e., Osprey, aims to eventually replace direct broadcast satellite service-delivered video content (Engebretson 2019). If these shifts from DBS satellite services to OTT are indicative of the trend line, then satellite revenues are likely to see a major shift. Today DBS satellites do provide other services such as DVB-RCS and DOCSIS types of enterprise services for corporate customers and enterprise data networks, but these are only a modest amount of the overall revenue stream.

Today dozens of digitally streamed OTT service providers are now beginning to blanket the world. The nearly global coverage of these streaming services is indeed softening the subscriber base of the paid satellite television subscribers. The shifts away from DBS service will occur first in the USA, Europe, and Japan. In some parts of the world, it is still easier to access broadcast satellite television through Internet service, but clearly change is happening everywhere. Below is the global coverage map for NetFlix streaming service, and other services such as Amazon Prime are nearly as extensive (Asssayag) (see Fig. 2).

Clearly the rate of that change will be crucial, and it will be different from the regional difference around the world. The crucial question is whether the large-scale digital satellite networks that are now being deployed to serve digital networking and

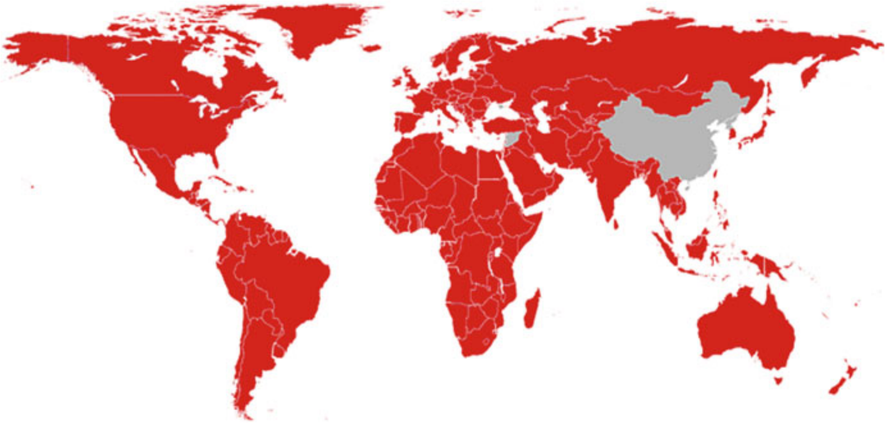


Fig. 2 Worldwide map showing nearly universal coverage of NetFlix and in OTT service. (Graphic courtesy of NetFlix)

broadband Internet and 5G cellular services going to be strategically time to meet new demand that fiber-optic networks cannot respond to effectively?

The current financial status of the top five satellite communication service companies that are providing fixed satellite services (FSS) and some direct-to-the-home satellite services is shown in Table 3. This does not include the revenues for providers of direct broadcast satellite services which represent even higher levels of revenues which are shown in Table 4.

For both types of satellite service companies, the one clear conclusion is that today, the top revenue production for the satellite industry comes from and is dominated by operators of geosynchronous satellites (List of communication satellite companies). The one exception is SES that is now the operator of 44 GEO satellites plus the 20 satellite MEO constellation known as O3b. Also Viasat, which operates Viasat 1 and 2, has indicated that it too plans to move to the provision of digital services on a new MEO satellite network. Intelsat's plan to merge with OneWeb was not consummated and is no longer pending.

Today, it is only in the mobile satellite services (MSS) area that LEO constellations play a major part of the global satellite service infrastructure. Iridium NEXT and the second generation of Globalstar do heavily rely on LEO constellations. Their experience provides useful background and information with regard to the operation, frequency of switching from one beam to another in low orbit, deployment, end-of-life disposal of satellites, and economics of such networks. The next 10 years will provide much more useful information about the safe operation of much larger LEO constellations. The next 10 years will provide much more useful information about the technical, operational, market viability, regulatory processes, and service makeup of small satellite constellations. There are many organizations such as Northern Sky Research, Bryce Research, Euroconsult, and other others that are seeking to understand how fast the global satellite services market will change. This in turn will

Table 3 Global revenue streams for the top five fixed satellite service (FSS) providers. (Prepared by the author)

The top five global satellite service providers of fixed and direct-to-the-home services (based on revenues in millions of dollars)		
Company	Revenues (euros/US dollars (2018))	Products
SES (Luxembourg)	2010 milion euros about $2400 million	44 GEO satellites and O3b MEO system Video and data networking services
Intelsat (Luxembourg)	$2161 million (Intelsat Announces 4th Quarter and Annual Earnings for 2018)	36 GEO satellites. Talks of merger with OneWeb failed
Eutelsat (France) (Henry 2019)	1300 million euros about $1600 million	37 GEO satellites
Viasat	$1600 million	Viasat 1 and 2 High-throughput GEO satellites and proposal for a 20 satellite MEO constellation
Telesat (Canada)(Telesat Reports Results for the Quarter 2019)	$903 million	14 GEO satellites and beginning to deploy LEO system

The total revenues for these FSS service providers were taken from publicly released annual financial statements for 2017 or 2018. These are considered to be only approximation of current revenue streams. Please consult corporate web sites for more current numbers

Table 4 Revenues for the providers of DBS services. (Prepared by the author)

Key providers of broadcast satellite services globally		
Name of company	Estimated total revenues	Satellite network
Sky Vision (owned by Comcast with subsidiaries operating in the UK, Ireland, Germany, Austria, Italy, Switzerland, and Spain) (Skyvission)	13 billion pounds (about 17 billion dollars)	In addition to network of Sky satellites offering pay TV, there are also offerings of broadband digital services and significant entertainment and media productions
DISH(DISH Network Reports Fourth Quarter 2019)	$13.6 billion (2018)	16 GEO satellite between 61 and 148 degrees west
Direct TV and various subsidiary companies (DirecTV)	On the order of $12 billion/yr (it is a part of the AT&T Entertainment Group, and precise figures are not available)	13 GEO satellites between 95 and 115 degree west
JSAT and sky perfect satellite network	200 billion yen (about $2billion dollars)	3 GEO satellites

The total revenues for these DBS service providers were taken from publicly released annual financial statements for 2017 or 2018. These are considered to be only approximation of current revenue streams. Please consult corporate web sites for more current numbers impact the world of satellite manufacturing, the launch services, the space insurance markets, and more.

The danger of many market forecasts is that they often look to the future by looking through a rearview mirror. All the past revenues, all of the millions of subscribers to pay TV satellite systems, all of the DBS satellites in orbit, and all of the millions of parabolic dish antennas deployed around the world now working via GEO satellites would suggest that this is a solid business. Small satellite constellations are not well suited to reception of video, movie, and news. But if the world changes so that people have access to 5G cellular service and broadband Internet, the advantages of DBS satellites can be severely undercut. The moves by AT&T/DirecTV and Dish/Internet to OTT-distributed media services and the shrinking revenues and number of subscribers to DISH and DirecTV are signals that satellite service providers need to look at new business models. Intelsat is already working with Softbank Japan to see a merger with OneWeb. SES has successfully deployed O3b and has plans for a new MEO system that can deliver laser system-type throughput and new levels of cost efficiency. Viasat that operates Viasat 1 and 2 that represents the highest throughput GEO system in the world currently in operation has announced plans to move to a MEO system as well.

The strategic business and market indicators seem to suggest that the world data networks and media distribution networks are all moving in the direction of digital streaming and broadband distribution networks that are geared to low latency. The Internet, IP-based networking, and broadband networking geared to support 5G, Internet of Things connectivity, and media distribution will contain a satellite component for some years to come. This conclusion is inescapable when one considers the vast regions of the world where fiber-optic cable cannot provide connectivity to users. There are large areas of the Earth such as the oceans, lakes, deserts, jungle and mountain regions, the arctic areas, and more where satellites can offer broadband digital networking connectivity. Even in areas where DBS areas may be replaced by OTT services using terrestrial telecommunications capabilities, the transition will take time.

The point of this analysis is that the huge installed base of parabolic DBS dishes for home entertainment and news could become meaningless resources to be recycled if the DBS satellites are no longer beaming down programming. There are concerns among industry officials and analysts that there is now enormous momentum that entertainment and news services are shifting their distribution to OTT streaming systems. These systems can provide movies and news at a fraction of the now available DBS networks. Of course this is only the case in regions of the world where reliable, affordable, and technically viable Internet connections are available.

One of the groups studying the changes to the world of satellite communications is the BusinessandMarkets.com group. They have developed the following key questions that they will address in conducting a systematic study of how the world of satellite communication services will change in the coming decade and the top market, strategic, and technical forces that will shape this change – particularly in terms of small satellite constellations and its impact on the established world of geosynchronous satellite networks. These are key strategic questions, and the answers once developed will provide useful insight. Of all these key questions as noted below, the prime one not stated, seems to be how large a role will communication satellites play in providing news and entertainment to the world and via which types of satellites in a world that has large shifted over to 5G cellular service, digital streaming, and most devices enabled with IoT connectivity?

- "How has the satellite communication market performed (segmented by region and services) in the last 5 years?
- What was the regional and services market shares of the top satellite operators in the last 5 years?
- Who were the top-performing satellite operators in terms of revenue generation and revenue growth in the last 5 years (segmented by region and services)?
- What are the key industry trends that may drive/restrain the satellite communication market growth?
- What are the key value propositions by the new market entrants?
- How are incumbent players responding to the market challenges and competitions?
- How is the satellite communication market (segmented by region and services) forecasted to grow from 2018 to 2025?

3 Conclusion

The number one market consideration with regard to the future of satellite networks seems to be related to the satellite distribution of global entertainment and news. The question is whether existing satellite broadcasting systems and direct-to-the home television systems that are today essentially dependent on GEO satellites in Clarke orbit will give way to new digital streaming networks and OTT systems? It is not clear as to how quickly a transition to OTT will occur and how this will be different in different parts of the world. Today GEO satellite networks in locations such as India, China, Indonesia, Brazil, Nigeria, and many underserved portions of the world use satellite for television, radio, and telecommunications systems. This is even more important for rural and remote areas that lack terrestrial telecommunications networks or even reliable access to power.

Of course, the issue of whether satellite networks are used to provide television, radio, and connectivity to the world has implications that are, in fact, much wider. To the extent that remote access shifts from satellite networks to terrestrial systems and 5G data streaming for news and entertainment, it will also shift for virtually all other applications. In this new data streaming, world small satellite constellations with low latency will be better adapted to providing this service than GEO networks that are so dominant today.

GEO satellite connections, of course, are now used to provide connectivity for news and entertainment, but they can also be utilized to provide a wide range of other essential services that are key to life, especially in rural and remote areas. Thus satellite connectivity can provide key conduits of information for safety and disaster warning alerts. It can provide a mechanism to provide tele-education and tele-health services, especially to rural and remote areas where these services might be quite limited if not totally absent. The key question is as follows: In a new world of OTT for news and entertainment and data streaming, how does this impact the world of satellite networking and services? Does this new world – the world of 5G broadband wireless connectivity and IoT device connectivity – foretell a major shift in satellite network design and deployment? Does it suggest that GEO-based satellite networks are phased out in favor of small satellite constellations with low latency and very high transmission speeds that are comparable to optical-fiber laser transmission speeds? If this transition occurs, how quickly will it occur?

Satellite broadcasting revenues using GEO systems only decreased 1.7% in 2018, but transitions to OTT systems by DirecTV and Dish/EchoStar to OTT systems suggest a more rapid change in coming years (Satellite Industry Association 2019).

This is of course about much more than entertainment and news services via satellite networks. It is a leading indicator for other such services and for other vital applications such as tele-education, tele-health, safety alerts, governmental services, and even tele-business and tele-work connection. Critical regions to monitor will be India and China where GEO satellite provides vital services such as tele-banking and other services including television and radio connectivity. There are other technical factors such as the design, cost, and availability of new electronic tracking ground antennas that are key to the speed of the rollout and use of LEO and MEO satellites for data streaming services. This too will be a key factor as to how quickly markets, services, and satellite networks change to the new data streaming world.

4 Cross-References

- ▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas
- ▶ Messaging, Internet of Things, and Positioning Determination Services via Small Satellite Constellations
- ▶ Mobile Satellite Communications and Small Satellites
- ▶ Radio-Frequency Geo-location and Small Satellite Constellations
- ▶ Remote Sensing Applications and Innovations via Small Satellite Constellations
- ▶ Smallsats, Hosted Payload, Aircraft Safety, and ADS-B Navigation Services

References

C. Asssayag, Where Does the Future of Satellite Television Fit into the Future of Television Via Access, Nov 8, 2017. https://www.viaccess-orca.com/blog/satellite-ott-4k-satellite-tv-future

Conviva Swings TVE Deal With EchoStar. https://www.lightreading.com/video/ott/conviva-swings-tve-deal-with-echostar/d/d-id/710336? Last accessed 5 June 2019

DirecTV. https://en.wikipedia.org/wiki/DirecTV. Last accessed 5 June 2019

DISH Network Reports Fourth Quarter, Year-End 2018 Financial Results, Feb 13, 2019. https://ir.dish.com/news-releases/news-release-details/dish-network-reports-fourth-quarter-year-end-2018-financial

J. Engebretson, AT&T: Phase Out of Legacy DirecTV to Begin with AT&T Osprey STB. *Telecompetitor*, March 12, 2019. https://www.telecompetitor.com/att-phase-out-of-legacy-directv-to-begin-with-att-osprey-stb/

C. Henry, Eutelsat, Amid revenue decline, says year will rebound. *Space News*. https://spacenews.com/eutelsat-amid-revenue-decline-says-year-will-rebound/. 19 Feb 2019

Intelsat Announces 4th Quarter and Annual Earnings for 2018, Business Wire. https://www.businesswire.com/news/home/20190220005448/en/Intelsat-Announces-Fourth-Quarter-Full-Year-2018-R. Last accessed 5 June 2019

List of communication satellite companies. https://en.wikipedia.org/wiki/List_of_communication_satellite_companies. Last accessed 3 June 2019

Ownership of the O3b satellite network. https://en.wikipedia.org/wiki/O3b_Networks. Last accessed 5 June 2019

J.N. Pelton, *The New Satellite Industry* (International Engineering Consortium, Chicago, 2002)

J.N. Pelton, *The New Gold Rush: The Riches of Space Beckon* (Springer Press, Cham, 2017)

Satellite Industry Association, 22nd State of the Industry Report, 2018. May 8, 2019. https://www.sia.org/22nd_ssir/

Skyvission. https://en.wikipedia.org/wiki/Sky_(company). Last accessed 5 June 2019

Telesat Reports Results for the Quarter and Year Ended December 31, 2018. March 1, 2019. https://www.telesat.com/sites/default/files/news/telesat_press_release_q4_2018.pdf

Messaging, Internet of Things, and Positioning Determination Services via Small Satellite Constellations

Joseph N. Pelton

Contents

Abstract

The focus of the satellite application market for many years has been on broadband services and especially on video services provided by large high-powered satellites located in geosynchronous earth orbit (GEO). This type of service, known in the parlance of the International Telecommunication Union (ITU) as broadcast satellite service (BSS), has been the top source of revenues. Companies providing direct broadcast satellite services have, in fact, produced over 70% of satellite service income. Today there is a burgeoning new market associated with digitally networked services that small satellite constellations might be able to provide with particular skill. Some of these services require only thin data streams

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_40

and can be provided by quite small and cost-effective satellite networks. Others may demand much higher data rates and thus may be serviced by significantly higher data rates.

The focus of this particular chapter is on messaging, machine-to-machine (M2M), automatic identification services (AIS), and new forms of satellite-based Internet of Things (IoT) services. These are the new types of services that much small satellite constellations with lower bit rates can provide. These new systems such as Orbcomm, Kepler, Spire, Else, Kineis, ELO, and others can be deployed at much lower cost than the bigger mini-satellite systems seeking to provide broadband services. They can also operate to much lower-cost omnidirectional ground terminals.

It is possible that mini-satellite constellations with much higher-throughput rates optimized for 5G services and video via over the top data streaming services will create very large new multibillion dollar markets. These types of services, however, will be provided by larger types of small satellites configured to operate in higher data rate constellations. These services will be reserved for either GEO high-throughput satellites or mini-satellite constellations. This gigabit per second market, if served by small satellites, will be reserved for those megaconstellations being implemented by OneWeb, SpaceX's Starlink, LeoSat, Boeing, Thales, and others.

This chapter concentrates on the interactive satellite messaging services that deal in megabits per month rather than process information in gigabits/second.

Keywords

Automatic identification services (AIS) · Data relay services · Else constellation · Eutelsat LEO for Objects (ELO) · Geolocation · International Telecommunication Union (ITU) · Internet of Things (IoTs) · Kepler · Kineis · Messaging · Machine-to-machine (M2M) · Orbcomm · Position determination · Spire · VHF data exchange services (VDES)

1 Introduction

The Surrey Space Centre, now known as Surrey Space Technology Limited (SSTL), played a key role in the early development of small satellites with advanced digital processing and storage capability that could provide messaging and store and forward services. These "Surrey sats" could provide messaging relays to support remote locations such as medical clinics, oil platforms, and remote mining sites and collect data from ocean buoys and score of other locations. These low-cost satellites that operated at low data rates did not require sophisticated or expensive ground terminals.

The idea that small and efficient satellites might be able to assist with messaging and location tracking continued with the GeoStar network that operated in geosynchronous orbit and then with the Orbcomm small satellite constellation that was deployed at the same time as the first systems for mobile satellite communications. The Orbcomm system, first developed by the Orbital Sciences Corporation, allowed trucking companies, shipping lines, rental car companies, bus companies, and others to stay in touch via messaging services. Additional capabilities that were added to provide GNSS capabilities via the GPS network augmented the messaging services with navigational and geolocation services as well.

In the world of cubesat and nanosat technology, there are today a number of systems that are deploying or developing new capability to deploy quite small satellites to use messaging or machine-to-machine (M2M) services for a much wider range of data relay services at modest data rates. These new networks are not seeking to compete with broadband high-throughput systems such as SpaceX, OneWeb, and many other companies that are now deploying. The emphases of these data relay satellite systems are messaging, machine-to-machine communications, geolocation, automatic identification services, and Internet of Things data relay. Some of the systems that are now providing these services or are planned for such services in the near term are discussed in this chapter. The presentations explain the various types of services offered, technical and service challenges and competitive options, and finally regulatory or standards issues that pose issues with regard to the provision of such services.

2 Orbcomm

The Orbcomm initial system was deployed in the 1990s. At that time this type of small commercial messaging satellite constellation represented a completely new start-up enterprise seeking to develop a new market. The Orbital Sciences Corporation provided the launch services, designed and manufactured the satellites, and was responsible for the marketing of the new global messaging services. Although it had a very innovative satellite design, low launch costs, and other positive attributes, it was an entirely new type and thus a high-risk undertaking. It had the difficulty of starting a new global messaging service from scratch where the intended customer base around the world had little appreciation of the value that could be derived from the new services provided. Further Orbcomm had little experience in marketing its service to customers who might most benefit from these services. The end result was that it went bankrupt. All of the somewhat parallel mobile satellite communication ventures, namely, Iridium, Globalstar, and ICO, also failed financially and so went bankrupt.

Orbcomm was reorganized under new management, and this messaging service gradually became financially viable. Currently a second generation of packet-switched (M2M) messaging satellites, as manufactured by Thales Alenia, has now been deployed at a cost of $240 million. This second-generation spacecraft is described by Orbcomm as offering up to six times the data throughput capacity and up to twice the transmission rate of the earlier satellites. This second generation of satellites was initially deployed as a network of 18 satellites. The second generation of Orbcomm satellites also has an L-band package that allows satellite-

Fig. 1 One of the second-generation Orbcomm satellites as pictured in orbit. (Graphic courtesy of Orbcomm)

based automatic identification services. System failures with the second generation of Orbcomm satellites (OG2), however, have reduced this second-generation network size significantly. The current network combines both first- and second-generation satellites, but 80% of the traffic is now on the second-generation satellites. There is also a cooperative agreement with Inmarsat to provide mutual support for services. A third generation of satellites is now under active study (Henry 2017a) (see Fig. 1).

Although the basic service is described as machine-to-machine (M2M) messaging, the range of services described under this general "umbrella" is now quite large, sophisticated, and geared to various industries. Over time many types of industries in areas such as transportation, product shipment, mining and resource extraction, etc. have learned the value of the various satellite services now on offer by Orbcomm and other messaging satellite service providers. The Orbcomm satellite services have also become more refined and diversified to respond to various types of market needs. The Orbcomm offerings now break down into three categories of (i) Web Applications, (ii) Radio Frequency Identification/Real-Time Location Services (RFID/RTLS), and (iii) IoT Solutions for Remote Monitoring and Control.

Under **Web Applications** Orbcomm offers services that include:

Road Transport. (i) Fleet management for trucks, trailers, and refrigerator units; (ii) CargoWatch (for trailers and chassis); and (iii) ReeferTrak (to provide compliance with regulatory requirements as well as optimized temperature levels for fuel savings).

Intermodal Transport This typically involves shipping, air, rail, and truck operations. This provides sub-options such as (i) Reefer Connect, (ii) Vessel Connect, (iii) Cargo Watch Security, and (iv) Fleet Edge (this last offering is designed to support various types of equipment telematics-related services and data interactions).

The second broad category of messaging service that Orbcomm now provides is **RF Identification (RFID)/Real-Time Location Services (RTLS)**.

This type of service is broken down into:

(i) **RFID Software** (for both manufacturing and inventory control)
(ii) **AssetWatch** (to provide for asset safety and security and inventory control)

The third area that is also now growing the most rapidly as a market is **IoT Solutions for Remote Monitoring and Control**.

In this satellite messaging arena, Orbcomm offers an entire toolkit of services as well as hardware options. These offerings range from a turnkey type of comprehensive service that provides software and hardware. There are also other types of satellite messaging services as well as more discrete satellite services or hardware options.

These offerings in the IoT Solutions area include:

DeviceCloud: This allows interactive communications with connected devices in a customer's system. This proprietary system, as provided by Orbcomm, creates a single interface to manage multiple networks and devices.

Application Enablement Platform known as iApp: iApp is an application enablement platform that Orbcomm claims can reduce the time, cost, and complexity of deploying high-performance RFID as well as sensor-enabled IoT applications. This can allow RFID and IoT applications to be communicated with interactively and on a global scale with only modest delays. With the second-generation OG2 satellite messaging connections, times have continued to improve with delays being measured in seconds or at most a few minutes.

Orbcomm Provided IoT Hardware: It is possible to obtain via Orbcomm a range of tracking and monitoring capabilities. The types of hardware that can be purchased or leased include programmable terminals and sensors and compatible satellite modems that allow a variety of telematics solutions. These various hardware offerings are designed with suitable software to operate under different international standards.

It is possible to sign up for a complete end-to-end IoT deployment that includes both the service and the hardware. These comprehensive end-to-end offerings include a suite of cloud-based software as a service (SaaS) capabilities. It is possible to operate these from a platform as a service (PaaS) basis. The purpose of these Orbcomm offerings is to allow near real-time reporting on the status of assets. Thus Orbcomm and other newer entries into the satellite messaging service industry can provide global tracking and managing of assets for many different types of industries with goods and materials widely distributed around the world (ORBCOMM 2019). These other satellite messaging services will be described below. Many of these new systems that are concentrating on IoT service or automatic identification service are presented below.

Orbcomm has the advantage of many years of experience. Over that time Orbcomm has become less and less an operator of small satellite constellation. Instead it has become a provider of services – and specialized telematics and data networking or geolocation hardware – to those involved in transportation and other industries such as mining, manufacturing, and other industries that are concerned with efficient management of assets – especially organizations that have resources widely deployed all over the globe and where supply chain efficiencies have become quite important.

This detailed reporting on Orbcomm services as provided above in many ways might be seen as a model for the types of satellite messaging services that can be expected to be offered by other small satellite systems now being deployed. The Orbcomm satellite experience in terms of developing tools and interactive capabilities well suited to client industries is a useful paradigm for a number of new companies now seeking to provide M2M messaging services via small satellite constellations to support safety and security, inventory control, interactive IoT services, automatic identification services, and position determination and geolocation updates.

3 Satellite-Based Automatic Identification Services (S-AIS)

The established small satellite constellation, Orbcomm, is now equipped via an L-band package to provide satellite-based automatic identification services (S-AIS). Nevertheless, Orbcomm is not unique or predominant in this satellite service area. It has strong competition from several other satellite service providers including from entities operating with new nanosat constellations which have shown innovation in this area such as more extensive coverage, very rapid domain identification capabilities as well as cost reductions for the service.

exactEarth, in particular, has deployed a near real-time network that now operates from a second-generation hosted payload capability installed on the Iridium Next constellation for this purpose. exactEarth has joined with the Harris Corporation to create the payloads and with Iridium to deploy its AIS payloads on the Iridium Next 66 host platforms that are employed to provide this global service.

Currently there are 58 operational exactEarth payloads plus 7 spares that are flying as hosted payloads on the Iridium Next system to form the exactEarth RT constellation. This second generation of the exactEarth constellation is capable of rapid domain identification for ships and ocean-going vessels (exactEarth's Revolutionary Global Real-Time Maritime Tracking and Information System now Fully-Deployed n.d.).

Automatic identification system (AIS) is a global standard for ship-related messaging services operating in the VHF band and 161 and 162 MHz. This service is designed to avoid collisions and aid search and rescue (SAR) operations and maritime domain awareness through near-instantaneous ship and other vessel tracking. AIS was ruled to be a mandatory safety and security service for all ships and vessels for A and B types of service under the International Maritime Organization's (IMO) International Convention for the Safety of Life at Sea (SOLAS). This Convention was adopted and entered into force in 1974. Satellite-based automatic identification service (S-AIS) allows for global coverage in remote areas, such as isolated oceanic and arctic regions. It complements terrestrial AIS and coastal radar coverage. This service is particularly important to enhance AIS connectivity in arctic and more isolated ocean areas where satellite access is largely the only available option (see Fig. 2).

The problem for the future is that the VHF band is only able to support very limited bandwidth services because of the now very intense use of spectrum between 30 and 300 MHz on a global basis. The very narrow bands available for the automatic identification service is on Channel A 161.975 MHz (87B) and Channel B 162.025 MHz (88B). Thus the offerings such as the VHF data exchange service cannot be expanded. The only option is more efficient coding that allows more bits/Hz to be transmitted.

The exactEarth constellation claims the following capabilities with regard to S-AIS domain identification for ocean-going vessels: (i) global average satellite revisit coverage of under 1 min; (ii) customer data latency under 1 min; (iii) reliable detection of both Class A and Class B AIS messages; (iv) tracking of large populations of small vessels with suitably equipped with AIS transceivers (this is known for the exactEarth-Harris service as exactTrax™); and (v) support for the future evolution of AIS to provide VHF data exchange service (VDES) and other initiatives in the maritime VHF band (exactEarth: Real Time Global Ship tracking n.d.) (as noted above the limited frequency spectrum available in L-band limits any great expansion of VDES).

In addition to exactEarth, the Spire small satellite constellation has developed a capability to provide global S-AIS services. In the case of Spire, it provides not only

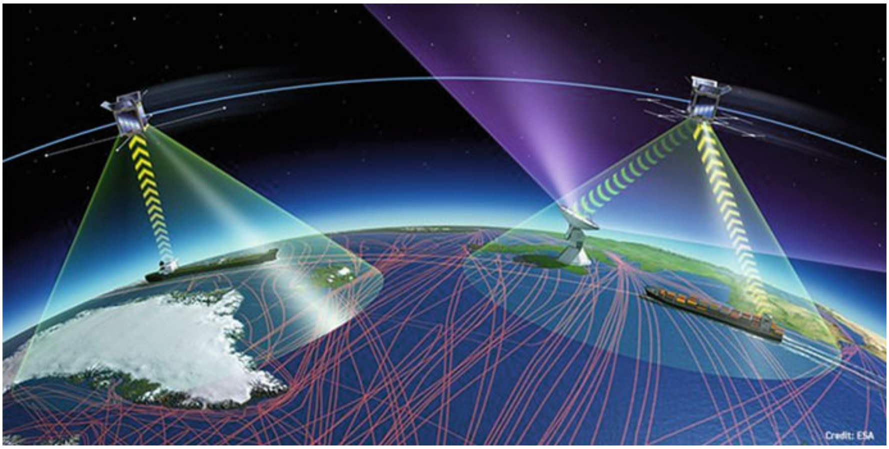


Fig. 2 Graphic showing satellite reception of S-AIS signals from ships on the high seas. (Graphic courtesy of the European Space Agency)

domain identification for ships and vessels but also data analytics that projects with good accuracy where a ship will be at the time of the next location update. There are also several other start-ups that are seeking to provide S-AIS services via new cubesat-type constellations.

There are detailed market studies that have projected that global shipping and demand for S-AIS services will continue to grow. One of these market analyses is the insight report known as the "Satellite-Based Automatic Identification Systems Market 2025 – Global Analysis and Forecasts by Type (Class A Transponder and Class B Transponder) and Applications (Ship, Defense, Aerospace, and Intelligence and Security)."

The question is whether this market is sufficiently large and diverse enough to sustain a growing number of small satellite constellations. Most systems such as Orbcomm, Spire, and several others have seen the S-AIS market as a source of incremental revenue, but exactEarth has seemed to focus on this service as a primary source of revenue (Satellite-Based Automatic Identification Market 2025 n.d.).

The market demand and size for S-AIS have been seen to be in flux. This market is currently still small and largely depends on governments contracting to obtain the S-AIS data in order to track shipping and vessel activity and provide for at sea safety and security. In many cases governments depend on coastal radar for tracking shipping movements within 100 miles (160 km) of their shores. Thus some governments see S-AIS as an optional service. Shipping lines are still seeking to prove that their savings in fuel, shortened port stays, and safety and security are sufficient to pay for such services.

The Canadian government contract services is a case in point. It awarded an initial contract to exactEarth S-AIS service provider in 2014 in the amount of $19 million (Canadian) or ($14.5 million US), but after fierce competition between Orbcomm and its Canadian subsidiary Skywave Mobile Communications for the renewal of this contract, it was determined that the Canadian requirements for data were to be severely cut back. The reduction of some $7 million in revenues (or $600,000 per month) represented about 25% of exactEarth revenues at the time. This major loss of revenues resulted in a major reduction in the stock price of exactEarth that is offered on the Toronto Stock Exchange. As more constellations join Orbcomm, Spire, and exactEarth to compete for AIS-type service (i.e., the Else nanosat constellation, the new Eutelsat LEO for Objects (ELO) constellation, the French Kineis constellation, and others), the profitability of quite so many messaging, IoT, and truly small satellite constellations may come into increasing question (de Selding 2016).

4 Other Systems for Messaging, IoT, AIS, and Lower-Data Rate Services

The idea behind many of the true small satellite constellations now being planned is that they can be deployed for a modest cost. Some estimates have been as low as $50 million and most at a cost of around a quarter of a million. Low cost alone is not sufficient. The key question is whether a low-cost small satellite system operating at low data rates can find sufficient market and revenue streams to sustain their operation. Some of these systems have started with test satellites funded by kickstarter programs on the Internet, and others have been funded by satellite companies operating geosynchronous satellite systems but envision that LEO constellations might be key to providing data services requiring low-latency transmission times. Each of the following small satellite constellations provides useful insight into these new systems and the thought process behind their planning and implementation.

5 Spire

Currently Spire Global Inc. characterizes its business operations in a much different way than when it first started**.** Today it indicates that its role is focused on data analytics related to tracking of global data sets derived from the tracking of maritime, aviation, and weather patterns. Its main focus shifted from data messaging and provision of AIS type services when it received major contracts in the weather data analysis areas. The breakthrough award came from the European Galileo project to conduct longer-term weather data analytics. This contract over time is potentially worth $2.7 billion (Sheetz 2018). This Galileo Award was preceded by 3 months by a much smaller award from NASA for a weather data and observations analysis contract. This NASA contract was, however, likely a critical antecedent to the European award (Mohney 2018)

Spire Maritime was launched as a new business unit at the end of 2018 and officially announced in February 2019. The purpose of this is to focus on use of L-band systems to collect automatic identification service information on a global basis using its Lemur 2 constellation of a 100 deployed nanosats to identify the names and ownership of all ships at sea and their routes on a near-instantaneous basis. Further they will seek to generate predictive data as well in order to provide historical data on vessel usage or cargo shipping patterns. The purpose of Spire Maritime analytics will be to help enforcement against illegal fishing, smuggling, drug running, polluting activities, etc. as well as to assist with more efficient routing of ships and vessels and provide for accurate tracking of cargo and improved safety and security on the high seas.

The idea is to seek to “reinvent the maritime world” through the use of data analytics. The leadership of Spire Maritime has state its goal to be “to create new technologies for the maritime industry under the guide of seasoned leaders. Spire Maritime will utilize technologies like machine learning to deliver real-time data and insights that raise the bar in the maritime world” (Spire Announces a New Business Unit for Maritime Data and Analytics n.d.).

It also uses its 100 satellite constellations of Lemur 2 satellites, the third largest constellations in the world in terms of operational satellites, to operate hosted payloads for automatic dependent surveillance broadcast (ADS-B) for airline tracking and safe navigation and security. (Note: the Iridium Next 66 satellite constellation now is the host platform for 58 ADS-B operational units plus 7 spares).

Spire thus lists its services to include (i) Spire Sense Cloud (satellite and terrestrial AIS); (ii) Spire AirSafe (satellite ADS-B); (iii) Spire Stratos (GPS-RO and GPS-R); and (iv) Orbital Services The main focus is the environmental and weather data

Fig. 3 Lemur 2 nanosat with payloads for AIS, ADS-B, and weather data. (Graphic courtesy of SPIRE Global Inc.)

analytics or Spire Stratos, although with its 100 satellite constellation deployed in orbit, it is a serious provider of all these services (Spire Global n.d.).

Spire was the first to launch its multiunit cubesats from the NanoRacks launch dispenser from the International Space Station (ISS), and it has also used a wide range of other launchers to get its large fleet to orbit. Since the Lemur satellite constellation only has a lifetime of 2–3 years, it is in need of rather constantly manufacturing new satellites at its joint facility with Clyde Space in Scotland, as well as to provide for deorbiting of defunct spacecraft (see Fig. 3).

6 Kepler

The Kepler constellation is a much more straightforward story in that this start-up had a clear commercial focus on creating a global small satellite constellation for messaging and highly efficient M2M services. Its prime market focus is seen as Internet of Things connectivity for very small and compact transceivers the size of credit cards. Its mission statement emphasizes that the system that they are designing, building, launching, and operating is “satellite communications simplified.” Kepler Communications website states that their ambition is designed to “integrate our satellite connectivity solutions into your global operations and communicate like never before.....to provide connections from small sensors to large ocean going vessels so that ‘One Standard IoT’ can be made available everywhere” (Kepler n.d.).

The emphasis of the Kepler offering is on a simple cellular link via a compact transceiver to provide connectivity for Internet of Things (IoTs) units. This is, in fact, a credit card-sized transceiver that runs on an AA-sized battery for years. This type of IoT-designed Kepler link is geared to provide service at up to 1 megabit capacity per ground transceiver per month for data collection and control messaging. In many ways this capability is similar to that provided by tradition supervisory control and data acquisition (SCADA) systems that operate with pipelines, elevators, or

Fig. 4 Kepler nanosat constellation that specialized in satellite links to credit card-sized transceivers so as to provide connectivity to Internet of Things (IoT)-enabled units. (Graphic courtesy of Kepler Communications)

utility operations. The Kepler constellation is uniquely designed for global connectivity including satellite service and coverage even in the polar regions (Kepler Services n.d.) (see Fig. 4).

In addition, Kepler with its S-AIS capability is also able to offer fleet and route tracking, alerts to any route variations, asset monitoring, and other services that are similar to those offered by Orbcomm, exactEarth, and other small satellite constellation discussed in this article.

7 The Else Nanosat Constellation

This project is a joint venture of Astrocast of Switzerland and Yahsat/Thuraya of Emirates. Around the world operators of geosynchronous-based satellite networks such as Intelsat, SES, Thuraya, Eutelsat, and Telesat are exploring how they might diversify into LEO-based constellations and capture data networking services that require low latency or minimal delay in their transmitted services. The Else nanosat system is to be operated by Yahsat. Yahsat now operates GEO satellite systems. This includes the Thuraya system which is a large GEO based system for mobile satellite communications services. The Else constellation represents the way that Yahsat is examining a way to enter the LEO constellationa market by means of a lower-data rate nanosat constellation. (Henry 2017b).

Astrocast that has designed and manufactured nanosats previously is manufacturing the Else small satellites. Thuraya, now owned by Yahsat, is providing the capital financing and also sharing its expertise in marketing satellite services in the Middle East, Africa, and elsewhere.

Fig. 5 Else cubesat constellation by Astrocast in partnership with Yahsat/Thuraya

The idea is to use limited L-band capacity to provide M2M messages via the Astrocast 64 satellite constellation. This constellation will consist of eight satellites located in eight planes. The terminal design for messaging from the ground will be even smaller than the Kepler system. Its currently proposed size is about the size of a stamp, and its L-band antenna will be about the same size. It can be battery operated or connected to a local power source. Its current objective is to be able to relay messages to its customers operations center within a 10–15 min time period (Henry 2017c) (see Fig. 5).

8 Eutelsat for LEO Objects (ELO)

Eutelsat has purchased from Tyvak International a number of nanosats for the purpose of providing a low-data rate Internet of Things (IoT) service. This represents yet another instance of a large GEO operator seeking to find ways to enter the LEO constellation market but not necessarily making a large capital investment to do so.

This project will be drawing on the technology currently used by Sigfox to operate a land-based low-power wide area network (LPWAN) messaging system. Sigfox and other similar operators use their WAN-based systems to provide asset tracking, environmental monitoring, and tracking of utility meters such as for water, electricity, natural gas meters, and other systems controlled by supervisory control and data acquisition (SCADA) networks. The range of coverage for these low-powered WAN networks with connectivity to nearby gateway or nodes is typically in the range of 10 km and at the outside is usually 20 km. This range is insufficient to provide coverage in areas such as the desert, jungles, mountainous terrains, and oceans. This is where a global constellation becomes quite useful. Although GEO systems are adept at many services, this type of data collection

Fig. 6 Eutelsat LEO Objects (ELO) nanosat designed for the IoT market. (Graphic courtesy of Eutelsat)

from very small terminals connected to Internet of Things-enabled devices and SCADA-like systems is difficult. This type of service at L-band is well suited to LEO constellations. In short the LEO constellation two test satellites will test this type of service before the full constellation is deployed (see Fig. 6).

Yohann Leroy, Eutelsat's deputy CEO and chief technology officer, has explained the reasoning behind the ELO constellation initiative as follows:

> "There are fundamental differences from a technical standpoint between the broadband market and the IoT market, which is a narrowband market. . .....The only way to transmit megabits per second with satellites that move through the sky is to have a tracking – and necessarily expensive – antenna on the ground. [For IoT], when you only need to transmit a few kilobits per second and not megabits per second, omnidirectional – and much cheaper – antennae are sufficient" (Henry 2019). This logic also means that the terminals and their antenna and their power sources can also be quite small.

9 Kineis

There is another important French nanosat constellation that is in active planning. This system is to augment and then replace the seven-satellite Argos system that has been in operation since 1978. It will use L-band systems for messaging, M2M, and IoT connectivity. The new system is to be known as Kineis. This is to be a 25-satellite constellation that will draw on the experience gained by the Argos satellite system that has been providing messaging services to a world community of environmentalists and other users for several decades. This project is backed by CLS, CNES, Thales Alenia, Nexeya, and others in France. There are currently two preliminary satellites in orbit to provide experimental tests with ground equipment and refine the design of the satellites and ground terminals. While Argos was a project of the French government and CNES, Kineis is seen more of a commercial venture (Kineis constellation n.d.).

10 Other Messaging Satellite Systems

The above discussion and summary discussion of planned small satellite messaging systems that also includes the second generation of Orbcomm still do not represent a completely exhaustive list of all the various types of small satellite constellations that have been announced as possible new initiatives in the field of AIS and messaging services. There are some that have indicated plans for a sort of satellite communications service that would be sold on a public subscription basis and other types for safety, development, and scientific services. The above listing is representative of the systems that seem likely to be deployed. The listing of constellations in Part 13.1 is provided as a more complete listing of various systems that might be deployed within the next 5 years.

11 Cost of System Versus Size of Markets

Most of the systems that are now envisioned or are in actual deployment at this time are quite cost-effective. Many of these systems can be deployed for a cost that is equivalent to the cost of the launch of a single high-powered and high-throughput geosynchronous satellite system that might be deployed by Intelsat, Eutelsat, Telesat, SES, or Viasat, but there is still doubt as to whether the market for such AIS and messaging services is sufficient to cover the total cost of operations of so many new LEO constellations planned for operation in the L-band with such limited data throughput capability. The messaging smallsat constellations, even with advanced new coding systems, are limited in their throughput. Planned expansion of VHF data exchange services (VDES) will be limited by L-band allocations for this service to ships.

For decades, the Argos system has been subsidized in its global messaging service by CNES. Now at least six LEO constellations, i.e., Orbcomm, Spire, Kepler, Else, ELO, and Kineis, are planning to provide these various types of messaging services. Clearly the new IoT market with perhaps many billions of interactive units seeking to be interconnected creates new market opportunities. Nevertheless some of the market analysis has now undertaken a question that the planned investment costs for these various systems that will likely top a billion dollar (US) can all be recouped.

12 Conclusions

The world of “NewSpace” and particularly the ongoing effort to create new types of small satellite services seem to continue apace. There is clear appeal to create new small satellite constellations, especially low-cost nanosat systems that can typically be deployed for under $300 million dollars. This is a business that start-up companies, especially if helped by larger satellite companies, can contemplate entering.

New space investment strategies that can be started with kick-starters and crowdsourcing and then financed by angel investors with rounds of funding have allowed companies such as Planet and Spire to soar into prominence. These two start-ups currently operate two of the largest satellite networks in the world.

The success of some of the smallsat constellations and new launch vehicle firms like SpaceX, Blue Origin, and Rocket Labs can create false expectations in some of the small satellite initiatives now seeking to create new LEO constellations to serve new markets that have yet to be entirely proven. The arena of data analytics is perhaps the new space market with the greatest potential for new vibrant space applications, but it is also the area where the greatest commercial risks might also lie. The large number of these new systems, existing and proposed, represent a risk that is now heightened by the economic downturn associated with the Covid-19 virus.

13 Cross-References

► Ground Systems to Connect Small-Satellite Constellations to Underserved Areas
► Messaging, Internet of Things, and Positioning Determination Services via Small Satellite Constellations
► Mobile Satellite Communications and Small Satellites
► Radio-Frequency Geo-location and Small Satellite Constellations
► Remote Sensing Applications and Innovations via Small Satellite Constellations
► Small Satellite Constellations Versus Geosynchronous Satellites for Fixed Satellite Services and Network Services
► Smallsats, Hosted Payload, Aircraft Safety, and ADS-B Navigation Services

References

P.B. de Selding, exactEarth beats Orbcomm for Canadian Contract Space News" (May 6, 2016) https://spacenews.com/exactearth-bests-orbcomm-for-canadian-contract-that-shrank-to-a-pittance/

ExactEarth: Real Time Global Ship tracking (n.d.) https://exactearth.com/technology/exactview-rt-powered-by-harris?ads_cmpid=1495401106&ads_adid=56746943934&ads_matchtype=e&ads_network=g&ads_creative=286787152932&utm_term=exactearth&ads_targetid=kwd-482432964226&utm_campaign=&utm_source=adwords&utm_medium=ppc&ttv=2&gclid=CjwKCAjwx_boBRA9EiwA4kIELsQFRFFrYKdJ-GviJ1grNLNP6DbhaB9Ipxkyf-Moth4EiR4bNFFxGRoClzoQAvD_BwE. Last accessed 10 July 2019

exactEarth's Revolutionary Global Real-Time Maritime Tracking and Information System now Fully-Deployed (n.d.) http://investors.exactearth.com/2019-02-14-exactEarths-Revolutionary-Global-Real-Time-Maritime-Tracking-and-Information-System-now-Fully-Deployed. Last accessed 8 July 2019

C. Henry, Three Orbcomm Og2 Satellite Malfunctioning, gate to be determined Space News, (Aug. 3, 2017a)

C. Henry, Meet else the Thuraya-backed smallsat startup. *Space News* (June 9, 2017b) https://spacenews.com/meet-else-the-thuraya-backed-smallsat-startup-that-wants-to-connect-things-with-cubesats/

C. Henry, Meet else the Thuraya–backed smallsat start-up that wants to connect things with cubesats, *Space News*, (June 9, 2017c) https://spacenews.com/meet-else-the-thuraya-backed-smallsat-startup-that-wants-to-connect-things-with-cubesats/

C. Henry, Eutelesat planning small 'Internet of Things' network, *Space News*, (April 3, 2019) https://spacenews.com/eutelsat-planning-small-leo-internet-of-things-constellation/

Kepler (n.d.) https://www.keplercommunications.com/. Last accessed 10 July 2019

Kepler Services (n.d.) https://www.keplercommunications.com/services/iot. 12 July 2019

Kineis constellation (n.d.) https://www.kineis.com/en/. Last accessed 15 July 2019

D. Mohney, Planet, Spire score NASA commercial Earth science pilot data contracts Spacebridge. com, (Oct, 18, 2018) https://www.spaceitbridge.com/planet-spire-score-nasa-commercial-earth-science-pilot-data-contracts.htm

ORBCOMM | IoT & M2M Solutions | Connecting The World's, (n.d.) (Last accessed 10 July 2019) Assets. https://www.orbcomm.com/?source=google&medium=cpc&creative=296955699074&term=orbcomm&matchtype=p&netw

Satellite-Based Automatic Identification Market 2025 (n.d.) https://www.theinsightpartners.com/reports/satellite-based-automatic-identification-systems-market. Last Accessed 8 July 2019

M. Sheetz, Start-up Spire Global lands deal with ESA's Galileo satellites for predictive weather data CNBC, (Dec. 11, 2018). https://www.cnbc.com/2018/12/11/spire-global-gets-2point7-billion-weather-data-partnership-from-galileo.html

Spire Announces a New Business Unit for Maritime Data and Analytics" (n.d.) https://www.globenewswire.com/news-release/2019/02/01/1709004/0/en/Spire-Announces-a-New-Business-Unit-for-Maritime-Data-and-Analytics.html. Last access 8 July 2019

Spire Global (n.d.) https://en.wikipedia.org/wiki/Spire_Global#Early_Years. Last accessed 8 July 2019

Remote Sensing Applications and Innovations via Small Satellite Constellations

Su-Yin Tan

Contents

Abstract

Small satellites are opening up new remote sensing applications and changing the economics of space. Small spacecraft missions are more affordable, have shorter development times, and are more flexible than traditional satellite markets. There has been a rapid evolution and diversification of technologies, and new business cases are being tested within the small satellite industry. The application of small satellites and constellations to Earth observation has arguably made the greatest impact, transforming our understanding of Earth, our ability to monitor the environment, and our capacity to address targeted scientific questions in a rapid and more affordable manner. Although many spacecraft utilize "off-the-shelf" components and instruments to perform remote sensing observations, there are

---

S.-Y. Tan (✉)
Department of Geography and Environmental Management, University of Waterloo, Waterloo, ON, Canada
e-mail: su-yin.tan@uwaterloo.ca

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_44

technical challenges for synthetic aperture radar (SAR) and hyperspectral imaging on small satellites, as well as limited launch opportunities, growing space debris, Earth observation policies, and communication frequency allocations among other constraints. This chapter provides an overview of satellite developments and constellations for remote sensing or Earth observation applications. The aim is to review current small satellite systems and innovations and to discuss developments in small satellite applications related to remote sensing with a special focus on small satellite constellations.

Keywords

Constellation · CubeSat · Department of Defense (DoD) · Defense Weather Satellite System (DWSS) · Disaster Monitoring Constellation (DMC) · Earth observation · Earth Observing System (EOS) · European Space Agency (ESA) · German Space Agency (DLR) · International Charter for Space and Major Disasters · Joint Polar Satellite System (JPSS) · Meteorological satellites · Microelectromechanical systems (MEMS) · Microsatellite · Nanosatellite · NASA · National Oceanic and Atmospheric Administration (NOAA) · National Polar-Orbiting Operational Environmental Satellite System (NPOESS) · NewSpace · OSCAR (Orbiting Satellite Carrying Amateur Radio) · Remote sensing · Sensors · Surrey Satellite Technology Ltd. (SSTL)

1 Introduction

Small satellites are a growing phenomenon and opening up a new class of remote sensing applications. These new tools have revolutionized the economics and technical approach for Earth observation. The growth of the small satellite industry is driven by its low costs for development, launch, and operation, which enable more access by universities, startup companies, emerging countries, and government space agencies. This also enables outer space to be more affordable to a larger group of people and for a variety of applications.

The growth of small satellites has created unprecedented opportunities for innovation in the broader satellite market and related businesses. Indeed, there has been rapid evolution and diversification of technology and business by the startup and growth of small satellite companies. This results in an interesting dynamic with traditional satellite markets, which rely on large spacecraft and complex designs.

More space-based remote sensing observations have also transformed our understanding of Earth, its environment, the solar system, and the universe at large. Small satellites enable experimenters and operational users to address targeted scientific questions as well as operational activities such as weather forecasting, smart farming, resource monitoring, and many other practical services in a rapid and more affordable manner. Many small spacecraft utilize “off-the-shelf” components and instruments for less expensive ways to perform remote sensing observations. This is not always possible. There are technical challenges for synthetic aperture radar (SAR) and hyperspectral imaging on small satellites, which may offer more high-resolution observation capabilities for supporting future space applications. These may require more specialized sensors.

This chapter provides an overview of small satellite developments since the launch of Sputnik 1 and historic and current developments for remote sensing or Earth observation applications. This review has three objectives: (a) to provide a historical overview of the development of the small satellite industry, (b) to review current small satellite systems and innovations, and (c) to discuss developments in small satellite systems for applications related to remote sensing or Earth observation with a special focus on small satellite constellations. Since the small satellite industry is rapidly evolving, this review may not be exhaustive in nature but mainly focuses on examples of small satellite systems in relation to remote sensing and their current and future applications.

2 A Historic Perspective

In the beginning, all satellites were small. These satellites were “small” because launch capacity was limited and there was initially no need to make satellites of great size. Sputnik 1 was launched in the Fall of 1957 and had a mass of 83 kg. The first US satellite was Explorer 1 launched on January 31, 1958. This was followed by Vanguard 1 that was launched on March 17, 1958. Both of these satellites would be considered small by today’s standards, and indeed Vanguard 1 had a mass of only 1.6 kg. Spacecraft for Earth observation did not come until later, but at the start, they too were smaller but, over time as they were designed to achieve higher resolution, became larger and larger until they became quite large such as Envisat, which had a mass of over 8,000 kg and was launched in 2002 by the European Space Agency (ESA). This satellite and the dangers of launching gigantic satellites will be discussed later in this chapter.

Any trend in satellite development – and especially in satellite applications – has been to design them to be larger and larger. This has certainly been the case for telecommunications and meteorological and remote sensing satellites that are also widely known as Earth observation satellites. Each spacecraft and all of their subsystems including their thermal control, solar power and battery systems, propulsion, attitude determination and control, TT and C, communications as well as payloads for telecommunications and Earth observation grew larger and more sophisticated. The drive was for greater and greater economies of scale and higher performance. There was also the thought that a more thoroughly tested satellite could minimize risk and provide greater reliability. On the other hand, this also brought disadvantages. These included higher launch costs, higher design and development costs, long-term manufacturing schedules, and increasing testing costs. This trend also required large technical teams and sophisticated manufacturing facilities; these also added to the cost and made the systems more and more intricate in design.

Spacecraft design for meteorological satellites, remote sensing, and telecommunications for the last half century has been in many ways quite parallel. This has sometimes been called technology inversion. The satellites had become larger, more complex, and more capable in space, while the ground systems had become simpler. The earliest satellites were small as a result of both limited launch systems and limited mission requirements. Application satellites became larger and larger since the 1970s and 1980s. The launchers became perhaps 100 times more capable, and the satellite infrastructure strengthened in capabilities. In the case of Earth observation, there were also military requirements that drove the need for sophisticated satellites with space reconnaissance capabilities. In the early 1990s and at the end of the Cold War, some of these dynamics began to change. Small satellite systems with surprising new capabilities began to emerge. Some of the larger and more complex projects of NASA and ESA and other space agencies experienced fewer launches. Some of the projects that involved space applications became much more extended in length.

The overall NASA approach to developing remote sensing was known as the Earth Observing System (EOS). This program was initiated in the early 1980s. It comprised of a series of satellite missions in Earth orbit to carry out long-term global observations of the land surface. It was quite ambitious in that it was designed to observe the biosphere, the oceans, and the atmosphere. The satellite component of the program extended over several decades and included satellites that included Terra (which was once known as AM-1) (1999), Aqua (2002), and Aura (2004). This program was also publicized as part of the "Mission to Planet Earth."

The National Polar-Orbiting Operational Environmental Satellite System (NPOESS) also was conceived as a joint program funded by both NASA and the US Department of Defense. It was to produce meteorological data that was useful for atmospheric research but could also support the requirements of the Defense Department for up-to-date weather information as well. In short, this system was to be the next-generation satellite system. This lower polar orbiting system could monitor Earth's very wide range of conditions that included the upper atmosphere, and near-space conditions, the oceans of the world, and land and agricultural conditions and also provide current weather information. In a joint US Department of Defense (DoD)/NOAA/NASA tri-agency endeavor, the intention was to combine the civil and military operational polar-orbiting meteorological satellite programs for both the DoD's DMSP and the NOAA Polar-Orbiting Operational Environmental Satellite (POES) series. However, the NPOESS program was terminated by the US government in 2010 due to severe cost overruns and program delays. In the aftermath of the White House's decision to cancel NPOESS, a new civilian satellite program, the JPSS (Joint Polar satellite System) was created, which would be managed by NASA/GSFC, while the spacecraft would be owned and operated by NOAA. The DoD's portion of the NPOESS program was called DWSS (Defense Weather Satellite System), which was subsequently cancelled in 2012.

Initially designated as JPSS-1 prior to launch, the first satellite in the JPSS program is now known as NOAA-20, which was constructed by Ball Aerospace & Technologies Corp. and launched on November 18, 2017. It joined the Suomi National Polar-Orbiting Partnership (Suomi NPP) satellite in the same orbit. The project incorporated five instruments, providing meteorologists information on atmospheric temperature and moisture, clouds, sea surface temperature, ocean color, sea ice cover, volcanic ash, and fire detection, thus enhancing weather forecasting, including hurricane tracking.

A well-known example of a large and complex European Space Agency (ESA) project is Envisat ("Environmental Satellite"). This very large, complex, and expensive undertaking represents what was the world's most complex and mammoth Earth observation satellite by a civil space agency. The planning for Envisat started in the early 1980s and took essentially two decades from conception to launch. It was not until March 2002 that it was finally launched. This huge satellite had ten different instruments for remote sensing and cost some 2.3 billion Euros to build and place in orbit. The objective of this satellite was to monitor the Earth's resources, study the world's atmosphere, and also explore the dynamics and composition of the globe's crust and even its interior composition. Unfortunately, the control of this very expensive satellite was suddenly lost on April 8, 2012. After several concerted attempts to re-establish communications and control, the mission ended as of May 9, 2012. This huge satellite now constitutes the largest cross-section for a low Earth orbit collision as the spacecraft with a mass of over 8,000 km represents a danger and is currently the top candidate to be removed from orbit. In many ways, Envisat represents a strong case for small satellites that undertake Earth observation using smaller spacecraft rather than using a massive satellite with a very large number of sensing capabilities on a giant satellite (Kramer and Cracknell 2008).

Combining remote sensing activities on a large satellite lessened the opportunity for technical advances and lessened flight opportunities. If control of such a spacecraft was lost, then all the experiments could be lost all at once. This also lessened opportunities for scientists and technical experiments to gain experiments with smaller and less costly missions that could be undertaken at lower cost and on a more compressed time scale (Sweeting 1991). Furthermore, austere funding climates have encouraged interest in cheaper and more frequent missions, which is forcing established space agencies to rethink their approach to spacecraft procurement and mission design.

Change takes time, but significant growth in the small satellite industry and a trend towards small satellites was in the making for over a decade with advancements accelerating during the last several years. Changes have been not just in spacecraft mass but in more than just a single design parameter, ranging from different approaches in planning and development to operations and financing. Changes have also included simpler vehicles, a higher risk tolerance, easier acceptance of new technology, and a significant reduction in costs. Such divergent paths can be considered to be a form of "disruptive innovation" for the satellite industry, redefining the trajectory of the satellite market and focusing on simpler, more convenient, and less costly products. This has also generated lower barriers to entry to the remote sensing satellite market and opportunities for new innovation in what used to be the traditional satellite path in the industry (Rivers 2015).

3 The Small Satellite Industry

Small satellites were often overlooked by space agencies and the established space industry. However, small satellites had been used by the international amateur radio satellite community and universities due to financial and technical constraints. The Radio Amateur Satellite Corporation (AMSAT) was an educational organization formed in the District of Columbia during 1969 to foster space research and communication for amateur radio satellites. AMSAT likely coined the term “micro-satellite,” since their communication spacecraft was below 10 kg – orders of magnitude smaller than established spacecraft missions at that time. The international amateur radio satellite community and universities are regarded as the true pioneers of small satellite technology (Kramer and Cracknell 2008).

Surrey Satellite Technology Ltd. (SSTL) was formed in 1985. This entity was a spin-off company from the University of Surrey (UK). Its mission was to transfer the technology that it had developed from its research and use it to create a new commercial company. This effort began with the development of what were essentially amateur radio satellites. These first satellites were known as UoSATs that reflected their origin as University of Surrey Satellites. These early small satellite were known as OSCAR satellites. The name OSCAR stood for Orbiting Satellite Carrying Amateur Radio. The first of this series was known as UoSAT-1. This satellite was notably constructed using commercial-off-the-shelf (COTS) components. It was launched on October 6, 1981 as a secondary payload to NASA’s Solar Mesosphere Explorer (SME) mission. This satellite had a mass of 72 kg and was about the size of a mini refrigerator. This UoSAT-1 was less costly and was much smaller and faster to build than traditional satellites of this time. It was also included in reprogrammable computer and in a charge-coupled device (CCD) that formed an array that was capable of imaging the Earth from space.

UoSAT-2 was launched on March 1, 1984. This small satellite was a secondary payload that flew as an adjunct to the Landsat 5 launch. UoSAT-1 and UoSAT-2 microsatellites thus both also carried key experimental packages for telecommunications and for technology demonstrations. These satellites were not only small and demonstrated new technology but also successful technology for 8 years in the case of UoSat-1 and 5 years for UoSat-2 (Kramer and Cracknell 2008). UoSat-3 was the third in the series. It was launched on January 22, 1990. It used a new modular bus design, which has become key to small satellite designs that have followed. This type of modular construction allows for more rapid construction and flexibility to respond to different types of payloads and a variety of missions.

Martin Sweeting of SSTL, who has been knighted for his innovative aerospace and small satellite designs, first proposed a classification system that is largely accepted as the basis for small satellite design. This classification system is based on mass (as shown in Table 1). What constitutes a small satellite is a very relative concept. A space agency’s small satellite may be considered to be a very large spacecraft to a university or a student experimenter. There are other criteria on which a satellite classification system could be based. These include size, type of orbit, function, cost, and performance. Classification of satellites by mass has been widely

Table 1 The first satellite classification developed by Sweeting (1991)

Nanosatellite	<10 kg
Microsatellite	10–100 kg
Minisatellite	100–500 kg
Small satellite	500–1,000 kg
Large satellite	>1,000 kg

Table 2 A satellite classification according to mass modified from Table 1 (Xue et al. 2008)

Femtosatellites	<100 g
Picosatellites	0.1–1 kg
Nanosatellites	1–10 kg
Microsatellites	10–100 kg
Minisatellites	100–500 kg
Medium satellites	500–1,000 kg
Large satellites	>1,000 kg

used due to its direct bearing on the launch cost of a spacecraft, which is a significant challenge of any mission.

Subsequently, the classification of satellites by mass was further modified as shown in Table 2. It should be noted that the size of satellites known as minisatellites is sometimes considered to range up to 1,000 kg. These changes also include adding smaller mass classes (e.g., pico- and femto-) to Sweetings' original classification. Barnhart et al. (2007) also noted particular trends in emerging small satellite technologies, including advances in electronic miniaturization and associated performance capability, such as micro-engineering pioneered by Helvajian and Janson (2008). These innovations are largely based on microelectromechanical systems (MEMS) sensors and micro-fabrication. In parallel with the introduction of micro-engineered aerospace systems, the concept of multifunctional structures and architectures has also backed the idea of low-cost mass production of satellites. This proposes that satellites be built and rapidly deployed using streamlined manufacturing processes and modular technologies.

The lack of sufficiently small or inexpensive launch vehicles for putting small satellites to orbit is another key factor that is considered by some to constitute a significant barrier to small satellites. One solution has been that of launching small satellites as secondary payloads. The Indian Polar Satellite Launch Vehicle has famously launched over a hundred CubeSats as part of a "piggyback" launch operator. The SpaceX reusable launch operations have now indicated that it will reserve space for small satellite launches and at a very low rate and a regularly scheduled base. Blue Origin is apparently seeking to offer, in the future, a similar type of capability.

In the past, the costs of such piggyback launches have often been quite high. In some cases, the costs have been greater than the specific cost ($/kg) of the launch vehicle itself (Crisp et al. 2015). This, however, no longer seems to be the case. Other constraints of piggyback launches include a lack of flexibility and control over the launch schedule and destination orbit of the vehicle.

In addition to the ability to fly on larger launchers as a “piggyback” launch or to be dispensed from the International Space Station, several new small launchers are starting to address the need for dedicated microsatellite and nanosatellite launch capabilities.

Some examples include the Virgin Galactic LauncherOne, the XCOR Aerospace Lynx Mk.III suborbital vehicle, and the DARPA ALASA program that are working towards launching a 45 kg payload to orbit for less than $1 million. Nevertheless, the present lack of sufficiently small launch vehicles still makes the launch of nanosatellite and picosatellites a challenge unless launched in large numbers. The Planet Labs Flock constellation of 3 U CubeSats was achieved by a resupply launch to the ISS. There is still much dependency on the deployment of small satellites as secondary payloads.

The emergence and rapid growth of the small satellite market has created significant opportunity for new technologies, business practices, and markets for the space industry. There is a continuing trend of reductions in mission complexity and associated costs often associated with management, meeting safety regulations, etc. (Barnhart et al. 2007). Although the actual cost per kilogram payload on a micro- or nanosatellite can be equal to or exceed costs of traditional larger satellites, the quick turnaround and fast response times are also important advantages to consider. Notably, small satellites are also important avenues of exploring and testing new devices and ideas for spacecraft missions without spending a significant amount of funds (Xue et al. 2008).

4 Small Satellite Systems and Innovations

Small satellites represent a “disruptive innovation” for the satellite industry that has opened up many new opportunities. A disruptive innovation has been defined as changes that “disrupt and redefine that trajectory by introducing products and services that are not as good as currently available products. But disruptive technologies offer other benefits-typically, they are simpler, more convenient, and less expensive products that appeal to new or less-demanding customers” (Christensen et al. 2015).

Small satellite ventures experience much lower barriers to entry to the satellite market. Satellite ventures based on cube satellites have a higher tolerance for failure. Not only are satellite and launch costs much lowered, but there is significantly shorter planning, manufacturing, testing, and deployment times. This enables the small satellites not only to serve as a test bed for new ideas but increasingly as operational systems such as the Spire system that is based on three-unit CubeSats.

For many years space-based remote sensing programs have traditionally used large platforms. This has involved high costs in terms of mass, size, testing, launch arrangements, and overall complexity. Further, it has often been the case that those serving as the spacecraft manufacturers as well as the operators of remote sensing satellite networks are not closely in sync with the needs of the remote sensing user community. How existing small satellite technology could be more effectively designed for the purposes of remote sensing applications is discussed in a number of useful sources (Cvetkovic and Robertson 1993).

In the remainder of this section, major design problems and constraints influencing small low-cost remote sensing satellites are discussed and organized based on a subsystem approach. Key design areas include the improvement of battery technology and the development of a deployable solar array, attitude control assemblies, onboard data processing/storage, and ground data acquisition (Xue et al. 2008).

One of the key concerns with regard to the use of small satellites for remote sensing is its reliability requirements. Many see the potential lack of reliability that is associated with a small satellite network as possibly conflicting directly with their low-cost mission design, limited reliability testing, and overall development approach. One of the key challenges in this regard is the command and data handling (C&DH) subsystem. Most designers of remote sensing satellites believe that these and other critical subsystems require more mass and power resources to produce reliable and capable systems.

These critics believe that remote sensing satellites, which also do not meet a certain mass and power budget, cannot fully meet reliability requirements. There is also a concern with processing power – and in some cases, preprocessing power – that must be sufficient for supporting increased software functions required for remote sensing systems.

These requirements include not only basic data processing but also such capabilities as compression, failure detection, and rapid response to functional failures. Further concerns are overall flight safety and redundancy with regard to the execution of critical single point of failure processes (Homan and Young 2008).

In the case of more sophisticated payloads, there is a perceived need for higher data rates and larger data storage requirements and adaptability to some component failures. This can translate into the need for greater input and output (I/O) capabilities. Such expanded capability may provide additional safety, switching flexibility, etc. These issues are often addressed by the addition of greater levels of monitoring hardware and more redundancy. These perceived needs can be difficult to meet without adding to the mass and power budgets available for most small satellites, although 12-unit CubeSats and larger are becoming more adept. The response by some operators such as Spire has been to add more satellites to their network, rather than increase the size and redundancy of their spacecraft.

The Guidance, Navigation, and Control (GN&C): This subsystem represents a critical operational capability. The GN&C includes both the components used for position determination and the components used by the Attitude Determination and Control System (ADCS).

The performance specification for small spacecraft GN&C performance can vary. Perhaps the most common capability specification is 1.5 m accuracy for onboard orbital position accuracy. This is typically achieved using Global Positioning System (GPS) capabilities. Also a pointing accuracy of better than 0.1° is typically achieved by using a combination of reaction wheels, gyros that employ MEMS technology, and a star tracker. These combined capabilities are designed to change a spacecraft's attitude to achieve the needed level of performance. A magnetorquer that might be used for a student experiment, for instance, would not be sufficient for precision remote sensing (Burton et al. 2016).

Many attitude control and determination algorithms and equipment might be suitable for use in small satellites for such activities as an experiment or technology demonstration. Most of the technology for key components used for precision pointing for many Earth orbiting missions is now mature (NASA Ames 2018). Although 3-axis stabilized and GPS-equipped spacecraft are sufficient for the precise operation of 100 kg spacecraft (about the size of a small refrigerator) for a number of years, it has only been in recent years that precise pointing systems for smaller satellites in the 10–100 kg category have become available. There is a continuing trend towards the miniaturization of existing Guidance, Navigation, and Control (GN&C) technologies for use in small spacecraft. This has allowed small satellite design for even hyperspectral sensing systems.

Telecommunication Relay System: Another key subsystem is that for communications that can both transmit data and telemetry to the ground and receive commands. It is essential that small satellites for Earth observation be able to relay information to ground systems and vice versa. The design of these telecommunications subsystems is driven by the challenges of minimal size and yet maximum power. Any miniaturization of the antennas used on small spacecraft reduces antenna gain. The lower the gain, the lower the amount of information that can be transmitted.

CubeSats typically use (lower gain) whip or patch antennas that also require lower power. This limits the data that can be transmitted (NASA Ames 2018). The decrease in antenna gain can be offset by operating in a lower orbit to limit path loss or by increasing power. Power, however, is a significant challenge in small satellite systems. Power requires either solar arrays or batteries, and both require mass and volume.

The higher data rates desired for an operational spacecraft that is engaged in remote sensing are considerable. There is a need for power and higher gain antennas to relay higher data rates that systems are engaged in activities such as hyperspectral sensing. There is a need in this case for large increase in the power dedicated to the communications subsystem. One solution is to use a constellation of three small satellites in place of one larger satellite (Homan and Young 2008). Another trend that aids in improving RF-based communication systems is the development of software-defined radio (SDR). Laser-based communication (lasercom) has been used in larger spacecraft (e.g., LADEE). Optical communications for small satellites have been successfully demonstrated and transmitting data, such as the Optical Communications and Sensor Demonstration (OCSD) mission, launched in 2017 (NASA Ames 2018). Laser communication systems could potentially increase performance in future small spacecraft.

Electrical Power Subsystem: The electrical power subsystem (EPS) is another critical aspect of a small satellite for Earth observation that encompasses electrical power generation, storage, and distribution. The electrical power is not only a major subsystem which can take up to 25–33% of the mass of the spacecraft, but it is also often the basis of satellite failure. The only plus here is that it tends to be scalable. More solar or photovoltaic (PV) cells and larger batteries can be added to adjust to larger power needs. The diodes, power converters, shunts, and grounding systems are also all fairly scalable. Some of the challenges with regard to design and reliability are the solar array drive mechanisms, temperature control, and battery lifetime (Homan and Young 2008). The ongoing challenge is fitting the electrical power system and all of its components within size constraints. It is difficult to achieve a high power-to-mass ratio when designing a small satellite system – especially for certain Earth observation systems such as radar satellites and hyperspectral satellites (NASA Ames 2018).

Thermal Design: Miniaturized thermal management systems are another major challenge. Such systems are required to ensure thermal control requirements do not overheat or freeze components in a small satellite. Sufficient power, mass, and volume are required for heaters, temperature sensors, etc. (Homan and Young 2008).

Structural Design: The choices to meet the design of a small satellite structure and materials are really limited. The choices for the primary structure design in small satellites frequently come down to either commercial-off-the-shelf (COTS) structures or custom machining or specially printed components that are made to order. If it is possible to use COTS components, this can simplify the development of a small spacecraft. The threshold question is: Can the mission needs and payload requirements be met reliably and fully within the COTS structure offered? It is essential that structural components are as volume-efficient as possible but also serve the necessities of thermal management and radiation shielding (NASA Ames 2018).

Propulsion System: A variety of propulsion systems for small satellites are available. Nevertheless miniaturization of these systems for small satellites remains particularly challenging (NASA Ames 2018).

This subsystem is desirable for many functions that may or may not be required for a particular mission. These functions include attitude control, orbit boost or orbital adjustment, precise station keeping, and end-of-life disposal. Cold gas or pulsed plasma systems for small delta-V maneuvers are possible via a number of systems that are commercially available. Higher levels of propulsion – or higher delta-V applications – require newer systems that are still in the development stages (NASA Ames 2018).

The latest versions of chemical and electric propulsion systems have also significantly matured during recent years. Improved propulsion systems for smaller CubeSat buses, called electric propulsion devices, are being miniaturized and adjusted to small buses. These only provide low-thrust options.

There have also been technological advances in new alternative green propellants that involve less dangerous and noxious gases than the hypergolic fuels that have been used in chemical systems for many years. There are also propellant-less systems. There have been tests such as of LightSail, which employs solar sail capabilities for small satellites (NASA Ames 2018). Most small satellites have operated in low Earth orbit (LEO). There are increasing plans to use small satellites for MEO, GEO, or even deep space missions. Propulsion systems for such missions will require new and increased power propulsion systems.

Flight Software: The software needed to support a mission is a direct function of the complexity of the spacecraft and the purpose of a particular mission (Homan and Young 2008). These requirements may change to accomplish a particular "high mission utility." In some cases, there is a direct trade-off between the hardware design and the software design. In such cases, this can and does influence spacecraft design. The most obvious way would be in the design of the mission's main processor as well as the size of its memory storage capabilities. These decisions on software and hardware design can lead to an increase – or decrease – in the mass and power of the spacecraft. This could, in turn, affect the overall cost of the mission. Telecommunication satellites are often referred to as software-defined processor in space. This is almost equally true of Earth observation satellites – if perhaps not more so.

The current challenge is that customers that rely on remote sensing data are increasingly depending on these space systems for high reliability in the data they use for farming, mining, fishing, urban planning, control of pollution, or even law enforcement. There is clearly now conflicting demands. On one hand there is a desire for reliable, space-qualified hardware and software to produce actionable data. Yet there is also an offsetting desire to receive this data at lower cost. This is likely to be achieved via spacecraft that is smaller in size and mass, with a shorter development time.

Despite current trend innovations coming from the small satellite industry, it is unlikely that small satellites will be able to replace the larger space with higher levels of resolution and other requirements related to meteorological requirements, climate change monitoring, and military and defense requirements.

This suggests that small satellites will not replace larger and more conventional remote sensing satellites, but rather there will likely be a form of coexistence. It is possible that there will be a sharing of the market that might ultimately prove beneficial to both. One of the unresolved questions is where remote sensing using aircraft and high-altitude platform systems (HAPS) will be a part of the mix. These are issues to be resolved in the aerospace industry in the coming decade as a whole (Rivers 2015). It is also likely that these markets will directly compete at times but, in other cases, they will find a symbiotic relationship.

5 Emergence of Small Satellite Constellations

Small satellite constellations that are deployed in large numbers can offer widespread and rapid updates of complete global coverage when deployed in low Earth orbit (LEO). In was in the 1990s that there were various proposals for small satellite constellations. These initial proposals were made to exploit advances in digital communications technologies. The first of these systems was to support mobile communications (i.e., Globalstar and Iridium), data networking (i.e., Orbcomm), and in one case, broadband communications (i.e., Teledesic) (Sweeting 2018). It was thought that stabilized geostationary Earth orbit (GEO) satellites could not provide such services, even though systems such as Inmarsat and Thuraya did develop viable mobile satellite networks from GEO after the LEO-type systems were deployed.

There were consistent initial financial failures and bankruptcy associated with the Iridium, Globalstar, Orbcomm, and Teledesic systems. The proposed ICO system in MEO orbit was never deployed even though it also experienced bankruptcy. But now almost three decades later, small satellite technology has matured, and new types of markets for satellite data and networking have been developed. Thus there recently has been renewed interest in new constellation projects for low and medium Earth orbits for supporting worldwide communications, broadband data networking, and Internet of Things (IoTs) services – especially in remote areas. Not only were the second generation of Globalstar and Iridium-NEXT satellites launched in 2017, but another player has since emerged, which is the O3b constellation owned by the satellite operator SES. The first O3b satellites were launched on June 25, 2013 with initial services offered in March 2014. The last four of the 20 satellites in the O3b Medium Earth Orbit (MEO) telecommunications constellation were successfully launched by Arianespace from the Guiana Space Centre in French Guiana on April 4, 2019. The constellation was deployed in a circular orbit along the equator at an altitude of 8,000 km in MEO, offering greater capacity, enhanced coverage, and improved efficiency and reliability. This system has become financially viable, and now a second generation has been launched. This has created a rush of interest. Some 20 different systems of LEO small satellite constellations are now planned to provide either broadband or narrowband networking or an automatic identification system (AIS).

Thales Alenia Space, among others, has established a particular expertise to develop and manufacture LEO and MEO telecommunication satellites at low cost. It has also been working on a number of startups, such as a joint venture LeoStella LCC to build BlackSky and a constellation of 60 optical high-resolution satellites that offer high revisit times. France's Nexeya is also planning to develop Kinesis, which will be a constellation of 20 nanosatellites dedicated to the Internet of Things. Also up to three Chinese commercial companies are deploying LEO systems for optical imaging using Chinese technology.

The use of satellite constellations for communications is expected to continue to grow, since constellations satisfy a unique combination of needs in terms of achieving global coverage and low latency and minimal path loss associated with space to Earth transmission. Such systems, as they are deployed in the 2020s, are expected to complement existing geostationary satellite communications system rather than to replace the established networks. The question is how many of these new systems can be successfully deployed commercially. Already the LeoSat system has gone bankrupt, and other failures seem to be likely. Even with the rising demand for global data networking and need for greater communications coverage, it seems unlikely that the dozens of new systems can all succeed.

6 Remote Sensing Applications of Small Satellites

Modern small satellites have matured during the early 2000s to combine technology, use of commercial-off-the-shelf components, reduced cost for satellites and launches, and overall utility.

There have been many innovations that allow Earth observation satellites to use small satellite technology very efficiently. This has been coupled with many technological improvements in sensors, high-speed data downlinks, precise pointing and attitude control, and onboard data storage handling capacity, among other innovations. Small satellite Earth observation missions are now able to exploit two-dimensional CCD area arrays that provide new economies. Small satellites are also able to use multispectral push-broom imagers. These are just two of the major innovations which are now possible to increase the performance of small satellites for remote sensing. The miniaturization of sensors, electronics, and digital processors has all allowed for greater performance and improvement in the cost and reduced size of Earth observation satellites.

Some small satellite Earth observation missions that are now possible due to these types of innovations are explicitly shown in the Bispectral and Infrared Remote Detection (BIRD) satellite that was developed by DLR the German Space Agency. This spacecraft, developed in Germany, was launched by the Indian Space Research Organization (ISRO) as early as 2001. This was a microsatellite technology mission with remarkable capabilities for its time. This spacecraft hosted a two-channel infrared sensor system as well as a Wide-Angle Optoelectronic Stereo Scanner (WAOSS). The spacecraft had a new and remarkable fire detection capability. It managed to operate successfully for 2 years before experiencing a gyro malfunction.

SMART-1 was a Swedish-designed European Space Agency (ESA). This satellite orbited around the Moon to map the lunar surface, and it was launched on September 27, 2003 from Kourou, French Guiana. This microsatellite was comparatively lightweight in comparison with other probes. SMART-1 ended its mission after about 2 years and performed extremely well even though it was quite low in cost for a lunar exploration spacecraft. SMART-1 was part of ESA's strategy to build very inexpensive and small spacecraft. This spacecraft represented a total cost of only 110 million Euros (or about US$170 million).

RapidEye represents another milestone in the remote sensing industry. This company was established in 1998 with the idea of carrying out imaging using microsatellites as a commercial operation. This company's plan was to use a constellation of five microsatellites for global coverage. The German-based geospatial information provider was able to deploy and operate a constellation of five satellites built by Surrey Satellite Technology Ltd. (SSTL) of the UK. Despite the small size of its satellites, it was able to produce imagery with 5 m resolution. All satellites were placed in LEO with a common altitude. SSTL was subcontracted by MacDonald Dettwiler (MDA). Each satellite measured less than 1 cubic meter and had a mass of only 150 kg – each with identical sensors. The five satellites as a constellation were capable of providing five-band color imagery daily over a broad area of the Earth. RapidEye's satellites had several unique capabilities. One of these was the fact that these satellites were sensitive to detecting changes in chlorophyll content through their ability to sense the “Red Edge band.” This ability to detect the Red Edge band was used to monitor vegetation health. It could also help to allow analysts to separate various types of vegetative species. It also provided a new type of tool for measuring nitrogen and protein content in all forms of biomass (Sweeting 2018). RapidEye unfortunately filed for bankruptcy in 2011. It has now been acquired by Planet as of 2015. Today the so-called Planet “flock” satellites provide rapid updates of the global imaging database with lesser resolution, while RapidEye satellites provide higher-resolution imaging where greater precision of imaging is required.

It is evident that there are many applications for small satellites today and these keep growing. The uses of remote sensing spread across such areas as scientific research, atmospheric and pollution monitoring, ship tracking, airplane navigation and detection, and Earth observation. Although these applications continue to expand, it seems unlikely that small satellites will entirely displace existing methods of data collection. A combination of sensing in the future that combines aircraft, drones, high-altitude platforms, LEO small satellites, and GEO satellites may be seen. This combination of capabilities will thus form a more comprehensive and supplementary form of data collection. The uses continue to multiply. Geospatial information is now needed to support agriculture, forestry, security and law enforcement, emergency services, fire detection, environmental protection and climate change monitoring, energy- and infrastructure-related services, and much more.

6.1 Disaster Management

Effective disaster management activities are said to follow a cycle of four phases. These include preparedness, mitigation, response, and recovery (Santilli et al. 2018). Satellite data for supporting disaster management often translates into the urgent need for high to very high spatial resolution requirements. There is not only a need for satellite data on a rapid demand basis but for analysts that can properly interpret the data with a high degree of accuracy (Tobias et al. 2000). Moreover, disasters often extend beyond borders and affect ground infrastructures, affecting the accessibility and surveillance of an area. This type of data can most frequently be provided via constellations of satellites in low Earth orbit, which are able to meet disaster management requirements and are becoming more affordable and accessible. Although using satellites for disaster management is not new, the explicit statement of disaster management requirements as a mission objective in the design of remote sensing systems is a significant new development.

Albayrak (2005) suggests that dimensions of disaster management that restrict the utilization of small satellites or dictate the requirements of a satellite constellation system include:

- The type of disaster (Is it a natural, terrorist, or some other form of manmade event?)

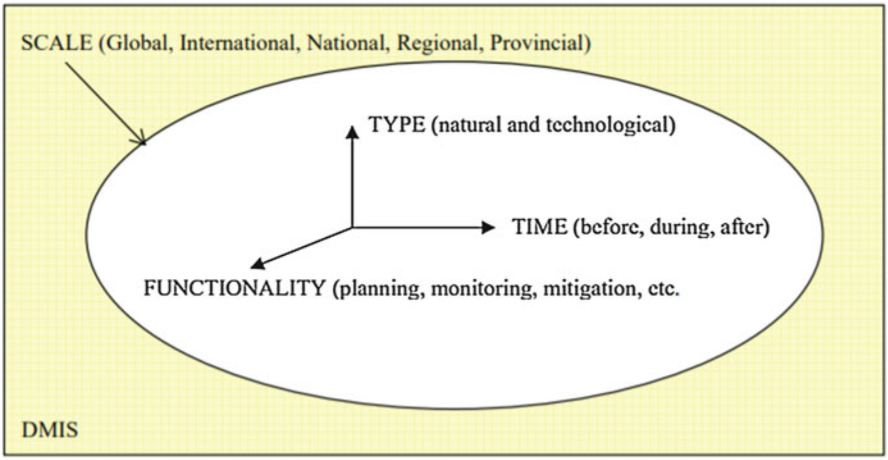


Fig. 1 The application of small satellites at four dimensions of disaster management. (Courtesy of the Disaster Management Information System)

- Time (Is the mitigation or response being directed before, during, and after a disaster?)
- Functionality (What is the nature of function such as preparedness, mitigation, response, and/or recovery?)
- Scale (Where is the disaster occurring and how widespread are the impacted areas, such as local, regional, national, international, global?)

Figure 1 illustrates the utilization areas of small satellites for a Disaster Management Information System (DMIS) based on these four dimensions. The two figures below suggest that small satellites can be utilized for all types of disasters, for every time period, and for every functionality. Better results are attainable by small satellites for larger-scale disasters, such as international and global. There are nevertheless important applications that can be achieved even for very localized disaster events (see Fig. 1).

Remote sensing products are currently used daily in all phases of risk management. This is done despite their limitations as to precision or rapidity of updates. For example, the European Remote Sensing (ERS) satellites have been used since 1991 to develop numerous products for applications. These uses might include detection and monitoring of oil slicks, identification of algae blooms, detailed imaging of landslides, and monitoring of flooding risks (see Fig. 2).

Rather precise fire hazard indices have been developed using data provided from the Advanced Very High Resolution Radiometer (AVHRR). These indices have been developed based on a combination of vegetation and meteorological data. There is now a growing demand for observations with high temporal resolution or quick updates of the impacted sites. These response times usually vary between 30 min and 1 h up to 7 days. There are also different types of demand for the precision of the imaging. These can typically vary between medium to high spatial

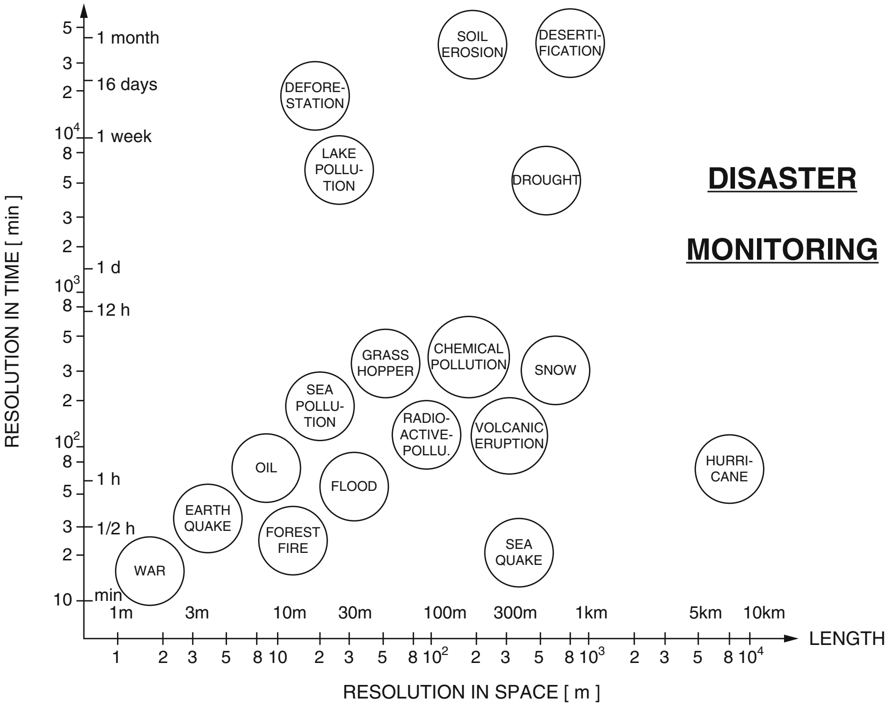


Fig. 2 Types of disasters and their temporal and spatial resolution requirements. (Adapted from Iglseder et al. 1995)

resolution and between 10 m and 1 km for most disaster monitoring events. A spatial resolution of 10–30 m is often desired for most disaster monitoring requirements. The swiftest repetition times can especially be accommodated by a large constellation of small satellites.

The particular type of disaster will, of course, dictate the technical requirements for a sensor design (Iglseder et al. 1995). The ability of satellite constellations to provide updates also depends on the number of orbits, the quantity of satellites in each orbit plane, and their elevation and altitude. Mean time gaps between contacts for five small satellite constellations which is based on a sun synchronous orbit are provided in Table 3. A constellation with four orbital planes and eight satellites at each orbit is probably sufficient to provide temporal resolution for monitoring most kinds of disasters, although a larger constellation such as that provided by Planet or Spire is probably even more desirable (Iglseder et al. 1995).

The number of satellites in a constellation is a significant cost driver for the overall mission. The relationship between the type of constellation, elevation, and resolution is time, as illustrated in Fig. 3. For example, for securing a revisit time of about 30 min, a constellation of at least 32 satellites would likely be necessary (Iglseder et al. 1995). Such constellations can potentially be developed by multiple

Table 3 Mean time gaps between contacts for small satellite constellations using sun synchronous orbits. (Adapted from Iglseder et al. 1995)

	Orbit planes/satellites p. Pl.				
Elevation	4/1	4/3	4/8	6/2	8/4
10°	51.0′	19.6′	2.1′	24.9′	2.3′
20°	73.5′	24.0′	5.9′	25.4′	6.2′
30°	101.9′	31.3′	11.9′	35.0′	10.2′
40°	143.3′	45.1′	18.0′	51.0′	17.3′
50°	165.7′	62.2′	22.9′	60.8′	23.0′
60°	253.3′	253.3′	34.4′	103.2′	39.2′
75°	339.3′	339.3′	92.8′	121.7′	142.4′

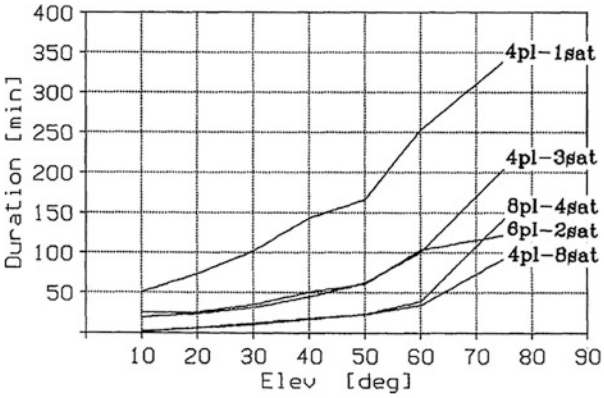


Fig. 3 Time gaps between contacts versus elevation. (Adapted from Iglseder et al. 1995)

country players as has been the case in the past. The Disaster Monitoring Constellation (DMC) described below is one specific case in point.

TopSat is an example of a British Earth observation (EO) satellite with disaster monitoring applications. This particular satellite operates in LEO. It was launched in October 2005 from Russia and built in the UK by Surrey Satellite Technology Ltd. (SSTL) with supporting participation from QinetiQ and the Rutherford Appleton Laboratory. This project was funded under the British National Space Centre Mosaic program.

TopSat was designed to be three-axis stabilized. Its specifications include panchromatic imaging with a 2.8 m resolution and 5.6 m multispectral imaging capability. Despite these relatively high resolutions, it was still quite a bit smaller and less costly than imaging satellites with similar high-resolution capabilities.

The high resolution was possible as a result of using a precise three-axis fiber-optic gyro. This allowed the sensor to be pointed to observe its particular target for a longer period of time. This was in some sense like an analog camera taking a picture with a longer exposure time from space. TopSat has also been used to demonstrate the feasibility of providing higher-resolution images on demand to portable ground stations. This demonstration by TopSat showed the capabilities and associated affordability of using small satellite constellations for traditional remote sensing missions. The result being significant cost savings.

The Disaster Monitoring Constellation (DMC) is another example of a small satellite constellation developed for Earth observation and disaster monitoring. The satellites for this constellation were all constructed by SSTL even though the five satellites were paid for by five different countries. The design of the DMC was envisioned as being able to provide emergency Earth imaging for disaster relief under the International Charter for Space and Major Disasters. These remote sensing satellites are owned individually by the participating countries which are Algeria, Nigeria, Turkey, the UK, and China. Nevertheless these five satellites are operated together as a single system. The DMC can thus provide rapid response Earth observation data to support national response to disaster needs and international disaster relief on demand. The DMC, since it was designed for this purpose, is able to cover far larger spatial areas than government remote sensing satellites such as Landsat. It is also important that higher-resolution imagery can be provided far more rapidly and with far more frequent revisit times as a result of having multiple satellites in orbit. The five satellites of the DMC constitute a constellation that can observe any location on Earth at least once per day, although cloud cover does not guarantee that images will always be usable.

During the period 2003 to 2008, seven DMC satellites were launched. It was significant that all of these small satellites were built to a common standard to enable commonality of image resolution so that images could be easily interchanged (Sweeting 2018). The DMC has monitored the effects and aftermath of the Indian Ocean Tsunami (December 2004), Hurricane Katrina (August 2005), and many other disasters. The next phase of the DMC system is called DMC-3. This is a three-satellite system that SSTL is building for the Chinese company known as the Twenty First Century Aerospace Technology Company (21AT). This will particularly be utilized to respond to Chinese disasters, but the constellation will also assist with global disasters (Disaster Monitoring Constellation-3 2020).

6.2 Fire Detection

Forest fire detection requires simultaneous imaging in various spectral channels and frequent revisit times for monitoring purposes. Fire managers have to make difficult decisions about resource allocation for fire suppression based on information such as the number of fires, their location, potential damage to property and human life, and harm to natural resources. There is a need to provide fast, reliable information on fire locations, especially when they are very small (<0.2 acres), as well as to integrate information on lightning strike locations and ground observations of fires. With traditional spaceborne systems, there have been challenges with very large data volumes that require substantial transmission and interpretation efforts, as well as difficulties in time coverage for efficient use of data during fire events. Fire classification based on temperature alone is not possible due to sensor saturation and existing spacecraft instruments, and sensors are not specifically designed to measure fire parameters. Small satellite constellations offer significant advantages from more frequent revisit times to tailored or dedicated payload design and signal processing for fire detection.

Most immediate and life-or-death decisions when fighting forest fires, such as sending smoke jumpers or calling an evacuation order, are made by firefighters and chiefs in ground command centers. The current system for fire detection would be greatly enhanced by the ability to detect small and nascent fires across regional or synoptic scales. Satellite and airborne data provide situational awareness and are important for planning fire management strategies. For example, NASA and the National Oceanic and Atmospheric Administration (NOAA) often utilize satellite constellations and a small fleet of aircraft operated by the US Forest Service (USFS) to help detect and map the spatial extent, spread, and environmental damage of forest fires (NASA 2019). As technology has advanced, the value of remote sensing data for forest fire detection has also been enhanced to better inform decisions for active wildfire suppression and capturing burned areas.

One of the first instances of using remote sensing for forest fire detection was in 1980 when two scientists, Michael Matson and Jeff Dozier, were working at NOAA's National Environmental Satellite, Data, and Information Service detected bright spots on the Persian Gulf on imagery from the Advanced Very High Resolution Radiometer (AVHRR) instrument on the NOAA-6 satellite (3.8 μm and 11 μm sensors) (NASA 2019). The observed bright spots were actually steel mills and campfire-sized gas flares caused by the burning of methane in oil wells. Dozier subsequently developed a mathematical technique to distinguish small fires from surrounding heat sources, which formed the foundation for subsequent satellite fire detection algorithms (Matson and Dozier 1981).

Initial developments with AVHRR helped to inform the design of NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), which was the first instrument that included spectral bands explicitly designed for fire detection. MODIS was launched in 1999 on the Terra satellite, and a second MODIS instrument was launched on Aqua in 2002 (NASA 2019). MODIS subsequently informed the design of the Visible Infrared Imaging Radiometer suite (VIIRS) on the Joint Polar Satellite System's NOAA/NASA Suomi-NPP and NOAA-20 satellites. Collectively, these technological advancements represented major advancements in fire detection technology for traditional large spacecraft.

The instruments onboard polar-orbiting satellites, such as Terra, Aqua, Suomi-HPP, and NOAA-20, are able to monitor and observe wildfires at known locations several times daily, whereas geostationary satellites, such as NOAA's GOES-16 and GOES-17 (launched in November 2016 and March 2018, respectively), provide continuous observations and updates at the same location, although at a coarser resolution. The optical and thermal bands on MODIS have continued to provide daytime visible imagery and nighttime data on active fires, contributing significantly to mapping fires and burn scars. However, the poor temporal resolution of MODIS sensors limits its ability for early warning and detection.

VIIRS has also improved fire detection capabilities by providing higher spatial resolution data (375 m), enabling smaller and lower-temperature fires to be detected. Through its Day-Night Band, VIIRS also provides nighttime fire detection capabilities, measuring low-intensity visible light emitted by smaller and lower-intensity fires. GOES satellites have also been used for early detection and precise geolocation of fires in remote areas, such as early detection of the Adobe Fire in California on July 2, 2018. Fire and characterization algorithms are continually improved for earlier fire detection and reduction of false positives.

The Multi-angle Imaging Spectroradiometer (MISR) instrument on Terra uses nine fixed cameras that can measure the motion and height of a fire's smoke plume. It is able to capture the amount of smoke particles from a fire, which provides further information about a plume's composition. Moreover, instruments from Forest Service aircraft can complement remote sensing data from spaceborne systems. For example, the US National Infrared Operations Program (NIROPS) integrates data from multiple systems and sources to visualize wildfire information in web mapping services, such as Google Earth. A NIROPS aircraft can detect a hot spot from an altitude of 10,000 ft that is 6 inches in size. As a result, infrared aircraft instruments are often able to fill some of the gaps in satellite data. Since 2003, NASA and the Forest Service have formed a tactical fire remote sensing committee, which discusses how to harness new and existing remote sensing technologies for detecting and managing wildfires (NASA 2019). NIROPS has addressed the operational need for acquiring, preprocessing, and near real-time delivery of high-resolution data, which enable the generation of fire mapping products that support situational awareness and informed decision-making by incident command teams.

As previously mentioned, the Bispectral InfraRed Detection (BIRD) Experimental Small Satellite of the German DLR was launched on October 22, 2001. This satellite operated until 2004 as an optimized fire detection satellite in a 568 km altitude orbit. BIRD was a small satellite weighing no more than 94 kg and was only a 60 cm cube in size. It was the first satellite to demonstrate that forest fires and their extent and the temperature of the flames can be identified early from space. BIRD was also the first satellite designed specifically to detect and examine fires. This led DLR, the German Space Agency, to develop a new generation of infrared sensors specifically designed for remote fire sensing and deployment on small satellites. Its main sensor payload consisted of a two-channel infrared Hot Spot Recognition Sensor system (HSRS) and a Wide-Angle Optoelectronic Stereo Scanner (WOASS-B). This led to new possibilities of the observation of hot events, such as forest fires and volcanic eruptions, from space, whereas other satellites are not specifically designed for the observation of hot events. With the infrared sensor technology installed on BIRD, new fire detection methods developed by DLR played a key role in FUEGO (Spanish for fire), which was a fire detection satellite project sponsored by the European Union.

More recently, the University of California (UC) Berkeley has collaborated on a proposed satellite system: the Fire Urgency Estimator in Geosynchronous Orbit (also called FUEGO). FUEGO is a proposed method for early detection and evaluation of

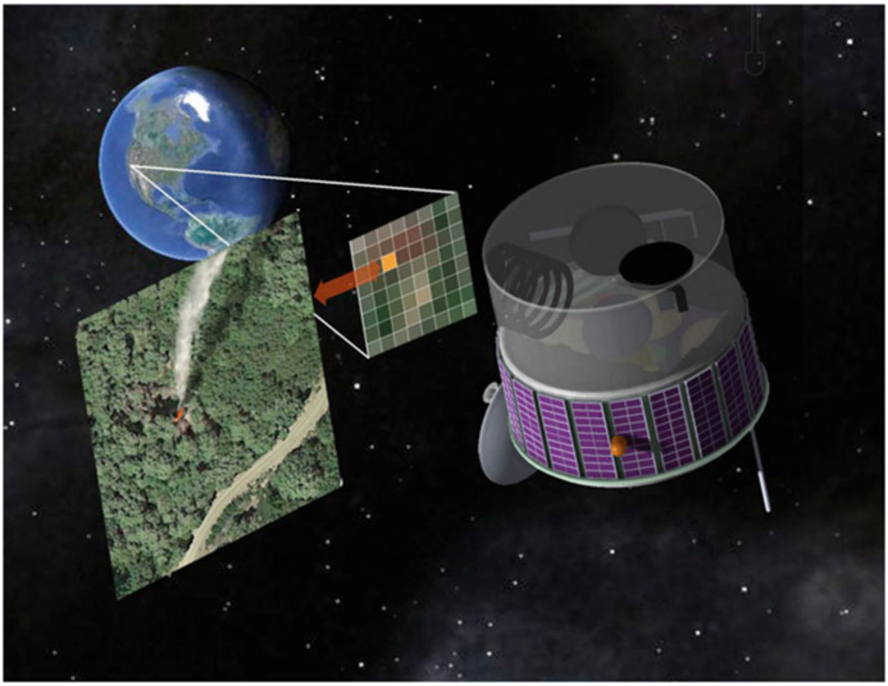


Fig. 4 An artist's concept of the Fire Urgency Estimator in Geosynchronous Orbit (FUEGO) operating during a fire alert. (Art by R.E. Lafever, Space Sciences Laboratory)

wildfires using a system of drones and satellites in geosynchronous orbit equipped with infrared sensors (Fig. 4). It is a space-based system designed to provide firefighters with a tool for early fire detection and monitoring of forest fires, as well as an efficient risk and damage assessment tool. Incorporating a small telescope with a 0.5 m diameter mirror and a 4 × 4 k mercury cadmium telluride IR detector registering 10 million photons per second, FUEGO can potentially detect a 10 m^2 fire within minutes of ignition. The growth rate of the fire can be measured, as well as observed in other spectral bands and compared to historical data.

The proposed FUEGO system also combines several new technologies. These include multispectral sensing using newly available large format HgCdTe sensors. It will also be able to provide rapid mathematical classification of trends and onboard software and computational hardware that can yield a wealth of information. This is intended to allow "calibrated decisions, time-sensitive autonomous, multispectral adjustment of detection thresholds, and precise spacecraft pointing and replicability for robust image acquisition" (Pennypacker et al. 2013). Figure 5 shows a comparison of FUEGO performance with existing and planned satellites, such as BIRD, GOES, ISIR, MODIS, etc. It is clear that timeliness, early detection, and responsiveness are critical to the future designing of truly effective wildfire detection systems.

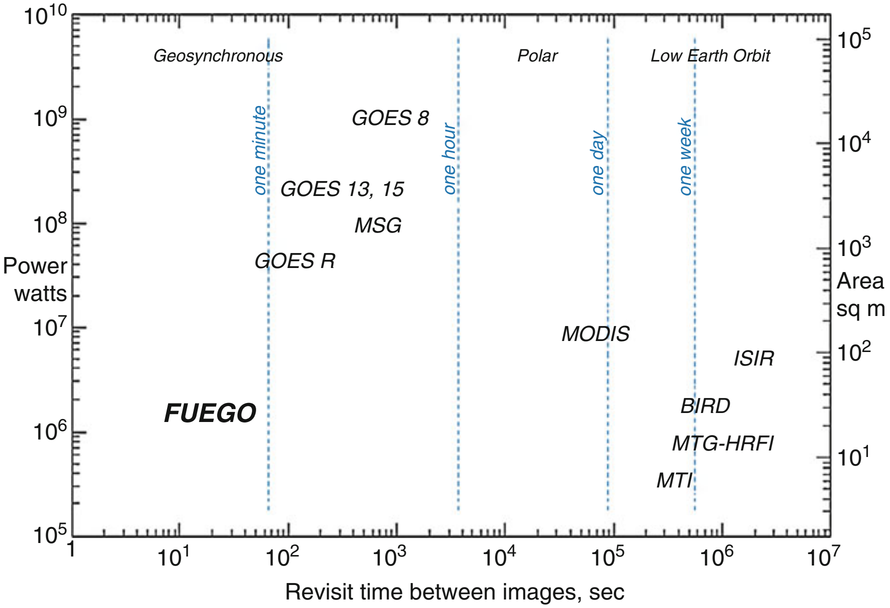


Fig. 5 Comparison of FUEGO performance with existing and planned satellites (Pennypacker et al. 2013)

6.3 Environmental Monitoring

Earth observation has undergone a dramatic revolution and now plays a major role in observing and understanding global environmental change and how it will impact humanity's future. Monitoring and predicting the human health consequences of environmental change are especially challenging, and there are substantial efforts to use satellite imagery to monitor environmental parameters and land cover change that influence the spatial and temporal patterns and spread of vector-borne diseases, such as malaria, dengue, and the Zika virus. A disease early warning system would enable high-risk areas to be identified and for directing control measures. For malaria, key environmental factors include vegetation type and condition, elevation, water bodies, land use, and human settlements. Satellite images can be used to estimate which areas have favorable weather, soil, and moisture conditions to support mosquito activity, as well as identify where human settlements are located and how accessible they are via transportation networks. Recent medical cases can be mapped to show where specific diseases have been treated. This has led doctors to identify settlements that require spraying and other control measures. Shortcomings of existing satellite systems, such as Landsat and SPOT, include timeliness and readiness of data access. These traditional systems often have insufficient spatial and temporal resolution for capturing trends and changes in sufficiently rapid fashion.

Remote sensing provides an adequate means for filling knowledge gaps related to heat and water budgets. These needs are critical for modeling meteorological, agricultural, hydrological, and environmental changes. The Infra-Red miniSatellite Unit for Terrestrial Environment (IRSUTE) was a scientific small satellite mission that provided thermal imagery for determining and analyzing soil/vegetation/atmosphere processes (Becker et al. 1996).

This system was designed to provide high spatial resolution across- and along-track viewing capabilities. It also allowed for four thermal infrared bands, a 1-day revisit time, and an orbital altitude of 540 km. The instrument is useful for meteorological, hydrological, and agricultural studies, especially for environmental monitoring, such as frost mapping, forest fires, volcano activity, and thermal pollution. The small satellite design of IRSUTE was largely driven by the need to meet specific characteristics and limiting factors, such as measurement physics (including atmospheric effects), high spatial resolution for accurate estimates of regional surface fluxes, and frequent revisit time to capture the natural variability of surface fluxes (Seguin et al. 1999).

Yang and Yang (2002) conducted a feasibility study of using a small satellite constellation to perform Interferometric Synthetic Aperture Radar (InSAR) global 3D imaging. This comprised of three identical small satellites, including two flying along parallel orbits with slightly different ascending nodes and observing the same area. The purpose of this effort was to develop interferometry in real time without any time delay (Xue et al. 2008). The third satellite thus flew along another orbit and observed the same area within a short revisit time to provide virtual real-time correlation. Together, the three satellites performed differential interferometry. This enabled surface changes and deformations to be observed accurately.

It is evident that satellite Earth observation systems provide consistent and accessible information about the state of the natural environment. Much of government-owned environmental satellite data is provided freely to users. NASA is currently providing data from its approximately 20 Earth observation satellites online. The European Space Agency operates the Copernicus Programme that provides environmental data from satellites freely to users. Other government agencies in countries such as Japan, India, Brazil, China, and South Korea operate Earth observation satellites and provide at least some of the data for free. Emerging for-profit companies mainly operate satellites with cameras that produce imagery in the visible part of the spectrum (Wood and Stober 2018). Commercial satellite Earth observation companies generally charge an access fee for either original data or access to value-added services or data analytics based on their data. The market for commercial satellite Earth observation is still evolving, and new business models are continually being proposed and examined.

The evolution of small satellite Earth observation companies, such as RapidEye, Skybox, BlackBridge, and Planet (Labs), is an example of the significant growth that has taken place and volatility of the remote sensing small satellite market (Sweeting 2018). As previously mentioned, RapidEye (Germany) was the first commercial Earth observation constellation of small satellites. However due to financial difficulties, it was eventually acquired by BlackBridge (Canada) in 2011 after filing for bankruptcy. It was finally then acquired by Planet in 2015.

Skybox Imaging is another startup company that was formed in California in 2009 and eventually also acquired by Planet. Skybox Imaging launched its first 83 kg Earth observation microsatellite, SkySat-1, on November 21, 2013, which provided 0.9 m resolution panchromatic imagery. It was the first company to release HD video from space, capturing up to 90 s video clips at 30 frames/s at a spatial resolution of 1.1 m at nadir. It was envisioned that the high-definition satellite video would help understand the world better by analyzing the movement of goods and people and observing objects that affect the global economy, such as road vehicles and shipping containers. The first two prototype satellites (SkySat-1 and SkySat-2) were produced in-house and did not have a propulsion system. The other 13 satellites (SkySat-C series) were slightly larger and heavier (about 120 kg) and manufactured by Space Systems/Loral (SSL) with satellite thrusters built by ECAPS and optical payloads developed by L3 Technologies. Google acquired Skybox Imaging for about $500 million in 2016, and it was subsequently renamed as Terra Bella with the intention of supplying Google's imagery repository for keeping Google Maps up-to-date. However, in early 2017, Google sold Terra Bella and its Skybox constellation to Planet Labs and made a multiyear agreement to purchase imaging data produced by these satellites. Planet has since launched 6 more now renamed SkySat satellites with 15 SkySat satellites launched in total, which complement Planet's Dove 3 unit CubeSats. The constellation's goal is to provide high-resolution satellite imagery of any place on Earth multiple times a day.

Planet Labs (now Planet) is an American private Earth imaging company founded in San Francisco in 2011 as a startup by former NASA employees. Their goal is to image the entire planet daily to monitor changes and to identify trends. The company designs and manufactures Triple-CubeSat miniature satellites called Doves, which are mainly secondary payloads on other launch missions. Each Dove satellite continuously scans the Earth's surface, forming the largest satellite constellation in the world and providing complete global coverage at 3–5 m optical resolution via a technique called line scan. Planet designed and manufactured 5 kg CubeSats with a "3 U" form factor (10 × 10 × 30 cm) with foldout solar arrays and antennas and a 3-year design lifetime. Dove satellites were first launched in 2013 and were shortly followed by the first "flocks" of multiple small satellites to form a constellation. With the acquisition of BlackBridge in July 2015, Planet launched 87 Dove and 5 RapidEye satellites. Planet also launched an additional 88 Dove satellites in 2017 on the Indian Polar Satellite Launch Vehicle. This represents the largest fleet of small satellites ever orbited on a single launch. This successful launch brought their total number of Dove satellites launched into orbit to over 150 as of early 2020. The images gathered by Doves are transferred to Planet's cloud infrastructure and into the company's data processing and distribution pipeline, which has some open data access imagery available. By September 2018, the company has launched nearly 300 satellites in total of which about 150 are active.

ICEYE Oy is a Polish and Finnish startup company and microsatellite manufacturer based in Finland and founded in 2014. In 2015, the company demonstrated that synthetic aperture radar (SAR) could be used on small satellites to monitor hazardous ice features, such as pack ice. Its proposed constellation of microsatellites provides SAR imagery for a variety of applications, ranging from urban infrastructure planning and monitoring marine shipping ports to various environmental applications. Its first satellite (ICEYE-X1, also known as ICEYE POC1) was launched on a PSLV-XL rocket on a PSLV-C40 mission from the Sriharikota Launching Range. It was the first satellite under 100 kg to carry a SAR instrument, and it was also the first Finnish commercial satellite. Up-to-date, 5 satellites have been launched, which is part of the ICEYE vision to develop a satellite constellation of 18 microsatellites equipped with SAR in collaboration with ESA.

SSTL adopted an innovative business model in 2015, which was adapted from the geostationary communication market, where many service providers lease transponder bandwidth and time from satellite owners on a pay-as-you-go basis. This allowed for a maximum of flexibility in response to demand for the service provider while minimizing capital outlay (Sweeting 2018). This model was adapted to the Earth observation market by launching three 450 kg minisatellites, while leasing guaranteed imaging payload capacity to separate international Earth observation service operators, while retaining ownership and orbital operations. The advantage of this model was enabling service providers to focus on their imaging services for customers, rather than satellite operations and housekeeping. Three optical Earth observation minisatellites were launched in 2015 providing 1 m panchromatic and 4 m multispectral imagery daily global coverage, which was leased by a single customer.

A fourth satellite developed by SSTL was the NovaSAR-1, which is a small synthetic aperture radar (SAR) mission designed to be a low-cost S-band SAR mission on a minisatellite. It was launched on September 16, 2018 on the PSLV-C42 vehicle of ISRO from Sriharikota. As a joint technology initiative of SSTL, UK, and Airbus DS, funded by the UK Government, the overall objective of NovaSAR-1 was to make SAR observation missions more affordable to a customer base and to open up new applications in the microwave region of the spectrum. There is a range of applications including urban planning, agricultural monitoring, land classification, natural resource management, and disaster monitoring.

7 Challenges of Small Satellite Constellations for Remote Sensing

As previously mentioned, several challenging factors constrain the development of small satellite constellations for Earth observation. A major constraint will continue to be the availability of low-cost and timely launchers, which will continue to limit the growth of the small satellite market. The mushrooming of nanosatellites and microsatellites has spurred the growth of small launcher developers. This includes some from space agencies, such as Vega/ESA, Kuaizhou/China, and Epsilon/Japan. There are also a host of startup companies that include Rocket Lab and Orbital Express. In some ways the launcher companies that are pioneering reusable launch vehicles such as Space X and Blue Origin may ultimately bring the greatest new economies to launch operation for small satellites.

There are about 50 new small launch vehicles in various stages of development, and several of them have gone bankrupt already, but perhaps many of them will succeed and bring new vigor to the launch industry (Sweeting 2018). Several of these intend to utilize "green" propellants. There is some debate about the resulting $/kg for small satellites on small launchers versus large launchers. It appears that medium launchers capable of 1,200–1,500 kg to sun synchronous orbit may be optimal, such as Dnepr and PSLV, where payloads with similar schedule and orbit requirements can be grouped together (Sweeting 2018).

SpaceX has developed the Falcon 1 launcher for small satellites in 2008, which successfully delivered the Malaysian RazakSAT satellite to an equatorial orbit in 2009. Future potential may also exist in air-launch proposals (e.g., Virgin Galactic) associated with the market for space tourism, although this business case may be difficult to manage and predict. A new trend is the emergence of launch brokers (e.g., Spaceflight and TriSept), which accumulate customers for specific rideshare missions (Sweeting 2018). Therefore, launch cost is still a primary driver of the mission cost and associated commercial business cases for small satellites. In order to observe significant cost reductions, radical innovations in future satellite design and manufacturing approaches will bring about new business models.

Other concerns that constrain the growth of small satellite businesses include space debris, Earth observation policies, and communications frequency allocations. The abundance of small satellites launched since 2005 has resulted in significant pressure and demand on frequency spectrum allocations, especially since many amateur satellite services have used VHF and UHF allocations (Sweeting 2018). Available bandwidth continues to be highly restricted, although many university-grade microsatellites are relatively short-lived and allow the frequency to be reused. Significant spectrum demands and competition exist, especially for larger "mega-constellation" small satellite missions.

Small satellites are in themselves not necessarily a major space debris issue, as long as they do not fragment and have a natural end-of-life deorbit, such as through a deorbiting mechanism (e.g., a drag sail or robotic capture). In fact, it is often said that one factor in the original conceptualization of the 10 × 10 × 10 cm CubeSat design was the minimum size that was detectable and trackable by the US Air Force in LEO. Small satellites can pose as additional space debris, if they do not have the propulsion capability to maneuver out of the way of orbital debris and do not comply with deorbit guidelines. Large numbers of satellites can also arise out of constellations, which suggests that the creation of an analogous space traffic control system may be required in the future (Sweeting 2018), especially if space debris continues to increase. Several small satellite missions are being proposed for active debris removal, such as the European Union's (EU) low-cost in-orbit microsatellite demonstrator mission called "RemoveDEBRIS."

There are also significant issues with Earth observation policies and regulatory mechanisms, especially with privately owned commercial small satellite constellations that provide high temporal and spatial resolution of 0.5 m or better. More precise data that is constantly being updated is changing the world.

This level of high resolution raises personal privacy concerns. Currently, countries control data collection and delivery and can potentially interrupt services for political motivations or national security reasons. We are also entering an era of big data availability from a combination of in situ sensors, airborne platforms, and remote sensing satellites, which already cause issues with data quality, handling, and integration. Moreover, the maintenance of metadata standards across all of these platforms needs to be addressed, if reliable information about these sources is to be made readily available.

Constellations present unique problems of satellite coordination and integration or interoperability with other satellite constellations. Examples of constellations for navigation and geodesy include GPS, Galileo, and GLONASS, while examples for remote sensing include the Disaster Monitoring Constellation (DMS), RapidEye, COSMO-SkyMed (Constellation of small Satellites for the Mediterranean basin Observation), and the Huanjing constellation (the Small Satellite Constellation for Environment Protection and Disaster Monitoring). The primary benefits of constellations are enhanced sensors, continuity of data, timely observations, global coverage, and extraordinary pace of development and manufacturing. As a result, small satellite constellations can generate a huge amount of data on a daily basis, and there is significant processing demand from the remote sensing user community.

Integration of remote sensing data within Geographic Information Systems (GIS) enables improved access to geographic information for enhanced analysis and decision-making. GIS may also play a role in the dissemination of data or purchasing of imagery from private satellite companies. Advances in computer-based planning models, satellite imaging, and machine learning are able to optimize available data for infrastructure planning, lowering costs, and ultimately making better decisions.

The biggest change of all is in the area of data analytics and the more intensive use of data derived from small satellite remote sensing data. There is now what might be called a "deep learning revolution." This is coupled with the availability of faster and cheaper computing, as well as advantages in artificial neural network models; it is expected that artificial intelligence will transform big data into useful information in the future – and at a faster and faster rate. The data that comes from the skies will be fed into value-added economic systems at a faster and faster pace. Satellite remote sensing will be coupled with advances in artificial intelligence and data mining techniques. It may become easier for analysts to extract features from satellite imagery semiautomatically and to turn data into meaningful information.

8 Conclusion

Small satellites have been exercising a disruptive force in the satellite industry, in both an economic and technological sense. As a result of rapid innovation and technical disruptions, the small satellite market is changing rapidly. There are now lower barriers to entry with respect to capital and infrastructure. The main paradigm seems to be a modular-based manufacturing model. This small satellite revolution is also fueled by frequent and greater launch opportunities at lower costs. Another part of this revolution seems to be a higher tolerance for failure. This in turn enables a shorter timeline to market compared to the traditional satellite market. However, small satellites will likely not replace large satellite missions in the near future but will become often complementary in nature. This is due to different goals, market opportunities, and competing advantages/disadvantages. The primary benefits of small satellites include the speed and lower capital costs of adopting new technologies, as well as rapid product and development cycles. This, in turn, allows low relative costs and the ability to exploit a more agile management and business model (Sweeting 2018).

Modern innovations with small satellites in LEO are especially changing the remote sensing business. These include new applications such as the linking of big data warehouses and artificial intelligence data mining, machine learning, and data analytics. These systems and commercial satellite operators are not only engaging in remote sensing by satellites, but also focusing on analyzing the data that they collect to create new understanding of the practical implications of this data. In short, these new small satellite companies are selling the "data analytics" derived from the EO data rather than the collected data. It is in this way that the greatest value can be derived and the key objective is to rise higher up the economic value chain.

The greatest constraint to the growth of the small satellite market was once feared to be the cost and availability of launch to orbit. Innovations in the launcher industry such as reusable launchers and other innovations in production techniques and even materials are serving to change the level of concerns of this nature (Sweeting 2018).

Small satellite constellations – primarily for telecommunications, networking, and remote sensing – result in the mass production of small satellites that have contributed to a more crowded space environment, especially in LEO, and a greater demand for launch capabilities and big data processing. There is ongoing research into the in-orbit manufacturing of satellites and new launch technologies to support the assembly of large systems and so-called mega-constellations.

It is expected that small satellites – both for networking and EO activities and related data analytics – will continue to change the economics of space. Their low cost, rapid development times, and relative simplicity remain appealing. There are concerns related to orbital debris and saturation of low Earth orbits, especially in the range of 700–1,100 km where the threat of orbital collision appears to be rising sharply.

Small satellite constellations will have to rapidly expand their services to customers. This will lead to new ways to meet demands for reliable and responsive sources of imagery. This will rapidly lead to new approaches for monitoring the Earth's surface and new ways to process the data for various applications. Such services have matured considerably based on experience gained through large traditional satellite systems over the last 50 years. The satellite industry has produced many new applications, such as smart farming, pollution controls, law enforcement, disaster management, and wildfire management, and scores more of new ways to use satellites to learn more about today's world. Such data streams have significant potential to be applied by different and nontraditional end users, customer bases, and research communities. The question also remains whether the economic value of data analytics will justify the large capital investment that is being made in large-scale constellations for Earth observation.

There is an exciting future ahead for small spacecraft missions, especially for the development of future cooperative distributed space systems, such as constellations and formations, to provide more capabilities and observation capacity in the field of remote sensing. New constellations will need to make use of new technological advancements in electronics, materials, and sensors to create satellites that are physically smaller, technically simpler, and more affordable to acquire, launch, and operate. This is an exciting time for small satellite design and testing new business plans in the "NewSpace" era, which will translate into innovation and greater benefits for government, industry, academia, and the global population. The small satellite revolution has been described in many ways. One insight is as follows: "Silicon Valley has discovered and revolutionized the space industry and it will never be the same."

9 Cross-References

- ▶ Messaging, Internet of Things, and Positioning Determination Services via Small Satellite Constellations
- ▶ Mobile Satellite Communications and Small Satellites
- ▶ Radio-Frequency Geo-location and Small Satellite Constellations
- ▶ Small Satellite Constellations Versus Geosynchronous Satellites for Fixed Satellite Services and Network Services
- ▶ Small Satellite Market Research Methods

References

O. Albayrak, Small satellite utilization for disaster management information systems. Small Satellites for Earth Observation: Selected Proceedings of the 5th International Symposium of the International Academy of Astronautics, Berlin, April 4–8 2005 (2005)

D.J. Barnhart, T. Vladimirova, M.N. Sweeting, Very-small-satellite design for distributed space missions. J. Spacecr. Rocket. **44**(6), 1294–1306 (2007)

F. Becker, B. Seguin, T. Phulpin, J.P. Durpaire, IRSUTE, a small satellite for water budget estimate with high resolution infrared imagery. Acta Astronautica. 39 (9–12), 883–897 (1996).

R. Burton, S. Weston, E. Agasid, State of the art in guidance, navigation and control: a survey of small satellite GNS components, Proceedings of Advancements in Astronautical Science, 157 (2016)

C.M. Christensen, M.E. Raynor, R. McDonald, What is Disruptive Innovation? (2015), https://hbr.org/2015/12/what-is-disruptive-innovation. Accessed 1 Dec 2019

N.H. Crisp, K. Smith, P. Hollingsworth, Launch and deployment of distributed small satellite systems. Acta Astronautica. **114**, 65–78 (2015)

S.R. Cvetkovic, G.J. Robertson, Spacecraft design considerations for small satellite remote sensing. IEEE Trans. Aerosp. Electron. Syst. **29**(2), 391–403 (1993)

Disaster Monitoring Constellation-3. https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/dmc3-2. Accessed 17 Feb 2020

H. Helvajian, S. Janson, Small satellites - past, present, and future. The Aerospace Press (2008)

D. Homan, Q. Young, The challenges of developing an operational nanosatellite, in 22nd Annual AIAA/USU Conference on Small Satellites, North Logan (2008)

H. Iglseder, W. Arens-Fischer, W. Wolfsberger, Small satellite constellations for disaster detection and monitoring. Adv. Space Res. **15**(11), 79–85 (1995)

H.J. Kramer, A.P. Cracknell, An overview of small satellites in remote sensing. Int. J. Remote Sens. **29**(15), 4285–4337 (2008)

M. Matson, J. Dozier, Identification of subresolution high temperature sources using a thermal IR sensor. Photogramm. Eng. Remote. Sens. **47**(9), 1311–1318 (1981)

NASA, State of the Art of Small Spacecraft Technology. (2018), https://sst-soa.arc.nasa.gov/. Accessed: 15 Nov 2019

NASA, NASA Tracks Wildfires from Above to Aid Firefighters Below. (2019), https://www.nasa.gov/feature/goddard/2019/nasa-tracks-wildfires-from-above-to-aid-firefighters-below. Accessed 1 Dec 2019

Pennypacker, C.R., FUEGO: A satellite system for rapid location of wildfires. (2014), https://spie.org/news/5328-fuego-a-satellite-system-for-rapid-location-of-wildfires?SSO=1. Accessed 1 Dec 2019

T.D. Rivers, Small satellites – evolving innovation for the entire market, in 31st Space Symposium, Technical Track, Colorado Springs (2015)

G. Santilli, C. Vendittozzi, C. Cappelletti, S. Battistini, P. Gessini, CubeSat constellations for disaster management in remote areas. Acta Astronautica. **145**, 11–17 (2018)

B. Seguin, F. Becker, T. Phulpin, X.F. Gu, G. Guyot, Y. Kerr, C. King, J.P. Lagouarde, C. Ottle, M.P. Stoll, A. Tabbagh, A. Vidal, IRSTUE: a minisatellite project for land surface heat flux estimation from field to regional scale. Remote Sens. Environ. **68**, 357–369 (1999)

M.N. Sweeting, Why satellites are scaling down. Space Technology International, 55–59 (1991)

M.N. Sweeting, Modern small satellites – changing the economics of space. Proc. IEEE **106**(2), 343–361 (2018)

A. Tobias, W. Leibrandt, J. Fuchs, A. Egurrola, Small satellites: enabling operational disaster management systems. Acta Astronautica. **46**(2–6), 101–109 (2000)

D. Wood, K.J. Stober, Small satellites contribute to the United Nations' Sustainable Development Goals, in 32nd Annual AIAA/USA Conference on Small Satellites (2018)

Y. Xue, Y. Li, J. Guang, X. Zhang, J. Guo, Small satellite remote sensing and application – history, current and future. Int. J. Remote Sens. **29**(15), 4339–4372 (2008)

Z. Yang, R.L. Yang, Feasibility study of using small satellite synthetic aperture radar for global 3D imaging. Proceedings of the IEEE International Geoscience and Remote Sensing Symposium and 24th Canadian Symposium on Remote Sensing, Toronto, Canada, 2002, 3162–3164 (2002)

Small Satellite Market Research Methods

Ken Davidian

Contents

Abstract

Small satellites are among the fastest-growing and evolving new markets today. Technological innovations include the ranges of satellite masses (*picosat*, nanosat, microsat, and minisats), sizes (including volume ranges from thumbnail to commuter bus), functions (Earth observation, communication, resupply, etc.), and project structure (e.g., individual satellites vs. large-scale constellations). This chapter asserts that a significant fraction of market analysis is initially conducted using variance methods, despite the lack of supporting theory and clear research questions. Despite challenges of high labor intensity and complexity of data interpretation, process research methods can underpin the development of relevant theory first, before variance research methods are executed. Furthermore, the data collected using process methods, if done thoughtfully and deliberatively, can support multiple research questions, and different data sets can be

---

K. Davidian (✉)
Office of Commercial Space Transportation, Federal Aviation Administration,
Washington, DC, USA
e-mail: ken.davidian@gmail.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_106

pooled, providing broader industry contexts in support of a given research question.

Keywords

Adaptive strategy · Industry emergence · Industry evolution · Industry infrastructure elements · Markets · Market models · Organization theory · Predictive strategy · Process · Process research methods · Research · Theory · Variance research methods

1 Introduction

Three major sources of new market creation include technological innovations, shifts in societal norms and values, and changes in laws and regulations (Aldrich and Ruef 2006). Small satellites are among the fastest-growing and evolving new markets today. Technological innovations include the ranges of satellites masses (picosat, nanosat, microsat, and minisats), sizes (including volume ranges from thumbnail to commuter bus), functions (Earth observation, communication, resupply, etc.), and project structure (e.g., individual satellites vs. large-scale constellations). Shifts in societal norms include the perception that space activities can be conducted by individuals and small groups and are no longer limited to sovereign nations or governmental agencies. Legal and regulatory changes have made these emerging markets possible, by lowering barriers of operational uncertainty and enabling the flow of private capital into these activities. Changes in all three of these areas need to be accounted for and modeled to understand the trends in small satellite markets.

This chapter discusses these perspectives to query, model, and analyze market dynamics and trends and industry emergence and evolution, more generally characterized as processes of organizational change and development. It begins with an introduction to the characteristics of research questions as applied to small satellite markets. Next, the approaches of market modeling are discussed, including systems of technologies, neoclassic economics, and social functions. This is followed by a brief discussion of analysis strategies, including the origins and mitigation of phenomenological uncertainties and the presentation of variance and process research methods. Each method employs certain instruments and methods and has certain advantages and disadvantages, is appropriate for different stages of the overall research process, and can ultimately complement each other. Finally, a discussion of data collection instruments is given.

Content for this chapter was collected primarily from existing literature, as noted in the Acknowledgments section. Additional concepts, explanatory text, and ideas were inserted as appropriate, to present complementary information and to target the discussion to topics of small satellite market emergence and growth.

2 Research Questions

Understanding of market phenomena is of great interest to both academics and practitioners. Industry and governmental practitioners (including business executives, government administrators, political leaders, and lawmakers, whether as individuals or as part of a collective body) communicate relevant policy challenges in ways that are easy to understand, typically in the form of brief, concise, declarative statements, or straightforward questions. Buried within these statements and questions are complex challenges that need to be expressed as well-formed research questions, before potential solutions can be found. Extracting those questions is an important job of the research community, and the nature of those questions will determine appropriate data collection approaches and theory development methods to be used. For the small satellite market, these questions include topics industry emergence, evolution, and change. Industry practitioners in technical fields naturally approach questions about market capability, capacity, and growth from a technological perspective. Government policy-makers commonly turn to neoclassical economic experts to analyze market emergence questions (Etzioni 1988). Recently, social science academics in organization theory (OT) have joined the discussion with a different perspective and approach, to answer these questions with increased methodical rigor and a broader contextual understanding. Generally speaking, social scientists (including economic and OT researchers) analyze rapidly emerging and evolving markets in two principal ways, using variance and process research methods (Mohr 1982).

For example, challenges to CubeSat industry emergence "include the reality and the perception of CubeSats generating orbital debris, spectrum challenges, and difficulties related to obtaining affordable access to space" (National Academy of Sciences Engineering and Medicine 2016, p. 71). Taking the orbital debris challenge as a particular example, "because CubeSats typically are not maneuverable, they are seen as orbital debris threats, especially in near-Earth orbits, with low Earth orbit being a special challenge because of the presence of the International Space Station. CubeSats comprise less than a percent of all resident objects in space and are expected to remain a small fraction, even as their number in space grows" (National Academy of Sciences Engineering and Medicine 2016, p. 75). The following questions are intended to demonstrate how these highly relevant statements need to be translated into many more complex and interesting research questions:

- How much of a real threat are CubeSats to the International Space Station (ISS)?
- Can anything be done to change the perception of CubeSats as a threat to other orbital objects?
- As CubeSat numbers increase, how will the real threat they pose change?
- What policies can be implemented to minimize the threat posed by CubeSats?

This chapter discusses the characteristics of these research questions and the approaches, strategies, and instruments that can be applied toward a solution. The first section discusses the types of theory and market models currently in use for analysis of market emergence, including modeling markets as technology systems, neoclassic economic systems, and societal systems. Next, the sources of uncertainty for each system are discussed, and two appropriate strategies for mitigating those uncertainties are described. Each strategy generally corresponds to a category of research methods, either variance or process (Mohr 1982). Finally, the common data collection instruments for each method are discussed briefly, giving the advantages and disadvantages of each and explaining how variance and process research methods, when appropriately employed, are complementary to each other.

3 Modeling Markets

3.1 Two Types of Theory

Theory can achieve two different goals. The first is to design, control, or predict the outcome of a given phenomenon, and the second is to describe or explain a phenomenon. The sample questions above demonstrate both types of theory development. The first and third questions convey research to design or control the outcome of an assumed process. The first question requires the researcher to quantify the value of risk to the ISS associated with the current state of CubeSats in orbit (i.e., by predicting the function of risk caused by the interaction of CubeSats and the ISS). The third question asks for a prediction of the change in risk as a function of CubeSat numbers. Both of these are predictive questions and will be generally better served through the development and application of variance models. The second and fourth questions are different, however. The second question asks for a description of threat mechanisms posed by CubeSats to other orbital objects, and the fourth question delves into alternative risk mechanisms that may exist as the number of CubeSats increases. These are questions that require the creation of process theory and models, to describe or explain the steps of a process, mechanism, or phenomenon.

In short, predictive questions, generally associated with variance research methods, tend to be “outcome driven,” starting with the dependent variables (DV), or outcomes (e.g., the threat level caused by CubeSats), and working backward to the independent variables (IV), or inputs, of the research topic. Predictive questions invoke analytic perspectives that can be described as overly reliant on analytic structure (“paradigmatic”), or hyper-rational (“logico-scientific”). As will be discussed below, predictive questions are commonly approached using the predictive strategy of uncertainty mitigation. In contrast to predictive questions, descriptive questions are event-driven, asking how the research topic develops or changes as a function of time, building forward from inputs to outputs. Descriptive questions generally best employ process research methods and the adaptive strategy of uncertainty mitigation, resulting in a narrative perspective.

3.2 Technological and Economic Systems

Research to describe and analyze emerging and newly evolving markets, such as small satellites and large constellations, can be conducted in many ways. Scientific and technical researchers and analysts tend to focus on their areas of expertise and interest, providing a microscopic perspective of technological issues and solutions, and attempt to link those results to a "market" by translating those details into estimates of price or cost. Despite the accuracy of their modeling efforts, the technical approach as applied to a sociological phenomenon has obvious disadvantages, having minimal connections to economic theory and ignoring entirely the real-world socioeconomic factors and interactions. Alternatively, neoclassical economists constrain markets through simplifying assumptions, resulting in a focus on aggregate indicators of financial resources and factors of industrial production. Self-imposed constraints in neoclassic economics include disregard for social connections (Fourcade 2007), methodological individualism (identifying collectivities as an aggregation of individuals) (Etzioni 1988), rational behavior (Malerba et al. 2016), and market differences based solely on production control and prices (Parsons and Smelser 1956), to name a few. Methodologically, economics has been primarily focused on predictive theory (Friedman 1953), with little interest in descriptive research. The underlying constraints limit the ability of neoclassic economics to sufficiently characterize the emerging and evolving markets phenomena of dynamic, industry-level interactions. Advances in evolutionary economics (Malerba et al. 2016; Nelson and Winter 1982) recognize the neoclassic limitations but are themselves also limited in different ways:

> We believe that there is a broadly shared view in this community that much of the modeling that has been done by economists over the past half century has not provided much insight into how the economy really works. Modeling efforts often aim at elucidating causal mechanisms, and may succeed at least in sharpening intuitions about particular mechanisms. Most of the models, however, have been too stylized to give us an understanding that is relevant to the complicated economic reality we need to know about, where multiple mechanisms are typically in play. To acquire such an understanding, it is necessary to face up to the intrinsic difficulty of the task, rather than assuming it away. We argue that in the future the models we build should be oriented more closely by what we know about particular segments of that complex reality, so as to provide more believable insight into those aspects that we are struggling to understand. This, of course, is the basic commitment of history-friendly modeling. But there is wider recognition today of the need to engage with the complexity of economic reality, even at the price of seeing it in 'a much messier, less pretty view (Krugman 2009).' (Malerba et al. 2016, p. 246)

3.3 Social Systems

Academics in economic sociology (Parsons and Smelser 1956; Smelser and Swedberg 2005) and OT (Baum 2005) engage with "the complexity of economic reality" by expanding the perspective of markets (beyond technologies, or financial and production factors) to include additional functions of a social system not previously modeled. Emerging markets are characterized to include numerous industry actors, both national and international, representing many sectors of society, including organizations that are private, nonprofit (nongovernmental), and governmental and networks that focus on issues, social movements, knowledge-based subjects, or belief-based topics (Fligstein 2005). These actors work in responsible or opportunistic ways, individually and cooperatively, to achieve long-term industry survivability. For new markets, actors build and accumulate critical resources to enable industry emergence (Etzioni 1963). These resources, referred to as industry infrastructure elements (Van de Ven and Garud 1989), contribute to critical market functions of institutional arrangements, resource endowments, and proprietary functions, respectively, corresponding to Parsons' functions of goal setting, integration, and adaptation (1960). Whereas this resource accumulation framework provides more realism (i.e., is "much messier" and "less pretty") to the representation of markets, especially in comparison to technology or neoclassic economic models, it under-represents the fourth critical social system function of culture. More recently, Geels (2002, 2005, 2006, 2010, 2018) expanded a multilevel perspective model of sociotechnical transitions, originally developed by Rip, Kemp, and Schot (Van Driel and Schot 2005), that includes all four social system categories, closing the gap of previous theory.

4 Analysis Strategies

4.1 Mitigating Uncertainty

For any of these market models, whether based on technologies, neoclassic economics, or OT, the overall uncertainty level of results is high. The study of organizational systems, such as markets, is different from studies in other types of sciences. Physical sciences, such as physics, can be highly deterministic, yielding results with low uncertainty. For example, the value for the acceleration due to gravity will remain constant in well-formed experiments, regardless of the number of trial runs, or who is conducting the research, because the phenomena being studied is unique, unchanging, and separate from the empirical examination process. Uncertainties begin to increase for studies in the natural sciences, yielding results that are more probabilistic when compared to the physical sciences. The phenomena may be unique, but there exists variation among the experimental specimens. Consider the anecdotal life sciences example often told about unlucky laboratory frogs. When a lethal dose of a drug is calculated for and injected into some number of frogs, a certain fraction of them die, while others show mild symptoms before getting better, and the rest show no reaction to the injection, whatsoever. In both the cases, however, no matter the degree of variation observed by the physicists or life scientists in their experiments, the phenomena they study do not themselves change.

Uncertainty levels increase still more in studies of social systems, due to the overall complexity of the problem and the free will of individuals. "People are not billiard balls, but have complex intentions operating in a complex web of others' intentions and actions" (Miles and Huberman 1994). Whereas some uncertainties of some sciences can be minimized through the collection of more data, models based in social systems are highly nonlinear with respect to the actions of individuals, and the ability to adequately predict individual actions (which is different than probabilistic outcomes of a social group) is low. Furthermore, social systems are performative (Fourcade 2007), meaning that as research is conducted and revealed, the laws (i.e., theories) act upon, and change, the social system they describe. In this way, social sciences may unwittingly be technologies instead of pure sciences, resulting in increased system interactions and complexity.

Two possible strategies for dealing with uncertainties, referred to as the predictive or adaptive approaches (Packard and Clark 2019), represent idealized extremes available to the researcher. Uncertainties result from "insufficiently known phenomena and . . . human acts of choice" (Von Mises 1949, p. 105), the former representing a lack of knowledge, and the latter being inherently unpredictable. The goal of the predictive strategy is to acquire more specific and higher-quality data, to more completely explain and understand the phenomenon being researched. An implicit assumption of the predictive strategy is that a theory-based model was developed prior to the data collection effort. Improved understanding of a given phenomenon is the goal, hidden in the shadows of uncertainty, and improved data collection is the light that can lead to the unique solution. On the other hand, the adaptive, or flexible, nonpredictive strategy assumes that the phenomenon can be understood through "effective navigation" of uncertainty via "rapid informational processing and response" (Packard and Clark 2019). Instead of focusing on specific data, the adaptive strategy collects data of general context. When based on common definitions of mid-level concepts (e.g., the innovation process), these events can be used collectively, in abductive theory development, by different researchers pursuing separate research questions based on the common, mid-level concepts, or by the same researcher, trying to solve different research questions. Alternatively, because of the broad scope of the data collected, multiple research questions can be served by the same data pool. This type of approach is implied by the process research method and is ideal for theory development, thereby implicitly appropriately positioning it before the predictive strategy. The predictive strategy implies the use of variance research methods.

Regardless of the type of research question, both variance and process methods make basic assumptions of the underlying mechanisms being investigated. On the one hand, variance methods are built on necessary and sufficient causality as a basis of explanation and uniformity across different contexts. Variance methods incorporate IV and DV that do not change in meaning over time and are related through immediate application of efficient cause. (This is a reference to Aristotle's description of four causes of why change occurs, or "aitia." (1) Efficient cause is described as being caused by an agent which is separate from the item being changed. (2) Material cause results from the material properties of the item being changed. (3) Formal cause is the pattern that guides a change to an item. (4) Final cause is the reason for the change to the item.) In efficient cause, the time ordering of IV has no effect on the DV.

On the other hand, process methods are based in probabilistic rearrangement of discrete states and events, where antecedents are necessary, but not sufficient, for the consequents. Process methods incorporate final cause as a reason for why change occurs, and time ordering of IV is critical to the resulting DV (Mohr 1982). In any case, neither approach is superior or inferior to the other.

Both research methods are appropriate at different stages of research. Process methods complement variance methods by supporting the early stages of theory development and the development of models. After that stage, variance methods are appropriate for the testing of hypotheses, so models can be verified and then appropriately applied to answer the design or prediction problem (Van de Ven 2007).

Whether using variance or process research methods, any theory of industry emergence and evolution should satisfy four basic criteria: it should include all relevant influential forces, provide satisfactory explanations of how organizational changes are generated and resolved, collect data directly from the process being investigated, and use analytic methods to discover and evaluate underlying process complexity. The reason variance research methods are characterized as "too stylized" is because these four criteria are not addressed sufficiently. For example, Mohr (1982) characterizes variance methods as taking a limited perspective of process, assuming "continuous change driven by deterministic causation," which is obviously not the case when considering industry emergence timeframes of decades, where multiple actors from different segments of society interact in discontinuous ways, with no guaranteed outcome for overall industry survival. A method of process research, on the other hand, "encompasses continuous and discontinuous causation, critical incidents, contextual effects, and effects of formative patterns." Variance research methods characterize change by an analytical expression, collecting IV and DV, or proxies thereof. Process research collects data of relevant events from the change process itself, thereby exposing the underlying phenomenology of industry emergence and evolution. Variance research methods can ultimately be used to complement the process approach in theory development but cannot substitute for or meaningfully precede it.

4.2 Variance and Process Methods

Research using variance and process methods adopts different definitions of process and employs different data collection instruments to support the work.

Common variance study instruments include cross-sectional and longitudinal panel surveys. These variance instruments typically conceive of process as a causal sequence of inputs (IV) and outputs (DV), or as a sequence of organizational actions, described by examining antecedents and consequents of the change process under investigation. The large sample size of the cross-sectional survey is an obvious strength. Shortcomings of this instrument include the use of summary or proxy indicators that provide little insight into the process being investigated, the reliance on the memory of survey respondents to recall historic events that will be subject to subjective biases or unintended mistakes, and the weak support for inferences of possible process causality. Longitudinal panel surveys provide stronger support of process causality than the cross-sectional approach, since longitudinal data can identify time dependence of a sequence of events. Also, unforeseen processes may be discovered within the data that would not have been possible with a single-shot, cross-sectional survey. A major limitation of the longitudinal survey, however, is the requirement to predict which variables (both IV and DV) are important enough to the process for measurement. Although the longitudinal survey improves on the cross-sectional survey, neither instrument can match the insights available with process research methods to understand the complexities of industry emergence and evolution processes.

Process research data collection differs from that of variance research methods, conceptualizing process as a sequence of events, with minimal regard for input-output variables or antecedents-consequents. As compared to variance methods, the data collected is greater in number, broader in scope, and more complex to efficiently and effectively process. These seeming disadvantages provide equally extreme advantages, supporting the inference of phenomenon causality, permitting the investigation of intermediate (mediating and moderating) process steps, and generating a rich and detailed narrative history of the process under investigation. Since the sample size in process research is the number of observed events, the sample size can be substantial although the number of cases being investigated is low. Furthermore, sufficient information may permit the estimation of the magnitude of influence a given event, or set of events, may provide at a given point in the process. The abundance of data allows for the investigation into additional research questions that may arise unexpectedly (a common occurrence in policy-making circles).

Ultimately, among the stages of research activities that iterate between problem formulation, theory building, research design, and problem-solving (Van de Ven 2007), the event-based identification of a phenomenon (using process methods) naturally precedes model development and validation (using variance methods). Process cannot be constructed from variance method concepts (such as causal sequence or organizational actions, defined by IV and DV constrained by implicit methodological assumptions), because of insufficient information collected. It is possible, however, and more logical, to reduce process and the event sequence data to a series of variables, or generalized narrative, satisfying the variance method definitions of process.

5 Conclusion

Industry and government leaders seek questions to answers in order to make decisions about the economy at the industry level and above. Typically, these questions are the bases for relevant research questions. Generally speaking, questions that seek to design, control, or predict a phenomenological process are based on preexisting theoretical understandings and use a predictive strategy to mitigating the uncertainty of the results. The variance approach of research is used to solve these types of problems. On the other hand, questions that seek to describe or explain a phenomenon call for process methods of data collection and theory creation. In this way, researchers are adopting an adaptive approach to uncertainty mitigation, not entirely sure of the path or end result of their research activities. These results can be more labor-intensive to collect, and complex to interpret, but process research methods provide three major advantages over variance research methods. First, the approach is flexible, allowing for the investigation of multiple research questions with a foundational set of data, enabling insights of new processes from the initial data set to be uncovered and subsequently investigated, and permitting the comparative evaluation of multiple competing theories that may not share common foundations of input-output variables, or antecedents and consequents. In turn, multiple theories can be combined into hybrid explanations of a complex process. Similarly, multiple process method data sets could feasibly be used to investigate a single process theory, provided a minimum level of commonality of the data collected at a pre-specified level of analysis. This was done in the Minnesota Innovation Research Program (Van de Ven and Poole 1990, 2000). A second advantage of process method research is that it complements variance methods, providing insights into the process phenomenology that is not possible with variance research. A third advantage of process research is that it acknowledges the complexity of the organizational change processes (including industry emergence and evolution), in contrast to traditional variance studies that are "under-socialized" (Granovetter 1985).

Governmental and academic research thus not only focused on understanding how big a particular market, such as small satellites, will grow or change over time. Rather, it is often focused on what impact a change will have on systems of social services, education, political, and ethical and how a particular industry impacts, and is impacted by, the overall social system. In the case of small satellites, issues such as orbital space debris, global interconnectivity of the Internet, and the impact on remote area education are important aspects of the industry analyses. In this way, market research is tied to the broader aspect of societal change and interaction.

6 Cross-References

- ▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas
- ▶ Messaging, Internet of Things, and Positioning Determination Services via Small Satellite Constellations
- ▶ Mobile Satellite Communications and Small Satellites
- ▶ Radio-Frequency Geo-location and Small Satellite Constellations
- ▶ Remote Sensing Applications and Innovations via Small Satellite Constellations
- ▶ Small Satellite Constellations Versus Geosynchronous Satellites for Fixed Satellite Services and Network Services

Acknowledgments The content and structure of this chapter draw from Poole et al. (2000). For an in-depth and comprehensive treatment of research question development, theory development, and model verification, refer to Van de Ven (2007). Special thanks are extended to Dr. Jennifer Woolley for her comments on earlier drafts of this chapter. The views expressed in this article are those of the author alone and are not those of the US Federal Aviation Administration.

References

H.E. Aldrich, M. Ruef, *Organizations Evolving*, 2nd edn. (SAGE Publications Ltd, London, 2006). https://doi.org/10.2307/3089484

J. A. C. Baum (ed.), *The Blackwell Companion* (Blackwell, Malden, 2005)

A. Etzioni, The epigenesis of political communities at the international level. Am. J. Sociol. **68**(4), 407–421 (1963)

A. Etzioni, *The Moral Dimension: Toward a New Economics*, 1st edn. (The Free Press, New York, 1988)

N. Fligstein, The political and economic sociology of international economic arrangements, in *The Handbook of Economic Sociology*, ed. by N. J. Smelser, R. Swedberg, 2nd edn., (Princeton University Press, Princeton/Oxford, 2005), pp. 4183–4204

M. Fourcade, Theories of markets and theories of society. Am. Behav. Sci. **50**(8), 1015–1034 (2007). https://doi.org/10.1177/0002764207299351

M. Friedman, *Essays in Positive Economics* (University of Chicago Press, Chicago, 1953). https://doi.org/10.2307/2551326

F.W. Geels, Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Res. Policy **31**(8–9), 1257–1274 (2002). https://doi.org/10.1016/S0048-7333(02)00062-8

F.W. Geels, The dynamics of transitions in socio-technical systems. Tech. Anal. Strat. Manag. **17**(4), 445–476 (2005)

F.W. Geels, Co-evolutionary and multi-level dynamics in transitions: The transformation of aviation systems and the shift from propeller to turbojet (1930–1970). Technovation **26**(9), 999–1016 (2006). https://doi.org/10.1016/j.technovation.2005.08.010

F.W. Geels, Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. Res. Policy **39**(4), 495–510 (2010). https://doi.org/10.1016/j.respol.2010.01.022

F.W. Geels, Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the multi-level perspective. Energy Res. Soc. Sci. **37**, 224–231 (2018). https://doi.org/10.1016/j.erss.2017.10.010

M. Granovetter, Economic action and social structure: The problem of embeddedness. Am. J. Sociol. **91**(3), 481–510 (1985)

P.R. Krugman, *A Few Notes on my Magazine Article: The Conscience of a Liberal* (New York Times, New York, 2009)

F. Malerba, R.R. Nelson, L. Orsenigo, S.G. Winter, *Innovation and the Evolution of Industries: History-Friendly Models* (Cambridge University Press, Cambridge, UK, 2016)

M.B. Miles, A.M. Huberman, Within-case displays: Explaining and predicting, in *Qualitative Data Analysis: An Expanded Sourcebook*, 2nd edn., (Sage, Thousand Oaks, 1994), pp. 143–171

L.B. Mohr, Approaches to explanation: Variance theory and process theory, in *Explaining Organizational Behavior*, (Jossey-Bass, San Francisco, 1982), pp. 35–70

National Academy of Sciences Engineering and Medicine, *Achieving Science With CubeSats: Thinking Inside the Box* (The National Academies Press, Washington, DC, 2016). https://doi.org/10.17226/23503

R.R. Nelson, S. Winter, *An Evolutionary Theory of Economic Change* (Harvard University Press, Cambridge, MA, 1982)

M.D. Packard, B.B. Clark, On the mitigability of uncertainty and the choice between predictive and non-predictive strategy. Acad. Manag. Rev. (2019). https://doi.org/10.5465/amr.2018.0198

T. Parsons, *Structure and Process in Modern Societies* (Free Press, Glencoe, 1960)

T. Parsons, N.J. Smelser, *Economy and Society: A Study in the Integration of Economic and Social Theory* (Routledge & Kegan Paul, New York, 1956)

M.S. Poole, A.H. Van de Ven, K. Dooley, M.E. Holmes, *Organizational Change and Innovation Processes: Theory and Methods for Research* (Oxford University Press, New York, 2000)

N. J. Smelser, R. Swedberg (eds.), *The Handbook of Economic Sociology*, 2nd edn. (Princeton University Press, Princeton/Oxford, 2005)

A.H. Van de Ven, *Engaged Scholarship: A Guide for Organizational and Social Research* (Oxford University Press, New York, 2007)

A.H. Van de Ven, R.B. Garud, A framework for understanding the emergence of new industries, in *Research on Technological Innovation, Management and Policy*, vol. 4, (JAI Press, Greenwich, 1989), pp. 195–225

A.H. Van de Ven, M.S. Poole, Methods for studying innovation development in the Minnesota innovation research program. Organ. Sci. **1**(3), 313–335 (1990). https://doi.org/10.1287/orsc.1.3.313

A.H. Van de Ven, M.S. Poole, An introduction to the Minnesota innovation research program, in *Research on the Management of Innovation: The Minnesota Studies*, ed. by A. H. Van de Ven, H. L. Angle, M. S. Poole, (Oxford University Press on Demand, New York, 2000), pp. 3–30

H. Van Driel, J. Schot, Radical innovation as a multilevel process. Technol. Cult. **46**(1), 51–76 (2005)

L. Von Mises, *Human Action: A Treatise on Economics* (H. Regnery Company, Chicago, 1949)

Radio-Frequency Geo-location and Small Satellite Constellations

Joseph N. Pelton

Contents

Abstract

The worldwide responsibility for the allocation of radio frequencies and the coordination of their use is assigned to the International Telecommunication Union (ITU), headquartered in Geneva, Switzerland. The ITU plenary assembly known as the World Radiocommunication Conference meets every few years and agrees on the global radio-frequency allocations to be used globally. The spectrum allocations are divided into three regions globally as follows: region 1, Europe and Africa; region 2, the Americas; and region 3, Asia and Australasia. The usage for radio-frequency spectra has grown enormously in recent years for terrestrial wireless usage (i.e., the of 5G broadband cellular services, emergency and first responder services, law enforcement and defense-related applications, radio and television broadcasting, non-licensed industrial and scientific usage, and microwave relay). There has been parallel growth of non-terrestrial uses such as for aviation communications and safety, high-altitude platform systems and UAVs, plus satellites of various types. The complexity of the global frequency a

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_46

allocation tables has increased enormously as well as the problem of frequency interference and jamming.

More and more types of shared usages have emerged, and higher and higher frequencies in the electromagnetic spectrum have been allocated to these many and growing applications. As this increase in usage and types of applications has emerged, there has been growing concerns and difficulties of unintended and intended interference, jamming, and disagreements between nations and other groups and commercial interests about how to coordinate spectrum use. There are increasingly challenging discussions globally about the best processes related to frequency allocations, frequency allotments, and frequency assignments (or national licensing practices). Terrestrial systems for monitoring the usage of radio-frequency spectra are increasingly inadequate to the task of accurately and precisely determining the nature and exact location this usage. Further the deployment of a significant number of new small satellite constellations will likely increase the problem of monitoring of spectrum use and interference in coming years.

It has been decided that one way to monitor radio-frequency spectrum use much more effectively on a global scale is the deployment of satellites that can consistently monitor frequency use around the world and also identify spectrum that is not being used or underutilized in various parts of the world. The first such satellite-based commercial system to seek to provide comprehensive and near real-time monitoring of frequency use – or misuse – on a global scale is the small satellite constellation known as Hawkeye 360. This low Earth orbit satellite constellation and its types of service offerings are described below. This chapter reports on the issue of increasing need for global frequency use and monitoring and the latest efforts to monitor spectrum usage using satellite networks designed and operated for this purpose.

The Hawkeye 360 system and its intended special ability to deliver actionable data to national administrations, commercial interests, and perhaps even defense-related interests around the world on a near real-time basis are also discussed. This rapid delivery of monitoring results is to be accomplished by making arrangements with new commercial data relay constellations designed to provide near real-time information to ground stations deployed around the world that can then connect to users of this data. This arrangement avoids the need to wait to download results until the LEO-based satellite is over a particular accessible ground antenna system.

This type of commercially based frequency monitoring service, of course, could be performed by other entities in the future, but currently the Hawkeye 360 is uniquely providing this type of service on a commercial basis. Currently the greatest problem of frequency interference and jamming typically occurs with regard to terrestrial radio and television broadcasts and other types of interference and jamming problems near the ground. Nevertheless the deployment of more and more satellites, high-altitude platforms, and the use of space planes and hypersonic transportation will increasingly bring these problems to near-space

(i.e., Protospace) and outer space. There is increasing concern about the issue of space debris; congestion of Earth orbits, especially low Earth orbit; and space traffic management or space traffic control. The problem often focuses on the issue of physical collisions, but frequency interference or jamming or cyberattack could also lead to accidents in space and the disabling of satellites or lead to physical collisions. Thus frequency monitoring and control in space are also going to be increasingly important as these future trends develop.

Keywords

Audacy satellite constellation · Cyber security · Deep Space Industries · Frequency interference · Frequency monitoring · Hawkeye 360 satellite constellation · GomSpace · International Telecommunication Union (ITU) · Jamming · Radio frequency (RF) · Space Flight Laboratories · Space traffic control · Spectrum allocation · Spectrum allotment · Spectrum assignment · Theia · University of Toronto

1 Introduction

The pattern of increase in the use of the electromagnetic spectrum can be revealed in the way that the spectrum bands, and the naming for frequency bands, has taken place as we have moved up and up the spectrum to higher and higher frequencies. We have today the following names for frequency bands as we move to higher and higher frequency. The range of frequencies that is characterized as ultrahigh frequencies (UHF) is 100 times lower than what we now call extremely high frequencies (EHF). In a linguistic sense, this makes no sense. When we first started to use the ultrahigh frequencies, there was not the technology or the imagined possible use or need for possible exploitation of the extremely high frequencies that are now being used by satellite communications and many other purposes.

High frequency (HF): 3–30 MHz
Very high frequency (VHF): 30–300 MHz
Ultrahigh frequency (UHF): 300–3000 MHz
Super high frequency (SHF): 3–30 GHz
Extremely high frequency (EHF): 30–300 GHz

In the nineteenth, twentieth, and now twenty-first century, we have gone from just the telegraph to the television, to the radio, to television, to direct broadcast satellite television, to the Internet, to 5G broadband cellular and streaming services and the Internet of Everything services. We have gone from no satellites to over 20,000 television channels distributed or broadcast via satellite, to perhaps as many as 20,000 satellites in operation in Earth orbit by 2030. Our ability to monitor, regulate, and control the use of the electromagnetic spectrum around the world has fallen behind our technological ability to use EM spectrum more and more intensively. Indeed our call for more and more usage associated with 5G broadband cellular, corporate enterprise networks, Instagram posts, and television streaming services is accelerating every day. The ability to keep up with the regulation and control such runaway growth in spectrum usage is lagging behind.

The process of frequency monitoring and control is the responsibility of individual nations within their own borders. The ITU has a process of coordination with respect to systems that operated internationally. In the case of satellite systems, the national administration that is a member of the ITU submits a filing that is then published by the ITU so that all of its members have the chance to determine if there is potential frequency interference. Nations are invited to seek a means to limit, minimize, or eliminate interference on their own. If this process is not successful, then ITU officials seek to oversee a process to reach agreement on an interference mitigation plan. In some cases this can be quite complex. In the case of the Iridium mobile satellite system, for instance, there is a coordinated interference reduction plan first worked out in 1998 whereby the Iridium system cells go electronically silent when passing over radio telescope facilities. And unfortunately Iridium did not fully comply with the “recommended” interference reduction plan. Since this was only part of the ITU-R recommended noise reduction plan without any enforcement mechanism, this is now an ongoing problem. This interference reduction in the case of radio astronomy facilities all over the world is a particularly challenging assignment today. Such a geographic dependent cessation of satellite transmissions is quite difficult to achieve, particularly in the extended area represented by the National Radio Astronomy Observatory’s Very Large Array in New Mexico. Today the range of difficulties involved with reduction of interference to radio astronomy facilities around the world just keeps expanding (Kimbrough 2019).

The deployment of perhaps 20,000 small satellites in low and medium Earth orbit satellites will thus make the problem of frequency coordination increasingly difficult. This is not only for LEO and MEO satellite but for GEO satellites which will be potentially subject to interference as LEO and MEO systems pass through the geostationary orbit arc. Thus the deployment of satellite systems like the Hawkeye 360 frequency monitoring satellite constellation can become an extremely important tool that can be used by national frequency management offices as well as regional bodies and the ITU to detect the sources of interference and improved spectrum management capabilities.

Even so, the challenges remain quite large and difficult to implement and enforce. The great bulk of frequency management and interference reduction responsibility falls to the many national governments around the world that are charged with this responsibility. The technical capabilities to detect and pinpoint the source of frequency interference and to have the resources to manage and enforce laws and regulations in this area vary enormously around the world. Even those countries with the technical means to detect interference and to enforce local laws and resources do not always have the enforcement personnel to address these issues in the timely and urgent manner that is desirable.

Table 1 Recommended scope of frameworks for national frequency plans (ITU-R guidelines for national frequency plans)

Frameworks: Telecommunication act of the country
Should give explicit reference chapters and articles about spectrum utilization
Should establish independent responsible authority for spectrum management
Should recognize key functions of responsible authority for spectrum management
Should consolidate radio licensing regime
Should equip spectrum management authority with powerful regulations to supervise spectrum utilization
Should recognize international nature and harmonized usage of spectrum

2 Basic Concepts of Frequency Allocation and Interference Reduction

The ITU has developed a sort of primer for how each country should oversee and organize radio-frequency spectrum management within its own territory. These guidelines for a regulatory framework are indicated below in Table 1 (ITU Frequency Allocation Table Training n.d.).

The ITU, in these essential briefing materials, recommends that in addition to the global frequency allocation table, each country should develop its own frequency allocation table and that it be structured as provided in Chart 1 (ITU Frequency Allocation Table Training S n.d.).

3 Hawkeye 360 Constellation

The first in a series of small satellites to carry out frequency usage mapping and analytics has now been launched and shown to be fully function. The Falcon 9 launch of the 'trio' of Hawkeye 360 satellites was accomplished on December 3, 2018 with precision and placed in the desired orbit. This system is thus now checked out and functional in its so-called Pathfinder phase (see Fig. 1).

Hawkeye 360's objective is to continue to launch at least six clusters of three satellites to create a fully functional global network. Beyond this 18-satellite network, the ultimate design is to deploy 30 satellites (in clusters of 3 with 10 clusters of 3) in orbit. The 18-satellite constellation would allow for rapid revisit coverage with a goal for rapid revisit coverage. When the full constellation of 30 small satellites is deployed, the rapidity of updated service is planned to drop down every 10–20 min. The first "trio" of these satellites is known as RFGEO. These three satellites were designed and manufactured by Space Flight Laboratories (SFL) of the University of Toronto, in cooperation with Deep Space Industries and Hawkeye 360. Hawkeye 360, in light of the success of the initial "trio," has contracted to build a second trio of these Hawkeye 360 satellites that are to be launched as soon as can be scheduled

Chart 1 Elements of frequency allocation table (FAT)

Frequency band classification
Exclusive bands
Shared bands
Receive-only bands (Radio Regulations footnote 5.340)
License-free bands (not by ITU decision)
Radiocommunication services
40 radiocommunication services are defined in Radio Regulations Article 1
About 30 radiocommunication services appear in FAT
More services could be defined by regulators
Radiocommunication service category
Primary
Secondary
Tertiary
Noninterference

Fig. 1 A Hawkeye 360 Pathfinder satellites – one of the RFGEO satellites shown in orbit. (Graphic courtesy of Hawkeye 360)

after they are complete and certified for launch (https://www.spaceitbridge.com/hawkeye-360-launches-commercial-rf-signal-mapping-from-space.htm).

These satellites are to be followed by the building and deployment of an augmented design of a dozen more satellites to complete a network of 18 satellites in the constellation. With the success of this deployment of a global constellation consisting of 6 “trios” of satellites, then the complete constellation of 30 satellites will subsequently be deployed assuming there is sufficient commercial demand for these services that are for the first time being offered as a commercial service..

The mission objectives for the Hawkeye 360 constellation have been clearly stated as follows:

> Space-based detection of RF signals allows HawkEye 360 to locate and characterize difficult-to-visualize wireless spectrum information in a more accurate and efficient

> manner when compared to terrestrial detection and image analysis. By taking RF data and turning it into information, HawkEye 360 will be able to give commercial enterprises and governments better knowledge to make critical decisions. (Microsatellites: Hawkeye 360 Pathfinder 2014)

One of the key milestones in the evolving Hawkeye 360 program came with the decision to award the contract for designing and building the platforms for the first three of their RF geo-location satellites to the University of Toronto Institute of Aerospace Analysis and the Space Flight Laboratory (SFL) in partnership with Deep Space Industries. The SFI team in partnership with Deep Space Industries (DSI) had established a track record by using their 15 kg small satellite design known as NEMO. This resulted in the successful 2014 two satellite formation experiment known as CanX-4/CanX-5 mission that was funded by the Canadian government.

Hawkeye 360 was seeking a low-cost small satellite platform that could fly in close but highly accurate formation so that through a triangulation process, the exact geo-location of radio-frequency emissions could be very accurately pinpointed. The precursor CANX-4/CANX-5 was a highly close fit to the needs for their intended RF geo-location satellite project. The facts that these satellites could be rapidly designed and built and their construction costs were considered quite reasonable were added incentives. Thus Deep Space Industries were selected for the precision propulsion system, and SFL was selected to build the small satellite bus (Ibid.).

In order for the triangulation to be calculated with sufficient accuracy, the relative position of the three satellites each had to be located with exact precision in space relative to each other. As SFL and DSI have indicated, their design was based on the following four critical attributes:

- Compact inter-satellite communication link developed by SFL to share data in real time
- High-performance attitude control system also developed by SFL to maintain precise small satellite pointing
- High-efficiency Comet-1 propulsion system developed by Deep Space Industries (DSI)

The initial “trio” of small satellites were launched in December 2018, and their performance checked out with sufficient accuracy that the follow-on contract for three more pathfinder satellites were placed with UTIAS-SFL and Deep Space Industries in March 2019.

The search is now on by Hawkeye 360 to find government, corporate, and defense agency customers that believe that this new system will be able to provide RF geo-location information and usage data (or abusive data) that is not possible with terrestrial detection methods – or at least not available with sufficient precision. Primary applications are now thought to be in the communications, broadcasting, transportation, and data analysis markets as well as to assist governments with their regulatory oversight. Other key applications could be to assist with the emergency rescue signals associated with downed aircraft, ship wrecks, mountain climbers and wilderness trekkers, or other lost individuals. The completely global geo-location capability across a wide range of frequencies is currently a quite unique capability, even though others might be able to pursue these RF geo-location techniques since this is not a technologically unique set of technologies (https://www.utias-ISF.net).

The final member of the technical team beyond Hawkeye 360, Deep Space Industries, and Space Flight Laboratories is GomSpace of Denmark. This NewSpace company is arranging the ground segment for the receipt of the signals from the low Earth orbit satellites. This too is a complex undertaking. In this instance the relativistic speeds of the orbiting spacecraft have to be taken into consideration to ensure the accuracy of the geo-location determinations, just as must be done with the GNSS position determinations (News n.d.).

4 The Global RF Geo-location Market

The commercial satellite application market is today widely established. The satellite communications and remote sensing servicing markets are well established and represent a $100 billion dollars a year in revenues. The current small satellite constellations are seeking to “extend” those markets. In the case of the small satellite systems for telecommunications, the thrust is toward extending the networking and Internet access capabilities in unserved regions of the world. There is also the additional objective of extending networking capabilities for corporate enterprise networks and to support 5G broadband Internet services. In the case of remote sensing system, there has been a focus on so-called analytics and the more rapid updating of strategic information that is partially enabled by lower capital and operating costs and quicker turnaround of analytical data.

The entirely new field of RF geo-location analytics is, in effect, a totally new enterprise that requires a new market development strategy. The dilemma that this market presents is that it is, at once, a giant new opportunity in so many different areas and because it is a totally new way of using satellite applications that those who might use these services will need to learn how to use them for the first time.

The strategy that Hawkeye 360 is using has a certain well-conceived logic to it. First it is deploying the network on a gradual basis and doing so with cost-effective satellite manufacturing and launch deployment services to limit their operating costs as a customer base is established. Secondly it has identified a number of key service areas where their RF geo-location services can best be strategically provided and seeking contracts in each of those areas.

Already Hawkeye 360 has contracted with the Government of New Zealand to use data provided from the Hawkeye 360 for radio use regulation and to support law enforcement activities. Assuming this activity in New Zealand is a success, then marketing this service to other governments will proceed with much great success. Other initial target areas are in the areas of sea transportation to monitor suspicious activities at sea such as pirate operations, drug smuggling, coast guard enforcement, etc.; land transportation to route long-distance bus or trucking operations more efficiently; and air transportation for air safety for planes, helicopters, drones, and autonomous vehicles.

One of the most obvious areas is to provide support to broadcasters of radio and television that are often subject to intentional and unintentional interference and jamming. This applies not only to terrestrial over-the-air broadcasters and to satellite systems providing either radio or television distribution or direct broadcasting. Currently the ITU process for overseeing the usage of RF spectrum on a global basis is highly decentralized with local authority for oversight being placed with the national government to administer their national RF allocation, allotment, and licensed assignment of frequencies to users within their country. This means that if the government in question has officially or unofficially sanctioned jamming of unwanted radio or television transmission, whether from terrestrial or satellite sources, there is no enforcement processes left open to the International Telecommunication Union. At this state of international development, only the World Trade Organization has the ability to place sanctions against national governments, including the right to impose fines. Thus RF geo-location satellite networks can more clearly identify infractions, but they do not offer a regulatory solution if national governments choose not to cooperate or are the source of the jamming operations themselves.

Another interesting area of possible application of new RF geo-location services might well be in the area of “crimes against humanity.” Already remote sensing satellites have been used in documentary evidence as to when villages have been burned or other acts of war or violence have taken place. The use of radio communications by those committing acts of terror or genocide might prove to be even more important tools to document horrendous acts of violence. The business model for how RF geo-location systems are used by governments is yet to be clarified. Will governments make an umbrella agreement for all types of applications? Such usages might be for such areas as RF spectrum interference detection and illegal use enforcement, national defense applications, criminal investigations and gathering of judicial evidence, drug enforcement, smuggling, etc. In theory there could be separate agreements with different types of governmental agencies and perhaps even at the national, state, regional, or local levels of government. Initially it seems likely that there will be umbrella agreements by national governments to receive all data for their country for all types of governmental functions and all levels of jurisdiction. In time these agreements may become more tailored. Such agreements would apply to governmental functions and not exclude other commercial applications in that country.

Another interesting application is for rescue operations. The cost of operations of various units around the world to detect emergency distress and indications of a plane crash or shipwreck is quite high. There are units installed on ships and aircraft known as emergency position-indicating radio beacon station (EPRIRBS) that are activated as emergency occurs. Today over 90% of the alerts are false alarms, yet a number of regional stations are staffed 24 h a day, 7 days a week to detect such alarms. It might be possible that RF geo-location satellites could largely automate such a system globally. This is but one of the many ways that such systems might be used to respond to emergencies and natural and man-made disasters. They could also be used to locate missing hikers or adventurers around the world or respond to a new type of global alarm system based on a newly designated alarm frequency. Again the issue of how such services fit into a commercial model of operation arises. These are just some of the many issues that arise with such a new global capability. When the laser was invented, its uses and utility were seen in a very narrow range of possibilities. Today there are many thousands of applications that were never dreamed of at the time. The same may prove true of the RF geo-location-type satellite. It may be in several decades there may be hundreds of applications developed that will prove to be of enormous importance to public safety, law enforcement, national defense, transportation, communications, health care, education, and a wide range of commerce.

One area that may develop as a particularly important new application could be in the area of cybersecurity. This may relate to aircraft and ground auto, bus, trucking, or train transportation safety. There is mounting concern on cyberattacks as there is more and more use of artificial intelligence in self-driving transport systems, in aircraft guidance and control systems, and in vital urban infrastructure, as well as in Internet of Things feedback systems. In this global environment, there may well be spurious commands and cyberattacks on these systems. These might come from terrorist and criminal organizations, and in some cases they might use identifiable RF-based attack frequencies. Thus, there may well be important opportunity to use space-based RF geo-location systems to identify the source of such criminal and terrorist cyberattacks and also, just as importantly, to provide proof of the origin of these assaults (Pellton and Singh 2018).

What is particularly compelling and interesting about the Hawkeye 360 small satellite enterprise is that all of the participants in this totally new service are a part of what is called the NewSpace industries or the Space 2.0 industries. Most of these companies are true start-ups or were truly so just a few years ago. Hawkeye 360 was organized in 2013–2014. Other Partners such as Deep Space Industries, Space Flight Industries of Canada, GOM Space, and even SpaceX the launching organization are all new enterprises. None of these organizations have a kinship to the long-established aerospace companies that grew out of the long-term military industrial complex that dates back to the World War eras. None of these enterprises bear any resemblance to the Lockheed Martin, Boeing Aerospace, or Northrop Grumman stalwarts of the traditional aerospace entities.

The remarkable thing about the new Hawkeye 360 small satellite system is not only what these RRF geo-location devices can do but that the spacecraft are only 15 kg in mass and that three of the initial “trio” launched in December 2018 were essentially an ancillary aspect of the overall Falcon 9 launch.

The remarkable technical and nuanced design of the The quite unsual thing about the Hawkeye 360 satellites are their nuanced and ‘sophisticated’ design that can provide a precise geolocation for a huge range of frequency spectrum uses on a global basis. Further, these are not two ton satellites that required 4 or 5 years to design and build. Rather they were designed, constructed, flight qualified, and launched within an 18 month schedule. If Hawkeye 360 is able to deploy its full

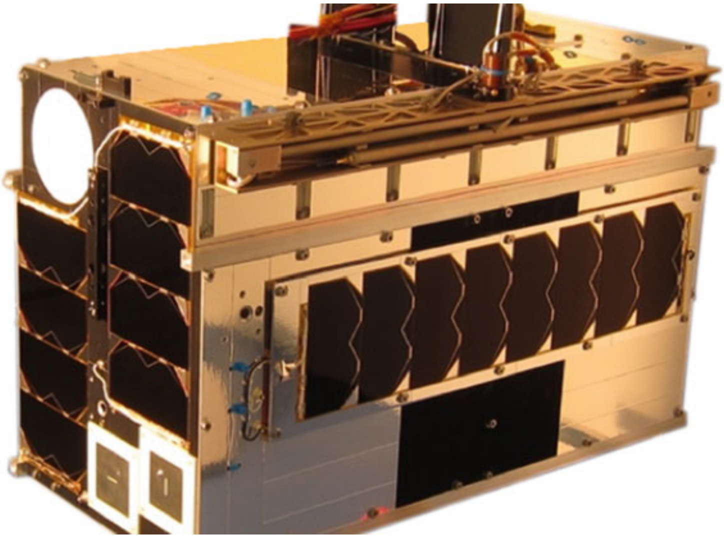


Fig. 2 Close-up of the Hawkeye 360 spacecraft. (Graphic courtesy of Space Flight Laboratories)

network and find sufficient customers to create a paying commercial and governmental group of customers, it will not only be a testament to finding and exploiting an entirely new market, but it will also be based on finding the right new technology and small satellite ingenuity to design, build, and launch this capability in a small satellite with a mass of only 15 kg (see Fig. 2).

5 The Hawkeye 360 System's Desire to Provide Rapid Data Distribution

Jamming, as well as various forms of RF interference, is something that service providers want to respond to with a sense of great urgency. In many cases such as broadcasting or most telecommunications services or downloads of remote sensing or Earth observation data, disruption of service can result in loss of revenues or even discontinuation of service and permanent loss of customers.

One possibility would be to make an arrangement for a commercial relay of the data from the "trios" of Hawkeye 360 satellite so that there could be a near real-time download of the day. This approach has the advantage of not necessarily making landing licensing arrangements with the countries where the data would be downloaded and be able to provide data for analysis by customers on a much more rapid basis.

One option that has been considered is the signing up with the new Audacy data relay satellite network for instant download of acquired frequency use data. This network is designed to download data instantly to ground stations located strategically around the globe. This system was conceived as being able to provide data relay service at a variety of data speeds from medium to quite broadband rates. Thus such a data relay system can support many types of satellite applications including remote sensing and analytics, frequency monitoring (i.e., RF geo-location), IoT services, meteorological services, or in fact any satellite services company that needs to move data on a near real-time basis. Increasingly there will be a need by many satellite operators to avoid storing data that can be downloaded only when passing over a suitably located ground station (https://www.spaceitbridge.com/new-space-startups-hawkeye-360-audacy-turn-up-partner-programs.htm). These arrangements, of course, will depend on Audacy being able to complete their financing and the full deployment of their proposed commercial data network. It remains a challenge for such a start-up venture to create a sufficient revenue stream to support the substantial capital investment that this network will require. Other arrangements might be made with other systems that can provide satellite data relay services.

6 Conclusions

The field of satellite applications has for quite a few years focused on three primary areas. These are satellite communications, remote sensing/Earth observation/meteorological satellites, and global navigational satellite services (GNSS) or precise navigation and timing (PNT) services. These are now well-established fields of satellite applications, and their commercially related services generate over $125 billion (US) in revenues. The new cost-efficiencies of small satellite constellations are now leading to new satellite applications that generate commercial revenues in new sectors.

One of the more promising new areas is that of RF geo-location services that is being pioneered by the Hawkeye 360 company that has partnered with the University of Toronto Space Flight Laboratories, Deep Space Industries, and GomSpace to create a new small satellite constellation that is expected to grow ultimately to a network of 30 15 kg small satellites configured into 10 “trios” or 3-each satellite clusters. Each three-satellite cluster is to be precisely configured together so that triangulation measurement processes can detect the geo-location of radio-frequency emissions over a wide range of frequencies. The application of this new type of satellite sensing capability is expected to give rise to a wide range of new commercial services and revenues.

The Hawkeye 360 constellation has determined that a particular value-added capability will be critical to its ability to sell its RF geo-location data much more effectively if its data can be provided to its commercial customers in as close to “near real time” as possible. Thus it has made pending arrangements with the Audacy commercial data relay system – positioned in a 14,000 km MEO orbit – to instantly download its data via this system to a worldwide system of three antennas established by GomSpace so that the data can be fed to its commercial users on a global basis as quickly as possible.

This new and currently unique commercial satellite service that is augmented by the Audacy instantaneous download capability makes this Hawkeye 360 network unique in the service capability that it provides. Today Hawkeye 360 is in the early stages of deploying its 18-satellite constellation of 6 “trios” of triangulating satellites. It is just beginning to operate globally and establish a number of commercial customers that are seeking a wide range of RF usage information. If this system of RF geo-location satellite services is commercially successful, it is likely that there will be other satellite systems that seek to offer competitive commercial services that are alike in their capabilities – including a near-instantaneous download service of RF usage with designation of exact location.

Satellite-based data relay systems that relay data have been around for some four decades starting with the NASA Tracking and Data Relay Satellite System (TDRSS) and then followed by the European Space Agency (ESA) and JAXA. Today commercially based data relay systems such as Audacy, Theia, and other such data relay and data services companies are starting to develop that are intended to operate as commercial enterprises rather than as governmental space agency operations.

7 Cross-References

- ▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas
- ▶ Messaging, Internet of Things, and Positioning Determination Services via Small Satellite Constellations
- ▶ Mobile Satellite Communications and Small Satellites
- ▶ Remote Sensing Applications and Innovations via Small Satellite Constellations
- ▶ Small Satellite Constellations Versus Geosynchronous Satellites for Fixed Satellite Services and Network Services
- ▶ Smallsats, Hosted Payload, Aircraft Safety, and ADS-B Navigation Services

References

ITU Frequency Allocation Table Training, Chart 5, (n.d.) https://www.itu.int/ITU-D/tech/OLD_TND_WEBSITE/spectrum-management_OLD/SMS4DC_AFR/Training%20Materials/SMS4DC_AFR_TM_4.PDF. Last accessed 1 June 2019

ITU Frequency Allocation Table Training S, Chart 2, (n.d.) https://www.itu.int/ITU-D/tech/OLD_TND_WEBSITE/spectrummanagement_OLD/SMS4DC_AFR/Training%20Materials/SMS4DC_AFR_TM_4.PDF. Last accessed 1 June 2019

A. Kimbrough, Satellite constellations and radio astronom, The Space Review, (2019) http://www.thespacereview.com/article/3702/1

Microsatellites: Hawkeye 360 Pathfinder, (2014) HawkEye 360 selects deep space industries to manufacture pathfinder small satellites. Accessed 1 June 2019 https://www.he360.com/hawkeye-360-selects-deep-space-industries-to-manufacture-pathfinder-small-satellites/

News, HE360.com (n.d.) Last accessed 14 June 2019

J. Pellton, I. Singh, *Smart Cities for Today and Tomorrow* (Springer, Switzerland, 2018)

Part IX

Defense- and Security-Related Services

Security Concerns Related to Smallsats, Space Situational Awareness (SSA), and Space Traffic Management (STM)

Joseph N. Pelton

Contents

Abstract

The strategic uses of outer space are today quite diverse and continue to grow in scope (i.e., diversity of defense-related applications) and scale (i.e., size of operations and funded activities).

These strategic activities in space include: (i) tracking capabilities on the ground and by satellite of all trackable space objects in Earth orbit and the ability to track all new launches into space including missiles (i.e., space situational awareness capabilities); (ii) deployment and operation of space precise navigation and timing systems that can be used for targeting and deployment of weapons systems as well as space communications and meteorological systems to meet national defense operations; (iii) deploying and operation of space systems that can detect explosion of nuclear weapons systems; (iv) procedures, limitations, and operational standards

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_47

related to rendezvous and proximity operations (RPO) and protections against attacks on strategic assets in orbit; and (v) conducting research on new space systems and technology of possible use in future defense-related systems such as on-orbit servicing, space debris removal or repurposing, lower cost launching systems, new data monitoring capabilities and facility optimization and inventory operations via satellite-IoT messaging, etc.

Many of these space systems and technology involve the deployment and use of what might be considered conventional space systems, but in a number of instances, this might also require the development of small satellite constellations, the use of hosted payloads, or concerns about orbital debris that could result from small satellite constellations. Such requirements are components of space security planning and implementation processes. This chapter, in particular, explores the issues of security-related space situational awareness as well as planning for future space traffic management systems, particularly as this relates to small satellite systems and in some cases hosted payload systems.

Today, many countries around the world with active space programs and space security activities are concerned with improved space situational awareness activities and are planning for future space traffic management systems. There are activities in these areas underway in China, Europe, India, Japan, Russia, as well as several other countries with evolving space programs. Nevertheless, for several historical reasons such as the United States' major role in conducting space situational awareness operations and sharing this data with allies, this is an area where the United States' activities have largely dominated, particularly since the end of the so-called "Cold War."

This situation has been further shaped by the 2018 activities of the United States to issue publicly the U.S. Space Policy Directive-3. This is not to say that there have not been increasing activities being planned or implemented in such areas as noted above. Further, the UN Committee on the Peaceful Uses of Outer Space has had an active Working Group on the Long-Term Sustainability of Outer Space Activities (LTSOSA) that developed and received approval of 21 new guidelines that in a number of instances touch on areas related to space situational awareness (SSA) and issues that concern space traffic management (STM).

This chapter seeks to address current concerns that come from the deployment of many new large-scale satellite constellations in Low Earth Orbit (LEO) and polar orbit and how these changes will impact the need for improved space situational awareness (SSA) capabilities and enhanced means of space traffic management (STM) in the years ahead. It notes the ways that commercial satellite systems and governmental and security-related satellite networks are interrelated and how this might complicate the way forward to safe space operations and could also lead to heightened concerns with orbital space debris.

Keywords

Joint Space Operations Center (JSpOC) · Liability convention · Low Earth Orbit (LEO) · On-orbit servicing · Satellite conjunctions · Space and Atmospheric Burst Reporting System (SABRS) · S-band Space Fence · Space data association · Space situational awareness · Space traffic management · UN Committee on the Peaceful Uses of Outer Space (COPUOS) · U.S. Space Policy Directive-3

1 Introduction

During the cold war era where the rivalry between the United States and the USSR was at its highest levels, there was concern about a possible nuclear attack by intercontinental missiles by these adversaries. There were radar systems installed by both countries to detect missile launches so as to allow an instantaneous counter initiative. This set of countervailing threats created great concern over possible preemptive nuclear attacks. The idea of mutually assured destruction (MAD) was aimed at creating a dynamic strategic balance whereby the opponent would know that any such attack would be followed by an automatic strike on the attacking country and would kill the citizenry of the attacking country in a devastating way (Wohlstetter and Kahn 2010).

Policy strategist Kahn noted that unless the mutual assured destruction was known to in place, then first strike approach by a nuclear power would possibly entertained.

He wrote in *On Thermonuclear War*: “In most postures that do not involve automatic mutual annihilation there will be an advantage in striking first.”(Kahn 1960).

The capability to detect missile launches with radar systems such as the Defense Early Warning (DEW) line have increased in capability and function over time and more and more satellites were launched into orbit and the function known as space situational awareness increased to not only detect possible missile attacks, but also to include the ability to track satellites in orbit, and to allow satellite or space facility to maneuver to avoid collisions. The U.S. Joint Space Operations Center (JSpOC), now a part of the so-called “Space Force”, is today becomes fully functional. This multibillion dollar facility that deploys Gallium Nitride S-band radar technology is operated by the U.S. Air Force. This sophisticated radar system located in the Marshall Islands in Micronesia was built under contract by Lockheed Martin. It will eventually be able to track up to 500,000 orbiting space objects and detect all missile launches with greater precision (Space Fence: How to keep space safe. 2019). (See Fig. 1).

A complementary S-band radar facility that could possibly be built in Australia is also under consideration (Pelton 2013).

The ability to track satellites to support strategic defense systems and to prevent possible collisions of satellites in orbit continues to increase in sophistication and precision. One key development is the creation of the Space Data Association that is a consortium of satellite operators that creates a means of sharing data among satellite operators with regard to possible conjunctions that might occur between various satellite systems. This Space Data Association is currently largely constituted by operators of GEO satellite networks but its membership could be expanded to include operators of small satellite constellations. Also there are a number of

Fig. 1 The S-band Space Fence to provide precision space situational awareness. (Graphic from the Global Commons)

nationally funded initiatives to undertake satellite tracking operations. Optical tracking capabilities are being installed at various locations such as in Germany, Australia, and elsewhere.

Another key development with regard to space situational awareness (SSA) is that a number of private contractors that have started to provide independent tracking capabilities of satellites and space debris. These private contractors include: Analytic Graphics Inc. (AGI), ExoAnalytics, Rincon, Lockheed Martin, LeoLabs, Boeing, Schafer Corp., and Applied Defense. Most of these are radar-based capabilities, but some such as ExoAnalytics are deploying telescopes with individual observers under contract now carrying out tracking operations at many locations around the world (Weeden 2016).

2 Separation of Commercial and Defense-Related Space Situational Awareness and Space Traffic Management Activities

There has been in the last few years increasing concern and discussion about whether there should be a separation of the tasks related to space situational awareness between commercial satellite networks and defense and strategic space operations? This issue that began to first be discussed seriously around 2016 was directly addressed in the United States when the Space Policy Directive-3 was issued. This document provided specific guidance on a number of points but in particular sought to address the respective roles of governmental agencies in providing SSA and STM services in support of commercial space activities versus defense-related missions and missile defense.

Thus Space Policy Directive-3 explicitly stated the need for a change in space policy in light of many new and growing "NewSpace" commercial activities, including the increased launch of small satellite constellations. It noted the problem as follows:

"The future space operating environment will also be shaped by a significant increase in the volume and diversity of commercial activity in space. Emerging commercial ventures such as satellite servicing, debris removal, in-space manufacturing, and tourism, as well as new technologies enabling small satellites and very large constellations of satellites, are increasingly outpacing efforts to develop and implement government policies and processes to address these new activities."(Space policy Directive-3 2018).

The result of this concern was that there should be additional steps taken to achieve a pre-launch certification of all space missions to reduce the possibility of creating additional space debris. It was also stated that a new process to undertake SSA and STM capability with regard to all of this new commercial space activities.

The US Government's Department of Commerce was charged with developing, in cooperation with the U.S. Department of Defense, a new capability to undertake "basic" SSA and STM activities with regard to the growing number of commercial space activities and especially small satellite constellations. The U.S. Department of Defense would continue to monitor space objects and launches and maintain an authoritative catalog of space objects from a national security of perspective. This new US national space traffic management activity and the organizations having responsibility for these space monitoring responsibilities was stated as follows:

(i) "The Secretaries of Defense and Commerce, in coordination with the Secretaries of State and Transportation, the NASA Administrator, and the Director of National Intelligence, should cooperatively develop a plan for providing basic SSA data and basic STM services either directly or through a partnership with industry or academia, consistent with the guidelines of sections 5(a)(ii) and 5(b)(ii) of this memorandum.

(ii) The Secretary of Defense shall maintain the authoritative catalog of space objects." (https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/ Section 6 d (i) and (ii).).

This U.S. Space Police Directive-3 provides a number of guidelines and spells out processes that are to be carried out with regard to SSA and STM under the US space program and its over sight and licensing of commercial satellite activities. It indeed carefully defines the nature and regulatory aspects of these activities from a commercial and defense-related perspective. Since as of 2019 no other nation has undertaken to define such guidelines in such detail, the full text of this Space Policy Directive-3 has been provided as an annex to this chapter.

A further reason as to why the full text has been provided below is because it has also been suggested that these regulatory procedures, as spelled out in the U.S. Space Policy Directive-3, could serve as a blueprint for what other countries might undertake with regard to their space activities in terms of spelling out pre-launch due diligence procedures to be carried out in order to better prevent the creation of space debris. It also better defined the meaning and scope of SSA and STM activities. In essence, it served to anticipate the coming issues related to expanded commercial space activities and the need for more explicit regulatory processes that are likely to be required as various types of commercial space activities, especially in the form of large constellations of small satellites, expand in the future. In short, it served to define what steps need to be taken in order to prevent or minimize the collision of space objectives and also lessen the opportunity for frequency interference (Pelton 2019).

As useful as these new space policies in the arena of SSA and STM, there remain any unresolved and key questions. These questions include:

Do we need new standards of safety operation or space traffic management in order to deploy and operate all of the large-scale satellite constellations in Low Earth orbit more safety? This becomes more and more urgent as the number of satellites and small satellite constellations continues to grow in number. There are now over 20,000 small satellites proposed for deployment, largely in LEO, and there seems to be a critical mass proposed for the altitudes between 700 and 1200 km (Muelhaupt et al. 2019).

There are subsidiary questions such as performance and safety standards for AI controls to network controls to prevent collisions, automatic end of life de-orbit, or other space traffic management regulation to preserve the safety of all constellations. Given that there are currently at total of some 1500 operational satellites in all types of Earth orbits, the changes in density of satellite deployments suggests that there are urgent answers needed to these questions. Some fear that a rash of satellite collisions in LEO orbit could serve to render access to space nearly impossible. Such a runaway build up of space debris would be the ultimate consequences of what is known as the Kessler Syndrome.

3 Hosted Payloads to Provide Space Situational Awareness to Detect Nuclear Explosions

The typical definition of space situational awareness includes all of the ground- and space-based equipment that is used to monitor the location of space objects or launched rockets primarily to detect if a launch represents a threat from a missile or if there is a threat of space objects colliding and creating dangerous orbit space debris. Yet another definition relates to monitoring devices in space that are able to detect a nuclear detonation. Today, there are satellites in orbit designed to detect the possibility of a space collision, but there are also devices designed to detect possible nuclear denotations. They also can monitor the impact of asteroids and meteors in order to more accurately determine the threat level posed by near-Earth objects.

The nuclear detection of detonation sensors are not separate satellites, but rather small hosted payloads (See Fig. 2).

The ability to use space-based sensors that can detect accurately nuclear explosion sensors are considered important both to monitor compliance with the Limited Test Ban Treaty (TBT) and the Threshold Test Ban Treaty (TTBT),

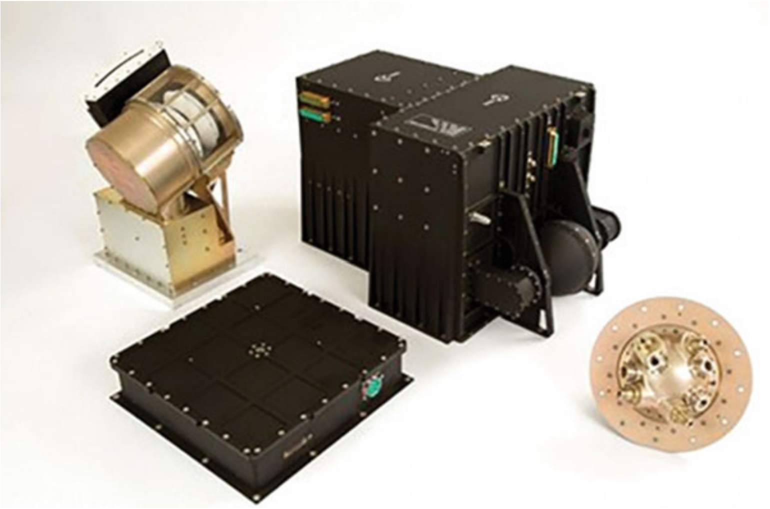


Fig. 2 Components of the hosted payload for space-based nuclear detonation detection. (Graphic courtesy of the U.S. Government)

and simply to detect any nation or entity that might detonate a nuclear device. In the United States, it is the National Nuclear Detection Administration that is housed at the Sandia and Los Alamos National Laboratories that are responsible for the design, manufacture, and testing of sensors to help enforce these test ban treaties. A responsibility that they have carried out for essentially a half century since the first of these treaties came into force. This space based nuclear test ban enforcement was accomplished with the launch of 12 dedicated Vela satellites starting back in 1963. These early satellites could only monitor nuclear test above ground on in space, but the Vela satellites were replaced with sensors located in hosted payloads that could detect nuclear explosions whether below ground, on the surface, or in space. These were launched on-board GPS satellites or other US satellites capable of including these sensors.

The most recently sensors are known as Global Burst Detectors (GBDs) and are primarily deployed as hosted payloads on GPS satellites. This system of on-board sensors are known as Space and Atmospheric Burst Reporting System (SABRS). The second generation of SARRS payloads began to be launched on GPS satellites in 1918 and have continued in 2019. Yet another payload known as SENSER that is intended to increase the performance of future GBD packages is also to be launched shortly. Some of the SBD payloads will be launched on Air Force satellites including the STPSat-6 (National Nuclear Detection Administration 2018).

While the Air Force satellites using to help track orbit space debris are large-scale satellites, the SABRS system is essentially a smallsat program deployed as hosted payloads. Figure 3 is an Air Force satellite that is designed to assist with the precise tracking of orbital space debris.

Fig. 3 Air Force satellite designed to assist with tracking of orbital space debris and missile launches. (Graphic courtesy of the U.S. Air Force)

The concern about the possibility of the launch of some 20,000 satellites being deployed into over a dozen of large-scale constellations is thus the primary small satellite issue by defense agencies and ministries. If projections of possible collisions that might occur both during the deployment or removal of the small satellites in these diverse large constellations, as made by the Aerospace Corporation, suggest that may defense space systems could be placed at risk (Muelhaupt et al., op cit.). Nevertheless, there are a number of possible applications of small satellites for defense-related applications. This thus creates a dilemma in that deployment of small satellites for strategic applications could complicate debris concern. Nevertheless, several different smallsat projects are under consideration.

4 Smallsat Projects by Defense Agencies

These smallsat applications for defense-related purpose range from experimental demonstration of technology for smallsats mission to test sensors for weather satellites for deployment in Low Earth Orbit (LEO), or orbital measurement experiments such as the Armadillo project. This is a three-unit project that was designed to measure the space debris environment in LEO at the submillimeter dust particle level. This project is key to the U.S. military's understanding of the characteristics of

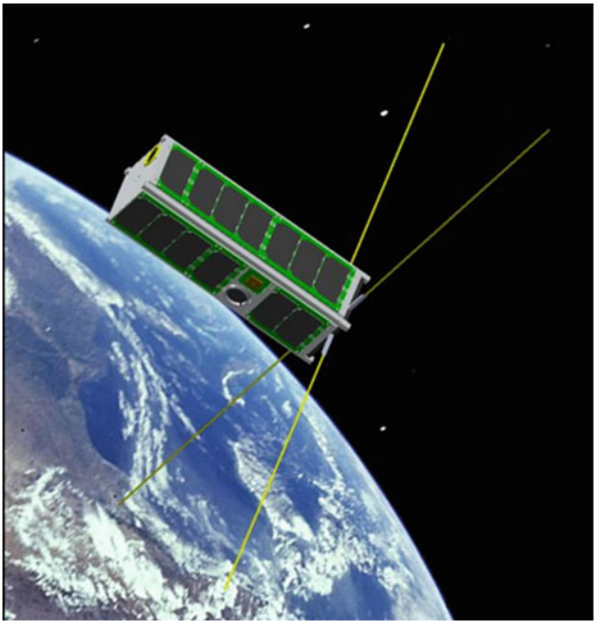


Fig. 4 The Armadillo 3 Unit Cubesat Submillimeter Debris Measurement Project. (Graphic courtesy of the U.S. Air Force)

the space debris at the smallest level and to understand its impact on satellites and to calibrate the SSA environment at the submillimeter debris conditions (Fig. 4).

Several countries had undertaken smallsat projects to test active debris removal experiments to cope with the rising amount of orbital debris, especially in Low Earth Orbit (LEO). These projects have included Switzerland's (Clean SpaceOne), Germany's (DEOS project), U.S. (Darpa's Orbital Express), and U.K./European Union (Remove Debris) (Pelton 2015).

The U.S. Defense Advanced Projects Research Agency (DARPA) completed a study of orbital debris risk known as "The Catcher's Mitt" in 2011 that assessed the risks that orbital debris presented to defense satellite networks. This intensive effort studied the risk level going forward in various orbits as then projected but that profile of the future has now changed and some projections of expected orbital collision such as by the European Space Agency (ESA) now concludes that a major accident will occur every 5 years (See Fig. 5).

It concluded that the space situational awareness and space traffic management, as now being implemented seemed adequate, that the problem of orbital space debris was considered "manageable." This DARPA study also concluded that an viable active debris removal capability that is capable of addressing the most severe risk factors such as the Envisat large-scale satellite stranded in LEO was also needed. The situation assessment, however, was based on the conditions that existed in 2011. Today, the environment has changed and the number of small satellites to be launched has increased exponentially (https://www.space.com/11657-space-junk-orbital-debris-cleanup-darpa.html).

Fig. 5 Simulated collision of a satellite collision in orbit. (Graphic courtesy of the European Space Agency)

There are also operational small satellite constellations also currently deployed such as the Mobile Users Operational Satellite system. This smallsat network provides key mobile satellite services for the U.S. defense network and provides prime mobile services and replaces many of the services that were previously provided by the Iridium and Globalstar system on a dual use basis.

5 Conclusion

The smallsat revolution that has come with new ways of designing and manufacturing satellites faster, at less cost, and new launch options that makes the deployment of LEO constellations much more attractive. This new wave of small satellite constellations has exploited the new capabilities that have come from the use of miniaturized components and use of new launch options.

These trends have led to a sharp rise in the number of smallsats that are planned to be launched in the next 5 years. Further, these networks will need to be resupplied on a time scale as short as 3 years and typically within 5–8 years. Thus there are a huge number of satellites planned to be launched on an intensive launch schedule, and if these networks are successful, this trend will follow into the foreseeable future. This trend seems to portend a strategic issue related to orbital space debris and critical buildup of orbital congestion in the LEO altitudes largely between 700 and 1200 km with a peaking around 900 km.

This future trend line suggests that there is a mounting strategic concern about the adequacy of space situational awareness and preliminary attempts at space traffic management. The UN guidelines for debris removal of deorbiting of space craft within 25 years of end of life no longer seem to be adequate to this new orbital environment. Many operators of small satellite constellations have suggested new guidelines such as removal within 1 year with some commercial operators now even suggesting practices that would remove defunct satellites within days. Defense agencies and ministries as well as commercial system operators are moving in a new direction to better cope with orbital debris issues. This is not only to be “better citizens” in the space domain, but because they understand that unless such steps are taken, the safe operation of constellations, particularly in LEO, will be increasingly at risk for all.

There are thus some conflicting values and interest now in play. On one hand, there are a number of defense-related operations best conducted in LEO. These include such activities as mobile communications satellite networks, meteorological network coverage, and even surveillance systems that have advantages when operated in LEO and polar orbits. On the other hand, it is important that SSA and STM capabilities be improved to cope with possible satellite conjunction that could lead to catastrophic collisions that endanger all future space safety. Billions of dollars of commercial, governmental, and military assets could be placed at risk.

The assessment in 2011 by the U.S. DARPA “Catcher Mitt” study that concluded that space debris concern and safe strategic space operations were “manageable” have seemingly begun to alter to a much higher level of concern. Risk assessment studies by the Aerospace Corporation have shown heightened risk of collisions when large-scale constellations are first deployed and also when removed from orbit. The current provisions of the U.N. Liability Convention does not create incentive to remove debris from orbit quickly.

The one specific step forward to address these increased orbital debris concerns has been the U.S. Space Policy Directive-3 that seeks to increase US capabilities for space situational awareness and to initiate certain enhanced steps for space traffic management. These new initiatives are to improve capabilities for both commercial systems on one side and defense and governmentally related satellite networks on the other.

It seems that other countries, and especially those countries with space security-related programs, will begin to move forward to increase their capabilities and regulatory controls with orbital debris, SSA, and STM-related measures. The French Space Operations Act was intended to be one such step forward, but its enforcement of the 25-year debris removal guideline, now appears somewhat dated in light of the very large number of satellites now planned to be deployed in the next few years.

It currently seems more likely that national laws and guidelines as well as national initiative to increase SSA and STM capabilities will be accomplished first rather than any new international guidelines concerning these issues. The U.N. Guidelines on Debris Removal required over 15 years to be discussed, agreed, and adopted. The new guidelines related to the longer term sustainability of outer space activities that were discussed and agreed within the UN Committee on the Peaceful Uses of Outer Space (COPUOS) were useful, but these remain well short of the needed steps necessary to allow any widely agreed approach toward some sort of international space traffic management system, or even an open world system to carry out effective space situational awareness (SSA) procedures or processes.

Finally, the types of steps outlined in the U.S. Space Policy Directive-3 on National Space Traffic Management Policy, as provided below, may possibly prove helpful to other countries in defining their own priorities and national aims as they amend and strengthen their efforts related to space situational awareness (SSA), space traffic management (STM), and safe strategic access to space and perhaps establish new guidelines for removal of defunct space objects from orbit in a more accelerated manner.

6 Cross-References

- ▶ Small Satellite Constellations: National Security Implications
- ▶ Small Satellites and Planetary Defense Initiatives

Annex

U.S. Space Policy Directive-3, National Space Traffic Management Policy

Adopted June 18, 2018

SUBJECT: National Space Traffic Management Policy

Section 1. Policy. For decades, the United States has effectively reaped the benefits of operating in space to enhance our national security, civil, and commercial sectors. Our society now depends on space technologies and space-based capabilities for communications, navigation, weather forecasting, and much more. Given the significance of space activities, the United States considers the continued unfettered access to and freedom to operate in space of vital interest to advance the security, economic prosperity, and scientific knowledge of the Nation.

Today, space is becoming increasingly congested and contested, and that trend presents challenges for the safety, stability, and sustainability of U.S. space operations. Already, the Department of Defense (DoD) tracks over 20,000 objects in space, and that number will increase dramatically as new, more capable sensors come online and are able to detect smaller objects. DoD publishes a catalog of space objects and makes notifications of potential conjunctions (that is, two or more objects coming together at the same or nearly the same point in time and space). As the number of space objects increases, however, this limited traffic management activity and architecture will become inadequate. At the same time, the contested nature of space is increasing the demand for DoD focus on protecting and defending U.S. space assets and interests.

The future space operating environment will also be shaped by a significant increase in the volume and diversity of commercial activity in space. Emerging commercial ventures such as satellite servicing, debris removal, in-space manufacturing, and tourism, as well as new technologies enabling small satellites and very large constellations of satellites, are increasingly outpacing efforts to develop and implement government policies and processes to address these new activities.

To maintain U.S. leadership in space, we must develop a new approach to space traffic management (STM) that addresses current and future operational risks. This new approach must set priorities for space situational awareness (SSA) and STM innovation in science and technology (S&T), incorporate national security considerations, encourage growth of the U.S. commercial space sector, establish an updated STM architecture, and promote space safety standards and best practices across the international community.

The United States recognizes that spaceflight safety is a global challenge and will continue to encourage safe and responsible behavior in space while emphasizing the need for international transparency and STM data sharing. Through this national policy for STM and other national space strategies and policies, the United States will enhance safety and ensure continued leadership, preeminence, and freedom of action in space.

Sec. 2. Definitions. For the purposes of this memorandum, the following definitions shall apply:

(a) Space Situational Awareness shall mean the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities.
(b) Space Traffic Management shall mean the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.
(c) Orbital debris, or space debris, shall mean any human-made space object orbiting Earth that no longer serves any useful purpose.

Sec. 3. Principles. The United States recognizes, and encourages other nations to recognize, the following principles:

(a) Safety, stability, and operational sustainability are foundational to space activities, including commercial, civil, and national security activities. It is a shared interest and responsibility of all spacefaring nations to create the conditions for a safe, stable, and operationally sustainable space environment.
(b) Timely and actionable SSA data and STM services are essential to space activities. Consistent with national security constraints, basic U.S. Government-derived SSA data and basic STM services should be available free of direct user fees.
(c) Orbital debris presents a growing threat to space operations. Debris mitigation guidelines, standards, and policies should be revised periodically, enforced domestically, and adopted internationally to mitigate the operational effects of orbital debris.
(d) A STM framework consisting of best practices, technical guidelines, safety standards, behavioral norms, pre-launch risk assessments, and on-orbit collision avoidance services is essential to preserve the space operational environment.

Sec. 4. Goals. Consistent with the principles listed in section 3 of this memorandum, the United States should continue to lead the world in creating the conditions for a safe, stable, and operationally sustainable space environment. Toward this end, executive departments and agencies (agencies) shall pursue the following goals as required in section 6 of this memorandum:

(a) Advance SSA and STM Science and Technology. The United States should continue to engage in and enable S&T research and development to support the practical applications of SSA and STM. These activities include improving fundamental knowledge of the space environment, such as the characterization of small debris, advancing the S&T of critical SSA inputs such as observational data, algorithms, and models necessary to improve SSA capabilities, and developing new hardware and software to support data processing and observations.

(b) Mitigate the effect of orbital debris on space activities. The volume and location of orbital debris are growing threats to space activities. It is in the interest of all to minimize new debris and mitigate effects of existing debris. This fact, along with increasing numbers of active satellites, highlights the need to update existing orbital debris mitigation guidelines and practices to enable more efficient and effective compliance, and establish standards that can be adopted internationally. These trends also highlight the need to establish satellite safety design guidelines and best practices.

(c) Encourage and facilitate U.S. commercial leadership in S&T, SSA, and STM. Fostering continued growth and innovation in the U.S. commercial space sector, which includes S&T, SSA, and STM activities, is in the national interest of the United States. To achieve this goal, the U.S. Government should streamline processes and reduce regulatory burdens that could inhibit commercial sector growth and innovation, enabling the U.S. commercial sector to continue to lead the world in STM-related technologies, goods, data, and services on the international market.

(d) Provide U.S. Government-supported basic SSA data and basic STM services to the public. The United States should continue to make available basic SSA data and basic STM services (including conjunction and reentry notifications) free of direct user fees while supporting new opportunities for U.S. commercial and non-profit SSA data and STM services.

(e) Improve SSA data interoperability and enable greater SSA data sharing. SSA data must be timely and accurate. It is in the national interest of the United States to improve SSA data interoperability and enable greater SSA data sharing among all space operators, consistent with national security constraints. The United States should seek to lead the world in the development of improved SSA data standards and information sharing.

(f) Develop STM standards and best practices. As the leader in space, the United States supports the development of operational standards and best practices to promote safe and responsible behavior in space. A critical first step in carrying out that goal is to develop U.S.-led minimum safety standards and best practices to coordinate space traffic. U.S. regulatory agencies should, as appropriate, adopt these standards and best practices in domestic regulatory frameworks and use them to inform and help shape international consensus practices and standards.

(g) Prevent unintentional radio frequency (RF) interference. Growing orbital congestion is increasing the risk to U.S. space assets from unintentional RF interference. The United States should continue to improve policies, processes, and technologies for spectrum use (including allocations and licensing) to address these challenges and ensure appropriate spectrum use for current and future operations.

(h) Improve the U.S. domestic space object registry. Transparency and data sharing are essential to safe, stable, and sustainable space operations. Consistent with national security constraints, the United States should streamline the interagency process to ensure accurate and timely registration submissions to the United Nations (UN), in accordance with our international obligations under the Convention on Registration of Objects Launched into Outer Space.

(i) Develop policies and regulations for future U.S. orbital operations. Increasing congestion in key orbits and maneuver-based missions such as servicing, survey, and assembly will drive the need for policy development for national security, civil, and commercial sector space activities. Consistent with U.S. law and international obligations, the United States should regularly assess existing guidelines for non-government orbital activities, and maintain a timely and responsive regulatory environment for licensing these activities.

Sec. 5. Guidelines. In pursuit of the principles and goals of this policy, agencies should observe the following guidelines:

(a) Managing the Integrity of the Space Operating Environment.
    (i) Improving SSA coverage and accuracy. Timely, accurate, and actionable data are essential for effective SSA and STM. The United States should seek to minimize deficiencies in SSA capability, particularly coverage in regions with limited sensor availability and sensitivity in detection of small debris, through SSA data sharing, the purchase of SSA data, or the provision of new sensors.

New U.S. sensors are expected to reveal a substantially greater volume of debris and improve our understanding of space object size distributions in various regions of space. However, very small debris may not be sufficiently tracked to enable or justify actionable collision avoidance decisions. As a result, close conjunctions and even collisions with unknown objects are possible, and satellite operators often lack sufficient insight to assess their level of risk when making maneuvering decisions. The United States should develop better tracking capabilities, and new means to catalog such debris, and establish a quality threshold for actionable collision avoidance warning to minimize false alarms.

Through both Government and commercial sector S&T investment, the United States should advance concepts and capabilities to improve SSA in support of debris mitigation and collision avoidance decisions.

(ii) Establishing an Open Architecture SSA Data Repository. Accurate and timely tracking of objects orbiting Earth is essential to preserving the safety of space activities for all. Consistent with section 2274 of title 10, United States Code, a basic level of SSA data in the form of the publicly releasable portion of the DoD catalog is and should continue to be provided free of direct user fees. As additional sources of space tracking data become available, the United States has the opportunity to incorporate civil, commercial, international, and other available data to allow users to enhance and refine this service. To facilitate greater data sharing with satellite operators and enable the commercial development of enhanced space safety services, the United States must develop the standards and protocols for creation of an open architecture data repository. The essential features of this repository would include:

- Data integrity measures to ensure data accuracy and availability;
- Data standards to ensure sufficient quality from diverse sources;
- Measures to safeguard proprietary or sensitive data, including national security information;
- The inclusion of satellite owner-operator ephemerides to inform orbital location and planned maneuvers; and
- Standardized formats to enable development of applications to leverage the data.

To facilitate this enhanced data sharing, and in recognition of the need for DoD to focus on maintaining access to and freedom of action in space, a civil agency should, consistent with applicable law, be responsible for the publicly releasable portion of the DoD catalog and for administering an open architecture data repository. The Department of Commerce should be that civil agency.

(iii) Mitigating Orbital Debris. It is in the interest of all space operators to minimize the creation of new orbital debris. Rapid international expansion of space operations and greater diversity of missions have rendered the current U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) inadequate to control the growth of orbital debris. These standard practices should be updated to address current and future space operating environments.

The United States should develop a new protocol of standard practices to set broader expectations of safe space operations in the 21st century. This protocol should begin with updated ODMSP, but also incorporate sections to address operating practices for large constellations, rendezvous and proximity operations, small satellites, and other classes of space operations. These overarching practices will provide an avenue to promote efficient and effective space safety practices with U.S. industry and internationally.

The United States should pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes. This effort should not detract from continuing to advance international protocols for debris mitigation associated with current programs.

(b) Operating in a Congested Space Environment.
   (i) Minimum Safety Standards and Best Practices. The creation of minimum standards for safe operation and debris mitigation derived in part from the U. S. Government ODMSP, but incorporating other standards and best practices, will best ensure the safe operation of U.S. space activities. These safety guidelines should consider maneuverability, tracking, reliability, and disposal.

The United States should eventually incorporate appropriate standards and best practices into Federal law and regulation through appropriate rulemaking or licensing actions. These guidelines should encompass protocols for all stages of satellite operation from design through end-of-life.

Satellite and constellation owners should participate in a pre-launch certification process that should, at a minimum, consider the following factors:

- Coordination of orbit utilization to prevent conjunctions;
- Constellation owner-operators' management of self-conjunctions;
- Owner-operator notification of planned maneuvers and sharing of satellite orbital location data;
- On-orbit tracking aids, including beacons or sensing enhancements, if such systems are needed;
- Encryption of satellite command and control links and data protection measures for ground site operations;
- Appropriate minimum reliability based on type of mission and phase of operations;
- Effect on the national security or foreign policy interests of the United States, or international obligations; and
- Self-disposal upon the conclusion of operational lifetime, or owner-operator provision for disposal using active debris removal methods.

(ii) On-Orbit Collision Avoidance Support Service. Timely warning of potential collisions is essential to preserving the safety of space activities for all. Basic collision avoidance information services are and should continue to be provided free of direct user fees. The imminent activation of more sensitive tracking sensors is expected to reveal a significantly greater population of the existing orbital debris background as well as provide an improved ability to track currently catalogued objects. Current and future satellites, including large constellations of satellites, will operate in a debris environment much denser than presently tracked. Preventing on-orbit collisions in this environment requires an information service that shares catalog data, predicts close approaches, and provides actionable warnings to satellite operators. The service should provide data to allow operators to assess proposed maneuvers to reduce risk. To provide on-orbit collision avoidance, the United States should:
   - Provide services based on a continuously updated catalog of satellite tracking data;

- Utilize automated processes for collision avoidance;
- Provide actionable and timely conjunction assessments; and
- Provide data to operators to enable assessment of maneuver plans.

To ensure safe coordination of space traffic in this future operating environment, and in recognition of the need for DoD to focus on maintaining access to and freedom of action in space, a civil agency should be the focal point for this collision avoidance support service. The Department of Commerce should be that civil agency.

(c) Strategies for Space Traffic Management in a Global Context.
  (i) Protocols to Prevent Orbital Conjunctions. As increased satellite operations make lower Earth orbits more congested, the United States should develop a set of standard techniques for mitigating the collision risk of increasingly congested orbits, particularly for large constellations. Appropriate methods, which may include licensing assigned volumes for constellation operation and establishing processes for satellites passing through the volumes, are needed.

The United States should explore strategies that will lead to the establishment of common global best practices, including:

- A common process addressing the volume of space used by a large constellation, particularly in close proximity to an existing constellation;
- A common process by which individual spacecraft may transit volumes used by existing satellites or constellations; and
- A set of best practices for the owner-operators of utilized volumes to minimize the long-term effects of constellation operations on the space environment (including the proper disposal of satellites, reliability standards, and effective collision avoidance).

(ii) Radio Frequency Spectrum and Interference Protection. Space traffic and RF spectrum use have traditionally been independently managed processes. Increased congestion in key orbital regimes creates a need for improved and increasingly dynamic methods to coordinate activities in both the physical and spectral domains, and may introduce new interdependencies. U.S. Government efforts in STM should address the following spectrum management considerations:

  - Where appropriate, verify consistency between policy and existing national and international regulations and goals regarding global access to, and operation in, the RF spectrum for space services;
  - Investigate the advantages of addressing spectrum in conjunction with the development of STM systems, standards, and best practices;
  - Promote flexible spectrum use and investigate emerging technologies for potential use by space systems; and

- Ensure spectrum-dependent STM components, such as inter-satellite safety communications and active debris removal systems, can successfully access the required spectrum necessary to their missions.

(iii) Global Engagement. In its role as a major spacefaring nation, the United States should continue to develop and promote a range of norms of behavior, best practices, and standards for safe operations in space to minimize the space debris environment and promote data sharing and coordination of space activities. It is essential that other spacefaring nations also adopt best practices for the common good of all spacefaring states. The United States should encourage the adoption of new norms of behavior and best practices for space operations by the international community through bilateral and multilateral discussions with other spacefaring nations, and through U.S. participation in various organizations such as the Inter-Agency Space Debris Coordination Committee, International Standards Organization, Consultative Committee for Space Data Systems, and UN Committee on the Peaceful Uses of Outer Space.

Sec. 6. Roles and Responsibilities. In furtherance of the goals described in section 4 and the guidelines described in section 5 of this memorandum, agencies shall carry out the following roles and responsibilities:

(a) Advance SSA and STM S&T. Members of the National Space Council, or their delegees, shall coordinate, prioritize, and advocate for S&T, SSA, and STM, as appropriate, as it relates to their respective missions. They should seek opportunities to engage with the commercial sector and academia in pursuit of this goal.

(b) Mitigate the Effect of Orbital Debris on Space Activities.

  (i) The Administrator of the National Aeronautics and Space Administration (NASA Administrator), in coordination with the Secretaries of State, Defense, Commerce, and Transportation, and the Director of National Intelligence, and in consultation with the Chairman of the Federal Communications Commission (FCC), shall lead efforts to update the U.S. Orbital Debris Mitigation Standard Practices and establish new guidelines for satellite design and operation, as appropriate and consistent with applicable law.

  (ii) The Secretaries of Commerce and Transportation, in consultation with the Chairman of the FCC, will assess the suitability of incorporating these updated standards and best practices into their respective licensing processes, as appropriate and consistent with applicable law.

(c) Encourage and Facilitate U.S. Commercial Leadership in S&T, SSA, and STM. The Secretary of Commerce, in coordination with the Secretaries of Defense and Transportation, and the NASA Administrator, shall lead efforts to encourage and facilitate continued U.S. commercial leadership in SSA, STM, and related S&T.

(d) Provide U.S. Government-Derived Basic SSA Data and Basic STM Services to the Public.

  (i) The Secretaries of Defense and Commerce, in coordination with the Secretaries of State and Transportation, the NASA Administrator, and the

Director of National Intelligence, should cooperatively develop a plan for providing basic SSA data and basic STM services either directly or through a partnership with industry or academia, consistent with the guidelines of sections 5(a)(ii) and 5(b)(ii) of this memorandum.

  (ii) The Secretary of Defense shall maintain the authoritative catalog of space objects.

  (iii) The Secretaries of Defense and Commerce shall assess whether statutory and regulatory changes are necessary to effect the plan developed under subsection (d)(i) of this section, and shall pursue such changes, along with any other needed changes, as appropriate.

(e) Improve SSA Data Interoperability and Enable Greater SSA Data Sharing.

  (i) The Secretary of Commerce, in coordination with the Secretaries of State, Defense, and Transportation, the NASA Administrator, and the Director of National Intelligence, shall develop standards and protocols for creation of an open architecture data repository to improve SSA data interoperability and enable greater SSA data sharing.

  (ii) The Secretary of Commerce shall develop options, either in-house or through partnerships with industry or academia, assessing both the technical and economic feasibility of establishing such a repository.

  (iii) The Secretary of Defense shall ensure that release of data regarding national security activities to any person or entity with access to the repository is consistent with national security interests.

(f) Develop Space Traffic Standards and Best Practices. The Secretaries of Defense, Commerce, and Transportation, in coordination with the Secretary of State, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall develop space traffic standards and best practices, including technical guidelines, minimum safety standards, behavioral norms, and orbital conjunction prevention protocols related to pre-launch risk assessment and on-orbit collision avoidance support services.

(g) Prevent Unintentional Radio Frequency Interference. The Secretaries of Commerce and Transportation, in coordination with the Secretaries of State and Defense, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall coordinate to mitigate the risk of harmful interference and promptly address any harmful interference that may occur.

(h) Improve the U.S. Domestic Space Object Registry. The Secretary of State, in coordination with the Secretaries of Defense, Commerce, and Transportation, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall lead U.S. Government efforts on international engagement related to international transparency and space object registry on SSA and STM issues.

(i) Develop Policies and Regulations for Future U.S. Orbital Operations. The Secretaries of Defense, Commerce, and Transportation, in coordination with the Secretary of State, the NASA Administrator, and the Director of National Intelligence, shall regularly evaluate emerging trends in space missions to recommend revisions, as appropriate and necessary, to existing SSA and STM policies and regulations.

Sec. 7. General Provisions.

(a) Nothing in this memorandum shall be construed to impair or otherwise affect:
  (i) the authority granted by law to an executive department or agency, or the head thereof; or
  (ii) the functions of the Director of the Office of Management and Budget relating to budgetary, administrative, or legislative proposals.

(b) This memorandum shall be implemented consistent with applicable law and subject to the availability of appropriations.

(c) This memorandum is not intended to, and does not, create any right or benefit, substantive or procedural, enforceable at law or in equity by any party against the United States, its departments, agencies, or entities, its officers, employees, or agents, or any other person.

(d) The Secretary of Commerce is authorized and directed to publish this memorandum in the Federal Register.

References

H. Kahn, *On Thermonuclear War* (Princeton University Press, Princeton, 1960), p. 144

T.J. Muelhaupt, M.E. Sorge, J. Morin, R.S. Wilson, Space traffic Management in the new Space era. Journal of Space Safety Engineering **6**(2), 80–87 (2019)

National Nuclear Detection Administration, 22 Mar 2018 NNSA delivers enduring space-based nuclear detonation detection capability. https://www.energy.gov/nnsa/articles/nnsa-delivers-enduring-space-based-nuclear-detonation-detection

J.N. Pelton, *Orbital Debris and Other Space Threats* (Springer Press, Switzerland, 2013)

J.N. Pelton, New solution for the space debris problem. Springer Press Chapter **5**, 53–60 (2015)

J.N. Pelton, *"Space Traffic and Frequency Management and Control in the New Space Environment" Paper 2014, IAASS Conference* (El Segundo, California, 2019)

Space Fence: How to keep space safe. https://www.lockheedmartin.com/en-us/products/space-fence.html. Last Accessed 21 Aug 2019

Space policy Directive-3: National Space Traffic Management Policy, https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/. 18 June 2018, Section 1 para. 3

B. Weeden, Time for the U.S. military to let go of the civil space situational awareness mission. Space News, 20 Sept 2016. https://spacenews.com/time-for-the-u-s-military-to-let-go-of-the-civil-space-situational-awareness-mission/

J. Wohlstetter, H. Kahn, Public Nuclear Strategy 50 Years Later (Sept 2010) Hudson Institute, Washington, D.C. pp. 3–4. https://www.hudson.org/content/researchattachments/attachment/842/kahnpublicnuclearstrategywohlstetter.pdf

Small Satellites, Safety Challenges, and Reforms Related to Strategic Space Defense Systems

Theresa Hitchens

Contents

Abstract

The question of how to manage and cope with increasing congestion in orbit in order to maintain safe and secure space operations has now come to the fore. This is the case in the USA, where policymakers and industry are involved in efforts to revamp current laws governing space activities, as well as in international fora where normative discussions are the dominant approach.

The increased salience of space traffic management (STM) has been largely driven by the growing commercial interest in the deployment of small satellites in mega-constellations, which inevitably will increase space congestion and challenge space safety. The increase in very small satellites in low Earth Orbit (LEO) makes space situational awareness more difficult. Complicating the picture is the advent of spacecraft capable of rendezvous and proximity operations (RPO) – operations that hold vast promise but also carry great risks.

Thus, the creation of a STM regime, including new safety standards related to removal of space debris from orbit, is becoming more urgent.

Unfortunately, ensuring space safety and assuaging national security concerns about protecting military space capabilities are in some ways contradictory. Safety and security often require opposing strategies; national versus international control often require opposing approaches. The US military and other

T. Hitchens (✉)
Center for International and Security Studies at Maryland (CISSM), Silver Spring, MD, USA
e-mail: theresa.hitchens0@gmail.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_49

operators of space security systems face a number of dilemmas in dealing with their needs vis-a-vis those of the wider space operating community, as discussed in this article.

This article, now with brief updates and some editorial amendments, previously appeared in the *Journal of Space Safety Engineering* 6(2), 2019. It is licensed to the publisher to be printed in the *Handbook of Small Satellites* by the author, who continues to hold the copyright. It is published here under its new title and with amended text.

Keywords

Active debris removal · Frequency interference · Mega-constellations · On-orbit servicing · Rendezvous and proximity operation (RPO) · Small satellite constellations · Space Data Association (SDA) · Space debris · Space environment · Space safety · Space situational awareness (SSA) · Space traffic management (STM) · STRATCOM

1 Introduction

The subject of space safety, space situational awareness of space objects and orbital space debris, and current rising concern about the deployment of a large number of mega-constellation is a subject of importance. It is of particular concern to those defense agencies charged with space security issues and defense and monitoring of space assets.

This article with brief updates and some editorial amendments previously appeared in the *Journal of Space Safety Engineering* (2019). It is licensed to the publisher to be printed in the *Handbook of Small Satellites* by the author, who continues to hold the copyright. It is published here under its new title and with amended text.

The number of working satellites in orbit is expected to skyrocket from the current level of more than 2000 to at least 10,000 within the next decade, and if all proposed launches are actually accomplished, the number could top 20,000. Many of these new satellites will be part of "mega-constellations" that will often number in the hundreds or even thousands (see Table 1).

Increased congestion inherently leads to increased risks, both of collisions and of radio-frequency interference. Further, new activities – such as remote proximity operations (RPO) that involve numerous maneuvers by spacecraft – also are likely to increase collision risks if not properly monitored and controlled. Complicating this picture is the fact that satellites are increasingly being operated by newcomers with less experience. There are at least some 90 governments and entities now owning and operating spacecraft including universities and nongovernmental organizations (NGOs). Unfortunately, neither the technology for monitoring all of this activity and allowing operators to ensure safe operations nor the regulatory mechanisms for controlling dangerous activities is currently adequate to face this new environment.

Table 1 Compendium of satellites in orbit or filed for launch in constellations

Country	Constellation	No. of sats	Radio-frequency bands
Argentina	Satellogic NuSat	300	Remote sensing
Australia	Fleet	100	Remote sensing
Canada	CANPOL-2	72	LEO and highly elliptical Earth orbit in VHF-, UHF-, X-, Ka-bands
Canada	Telesat constellation	117 sats plus spares	LEO in Ka-band
Canada	CONSTELLATION	Nearly 800 sats	LEO in Ka-band
France	Thales Group's MCSat	Between 800 and 4000	LEO, MEO, and HEO orbit Ku- and Ka-bands
China	CommSat	800	Ka-band
China	Lucky Star	156	Remote sensing
China	Hongyan	32	Remote sensing
China	Xinwei	32	Remote sensing
Liechtenstein	3ECOM-1	264	Ku- and Ka-bands
South Korea	Samsung	4500	Ka-band
Norway	ASK-1	10	Highly elliptical Earth orbit in X-, Ku-, and Ka-bands
UK	L5 (OneWeb)	650-750-1200-4000	Ku- and Ka-bands
USA	Boeing	1396–2956	V-band in 1200 km orbit
USA	SpaceX (Starlink)	4500 plus	Ku-Ka band
USA	SpaceX (V-band)	7500 plus	V-band
USA	Athena-Facebook	Details pending but of a large size	Ka-band
USA	Karousel MEO	20 MEO satellites	Ka-band
USA	Kuiper-Amazon	3236	Ka-band in three orbital tiers
USA	O3b mPower MEO	24	Ka-band
USA	Capella	48	Radar remote sensing
USA	Planet (Doves, Terra Bella, et al.)	300 plus	Active optical remote sensing
USA	Orbcomm	31	Active messaging (L-band)
USA	Iridium	72 plus spares	Active mobile satphone
USA	Globalstar	40 plus spare	Active mobile satphone

Note: This chart is not comprehensive, but of indicative of the many satellite constellations, mostly in low Earth orbit (LEO) either operational or filed for deployment (compiled from several sources)

In the USA, as in several other spacefaring countries such as France and Russia, the responsibility for monitoring on-orbit activity – the critical foundation for any future space traffic management (STM) regime, at either the national or international level – has been vested in the military. Only the USA, however, has a comprehensive system for "space situational awareness (SSA)" that includes maintenance of a "catalog" of space objects including active satellites and debris, conducting conjunction assessments, and providing collision warning/alert messages to spacecraft owner/operators around the world. The major civilian effort in this area, known as the Space Data Association, has a much lesser capability in this regard, and its efforts are currently focused on larger satellites in the geosynchronous Earth orbit (GEO) and not small satellites in low Earth orbit (LEO).

As of today, the 18th Space Control Squadron (18th SPCS), under the 14th Air Force at Vandenberg AFB in California, is tasked with promoting the responsible use of space, advancing spaceflight safety, and sharing of SSA data. Further, US Strategic Command (STRATCOM) has instituted SSA data sharing agreements with at least 16 nations to date and more than 70 commercial space operators (US Strategic Command 2018a). These agreements involve different "levels" of data sharing, with STRATCOM providing more precise data to closely allied governments such as those in the Five Eyes intelligence sharing network (Australia, Canada, New Zealand, and the UK).

This SSA architecture is enabled by the Space Surveillance Network (SSN) of ground- and space-based sensors (including optical telescopes and ground-based radar), also primarily owned and operated by STRATCOM, and until last year managed by the Joint Space Operations Center (JSpOC). In July 2018, US Strategic Command created the Combined Space Operations Center (CSpOC) at Vandenberg AFB to replace the JSpOC and to assume "operational command and control of space forces" (US Strategic Command 2018b). Reportedly this change was "designed to enhance coordination and cooperation between the USA and its allies in safeguarding the space domain" and to "provide input to develop and improve the ability to rapidly detect, warn, characterize, attribute, and defend against disturbances to space systems." Further, CSpOC missions include "missile warning; positioning, navigation, and timing; optimization and restoration of military satellite communications; theater battlespace awareness using overhead persistent infrared; environmental monitoring; theater support fires; defensive space situational awareness and space defense" (US Strategic Command 2018a, b). With the stand-up of the new US Space Command on Aug 2, 2019 responsibility for the mission has shifted from STRATCOM to Space Command – although the actual day-to-day operations remain the same.

It is important to understand that the primary mission of the US SSN Network and the SSA architecture is *not, and has never been,* to assure on-orbit safety or assist foreign/commercial satellite operators. Rather, the mission is to develop an "operational picture" that provides the technical foundation for the protection and defense of Defense Department and US Intelligence Community spacecraft. For this reason, the USA on June 18, 2018, signed Space Policy Directive-3 (SPD-3) on space traffic management (STM) Policy that outlines US policy and future governance of US space activities, including oversight of commercial actors (The White House 2018). The policy would see the Commerce Department becoming the linchpin agency in undertaking most related SSA/STM activities, shifting responsibility for providing SSA data and collision warning to commercial, civil, and non-US government operators from the military – in order for the Defense Department to "focus on protecting and defending US space assets and interests." This change, however, will require the approval of Congress – which has yet to take up the issue.

The change also raises a series of questions for Pentagon leadership and the US government about how military SSA activities will integrate with a future civil STM regulatory regime, as well as how both of these overlapping sets of activities will interact with other spacefaring nations/operators at the international level. Unfortunately, US decision-makers will face a number of security dilemmas about the future use of space that will not be easily resolved.

2 Space Situational Awareness: Safety Versus Secrecy

Perhaps the most fundamental of these questions is to what extent will the US government prioritize the military mission of SSA – which is considered a subfunction of "space control" designed to deter and defeat adversary space and counterspace abilities – versus the space safety and sustainability of the space environment? Unfortunately, these two SSA goals are in many ways inherently contradictory and create a classic security dilemma for Pentagon leaders.

For example, the US military does not include many of its national security satellites, especially classified Intelligence Community satellites, in the US space object catalog; nor does it routinely inform operators when one of those satellites becomes dysfunctional, even when it might put other operators at risk, as was the case with the DSP 23 missile warning satellite that malfunctioned in 2008 (Shalal-Esa 2008). Further, the USA does not require operators, whether commercial, civil, or especially military/Intelligence Community, to register and report satellite maneuvers. This lack of transparency actively undercuts the safety of other operators – especially those who do not have indigenous technical capabilities to maintain their own SSA system. And, sadly, if any space operator is essentially "flying blind," all space operators are put at risk, including the US military itself.

Another problem is that space object data shared publicly via the *Space.track* website does not include precise-enough data (or margins of error) for commercial operators to distinguish between a real possibility of collision and a false alarm, even though the 18th SPCS has higher-precision data. This is why, in 2009, a number of commercial space operators created the Space Data Association to share their own data about their satellite operations in order to better avoid interference (Space Data Association n.d.). "We discovered that the majority of conjunctions, or close approaches, were missed by the Joint Space Operations Center, and the majority of conjunction summary messages that went out advising us of close approaches were wrong," Richard DalBello, then vice president of Intelsat General for legal and governmental affairs, told a Feb 23, 2012, conference audience (Morring 2012).

According to US officials involved in the transition, DoD will continue to maintain the US Government's "authoritative catalog" of space objects and will continue to engage in military-to-military SSA data sharing and STM information exchange. DoD will continue to operate the SSN sensors for its military missions and to provide the Department of Commerce with SSA data. What data is shared with Commerce and at what level of precision remains to be seen – that is, will raw observational data be provided at higher levels of accuracy than the so-called two line elements currently publicly shared via the *Space.track.org* website or only information about potential conjunctions. If the latter, will margin of error calculations be provided?

Another question yet to be resolved is whether or not the Pentagon will have the authority to prevent Commerce from sharing data with better accuracy than that up to now provided by DoD. This is a critical issue, as currently Commerce is trying to figure out how to integrate the use of new sources of observational data – such as that being provided on the commercial marketplace by companies such as Analytical Graphics Inc. and data generated by foreign sensor suites – into the future civil SSA system precisely so as to be able to provide more accurate collision warnings. Kevin O'Connell, the head of the Commerce Department's Office of Space Commerce, speaking at a Nov 14, 2018 workshop sponsored by the University of Maryland's Center for Orbital Debris Research and Education (CODER), said that one major part of the office's responsibilities "will be to create an open architecture data repository that starts with the DoD catalog and enables a host of innovative capabilities and data sets provided by industry, academia, our allies, and partners." He added, "The repository is likely to be a very important source of innovation. Already within our early discussions, we hope to draw on state-of-the-art data management and data sharing capabilities, such as those that are available within cloud computing, and also allow for experimentation as new data sources and algorithms become available. There are important policy and technical questions about data fusion, but we will strive to create maximum opportunities for exploration, curation, and collaboration."

However, DoD may be reluctant to see foreign countries, especially those countries the Pentagon views as potential future adversaries, being given access to highly accurate satellite positioning data – especially about US satellites that DoD relies on for its own missions, which include many commercial communications satellites. This is because DoD sees SSA capabilities as part of the "space control" mission that includes offensive and defensive measures to ensure freedom of action in space.

Joint Doctrine 3–14 on Space Operations defines space control as follows: "Space control employs OSC [offensive space control] and defensive space control (DSC) operations to ensure freedom of action in space and, when directed, defeat efforts to interfere with or attack US or allied space systems. Space control plans and capabilities use a broad range of response options to provide continued, sustainable use of space. Space control contributes to space deterrence by employing a variety of measures to assure the use of space, attribute enemy attacks, and consistent with the right to self-defense, target threat space capabilities" (Office of the Joint Chiefs of Staff 2018).

It defines SSA as follows: "Situational awareness is fundamental to conducting space operations. SSA is the requisite foundational, current, and predictive knowledge and characterization of space objects and the OE upon which space operations depend including physical, virtual, information and human dimensions – as well as all factors, activities, and events of all entities conducting, or preparing to conduct, space operations. Space surveillance assets include a mix of space-based and earth-based sensors. SSA is dependent on integrating space surveillance, collection, and processing; environmental monitoring; status of US and cooperative satellite systems; understanding of US and multinational space readiness; and analysis of the space domain. SSA must incorporate understanding of the space capabilities and intent of those that pose a threat to our space operations and space capabilities" (Office of the Joint Chiefs of Staff 2018).

US Air Force doctrine further states that SSA "is foundational and fundamental to the conduct of all space operations functions and is especially critical to the effective conduct of counterspace operations" (Curtis Lemay Center for Doctrine, Development and Education, US Air Force 2018a, b). Counterspace operations include actions both to protect US space assets (i.e., "defensive counterspace") and to "deceive, disrupt, deny, degrade or destroy" adversary space systems (i.e., "offensive counterspace" (Curtis Lemay Center for Doctrine, Development and Education, US Air Force 2018a, b).

Thus, the US military also sees the SSA capabilities of other countries as part of their counterspace capabilities. A new report by the Defense Intelligence Agency, "Challenges to Security in Space," cites the SSA capabilities of both Russia and China as part of their counterspace capabilities noting that they could be used for targeting US systems (Defense Intelligence Agency 2019). Both China and Russia are developing a number of technologies that could enable ASAT systems, the DIA study finds, stating: "Both states are developing jamming and cyberspace capabilities, directed energy weapons, on-orbit capabilities, and ground-based antisatellite missiles that can achieve a range of reversible to nonreversible effects." It also states that China is considering the benefits of attacking US early warning satellites during a conflict, because those satellites are also being used to guide US missile defense interceptors to their targets. Therefore, it is obvious that there might be reluctance on the part of the US military and Intelligence Community to providing on-orbit data that might make targeting US satellites easier.

A related question is when DoD will be able to upgrade the software used for SSA tasks, including allowing the system to integrate sensor data from non-DoD owned telescopes and radar as well as orbital positioning data provided by outside operators. After years of cost overruns, delays, and requirements revamps, DoD in effect canceled the long-running Joint Space Operations Center (JSpOC) Mission System (JMS) program that was designed to upgrade current SSA data-crunching capabilities. The three-phased, $1 billion-plus initiative was aimed at upgrading hardware and software for space surveillance, collision avoidance, and launch support and enabling the generation of more precise and timely orbital information (International Defence, Security and Technology 2019). The new system was supposed to be able to integrate the massive amount of sensor data generated from the Space Fence ground-based radar system. The final increment, JMS 3, was supposed to transform the entire system into a battle management system, as well as allow the integration of orbital data provided by commercial industry and allied governments.

However, the Pentagon in early 2018 halted JMS 3, splitting the requirements into two pieces to be managed separately by the CSpOC and the National Space Defense Center (which coordinates with the National Reconnaissance Office) and renaming the whole effort the Enterprise Space Battle Management Command and

Control (ESBMC2) program (Clark 2018). Whereas the JMS 2, still in development, is focused on space safety, the ESBMC2 effort is squarely aimed at warfighting. EMSBMC2 is being designed as “a more dynamic, warfighting C2 system that was based on an open architecture systems with defined message standards, enabling us to rapidly on-board planning and tasking software applications,” according to the Air Force (Clark 2018). It also is aimed at “unity of effort” with NRO. While the overhaul of the Air Force SSA C2 and data management architecture revives hope for improving military SSA capabilities, there remain many questions about how (and even if) data will be passed from the National Space Defense Center and the CSpOC and how the ESBMC2 system will validate and integrate non-DoD generated data.

The fundamental view from DoD is that SSA is a warfighting tool. Therefore, there is a predilection toward secrecy, both about US space assets and about the accuracy of information (and the sources and methods by which it has been gathered) the USA has regarding the assets of other nations. However, secrecy about the space environment, including spacecraft and their movements, actively undercuts safety of operations. If the USA takes a too stringent hold on data release – that is, if national security concerns prevent sharing the best SSA data that is gathered – it will detract from safety and sustainability of the space environment for all. And, sadly, if any space operator is essentially “flying blind,” all space operators are put at risk, including the US military itself.

What is most critical with regard to all of the above questions and issues is the new space environment that is now anticipated. There are now many thousands of new space launches anticipated. Many new LEO and MEO constellations are either in active planning or being initially deployed, including OneWeb, the SpaceX Starlink and V-Sat networks, Athena, Kuiper, MCSat (by Thales Alenia), Telesat, Constellation, Theia, Planet, Spire, O3B, O3B mPower, and dozens more of these networks largely clustered between 700 and 1200 km altitudes with a critical concentration around 900 km.

3 National Versus International Approach; Restrictions Versus Freedom of Action

The nascent US approach to STM, as embodied in SPD-3, is also somewhat self-contradictory in that it is aimed at promoting US industry and bolstering US freedom of action in space while simultaneously calling on other countries to take up a similar approach.

The current effort as outlined in US Space Policy Directive-3 is attempting to establish a loose regulatory structure for US space activities that empowers the US commercial space industry to take a predominate position in the international market, as well as to provide the US strategic space program with innovative capabilities. SPD-3 acknowledges the need for a more robust structure for oversight of US space operators, especially for new types of space activities such as rendezvous and proximity operations (RPO) and active debris removal. SPD-3 states: “To maintain US leadership in space, we must develop a new approach to space traffic management (STM) that addresses current and future operational risks. This new approach must set priorities for space situational awareness (SSA) and STM innovation in science and technology (S&T), incorporate national security considerations, encourage growth of the US commercial space sector, establish an updated STM architecture, and promote space safety standards and best practices across the international community" (The White House 2018).

According to US officials, the administration intends to go its own way to develop a national STM regime based on industry-designed best practices and then attempt to convince other countries to adopt a similar approach. SPD-3 states: "The United States recognizes that spaceflight safety is a global challenge and will continue to encourage safe and responsible behavior in space while emphasizing the need for international transparency and STM data sharing. Through this national policy for STM and other national space strategies and policies, the United States will enhance safety and ensure continued leadership, preeminence, and freedom of action in space."

In an interview with *SpaceWatch Global* on Dec 2, 2018, Dr. Scott Pace, Executive Secretary of the US National Space Council, indicated that the USA will forge ahead on setting rules for new types of space activities apparently with limited consultation with allies or other space faring nations. He said that the US government is moving quickly to provide "mission assurance" authority for on-orbit activities by US space companies to the Commerce Department, including licensing procedures for "satellite servicing, bases on the lunar surface, and space stations." Asked about the administration's international approach, Pace said: "We don't know that we really need anything new" because the 1967 Outer Space Treaty is "fairly permissive" (Space Watch Global 2018).

However, given that the goal of SPD-3 seems to be to promote US industry and US freedom of action in space, what incentives will other nations have to go along? Indeed, there is already some evidence US allies in Europe are growing uncomfortable with the US space initiatives seeming lack of consideration for allied interests and concerns. At a November 2018 conference sponsored by the Institut français des relations internationales (IFRI), a number of European officials expressed unease with the US space initiatives commercial space policies. François Raffenne, strategic planning and analysis manager for ArianeGroup, told the conference that the USA is not listening to European views on vital questions for the future of the space environment, such as "What is space deterrence?" "What is 'victory' in space?" and "What is the difference between a civil and military space asset?" He said that there is a "need for regulations to follow, and that right now the USA is the only actor able to articulate those regulations." But, he cautioned, Washington is doing so "in support of national objectives; in support of US space dominance by civilian, military and commercial goals." He explained that the US space initiatives as outline in SPD-3 "will have implications that will dictate rules of the road; the question is how Europe will respond to the US lead" – warning that Europe has its own interests to look out for (Author's notes from attending the conference).

Further, the Trump administration has backed away from international efforts to develop best practices for space operations under the auspices of the United Nations at the Committee for the Peaceful Uses of Outer Space (COPUOS). According to State Department officials, rather than supporting new discussions to expand upon the set of 21 guidelines developed by the Scientific and Technical Subcommittee's Working Group on the Long-Term Sustainability of Outer Space and approved by the Committee in June 2018, the USA intends to focus on national implementation. And while the COPUOS Legal Subcommittee has had an annual agenda item on STM since 2015, the USA and the Russian positions have been that it is too early to seek a legally binding international accord on STM, as there is not yet an agreed multilateral understanding of the necessary parameters of such a regime. The US government also has argued during Legal Subcommittee meetings that the Scientific and Technical Subcommittee should first look at what technical approaches are even feasible to create such a regime.

An STM regime followed only by one or a handful of nations would do little to create a safer space environment. Worse yet would be a situation where the rules governing safe practices on orbit differ widely from country to country, as it would drive commercial industry to seek the locale with the least restrictive rules – as already a serious problem regarding the shipping industry where "flags of convenience" are common so as to minimize the need to comply with environmental safety and health regulations. As an example of how such problems could manifest, US firm Swarm Technologies in January 2018 managed to launch four very small satellites, called SpaceBEEs, on an Indian government Polar Satellite Launch Vehicle after having been denied a US launch license by the Federal Communications Commission because of safety concerns (Henry 2018). This violation of US licensing law was made possible because neither the company, Spaceflight, that arranged for the SpaceBEEs ride share on the Indian rocket nor the Indian government required Swarm to provide evidence of a license. Spaceflight, a US company, has now changed its operating procedures to require proof (Grush 2018), though there is no evidence that the Indian government has done the same.

The need for an international approach is recognized in SPD-3, yet the document also states that the end goal is US "freedom of action" in space – a goal enshrined in US national security space policy. The US military long has been wary of any international treaty or effort that would seek to restrict in any way its future actions in space. For the past several decades, the military's dim view of any new international legal mechanisms for governing space has been reflected in the long-standing US preference for voluntary measures, such as best-practice guidelines.

Of course, if any future international architecture for STM is primarily voluntary, and based on individual state practice, the Pentagon can always count of being exempted from any rules it finds too constricting since it can fall back on the provision in international law to have the right to self-defense.

An example is the case of US military adherence to the Space Debris Guidelines of the Committee on the Peaceful Uses of Outer Space endorsed by the UN General Assembly in 2007. Those guidelines actually were based on US government debris mitigation practices formulated by NASA, and most if not all are already incorporated into US government licensing rules for space launches. DoD Directive

3100.10, Space Policy, states that the “DoD will promote the responsible, peaceful, and safe use of space, including following the US Government Orbital Debris Mitigation Standard Practice (ODMSP)” (US Department of Defense 2016).

However, ODMSP allows for a waiver of the practices if approved by the “head of the sponsoring department or agency” (Sims and Braun 2017). The Air Force, which is responsible for most military satellite acquisitions, lays out the process for obtaining waivers in Air Force Instruction 91–217, “Space Safety and Mishap Prevention Program,” that includes review by the program safety officer, the Office of the Air Force Secretary, and the Secretary of Defense (Office of the Secretary of the Air Force 2017). DoD practice, according to Pentagon officials, has been that waivers are granted if compliance would result in significant increases in cost or place onerous constraints on important military missions. In the not-too-distant past, waivers for DoD space missions were easily obtained and quite common, according to Pentagon officials involved. The Obama administration, however, cracked down on the practice, so it is increasingly difficult for DoD satellite program managers to obtain them.

In addition, there is no explicit prohibition in US National Space Policy, DoD policies, or US military doctrine on the use of debris-creating antisatellite (ASAT) weapons. In fact, the Pentagon’s policies and doctrine allow for space control and counterspace operations that destroy adversary space and counterspace systems (as noted above). And while US military leaders, including Gen. John Hyten, newly appointed vice chairman of the Joint Chiefs of Staff, and former head of both US Strategic Command and Air Force Space Command, have been vocal about their disregard for debris-creating ASATs, the US government has up to now opposed any effort toward negotiation of a treaty to ban such weapons.

It should be obvious that if the USA can insert compliance waivers into its implementation of voluntary rules and guidelines for space activities, other nations could do the same. It should be similarly obvious that if all nations decide to exempt their military space forces and activities from compliance with any future national or international STM guidelines, the space environment likely will continue to be put at serious risk. Due to the laws of physics prevailing in outer space, the actions of any single space operator have the potential to affect all other operators – and no one can escape the laws of physics. Any STM regime would by necessity include some restrictions on certain types of activities and constrictions on how activities are undertaken; an international STM regime – especially if legally binding – would inherently restrict US freedom of action in outer space. Thus, the US military will need to be ready to accept some restrictions on its freedom of action for a STM regime to be developed, both at the US national level and the international level.

4 Conclusion

The US government and its military have a large stake in ensuring safety of space operations. This would seem to imply the need to support the development of future US and international STM regimes. However, such a position faces a number of dilemmas as STM governance processes unfold. There will be trade-offs to be made between secrecy and transparency, and between a controllable national regime and an international regime less in the control of the US government. There will be a dilemma of choosing between a closed-loop warfighting posture and an open, multi-stakeholder architecture for safety.

However, the skyrocketing population of small satellites coupled with the technological shortcomings in the current American SSA capabilities will force the US government and other space security actors to focus more clearly on these issues in the immediate future. In a positive sign, the US government since 2015 has been seriously investing in improved space situational awareness (SSA). In fact, a Government Accountability Office study in 2015 was able to track $6 billion in planned spending in this area through FY2020 (Government Accountability Office 2015).

However, the US military has yet to puzzle out how it intends to interact with the new civilian STM architecture envisioned by SPD-3. Because SPACECOM (like STRATCOM before it) has not yet resolved its serious software problems, the job of coordinating between the civil agency and the Pentagon will be extremely complicated. This will require both technical and organizational solutions as well as goodwill on both sides. Fortunately, at this time, there seems to be a good working rapport between current activities in the US Department of Commerce and DoD, with regular information changes ongoing.

The shift in responsibility for SSA and STM from the military to the Commerce Department further requires congressional approval and oversight. Unfortunately, lawmakers seem to still be divided on which civilian department should be made responsible for the new civilian body and processes. Some within the Congress believe the role of a civilian STM agency should not be given to the Commerce Department as laid out in SPD-3, but rather to the Transportation Department under the management of the Federal Aviation Administration (FAA), which has had long experience in handling space safety oversight for launch and reentry of space vehicles. This divide has meant limited progress can be made in developing STM approaches to the various issues at hand, including SSA data sharing and regulations for new types of space activities such as on-orbit servicing and mega-constellation operations. Meanwhile thousands of small satellites (i.e., nanosats, microsats, and minisats) for mega-constellations may be deployed before these issues are resolved.

Time, however, is of the essence. Space security officials in the USA and other space faring nations must face the challenges of SSA and STM now and not succumb to bureaucratic inertia. The commercial industry, both here and abroad, is surging relentlessly forward in development of new capabilities and launching small satellites at unprecedented rates. While Congress is currently deadlocked on granting legislative authority for the new civilian STM agency, that deadlock will not last forever, and there are a number of technical issues that can be hashed out in the meantime. Therefore, there is a role for industry and academia to play in setting the stage for a future regime by developing best-practice concepts both at the technical and operational level.

Finally, Washington needs to be aware that the international community is becoming increasingly unwilling to wait for, and follow, the USA lead on seeking international solutions to the ever-increasing congestion in space. As the US

National Space Council moves forward with the sweeping reorganization of space enterprise, there will be a need for new focus and coordinated effort to find solutions to the SSA/STM challenges that *include* cooperation and coordination with international partners.

5 Cross-References

- ▶ Security Concerns Related to Smallsats, Space Situational Awareness (SSA), and Space Traffic Management (STM)
- ▶ Small Satellite Constellations: National Security Implications
- ▶ Small Satellites, Hosted Payloads, Dual Use, and Strategic Space Services

References

C. Clark, Air Force teams with NRO for secret SSA bird, *BreakingDefense* (2018). Retrieved at: https://breakingdefense.com/2018/04/air-force-teams-with-nro-for-secret-ssa-bird-dumps-joint-mission-systems-upgrade/

Defense Intelligence Agency, Challenges to security in space (2019). pp. 20, 28. Retrieved at: http://www.dia.mil/Portals/27/Documents/News/Military%20Power%20Publications/Space_Threat_V14_020119_sm.pdf

Government Accountability Office, Space situational awareness: status of efforts and planned budgets (2015). Retrieved at: https://www.gao.gov/products/GAO-16-6R

L. Grush, Company that launched satellites without permission gets new license to launch more probes. *The Verge* (2018). Retrieved at: https://www.theverge.com/2018/10/4/17928452/swarm-technologies-spacebees-satellites-spacex-falcon-9-fcc-license

C. Henry, FCC fines Swarm $900,000 for unauthorized smallsat launch. *Space News* (2018). Retrieved at: https://spacenews.com/fcc-fines-swarm-900000-for-unauthorized-smallsat-launch/

T. Hitchens, Space traffic management: U.S. military considerations for the future. J. Space Saf. Eng. **6**(2), 108–112 (2019)

International Defence, Security and Technology, US DOD's thrust in space situational awareness, and space battle management to combat emerging space threats (2019). Retrieved at: https://idstch.com/home5/international-defence-security-and-technology/space/us-dods-thrust-in-space-situational-awareness-and-space-battle-management-to-combat-emerging-space-threats/

F. Morring, Jr, USAF satellite-conjunction advisories called inaccurate. *Aviation Week* (2012). Retrieved at: http://aviationweek.com/space/usaf-satellite-conjunction-advisories-called-inaccurate. *Note bene*: the conjunction summary messages were replaced in 2014 by conjunction data messages based on an improved and internationally agreed data format

Office of the Joint Chiefs of Staff, Joint publication 3–14 space operations, chapter II, p. 2, para. 3a (2018). Retrieved at: https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_14.pdf

Office of the Secretary of the Air Force, Air Force Instruction 91–217: space safety and mishap prevention program, April 11, 2014 (certified current May 16, 2017) (2017). Retrieved at: https://static.e-publishing.af.mil/production/1/af_se/publication/afi91-217/afi91-217.pdf

A. Shalal-Esa, U.S. missile warning satellite fails. *Reuters* (2008). Retrieved at: https://www.reuters.com/article/us-usa-satellite-idUSTRE4AN8FK20081124

E.M. Sims, B.M. Braun, Navigating the policy compliance roadmap for small satellites. *Center for Space Policy and Strategy, The Aerospace Corporation* (2017), p. 4. Retrieved at: https://aerospace.org/sites/default/files/2018-05/SmallSatRegulations_0.pdf

Space Data Association (n.d.). Retrieved at: https://www.space-data.org/sda/

Space Watch Global, SpaceWatchGL interview: Dr. Scott Pace of the U.S. National Space Council, Part I (2018). Retrieved at: https://spacewatch.global/2018/12/spacewatchgl-interview-dr-scott-pace-of-the-u-s-national-space-council-part-i/

The White House, Space Policy Directive-3: national space traffic management policy (2018). Retrieved at: https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/

US Air Force Curtis Lemay Center for Doctrine, Development and Education, Space situational awareness – annex 3–14 counterspace operations (2018a). Retrieved at: https://www.doctrine.af.mil/Portals/61/documents/Annex_3-14/3-14-D04-SPACE-SSA.pdf

US Air Force Curtis Lemay Center for Doctrine, Development and Education, Counterspace operations – annex 3–14 counterspace operations (2018b). Retrieved at: https://www.doctrine.af.mil/Portals/61/documents/Annex_3-14/3-14-D05-SPACE-Counterspace-Ops.pdf

US Department of Defense, Department of Defense Directive 3100.10: space policy, October 18, 2012 (incorporating change 1, November 4, 2016) (2016). Retrieved at: Homeland Security Digital Library, https://www.hsdl.org/?abstract&did=796643

US Strategic Command, US STRATCOM, Thailand sign agreement to share space services, data (2018a). Retrieved from: https://www.stratcom.mil/Media/News/News-Article-View/Article/1659776/usstratcom-thailand-sign-agreement-to-share-space-services-data/

US Strategic Command, Combined Space Operations Center/614th Air Operations Center (2018b). Retrieved at: https://www.stratcom.mil/Portals/8/Documents/CSpOC_Factsheet_2018.pdf

Small Satellite Constellations: National Security Implications

Mark Roberts, Christoph Beischl, and Sa’id Mosteshar

Contents

M. Roberts · C. Beischl · S. Mosteshar (✉)
London Institute of Space Policy and Law, London, UK
e-mail: Mark@ReflectSolutions.com; Christoph.Beischl@space-institute.org; Sa'id.Mosteshar@space-institute.org

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_52

Abstract

There are both positive and negative national security implications associated with the deployment of small satellite constellations, particularly those destined to be mega-constellations. This chapter attempts to discuss both sides, benefits, and risks, aimed to enable the reader to decide whether they are optimistic or pessimistic, or indeed cautiously ambivalent about small satellite constellations. In this context, this chapter first provides definitions for national security (taking into account personal and financial security), small satellites, and constellations. Its subsequent two sections deliberate about various potential positive and negative implications for national security of small satellite constellations in more detail. On the positive side, the analytical focus is on the capability enabling functions of small satellites, their antisatellite (ASAT) capability, as well as their ability to upgrade, enhance resilience of and reconstitute space system functionality. On the negative side, the chapter examines such national security-related risks as increased orbital congestion, frequency overcrowding, and the danger to people, property, and environment. The penultimate section deals with the issue of managing the risks, with particular consideration of the concept of *responsible use*, considering observability, maneuverability, communication and controllability, the ability of small satellites to operate safely, regulation, legality and ethical constraints, as well as liability. The chapter concludes with a brief summary and the authors' view on how progress might be made in a way that embraces small satellite constellations responsibly, to optimize their benefits, while protecting global security concerns.

Keywords

Satellite constellations · Mega-constellations · National security · Space security · Satellite applications · Antisatellite weapon (ASAT or ASAT weapon) · Space law · Space policy · NewSpace · Responsible use

1 Introduction

> There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things. Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new. (Machiavelli)

With the potentially exponential increase in small satellites, particularly those destined for mega-constellations, the world faces something of a dilemma – is this a good or bad development for national security? For the small satellite constellation advocates there is no doubt, they present an outstanding opportunity for the global community to access commercially competitive space products and services at a fraction of the historic costs, with the potential to enhance national (and personal) security. However, for those troubled by national security threats and issues, the burgeoning capabilities, combined with the sheer numbers of miniaturized orbital assets, and the ever-reducing cost of entry into this developing marketplace, the emergence of small satellite constellations is probably mildly alarming. Which view is right? They both are!

Of course, this is not a simple debate (good vs. bad), and the intellectual argument is somewhat skewed by the perspective one takes. Organizations committed to creating businesses associated with small satellite constellations will argue the very significant benefits to mankind of the low cost (or free) access to their services and products. For example, OneWeb's vision, "Internet access everywhere, for everyone" (OneWeb n.d.), is difficult to critique negatively, particularly as it resonates so eloquently with the values of freedom held dear by much of the global community. Depending on one's definition of national security, this type of capability could be seen as enhanced resilience beneficial to society and, therefore, national security. However, some states may view the vision with some concern, perhaps seeing it as a challenge to the systems that underpin the way their societies currently function. Similarly, nations that are the prime beneficiary of a constellation's products or services for national security purposes will doubtless argue for the benefits the capabilities offer and their right to exploit them; their adversaries might take a different view. Unsurprisingly for space, the debate will most likely gravitate to one of responsible use, which again is skewed by perspective.

This chapter attempts to offer both views, for and against, with the aim of enabling the reader to decide whether they are optimistic or pessimistic, or indeed cautiously ambivalent about small satellite constellations. The chapter covers:

- *Definitions*. To create the context, the chapter begins by defining national security, small satellites, and constellations. This section also provides a brief history of small satellites.

To consider whether and how a nation's security could be enhanced or degraded by small satellite constellations, the chapter turns to:

- *National Security Enhancements*. This section examines the potentially positive contribution of the emerging capabilities, examining inter alia: the capability enabling functions of small satellites; antisatellite (ASAT) capability; and the ability to upgrade or enhance resilience of Space system functionality.
- *National Security Risks*. The next section covers the potential risks to national security: orbital congestion; frequency overcrowding; the danger to people, property, and environment; the re-entry risk, the maneuver risk, the dangers of ride-sharing and piggyback launches; and attacks by microsatellites.
- *Managing the Risks*. The penultimate section deals with the issue of managing the risks, covering observability; maneuverability; communication and controllability; the ability of small satellites to operate safely; regulation; liability; legality; and, ethical constraints.

- *Conclusion.* The chapter concludes with a brief summary and the authors' view on how we might progress in a way that embraces small satellite constellations responsibly, to optimize their benefits, while protecting global security concerns.

It is important to state that the legality of the activities small satellites may undertake is not considered in the positive and negative contribution sections.

2 Definitions

2.1 National Security

There are numerous definitions of national security and the concept has, over the last six decades, morphed from that of repelling unwanted influences (normally using the military), to maintaining freedoms, prosperity, self-determination, and wellbeing (normally through use of all instruments of power).

Collins Dictionary defines national security as "A country's national security is its ability to protect itself from the threat of violence or attack" (Collins n.d.). The problem with this definition is that it does not address the subtlety of the threat of erosion of societal wellbeing due to the loss or erosion of services; this is important when we consider space and satellite capabilities. As the 2015 UK National Security Strategy points out, "Economic security goes hand-in-hand with national security" (HM Government 2015), making the clear link between national security and society's ability to function. When considering the benefits and risks of small satellite constellations, while violence and attack are relevant, taking this view only would lead to a myopic perspective of the issues. Therefore, to situate the following analysis in a broader context, it is preferable to adopt Charles Maier's definition of national security (as presented in his unpublished paper for the MacArthur Fellowship Program, Social Science Research Council, 12 June 1990):

> A capacity to control those domestic and foreign conditions that the public opinion of a given community believes necessary to enjoy its own self-determination or autonomy, prosperity and wellbeing.

This definition encompasses the societal aspects of national security, and by implication issues such as security of a nation, individual, and way of life, and the importance of assured (critical) services. For the purposes of this chapter those small satellite constellation capabilities that enable these elements are considered positive and those that degrade or deny the elements are negative.

2.2 Small Satellites

There is no universally accepted definition of small satellites; accordingly, most commentators use their attributes to differentiate small satellites from large(r)

Table 1 Classification of small satellites

Class	Mass (kg)
Mini-satellites	100–180
Micro-satellites	10–100
Nano-satellites	1–10
Pico-satellites	0.01–1
Femto-satellites	0.001–0.01

Table 2 Classification of small satellites

Class	Mass (kg)
Small satellite	500–1000
Mini-satellites	100–500
Micro-satellites	10–100
Nano-satellites	1–10
Pico-satellites	0.1–1
Femto-satellites	<0.1

satellites. Overall, small satellites, in comparison to large(r) satellites often have the following characteristics (Marshall 2008):

- Low cost ($50– $100 million)
- Fast turnaround (12–36 months from authority to proceed to launch)
- Use of latest technology
- More than one satellite per launch or use of small affordable launch vehicles
- Use of off-the-shelf technologies wherever possible (both commercial and other)
- Higher risk
- Less complexity
- Less durability
- Less orbital time
- Lower satellite and launch costs
- Speedier deployment rates

These attributes do not always stand up to scrutiny as differentiators, so the more common categorization of small satellites is by mass or size. Elizabeth Mabrouk (2017) described the following classes of small satellite (Table 1):

Sir Martin Sweeting, in his paper "*Modern Small Satellites–Changing the Economics of Space*" (Sweeting 2018, pp. 343–344), used similar but not exactly the same mass numbers for the different classes, and includes the specific class for "small satellite" (Table 2):

A 2017 International Institute of Astronautics (IAA) report (Cho and Graziani 2017) accords with Martin Sweeting's view, albeit combining the small and mini-satellite classes into one 100–1000 kg mini-satellite class. These differing views serve to highlight the lack of a common definition of small satellites, and as

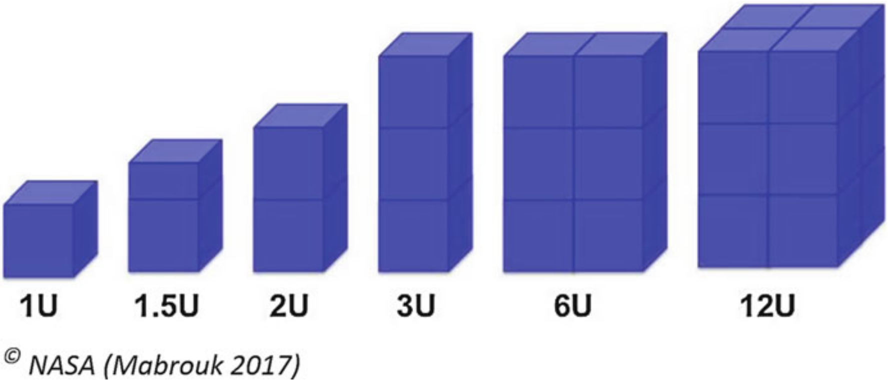


Fig. 1 CubeSat units. (© NASA (Mabrouk 2017))

Finkleman (2013) highlights, the mass discriminant belies size, orientation, maneuverability, and other discriminating attributes. The choice of orbital architectures for small satellites by any definition must consider these other characteristics. However, the *cursor* must be set somewhere, so for purposes of this chapter small satellites are those with a mass of <1000 kg.

2.3 CubeSats

It is worth a brief word on CubeSats, as many of the aspiring constellation providers are turning to this class of satellite. “CubeSats” are a class of nanosatellites that use a standard size and form factor. The standard CubeSat size is “one unit” or “1 U” measuring 10 × 10 × 10 cms, and is extendable to larger sizes, e.g. 1.5, 2, 3, 6, and even 12 U. CubeSats now provide a cost effective platform for science investigations, new technology demonstrations and advanced mission concepts using constellations, swarms disaggregated systems (Mabrouk 2017). The image below (Fig. 1) shows how these “units” can be aggregated to provide different sized nano-satellites.

2.4 Constellations

“A satellite constellation [...] is a system of satellites that work together to achieve a single purpose.” In line with this definition offered by Rouse and Haughn (2017), a constellation could be a relatively small number of satellites operating to provide a service (e.g., the GPS constellation). However, this chapter will consider small satellites forming large-scale constellations (mega-constellations), which are primarily planned for Low Earth Orbit (LEO); these are generally perceived to offer the following capabilities:

- Continuous, multipoint data gathering
- Fast download and upload speed
- A global imaging capability and capacity
- Modularity – the use of standardized units allowing flexibility such that satellites can cover the operations of other satellites
- Networked – the use of satellites that work together in a network to disperse the system capabilities
- Redundancy – the use of more satellites than are minimally required for the provision of the capability

As such, these capabilities offer significant commercial opportunities for the constellation suppliers, specifically as the cost of (equivalent to traditional space-based) service provision promises to be materially reduced.

Making a constellation of satellites work has very specific challenges:

- *Mission Design*. Constellations may have three forms of "control" – controlled satellites where some degree of propulsion maneuver is possible; uncontrolled swarms of satellites with no form of propulsion, and something between the two utilizing a slave/master approach. All of these approaches have weaknesses, covered in the vulnerabilities section below.
- *Critical Mass*. The mission architecture will define the coverage provided by the constellation, but whatever the architecture is, there will be a critical mass of satellites required to provide the coverage required.
- *More Satellites, More Risk*. If all the planned constellations are realized, the total number of operational satellites in orbit would quadruple, exacerbating the risk of catastrophic and cascading satellite collisions (Grush 2018). As constellations grow in size, they can no longer be considered in isolation and potential coupling with the background satellite population will become an increasing issue.

2.5 Constellation Vulnerabilities

- *Cyber*. The need to communicate with the ground may create the ability for a third party to intervene in operations making the satellite and potentially the constellation vulnerable to cyber-attack.
- *Vulnerability in Design*. Constellations made up of similar components have increased potential for systemic failure, due to common design elements.
- *Jamming and Spoofing*. Jamming or spoofing a subset of constellation could impact the integrity of the system as a whole.

2.6 Small Satellites and NewSpace – The Rise of CubeSats

The phrase NewSpace is used to imply a different approach and ethos to more established methods and business models associated with new entrants to the space

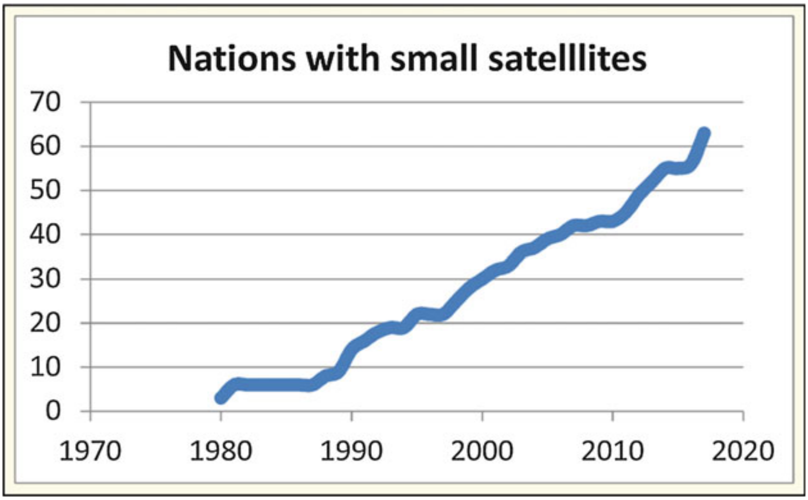


Fig. 2 The rise of nations with small satellites. (Sweeting 2018, p. 353)

sector and characterized by agility, entrepreneurship, and exploitation of off-the-shelf technologies (Sweeting 2018).

CubeSats have contributed to the NewSpace dynamic and the progressive evolution of the small satellite market. Affordability of design, manufacture, launch, and operation has dramatically increased the number of *space-faring* nations (as shown in Fig. 2 below), mainly for education and technology demonstration purposes. Advances in related R&D (e.g., components and sub-systems miniaturization) have also sparked a growing interest in civil, military, and commercial applications for CubeSats (ESPI 2018).

The growth of use of CubeSats is set to increase significantly with the large number of proposed CubeSat constellations (Fig. 2). With limited size and weight, CubeSats cannot match the capabilities of larger traditional satellites. For example, large optics are not feasible, and uncertainty exists with the reliance on yet to be proven launch vehicles, which may limit military use. However, constellations offer applications and services that could challenge some traditional satellite capabilities (ESPI 2018).

2.7 National Security Implications

It is perhaps unsurprising that there are both positive and negative security implications associated with the deployment of small satellite constellations, particularly those destined to be mega-constellations. The next two sections cover the positive and negative influences on national security respectively. These will be examined through the lens of the potential capabilities the constellations might provide and from the perspective of what constellations can do for a nation. This narrative does not comment on the potential *second order* impact on national security of a state resulting from an increased capability, i.e., it could be argued that for some nation's, an increased military (particularly hostile) capability could serve to decrease a nation's security as it may be perceived to be more threatening.

3 The Positive National Security Implications

3.1 Enhancement of Security-Oriented Applications

The applications or services potentially provided by small satellite constellations may not be new or indeed novel, but their availability and cost could be transformational for national security, particularly for nations that have not previously had access to capabilities. Even those nations that have previously enjoyed access to capabilities provided by their own or allies' government-owned satellite assets may find the offering from the commercial sector cost-effective and compelling.

As suggested by Larsen (2017, pp. 302–303) and Marshall (2008, pp. 154–157, 166–178), small satellite mega-constellations with remote sensing, communications, broadcasting, or navigation capabilities can offer functions that have potential to enhance a nation's security. Some notable functions are:

- *Intelligence*. A small remote sensing satellite mega-constellation positioned throughout LEO and the Medium Earth Orbit has the potential to provide a global optical and radar reconnaissance capability, with continuous or near-continuous coverage. This offers a nation an intelligence gathering capability that can, in some cases, dramatically improve a state's ability to monitor an adversary's activities and to improve their early warning potential against military build-up, maneuvers, activities, and even long-range ballistic missile strikes. The latter becomes increasingly relevant as more and more actors engage in the development long-range ballistic missile capability.

  This *intelligence* has broader security applications too. The ability to access what is happening on the ground with near-continuous coverage offers real benefits for disaster monitoring, planning and relief, enhancing a nation's resilience, an important aspect of the wider national security.
- *SIGINT*. A small satellite mega-constellation in various orbits offer nations a signals intelligence (SIGINT) capability that for some could be a significant enhancement of their ability to gather intelligence. As above, SIGINT provides a state and its military the potential to monitor an adversary's command and control networks and gain an insight into military or government activities.
- *Bandwidth*. A military communications and broadcasting small satellite mega-constellation in LEO and Geostationary Orbit (GEO) will increase demand for satellite communications bandwidth, with impact on spectrum availability for other uses.
- *Navigation*. Although this may be more in the realms of future capability, a small satellite mega-constellation may well provide navigation services, which

complement those provided by large satellite assets in GEO. This has the potential to enhance military navigation capability and provide a much-needed resilience to the loss of GNSS services. In addition to enhancing resilience and robustness of those capabilities that are reliant on space-based navigation products, such services can support a nation's ability to effectively employ modern precision-guided munitions; for some nations this could be transformational.

- *Timing*. Again, more in the future than today, but a small satellite mega-constellation may have the ability to provide a timing signal of sufficient quality to enable time-reliant systems to operate. In addition to the resilience this may provide for military capability, it also offers to mitigate the loss of timing and therefore provide resilience to the critical national infrastructure sectors' that have a reliance on timing to function.

3.2 Provision of Antisatellite (ASAT) Capability

Notwithstanding the unacceptability or legality of such a capability, it is technically possible for an appropriately enabled small satellite mega-constellation to perform as an ASAT weapon system for the purpose of neutralizing (perhaps temporarily) the functionality of an adversary's national security-oriented space system in times of conflict. This is clearly contentious and there are risks associated with ASAT activities, not least the potential for a direct or indirect response that could be deleterious to the attacking nation's own national security. There is also the significant risk of debris of the ASAT action because of its kinetic nature, again raising the potential of an escalation of retaliatory action if other nations perceive a threat to their national security. Ultimately, this can jeopardize the stable use of outer space or at least of certain orbits for any activity, including for the application of small satellite mega-constellations to advance states' national security, including personal security.

Drawing on the work of Baines (2004), Harrison et al. (2019, pp. 3–7) and Marshall (2008, pp. 160–162, 180–192), a small satellite mega-constellation can technically be configured as an ASAT weapon system, to employ a range of attack mechanisms.

- *Kinetic – Direct Impact Attack*. With an on-board propulsion system, a small satellite can be maneuvered to a conjunction with an adversary's satellite, with the intention of neutralizing or degrading a national security-oriented space capability in times of conflict. This effect could also be achieved by "nudging" another satellite to cause it to tumble. It is also possible for the attacking satellite to deploy pellets, specifically creating a targeted debris field with the intention of impacting and degrading an adversary's system.
- *Kinetic – Proximity Attack – Explosion*. A small satellite with on-board propulsion system combined with an explosive mechanism can be maneuvered to close

proximity of another satellite asset, and the charge initiated to damage the latter in times of conflict.

- *Kinetic – Proximity Attack – Capture*. A small satellite with on-board propulsion system combined with a method of capturing another orbital object, e.g., via a net or harpoon (University of Surrey 2018), and an explosive mechanism, can be maneuvered to close proximity to another satellite asset, and the charge initiated to damage the latter in times of conflict.
- *Data Disruption*. An ability to move close to another satellite with on-board propulsion and a payload with a spoofing or jamming capability could render the target satellite unusable or deny its product to an adversary. Similarly, an electronic or cyber-attack system could corrupt data on the platform degrading its systems. Satellite-based laser systems could also be employed to *dazzle* sensors, again eroding the data the sensors can both receive and manipulate.

As indicated above, it is reasonable to assume that a state's development and deployment of a small satellite mega-constellation aimed to advance its national security could be perceived by other states as a move that weakens their respective political and national security. This may lead to proliferation of these capabilities as states seek to develop and deploy better ASAT weapon systems capable of neutralizing the functionality of adversary's small satellite mega-constellation. Naturally, the application of any kind of ASAT weapon system is likely to escalate tension and perhaps result in conflict where otherwise it would not have occurred. Debris resulting from ASAT operations will jeopardize the stable use of outer space or some orbits.

3.3 Rapid Upgrade Potential

Given the anticipated life cycle of constellation-based small satellites – according to Larsen (2017, p. 279), as little as 9–18 months – there is significant potential to upgrade the security related capabilities in response to a changing threat, thus creating a form of small satellite capability *race*. With Marshall's deliberations in mind (Marshall 2008, p. 166), this is likely to be significantly more cost-effective than reliance on larger satellites remaining at the *cutting edge* (although advances in configurable software and on orbit manufacturing could challenge this hypothesis). It is the nature of small satellite constellations that there is a continuous replenishment requirement as satellites reach the end of their mission and deorbit. It is advantageous that these new small satellites can be built with a more recent generation of technology, thus upgrading the technological standard of their respective space system. Related to this is the fact that the necessary frequent replenishment missions permit operators to accept more risk in testing technology with a potentially lower readiness level, as well as to enjoy faster learning cycles in technological development.

3.4 Enhanced Resilience of Space Systems

As distinct from larger satellites, security-oriented small satellites have some features that make them innately resilient to certain types of ASAT attack. As societies (and military) reliance on many space-based products increases, the prospect of assured capability is extremely important to national security.

Leaning on related previous discussions (Baines 2004, pp. 150–152, 167–170; Larsen 2017, p. 303; Marshall 2008, pp. 166–182; Querejazu and Randazzese 2017, pp. 5–6), some of these features arguably are:

- *Small Size*. The smaller the satellites, the harder they become for an adversary to target them individually with physical ASAT weapons. Size also contributes to their individual resilience to space debris, as they are less likely to be impacted in random collisions. However, by contrast, for constellations, the large number of small satellites also makes it *more* probable that space debris hits one of them at some point – that said, the innate resilience of sheers numbers in mega-constellations is likely serve to mitigate this threat.
- *Number and Orbital Dispersion*. A constellation can comprise tens, hundreds, or even thousands of satellites situated in one or more orbits. As such, achieving a successful attack against a variety of small satellites will be extremely challenging for an adversary. Similarly, a large number of satellites potentially throughout different orbital locations make environmental events in space such as solar flares less of a threat to their collective capability. A few specific attributes can influence the difficulty an adversary would have to target and degrade a mega-constellation, and the innate resilience the system has to environmental threats:
  - The large number of satellites in the constellation, and potentially small number in particular orbital planes.
  - The distribution of different payloads among the satellites and orbits, providing a degree of system modularity. This presents the adversary with a challenge – which small satellites in the constellation do they target.
  - The satellites' potential to perform their tasks collectively and individually, presenting an adversary with a similar challenge to above – how to target effectively.
  - Satellite-to-satellite link or networking capability and multiple space-ground links or hops, which deliver innate resilience and redundancy.
- *Potential to Deploy Decoys*. Hiding decoy satellites in the constellation to increase the overall space system resilience against ASAT weapon attacks is a viable option, again challenging adversaries to determine which satellites to target.

3.5 Reconstitution of Space System Functionality

Assuming the worst where an adversary has successfully degraded a mega-constellation or its capability, the ability to cost-effectively reconstitute the system will significantly enhance a state's national security, especially when compared with the challenge associated with reconstituting larger satellite capabilities. As, mentioned in previous writings related to this topic (Baines 2004, pp. 150–152, 167–170; Larsen 2017, p. 303; Marshall 2008, pp. 179–182; Querejazu and Randazzese 2017, pp. 5–6), the attributes and characteristics of mega-constellations provide opportunity to reconstitute the system and capability comparatively rapidly. In particular:

- *Launch*. Their small size and weight means that multiple small satellites can be launched together and with a relatively low price tag. Many commercial and state launch services for small satellites are under development, offering a state more options to launch them rapidly and responsively. This also enables a state to build on-demand infrastructure and to store large quantities of spare satellites at relatively low cost. Small satellites might be launched as secondary payloads to large(r) satellites.
- *Speed of Development and COTS*. Small satellites are associated with fast, low-cost development and production cycles, due to the use of modular design and commercial off-the-shelf (COTS) products.

Notably, a potential beneficial secondary effect of a high space system resilience and reconstitution ability against ASAT weapon attacks is that it can dissuade or deter an adversary from carrying out such an attack in the first place.

4 The Negative National Security Implications

4.1 Increased Orbital Congestion

The deployment of mega-constellations in one or more similar orbits can lead to orbital congestion, potentially impairing or preventing the safe operation of security-oriented space objects in the orbits. There is also potential that congested orbits become progressively difficult to cross. Drawing on some related deliberations by ESPI (2018), Finkleman (2013), Greco (2019, pp. 105–106), Larsen (2017, pp. 277, 279–280, 289–290, 296–302), Marshall (2008, p. 178), and Shaw and Rosher (2016, pp. 319–321, 325–327), several notable attributes of small satellite mega-constellations, including with regard to operators, that affect this are:

- *Number of Small Satellites*. The deployment of small satellite mega-constellations comprising tens, hundreds, or even thousands of satellites positioned in one or more orbits can overcrowd the orbits and increase the risk of collision. Reportedly (Sweeting 2018, p. 356), the proposed small satellite mega-constellations (as of around early 2018) shall encompass nearly 25,000 small satellites, with ca. 23,000 for communications, 1500 for EO, and 800 for various services. Any such collision will lead to an increase in space debris, exacerbating the core problem. Although statistically unlikely, even with mega-constellations on orbit, an exponential increase in space debris could catalyze the so-called Kessler syndrome, where a chain reaction of conjunctions could render some orbits unusable.

- *Default Rate and Mission Life of Small Satellites*. Small satellites linked to mega-constellations still seem to have a rather problematic default rate, suggesting reliability may be an issue. For example (O'Callaghan 2019), SpaceX's first 60 small satellites launched as part of its "Starlink" small satellite mega-constellation project suffered a 5% failure rate (3 out of the 60 satellites did not work). Considering that Starlink shall consist of around 12,000 satellites at altitudes from 550 to 1100 km by the early 2020s, such a failure rate would result in around 600 inoperable satellites in these orbits just from this project. Furthermore, the mission life of small satellites can be short in some cases – according to Larsen (2017, p. 279), as little as 9–18 months, and not all of them might be successfully deorbited. Each of these factors can increase the amount of space debris in certain orbits, with the related consequences outlined under the previous point. This problem is compounded by the potential frequency of replenishment launches, necessary to maintain the constellation, that may also leave further space debris in the form of launcher components.
- *Lack of Public Registration of Small Satellites*. In the past, states have sometimes failed to register and to update the registration information of space objects for which they bear responsibility under international law, in the dedicated and publicly accessible United Nations Register of Objects Launched into Outer Space (UNOOSA n.d.), and their respective national registers. In the case of the UN registry, the information would include (Convention on Registration of Objects Launched into Outer Space, art. IV):
  (a) Name of launching State or States
  (b) An appropriate designator of the space object or its registration number
  (c) Date and territory or location of launch
  (d) Basic orbital parameters, including:
      (i) Nodal period
      (ii) Inclination
      (iii) Apogee
      (iv) Perigee
  (e) General function of the Space object

  Arguably, states' negligence to publicly register and frequently update the registration information of (mega-)constellation-forming small satellites for which they are internationally responsible can increase the collision risk in the constellation's orbit(s). Operators with space objects in the constellation's orbit(s) may lack important official information to properly predict, prepare for, and respond to potential conjunctions. Even the identification of the (mega-)constellation-forming small satellites' actual operators might prove challenging.
- *Insufficient Tracking Capabilities and "Stealth" Satellites*. There is no guarantee that an operator of space objects outside of mega-constellations has access to Space Situational Awareness (SSA) capabilities that allow sufficient tracking of small satellite mega-constellations. Similarly, there is no guarantee that an operator of a mega-constellation has access to SSA capabilities that allow for tracking

others' space objects, especially small satellites in other mega-constellations. Additionally, some satellites might be designed to have a minimal radar cross section and reduced emissions signature, specifically to better protect them from an adversary's ASAT capabilities. Thus, the deployment of one or more small satellite mega-constellations can create a situation in which some operators of space objects are unable to ensure safe navigation in the constellations' orbit(s), increasing the respective collision risk.

- *Maneuverability.* Small satellites often have no or only a limited onboard propulsion system. In the case of mega-constellations, such a technical restriction can increase the collision risk as the satellites are unable to maneuver away from a conjunction. Furthermore, constellation operators will have difficulty actively de-orbiting satellites at the end of their mission to avoid having them become space debris. A rule of thumb is that the higher the orbit of a satellite, the longer it will take to de-orbit without intervention.

4.2 Overcrowded Radio Frequencies

Building on discussions by Larsen (2017, pp. 283–287) and Shaw and Rosher (2016, pp. 313–314, 317, 321–324), operators are likely to want to use similar radio frequencies to communicate with their constellations, which over time will become a limited resource, and are subject to heavy international (mainly through the International Telecommunication Union) and national level regulation. As such, the deployment of various small satellite constellations in one or more similar orbits can lead to (localized) overcrowding of such radio frequencies. This overcrowding may lead to the degradation or denial of security-oriented capabilities. Moreover, it can make operators' interference-free communication with and thus safe control of their space objects difficult, with a consequential increase in the collision risk.

Adherence to the international spectrum regime of the ITU has a further security implication. Use of radio frequencies outside the agreed international regulatory regime can create intergovernmental discord that can grow into an intergovernmental conflict, possibly diminishing states' national security.

4.3 Danger to People, Property, and the Environment

Somewhat drawing on thoughts provided in Shaw and Rosher (2016, pp. 320, 326–327) and Staff Writers (2015), the deployment of mega-constellations has the potential to marginally increase the danger to people on Earth (injury), people's property (damage), and the environment (pollution).

Each of the many launches has the potential to fail and to distribute hazardous material, which could result in injury, property damage, or environmental pollution.

Additionally, every launch emits potentially harmful and CO_2 increasing pollutants into the atmosphere.

De-orbiting and burning up of the many launcher parts and short-lived small satellites in the atmosphere can be considered a form of pollution. Parts that do not burn up have potential to injure people, cause property damage, and pollute the environment otherwise. Naturally, the higher the number of launches and small satellites per constellation, the higher the risk to people, property and the environment.

5 Managing the Issues

As stated previously, in many respects what is a positive for the national security of one nation is very likely to be negative for another. Therefore, in terms of managing the issues around mega-constellations, the approaches taken are less focused on enhancing the positives or minimizing the negatives; they are centered on the concept of the *responsible use of space*, i.e., promoting what would generally be perceived as reasonable behavior.

There are potentially significant strategic, legal, or standards-based approaches (e.g., no-go zones, or driving behavior through an internationally agreed view of the asset and liability obligations) that may have a role in the future. Indeed, there is some guidance already in place, which is pertinent to small satellite mega-constellations; the text below comes from ISO/CDC/20991 (as cited in: Cho and Graziani 2017, p. 31):

> This standard describes minimum requirements for small spacecraft.
>
> Small spacecraft may employ untraditional spacecraft development and management philosophy. These spacecraft projects are usually budget-limited or mass-limited, which makes a single (exclusive) launch unaffordable.
>
> The scope of this standard encompasses different categories of small spacecraft, so-called mini-, micro-, nano-, pico-, and femto-, as well as CubeSat spacecraft. Therefore, for the sake of convenience, the term “small spacecraft” is used throughout this document as a generic term. Regardless of the development philosophy, there are minimum requirements every spacecraft shall comply with. This standard explicitly states those requirements and also refers to existing applicable standards. In that sense, this standard serves as the top standard to cover the minimum requirements for various stages of small spacecraft system life-cycle with emphasis on design, launch, deployment, operation, and disposal phases. In this way, (1) safety, (2) harmlessness to co-passengers and launcher, and (3) debris mitigation are all assured.
>
> This standard is addressed to small spacecraft developers, as well as dispenser providers and the launch operators.

Verification was added to address the issue on how the requirements described above should be verified. ISO/CDC/20991, provides (as cited in: Cho and Graziani 2017, p. 33):

> 6 Verification
>
> Verification of compliance with requirements listed below shall be documented with sufficient precision and quality to allow review and approval by the appropriate authority.
>
> - Safety (5.2)
> - Main payload, adjacent payload(s), and launcher harmlessness (5.3)

- Debris mitigation (5.4)
- Use of radio frequencies (5.5)
- Testing related to safety, debris mitigation, and harmlessness to co-passengers and launcher (5.7)
- CubeSat (5.8)

The documentation regarding these verifications may be required by the launch operator to guarantee harmlessness to the main passenger or the co-passengers of the flight.

However, international space law and protocols are notoriously slow to implement, and the *problem* is here now. Therefore, a more tactical approach to mitigating the risks associated with mega-constellations is needed.

There are a number of technical solutions that can be implemented as characteristic of responsible use:

5.1 Situational Awareness

The ability to determine the location of a satellite at any time is critical to the safe operation of small satellite constellations, as with any space object. In the case of small satellite constellations that have limited or no maneuverability, the choice of orbit architecture has to balance the cumulative time a satellite can be observed by limited ground-based sensors and the area of the Earth it can cover over time. This balance will determine the optimal inclination and apogee of the orbit chosen.

Observation of the satellites by radio telescopes could be more ubiquitous as they will inevitably have radio frequency signatures from both electronic devices on-board and communication transmissions. These can provide highly accurate orbit observations (Finkleman 2013).

5.2 Collision Risk: Maneuverability

The ability to maneuver a satellite, combined with accurate situational awareness, will obviously reduce the risk of conjunctions. Such capability would require either propulsion or the use of aerodynamic characteristics. The mass limitations of many small satellites, such as small CubeSats, will not allow storage of chemical propellant on-board. A better alternative is electronic propulsion, but its use is limited by the lengthy period of continuous thrust that may be required. Such thrust is necessitated by the few hours within which satellite trajectories can be estimated.

There are other possible alternatives, such as catalysis of gas or fluid into high-pressured gaseous propellant, but these also add mass to the satellite. All these possibilities for maneuver are only really effective for small orbital or attitude corrections and not for conjunction avoidance (Finkleman 2013, p. 2).

5.3 Re-entry Risk

Spacecraft and launcher upper stages in LEO will deorbit naturally by orbital decay by the operation of drag and gravity at random and by uncontrolled re-entry.

They can also be deorbited in a controlled re-entry to a known location, using on-board propellant. A controlled re-entry would also require reliable on-board computer, attitude control, and other subsystems, which add to the cost of the space object.

To achieve the less costly uncontrolled re-entry within 25 years, as stipulated in current debris mitigation guidelines, the orbital perigee is lowered to an altitude that increases atmospheric drag. The re-entry location of an uncontrolled space object, necessarily at a shallow angle, can at best be predicted within a margin of ±2,740 km, due in part to uncertainty of atmospheric density at the time of re-entry.

In the absence of agreed international norms on risks posed by re-entry of space debris, there are varying national thresholds stipulated by some countries, but by no means all space active countries. For example, French law prohibits uncontrolled re-entries from January 2020. The USA has no proposal to change its existing acceptable risk threshold defined by NASA in 1997 of 1 in 10,000 per re-entry.

Although the re-entry risk associated with the light satellites in mega-constellation is small and would meet the US threshold. However, the increasing number of launches for the predicted mega-satellite constellations will result in a growing population of dead satellites and launch upper stages that would lead to many daily re-entries. These would escalate the risk of damage and injury on the ground, at sea and to flying aircraft, unless uncontrolled re-entry is banned or acceptable risk thresholds are internationally agreed and enforced. (Staff Writers 2015)

5.4 Regulatory, Legal, and Ethical Constraints

The growing capability and maneuverability of CubeSats in particular pose security, policy, and regulatory challenges for governments responsible for their authorization and supervision. The balance has to be struck between ensuring and managing security associated with the current and foreseen growth of the CubeSat market and mega-constellations while not unduly hampering the NewSpace market dynamic. The approaches, regulations, standards, and guidelines will inevitably be at the national level, although they need to be internationally harmonized to develop a shared framework (ESPI 2018, p. 2).

It has been argued that small satellite constellations do not and cannot meet current regulatory requirements, let alone as they might evolve and regulations develop. In addition there are a number of ethical and technical guidelines relating to satellites, without differentiating between small and large satellites. Clearly these will have to be refined and developed to be effective (Finkleman 2013, p. 5).

There can be little doubt that some international solution is needed to regulatory, legal, and ethical issues surrounding small satellites and mega-constellations. As mentioned previously, there is a critical balance to be struck, between making the activities safe for all and promoting the markets that will inevitably grow with the capabilities.

5.5 Liability Considerations

An indirect threat to a state's national security is its international liability (e.g., fault liability in orbit, and absolute liability on Earth) to damage caused by small satellite mega-constellations for which it bears liability under international law. Importantly, even if the constellation is operated by a private entity, the state bears the liability. The need for an understanding of the responsible use of these capabilities is paramount and could be exercised through a robust regulatory and licensing regime. However, what is acceptable *responsible* behavior for one nation may not be the same for another, so once again there is need for international norms.

An operator's mishandling of a mega-constellation can potentially wreak havoc to foreign operators' space objects in the same orbit(s). This can expose the state liable for the constellation to catastrophic losses and thus strain its financial stability, which in turn can affect its national security. Also, if the liable state is unwilling to pay up for any of the above, there is the potential for an international conflict.

6 Conclusion

The world does indeed face a dilemma with the emergence and proliferation of small satellite mega-constellations. The potential benefits to national security are very significant, particularly for those nations for whom the access to cost-effective space capability is new. But even for the traditional space-faring nations, there are very considerable national security advantages associated with the exploitation of small satellite mega-constellations. These include: intelligence, SIGINT, bandwidth, navigation, timing, ASAT, the ability to rapidly upgrade and reconstitute space capabilities or enhance the resilience of space systems. These are all potentially significant national security positives, for some nations, transformational.

But all these potential benefits come with some risks to national security: potentially increased orbital congestion, overcrowded radio frequencies, and the danger to people, property, and the environment.

It is fair to say that one nation's benefit could well be another nation's threat or risk, so the dynamic of the impact of small satellite mega-constellations on national security is not straight forward. It is clear that to optimize the benefits and mitigate the risks, both must be managed, ideally internationally. It is likely that any legal or regulatory approach at the international level could well take considerable time to agree and implement, which points to national solutions in the short-term, perhaps based on the concept of *responsible use of space*.

While this chapter is intended to provide some food for thought, it would be odd not to offer some concluding remark. Small satellite mega-constellations are here now, and the subsector is only destined to grow. Are they a good thing? They do offer much, particularly in the realms of national security in its widest sense. However, it is necessary to exercise caution, if only to ensure that the commercial opportunities can be realized, and the potential benefits to national security are delivered.

7 Cross-References

- ▶ Commercial Small Satellites for Business Constellations Including Microsatellites and Minisatellites
- ▶ Ground Systems to Connect Small-Satellite Constellations to Underserved Areas
- ▶ Messaging, Internet of Things, and Positioning Determination Services via Small Satellite Constellations
- ▶ Overview of Commercial Small Satellite Systems in the "New Space" Age
- ▶ Overview of Cubesat Technology
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Radio-Frequency Geo-location and Small Satellite Constellations
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellites, Hosted Payloads, Dual Use, and Strategic Space Services
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation
- ▶ The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and CubeSats

References

P. Baines, Non-offensive defences: space protection without space-based weapons. Astropolitics **2** (2), 149–174 (2004). https://doi.org/10.1080/14777620490489426

M. Cho, F. Graziani (eds.), *Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery* (International Academy of Astronautics, Beijing/Paris, 2017), https://iaaweb.org/iaa/Scientific%20Activity/Study%20Groups/SG%20Commission%204/sg418/sg418finalreport.pdf. Accessed 1 Nov 2019

Collins, Definition of 'national security'. (Collins, n.d.), https://www.collinsdictionary.com/dictionary/english/national-security. Accessed 1 Nov 2019

Convention on Registration of Objects Launched into Outer Space, (adopted by UNGA on 12 November 1974, opened for signature on 14 January 1975, entered into force on 15 September 1976), https://treaties.un.org/Pages/ViewDetailsIII.aspx?src=TREATY&mtdsg_no=XXIV-1&chapter=24&Temp=mtdsg3&clang=_en. Accessed 1 Nov 2019

ESPI (ed.), *ESPI Briefs No. 25: Will Maturing CubeSat Propulsion Call for More Regulation?* (ESPI, October 2018), https://espi.or.at/downloads/send/5-espi-executive-briefs/391-espi-brief-25-will-maturing-cubesat-propulsion-call-for-more-regulation. Accessed 1 Nov 2019

D. Finkleman, The small satellite dilemma, in *Proceedings of the 6th European Conference on Space Debris*, ed. by L. Ouwehand. 6th European Conference on Space Debris, Darmstadt, Germany, 22–25 April 2013. Conference Proceedings, ESA SP-723 (ESA, August 2013), https://conference.sdo.esoc.esa.int/proceedings/sdc6/paper/123/SDC6-paper123.pdf. Accessed 1 Nov 2019

O. Greco, Small satellites: a threat for the future sustainability of outer space exploration? Air & Space Law **44**(1), 91–110 (2019)

L. Grush, As satellite constellations grow larger, NASA is worried about orbital debris. (The Verge, 28 September 2018), https://www.theverge.com/2018/9/28/17906158/nasa-spacex-oneweb-satellite-large-constellations-orbital-debris. Accessed 1 Nov 2019

T. Harrison, K. Johnson, T.G. Roberts, M. Bergethon, A. Coultrup, *Space Threat Assessment 2019, Report of the CSIS Aerospace Security Project* (Center for Strategic and International Studies, Washington, DC, 2019), https://csis-prod.s3.amazonaws.com/s3fs-public/publication/190404_SpaceThreatAssessment_interior.pdf. Accessed 1 Nov 2019

HM Government, *National Security Strategy and Strategic Defence and Security Review 2015. A Secure and Prosperous United Kingdom* (Printed in the UK by the Williams Lea Group on behalf of the Controller of Her Majesty's Stationery Office, November 2015), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/555607/2015_Strategic_Defence_and_Security_Review.pdf. Accessed 1 Nov 2019

P.B. Larsen, Small satellite legal issues. J. Air Law Commerce **82**(2), 275–309 (2017), https://scholar.smu.edu/cgi/viewcontent.cgi?article=4054&context=jalc. Accessed 1 Nov 2019

E. Mabrouk, What are SmallSats and CubeSats? (NASA, 7 August 2017), http://www.nasa.gov/content/what-are-smallsats-and-cubesats. Accessed 1 Nov 2019

W. Marshall, Reducing the vulnerability of space assets: a multitiered microsatellite constellation architecture. Astropolitics **6**(2), 154–199 (2008). https://doi.org/10.1080/14777620802147329

J. O'Callaghan, 'Not good enough' – SpaceX reveals that 5% of its Starlink satellites have failed in orbit so far. (Forbes, 30 June 2019), https://www.forbes.com/sites/jonathanocallaghan/2019/06/30/not-good-enough-spacex-reveals-that-5-of-its-starlink-satellites-have-failed-in-orbit/. Accessed 1 Nov 2019

OneWeb, Our Vision & Values. (OneWeb, n.d.), https://www.oneweb.world/our-vision-values. Accessed 1 Nov 2019

D. Querejazu, L. Randazzese, in *Small Satellites, Big Missions. The Implications of the Growing Small Satellite Market for Launch and Key Applications*, ed. by A. Hunter, K. Johnson. Report of the CSIS Defense-Industrial Initiatives Group (Center for Strategic and International Studies, Washington, DC, 2017), https://csis-prod.s3.amazonaws.com/s3fs-public/publication/170921_Hunter_SmallSatellitesBigMissions_Web.pdf. Accessed 1 Nov 2019

M. Rouse, M. Haughn, Satellite constellation (satellite swarm). (WhatIs.com, March 2017), https://whatis.techtarget.com/definition/satellite-constellation. Accessed 1 Nov 2019

A. Shaw, P. Rosher, Micro satellites: the smaller the satellites, the bigger the challenges? Air & Space Law **41**(4/5), 311–328 (2016)

Staff Writers, Escalating satellite reentry risk of internet mega constellations. (Space Safety Magazine, 15 August 2015), http://www.spacesafetymagazine.com/space-debris/falling-satellite/escalating-satellite-reentry-risk-of-internet-mega-constellations. Accessed 1 Nov 2019

M.N. Sweeting, Modern small satellites–changing the economics of space. Proc. IEEE **106**(3), 343–361 (2018). https://doi.org/10.1109/JPROC.2018.2806218

University of Surrey, Net successfully snares space debris. (University of Surrey, 19 September 2018), https://www.surrey.ac.uk/news/net-successfully-snares-space-debris. Accessed 1 Nov 2019

UNOOSA, *United Nations Register of Objects Launched into Outer Space* (UNOOSA, n.d.), https://www.unoosa.org/oosa/en/spaceobjectregister/index.html. Accessed 1 Nov 2019

Small Satellites, Hosted Payloads, Dual Use, and Strategic Space Services

Joseph N. Pelton

Contents

Abstract

The concept of dual use of and hosted payloads on commercial satellites for strategic or defense-related service requirements developed relatively early in space age. The Intelsat II satellite was deployed for the prime purpose of meeting NASA tracking, telemetry, and command needs associated with the Project Gemini mission in the late 1960s. The Marisat program in the 1970s, as funded by the US Navy, was perhaps the first instance of a hosted payload where a satellite deployed both commercial and defense related payloads at the same time. The design and deployment of small commercial satellites in low Earth orbit (LEO) by Iridium, Globalstar, and Orbcomm were strongly supported by military

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_97

programs that saw the opportunity to use small satellite constellations to meet strategic communications needs of remotely deployed personnel. Indeed there have been ongoing instances where commercial satellites, small, medium, and large, as well as hosted payloads, have been employed in a dual use mode to meet defense-related needs and strategic governmental purposes. This has been true in past decades and seems likely to continue for the future.

This chapter reviews some of the history associated with the use of small satellites and hosted-payload systems to meet strategic needs both via dedicated and dual use systems. These needs have included: (i) tactical, strategic, and routine telecommunications and networking services; (ii) support for tracking, telemetry, and command; (iii) remote sensing and surveillance; (iv) weather monitoring and real-time updates on both Earth and space weather conditions; (v) monitoring services related to aircraft safety and aircraft operations; and (vi) registering instances of nuclear device testing.

Going forward strategic use of space might be in some senses reimagined. Strategic analyses have noted that some of the challenges of the future may relate to shortages of strategic resources such as water, depletion of aquifers, or other consequences of climate change. Thus, deployment of satellites for future strategic needs might be associated with monitoring climate change, international peacekeeping or international law enforcement associated with resource shortages, etc. As global population and urbanization grows, desertification and water shortages, and concerns with illegal migration or international law enforcement increase over time, there may be new missions for space system usage in a broader definition of military and defense activities. These aspects will also be briefly discussed in this chapter.

Financial oversight organizations have consistently suggested that cost savings can be achieved by using commercial networks on a "dual use" basis to meet many of the needs of defense-related organizations and that this has seemed to be particularly true with regard to the use of small satellite systems and in the case of hosted-payload or "piggyback" systems where particular economies are possible.

This chapter seeks to review the past history of instances where dedicated or dual use small satellites or hosted payloads have been used to meet security and defense-related service needs and also to explore the future trends with regard to the more effective ways to use smallsats and hosted payloads to meet security needs in coming years. These future opportunities will be assessed in terms of costs and possible cost reductions, ability to respond quickly to service needs, and reliability and resilience of the space-based services that are needed.

Keywords

Automatic Identification Services (AIS) · Blackjack · Climate change · DARPA · Department of Defense · Dual use · exactEarth · Governmental Accounting Office (GAO) · Globalstar · Gunsmoke-L · Hosted payloads · Iridium · Internet Router in Space (IRIS) · Marisat · Meteorological services · Milamos · Mobile Satellite Services (MSS) · Networking · Orbcomm · Over the top television streaming · Responsive Environmental Assessment Commercially Hosted (REACH) · Satellite-Internet of Things (IoT) services · Space Strategic Command (SPACECOM)

1 Introduction

There has been a long-term cooperative relationship between security and defense-related agencies and high-tech companies. This relationship was strengthened when the "aerospace and defense industries" worked closely with military units to develop new aircraft, weapon systems, and the atomic bomb. The significance of the so-called military-industrial complex was emphasized by President Eisenhower as he left office in 1961. In his famous farewell address President Eisenhower said: "...We have been compelled to create a permanent armaments industry of vast proportions. This conjunction of an immense military establishment and a large arms industry is new to the American experience." He noted that this partnership, born of World War II challenge, was a great new capability but also a strong new alliance that must also be seen as a cause of potential concern. He noted that this capability could produce new capabilities that could be used for peace but also for warlike aggression alike (President Dwight D. Eisenhower's Farewell Address 1961).

In early 1960s, the space race between the United States and the Soviet Union had become an issue of prime strategic focus. The development of missile weapons systems and civilian space programs were seen as closely allied enterprises. The objective set by President Kennedy of the United States to send and return an astronaut to the Moon by the end of the decade was set in the strategic context of a "Cold War" contest between the United States and the USSR (Logsdon 1970). Likewise the initiative to create a global satellite system as also called for by President Kennedy in early 1961 in a speech to the United Nation was an effort to use space applications as yet another way to showcase US technology in the space applications domain (Pelton 1974).

The US military sought to deploy satellite technology to provide secure global telecommunications with the deployment of the Initial Defense Satellite Communications System (IDSCS) in 1965 as a small satellite constellation low Earth orbit (LEO) with random spacing. This type of system, however, was not continued when the Syncom 2 and 3 satellites followed by Intelsat I (i.e., Early Bird) showed in a convincing manner that GEO systems were sustainable and operational viable.

The shift to GEO systems and increasingly larger and complex satellites in general was adopted not only by the US military systems but also by other charged with security responsibilities in Europe, India, China, Canada, Japan, and the USSR/Russia. This did not mean that interest in smaller satellites was dropped. Further, military and security-monitoring organizations also recognized that the concept of hosted payloads on satellites of all sizes opened up another option. Hosted payloads could be used to test new technologies and system capabilities or to create a complete new capability if deployed on a global constellation.

These various ways that have been employed to use small satellites or hosted payloads are reviewed below. These instances are now quite numerous and going forward are likely to increase in number. The US General Accounting Office published a report with regard to the placing of hosted payloads on commercial satellites since 2009 and included several planned through 2022. Its independent conclusion with regard to this approach in the case of the US military was as follows: "The GAO and others have found that using commercial satellites to host government sensors or communications packages – called payloads – may be one way DOD can achieve on-orbit capability faster and more affordably. Using hosted payloads may also help facilitate a proliferation of payloads on orbit, making it more difficult for an adversary to defeat a capability. . .DOD estimates that it has achieved cost savings of several hundred million dollars from using commercially hosted payloads to date, and expects to realize additional savings and deliver faster capabilities on orbit from planned missions" (U.S. Governmental Accounting Office 2018).

Cost savings are not restricted just to "hosted payload" systems. The development and use of dedicated small satellite projects – both as specific missions and larger-scale constellations –can also provide cost economies to security-focused activities. Of the six applications listed in the abstract and perhaps more, the use of small satellite systems can help to lower costs. These cost savings can come from: (i) new designs such as using miniaturized components, (ii) new construction techniques (i. e., additive manufacturing), (iii) use of standardized and sometimes off-the-shelf components, (iv) use of new launch technology (i.e., reusable first stage launchers), or (v) use of new digital or smart software that allows smaller spacecraft to accomplish new functions or services such as video streaming; improved synthetic aperture radar sensing; or three-dimensional terrain mapping.

2 Transition from GEO-Based Satellites for Defense and Security-Related Services to Smallsats

For many years one of the larger applications for dual use of larger-scale GEO satellites, at least in terms of revenues, was for television entertainment distribution. Most of such video distribution activities were not strategic in nature. These satellite telecommunications that relay functions for defense agencies have included such activities as distribution of sports and entertainment television and radio programming, or personal communications between troops and family. Yet such activities were still clearly in support of defense-related missions such as overseas deployment of troops and troop morale. In the future it is possible that some of the new large-scale networking constellations, and projects such as the Karousel elliptical orbital system, that seek to provide video streaming might meet such security or defense-related service needs on a 'dual use' basis.

The existing ground system configurations, however, may well serve as a key reason as to why these video-related services might largely remain the preserve of large-scale geosynchronous satellites for a number of years to come. In a number of cases it will be the cost and configuration of ground systems that will dictate which types of satellites provide which types of services for a number of years to come. In general, the cost of flat panel antennas with electronic beam forming and the rate at which the cost of these systems fall will be a strong factor of small satellite constellation success in many markets – commercial, governmental, and defense-related alike.

3 Security and Defense-Forces Deployment of Hosted Payload Small Satellite Programs

There are a number of instances where US DOD defense-related projects have gone forward or are now in planning or active construction. These projects have served to a test of key new space technology concepts. On November 23, 2009, the IRIS (Internet Routing in Space), as designed and fabricated by CISCO Systems, was launched on-board the Intelsat 14 satellite. This piggyback mission was to test the feasibility of high-speed on-board processing and routing of signals in space. This successful test led to the conclusion that the ground segment for DOD telecommunications and networking satellite networks could be simplified and thus deployed at much less cost without losing network capability (Brinton 2009) (Fig. 1).

Perhaps the other end of a hosted payload-type project for defense purposes from the IRIS one-off technology feasibility test is the DOD REACH system. This is the Responsive Environmental Assessment Commercially Hosted (REACH) program that involves the installing of over 30 dosimeter instruments on a number of different

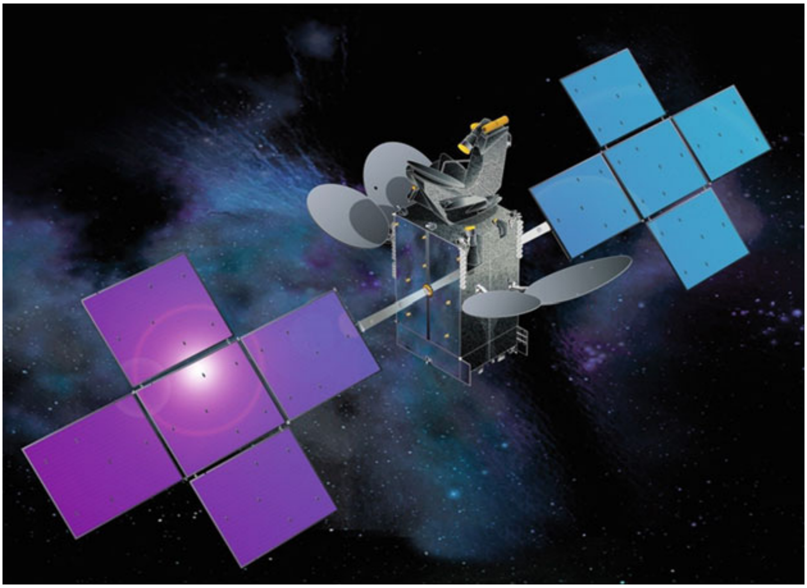


Fig. 1 The Intelsat 14 satellite with hosted payload IRIS router aboard (see gold and black units). (Graphic courtesy of Intelsat)

commercial satellites to create a systematic monitoring of space radiation. These instruments that were inserted in a number of different commercially deployed LEO satellites each had two dosimeters of differing sensitivities to detect radiation from space weather or from a nuclear explosion that released radiation.

This configuration was not to test a new technology, but rather an operational system to detect radiation from a global perspective. This system was designed to detect radiation from a coronal mass ejection from the sun, a nuclear explosion, or even cosmic radiation (Mazur et al. 2017).

Independent assessment of the implementation of the REACH program on-board commercial systems rather than as stand-alone networks found that it was deployed at an estimated cost savings of $230 million. The additional finding was that the system was able to be deployed in a more rapid manner due to the use of a variety of LEO-deployed commercial satellites to carry these REACH instruments. Although it was not a part of this assessment, it is also clear that the use of piggy-backed instruments, rather than deploying them as free flyers, also reduced the space debris concerns when these instruments reached their end of life (U.S. Governmental Accounting Office 2018).

Yet another payload arrangement has been used in the GEO-based MUOS network for mobile communications deployed by the US Navy for naval and other DOD net-centric mobile operations. In this case there is a UHF-legacy package that flies on the MUOS satellites. The MUOS system has 16 times greater throughput capability than the original UHF satellite system and will eventually replace the UHF Satellites. These MUOS satellite carry a small “legacy” payload that will provide UHF telecom service until the old narrow band UHF SATCOM system is entirely phased out (U.S. Navy Program Executive Office 2016).

4 Dedicated Small Satellite Programs for Defense and Security-Related Programs

Clearly the US DOD is still heavily focused on large GEO networks. Although it has supplemented its mobile capabilities through dual use of the Iridium and Globalstar systems, its legacy, SATCOM UHF and MUOS (Mobile User Objective System), is based on GEOS networks with large deployable multi-beam antennas.

Although the US Department of Defense has been funding in the last few years, i. e., since 2017, commercial efforts to develop small launcher capabilities, it has been slow to develop specific programs for dedicated small satellite networks. There have been few dedicated smallsat projects undertaken or even started. Instead, there have only been the hosted payload projects such as the REACH network, and the legacy UHF payloads on the MUOS satellites.

In the US 2019 budget there was a new line item that includes $47.6 million procurement funding line for the procurement of smaller capacity launchers that can lift up to a capacity of 3636 kg (or up to 8000 pounds). This is for the so-called Rocket Systems Launch Program and would cover both LEO up to GEO launches.

Fig. 2 The Vector Smallsat Launcher designed for rapid deployment from flexible launch locations. (Graphic courtesy of Vector Launch, Inc.)

Presumably this would be for rapid deployment capabilities and for a variety of small satellite launch requirements (Erwin 2018a).

Under the DOD small launch vehicle program the idea has been to fund perhaps two launcher programs. This is a difficult activity to decide since there are now on the order of 150 small launcher development programs vying for support. There are several front runners such as Vector, Virgin Orbit, and Rocket Labs who have been mentioned as lead candidates. The truly unsolved mystery is what payloads are to be launched and whether these will be for LEO constellations or GEO-based missions – or perhaps both (Hitchens 2019) (Fig. 2).

The US Defense Advanced Research Projects Agency (DARPA), however, has an active R&D effort known as “Blackjack.” The purpose of this program would be to create a series of “interchangeable payloads.” The apparent objective under the R&D program would be to develop a series of “commodity-like” set of different payloads that would be capable of being “plugged into” a common bus. The process has been likened to developing common payloads which could be “snapped” into a common satellite bus very much like “Lego” units. This would eliminate the need to create different small satellite buses over and over again. There have been reports that the Air Force might seek to transfer the findings from the Blackjack R&D into actually implementation. This US Air Force project is currently called CASINO (Commercially Augmented Space Inter Networked Operation). The funding for this program is currently not authorized by Congress (Paul “Rusty” Thomas 2019).

In 2018 the US Army Space and Missile Defense Command (SMDC) took two actions on the small satellite front. On the one hand, they cancelled the Kestrel Eye small satellite experiment. This was a $2 million project which had been ongoing for a couple of years. Its objective had been to test the feasibility of a dedicated network of LEO smallsats that would be able to provide tactical communications to ground troops. There was no explicit reason provided for the cancellation of this test program.

The Army Command however in close proximity announced that they had selected Dynetics as the contractor that would be developing two new small satellites for a classified program known as Gunsmoke-L. The purpose of this $.3 million project was to develop two small tactical spacecraft that would operate in low Earth orbit for at least 2 years and would be used to support tactical operations of the Army in an unspecified manner (Erwin 2018b).

There are many unknowns at this point in terms of small satellite launcher firms that will play a leading role, the types of satellites, missions, and orbits that will be pursued in the new US space initiatives that have been announced under new initiatives that have been various described as a "US Space Force" or new "US Space Command" or "SPACECOM" which has been described as a new capability "to defend America's vital interests in space." This so-called Space Command – one of 11 specific commands – would presumably take the place of the so-called Space Force that had originally been backed by President Trump. Until the mission, objectives, and strategies of the US SPACECOM are better defined, the plan for expanded use of dedicated smallsats and expanded use of lower cost and smaller cost launchers of small satellites will likely remain somewhat nebulous (Howell 2019).

Further this uncertainty will also likely impact the future planning and space security programs of other space powers such as China, Russia, Japan, Europe, and other countries such as Israel, Iran, and North Korea. The uncertainty created by the US efforts in the arena of space security and space defense was one of the top areas of discussion and concern at the European Space Policy Institute's annual conference in Vienna, Austria.

There has been a broadly based international effort to define a common global terminology with regard to space security matters and military uses of outer space that began in May 2016 known as Milamos. This effort was undertaken to create a "Manual on International Law Applicable to the Military uses of Outer Space (Milamos)" and especially issues related to possible space hostilities. The purpose of this project is as follows: "Such a manual will clarify the limitations international law places on the threat or use of force in outer space. It aims to look at how, against the backdrop of rapidly developing technologies and applications, what military uses and objects are considered lawful or outrightly prohibited in outer space" (Manual on International Law Applicable to the uses of Outer Space (MILAMOS) 2016a). This effort is financially backed by the Canadian Government and involving space lawyers from a wide range of universities around the world. Participating institutions are McGill University, St. Thomas University, the University of Cologne, Beijing Institute of Technology, St. Petersburg State University, Institute of Defense Studies and Analysis, Western Sydney University, and the Secure World Foundation (Manual on International Law Applicable to the uses of Outer Space (MILAMOS) 2016b).

This effort is known as the Milamos project and it has tried to confirm the peaceful uses of outer space patterns under existing international law and international treaties and conventions that have been approved by the international community of nations ever since the "Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space," which had been adopted by the General Assembly in its resolution 1962 (XVIII) in 1963. This was followed by the adoption and entry into effect of the Outer Space Treaty of 1967 known formally as the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies" (UN Office of Outer Space Affairs 1967).

It is still too early to know the practical effects of new initiatives in military space. The new US Strategic Command for Space appears to suggest that there will be a more confrontation environment. On the other hand, the international Milamos effort to create a new international manual to address international law provisions and terminology seeks to minimize confrontation and spell out more clearly what the "rules of road" for outer space, especially in Earth orbit, actually are today.

5 Fast Deployment Concepts

The idea of being able to deploy special capability to provide telecommunications and networking capacity to a particular area where hostilities might occur over land or littoral locations has been suggested as a need that might occur when a war or armed confrontation breaks out where limited communications or other services are in very short supply. The original context was that a GEO satellite might be ready to be quickly deployed on a separate launch operation on demand and with minimal delay.

The development of new small satellite technology and rapid availability of small satellite launchers that can be quickly be configured for virtually instance deployment has advanced the feasibility of such a concept. Other requirements for radiation detection instrumentation, surveillance systems, or other applications could be designed as rapid deployment space systems. The problem is that most rapid deployment systems would make sense as GEO-sat systems because these systems provide coverage of up to 40% of the Earth's surface, while LEO and MEO systems require a good sized configuration to provide wide area coverage.

The development of new smaller launch vehicles that can be quickly deployed and virtually instantly launched would seem to be the major advancement in this area. It is still not clear how significant this type of capability might be and when this type of rapid deployment capability might actually be used to respond to future strategic needs.

6 Use of Commercial Small Satellite Programs for Dual Use Services

The history of space applications and services in the domain of military defense and national and regional security systems suggests that the military and defense-related aspects of outer space have continued to expand. Strategic concerns about the space domain are expanding due to new technology and applications related to system systems. A part of the concern and strategic “confusion” arises from the expansion of “dual use” applications of commercial systems and a rising number of hosted payloads wherein military and defense-related capability are added to civil governmental or commercial space systems.

There is currently a significant use of commercial mobile communications as a backup, supplement, or even primary mode of mobile communications to support military purposes. Thus the Inmarsat system is used for mobile communications on the move as well as service to Inmarsat I phones in support of strategic mobile services in Europe. The Globalstar OG2 and Iridium Next LEO-based networks are still heavily relied on for various forms of voice and data communications by US defense networks even though the deployment of the MUOS system has lessened these requirements to some extent. The latest generations of these satellites are now at the upper limits of what can be considered to be minisatellites. Further the Aireon system on the Iridium Next is also of assistance in military air navigation capabilities as well (see Fig. 3).

Even the Thuraya GEO-system for mobile satellite services is relied on by some defense units. The Inmarsat and Thuraya commercial systems can provide higher data rate services, but the Globalstar and Iridium services can provide mobile voice and data services with greater reliability at the higher latitude regions of the world.

The other key dual use issues as posed by small satellite constellations in terms of strategic and defense related applications are the large number of new Mega-Leo systems now being deployed or planned for launch within the next 5 years. These present both potential opportunities and potential concerns. Many dozens of new these new systems are being deployed for broadband communications and networking, for optical and radar remote sensing, and some totally new uses such as

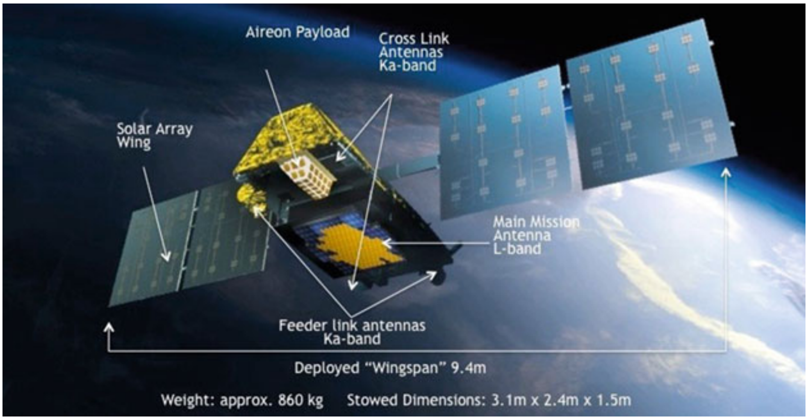


Fig. 3 The Iridium next generation of mobile satellites is still used to provide dual use military mobile communications to several nations. (Graphic courtesy of Iridium)

commercial data relay from LEO to GEO satellite or MEO satellites or RF Geolocation. It is entirely possible that defense and military applications will be found for many of these new networks. The deployment of so many of these satellites, however, also poses risks of satellite collisions and thus danger to military satellite networks.

Many of these new LEO-based systems will provide greatly expanded coverage and remote area services that are not available with existing GEO networks. The ability of the broadband Mega-LEO networking satellite systems to provide interconnection via low-cost Wi-Fi networking services in rural and remote area might offer dual use capabilities that might prove of significant value to future defense-related needs.

There are also clear value that the data relay and machine-to-machine (M2M0) commercial systems can provide for dual use in such areas as automatic identification services (AIS), for Internet of Things (IoTs) data relay, and other forms of data relay associated with mobile platforms, vehicles, and ships. Systems like Orbcomm, Spire, exactEarth, and others offer AIC, M2M, and IoT data and more that will likely find a variety of dual use applications. Some of the new systems such as exactEarth provide significant economies for vital data that can pay for the service simply by such measures as fuel savings for ships that can be steered much more efficiently from port to port or avoidance of dangerous storms at sea (see Fig. 4).

The ability of some of these systems, particularly those operating MEO systems that might provide new dual use options for offering video streaming service needs, could also offer new options for providing sports and video entertainment to overseas troops or other dual use needs such as support for UAV systems carrying out remote surveillance service needs. In short, these new LEO and MEO system potentially offer many dual use opportunities and new cost efficiencies.

Fig. 4 There are dual use opportunities from smallsat systems like the exactEarth small satellites as pictured below. (Graphic courtesy of exactEarth)

7 Extremely Small Satellites for Strategic or Defense-Related Needs

Most of the dual use applications of commercial small satellite systems that have been discussed above are geared to wide area coverages on a regional or global basis, since satellite altitudes offer the advantage of wide coverage as one of their prime advantages. There are however other types of applications that can be pursued in the case of the very smallest of satellites such as femtosats, chipsats, picosat, pocketqubes, and cubesats. In the case of field effects such as radiation or changes to the Earth's magnetosphere, coronal mass ejection storms hitting the Earth's atmosphere, it might be very useful to have a cluster of something like chipsats, femtosats, etc., to fly into an area in proximity to a mother ship. This could allow a group of these smallest of satellites to collect data and to report data back to a central satellite that can relay data back to Earth.

There are also conceptual studies of creating a virtual antenna system that is created by a large collection of picosat electronic units that can be combined together to create a large-scale "virtual electronic" transmitting and receiving system. This type of architecture might allow the creation in space of new types of antennas that are no longer "dishes" or even solid structures but simply a cluster that is shaped by electromagnetic forces. This might be used for interplanetary communications or other future scientific or strategic purposes (Iida et al. 2003).

8 The Smallsat Advantage for Defense and Security Services

The expansion of the military and defense establishment into the small satellite has understandably been a slow, cautious, and deliberate process. The first steps have been through the installation of hosted payloads on to commercial platforms, the use of small satellite projects to test new technology and to carry out experimental projects, and to exploit commercial small satellite via dual use applications starting with mobile satellite services. This experience has been generally favorable.

Independent assessments of these uses of small satellite systems, technologies, hosted payloads, and experimental projects have suggested that reduced costs have been achieved, program objectives were effectively met, and projects were generally advanced over being carried out through dedicated defense, military, or especially designed security systems.

The current conditions seem to indicate that the next step appears to be to move into dedicated small satellite constellations. The DARPA Blackjack, the Army Casino initiative, and the Gunsmoke-L initiatives will likely help to define new dedicated projects and full-fledged constellations. This does not mean a rapid shift away from large-scale GEO-based systems and MEO-based networks such as the Global Positioning System (GPS). Rather it suggests a more balanced and agile combination of types and sizes of satellite systems. In general, it seems likely that European defense initiatives will build on the experience gained by Air Bus and

Thales Alenia in building a significant number of LEO-based systems to meet future strategic and military systems with a reliance on dual use systems as well.

9 Space Satellite Constellations to Meet Strategic Space Concerns of the Future

The military, defense, and strategic uses of outer space are often used interchangeably to refer to space systems for national and regional defense. These systems might be used to support surveillance, telecommunications, networking, or broadcasting services of a tactical or operational basis, weather monitoring, navigation, targeting or guidance, monitoring the skies for enemy attack, or assessing radiation or other signs of the use of weapons of mass destruction. There have been studies of future trends that suggest that in future the results of climate change, particularly water shortages, desertification, and resulting patterns of migration could become strategic and national defense-related issues.

The ability of satellites today to support positive developments such as the meeting of the UN Sustainable Development Goals (SDGs) may tomorrow also be used strategically to monitor scarce resources, or to monitor key aspects of climate change in a strategic sense of the word. Strategies that can be used today to cope with climate change in a sustainable way might become increasingly important. Small satellite constellations equipped for Earth observation, data analytics, water conservation, and sustainable urban planning and operated as commercial or civil governmental space agency operations may become increasingly important in a strategic sense in coming decades.

10 Conclusion

The future of military and defense-related satellite systems is at strategic point where a number of key decisions will need to be made. These decisions will largely hinge on whether to continue to focus primarily on a space infrastructure investment program that is concentrated on large, sophisticated GEO-based systems for telecommunications, networking, surveillance, and meteorological systems and high MEO GPS systems or to diversify more into the accelerated use of various forms of small satellite systems.

11 Cross-References

- ▶ Security Concerns Related to Smallsats, Space Situational Awareness (SSA), and Space Traffic Management (STM)
- ▶ Small Satellite Constellations: National Security Implications
- ▶ Small Satellites and Planetary Defense Initiatives

References

T. Brinton, CISCO views IRIS experiment as market primer for space market. Space News (Nov 27, 2009), https://spacenews.com/cisco-views-iris-experiment-market-primer-space-routers/

S. Erwin, DOD space budget: billions for next gen satellites; new launch vehicles; new funding for "rapid acquisitions." Space News (Feb 13, 2018a), https://spacenews.com/sn-military-space-dod-space-budget-billions-for-next-gen-satellites-launch-vehicles-new-funding-lines-for-rapid-acquisitions/

S. Erwin, U.S. army kicks off new small satellite program. Space News (Nov 14, 2018b), https://spacenews.com/u-s-army-kicks-off-new-small-satellite-program/

T. Hitchens, Vector aims to be one of two DOD small launch firms. Breaking Defense (May 8, 2019), https://breakingdefense.com/2019/05/vector-aims-to-be-one-of-two-dod-small-launch-firms/

E. Howell, Trump launches US space command to control the "next warfighting domain." Spaceflight (Aug 30, 2019), https://www.space.com/trump-launches-us-space-command.html

T. Iida, J. N. Pelton, E. Asford (eds.), *Key Trends in 21st Century Satellite Communications* (AIAA, Washington, DC, 2003)

J. Logsdon, *The Decision to Go to the Moon* (MIT Press, Cambridge, MA, 1970). https://mitpress.mit.edu/books/decision-go-moon

Manual on International Law Applicable to the uses of Outer Space (MILAMOS) (2016a), https://mcgill.ca/milamos. Last accessed 4 Sept 2019

Manual on International Law Applicable to the uses of Outer Space (MILAMOS) (2016b), https://mcgill.ca/milamos/partner-institutions. Last accessed 4 Sept 2019

J.E. Mazur, T. Guild, W. Crain, S. Crain, D. Hoker, P. O'Brien, S. Quintana, M. Kelly, R. Barnes, T. Sotierelis, Monitoring space radiation hazards with Responsive Environmental Assessment Commercially Hosted (REACH) NSREC conference (2017), https://cpaess.ucar.edu/sites/default/files/meetings/2017/documents/mazur_REACH_NSREC_2017_extended_abs.pdf

Paul "Rusty" Thomas, "Blackjack" DARPA program information (2019), https://www.darpa.mil/program/blackjack. Last accessed 1 Sept 2019

J.N. Pelton, *Global Satellite Telecommunications Policy: INTELSAT, Politics and Functionalism* (Lomond Systems, Mt. Airy, 1974)

President Dwight D. Eisenhower's Farewell Address (1961), https://www.ourdocuments.gov/doc.php?flash=false&doc=90. Last accessed 1 Sept 2019

U.S. Governmental Accounting Office, DOD's use of commercial satellites to host defense payloads would benefit from centralized data, GAO-18-493, Report to the U.S. Congress House of Representatives, Committee on Armed Services (2018)

U.S. Navy Program Executive Office, Fact sheet on MUOS (2016), https://www.public.navy.mil/navwar/PEOSpaceSystems/Documents/146_FactSheet_MUOS5_%202016_FINAL_7Oct16.pdf

UN Office of Outer Space Affairs, Treaty on principles governing the activities of states in the exploration and use of outer space, including the Moon and other celestial bodies (1967), http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

Part X

Key New Uses of Smallsats to Meet Social and Economic Needs

Small Satellites and New Global Opportunities in Education and Health Care

Joseph N. Pelton

Contents

Abstract

The advent of satellite communications has opened new doors to health and education services around the world. This has been true from the very earliest day of the space age – particularly in rural and remote areas of the world but also all across the world. As satellite communications system became more powerful and capable, this enabled the use of smaller and less costly ground antenna systems that required much less power. This extended the global footprint of where satellite services – including those for tele-education and tele-health services – could be delivered.

This expanded ability to deliver satellite services, even into rural and remote areas, enabled the creation of satellite-based health care and schooling in many areas of the world where such services were limited or even totally lacking. The latest evolution in the satellite industry now involves innovations in the field of

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_54

small satellite systems. One of the objectives for these small satellite constellations is for them to be designed, built, tested, and deployed at significantly lower cost.

A further objective is to operate such low Earth orbit constellation with minimal transmission delay and thus optimize them to provide Internet-based services to rural and remote areas, perhaps more efficiently than GEO-based satellite networks. Such new abilities to offer broadband Internet-based services with minimal transmission delay are thought to allow new options. Prime among these options are a wide variety of new satellite-based health and education services that opens the door to such offerings being much more widely. Indeed the aspiration is to provide expanded services to billions of now unserved or underserved populations – especially in Africa, South and Central America, Asia, and the South Pacific – and perhaps even expand rural and remote populations in economically developed countries wherever they might live. There is a long history, now longer than over 40 years, of using satellites to provide rural and remote health and educational services. This article will review some of this history and explore the potential of new large-scale low Earth orbit satellite networks being equipped to extend these tele-education and tele-health services even further.

Keywords

Broadband services · Digital divide · Flat panel antennas · Internet service provider · Geosynchronous Earth orbit (GEO) · Low Earth orbit (LEO) · Medium Earth orbit (MEO) · Photovoltaic · Small satellite constellations · Solar power and battery systems · Tele-education · Tele-health · Virtual private networks (VPNs) · Wi-Fi systems · Wide area networks

1 Introduction

The great advantage of satellite communication technology has always been its ability to provide very broad coverage of the world and especially to connect to rural, remote, and island areas. The initial geosynchronous Earth orbit (GEO)-based satellite systems, from the first, were well suited first to providing television distribution services and coverage to remote areas. As satellite technology and systems became more powerful and capable, these networks also became enabled to provide direct broadcast television and broadcast radio service. Although the commercial market for broadband GEO satellites has been largely supported by the demand for entertainment, news, and sports-related services, there has been, in parallel, a significant use of these satellites for health, education, and training purposes. With the birth and expansion of Internet-based services, however, there has been a shift toward the use of interactive health and education services via networked services, especially via the Internet, that have often used terrestrial cable and wireless services. In a number of cases, this has led to a transition off of satellite networks and on to Internet-based or networked streaming services.

GEO satellites have sought to respond to the challenge of providing streamed network services and multi-casting-based operation. These attempts to optimize GEO satellite systems to offer networked services have included “spoofing” and new standards to compensate for transmission delays and the creation of virtual private networks. This has, in particular, led to the development of so-called Internet Protocol over Satellite (IPoS) standards. These have included IA Standard 1008, IPoS, November 2003, and TSI Standard TS 102354, TSS-B, January 2005. These standards for providing IPoS via GEO orbit satellites have allowed the following adjustments to occur for more efficient provision of networked services (Hughes Network Systems (HNS) briefing at Intelsat Headquarters):

- Increase window size so that latency is not confused with system congestion and thus force a resort to slow recovery.
- Provide “spoofing” so that each transmission leg is optimized.
- Operate under the IETF-recommended “DiffServ” mode of operation with per-hop behavior (PHB) optimization.
- Flags are generated so that new headers can be correctly read.
- Cope with IP Sec (Internet Protocol Security) processes in virtual private networks (VPNs).

Despire these efforts to GEO satellites for networked services, limitations still remain. This is a particular problem where the flow of data is not highly assymetrical and especially where there is continuing flow of information in both directions and at higher data rates. Indeed in many cases, GEO satellite systems operations in rural and remote areas have been designed to broadcast broadband services on the downlink and then use terrestrial networks for narrower-band return link services.

But the newer MEO and LEO satellite constellations that have been deployed, starting with Iridium and Globalstar, and more recently with the O3b medium Earth orbit (MEO) constellation, have been optimized for networking services. It is the aspiration of the new LEO-based constellation such as OneWeb and a number of other large constellations of small satellites to be better equipped to provide networked services and especially to support Internet-based services. Nevertheless GEO-based systems such as Intelsat, ViaSat, EchoStar/HNS Jupiter services, etc. continue to offer a range of networked services in both developed and developing regions of the world using the optimized standards noted above.

What is indisputable is that these new LEO and MEO systems are much closer to Earth and have much lesser transmission delay. Thus, in some ways, these constellations are better suited to data networking. In fact, in some of the lowest altitude of these systems, such as Starlink by SpaceX, transmission latency is equivalent to or better than terrestrial fiber-optic networks. These systems are thus well suited to providing broadband interactive services to support the latest forms of networked health and educational services designed explicitly to operate via the Internet.

In light of the already rich history of satellite-based tele-education and tele-health services via GEO satellites, there are high hopes with regard to the future use of small satellite constellations in this way. The aspiration is to use these new LEO constellations to provide the newest and latest forms of streaming and networked services for health and education purposes. It may well be that it is really not the technical and operational capabilities that are the main issue but rather financial, social, and regulatory issues that might represent the largest obstacles to this expanded usage.

Nevertheless this article will examine the degree to which LEO and MEO constellations are well suited to provide extended technical and service capabilities via networked delivery systems hosted on the Internet. It will explore the unmet needs of the estimated three and half billion people who now have limited or no access to the Internet.

This in turn results in limited access to health, education, and training services in their remote or isolated communities since so much of these resources are now only accessible via the Internet. It is some of the largest providers of access to the Internet globally who are pushing to extend Internet access to the billions of unserved peoples. Thus these backers are companies like Google, Amazon, and Facebook as well as banking institutions, broadcasters, and a wide range of other commercial enterprises who operate primarily via networked services. Yet, beyond these commercial interests, there are others who see the opportunities for providing vital social and civic services in a more effective and cost-efficient manner ("Broadband for the Next Billion" n.d.).

This extension of the digital network via LEO constellations to serve all the 7.8 billion habitants of the planet will help to reduce the "digital divide." It extends a whole new range of education, training, and health services to underserved regions of Africa, Asia, Central and South America, and the South Pacific.

The expanded capacity that these smallsat constellations provide is some sense being deployed at a critical time to meet growing unmet needed in education and health care. Some estimates suggest that the billions of students to be educated within the next three decades are equivalent to all the students up to this point in history. These estimates are based on the growth of global population, the rise of so-called megacities, and the extension of education and health-care services to an expanding range of people that will come with expanded communications and networking. These projections are based on estimates of nine billion people on Earth by 2050. The astonishing growth of world population is shown in Fig. 1.

The requirements of these various services are different in many ways, and thus health-care-based services, educational services, and training services will be broken down to examine what some of the technical differences that apply. This analysis will also explore some of the practical and operational service requirements that will need to be met to serve the needs of these underserved populations.

2 Historical Background

The use of satellite transmission to support medical and health systems, education, and training links back to the first commercial satellite services. One of the early television satellite broadcasts featured Dr. Michael Debakey, while performing a heart transplant in South Africa, sharing his procedures with doctors in the United States and Europe (Pelton and Alper 1986). The world's first truly global television

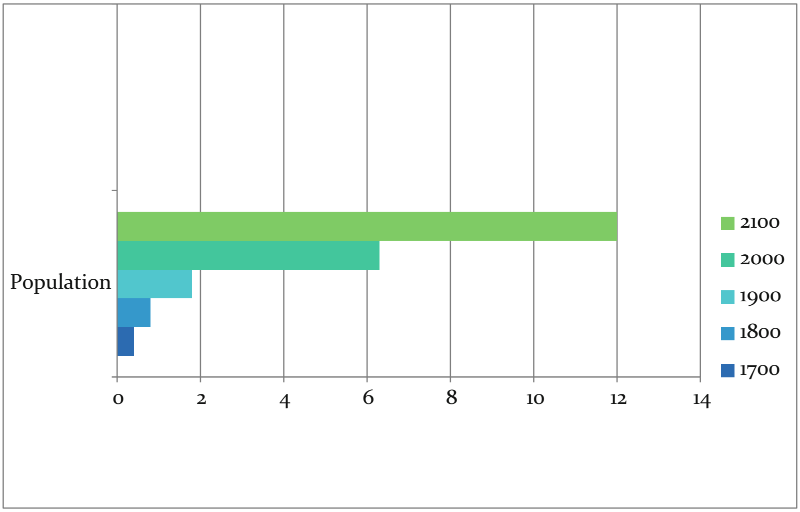


Fig. 1 The growth of human population since 1700 and projections through 2100. (Graphic prepared by Dr. Joseph N. Pelton. All Rights Reserved. Licensed for use by Author)

broadcast via Intelsat III satellites over the Atlantic, Indian, and Pacific Oceans was the coverage of the first landing of astronauts on the Moon in July 1969 a half century ago. This was not only a news event, but it was also a global educational event. Three Intelsat III satellites provided a worldwide "live" audience of over 500 million people an understanding of the technology that was involved and knowledge of how an Intelsat satellite had been moved from the Pacific Ocean to the Indian Ocean a little over a week before to create a truly global satellite network (Teitel n.d.) (See Fig. 2).

In the 1970s the Intelsat system began to provide not only international services, but it also began to lease transponders to countries to allow them to create national satellite networks beginning with Algeria in Africa. This network in Algeria connected with live telephone, data, and television services over a dozen regional capitals with telephone and data services during the day and television programming after 5:00 pm. This television service included news, entertainment, and educational programming. The harsh Saharan desert conditions had not allowed this type of telecommunications services using terrestrial connections. This new system allowed the transmission of educational television and public health messages. After the Algerian domestic network was established, over 70 domestic satellite systems were established around the world (Joseph 1986).

On the occasion of Intelsat's 20th anniversary, it was agreed to create what was known as Project SHARE. In this case SHARE stood for Satellite Health and Rural Education. An international advisory committee was established, and a joint cooperative agreement was established between Intelsat and the International Institute for Communication (IIC) in London that was signed to help administer the program. Under this program over 50 different programs were carried out to use Intelsat satellites, free of charge, to provide national or international television projects for

Fig. 2 Neil Armstrong descending from the Lunar Excursion Module Eagle 1 in July 1969. (Image courtesy of NASA)

educational and/or health-related programs. One of these projects included creating a Chinese National Educational Television University in 1985, 1986, and 1987. This project started with dozens of small terminals deployed in rural areas that were connected to an Intelsat satellite to provide educational and health-related programming (See Fig. 2). The programming for this network was developed by Central China Television and the Ministry of Education. When this system was transferred to a domestic ChinaSat network, this program ultimately grew to 90,000 very small aperture terminals serving 10 million students (Pelton and Marshall 2019) (see Fig. 3).

In another project there was a televised program of the world's leading doctors with expert knowledge of AIDS that was shared with 60,000 doctors and medical caregivers in Africa, Europe, North America, and South and Central America to advise this large audience the latest in research knowledge about this disease, its prevention, and treatment. And the Intelsat Project SHARE activity was just one of many such programs.

In India there were experiments with NASA's ATS-6 satellite that were successful in delivering educational and health-related programming to rural and remote communities. This led to the current INSAT educational satellite program that is delivering health and educational services to over one million students. In addition to the satellite programs in China and India, there are dozens of other programs. The Indonesia satellite program with Indosat was one of the earliest and was innovative in that it combined commercial service sites for oil, mining, or other industrial activities with earth station connections to serve education, health, and community needs (Satellite Television in Indonesia n.d.). Other significant programs can be

Fig. 3 The distribution of satellite TVRO terminals for Project SHARE tests sponsored by Intelsat. (Graphic courtesy of Joseph N. Pelton, Director of Project SHARE)

found in Mexico with Satmex, Nigeria, Malaysia, Brazil, The University of the South Pacific, the University of the Caribbean, Canada, and the United States plus a number of programs transmitted via the Arabsat network that supports services in a number of Middle Eastern countries programs.

In the last few decades, there have been many innovations in satellite-delivered public education at the primary and secondary levels, in college degree programs, as well as in medical tests and diagnosis and clinical treatments from remote locations. These programs have been carried out via telephone lines, coaxial cable and fiber connections, wide area networks, microwave relays, and satellite connections. Virtually all of these satellite-delivered services to date have been carried out through GEO-based satellite networks – global, regional, or national. The satellite systems are well equipped to deliver broadband video, but the return channel service for interactive services, from remote areas, has been a limitation. The various efforts to create interactive tele-education and tele-health services that operate via the Internet or digital networking systems have been the limiting factor that LEO constellations seek to address. These new networks, some with plans for thousands of satellites in low Earth orbit (LEO), are designed to operate with minimal delays that are comparable in end-to-end speeds of fiber or coaxial cable systems. The speeds of these small satellites which travel hundreds of kilometers rather than tens of thousands of kilometers do not have a problem with delay that can be confused with system congestion and trigger recovery processes.

3 Enabling Technology

The advantage of GEO, or Clarke orbit, satellites was in not requiring ground antenna systems that tracked the satellite as this type of satellite appeared to hover above continuously in the sky. This was a large advantage as satellite ground systems from tens to hundreds, to thousands, to literally millions of very small aperture terminals. This technical capability was first demonstrated by the experimental Syncom satellites in 1963 and 1964 and then the Early Bird satellites in 1965. As spot beams were added to allow more frequency reuse and greater power concentration this advantage further increased. This was because there was not a need to switch connections from beam to beam with a ground tracking antenna. In the case of LEO and MEO constenllations much more frequent switching was required between spot beams with a greater risk of a dropped connection.

It was only in the age of the Internet and the age of fiber-optic cable systems that supported very high broadband transmission rates at very low cost and low latency transmission that transmission delay of GEO-based satellites became of major concern. Some even began to claim that satellites for telecommunications services in the age of fiber networks were obsolete.

The ultimate success of the Iridium and Globalstar mobile satellite systems was key. These systems could not only work to handheld transceivers but they eventually proved capable of successul switching from beam to beam about once a minute and from satellite to satellite every 6 to 7 minutes. This proved that low latency LEO constellations could be viable for mobile voice service. It was improvment in digital communications and integrated circuits, especially application-specific integrated circuits (ASIC), that was key to creating viable ground terminals that could work technically and not be hugely expensive.

The next step forward that has been key to finding a technical solution to ground systems that could follow the fast-moving satellites in low Earth orbit (LEO) constellations is what are called flat panel antennas or electronically tracking antennas that can be manufactured at relatively low cost. It is actually the revolution in ground segment technology as much as improved small satellite design and manufacture that completes the technological breakthroughs to make large-scale satellite constellations viable in their operations both in the skies and on the ground. If these ground antennas for users were to be hugely expensive, the whole financial viability of such networks would not work for all sorts of networked services and especially not for educational, training, or health-based services.

Thus a combination of need to provide low latency data networking services to unserved or underserved portions of the world and new satellite systems technologies that have given birth to new telecommunications services in area of the world that have been described as suffering from the “digital divide.”

The enabling technologies on the ground are (i) flat panel antennas that can provide rapid electronic tracking of LEO satellites; (ii) new ways to provide low-cost sustainable power to remote areas (e.g., solar, wind, battery systems, etc.); (iii) new community-based ground systems to interconnect satellite ground systems with Wi-Fi and Wi-Max connections to cell phones and computers; and

(iv) even installations at schools, universities, hospitals, and medical clinics that can allow hybrid ground systems that can work to GEO, MEO, and LEO satellite systems as well as localized Wi-Fi coverage.

The enabling technologies that have come in the sphere of space systems design efficiencies include (i) the ability to produce on a mass production basis many small satellites and to do so with a high level of reliability and manufacturing quality, including use of additive manufacturing techniques; (ii) the use of miniaturized components, phased array antennas, power systems, and other design features to shrink the mass and volume of new satellites design; (iii) new reduced-cost launchers and rocket motors produced by 3D printing, including reusable first-stage rockets plus the ability to launch many small satellites on a single combined launch; and (iv) new sparing concepts that simply provide for replacement of failed satellites rather spending large amounts of time and money on reliability testing to highly exacting levels when networks consist of only a few very large and expensive GEO satellites.

4 Use of Large-Scale Constellation for Educational Services

The easiest and most cost-efficient way to utilize the new small satellite constellations for vital community services is in the area of training and education. The ubiquity of instructional materials, in a wide range of languages, available on the Internet just keeps growing. Most educational programs do not require a particular level of image resolution, and in some cases experiments have shown that even radio- or audio-based educational programming can be quite successful.

Today’s online educational systems such as computer labs for instruction in foreign languages, science, mathematics, and engineering are often available free or at low-cost licensing fees. Nevertheless there are problems of language and cultural sensitivities. The number one lesson learned from the Project SHARE activities was that when educational programs were locally produced within a country in native languages and with native teachers, the programs had a good chance of being sustained over time. It was equally true that instructional programs which were imported from one country to another by outside teachers and the teachers were not communicating in a native language, then these programs did not sustain themselves (Project SHARE Report, Intelsat, Washington, D.C. 1986). The same experience was found to be true in the case of other programs such as the NASA ATS-6 educational broadcasts in India versus the Edusat programs produced for the INSAT educational broadcast programs, the Indosat program in Indonesia, etc.

Another key finding is that on-site instructors are needed to supplement tele-educational programs delivered by satellite or Internet access. There is the case of health programming about house flies that was provided to Indian school children in the ATS-6 experiments. One of the early satellite television broadcasts to Indian village was a health program that discussed how flies could spread disease. The local instructors who talked to the villagers after seeing the health instruction were surprised with the responses and the lack of understanding of what they had seen. The villagers noted that it was interesting, but fortunately their town was not infested with these gigantic flying vermin. They had not understood that they had seen extreme close-ups that almost completely filled the television screen. The villagers thought the flies were a thousand times larger than they actually were. They did not recognize that these were indeed the same flies that bred freely in their own homes.

Local instructors are needed to interpret new materials, clear up false impressions, and extend knowledge essential to complete actual learning. The lessons that television program can start to provide must be accompanied by interactive learning. It is the essence of learning to start with bodies of learning and information, but this must be completed by questions and answers between students and teachers. One-way broadcasts are the start of learning, but interactive intercourse and research challenges are needed to complete true understanding and ultimate wisdom.

Arthur C. Clarke, the father of satellite communications, and futurist of great renown, made a speech at UNESCO in Paris with regard to the International Programme for the Development of Communication (IPDC) at its inaugural session in the early 1980s (UNESCO n.d.). In this talk he explained the great potential of not only satellite communications for instruction but also the possibilities that could come with the integration of satellites, computer networks, and artificially intelligent software.

Thus he foresaw the power that low-cost and globally updatable computer systems could bring to instruction. After his talk reporters asked if he was suggesting that automated systems should prevail and that there were no longer a need for teachers. Clarke responded to say that there would always be a need for teachers and question and answer interaction between students and instructors. But then he added: "..perhaps a teacher who can easily be replaced by a machine might be indeed become expendable and he or she might consider another line of work."

Clarke in his presentation noted a possible future where an "electronic tutor" might contain a great body of information that could be easily updated by an electronic network as well as a global satellite system geared to meeting worldwide educational and training needs. He stressed his vision of updatable handheld "electronic tutors" might evolve in unexpected ways. He suggested that the personal educational devices he envisioned might have as much to do with the future business models of Mattel or Tyco than IBM. By this statement he meant that the cost of massively integrated chips was becoming so low that by the twenty-first century, terabytes of educational information might be stored on the equivalent of toys. The device he described in several ways is remarkably similar to the "smart software" we know today as SIRI and ALEXA. The deployment of low Earth orbit (LEO) constellations of small satellites that brings low-cost wireless access to the entire world and can enable easy access to the world's storehouse of knowledge could complete Clarke's vision some 40 years ago (Op cit: Joseph Pelton and Peter Marshall).

The problem with describing the educational, training and health capabilities that new LEO constellations might provide is the sheer number and diversity of systems that are currently planned to be deployed. Between 2020 and 2025, the satellite services research company has projected that somewhere upward of 7000 new small satellites in constellations will be deployed, and some even foresee that as many as 20,000 small satellites for telecommunications, networking, remote sensing, frequency monitoring, information gathering, technology verification, and scientific experimentation will be deployed (Northern Sky Research).

The educational and training applications and services are thus still largely being conceived, and the hardware and software are still being rolled on. The new satellite networks and ground equipment are the hardware that will enable tens of thousands if not hundreds of thousands of new educational opportunities. The software and instructional programs are the next round of innovation that is still largely yet to come. There are potentially some 3.5 billion people that will be able to access the Internet via these new systems, but the key word here is "potentially." There are a myriad of economic, regulatory, cultural, and even religious factors that will be involved in whether the educational and training potential are unlocked.

Those involved in the satellite communications industry tend to focus on the successful deployment of the satellites and the design and implementation of ground systems, but the hard part of most educational and training programs comes with what happens next. Are the flat panel antennas on the ground interconnected to Wi-Fi systems that allow connection to cell phones or local schools or universities or training centers?

The Arthur C. Clarke Foundation some 20 years sought funding to carry out a series of tests and demonstrations known as the Millennium Village. This program sought integrated programs to benefit rural and remote villages in developing countries. The concept was to create an integrated program that would combine health-care services, solar light and electricity, emergency warning services, and sufficient power to support electricity for computers in schools and training centers. Perhaps most critical it was designed also to support new tele-work opportunities and training for villagers to learn particular skills in order to add new jobs. These might be activities that they could perform directly in the village such as in education, health care, or production of new products. It would also be designed to help create new positions and training programs. This training might support either new industry or services for the local village or could be in the form of teleservices. These new opportunities might well be designed to support urban enterprises via computer networking or telecommunications on a full-time or part-time basis (Freling and Herzfeld 2001).

The theory was to design a comprehensive set of services, education and training programs, health-care opportunities, power and lighting, and new economic and teletraining activities that could over time repay the new capital investment that the Millennium Village program would envision. This program would have depended on VSAT transceivers connected to GEO satellites and solar power and light systems that would have perhaps been too expensive to break – even within a decade – and networked services would be limited by the transmission delays associated with GEO satellites.

There is a real prospect that today integrated services that integrate remote education and training systems with economic development, power and lighting,

Millennium Village Project Objectives-Evaluation Criteria

- Increase in jobs & training
- Increase in literacy & education
- Increase in health care & disaster warning
- Economic development
- Generation of new investment/capital
- Improved infrastructure (especially power & lighting)

Fig. 4 Programmatic goals for evaluation for the Millennium Village Project in 2001. (Graphic courtesy of the Arthur C. Clarke Foundation)

and other services might have a much better chance of financial viability due to lower cost and the benefit of optimized networking services. The objective was to carry out projects in different countries and carefully monitor outcomes and success and failures to see which aspects succeeded or failed after care evaluation. The idea of seeking an integrated set of objectives rather than looking at various objectives on a piecemeal basis was an important concept two decades ago, but it might be even more important today. The figure below includes the evaluation criteria that were considered to be of prime importance then. Today other criteria related to the environment and climate change and the UN Sustainable Development Goals might well be added (see Fig. 4).

5 Use of Large-Scale Constellations for Heath Services

There is often a tendency to lump together tele-services and networking systems for education, training, and health-care services. It should be noted that the approach used for satellite or other forms of tele-services for connecting remote communities with doctors, practicing nurses, clinics, and hospitals represents, for a number of reasons, a special case. These reasons include such factors as (i) legal liabilities that can and often do apply; (ii) the resolution and clarity of images associated with treatment and diagnosis that can make a significant difference between the right and wrong decision as to the medical treatment needed and indeed what the actual ailment might be; (iii) viewpoints and even linguistic nuances and misunderstandings that can lead to problems and concerns as to how a patient can be properly given a medical checkup and evaluation, treatment, and prescribed medicine; etc.

In the case of education and training, a teacher might give a bad lesson, but this will not create a lasting problem that cannot be overcome. If a medical practitioner cannot see the patient and his or her symptoms clearly, this can be a major problem.

If there are fuzzy or incomplete views of X-rays, sonogram images, unclear medical readings, or even slightly off colorations of skin tones, such as in the case say of jaundice, there can be long-term adverse health consequences through misdiagnosis or ordering of the wrong medical treatment. In short, in case of tele-medicine applications, higher resolution and higher levels of reliability and visual and audio accuracy are required.

The issue of legal liability in the provision of health and medical care is also of major concern, particularly in litigious countries. In this case the providers of satellite services for medical treatment, either the patient or the care provider, might charge that the quality or the reliability of the service was inadequate and led to a patient's collapse or even death. In the world of education or training, there are no life or death issues that would normally arise, but in the area of medical care and services, this is also a possible area of legal contention that could arise.

Finally there are cultural, social, religious, or even language issues that could become a problem that can affect those offering tele-health services via a satellite or telecommunications network. There are many cultural or language-based misunderstandings that can arise in the case of medical examination process. This can involve mishearing or not understanding of symptoms, or not understanding cultural standards of modesty, or limitations on acceptable treatment processes or medication. Clearly arrangements to have doctor and patient to be of the same sex, language, and cultural background are advisable, but the provider of the telecommunications or network service is often not able to control such factors. Nevertheless, the scheduler or administrative staff that make the initial arrangements may find themselves in the line of fire in a court of law even though they had no particular choice or say as to who the patient or caregiver might be in a particular instance where a transgression is alleged.

The bottom line is that education and training services, in contrast to tele-health and tele-medicine activities, are less demanding as to the quality or reliability of the service or exposure to liability. This does not mean that issues of quality or liability never arise in the case of training and educational services, but they are definitely much less likely to arise.

6 Cube Satellites for Innovative Educational and Health-Care-Related Uses in Rural and Remote Areas

The advent of cube satellite technology and systems design, which might be anything from a PocketQube to a six-unit CubeSat, provides a new wide-open opportunity for experimentation and new design concepts as to how truly small satellites might be used to aid the cause of education, training, health, or medical care. When satellite applications were thought of in terms of huge multi-ton GEO satellites the opportunities in terms of space services were limited to leasing capacity from large enterprises that could launch such large and expensive systems. Today there are a wide range of new ideas and experimental concepts as to how small satellite experiments and projects might be built and launched in the range of

$50,000 to $500,000 dollars. There are many innovative ideas as to how true small satellites might be used in such ways as:

(i) Tracking of urban growth patterns
(ii) Tracking and reporting of water levels and flows of lakes and rivers
(iii) A neighborhood by neighborhood alert systems that could precisely chart the spread of pandemics or major disease outbreaks
(iv) The detection and reporting of crop or forestry diseases
(v) The detection of schools of fish for local fishing industries
(vi) The monitoring of and reporting to environmental authorities of industrial or organic pollution patterns
(vii) Testing of the designs, effectiveness, and lifetimes of sensors, routers, solar cells, batteries, torque rods, passive deorbit systems for satellites at end of life, or hundreds of other purposes
(viii) Many other reasons and purposes that can now be accomplished at lesser cost and greater effectiveness in terms of coverage and timely response

The reduction of the cost of actual in-orbit activities can now be financed through a university, a medical clinic or hospital, or even crowd funding programs. These innovations have opened the door for students in colleges and universities or trainees and interns in hospitals to come up with experimental ideas or even possible new operational space systems in totally new ways and via start-up enterprises. The Spire Series of satellites began with a crowd-funded satellite.

Students can now not only learn about space sciences and engineering, but they can actually have the opportunity to design and arrange for the launch of small satellites. Space agencies have created opportunities for students and professors to design and build small sats to test new ideas.

NASA began its CubeSat program for land-grant colleges and university. Today the European Space Agency (ESA), the Japanese Space Agency (JAXA), and others have followed suit to encourage student innovation and expertise. Even corporations have sponsored such small satellite experimentation. The LifeSat program launched two small satellites that allowed world wide connectivity via just two low Earth orbit (LEO) cubesats. This project was sponsored by Japanese corporations. These two CubeSats allowed data relay services from remote clinics. This allowed doctors isolated from the Internet to request information from the latest medical journal and experts from all over the world and get a response within a few hours.

Another project, a not for profit activity called Volunteers in Technical Assistance (VITA), offered engineering and other expert advices in rural and remote areas via GEO satellites and CubeSat relays, primarily in South America, where reliable terrestrial communications were not available (Volunteers in Technical Assistance n.d.).

Thus there are ways to deploy small satellites, even one or two satellites at a time to provide connectivity to isolated areas that provide elements of training, education, access to information from the latest researchers, and even various forms of testing and certification. There is valuable experience with institutions such as the

University of the South Pacific, the University of the South Pacific, and others as to how to operate successful tele-education, tele-training, and even tele-health programs. This experience can be valuable in developing new LEO-based cubesat programs in terms of extension of services and more cost-effective programs.

In the case of the University of West Indies, the cost-effectiveness of satellite communications systems allowed this multi-island university program to be structurally reorganized. The University decided that different campuses would specialize expertise in various disciplines at different island locations. Thus one campus would focus on forestry, another would center their research on agricultural crops and horticulture, and so on. With the ability to tie all the campuses together via satellite networking, the entire regional university could act as an integrated and holistic facility that can avoid a high level of duplication of faculty by hiring on a duplicative basis many areas of research. These types of experiences and beneficial uses of communications to organize more efficiently can potentially represent beneficial examples that can be greatly expanded as new broadband LEO satellites services are deployed.

These early programs encountered difficulties and limitations due to the cost of ground systems, or limitations due to lack of bandwidth or latency in the case of computer-networked activities. This was due to such factors as GEO satellite delay, available bandwidth, high cost of transmission, or the limitations of machine-to-machine data relay that slowed down communications. In most cases, however, it was not the technical nor operational constraints that were the largest barriers to the use of satellites to provide rural and remote educational and health-care services. In fact it was largely limited financial resources, a lack of understanding the potential of tele-health and tele-educational services, and social, cultural, and regulatory constraints.

There are some of the satellite systems that have been designed to provide rural services such as the network that was designed to provide direct broadcast radio satellite services to Africa and South America and the Caribbean that sought to address these issues over a decade ago. There was, on one hand, a foundation established whose purpose was to provide health and education services that were a part of the overall development plan for this new satellite program. The system was designed, for instance, to provide during nighttime hours, when usage of the satellite transmissions was low, the ability to low-load short educational television programming, in lieu of radio broadcasting. One of the biggest barriers to the use of the AfriStar radio broadcasting satellite for its intended purposes was that governments in Africa placed a 100% tariff on the low-cost radio receivers so that instead of costing $50 (US) per receiver, the effective cost was $100 (US) per receiver. It is such aspects that are sometimes not anticipated in the rollout of educational or health-care delivery systems that can become a major barrier to the success of such programs.

7 Conclusion

It is clear that a number of new small satellite-based large-scale constellations are designed to operate in low Earth orbit. A number of these systems are described in some detail in this handbook of small satellites. They are variously described in terms of their technical characteristics, dates of deployment, operational parameters, etc. It is important to recognize that the ability of such new satellite networks to provide networked services and to provide global coverage does not constitute an immediate opportunity for significantly expanding the range of satellite-based tele-education and tele-health services.

The truth of the matter is that the transmission delivery is just the start of a long and difficult process. The ground systems for connecting to the users in rural and remote areas at a cost that is affordable are a huge obstacle to overcome. In many regions of the world, there is a lack of electrical power that is sufficient to operate the user devices. There can be tariffs applied to user devices that, in effect, double their cost to the students or patients that would seek to use new forms of satellite-based programming for training, education, or health care.

8 Cross-References

- ► Precision Agriculture and Forestry: Bytes for Bites
- ► Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently
- ► Small Satellites, Law Enforcement, and Combating Crime Against Humanity
- ► Small Satellites and Governmental Role in Development of New Technology, Services, and Markets
- ► Small Satellites and New Global Opportunities in Education and Health Care
- ► Small Satellites and Risk management, Insurance, and Liability Issues
- ► Smalls Satellites and the 17 United Nations Sustainable Development Goals

References

"Broadband for the Next Billion" Geeks without frontiers (n.d.) http://geekswf.org/initiatives/broadband-next-billion/. Last accessed 2 May 2019

R. Freling, H. Herzfeld, "The Millennium Village Project", Presentation at the Clarke Institute for Telecommunications and Information Inaugural Event at Intelsat Headquarters, (Washington, D.C., July 2001)

J. N. Pelton, J. Alper (eds.), *The INTELSAT Global Satellite System* (AIAA, New York, 1986)

J.N. Pelton, P. Marshall, *The Oracle of Colombo: How Arthur C. Clarke Revealed the Future*, 2nd edn. (PM Associates, London, U.K., 2019), p. 121

Project Share Report, Intelsat, Washington, D.C., 1986

Satellite Television in Indonesia (n.d.) https://scholarspace.manoa.hawaii.edu/bitstream/10125/21612/SatelliteTelevisioninIndonesia/. Last accessed 3 May 2019

A. S. Teitel (n.d.) How "Nasa Broadcast Neil Armstrong Live from the Moon" Popular Science. (May 18, 2018). https://www.popsci.com/how-nasa-broadcast-neil-armstrong-live-from-moon

UNESCO, "International Programme for Development of Communications" (n.d.) https://en.unesco.org/programme/ipdc. Last accessed 4 May 2019)

Volunteers in Technical Assistance (n.d.) https://www.appropedia.org/Volunteers_in_Technical_Assistance. Last accessed 9 May 2019

Small Satellites, Law Enforcement, and Combating Crime Against Humanity

Joseph N. Pelton and Amit Maitra

Contents

Abstract

The strategic uses of balloons, aircraft, and then satellites have been an established practice to carry out reconnaissance, remote sensing, monitoring, and intelligence both for military and law enforcement purposes starting several centuries ago. The use of satellites for this purpose started with the Corona spy satellite. Today reconnaissance satellites are used by a number of countries for strategic purposes. These spy satellites are typically large in mass and volume and highly sophisticated with very high spatial resolution. The small satellite revolution has shown that small satellites of much less cost and size can be used

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

A. Maitra
The Foundation for Emerging Solutions Inc., Oakton, VA, USA
e-mail: amaitra@emerging-solutions.us

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_55

for many new purposes that range from industrial espionage to surveillance for law enforcement purposes by a growing number of countries. Further remote sensing satellites with time-stamped imaging have also been used in international courts to provide visual images to document attacks against towns and villages that have been described as crimes against humanity and even genocide.

Small satellites have become able to offer a range of new capabilities. These new capabilities have included much more frequent temporal resolution – sometimes providing coverage more frequently than once a day. They have also been able to provide updated information at much lower cost and with augmented data analysis that have provided valuable to police, coast guard, United Nations peacekeepers, and others charged with law enforcement and border protection and even with protecting the world against crimes against humanity.

This chapter explores some of the ways that new small satellite constellations can be designed to carry out improved forms of law enforcement, strategic defense, and even new ways to combat crimes against humanity. These new capabilities can sometimes work with a variety of capabilities from cubesat systems, to microsats or minisats, to large-scale satellites or various types of high-altitude balloons or aircraft such as UAV, or other means, in order to provide a full range of surveillance and observation capabilities. The primary focus of this chapter is on satellite imaging. Nevertheless the opportunities now presented by small satellite constellations for law enforcement and related activities from zoning enforced up to combating crimes against humanity are numerous and still growing. Today such satellite and high-altitude platform capabilities include position tracking, RF-geolocation detection, artificial identification system (AIS) monitoring, and in the future perhaps monitoring of wireless messaging and conversations.

While small satellites in the area of law enforcement and other strategic services are not a unique capability, they can combine with other resources to provide valuable service capabilities for detection, monitoring, security planning, enforcement, and legal prosecution. These capabilities can include optical, infrared and new infrared imaging, radar, as well as augment the abilities for tracking and monitoring such as AIS, near real-time tracking and identification, and entirely new capabilities such as RF-geolocation.

This chapter describes some of the innovative ways that small satellite constellations can offer security officials, law enforcement officers, and even jurists useful information to undertake law enforcement, protection of the peace, and valuable information that can be used in court cases to help to prosecute crimes against humanity and international criminal cases such as drug smuggling, fishing and pollution violations, and illegal trafficking across national borders.

Keywords

Code enforcement · Crimes against humanity · Cubesats · Illegal fishing · Illegal search and monitoring · Illegal trafficking · Infrared imaging · Law enforcement · Microsats · Minisats · Pollution monitoring · Radar imaging · RF-geolocation ·

Small satellite constellations · Smuggling · Spatial resolution · Surveillance satellites

1 Introduction

Military organizations in the United States and the Soviet Union have used spy satellites such as the Corona spy satellites to carry out strategic surveillance starting some 60 years ago. Such satellites were very massive and expensive and in some cases have costs billions of dollars to design, build, and operate.

While governments are now still vigorously developing its next generation of spy satellites, the commercial spy satellite industry is selling slightly less detailed imagery to both public and private sectors. The most detailed commercial reconnaissance systems have resolutions that are as refined as 25–35 cm in spatial resolution. In some cases these high spatial resolution commercial satellite systems are restricted to shutter control for very sensitive military locations. It has been noted, however, that this use of shutter control over the territories of various countries, so these sites are obscured actually serves to identify exactly where sensitive military and security facilities are indeed located.

Images from these high-resolution satellites provide detailed pictures of cities, homes, cars, aircraft, and various equipment and weaponry. Coverage and access to satellite imagery has created new market opportunities across all domains, including agriculture, forestry, fishing, mining, urban planning, pollution detection and control, and a variety of law enforcement activities. Law enforcement and security analysts can use reconnaissance from spy satellite, aircraft, UAV, and drone imagery in a wide variety of actions. These might include damage assessment such as from a bomb or improvised explosive device, search for a dangerous criminal or escapee, and as security for a special venue such as a major sporting device or meeting of heads of state.

The advent of small satellite constellations has not really been a “game-changer” in terms of transforming the use of satellites for law enforcement and efforts to use imaging in such efforts to combat crimes against humanity, but it has definitely altered the economics and patterns of use in terms of frequency of updates of information and the economics of and cost effectiveness of such usages.

2 Historical Perspectives on Use of Surveillance-Sats in Law Enforcement and Related Purposes

There are many documented high profile cases where surveillance satellites have been used not only for law enforcement, but for recovery from terrorist attacks, preventive policing actions to provide for setting up site protection for a critical venue, or time stamped images employed to prosecute instances of war crimes and instances of alleged cases of crimes against humanity. Some key instances are noted below.

- In the September 11, 2001, attacks on the World Trade Center, essentially seven skyscraper buildings on top of a large subway system and surrounding lower-rise buildings were destroyed. Several government agencies were consulted and cooperated not only to assess the damage, but to consider how to best undertake recovery and assist with the planning a coordinated response regarding damaged infrastructure such as transportation systems, electrical grid, water and gas lines, etc. These agencies were able to compare satellite images of the impacted site and the damages incurred after the attack with images taken immediately before and after the attacks. NASA Landsat images as well as images taken by astronauts on the International Space Station (ISS) were also brought to bear. The images from spy reconnaissance satellites were likely the most useful in this regard. This allowed a sort of response teams to develop a sort of triage plan to see where there might be immediate threats and dangers to address in terms of possible loss of life, dangerous potential collapses, areas of greatest threat to such aspects as subway infrastructure, flooding, dangerous gas releases, and other vital information that could help with recovery, restoration, and identification of dangers to assist first responders and other personnel on the site.
- In the fall of 2002, there were a series of sniper attacks where unsuspecting victims were shot and killed. This ongoing terrorist activity essentially paralyzed the Washington, D.C., for many days. Pentagon officials, the National Security Agency (NSA), and the 14 members of the United States "intelligence community" were consulted as to whether they might be able to use classified surveillance imaging to help locate and apprehend the sniper. Pentagon officials decided against using satellites, and instead Defense Secretary Donald Rumsfeld approved a plan to dispatch sophisticated military surveillance aircraft with law enforcement personnel aboard to assist with this urgent search for what ultimately was found to be a two person operation undertaken by a marksman and a younger assistant. Spy satellites, if used, would have offered more detailed imagery of several kilometers around the site of an attack immediately after it occurred, thereby aiding in the identification of the vehicles in the vicinity. The more targeted data from higher altitude aircraft was considered to be the more appropriate search tool, and thus this approach was used instead (Korody 2004).
- The Secret Service, local police, and the Federal Bureau of Investigation (FBI) employed satellite imagery while providing information necessary to secure the venues of the 2002 Winter Olympics in Salt Lake City, Utah. It was later alleged by the American Civil Liberties Union (ACLU) and others that there had been widespread monitoring of the athletes and attendees by visual surveillance and cellphone monitoring of attendees, but this activity was never proven or admitted by US governmental officials (Marisa Payne 2017).
- There have also been suggestions that spy satellite imagery provided useful information to secure the Ronald Regan funeral procession in June 2004 and to provide a monitoring capability similar to that used to provide security support to the Winter Olympics in Salt Lake City, Utah (Satellite Imagery 2004).
- In a more recent instance, the US National Geospatial Intelligence Agency (NGA) has partnered with several non-governmental organizations concerned with

human rights abuse and crimes against humanity with a special focus on potential violations by North Korea. In this case, the Agency has supplied unprocessed imaging data and specialized computer applications designed for imaging analysis to partner NGOs. The objective was to allow these organizations to search for such things as possible mass graves or perhaps concentration camps. It is unclear from public sources whether this was exclusively satellite imaging or included any high-altitude aircraft imaging (McLaughlin 2018).

- One of the more frequent new uses of satellite imagery has been to detect, or to confirm, reports received of growing of crops such as marijuana or poppy seeds as part of drug enforcement programs. Such uses do not require sophisticated spy or reconnaissance satellites. Commercial satellite systems have sufficient resolution to detect the growing of illegal substances (Satellite imaging 2019).

The foregoing examples, of which there are many others, illustrate that when near real-time, high-resolution satellite surveillance, or satellites with high temporal resolution (i.e., quick return of coverage to the same site), is utilized over major population centers or other critical sites, the scope and efficiency of law enforcement can increase. Yet at the same time, there are also parallel concerns that abuse of such capabilities can lead to violation of personal liberties. These can include the right to personal privacy, the right to be protected against illegal searches, and other freedoms expected in a democratic society. This is a topic addressed later in this chapter.

The potential applications are broad and many. The uses could include establishing security perimeters and weaknesses in security operations. It can involve locating escaped criminals and fugitives from the law. It can also involve detection of smuggling operations, illegal fishing, or cutting of timber operations, various forms of zoning violations, or industrial-operated activities leading to various forms of polluting or even illegal diversions of water supplies from lakes or rivers. Analysis of various forms of surveillance information to determine patterns and suspicious activities can also lead to crime detection or even prevention.

3 Current Innovations Using Satellite Technology for Law Enforcement and Related Activities

The use of satellite imaging, sensing, signal detection, and illegal radio-frequency detection keeps increasing. New commercial systems and particularly use of new commercial small satellite constellations are adding to available capabilities at a rapid rate. Today there are radar and infrared imaging systems available. These are being combined with optical imaging. Radar and infrared satellites are effective in darkness and through cloud cover, thereby ensuring wide advantages for surveillance of suspected criminals. Indeed the creation of data fusion centers designed to combat terrorism are often equipped to be able to combine a large amount of geospatial data together. Many such fusion centers are able to draw on additional elements of information such as conversations or messaging on cell phones, wiretap information, and other types of entirely new types of information such as illegal use of radio frequencies. This type of information can be provided from RF-geolocation satellite systems such as the new Hawkeye 360 small satellite constellation.

Conventional commercial satellites such as Spot Image and GeoEye, for instance, have been used for local code enforcements as noted in these examples below.

- State law enforcement agencies use satellite imagery to investigate violations of zoning and environmental regulations. A case in point is the Arizona Department of Water Resources, which has used satellite imagery from a French Spot Image satellite to find violations of irrigation permits. In another instance, satellite imagery has been helpful in discovering unreported and illegal timber harvesting (Korody 2004).
- North Carolina jurisdictions are using satellite remote sensing "to find unreported building activities, agricultural development and other property improvements that would raise property-tax assessments." Remote sensing from small satellite constellations are now being used to detect code violations such as building without official permit violations such as the building of small backyard porches or other more serious violations. Another instance was that of a farmer being fined for violation of water permits and illegal diversion of water based on satellite imaging (Korody 2004).

The future of law enforcement through the use of space remote sensing does not have to depend on super high spatial resolution governmental spy satellites, nor even very large and sophisticated commercial remote sensing satellites. There are many law enforcement and detection functions that may be possible by means of small satellite constellations.

Going forward, small satellite constellations that operate at low cost with quicker return to a particular site or new capabilities such as RF-geolocation, artificial identification systems (AIS), and more sophisticated data analytics might be able to offer new capabilities for law enforcement or related services. The extent to which these capabilities might be used in the future is just beginning to be explored.

The Planet Dove, Terra Bella, and other higher-resolution small satellite constellation can combine to provide a combination of capabilities. The Planet Dove constellation has high temporal resolution with its larger-scale 3-unit cubesats to provide quick updates. Its higher-resolution systems such as its Terra Bella satellites can provide relatively clear and precise images. This combination of system data and increasingly sophisticated data analytics is provided to Google under the contractual arrangements under which Planet Labs acquired Terra Bella from Google and became simply "Planet." Figure 1 below from Google Earth shows the Chinese hidden camps in the desert used for detainees. These images were first developed via the Sentinel imaging satellite that was developed by the European Space Agency and had a mass of measuring around 2 mt. But today these images of isolated spots of interest can be quickly updated via the Planet small satellite constellations or other small satellite systems. Other small satellite systems using radar sensing such as ICEYE and Capella can become particularly adept at detecting metal structure in remote locations.

A satellite swung over the rolling deserts and oasis cities of China's vast far west on 12 July 2015. The images it captured that day just showed a patch of empty, untouched, ashen-grey sand - an unlikely place for an investigation into one of the most pressing human rights concerns of our age.

Rapid development in the high desert has occurred since July 2015 as detention camps have expanded over the site.

- Satellite photos taken of that same piece of desert on 22 April 2018 and again in October 2018 show how quickly the site has been developed. .
- Dabancheng, as seen in Sentinel images in October 2018, shows an enclosed area with a 2km-long exterior wall punctuated by 16 guard towers.

Fig. 1 Images taken by the Sentinel remote sensing satellite designed ESA provide images of China's camps being built in Dabancheng. (Graphic courtesy of Google Earth)

4 Potential Uses of Small Satellites for Law Enforcement

The potential for the future are broad and of significant impact. Currently the vast ocean areas that cover some 75% of planet Earth are today almost impossible to police effectively. Illegal, unreported, and unregulated fishing adversely impacts the profit margin of legal fishing. It is estimated that illegal, unreported, and unregulated fishing amounts to 26 million tons of fish each year. This is estimated, as calculated based on global profits, to represent an amount that is a quarter of that derived from legitimate and authorized fishing operations. Illegal fishing fleets that are now operating represent what amount to a multi-billion-dollar criminal activity. This actually harms legitimate fishermen. Unauthorized fishing is even more harmful in terms of the environmental damage that is created over time by overfishing. Increasing new surveillance capabilities now being deployed in terms of small satellite constellations that are now available in low-Earth orbit, policing has now become possible at a reasonable cost. Black market operations can be spotted and illegal fishermen brought to justice (Hambling 2019).

Commercial small satellite startups known as Capella, from the United States and another from Finland called ICEYE are both equipped with radar sensors. Since radar sensor receives a sharp reflection from metal, both of these systems are excellent for detecting ships and boats at sea (Fig. 2). Even with relatively low resolution, these satellites are able to distinguish ships from fishing boats, and with the correct data analysis they can determine which fishing boats are operating in legitimate fishing waters or not. Also since radar operates during the day and night, these systems are capable of finding fishing boats that violate fishing waters

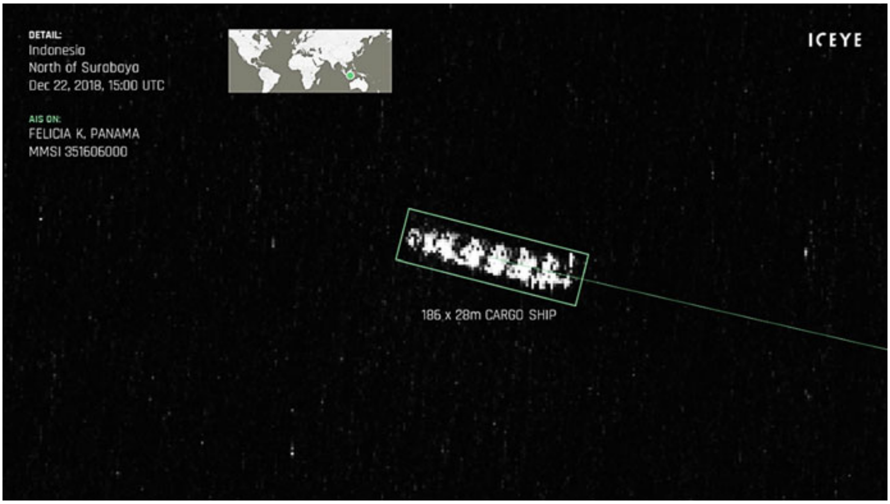


Fig. 2 A cargo ship identified by an ICEYE satellite at a location North of Surabaya, Indonesia, on December 22, 2018, 15:00 UTC. (Graphic courtesy of ESA and ICEYE) (ICEYE and Spire joins 2019)

24 h a day and especially to spot those that use the cover of night to go into prohibited waters.

Further the small satellite system known as SPIRE has also joined with ICEYE in the small satellite systems that are working to detect illegal fishing in cooperation with the European Space Agency. SPIRE is equipped with the ability to track and locate ships (and vehicles as well) that emit an automatic identification systems (AIS) signal. Currently there are about a dozen of small satellite constellations equipped with this capability in operation or proposed for service. When ships detected by ICEYE at sea do not link up with an AIS signal detected by SPIRE, then this ship becomes a “dark ship” and is presumed to be carrying out an illegal function such as smuggling, illegal fishing, or some other covert activity. In other cases an active AIS signal indicates it is at a location where it should not be traversing or fishing.

The partnership between ESA, ICEYE, and SPIRE is not just restricted to locating illegal fishing, detecting pollution, or illegal activities such as smuggling, but a number of positive environmental and other useful activities. The focus of these joint activities have been characterized as follows: “Challenging issues such as natural disaster response and climate change research, oil spill and illegal fishing detection all require repeated and timely imaging, regardless of the weather conditions or time of day. This shared effort to gain vast SAR imaging capabilities from new technological developments impacts the whole Earth observation industry and its end users.” Indeed the original prime mission of ICEYE was to observe ice cover and identify and monitor dangerous icebergs (ICEYE and European Space Agency 2019).

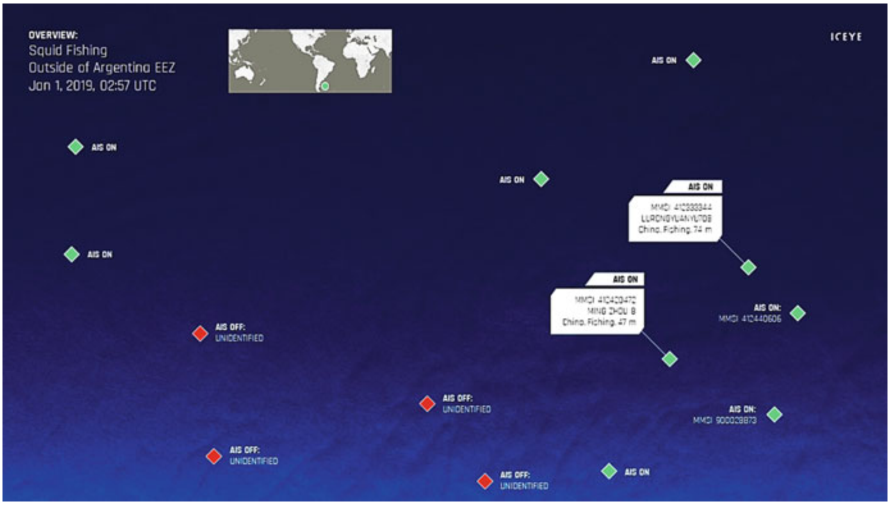


Fig. 3 Squid fishing near Exclusive Economic Zone (EEZ), Argentina. (Graphic courtesy of ICEYE)

In some cases the process works not as active detection of illegal activity but rather as a warning or alerting system that allows a ship to be alerted that it is close to or near a restricted area for fishing or secure area zone. In Fig. 3 AIS location signals are used to alert two Chinese ships that they are nearing an Argentine Exclusive Economic Zone. There is the further issue in this case of a “dark ship” whose AIS signal is not active.

5 Does Use of Satellite Imaging, GNSS Tracking, and RF-Geolocation Detection of Artificial Identification System Monitoring Constitute “Illegal Search”?

Clearly new small satellite constellations are creating a variety of new law enforcement capabilities. These can be used in dozens of ways to help law enforcement at the domestic level or on the high seas. These tools can be used as a warning system, as a detection or monitoring system, or even as a form of search and article of prosecution. The farmer who diverted the water and the person that builds a back porch or adds on to the back of their house and does not report it to tax authorities would in the past not be fined or have their home reassessed without a search and someone coming to a property to verify an infraction. In the world of satellite imaging, AIS signals, RF-geolocation, and other data analytic tools, the abilities of law enforcement and even exhibits for criminal prosecution are available simply as data readouts.

The law of what constitutes a legal search anymore is no longer clear. A judge does not have to sign a search warrant for every image taken by a satellite in orbit or a high-altitude platform hovering at 20 km overhead.

There is an ever-growing ability of satellites to operate as a hidden yet increasingly constant surveillance tool operating overhead. Satellites and high-altitude platforms can now observe individuals and activities with ever higher levels of spatial resolution. These tools are now increasingly being used to meet the needs of law enforcement agencies. In the days of terrorist attacks such as those that have occurred in Paris, London, Bali, and most sensationally New York City and Washington, D.C., in the so-called 9/11 attacks, public opinion tends to favor heighted secured and more surveillance tools in the name of safety and anti-terrorist protections.

At the same time, this ability pushes the limits of constitutional protections. It is not clear as what today's reasonable expectations should be within a free and democratic society. What are today's reasonable privacy expectations? What is an invasive and illegal search of one's person or property in the twenty-first century? It is not just a matter of satellites or high-altitude platforms armed with sensors, imaging devices, and other tools of cover observation. There are close circuit cameras, recording devices, and security systems almost everywhere in today's urban settings.

Controlling crime, combating terrorism, and maintaining public order is necessary within a free country. These requirements lead to implementation of reasonable limitations on some civil liberties. A free society can be held hostage to excessive crime and an atmosphere of violence. For example, in today's turbulent environment, individuals are not allowed to enter an airport terminal unless they agree to a search of their persons and items they carry. The concerns of air travelers to be free from acts of terrorism outweigh individual freedom of unrestricted access to a public airport terminal. Nevertheless judicial systems to protect an individual's right not to be subject to unreasonable search and their right to privacy remain important to a free society. Methods to check technological intrusions into one's personal life and not to allow unrestricted observation and digital snooping will become ever more important in the time ahead.

No discussion on how law enforcement embraces new technology that collects evidence of a crime is complete without reference to privacy concerns regarding the use of surveillance satellites that observe individuals and their activities and movements. The new technologies that law enforcement uses include Global Positioning System (GPS) tracking devices, radar, night vision, thermal imagers, and other sensors. As these devices and sensors are integrated together, then surveillance satellite technology becomes just another tool to be used. As technology advances and imagery becomes more readily available to law enforcement, the use of surveillance satellites will increase in a wide variety of law enforcement actions. While new surveillance power strengthens law enforcement's operational efficiency, legal questions that mostly center on whether use of the technology infringes on the privacy interests of individuals also must be addressed.

In the United States the Fourth Bill of Rights provides protection against "unreasonable searches" and unfortunately there is nowhere in the Bill of Rights a right to privacy defined. The US Supreme Court has moved back and forth in defining what unreasonable searches constitute. They have often found in favor of individuals being unreasonably searched by police, particularly within the home, but have not been so protective when it comes to technology. In the case involving a helicopter flying over a back yard, the US Supreme Court ruled that the Fourth Amendment did not provide such protection. It is on this basis that satellite surveillance seems to have a wide area of discriminatory powers (Florida v. Riley 1989).

6 Conclusion

The ability of small satellite constellations to provide a greater ability to provide new tools for law enforcement and anti-terror methods and even provide evidence in cases combatting crimes against humanity seems likely to continue to increase in years to come. These small satellites will likely become for refined in terms of law enforcement capabilities for many reasons. These include improved and higher-resolution sensor technology, lower launch costs, faster digital processing capabilities, and new software applications to conduct image processing at faster speeds. These and other technological efficiencies born of the "NewSpace" revolution seem to hold out the prospect of increasingly sophisticated surveillance capabilities. Part of this enhanced capability will come with integration of various capabilities.

Today small satellite constellations plus high-altitude platforms and stratospheric systems seem to hold a number of key new tools for law enforcement and related capabilities. Thus there are small satellites that have reasonably high spatial and temporal resolution with optical, infrared, and radar-based sensors. These can be linked through digital processing systems and so-called "fusion analysis" centers to create integrated surveillance and data analytics to produce holistic results. Thus small satellites with automatic identification systems (AIS) signal collections can put together data from small satellite radar systems to identify "dark ships" across the world's oceans. The many small satellites involved in the Capella and ICEYE radar systems can link together with the SPIRE data analytics to help identify smugglers and illegal fishing boats.

This is but one example of the new sensing and imaging capabilities that can link to data analytics to support law enforcement. There are today scores of newly deployed or planned small satellites with remote sensing and surveillance capabilities (optical, infrared and near infrared, radar, etc.), with capabilities for AIS signal, RF-Geolocation, data relay, etc. These sensing capabilites can also be linked to Global Navigation Satellite Systems (GNSS), meteorological, and commercial data bases to assist in detecting criminal activity, protect against data breaches, providing warnings against physical or cyber intrusions and more. There are also satellites that can relay Internet of Things signals from activated units that will in many cases be related to security related information such as whether a door has been opened or a circuit activated that should not have occurred.

The addition of all these capabilities related to small satellite system opens a wide range of new capabilities to fight criminal behavior, stop terrorist attacks, and help combat crimes against humanity. There is a downside of this progress. The automation of so many of these functions also creates new vulnerabilities that cybercriminal or cyberterrorists may also find to exploit. Further as noted above, these high-tech tools can also be invasive. This means that all of these new capabilities can also reduce an individual's sense of privacy and subject citizens to more circumstances where unreasonable and unwarranted searches can be made by sensors that may be on the ground or in the sky. It is the job of technologists and legislators to try to find a middle way between protection of citizen's safety against criminal attack and preservation of a citizen's right to privacy and unreasonable and unwarranted search.

7 Cross-References

- ▶ Precision Agriculture and Forestry: Bytes for Bites
- ▶ Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently
- ▶ Small Satellites and Governmental Role in Development of New Technology, Services, and Markets
- ▶ Small Satellites and New Global Opportunities in Education and Health Care
- ▶ Small Satellites and Planetary Defense Initiatives
- ▶ Small Satellites and Risk management, Insurance, and Liability Issues
- ▶ Smallsats, Hosted Payload, Aircraft Safety, and ADS-B Navigation Services

References

Florida v. Riley, 488 U.S. 445, 451-52 (1989)

D. Hambling, How small satellites will help police Earth's vast oceans. Popular Mechanics (February 4, 2019), https://www.popularmechanics.com/space/satellites/a26112020/satellites-fishing/

ICEYE and Spire join forces to enable global monitoring of dark vessels at sea, ICEYE Press Release (January 22, 2019), https://www.iceye.com/press/press-releases/iceye-spire-join-forces-enable-global-monitoring-dark-vessels-at-sea. Last accessed 1 Nov 2019

P. Korody, Satellite surveillance within U.S. borders. Ohio State Univ. Law. J. **65** (2004), https://kb.osu.edu/bitstream/handle/1811/70994/OSLJ_V65N6_1627.pdf. Last accessed 1 Nov 2019

Marisa Payne, NSA denies 'blanket spying' on spectators and athletes at 2002 Olympics in Salt Lake City. Washington Post (February 22, 2017), https://www.washingtonpost.com/news/early-lead/wp/2017/02/22/nsa-denies-blanket-spying-on-spectators-and-athletes-at-the-2002-olympics-in-salt-lake-city/

J. McLaughlin, U.S. spies to partners with human rights groups to keep an eye on North Korea. Foreign Policy (February 21, 2018), https://foreignpolicy.com/2018/02/21/u-s-spies-to-partner-with-humanitarian-groups-to-keep-an-eye-on-north-korea/

Satellite Imagery Keeping Eye on U.S., Washington Post (October 10, 2004)

Satellite imaging for drug enforcement, MIT Technology Review (June 26, 2019)

Precision Agriculture and Forestry: Bytes for Bites

Scott Madry

Contents

S. Madry (✉)
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_56

Abstract

This chapter will present the historical, current, and future status of the use of space technologies, including the new generation of small satellite constellations, for precision agriculture and forestry. Human population growth and urbanization, along with environmental issues and climate change, will continue to put pressure on our global agriculture and forestry resources. New and improved methods of feeding the world's growing population, while at the same time protecting our finite natural resources, will be needed and must be developed now if they are to meet the coming demands. This chapter will consider the benefits and challenges of this emerging new technology and how the small satellite revolution will impact this important capability.

Keywords

Precision agriculture · Precision forestry · Global population growth · Remote sensing · GIS · GPS · Decision support system (DSS) · Climate change · Hyperspectral

1 Introduction

1.1 Historical Context, the Origins of Agriculture

For the majority of human history, we were hunter-gatherers, living in small bands, constantly roving across the landscape. The first agricultural revolution occurred independently around the planet, with the domestication of plants and animals for crops and food happening in the Middle East, Asia, and the Americas between 11,000 and 8000 years ago in many independent locations (Tauger 2008). This may well have been enabled by the end of the last Ice Age, which occurred around 13,000 years ago. The domestication of plants and animals allowed for a sedentary lifestyle and larger communities, and surpluses led to more complex social structures and more stratified societies, including social complexity and the emergence of elites. Agriculture soon became the norm around the world, and people settled into stable agricultural production systems that were focused both on centralized production in places like China and Mexico, as well as on small farms, and local production sufficient to meet local needs. In the Middle East, large-scale agriculture was well established in the "fertile crescent" of Mesopotamia and in Egypt by 10,000 years ago, with a wide variety of crops and domesticated animals being managed (Janick 2002). Human population around the world increased, and complex societies developed with specialized occupations beyond farmers (Fig. 1).

Fig. 1 Agricultural scenes from ancient Egypt, from the tomb of Nakht from about 3400 years ago. (Image courtesy Wikimedia https://commons.wikimedia.org/wiki/File:Agricultural_Scenes,_Tomb_of_Nakht_MET_DT306954.jpg)

2 The Second Agricultural Revolution

The second agricultural revolution occurred during the Industrial Revolution in the eighteenth and nineteenth centuries. The development of the steam engine, railroads, mechanical seed presses, automated threshers and reapers, and other developments provided a massive improvement in the productivity of agriculture. This, in part, enabled the Industrial Revolution by providing a growing urban labor pool, as many workers were no longer needed on the farms. Innovations, such as the horse-drawn seed press, mechanical cotton gin, improved plows, the mass adoption of new crops such as the potato and corn (both American imports), and improved crop rotation methods and nitrogen-fixing plants, all led to significantly increased agricultural output in Western Europe and North America (Mingay 1977). Similar advances were made in animal husbandry, with many new breeds of cattle, pigs, and horses being introduced. Agricultural markets became national and even international, and people no longer had to grow all they needed themselves. People began buying and selling their produce on the open market, often at a national scale, and money overtook the barter of goods. This significant increase in agricultural productivity laid the

Scientific American.

THE ADVOCATE OF INDUSTRY, AND JOURNAL OF SCIENTIFIC, MECHANICAL, AND OTHER IMPROVEMENTS

VOLUME XII. NEW-YORK, FEBRUARY 21, 1857. NUMBER 24.

THE
Scientific American,
PUBLISHED WEEKLY
At 128 Fulton street, N. Y. (Sun Buildings.)
BY MUNN & CO.
O. D. MUNN, S. H. WALES, A. E. BEACH.

Responsible Agents may also be found in all the principal cities and towns in the United States.

Sampson Low, Son & Co., the American Booksellers 47 Ludgate Hill, London, Eng., are the English Agents to receive subscriptions for the Scientific American.

Single copies of the paper are on sale at the office of publication and at all the periodical stores in this city, Brooklyn, and Jersey City.

TERMS—$2 a-year.—$1 in advance and the remainder in six months.

☞ See Prospectus on last page. No Traveling Agents employed.

Industrial Statistics.

We are indebted to S. W. Huse & Co., publishers of *Vox Populi*, for the following industrial statistics of Lowell, Mass :—

The Middlesex Company make use, annually, of 2,000,000 teasels, 2,000,000 lbs. fine wool, 50,000 lbs. glue, $30,000 worth of dye stuffs, and $13,000 worth of soap.

In addition to the above, the Merrimack Manufacturing Co. use 1,000,000 lbs. of madder, 380,000 copperas, 60,000 alum, 50,000 sumac, 40,000 soap, and 45,000 indigo, per annum.

The Lowell Bleachery uses 40,000 lbs. indigo, and $30,000 worth of other dyeing materials, per year.

The population of Lowell in 1828 was 3,532. In 1840 it was 20,796. In 1850 it was 33,385. Increase in ten years, 12,289. Population of Lowell in 1855, 37,553.

The Lowell Machine Shop, located among the above mills, can furnish machinery complete for a mill of 6,000 spindles in three

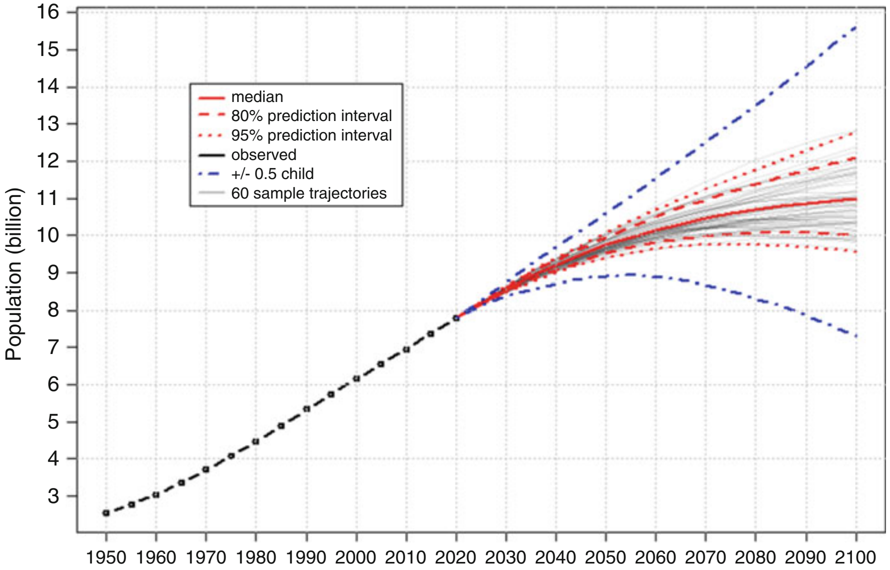
HURD'S SEED DRILL.

Fig. 2 *Scientific American* (1857) image of Hurd's automated seed drill. (Image courtesy Wikimedia https://upload.wikimedia.org/wikipedia/commons/thumb/1/1f/Scientific_American_-_Series_1_-_Volume_012_-_Issue_24.pdf/page1-709px-Scientific_American_-_Series_1_-_Volume_012_-_Issue_24.pdf.jpg)

foundation for much of modern life, with fewer and fewer people working the land and with smaller and smaller amounts of the land devoted to agricultural production. Even so, today, some 1/3 of the population of the Earth is involved in agriculture, with many of them surviving on subsistence farming. Many of these are the poorest among us (Fig. 2).

3 The Third Agricultural Revolution

We stand on the cusp of a third global agricultural revolution, the precision agricultural revolution, a revolution that is going to be much needed and which holds tremendous promise to meet the growing needs of our future population and changing climate, but which also holds many unanswered questions. What is driving all this? There are three major forces that are shaping our global future need for new methods of producing food.



© 2019 United Nations, DESA, Population Division. Licensed under Creative Commons license CC BY 3.0 IGO.
United Nations, DESA, Population Division. *World Population Prospects 2019*. http:// population.un.org./wpp/

Fig. 3 Total world population estimates. (Image courtesy United Nations DESA, Population Division. https://population.un.org/wpp/Graphs/Probabilistic/POP/TOT/900)

3.1 Human Population and Urbanization Growth and the Need for Improved Agricultural and Forest Productivity

According to the United Nations, there are currently over 7.3 billion people living on the Earth, and this is projected to increase to over 9.7 billion by 2050, as shown in the figure below (UN 2019). Some estimates are that we will require 70% more food by then. Our current agricultural production capability will require a massive increase in order to meet this demand. Either millions of hectares of new land will have to be brought into agricultural production, or we must find significant increases in agricultural productivity (Fig. 3).

4 Urbanization

A second related component of our future food requirements is the increase in urbanization and the development of megacities containing many tens of millions of people each (United Nations 2018). Again, according to the UN, for the first time in human history, more people now live in urban areas than rural locations in our world. In 1950, 30% of the global population was urban, but by 2018, it was 55%, and by 2050, it is projected that 68% of us will be urban dwellers. And 90% of this

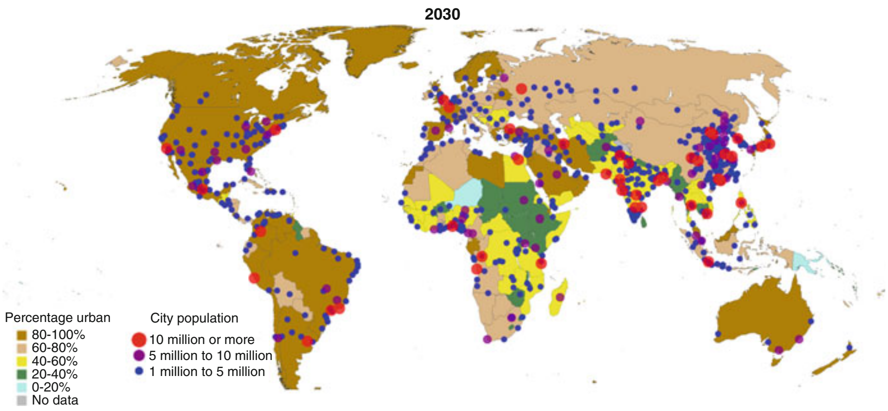


Fig. 4 Urban agglomerations by 2030. The large red circles will have a population of over ten million persons. Blue dots are between one and ten million. (Image courtesy United Nations https://population.un.org/wup/Maps/)

urban growth will be occurring in the developing regions of Asia and Africa. China, India, and Nigeria alone will provide 35% of this new urban population. India alone will add over 400 million new urban residents by 2050. Today, we have some 33 megacities with over ten million residents each, but by 2030, there will be an estimated 43 megacities, with most of these being located in the developing world. These new megacities will remove much of the productive agricultural lands which currently border these locations, so there will be an associated reduction in agricultural productivity in the immediate vicinity of these large urban growth zones (Fig. 4).

5 Global Climate Change

Lastly, we must consider the role that climate change will play in all this. There is a strong scientific consensus that global warming and climate change are real and are beginning to play an increasing role in changing our environment, and this includes agriculture. A recent analysis from the National Academy of Sciences of the United States shows that each 1 °C rise in global mean temperature would, on average, reduce global yields of wheat by 6.0%, rice by 3.2%, maize by 7.4%, and soybean by 3.1%. These four foods provide some 75% of global nutrition (Zhao et.al 2017). These amounts will vary spatially around the world. For example, wheat reduction will be more severe in India and Russia than in North America, but all will see reductions (Fig. 5).

These three powerful forces, population increase, urbanization, and climate change, will drive a profound global change in how the world gets fed. This also brings new meaning to the importance of the concept of sustainable development. How the developing nations in Asia and Africa will be able to support this

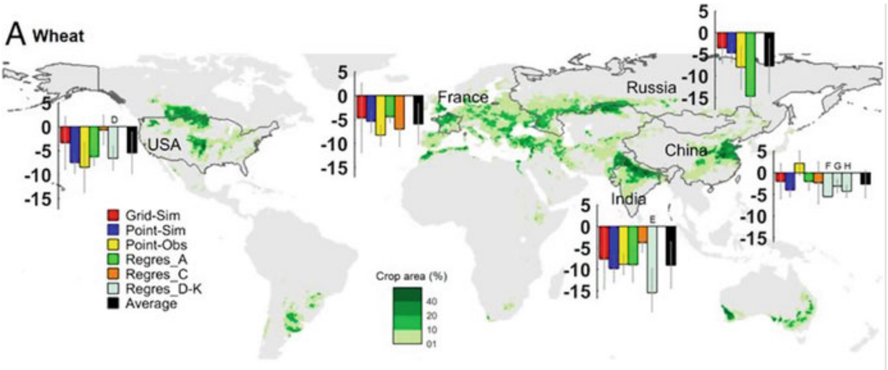


Fig. 5 Possible reduction in global wheat production with a 1 °C rise in global temperature average, according to several models. (Image courtesy National Academy of Sciences of the United States https://www.pnas.org/content/114/35/9326)

population and urban growth in societal, economic, and environmental terms is unclear, but the one thing that is certain is that these millions of new urbanites will need to be fed, and the environmental impacts of these processes must be understood and managed now. At this point, we do not have the agricultural capacity to feed all of these new people, and so new and more efficient means of agricultural production must be developed. This is the context within which precision agriculture must be viewed.

6 Initial Efforts in Large Area Agriculture Monitoring

There have been several very interesting and relatively successful attempts to harness advanced technologies for agriculture that have laid the foundation for precision agriculture. The US Department of Agriculture (USDA) had been using aerial photography since the 1930s to assess agricultural production in the United States. As soon as the Space Age began, there were discussions about how satellites and space remote sensing could be applied to improve this regional agricultural monitoring and forecasting, both domestically and abroad. The first major attempt was the LACIE (Large Area Crop Inventory Experiment) project. This was a 3-year, joint activity of NASA, NOAA (National Oceanographic and Atmospheric Administration), and the US Department of Agriculture (USDA). It took place in 1974 through 1977, which was very early in the first era of civil remote sensing with the Landsat 1 data (originally the ERTS (Earth Resources Technology Satellite)), launched on July 23, 1972. The goal was to determine if Landsat data, combined with weather satellite and other information, could remotely assess continental-scale wheat production with a precision that would be useful for the USDA and other government agencies. The goal was to determine regional and continental wheat production estimates that would be within 90% of the actual yield 9 years out of 10.

Fig. 6 The LACIE project logo. (Image courtesy NASA)

This was actually achieved in the third and final year of the project covering the 1976–1977 growing season in Russia, the primary target of the program (Fig. 6).

Understanding the success or failure of the Russian wheat crop was considered to be a national security issue for the US government, as a major crop failure could be a source of global economic and security instability. The overall method utilized is shown in the graphic below. Landsat satellites acquired imagery over vast areas of Russia and North America (as a control that could be field checked) during the wheat growing seasons, and the data were telemetered down to the ground and processed into different classes of vegetation, including wheat. These data were stored and analyzed by agricultural and imagery specialists, along with NOAA weather satellite data, various ground and textual data, and other sources of information, all to generate the final crop estimation figures, which were then compared with actual results after the growing season was over (Fig. 7).

The method was revised and improved over the three growing seasons of the project, and by the third season, the estimates were surprisingly robust. The Soviet government predicted wheat production in 1977 of 213.3 million tons, which would have been a 13% increase over the 1971–1976 yield averages. The LACIE estimate was for 91.4 million tons, and the actual yield, determined from records made available after the fall of the Soviet Union, showed an actual harvest of some 92 million tons of wheat, within 1% of the LACIE estimated value (Erickson, 1984). This was a very ambitious program using very early 80-m and 6-bit remote sensing imagery and using very primitive (by today's standards) image processing and analysis capabilities. The results showed that the global monitoring of food and fiber production using satellite remote sensing and ancillary data was, indeed, possible (Fig. 8).

The success of the LACIE project led to a follow-on activity named AgRISTARS, also a joint NASA, NOAA, and USDA effort, along with the Department of the Interior and the Agency for International Development (NASA 1982). This program began in 1978, and was a 6-year program to further determine the application of advanced space remote sensing, weather satellite data, computing, numerical modeling, and other approaches to provide the USDA with global crop forecasting, analysis, and other capabilities. There were a total of seven technical aspects, plural to plural:

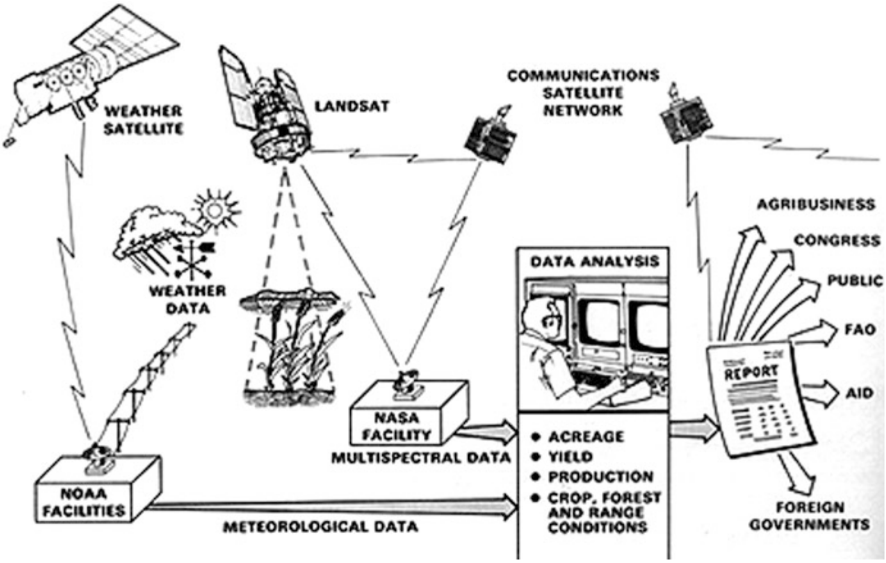


Fig. 7 LACIE experiment design. (Image courtesy NASA. https://www-legacy.dge.carnegiescience.edu/SCOPE/SCOPE_23/SCOPE_23_4.4_chapter8_191-217.pdf)

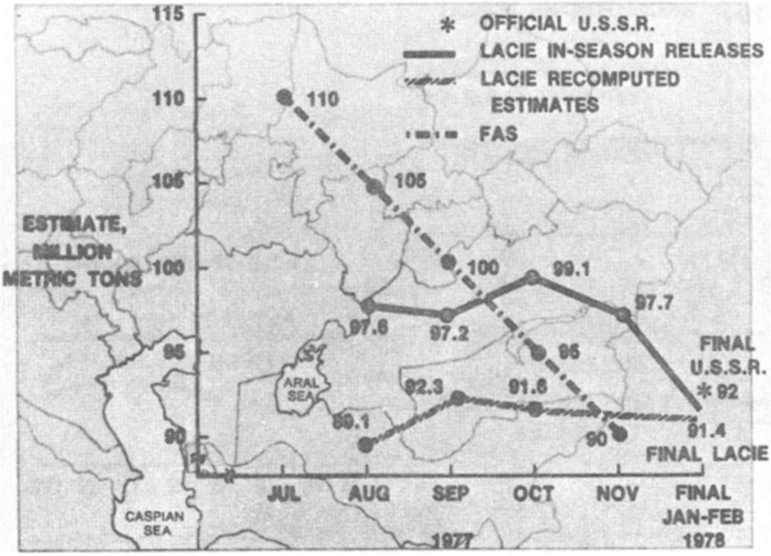


Fig. 8 LACIE results for 1977 Soviet wheat crop. The estimate was within 1% of the actual final amount. (Image courtesy NASA https://www.legacy.dge.carnegiescience.edu/SCOPE/SCOPE_23/SCOPE_23_4.4_chapter8_191-217.pdf)

Fig. 9 AgriSTARS: Agriculture Resources Inventory Surveys Through Aerospace Remote Sensing. (Image courtesy NASA)

- Early warning of change affecting production and quality of commodities and renewable resources
- Commodity production forecasts
- Land use classification and measurement
- Renewable resources inventory and assessment
- Land productivity estimates
- Conservation practices assessment
- Pollution detection and impact evaluation

AgRISTARS prepared for the use of the new generation of 30-meter Landsat Thematic Mapper satellites, first launched in 1982, which provided vastly improved 30-m spatial resolution and 8-bit data, along with new NOAA satellite data and improved modeling and analysis techniques. Additional crops like corn and soybeans were analyzed, as were forested areas, and the program was quite successful (Caudill and Hatch NASA, n.d.).

The success of LACIE and AgRISTARS projects demonstrated the effectiveness of this approach, and there have been several follow-on capabilities, as shown in Fig. 9, which is an operational dataset produced by the USDA National Agricultural Statistics Service. The USDA Foreign Agricultural Service (http://fas.usda.gov), to this day, prepares global and regional strategic crop forecasts for the US government on a recurring basis as an input into its national security and economic monitoring activities (Fig. 10).

The United Nations Food and Agriculture Organization (UN FAO) is the UN organization responsible for monitoring global agriculture, forestry, and fisheries and defeating hunger. Its Latin motto “Fiat Panis” means “Let there be bread.” FAO collects a wide range of statistics and operates a database called AMIS (Agricultural Market Information System). This program began in 2011 and is a G20 program

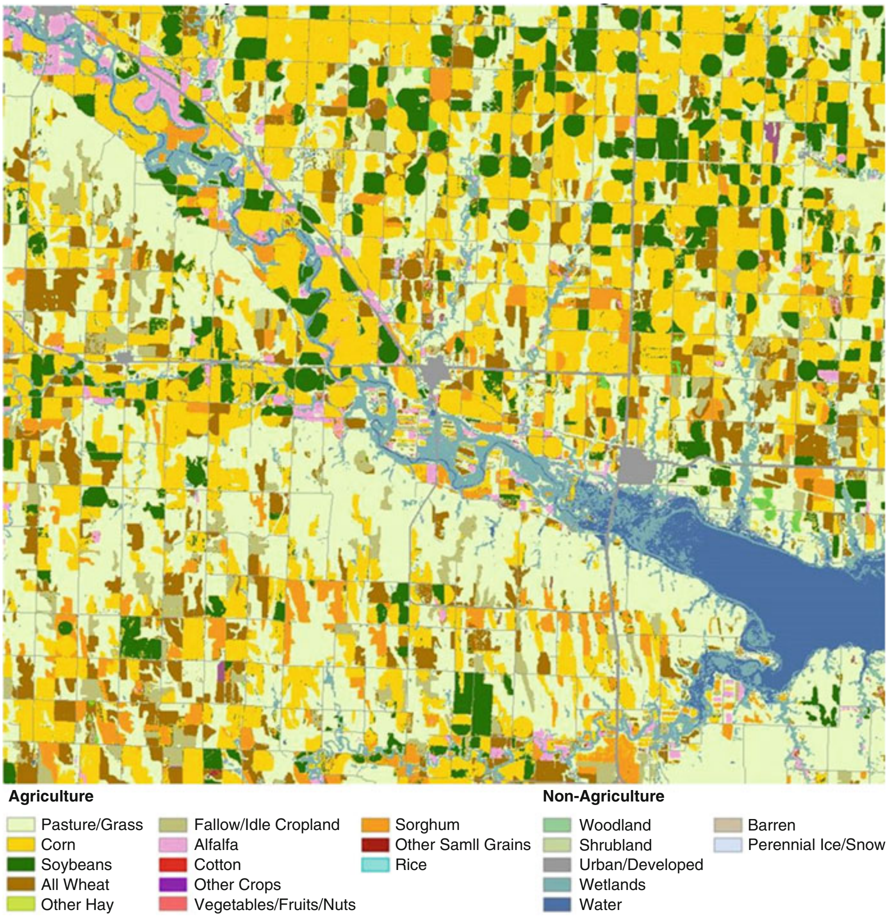


Fig. 10 A production USDA satellite image vegetation classification. (Image courtesy USDA National Agricultural Statistics Service)

designed to accurately forecast the global, short-term market outlook for wheat, rice, maize, and soybeans on a monthly basis (UN FAO 2013). Also launched at the same time was the GEOGLAM (Group on Earth Observations Global Agricultural Monitoring Initiative). The purpose is to "strengthen global agricultural monitoring by improving the use of remote sensing tools for crop production projections and weather forecasting by providing coordinated Earth observations from satellites and integrating them with ground-based and other in-situ measurements" (GEOGLAM 2019).

Both of these UN initiatives also serve to support the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals. These goals include eliminating poverty and hunger, sustaining our natural resources, and responding to

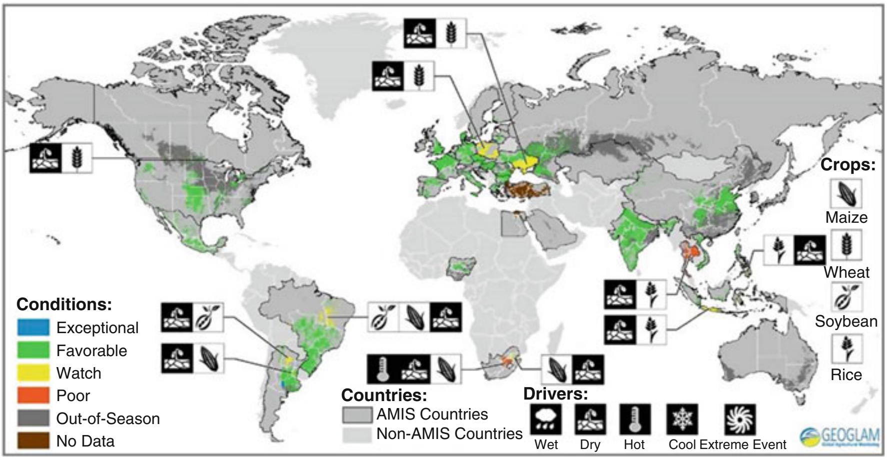


Fig. 11 A GEOGLAM product, showing global crop conditions and drivers for February 28, 2016. (Image courtesy USDA. http://www.geoglam.org/index.php/en/global-regional-systems-en/crop-monitor-for-amis)

climate change. Advanced technologies clearly play a role in this ambitious and difficult process (Fig. 11).

Today, in addition to the USDA in the United States, many nations around the world conduct their own crop forecasts. As just one example, in India the Mahalanobis National Crop Forecasting Centre has a staff of 20 and an annual budget of some US$1.5 million. They produce the FASAL (Forecasting Agricultural output using Space, Agro-meteorology and Land-based observations) program, producing crop forecasts at district and national levels for nine major crops, including jute, kharif rice, sugarcane, cotton, rapeseed and mustard, rabi sorghum, wheat, rabi pulses, and rabi rice (Mahalanobis National Crop Forecasting Center 2019). An excellent review of several national agricultural monitoring systems is available online from the UN FAO (UN FAO 2016).

In addition to these, and other governmental activities around the world, several major agribusiness interests such as Nestle, General Mills, and other international agribusinesses, as well as commodities exchanges and other financial trading institutions, also have crop estimation capabilities, either in-house or contracted, to look at the changing status of strategic commodities and their financial implications (Fig. 12).

6.1 Moving from Monitoring to Managing Agricultural Production

These continental and national-scale agricultural monitoring programs primarily record what is being produced or what *has* been produced, but what has been lacking

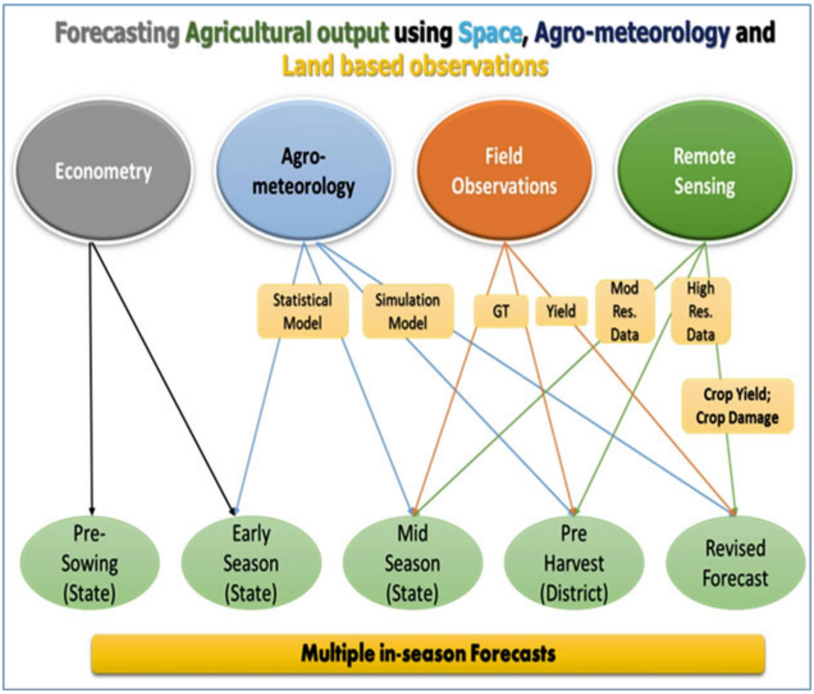


Fig. 12 Indian FASAL agricultural forecasting method. (Image Courtesy Indian Ministry of Agriculture and Farmers Welfare. https://www.ncfc.gov.in/about_fasal.html)

is local data to *drive* significant improvements in agricultural production. This is the promise of the third agricultural revolution, precision agriculture.

Scale is a vital aspect in the application of advanced technologies to the agriculture and forestry domains. The figure below shows a representation of agricultural scales, players, and issues (Fig. 13).

It is clear that agriculture operates on many different scales, from individual fields to global production, with many different commercial and governmental players, and complex issues of production, monitoring, and management that also vary widely around the world. Farming in North America is largely a multimillion dollar per year agribusiness, conducted on a vast scale and involving millions of dollars per operator. In much of the world, agriculture is still a very local activity driven by basic subsistence needs.

7 Current Precision Agriculture Systems

Technologies across the board have improved significantly since these modeling and forecasting capabilities were put in place. The next major development was the concept of precision agriculture as an integrated system for managing and improving

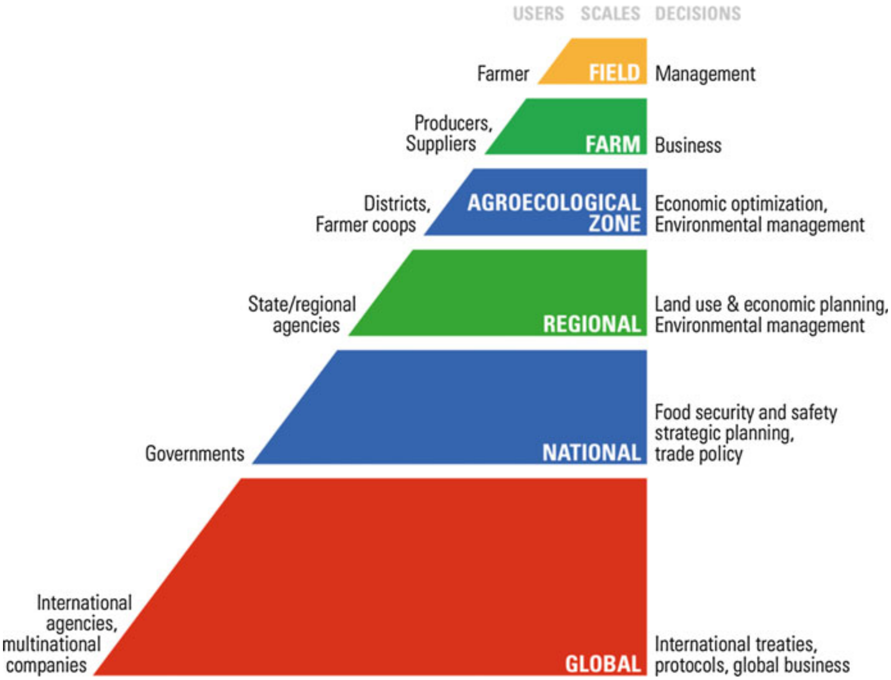


Fig. 13 The scales and players in agricultural forecasting. (Image courtesy UN FAO http://gsars.org/wp-content/uploads/2016/03/AMIS_CYF-Methodological-and-Institutional-Aspects_0303-web.pdf)

agricultural production, as opposed to large area crop monitoring that simply tracks what is being produced. The goal here is to actually *improve* the production process on a local level with improved yields and decreased cost and environmental impact.

So what exactly is precision agriculture? It has several names, including smart farming, satellite farming, and site-specific agriculture. I like calling it "bytes for bites," but they all refer to the concept of an integrated and real-time technology-based crop management system that monitors and shapes the crop throughout the entire growth cycle from pre-planting through harvest and distribution. In such a system, the detailed particulars of the crop fields, in relation to historical crop productivity, soils, slope, fertility, moisture, and other factors, are entered into a geographic information system (GIS) with data down to the square meter or less for each field. Satellite navigation and GPS are key aspects of such a system, and robotic tractors are now routinely able to drive the exact same route with sensors that can record various parameters, with the farming only monitoring the vehicle from the cabin in air-conditioned comfort. Another key part of the system is the VRS mechanism, or variable rate system. This allows the computers on the field tractor, based on the historical, current, and projected data, to distribute seed, water, fertilizer, herbicides, and pesticides on the field square meter by square meter, instead of simply putting out equal amounts of these, regardless of the particular field needs or conditions on the ground. And the system knows what the field characteristics are, what has been distributed, how the crops are doing, what is needed next, and when to harvest, all with quantitative precision. Remote sensing, from both satellites, aircraft, and now from drones, provides the real-time crop status and growth history, as well as soil moisture and crop stress from drought or disease. These data and in situ measurements from the fields and GPS tractors are fed wirelessly and automatically into the GIS system for analysis and determination of future activities. A decision support system (DSS) approach is often used, where specific rules are defined in the crop management software that trigger actions to produce the maximum crop yield for the minimum financial cost. Numerical modeling and even daily agricultural futures and estimated crop prices vs. total expenses provide daily estimated crop yield in terms of total amounts and also in dollars per acre (in the United States).

The benefits of this approach are clear, and major production systems are in operation today in North America, Australia, Argentina, and Brazil that demonstrate up to 30–50% decrease in cost and in the required application of fertilizers and pesticides, with equally significant increased yields. The environmental benefits of reduced water use and fertilizer and pesticide application are also important benefits of the precision agriculture approach.

The initial research and development was conducted in the United States, and early prototype systems were developed in the United States, Canada, Australia, and Brazil. There were relatively simple at first but have grown in complexity and sophistication. There was less initial interest in Europe, where agricultural scales are on a much smaller size and where governmental crop subsidies and policies were key economic factors in agricultural decision-making. But inroads in the UK and then France were made. There was, and still is, much less involvement in Asia and Africa, where the high initial cost and technical requirements make such approaches less interesting. There is tremendous potential in China and India, but these have not yet been realized.

7.1 Current Status

Precision agriculture has matured to where, for certain classes of large-scale agriculture in the developed world, it can be implemented with off-the-shelf technologies and equipment and which will provide measurable benefits. Farming operations can purchase their own systems or can contract with companies which provide a contract service. The growth potential is huge. A recent 2018 market report by Zion Market Research states that the global precision agriculture market is currently values at around US$5 billion and is expected to grow to over US$15 billion by 2025, a 13% increase (Zion Market Research 2018). Another market forecast by Grand View Research, Inc. projects a global market of over US$43 billion by the same 2025 date (Hexa Reports 2019), driven by its increasing visibility and potential for efficiencies and reduced waste. This report states that the Asia-Pacific region is poised for significant growth led by China, South Korea, and Japan, which all share an advanced level of technical capability. Japan and South Korea also share a drastic need for improved agricultural production on very limited available land areas.

8 John Deere: Nothing Computes Like a Deere

The John Deere tractor company of the United States has established itself as a world leader in precision agriculture. Starting his business in 1804, John Deere was a blacksmith who introduced a steel self-scouring plow, which he introduced in 1837. This was much more appropriate for American needs, and was quickly adopted, making the company a leading provider of agricultural equipment to this day. As early as 1997, John Deere offered GPS receivers and computers as options for their many tractors. These early activities have grown to where they are deeply involved in not only GPS and computer-aided tractors and variable rate distribution systems. They purchased the NavCom GPS company in the 1990s and partnered with NASA's JPL in 2004 to be able to provide highly accurate GPS data (down to a few centimeters or 1 inch) to their autonomous GPS-equipped tractors in fields around the world. In 2017 they purchased Blue River Technology, an early artificial intelligence computer vision, and robotics start-up from Silicon Valley to continue their development of advanced smart farming systems (Fig. 14) (Gagliordi 2018).

According to John Deere, today some 1/3 of croplands in the United States are farmed using GPS-guided precision agriculture tractors, along with half of the crop areas in Europe and South America, and a surprising 90% of farmlands in Australia (Anderson, G 2018). (N.B. I find the 50% number for Europe to be quite high and believe it to be significantly lower).

Precision agriculture has arrived, and there are many other players. L3Harris Technologies is very involved, and major international agribusiness such as Monsanto and several others are as well. The European Union has become a major supporter of smart farming, seeing this as a means to support the continuation of agriculture in Europe, while providing environmental benefits and reducing agriculture-related pollution European Commission (2019).

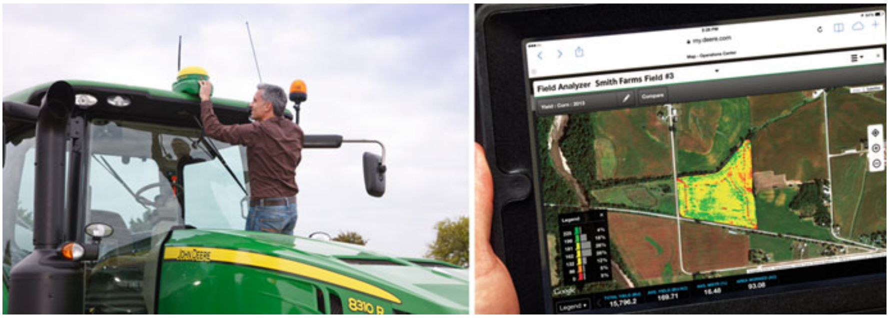


Fig. 14 A John Deere smart tractor and computer display. (Images courtesy NASA and John Deere https://www.nasa.gov/sites/default/files/thumbnails/image/spinoff_johndeere2.jpg)

8.1 Expanding the Precision Agriculture Model Beyond the Major Field Crops in the Developed World

Precision agriculture will not be limited to traditional crops like wheat and corn. Prototype projects have been conducted for fruit orchards, nut trees, and vines as well. There are similar approaches that are being developed for livestock using smart RFID sensors and automated feed and water distribution devices, ventilation and cooling, and "smart stalls" that weigh the animals and "smart collars" that monitor animal health. Similar systems are being developed for precision aquaculture, again consisting of in situ monitoring devices, DSS software, and automated water quality and feed dispensing systems. There are even prototypes for precision beekeeping systems. These systems have demonstrated the benefits, but, at present, precision agriculture is more suited to very large area mono-cropping in the developed world, where massive fields, up to 1000 hectares each, are managed using enormous and complex tractors costing millions of dollars and where high-speed Internet and computing is the norm. But there are currently relatively small agricultural businesses that are finding increases in efficiencies and profit using these systems.

9 Precision Forestry

Forestry is a very interesting and different industry, but which also has great promise regarding precision forestry technologies. There are currently some 300 million hectares of plantation forests in the world and an additional 900 million hectares of natural forests used for wood resource extraction. The value of this industrial forest is over US$200 billion, and wood remains the primary source of heating and cooking in the poorer regions of our world Choudhy, H. (2018). The world's forests also provide important environmental, recreational, animal habitat, and carbon sequestration benefits. The same basic concepts of precision agriculture can be applied to forestry, but there are also major differences and impediments. These include the fact that many forests are relatively unmanaged, are owned by governments, and are in remote and inaccessible terrain. Other forests are basically agricultural monocrops, but with a time frame of ~50 years per crop. Forestry is, like agriculture, a very conservative industry, little changes since the first scientific forest management concepts were developed in Germany in the nineteenth century, but this is all changing. Sweden has pioneered highly automated forest extraction systems that significantly increase the efficiency, safety, and speed of timber removal, and this has been widely adopted and has opened the industry to new and innovative techniques. A second recent innovation is the introduction of airborne LiDAR remote sensing, which is extremely useful for efficiently measuring large areas of timber resources (Fig. 15).

Today, forest management companies are beginning to consider the benefits of the precision agriculture model for forestry. The potential benefits of reduced costs and increased production are attractive, especially in regions of the world like Western Europe and parts of Asia where forest lands are limited. Deforestation

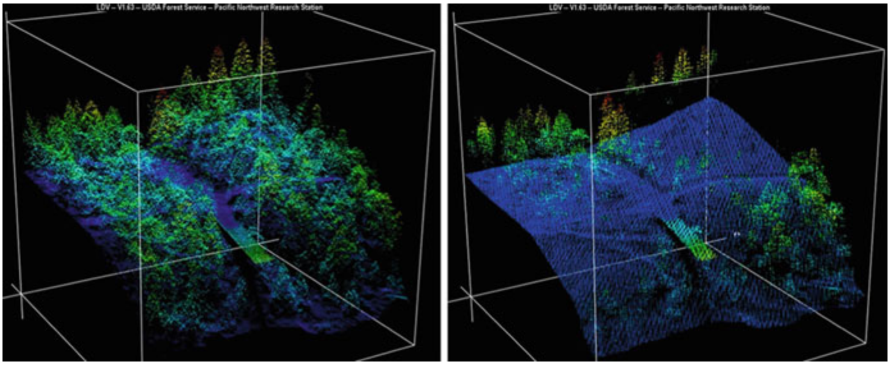


Fig. 15 Before and after airborne LiDAR images of the 2014 King fire region in El Dorado National Forest, California. (Image courtesy NASA JPL. https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA19360)

and climate change impacts will also be increasingly important factors affecting where and how forest resources are available.

10 The Present Becomes the Future

This is the current status of these integrated tools, but the future, the very near future, will be very different and potentially quite amazing.

In my recent book on disruptive technologies and innovations and the new commercial space revolution, I discuss the synergy of many new IT and space technologies, driven by a new generation of space entrepreneurs, which will drive the next revolution in space applications here on Earth (Madry 2019). We are quickly approaching a new world where the integration of powerful new technologies and innovative and disruptive "Silicon Valley" entrepreneurial space ideas is fundamentally altering how we do space and what that means here on Earth.

What we are seeing is the development of an integrated and synergistic combination of enabling technologies that will soon revolutionize many activities here on Earth. These include, but are not limited to, satellite positioning, navigation, and timing (PNT), geographic information systems (GIS), airborne and satellite remote sensing, aerial drones, vast networks of in situ measurement devices, robotics and automation, big big data, cloud computing, the Internet of Things (IoT), artificial intelligence (AI) and machine learning, decision support systems (DSS), computer vision, 5G wireless Internet, machine-to-machine communications, nanotechnologies, advanced genetics and genetically modified organisms, miniature biological sensors, and much more.

The implications for agriculture are clear. Detailed and local soil, moisture, and weather models could provide input into which places to plant which crops. With global climate change, this could allow proactive restructuring of where which crops are planted to match the best field conditions with changing crop market values and changing needs. Making sure that each seed is put in exactly the right place and depth, with the right soil conditions and moisture content to allow each individual plant the best chance for maximum growth at minimum cost, is within the realm of reality and then tracking and nurturing that plant all the way through to harvest. Let us look at just a few examples of some of these new capabilities and how they will soon impact global agriculture and forestry.

11 Big Data and the Internet of Things

Agriculture, at every level, is an extremely complex and inefficient system of systems. We tend to focus on the crops in the fields and the process of growing and harvesting, but agriculture takes much more than this to bring food to the table. Big data and the Internet of Things have great potential to improve efficiency at all levels of the agricultural cycle. This includes the distribution of just the right type and amount of seeds and materials to the farm; fuel management; management of water, fertilizer, herbicides, and pesticides; and the entire distribution system of the harvested crops to storage, market, wholesalers, food processers, and, ultimately, the end users. Agricultural fleet management, from harvest to delivery to your local grocery store, could also be significantly improved, reducing fuel use and pollution and eliminating produce spoilage. An amazing 1/3 of all food produced globally today is lost, ruined, or wasted, according to McKinsey & Company (Mangin, C. 2016). This is an equally amazing $940 billion economic loss per year, and no other comparable global activity comes close to this level of inefficiency, not to mention that almost 800 million people on Earth, 1 out of every 9 of us, go hungry each day. It therefore also has some of the greatest potential to be easily reduced using emerging big data, data analytics, and IoT systems. Tools like RFID and cloud computing could also significantly improve global agricultural production and supply chain management, solely through decreasing the vast amount of inefficiencies, theft, waste, and loss.

12 Big Weather

Improved weather forecasting can also play a major role in better crop management, through the reduction of the use of irrigation and potential crop damage such as hail, severe winds, or other severe weather. No less than IBM has developed a new precise weather forecasting system that they call Deep Thunder, which can feed data into improved models and production management systems. Based on the IBM Thomas J. Watson Research Center in New York, this program uses IBM's supercomputing power and data to develop new detailed weather models. These are based, in part, on over 200,000 Weather Underground personal weather stations and smartphones in a powerful example of crowd sourcing and citizen science, in addition to other sources including weather satellite data. It creates 24–48-h weather forecasts at 1–2-km resolution. The future potential is for accurate forecasts down to the square meter.

This concept could lead to more precise timing of planting, harvesting, irrigation, and mitigating potential damaging events such as severe winds or citrus freezes. IBM estimates that crop losses from severe weather events alone could be cut by 25% using this system (IBM 2019).

12.1 The Next Revolution: The New Mega LEO Satellite Constellations

Most precision agriculture systems today are stand-alone. Many are based on a single computer or local system, one GPS tractor, and are used to manage a single agricultural operation. The current limitations, including the lack of high-speed wireless bandwidth, particularly in the developing world, significantly limits the broad utilization of this technology, but this is soon about to change. This is because we will soon be able to add to this list of technologies the several new mega LEO satellite constellations that will provide seamless and low-cost telecommunications and remote sensing across the globe. Each of these technologies discussed briefly above is a stand-alone technology, but it is the synergy of these that will bring the powerful benefits of precision agriculture. Much of this synergy depends on the ability to pass large amounts of data seamlessly between different data monitoring, acquisition, and analysis systems and sensors in the fields and on the tractors and from satellites in space to the ground.

12.2 The Coming Mega LEO Revolution

A new generation of LEO remote sensing satellites is also an important part of the precision agriculture revolution. Led by Planet (formerly Planet Labs), there is a new generation of civil remote sensing satellites that are smaller and which can provide daily or even hourly image acquisition of the entire planet, an important component of detailed agricultural monitoring (Fig. 16).

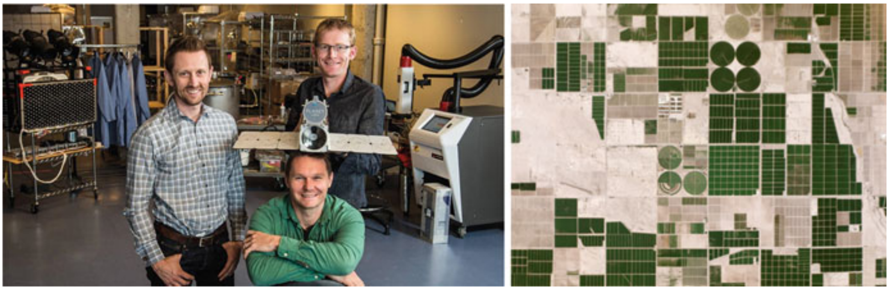


Fig. 16 (**a**) Planet “dove” satellite (and designers), a 3-U CubeSat remote sensing design. (Image courtesy Planet, Inc. https://www.sciencemag.org/news/2015/04/feature-how-tiny-satellites-spawned-silicon-valley-will-monitor-changing-earth). (**b**) A Planet satellite image of agricultural fields. (Image courtesy Planet, Inc. https://www.planet.com/pulse/planet-labs-strikes-agreement-with-wilbur-ellis-to-enhance-agverdict-data-tool/)

Planet has announced strategic partnerships with two major precision agriculture providers. In 2015 they announced a partnership with Wilbur-Ellis, to provide imagery for their AgVerdict data product (Alban 2015), and also with Farmers Edge, another major precision agriculture service company, to provide imagery to their products and services (Grassi 2017).

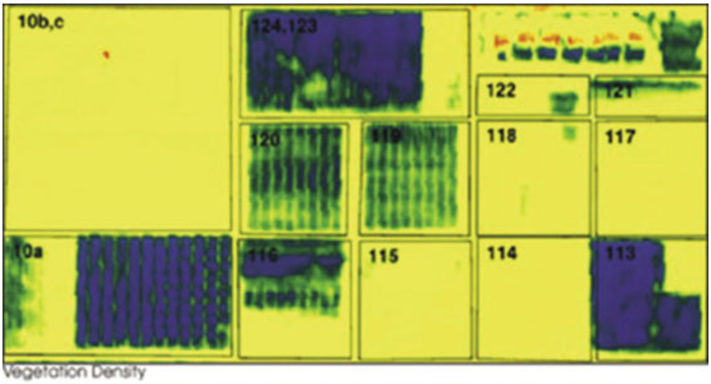
There are other LEO remote sensing systems active and in development, including hyperspectral systems, which can significantly improve agricultural classification. Also now available are a new generation of high-resolution RADAR satellites, which are particularly useful in agricultural areas with persistent cloud cover.

Urthecast (urthecast.com) currently offers 75-cm pan-sharpened imagery as well as their OptiSAR RADAR constellation. This system has 16 satellites in two orbital planes, and combines multispectral optical and SAR RADAR satellites flying in tandem, providing 1-m imagery and .5-m RADAR on a daily (or more frequent) basis. No matter what the weather is on the ground, data can be acquired, and the fusion of optical and RADAR data provides added detail.

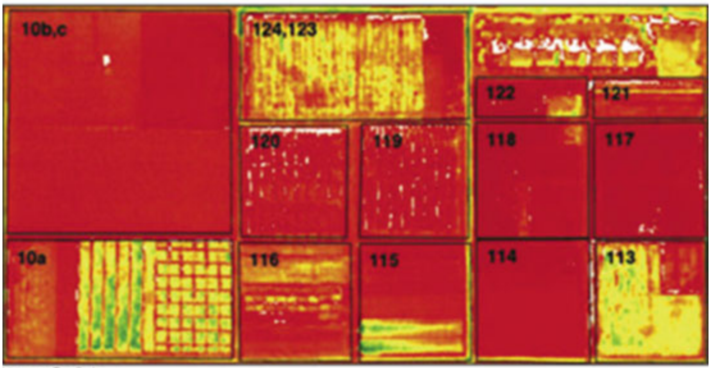
And a new generation of hyperspectral imaging satellites is in development and already in orbit. These systems sample the electromagnetic spectrum in hundreds or thousands of slices, providing much more information for precision agriculture, but they also require more sophisticated satellites, plus more data transmission, and data processing. Recent increases in data processing and lower data storage costs will mitigate these in the future. In the private sector, San Francisco-based HyperSat LLC has raised $85 million to launch two hyperspectral satellites in 2020: NorthStar from Canada plans a 40-satellite constellation and has over $80 million in financing, including funding from the Canadian government, and Brazilian company Satellogic has raised $27 million and has launched three satellites so far. Constant satellite imaging of the Earth is now a reality, and this is a powerful part of the precision agriculture future. Ultimately, it will be the combination of all of these systems, as well as airborne and drone systems, that will provide increased crop classification, as well as improved drought and stress monitoring for input into the precision agriculture management process (Fig. 17).

12.3 The New Broadband LEO Systems

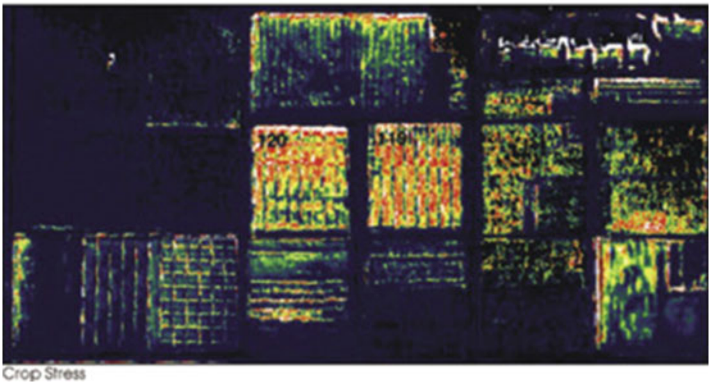
But the real LEO revolution is the coming wideband telecommunications constellations that are currently in development. There are several proposed mega-low Earth orbit (LEO) satellite telecommunications systems coming soon. All of these share a general architecture and goal: to provide high-speed and low-cost, wideband Internet connectivity worldwide. The benefit of LEO constellations for telecommunications and broadband Internet services is the low signal latency. Being only a few hundred km above the Earth, these systems have a very low signal delay, as opposed to the traditional GEO orbit at 35,786 km (22,236 mi), which can have a signal delay of some 540 milliseconds (~1/2 s) round trip. The downside of LEO constellations is that they require many more satellites to provide global coverage, due to the small footprint on the ground at that lower altitude. One GOES telecom satellite can cover nearly 1/3 of the planet, where it takes several hundred satellites to provide global



Vegetation Density



Water Deficit



Crop Stress

Fig. 17 NASA hyperspectral image showing vegetation density, top; water deficit, middle; and crop stress, bottom. Using algorithms and techniques, it developed with funding from Goddard Space Flight Center. This image was developed by the NASA Goddard Space Flight Center for the precision agriculture firm GeoVisual Analytics to let them learn more about their customer's crops, including predicted yields. (Image courtesy NASA. https://spinoff.nasa.gov/Spinoff2017/ee_8.html) coverage from LEO. This means you must build, launch, and operate a much larger number of satellites, but they can also be smaller and less complex than the very large, and very expensive, traditional GEO telecom satellites, and new lower-cost launch systems like the SpaceX Falcon 9 significantly reduce the cost of launch. One added complexity of these is that the satellites come into and leave the view of any place on the planet quite quickly, so satellite-to-satellite optical laser links are required to maintain the connection between any two places on the Earth. While this adds complexity, the speed of light in the vacuum of space is actually faster than through terrestrial fiber optic lines, so the speed of a LEO space Internet connection will be, at least theoretically, faster than today's systems. The satellites also must be replaced more frequently due to the atmospheric drag at lower altitudes. But the benefit will be truly global broadband Internet services. It must be remembered that only some 20% of the world today has high-speed cell service. The change will be revolutionary. So who are the new entrants?

OneWeb, which is obtaining new financing from the U.K., is now seeking to move on from its bankruptcy so it can deploy its large LEO constellation. Airbus, which is the manufacturer of the satellites as well as an investor in OneWeb, has built a low-cost mass production plant in Florida in the U.S. where the smallsats are being constructed. The deployment schedule for these satellites has been disrupted by the bankruptcy and will be delayed beyond the 2021 deployment date.

Elon Musk's SpaceX is developing the Starlink constellation, which will consist of some 12,000 (!) LEO satellites in several different orbits. Two prototypes are already in orbit for testing, and in May of 2019, the first 60 operational satellites were launched, on a single previously flown SpaceX Falcon 9, of course. The total cost of the system is estimated to eventually be some $10 billion. Often overlooked is the significant ground infrastructure that these will require. SpaceX Services, Inc. filed an application with the US Federal Communications Commission for the licensing for up to one million fixed satellite Earth stations, which would be the user terminals for the system. This system is designed, in part, to provide commercial funding for Musk's Mars exploration activities. He has received a $1 billion investment by Google and Fidelity to build out the system.

Kuiper Systems, a wholly owned subsidiary of the Jeff Bezos-led Amazon, filed documents requesting permission to launch a 3236-satellite constellation. The system would place the satellites into 98 orbital planes at altitudes of 590 to 630 km, including 784 satellites at an altitude of 590 km, 1296 satellites at a height of 610 km, and 1156 satellites in 630-kilometer orbits. The goal, again, is global broadband Internet service direct to end customers.

The Canadian company Telesat is creating a 300-satellite LEO constellation for Internet services, which should be capable of offering service throughout Canada by 2022 and globally by 2023. This system has received US$60 million from the Canadian government (Henry 2019).

Fig. 18 Canadian Telesat LEO satellite. (Image courtesy Telesat)

Thales Alenia Space and LeoSat of Luxembourg have also announced plans for a similar satellite broadband system, with 108 LEO satellites in 1400-km polar orbits that will be more focused on governmental and large corporate customers (Fig. 18).

Finally, technology giant Samsung has announced a plan to develop a 4600-satellite constellation, designed to provide up to 200 Gb per month directly to up to 5 billion of the Earth's people, but they have not yet made a final commitment (Khan 2019).

These systems, even if all are not built, and probably will not all survive in the open marketplace, will create a new and integrated digital world, including a global Internet of Things. But by far the greatest difference is the new generation of commercial space entrepreneurs who see IT and space as a launch pad to new commercial and humanitarian capabilities that exceed our current mindset. We are rapidly approaching a very different and challenging global context regarding food and agriculture, one that also brings a hopeful and possibly revolutionary technological environment that could make a real impact. But where do we go from here?

13 Discussion

Some conclusions and recommendations for the further implementation of precision agriculture are appropriate here, as a guide for consideration of adoption of precision agriculture more broadly in the developed world and also in the developing world nations of Asia and Africa. A European Union focus group in 2015 on the mainstreaming of precision agriculture in Europe made several important conclusions and recommendations that are relevant to this question (European Commission 2019). A liberal paraphrasing of some of these conclusions includes the following important points:

1. Farmers must be actively involved in the development of these tools.
2. Skilled advisors will be important to successfully bring these tools to farmers.
3. Potential economic benefits are hard to measure and must be clearly and convincingly demonstrated.
4. Small and medium farms need reduced up-front investment and lower risk before they can consider adoption.
5. Technical progress must continue, and costs must continue to come down.
6. Shared data is an issue for farmers.
7. More research is needed on applying these rapidly advancing technologies to small and medium farms.

Recommendations included:

1. Development should focus on practical farming problems and not on technology.
2. Multi-actor collaboratives are needed to address the complexity of the problems, and teams need to be formed consisting of farmers, technologists, and others.
3. Analytic support tools and training tools are needed.
4. DSS models and related tools are needed to help farmers determine if this will work for them before they invest.
5. Up-front and total cost and ease of use are important.
6. New business models for data management are needed.

These general conclusions and recommendations can be more broadly applied regarding the appropriateness of advancing these technologies around the world. Clearly, in Asia, Africa, and poor nations around the world, there will be very different contexts regarding the introduction of precision agriculture. But the general conclusions and recommendations listed above serve as a good guideline for consideration.

Clearly, farmers must be involved in the development of these tools if they are going to be successfully implemented. This goes for other key players as well, including the financial institutions that traditionally finance the annual up-front costs of farmers for seed, etc. This brings up the issue of technology push vs. user pull. We are very good at developing new technologies, which we push out to potential users, often without success. This approach is unlikely to succeed in such a very traditional and non-tech industry such as agriculture. Precision agriculture is certainly a technology push approach, and we need to find additional ways to bring the farmers and agricultural interests more into a user pull mode, where they work with precision agriculture interests to develop tools that they actually need and want to adopt and actually *can* adopt. A key component of this will be developing credible case studies that demonstrate the benefits of these systems to a variety of use cases, crops, scales, and geographic locations. The up-front costs required of such technologies need to be reduced, and the level of technological sophistication required by farmers needs to reduced significantly. Training opportunities for potential users must be developed that are realistic and made widely available. Ultimately, new business models for farmers are going to need to be developed that are relevant to the cultural, social, political, and economic realities of farmers who are not accustomed to this new way of integrating advanced technologies into their farming operations.

There are already several innovative and culturally and technologically appropriate activities already occurring. For example, in Kenya, a platform for connecting agricultural producers and purchasers has been established called Sokopepe (https://sokopepe.co.ke), that links small farmers to bulk purchasers. They also have an information system providing small farmers access to data, market information, weather, and more, all using the prevalent SMS systems found throughout Africa. Another similar tool there using SMS is called MFarm (https://www.mfarm.co.ke). This provides current commodity prices for different regions and connects small farm operators with buyers in ways that have traditionally been impossible for them. Previously, small producers were never aware of the different prices buyers were offering, and they would simply sell to the nearest market. Now they can find the best prices for their products in their region, and get connected with wholesale buyers directly, all through SMS. There will be many developed vs. undeveloped world issues this all plays out. There will not be a one-size-fits-all version of precision agriculture.

All of this will raise many new and complex legal and policy issues. There is already a strong reluctance of farmers to release data on their operational efficiencies to banks and governments, for obvious reasons. Who will own all of this very detailed data? Who has access? Who is liable if mistakes are made due to incorrect data? How vulnerable would these systems be to hacking by criminals, non-state actors, terrorists, or hostile nations?

Closely related to the legal issues are the myriad national and international policy issues that will involve the intellectual property, copyright, and digital data issues that will be raised. Who will benefit from these decisions? Will it be only the large international agribusiness? Will the interests of small and medium farmers and producers be protected? Policy and legal decisions always trail behind technology developments, especially today, and so policy-maker and lawmakers are always playing catch up.

Food safety is another important aspect of the global agriculture equation that could be impacted by this new generation of agricultural technologies. Creating a digital data chain that allows the consumer or government agency to track a food product all the way back through the production and distribution chain to the producer could revolutionize food safety management and the response to outbreaks of food-borne diseases or food terrorism, which is, sadly, a growing concern.

Another key concern moving forward is the potential dependency upon these complex and computer-based technologies for our global food supply. In traditional agriculture, the individual farms and farmers are highly independent and not dependent upon outside factors. An integrated global precision agriculture system brings the promise of increased yields and efficiencies, but what do we do when the system goes down, whether if from accident, mistake, or intentional attack? The potential dangers of this are evident. Complex systems that can fail will fail.

And these systems do not come for free. Million dollar GPS tractors are not likely any time soon in most African contexts. Any increases in productivity must also pay for all of the cool tech that will be required and the satellite builders, tech developers, and systems administrators that will have to be paid. Agricultural labor is among the cheapest in the world, hyperspectral satellite data analysts and satellite constellation controllers are not. Automation of much of the data processing flow will be vital if precision agriculture will be able to succeed in the developing world.

14 Final Conclusions

Global population growth, urbanization, and climate change will bring unrivalled pressures upon the global food supply system, and new efficiencies and capabilities will be required sooner than many believe. Precision agriculture will soon bring powerful new capabilities to a world that will see tremendous new food and fiber needs, but there are significant technical and cultural challenges.

While these new technologies, including the upcoming new generation of mega LEO satellite constellations, will bring low-cost and high bandwidth data around the world for the first time, their broad adoption in agriculture is far from certain. These new capabilities, combined with the new persistent remote sensing systems and allied GNSS and other technologies, could bring a new revolution in agriculture. But agriculture is the world's most traditional sector, and how it is willing or able to adapt to these radical changes will be interesting to watch. Our dinner may well depend upon it.

15 Cross-References

- ► Planet's Dove Satellite Constellation
- ► Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently
- ► Smalls Satellites and the 17 United Nations Sustainable Development Goals

References

J. Alban, Planet Labs strikes agreement with Wilbur-Ellis to enhance AgVerdict® data tool (2015), https://www.planet.com/pulse/planet-labs-strikes-agreement-with-wilbur-ellis-to-enhance-agverdict-data-tool/

G. Anderson, How NASA and John Deere helped tractors drive themselves (NASA Space Tech, 2018), https://www.nasa.gov/feature/directorates/spacetech/spinoff/john_deere

C. Caudill, R. Hatch, Overview of the AgRISTARS research program (NASA, n.d.), https://www.nass.usda.gov/Education_and_Outreach/Reports,_Presentations_and_Conferences/GIS_Reports/OverviewOfTheAgRISTARSResearchProgram.pdf

H. Choudhy, Precision forestry: a revolution in the woods (McKinsey & Company, 2018), https://www.mckinsey.com/industries/paper-and-forest-products/our-insights/precision-forestry-a-revolution-in-the-woods

J.D. Erickson, The LACIE experiment in satellite aided monitoring of global crop production, in *The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing*, ed. by G.M. Woodwell (Wiley, 1984)

European Commission, EIP-AGRI focus group on precision farming: final report (2019), https://ec.europa.eu/eip/agriculture/en/publications/eip-agri-focus-group-precision-farming-final

N. Gagliordi, How self-driving tractors, AI, and precision agriculture will save us from the impending food crisis (TechRepublic, 2018), https://www.techrepublic.com/article/how-self-driving-tractors-ai-and-precision-agriculture-will-save-us-from-the-impending-food-crisis/

M. Grassi, Precision Ag. Farmers Edge, Planet Labs announce multi-year exclusive imagery distribution agreement (2017), https://www.precisionag.com/industry-news/farmers-edge-planet-labs-announce-multi-year-exclusive-imagery-distribution-agreement/

Group on Earth Observations Global Agricultural Monitoring Initiative, 2019 GEOGLAM stocktaking report (2019), http://earthobservations.org/geoglam_resources/1%20Home/Planning%20and%20Reporting/G20%20Stocktaking%202019%20Japan.pdf

C. Henry, Canadian government pledges $521 million for Telesat LEO constellation. SpaceNews, 24 July 2019 (2019), https://spacenews.com/canadian-government-pledges-521-million-for-telesat-leo-constellation/

Hexa Reports, Precision agriculture market analysis by component (hardware, software & services), by technology (variable rate technology, remote sensing, guidance systems), by application, by region, and segment forecasts, 2014–2025 (2019), http://www.hexareports.com/report/precision-agriculture-market

IBM, Icons of progress. Deep thunder (2019), https://www.ibm.com/ibm/history/ibm100/us/en/icons/deepthunder/transform

J. Janick, Ancient Egyptian agriculture and the origins of horticulture (PDF). Acta Hort. **583**, 23–39 (2002)

F. Khan, Mobile internet from the heavens (2019), https://arxiv.org/ftp/arxiv/papers/1508/1508.02383.pdf

Mahalanobis National Crop Forecasting Center, (2019), https://www.ncfc.gov.in/about_fasal.html

S. Madry, *Disruptive Space Technologies and Innovations: The Next Chapter* (Springer Press, Switzerland, 2019), https://link.springer.com/book/10.1007%2F978-3-030-22188-1

C. Mangin, How big data will revolutionize the global food chain (2016), https://www.mckinsey.com/business-functions/digital-mckinsey/our-insights/how-big-data-will-revolutionize-the-global-food-chain

G.E. Mingay, ed., *The Agricultural Revolution: Changes in Agriculture 1650–1880* (1977), p. 3

NASA, AgRISTARS agriculture and resources inventory surveys through aerospace remote sensing. Annual report – Fiscal year 1981 (1982), https://www.nass.usda.gov/Education_and_Outreach/Reports,_Presentations_and_Conferences/GIS_Reports/AgRISTARS%20Annual%20Report%20(FY%201981).pdf

M. Tauger, *Agriculture in World History* (Rutledge Press, 2008)

United Nations, Department of Economic and Social Affairs, World urbanization prospects, the 2019 revision (2018), https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf

United Nations, Department of Economic and Social Affairs, World population prospects (2019), https://population.un.org/wpp/. Accessed 16 Nov 2019

United Nations Food and Agriculture Organization, Agricultural Market Information System (AMIS) (2013), http://www.fao.org/fileadmin/templates/worldfood/Reports_and_docs/AMIS_Information_Brief_2013.pdf

United Nations Food and Agriculture Organization, Crop yield forecasting: methodological and institutional aspects (2016), http://gsars.org/wp-content/uploads/2016/03/AMIS_CYF-Methodological-and-Institutional-Aspects_0303-web.pdf

C. Zhao, et al., Temperature increase reduces global yields of major crops in four independent estimates, in *Proceedings of the National Academy of Sciences of the United States* (2017), https://www.pnas.org/content/114/35/9326

Zion Market Research, Global smart agriculture market worth $15,344 million by 2025 (2018), https://www.globenewswire.com/news-release/2018/08/07/1548245/0/en/Global-Smart-Agriculture-Market-Worth-15-344-Million-by-2025.html

Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently

Scott Madry and Joseph N. Pelton

Contents

Abstract

The UN Committee on the Peaceful Uses of Outer Space and its Working Group on the Long-Term Sustainability of Outer Space Activities (LTSOSA) have sought to develop recommendations that could help allow humans to continue to access space for the longer term on a sustainable basis. The United Nations General Assembly has also approved a series of 17 sustainable development goals to assist nations to create clearly defined aims to improve the human condition for the longer term by means of well-defined objectives. These include goals to improve the atmosphere, the land, water, energy systems, transportation,

---

S. Madry (✉)
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_57

and more. These various efforts of UN COPUOS and the UN General Assembly are described elsewhere in this chapter.

This chapter, however, is not about attaining these various clearly set goals and recommended actions. Rather it is about the opposite side of the coin. Thus it specifically addresses how small satellite projects and activities can provide capabilities to improve performance in many areas and also to aid new monitoring and enforcement capabilities. The areas of monitoring and enforcement can be as wide as new zoning and planning systems, a strengthening of environmental protection practices, or various forms of law enforcement and national defense. These new tools can help to assist nations, in both developed and developing economies, to exploit new and cost-affordable small satellite capabilities to make many industrial, corporate, or business more efficient on one hand or to prevent harmful practices related to the air, land, and sea environment.

The monitoring of certain key resources such as fish or fresh water or key natural resources might serve a key function of monitoring the "health of our planet" as a sustainer of life, especially human life. In short small satellites that monitor and keep track of our supplies of drinking water and nourishment and help protect vital resources could serve the function of a canary in a coal mine of letting us know when the dangers of overconsumption have reached perilous levels.

This can also be stated in a more positive and proactive way. Our new cost-effective "eyes in the skies" can be translated into finding new ways to manage resources such as fishing grounds, water, forests, natural resource mining, and other finite materials that need better management and systematic recycling. These new satellite tools can assist with longer-term goal setting to meet the needs of future generations. Such efforts may need deployment and use of not only small satellite networks but new regulatory processes, laws, or best practices that can be established on a global basis and consistently followed around the world.

This chapter seeks to address the use of small satellites to address areas of water, energy, transportation, and environmental concerns, as well as the use of satellites to help provide oversight and enforcement processes in these and related sectors. These sectors of regulatory concern include such areas as fishing, mining, packaging, and even recycling practices. Ultimately, addressing these issues involves more than efficiency of global operations and economic success but sustainability of humans and all the life forms on Earth over the longer term. Thus it is now recognized that one must produce energy for use by consumers and industry but do so in a sustainable way. The same is applied to transportation systems, mining, food production, and so on. The prudent use and supply of potable water may prove to be one of the greatest challenges of the coming decades.

Thus the topics that will be considered are addressed not simply in terms of economic output but in other ways that include possible enforcement practices, environmental concerns, and perhaps ways to create new incentives for positive behavior by citizens and businesses.

The special emphasis will be on how small satellites and related ground systems and data analytics might be combined together and used in a constructive

way to achieve required results around the world to preserve the resources needed for future generations. In some ways, this chapter closely correlates to the chapter on small satellites, resource management, and "smart farming" and "smart forest management." The discussion of "smart farming" and "smart forestry management" is geared to see how constructive use of new satellite technology and systems can increase productivity and multiply output; yet here too, there may well be a need to develop improved standards and environmental enforcement measures to achieve overall desired results.

Keywords

Anthropocene Age best practices · Developing nation · Digital divide · Energy consumption · Environmental enforcement · Fishing · Hyper-spectral sensing · Legal rights of future generations · Natural resource mining · Oil spills · Packaging · Paris Accord on Climate Change · Polluting practices · Quotas · Remote sensing · Strip mining · Sustainability

1 Introduction

There are increasing concerns that humans are overconsuming a wide range of resources. As there are more people, more urbanization, and more consumption of energy, food, fish and water, metals, wood, petroleum, and hydrocarbon fuels, there is also more pollution. These patterns of overconsumption and a lack of recycling are sometimes referred to as "non-sustainable" economic practices. The lack of a positive circular economy where resources are reclaimed rather than consumed is quite negative, in the longer term, for both developed and developing economies. Population growth compounds these overconsumption patterns.

These negative results can be seen in many ways that include climate change; shortages of potable water and, over time, food and fish; the dying off of many species of animals and plant life; and systematic flooding of coastal areas.

Geologists have informed us that we have now entered the Anthropocene Age, where humans are the major shaper of change in our world today. A recent UN report documents the accelerated rate at which more and more species are dying out under human influence (Fears 2019). All of the trends raise serious concerns. One of these negative consequences is that the future needs of generations yet to come are increasingly at risk.

These are not self-correcting issues. But issues as large in scope, magnitude, and timescale that have been called by ecologist and English professor Tim Morton "hyperobjects" are difficult for people to cope with in any sense of competence. Unless we are hit over the head by a catastrophic event, we are slow to take any corrective action. So far most of the human response to the ongoing climate crisis has been more like putting a band aid rather than applying a tourniquet.

Although some economically developed nations have reached zero population growth, some of the largest nations in the world such as India, Nigeria, Indonesia, and Brazil and many Middle Eastern countries have substantial population growth rates. The current global population rate may bring human levels to as much as 12 billion by 2100. Population growth rates as they are occurring today more than offset “green initiatives” such as electric cars or solar or wind energy systems. Population growth is largely outstripping global supplies of food, fish, and especially water.

Of all the scarce resources on Earth, fresh or potable water is now the most critical. If one starts with all the world’s water, this seems to be far from true. There is a total of 35 million cubic kilometers of all types of water. Of this amount only 2.5% of the total represents fresh water. And of this supply, at least 70% is not accessible either because it is frozen in the polar ice caps, permanent snow cover, or it is buried deep in crater lakes. Thus today humans, animals, and all vegetation can get access to about 200,000 cubic kilometers of fresh water. The following graphic prepared by the Sierra Club dramatically shows the limited supply of water compared to the total volume of Earth (see Fig. 1).

Further, the fresh water available is far from evenly distributed. Studies undertaken by the UN Food and Agricultural Organization have estimated that by 2025, 1.8 billion people will be living in areas where access to potable water will be limited or extremely scarce (Ruz 2011).

Of all the functions that small satellite constellations will carry out, providing inventories of water, water shortages, and information about such things as water leakages and information about underground water aquifers may well prove to be the most vital function.

The good news is that small satellite constellations that are combined with data analytics could begin to provide useful and actionable information to national

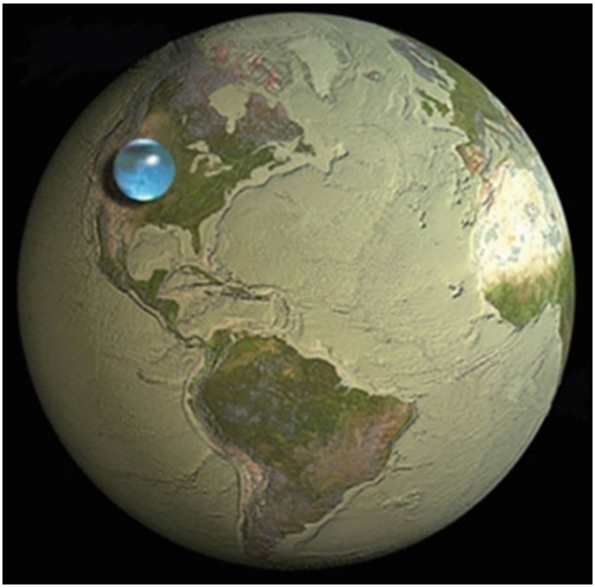


Fig. 1 Graphic showing the limited supply of water compared to Earth’s volume. (Graphic courtesy of the Sierra Club)

planners and regulators around the world and many types of resources including food, fish, and water. Remote sensing satellite constellations could chart the global supply and demand patterns of any types of resources with new precision.

The data analytics could produce growth trends in consumption rates of food, fish, water, and energy; car, truck, and bus miles driven; desertification; loss of arable land; loss of wet lands; and even presence or extinction of endangered species. The analysis that follows can start to document what existing sensing data is already telling us about key consumption patterns. The question that remains is whether there will be systematic attempts to get more fine grain data that could be used by regulators. Small satellites, particularly in remote sensing, could be used in such areas as pollution oversight and regulation, taxation policy to create new incentives and disincentives, and so on.

2 The Use of Small Satellite Consortiums as a Source of Regulatory Control and Incentive

The first question is whether small satellite-collected data can and will be effectively linked to new regulatory controls and/or tax incentives, and if so, will these new processes be embraced and used in national, regional, or even other forms of global planning to reduce pollution and make industrial and consumer practices “greener.”

The new small satellite consortia such as Planet and Spire and other new remote sensing satellite systems around the world will be able to generate not only a prodigious amount of information but with a return rate measured in hours – not days or weeks. The key is whether governments, nongovernmental organizations, and environmental groups join forces to make this data actionable.

If the right incentives – and penalties – are devised and enforced, this new satellite-based information can encourage and bring into being “circular economies” around the world. A circular economy is one that uses renewable energy rather than disposable energy. A circular economy is one that that is focused on reusing metals and chemicals and consuming food that grows in fields rather than depending on livestock. In short, a “circular” economy is the reverse of a “disposable” economy that eats up its resources rather than recycles them.

The new and rather precise tools that collect information about all forms of consumption several times daily are a very powerful mechanism that can be used to rein in the worse forms of abuses in terms of pollution, overconsumption, and lax practices with regard to recycling, overfishing, and wastage of water, food, and metals and also help to limit the use of dirty fuels. Alternatively there could be new incentives created to eat less meat and consume more environmentally friendly foods, use less water, use greener energy, and generally pursue more environmentally benign patterns of behavior. The use of more incentives such as lower taxes or rebates on green resources could be a powerful tool for conservation, if consumers are willing to “buy into a monitoring system” that provides a degree of tracking of their consumption habits.

The new “eyes in the skies” tools can do more than monitoring pollution or overconsumption patterns. These tools can be used in many other ways. This might be used to help develop better transportation and distribution processes and aid in the improvement of weather data and agricultural processes and hydroponic farming techniques. Essentially the key is to link up global patterns of consumption and environmental changes with important new processes. This might be the restocking of fishing areas, the monitoring of mining, or the recycling processes or other uses of big data analysis to see where progress is being made and where overconsumption or disposable economic practices are increasing.

The key is really not small satellite constellations and their data gathering but big data analytics and the creation of new tools to allow critical data to be acquired in a systematic basis. There are ways to encourage and incentivize a range of “green” practices, “circular” economic practices, zero-growth population practices, etc., and these can, of course, also be linked to penalties for abuses linked to overconsumption.

It might reasonably be observed that a good deal of data is already available, yet despite this information, a number of environmentally destructive and counterproductive behaviors by consumers, industrial producers, and governmental legislators and regulators still continue. This is a valid and quite significant point to address.

One might hope that if the data can be applied to the day-to-day practices of individual consumers, so that they could actually “see” how their particular behaviors are creating unacceptable levels of overuse, people could see in near real time how their patterns of consumption or unintentional polluting activities might be reformed by new patterns of consumption, and they might indeed be motivated to change.

If people – or companies or governments – could almost instantly see where their consumption patterns, when compared to others in their town, city, state, region, or country, were out of step, then they have a much greater chance of changing their consumption practices.

If the data analytics, linked to high-performance but low-cost small satellite sensing networks, can show people their excessive consumption actions, and what simple changes could make a difference, there can be potential for both better understanding and eventual reform of their practices.

It is quite possible for many people to be unaware of when they are needlessly consuming too much water, using too much energy, eating too many calories, polluting the air too much, etc.

The key to change is a clear and viable offering of reasonable and cost-effective alternatives. These options will often need to be tied to various penalties and incentives that complete the picture. The appeal to people to save resources for their grandchildren and great grandchildren is fine, but alternatives must show a reasonable way forward. Most people will start to reform if they can, for instance, find ways to use less water than before, save money as well as water, and make available to others a resource that they desperately need. The most important change will perhaps be “institutional change.” This might be new laws and penalties to create limitations with teeth against significant new developments in deserts where water is already in short supply.

There are impressive projects such as undertaken by Dr. Jerome Glenn that monitor many key patterns of consumptions and chart key trends, but this data is provided as macro-data to corporate, government, and defense-related officials. It is meaningless to individuals if they cannot see the impact of their everyday practices in terms of what it means for their family versus the families in other towns, cities, or nations. If they could see in ways that they could readily understand what their “standard of living” means to others in the world or subtracts from the heritage of their grandchildren, it becomes a more powerful story. If they could also see the ways that they could pollute less, consume less water, and waste less energy, progress might well be made. The key might well not be the new small satellite constellations that produce new data every 4–6 h but the data analytics that can show the implications in near real time of what their patterns of consumption, pollution, or waste actually mean to others that are denied resources that are being wasted without much thought of their larger implications. Much indifference is likely born of a lack of understanding as to what the implications of their action really entail.

At least a substantial number of people would respond to the actual knowledge that in the last 12 h, they had used four times more water, ate twice the amount of food, used three times more energy, or created one and half time waste than a counterpart in say rural Portugal. Especially if they could understand how they might re-equip their house, plan their water and food consumption differently, or use a different type of car or solar or wind source to be environmentally more friendly, at least the hope would be that many would use that new information in a constructive ways if they were consistently made aware of their consumption patterns. Such a localized and personalized reporting system on consumption is, of course, not a panacea. Some people would be indifferent to such information, but they might respond to thought leaders or seek to conform if their neighbors began to behave differently and they began to stand out overtly as being outside the norm. In some cases, parents might refuse to adapt, but their children would see the social, cultural, and moral value of change. Let’s explore some of the data that is now available at least at the macro-level, even though it is not broken down to the level of towns, neighborhoods, and households.

3 Food, Fishing, and Water

The following profile of global food consumption is broken down on a calorie consumption basis. It shows the differences in diet around the world and also shows an upward trend in calories in all regions of the world (Global and Regional Food Consumption Patterns and Trends 2019) (see Table 1).

The question is: Is this consistent growth in food and calorie consumption actually a positive trend line when seen against the longer-term needs of the planet? If one projects the population of the world which is now around 7.8 billion, which could reach 12 billion by the end of the twenty-first century, and food consumption of humans averaged some 3000 calories per day, that would total 36 trillion calories of food each day or 1.3 quadrillion calories per year. This, of course, does not take

Table 1 Daily food consumption measured in calories for regions of the world

Region	1964–1966	1974–1976	1984–1986	1997–1999	2015	2030
World	2358	2435	2655	2803	2940	3050
Developing countries	2054	2152	2450	2681	2850	2980
Near East and North Africa	2290	2591	2953	3006	3090	3170
Sub-Saharan Africa (but not South Africa)	2058	2079	2057	2195	2360	2540
Latin America and Caribbean	2393	2546	2689	2824	2980	3140
East Asia	1957	2105	2559	2921	3060	3190
South Asia	2017	1986	2205	2403	2700	2900
Industrialized countries	2947	3065	3206	3380	3440	3500

These statistics and projection for 2030 come from the UN Food and Agricultural Organization

into account food for horses, cattle, dogs, cats, and all the other animals that inhabit Earth. In many ways, this path forward for an Earth of finite resources is quite troubling in terms of potable water supply where nearly a billion people have an inadequate supply today. And for the longer term, this will also translate into an inadequate food supply. Already there are lists being developed of many resources especially metals that are becoming scarce.

In 1800, there were only 800 million people on our planet. In 1900, there were 1.8 billion. Today there are 7.8 billion, and in 2100 there will be perhaps 12 billion. It is reasonable to project that this time, there will be shortages at many levels. Some of these key areas are most likely to be potable water, food, fish, and cost-effective and clean energy supplies, as well as major gaps in education and healthcare systems, sufficient transportation systems, and certainly many minerals, metals, and other natural resources (Pelton 2019).

The average of calorie consumption for a country or region does not reveal the variation in calorie intake. There are charts that show that for certain regions and countries, the disparity of calorie intake is quite high. Indeed studies have shown that in many countries such as China, Mongolia, and other parts of Asia, plus over a dozen countries in Africa, there is a wide variance as to the daily caloric intake between the wealthy and poor. In some cases there are truly dramatic differences (Roser and Ritchie 2019).

The bottom line is that there is a significant likelihood of food shortages coming in future decades, and so the supplies and areas of shortages need to be carefully monitored. Some of this gap will come from population growth, and other aspects may come from a higher standard of living and more food intake. One area that is not always carefully considered is the consequences of climate change and more crop loss due to violent storms such as floods, hurricanes, typhoons, and tornados that can wipe out many crops. On top of this, climate change conditions that will lead to droughts in some areas and flooding in others will create areas with intense shortages and major changes in food production areas requiring changes in infrastructure and land use. The biggest single factor may be the lack of water. Cape Town, South Africa, faced a near-zero hour water supply crisis in 2018, where there simply would not be drinking water available to millions of people in a major urban area. In many areas of the world, access to water will lead to limited crop production, desertification, or even famine in the decades ahead.

The problem of water supply is clearly increasing as shown by the imaging from space documenting the "desertification" of our planet. The key statistics are not encouraging. This is a quote from a recent article in The Guardian newspaper in the UK: "Currently, 844 million people – about one in nine of the planet's population – lack access to clean, affordable water within half an hour of their homes, and every year nearly 300,000 children under five die of diarrhea, linked to dirty water and poor sanitation" (Harvey 2018).

Remote sensing satellites can show not only the immediate status of the world, but analytics can show the annual cycle of rainfall, the cycle of vegetation, and the longer-term movements toward desertification. Figure 2 shows the spread of the Saharan desert that has forced residents of the region to relocate in search of consistent access to water supplies.

And the problem of access to potable water is getting worse. The NASA Gravity Recovery and Climate Experiment (GRACE) satellite project has mapped nearly 20 hotspots over a period of 15 years. These hotspots are specific areas where water resources are drying up and underground aquifers are becoming saltier and depleted of water. These include areas in China, India, the Middle East, and even California in the USA. The data from the GRACE satellite observations have confirmed the predicted likely outcome when the GRACE satellite was launched. The data show that areas prone to drought are indeed drying up, including major key aquifers, and

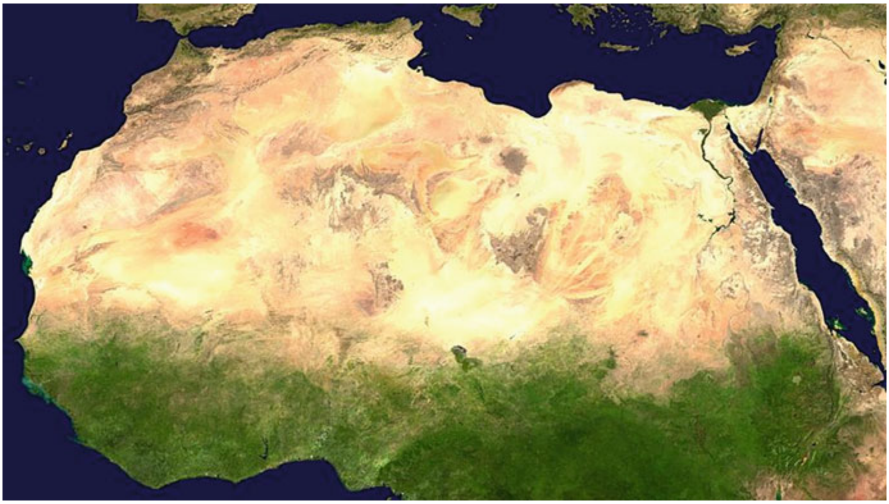


Fig. 2 Imaging from space that shows the southward growth of the Sahara Desert. (Graphic courtesy of NASA)

Table 2 Key applications of smallsat constellations for fishing, food, and water conservation

Small satellite constellation-based services for fishing, food, and water conservation
Global monitoring of aquifers that are being depleted or becoming polluted with salt
Measurement of levels for lakes, rivers, and reservoirs and analysis of why changes are occurring
Development of new systems to measure loss of vital habitats and systematic ways to monitor the loss of species in both the animal and plant worlds
Detection of faults in dams, leaks in pipelines, and other water wastage
Detection of schools of fish and changes in patterns in schools of fish
Measurement of productivity of crop fields and detection of crop diseases
Support to "smart farming" by new ability to apply water and fertilizers in a targeted manner
Better ways for ordering fertilizers and supplies and arranging delivering at lower cost
Ability to monitor markets and finding the best time and location to bring crops to market
Ability to take remote training courses in water management, agricultural production, and water conservation

areas that are already wet are typically getting wetter. The drying up of these major aquifers may represent the biggest challenge of all (NASA Gravity Recovery and Climate Experiment 2019).

Currently, about 65% of the total fish food supply is obtained from fishing in marine and inland waters, while the remaining one third is derived from so-called aqua-farming. During the last years of the twentieth century, total production from both inland and marine capture fisheries has reached a peak of about 10 kg per capita. Increases of productivity in fishing for the last 20 years have come from aqua-farming. This is particularly the case for the highest value fish.

There is considerable evidence that new small satellite constellations for networking, remote sensing, etc. can make significant contributions to fishing, food production, water conservation, and detection of sources of desertification and depletion of aquifers around the world. The applications indicated in Table 2 are just some ways that these new systems can increase productivity, sales, and profits and detect problems in these areas. The improved use of these systems will in time greatly expand, particularly as hyper-spectral analytics and other new ways to use these space tools evolve.

Clearly there is growing evidence that there is a correlation between human activities and the loss of more and more species as has been reported in the recent UN report. This disturbing report has indicated how the spread of people across the world is threatening all sorts of biota on land and in the sea (Leahy 2019). The UN report has warned that as many as a million species are now at risk (see Fig. 3).

4 Smallsats and New Trends in Energy Systems, Climate Change, Tele-services, and Transportation

The world has depended on some form of hydrocarbon fuels for a very long time. This was first wood, then coal, and now natural gas and oil. The human population keeps growing and has now nearly reached 8 billion and is headed to perhaps

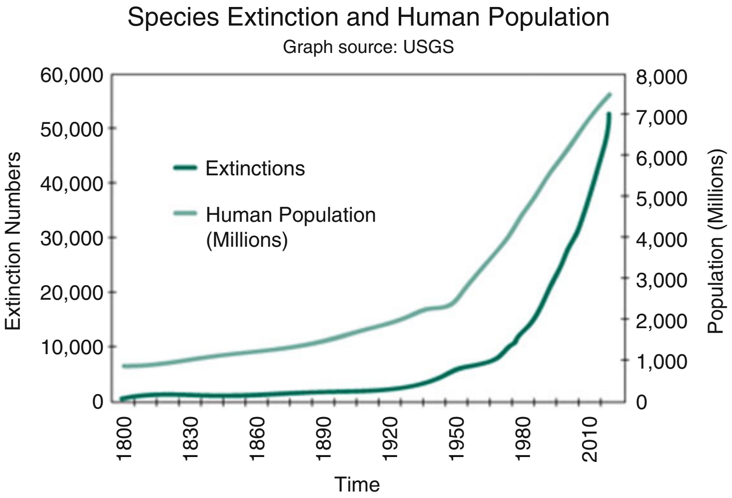


Fig. 3 Plotting of human growth versus rising number of species extinctions. (Graphic courtesy of the US Geospatial Services)

Table 3 Some of the world's largest CO_2 producers. (Source of information: "Our World in Data")

Country	% of world population	% of CO_2 production	Ratio
China	18.64%	29.25%	1.56
India	17.8%	6.69%	0.37
U.S.	4.36%	17.8%	4.08
Indonesia	3.51%	1.35%	0.38
Russia	1.96%	4.82%	2.46
Japan	1.73%	3.55%	2.04
Mexico	1.71%	1.38%	0.80
Germany	1.11%	2.28%	2.05
Iran	1.08%	1.85%	1.70
South Korea	0.69%	1.71%	2.475

12 billion. Today the increase in fuels used in transportation systems, aircraft, buses, trucks, and automobiles is still largely fueled by petroleum products, and this is no longer sustainable.

Table 3 shows the countries of the world that largely represent the biggest uses of hydrocarbon fuels producing the greatest amount of CO_2 pollution. The table displays each of country's size as a percentage of the world population and percentage of the world's CO_2 production that they release into the atmosphere – again as a percentage of the total human-based production. In these metrics, China is the biggest carbon polluter in terms of total production, but the USA is the biggest carbon polluter in terms of it relative population size.

The USA currently produces over four times the amount of pollution it might be expected to produce simply based on the number of its inhabitants. At this time just four countries, namely, China, the USA, India, and Russia, produce almost 60% of the world's greenhouse gas (GHG) pollution. Most developing countries produce proportionately less pollution today. However, the increasing level of industrialization and mechanization of agriculture across the globe is increasing greenhouse gas emission across the world economy. This increase is occurring due to population growth and industrialization. The increase in GHGs continues to occur despite the Paris Accord and other such efforts. The relentless rise of the average global temperature continues to rise despite the efforts to transfer energy use and transportation systems to cleaner systems based on solar, wind, and other green and recyclable energy systems that limit pollution (CO2 Emissions).

The new small satellite networks, and their associated data analytics, can help to accelerate the transition to "green" energy sources in a variety of ways. The large constellations for telecommunications and network streaming services can aid the development and operation of tele-health and tele-education programs to rural and remote areas. The first of these new networking-oriented systems for unserved or underserved parts of the world was the MEO orbit system known as O3b. This name refers to the "other three billion" people of the world. This name was devised by founder Greg Wyler, who chose this name well. It was his intent to create a new system that could bring connectivity to the three billion plus people who today live in locations that are largely without effective or low-cost connection to the Internet, the World Wide Web, or telephonic services.

Unfortunately such connectivity is becoming critical. Low-cost and effective connection to the Internet and electronic digital communications is becoming more and more essential to meeting a variety of needs in the modern world. Even remote farmers need to be able to find the best price to buy and deliver fertilizer and know where and when to sell their crops. Indigenous peoples are today finding a need for communications to receive medical care and sell their products and wares to others.

Essentially, the transformation that is increasingly occurring in the world of eight billion people is to substitute telecommunications, broadcasting, and networking for physical transportation. It is always easier and more cost-effective to transport electrons than people. Commuting to and from work each day consumes a good deal of energy, increases pollution, and can consume 1–2 h or more. It requires the building and maintaining of streets, highways, bridges, and tunnels. People that can be remotely trained to perform new jobs and then tele-commute to work can save energy, reduce pollution, eliminate the time lost in daily transit to and from work, and reduce the high costs of transportation. This concept of tele-work has largely been applied to industrialized nations, but today it can be effectively applied not only to national labor markets, but one can also see "electronic immigrants" performing service jobs remotely from one country to another.

Increasingly, activities such as accounting and editing of books, magazines, and even newspapers as well as tele-marketing and other tele-services have been shifted to countries as diverse as India, Jamaica, and Ireland. Even within a country, telework services can be moved from urban areas to rural areas via tele-work systems. The new small satellite-based networking systems provide greatly expanded new links to rural and remote areas. If established in effective ways, this can allow new pools of workers to be trained to carry out a wide range of tasks.

If the small satellites networks are efficiently set up to provide tele-health, tele-education, and then professional tele-training services, a huge new pool of workers can be trained to perform a wide range of new services at reduced salaries. These workers can fill in labor shortages in the service sector. There are people in Barbados and Jamaica that were trained to perform parts inventories for US airlines. The back offices of banks in New York and California have tele-workers in Ireland doing the back-office operations.

Forty years ago the cost of long-distance and especially overseas communications was 10–50 times the hourly rate of many workers. Today the ratio has almost reversed. The super low cost of small satellite constellations for networking services might be as low as $0.01 an hour to $0.10 an hour. This inversion in the cost of broadband communications with respect to workers' salaries, even in developing countries, opens the door to new forms of tele-work within countries and even on a global basis (Iida et al. 2003).

The bottom line is that the new networking small satellite constellations that will cover the globe will not only bring the Internet and broadband fifth-generation (5G) cellular services to the world, but it might ultimately serve to bring more than a billion new tele-services workers into the global economy. This could, in time (i.e., perhaps over the next 20 years), have almost revolutionary impact on global education, the provision of health care services, and the salary structure for companies that are heavily invested in tele-services (e.g., banking, insurance, transportation and airline and hotel bookings, bookkeeping, editing, inventory control, etc.).

Of course small satellites for remote sensing, Earth observation, and data analytics could impact transportation, energy, and patterns of transportation systems usage in new ways as well. This can be in many diverse ways. One might be able to use these systems and data analytics to do many things differently. This could be as diverse as prospecting for new sources of oil and natural gas to planning new roadway systems or train tracks in difficult areas such as mountain ranges, dessert areas, jungles, or wetlands. These small satellite systems could be used in planning new pipelines or restoring old ones or planning high-voltage electrical transmission systems. Certainly these systems could be used to improve the energy efficiencies of buildings by measuring their release of heat, or they could be used to detect noxious gas emissions.

The key in this regard is to design these systems and the analytics processing and algorithms to be able to accomplish more effective management on one hand and governmental regulatory oversight and enforcement processes on the other. The advent of some new capabilities such as driverless cars, improved "smart" electrical grids, and other oversight of transportation and energy systems safety, especially in the area of cybersecurity, opens up new areas of opportunity to implement new capabilities for efficiency and better regulatory oversight and safety measures. We must also consider that unscrupulous business interests might use the same technologies to accelerate their improper or illegal fishing or mineral extraction for short-term financial gain. This is why enforcement use of this information will become more and more important.

There are clearly a large number of ways that new small satellite constellations can open up doors to better manage energy systems and transportation systems,

Table 4 Improving systems to manage energy, transport, and tele-services and limit pollution

Using smallsats to better manage resources for energy, transport, pollution, and tele-services
Policing of release and excess generation of greenhouse and noxious gasses (GHGs)
Monitoring of wasted heat at power generation stations
Optimizing traffic planning and urban planning to relieve congestion
Replacing daily commuting with tele-workers
Tele-training of remote workers for tele-services jobs
Redesigning and optimizing buildings to be more energy-efficient
Improved design of new roadways and train tracks in remote and isolated areas
Improve efficiency of government services using broadband cellular services
Use of monitors to improve traffic flows and customs inspections

exploit new types of tele-services, and provide better oversight of pollution and climate change mitigation procedures. Some of these new opportunities as discussed above are summarized in Table 4.

5 Natural Resources

The intensive mining of metals and rare-earth materials is now starting to lead to shortages and listing of resources that are now considered scarce. There is a growing number of common metals that are becoming much more difficult to find such as gold, platinum, zinc, lithium, and copper, as well as many rare-earth metals such as selenium, hafnium, gallium, and indium. Although metals can be recycled, there will at least be price increases unless new reserves are found. There are even several "space mining companies" who have suggested that new valuable metals can be found in outer space. These companies are known by such names as Planetary Resources Inc., Moon Express, and Deep Space Industries. Some have indicated that they will be seeking out asteroids that are quite high in platinum that might be worth many billions of dollars. In fact, many of these enterprises have indicated that their first objectives are actually the so-called volatiles such as water. This is because, in space, water, by containing both hydrogen and oxygen, constitutes the equivalent of rocket fuel that is quite expensive to lift into orbit.

The various types of new smallsats for remote sensing and Earth observation are important tools for the exploration and discovery and even the ultimate exploitation of mining of resources. Radar sensors, infrared sensors, and multispectral and hyperspectral sensors all can be used in a variety of ways to identify geological clues as to what resources might be hidden below the ground or even at modest depths of the ocean.

The new space satellites for networking and broadband cellphone connectivity can provide vital services once a resource is discovered. Remote mining operations need connectivity to carry out operations in isolated areas. The ordering of equipment, the scheduling and arrangements for shipments in and out, and all sorts of telecommunications, streaming, and networking services are needed to sustain the staffing, food and supplies, and accounting and management of a remote mining operation. There is also the need to have reliable remote communications from networking satellites and other regulatory or government functions such as oversight, safety inspections, permitting, and zoning.

6 Conclusion

The difficulty in attaining clear-cut understanding of the potential applications and effective uses of the new constellations of small satellites is that so many of these are still only proposed, licensed, or in production, but not actually deployed in orbit. Many of the indicated applications will indeed prove to be important and will benefit those in unserved areas of the world as now envisioned. In truth, forecasting the benefits of large-scale smallsat networks for networking, remote sensing, and data analytics at this time is challenging. Forecasting the prime usages is somewhat like projecting the benefits of the Internet at the time experiments were being conducted via the so-called Arpanet that preceded the actual Internet global data network. Many of the benefits discussed in this chapter will be proved as these networks are fully deployed, but new and unanticipated applications will evolve over time.

If one were to define all the needs of the so-called "Global South" countries of the world that exist today, there can be reasonable prospects that these new smallsat networks will provide substantial assistance in some ways to virtually all these unmet requirements. The question is whether they do so in the ways that are currently anticipated and explained above or in a new and totally unexpected manner.

Clearly, key areas of concerns related to food, fishing, water, energy systems, transport, pollution and climate change, training, and remote tele-services and obtaining key natural resources will benefit from the new small satellite constellations and in important ways that we cannot yet see.

The tendency to view these new systems solely in terms of the satellite hardware is largely a tactical mistake for at least two reasons. First it is likely to be new and innovative software that truly unlocks the practical use of using these systems. It is the software and computer-based analytics that will be the key aspect of how these small satellite systems will achieve future success. In truth, it will be the interface with users that will allow these networks to unlock future problem-solving, market successes or failure, and beneficial results. As Clive Thompson, a contributing editor to Wired Magazine, has recently stated: "Spreading the creation of software…. doesn't just expand economic opportunity, it also encourages other ideas." This may be one of the essential ideas to the longer-term success of small satellite constellations. It is the software rather than the hardware that will ultimately triumph (Thompson 2019).

Secondly, the ground systems are also crucial. It will be the flat-panel antennas, electronic tracking of the fast-moving satellites, and the seamless connection to 5G cellular systems, to the Wi-Fi networks, and to mobile networked multiple-input/

multiple-output (MIMO) antennas that are crucial. These ground systems and their interface to actual users will be the true key to the ultimate success of these satellite networks in the day-to-day marketplace where consumers, businesses, and government agents work.

7 Cross-References

- ► Precision Agriculture and Forestry: Bytes for Bites
- ► Small Satellites, Law Enforcement, and Combating Crime Against Humanity
- ► Small Satellites and Governmental Role in Development of New Technology, Services, and Markets
- ► Small Satellites and New Global Opportunities in Education and Health Care
- ► Small Satellites and Risk management, Insurance, and Liability Issues
- ► Smalls Satellites and the 17 United Nations Sustainable Development Goals

References

D. Fears, We are killing off our planet and our enlightenment may come too late. *Washington Post*, May 5, 2019. https://www.washingtonpost.com/opinions/were-killing-off-our-planet-and-our-enlightenment-may-come-too-late/2019/05/06/866d4620-7036-11e9-9f065fc2ee80027a_story.html?noredirect=on&utm_term=.e6b44e057aa6

Global and Regional Food Consumption Patterns and Trends, U.N. Food and Agricultural Organization, Global and regional food consumption patterns and trends. Last accessed 2 June 2019

F. Harvey, Are we running out of water. *The Guardian*, June 18, 2018. https://www.theguardian.com/news/2018/jun/18/are-we-running-out-of-water

T. Iida, J. Pelton, E. Ashford (eds.), *Satellite Communications in the 21st Century: Trends and Technologies* (AIAA, Reston, 2003). Chapter 1

S. Leahy, One million species at risk of extinction, UN report warns. *National Geographic*, May 6, 2019. https://www.nationalgeographic.com/environment/2019/05/ipbes-un-biodiversity-report-warns-one-million-species-at-risk/

NASA Gravity Recovery and Climate Experiment, Jet Propulsion Labs. https://www.jpl.nasa.gov/missions/gravity-recovery-and-climate-experiment-grace/. Last accessed 16 June 2019

J.N. Pelton, *Preparing for the Next Cyber Revolution* (Springer Press, Cham, 2019)

M. Roser, H. Ritchie, Food Per Person – Coefficient of Variation (CV) in per Capita Caloric Intake. https://ourworldindata.org/food-per-person. Last accessed 2 June 2019

C. Ruz, The six natural resources most drained by our 7 billion people. *The Guardian*, October 31, 2011. https://www.theguardian.com/environment/blog/2011/oct/31/six-natural-resources-population

C. Thompson, Tech needs to escape. *Wired Magazine*, p. 26, June 2019

Who emits more of their share of CO_2 Emissions. https://ourworldindata.org/share-co2-emissions

Small Satellites and Governmental Role in Development of New Technology, Services, and Markets

Joseph N. Pelton and Eric Dahlstrom

Contents

Abstract

The evolution of new technology from research laboratory to prototypes and then commercial mass production has shown a fairly consistent pattern of development through at least the eighteenth, nineteenth, twentieth, and now the twenty-first centuries. New ideas have first been developed by inventors or in research

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

E. Dahlstrom
International Space University (ISU), Strasbourg, France
e-mail: Eric.Dahlstrom@InternationalSpace.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_58

laboratories. Patents are filed that protect the original inventor but also establish a framework for further development and improvements.

Often the next step is to produce various prototypes that gradually increase the practical capabilities of the new invention, service, or product. These early evolutionary stages help to increase performance and reliability of the new invention. This can also lead to additional developments, new formats, or designs. This can lead to additional patents and production processes which can allow the new product to be manufactured with increased speed and reliability and thus converted from the original prototype to a mature product for a mass-produced marketplace. This evolutionary development process has been true, in varying degrees for steamboats and locomotives, for automobiles, for aircraft, for submarines, for various types of guns and munitions, for telecommunications and networking systems, for radio and televisions, for computers and cell phones, and for a wide array of other inventions and new products consumed by civilians.

New products related to military defense and related strategic systems such as for weapon systems, avionics, aviation, telecommunications, computers, and artificial intelligence have particularly seen a high level of governmental research and development involvement in the front end of the research and development to move inventions, to prototypes, to improved prototypes, to initial manufactured products or system, and ultimately to refined systems.

Further governments often represent and provide the initial market for a new technology as well. In the case of space systems, governments and military ministries were among the first users of satellites for communications, remote sensing, Earth observation and meteorological monitoring, and GNSS and precise navigation and timing services. In short, in the field of space systems and applications, it has typically been military-related research and governmental spending that has had the predominate role in defining new space technologies and systems and guided their development. This has been true, especially in the USA, Europe, and largely countries of the OECD for a half century. This chapter addresses how "new space" and the small satellite industry has for the first time since World War II redefined the future direction of the space industry. In this new space environment, the new paradigms are being developed not by the key players in the so-called "military-industrial" complex but rather by start-ups, "Silicon Valley"-type entrepreneurial thinking, and even projects pushed by Google, Amazon, and Facebook and entrepreneurs such as Elon Musk, Jeff Bezos, etc. This chapter explains how the small satellite revolution and its overall development in terms of new types of launch vehicles, new types of satellite and ground systems design, and new types of space services also represent a shift in the development of space enterprise and services in the twenty-first century. Governments have not led the way but are now supporting this new technology but using it in their own missions and purchasing new types of space services supplied by new small satellite start-ups.

Keywords

Entrepreneurial · Latency · LEO constellations · Markets · Mass production · Miniaturization · "NewSpace" technology and markets · Off the Shelf products and systems · Research and development · Silicon Valley · Sparing philosophy · Start-up companies · Testing procedures

1 Introduction

In the new industrial age, represented by the post-World War II era, governmental research labs have often done a good deal of the "heavy lifting" that is required for expensive and difficult initial investigations of new high technology. These basic and applied research efforts have led to key inventions and have often underwritten much of the cost of demanding development work. This applied research can convert early ideas and prototypes into actual products that can be mass produced. This process of invention, prototyping, and then mass production can be a demanding and expensive process. The evolutionary process or development cycle where governmental research and development efforts are typically involved can last years or even a decade or two.

The time from the first invention to the time when actual mass production of a new product or provision of a service, in some cases, can be long indeed. Yet in most economies that operate on a capitalist basis, wherein private enterprises produce virtually all products and services and governments let free enterprise predominates most production, this transition almost always occurs. Thus the front-end transition from R&D to production and phased out of government involvement typically occurs within a decade and seldom requires as much as two decades for the government's role to phase out.

This transition from governmental research involvement to high-technology companies ultimately taking over production has been the case in such areas as aviation, aerospace systems, advanced telecommunications, artificial intelligence, robotics, computer systems, and even munitions and explosives. The idea has been that free enterprise industry within a competitive market can, in the longer run, produce products for both defense and consumer markets more efficiently. This transfer of even high-technology products from governmental research labs to commercial mass production has been the most common approach for capitalist economies around the world. It can also be seen that the longer this hand-over process lasts, the greater influence of the governmental/military influence on the technology and the larger the impact on products for the markets produced. This has seemed to be the case with the development of space technology and space-related markets. But the pattern of development as related to small satellites has been quite different. It has largely been the case that governmental and defense agencies have followed the efforts that have come out of university-based start-ups that have led the way. Large and sophisticated space projects have been dominated by large and established aerospace companies and governmental and defense agencies, while totally new space enterprises have led the “newSpace” revolution.

This chapter discusses the development of new space technologies and the exceptional case of government and military laboratories and agencies playing a role of direct involvement for a much longer period of time. However, today, new business models and technological innovation from the world of networking and computers are disrupting the aerospace industry and driving the market and the technology in new directions.

In short, the longer-term impetus from governments and established aerospace companies in the direction of “bigger and more complex” for commercial space systems is now being challenged. This is no longer accepted by “New Space” entrepreneurs as the best path forward. Today the civil space agencies and defense ministries have recognized the potential of small satellite technology and systems. What was once an effort to encourage student research and recruit new talent into the space industry today has now transformed into a recognition that smallsat systems can be a mainstream effort. Increasingly governmental and defense agencies are embracing the “smallsat” paradigm as a mainstream approach to more cost-effective space research and expansion of space application opportunities.

What this chapter explores is how the small satellite industry and the development of new types of reusable launch systems, etc. represents a departure from past patterns of how the field of space has developed. These new entrepreneurial directions have not grown out of governmental research programs nor from the initiatives of established aerospace companies. These new directions lately seem to arise from entirely new types of entrepreneurial thinking and technological innovation that have occurred largely in the last 20 years and especially the last 10 years.

Governments and especially governmental space agencies and military ministries have been slower to accept the transfer of their prime responsibility to industry in the space field. Instead governments and defense ministries have pursued a joint program of shared development with an emphasis on large-scale projects. There has been continuing efforts to retain governmental leadership for large-scale space systems such as space platforms and sophisticated space weapon systems. Further in the case of such activities as space communications, Earth observation, and precision navigation and timing (PNT) satellites (also known as Global Navigation Satellite Systems (GNSS)), the path forward has largely been led and predominated by a coalition of governmental and defense agencies in cooperation with large and established aerospace companies. The mainstream approach for these space systems and applications has been in the direction of “bigger, better, and more complex.”

The governmental designs and processes have guided the direction of technological in these areas to a very large extent – for governmental, defense, and even related commercial systems. Aerospace industries have found that following the lead of military and governmental civil space agencies in this direction was a highly beneficial direction to proceed in terms of large-scale contracts.

What this chapter explores is how the small satellite industry and the development of new types of reusable launch systems have not grown out of governmental research programs but largely out of entirely new types of entrepreneurial thinking and technological innovation.

Especially new “smallsat” initiatives have emerged from true entrepreneurial innovation. These new directions have come out of university laboratories and start-up companies often arising from the computer and networking industries. In this new “Silicon Valley-type” thinking, satellites and launch vehicles can be much smaller and start-up costs much smaller. The old assumptions about how to design, build, launch, and operate a satellite have suddenly changed. With these changes, the types of markets to be served and how to best serve new clients also have altered greatly as well. In short, “small satellites” are a part of a major paradigm shift affecting many aspects of the commercial space industry that spreads across a wide range of areas.

“New Space” or “Space 2.0” thus represents a new space revolution created by entrepreneurs and start-up companies. They have shown the logic of pursuing new technology, new methods of production, new types of satellites and constellation design, new types of ground systems, new types of launch vehicles, and the development many new types of space services and analytics. This “revolution” has opened a whole new set of questions as to what satellites are supposed to do, who can design and sell commercial space systems and services, and even who are the customers for these new offerings.

Indeed, most of the leadership in the development of these new technologies have come from young minds and young firms. Out-of-the box thinking has led to the creation of new high-tech markets. The established and large aerospace companies have largely been the followers. Only recently have the major aerospace organizations and the space agencies such as NASA, ESA, and others such as DARPA joined in to develop and exploit this new technology and stimulate this new market. The lesson now seems to be clearly learned, and established aerospace companies, governmental space agencies, and defense ministries have learned to embrace “smallsat” systems and technology as a mainstream approach for both research and operational systems. The convergence has now been complete. ESA, NASA, JAXA, the European Union, and others have now embraced the potential of smallsats as have defense-related space programs. The background surrounding this unusual pattern of technological development, and the new ways that governmental and defense space agencies are seeking to employ smallsat technology and systems represents the main purpose of this article.

2 Historical Background

The so-called military-industrial complex was largely born of World War II. This merging together of governmental research establishments and large and sophisticated high-tech munitions, aerospace, and computer companies gave birth to atomic weapons, fighter jets and bombers, high-speed computers, and subsequently the Internet.

Today governmental research labs and governmental science and technology ministries are funding the development of applications for life and medical sciences, cloning, artificial intelligence, and robotics. There also continues to be large investment at least within military ministries and agencies in developing more and more sophisticated new space systems. This is focused, however, on big and sophisticated space systems such as sophisticated military missile systems, larger and more complex launch systems, space stations, and even space colonies.

This “in synch” governmental, military, and commercial development continued for decades along the line that has sometimes been called “technology inversion.” Thus this approach supported the development of larger launchers, more powerful and higher gain satellites which in turn allowed ground systems to be simpler, smaller in size, and less costly. Under this approach one can install very small dish antennas which are low in cost and easier operate.

The principle of larger and more and more capable satellites which giant rockets were capable of lifting to geosynchronous orbit worked very well for communications and broadcasting satellites. Thus the needs of military systems for large and capable missiles also worked well to meet the perceived needs of commercial space applications, especially for the largest market of satellite communications including fixed, broadcast, and mobile services. This cooperative and supportive relationship was further reinforced by the so-called dual use of commercial satellite networks to meet the needs of not only commercial markets but of military services for non-tactical communications.

The graphic in Fig. 1 shows the usual pattern of new high technology development. In many cases governmental R&D supported the upfront development that typically then transitioned rather quickly into largely independent commercial mass production.

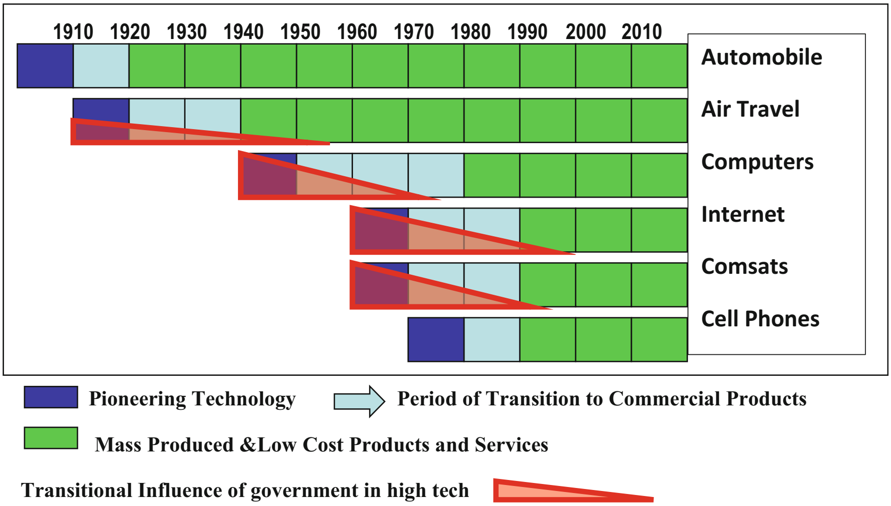


Fig. 1 Governmental influence on new technology, systems, and markets. (Graphic courtesy of Eric Dahlstrom)

But space systems have largely been different. For nearly a half century, there has been an ongoing symbiotic relationship that has sustained itself. The aerospace and electronics companies represented by Airbus/EADS, Thales Alenia, McDonald Detwiler, Boeing, Northrop Grumman, Lockheed Martin, Raytheon, and many others have been extremely closely knit together with governmental space and military activities.

The space industry and the role played by government have clearly been different from the role played by governmental research agencies and the industries depicted in Fig. 1. Even in the case of the cell phone industry, governmental technologies and regulatory officials played a key role in terms of establishing a process to allocate spectrum that could be used to provide expanded mobile communication services. In this case the assistance was largely focused on providing a regulatory framework for reallocation of spectrum, rather than aiding in the development of the new multiplexing and encoding systems.

One of the key factors to the ongoing relationship between governmental and military entities and the mainstream aerospace industry is that many of the products produced and those required by the military have remained so parallel since the end of World War II. Also the leadership pool for the military and the aerospace industry has frequently overlapped for many decades as well. The parallels in the technology development and the perceived market and service requirements have continued to align closely for at least a half century.

But starting around 2010, there was a disruption that for the first time saw the technology and commercial aerospace trends and market patterns start to diverge from those of the governmental and military worlds. These new technology and market trends largely did not come from the aerospace industry but emerged from the pool of entrepreneurs in Silicon Valley, university research labs, and the world of the Internet and networking. Instead of a continuation of space systems, satellites, and launch vehicles, continuing to grow bigger and bigger and more complex, the new thrust was toward smaller and in some cases away from complexity as well.

The “NewSpace” industry revolution and the emergence of the small satellite market had started to unfold. The new business paradigms that emerged from the new start-ups and new initiatives such as the “XPrize competition” directly challenged the conventional wisdom and the thinking of conventional aerospace companies, established satellite service providers, and most military and civil space agencies about the future of space activities.

3 Evolution of Small Satellites and New Commercial Launch Systems Markets and Governmental Support

This “NewSpace” revolution largely first occurred in the area on remote sensing markets, although it could be argued that the various new space initiatives that began in the 1990s such as Iridium, Globalstar, ICO, Orbcomm, and Teledesic were a key part of the new thinking about smallsats and commercial services from LEO constellations.

Yet it was the true entrepreneurial initiatives that came from such organizations like Planet Labs, SkyBox, and Spire which were entirely new start-ups that signaled that this was the start of something quite new and different. These new entrepreneurial initiatives emerged based on entirely new business models and technological approaches. This was in part led by key advances related to the miniaturization of sensors. These start-up organizations demonstrated that they could deploy much lower-cost spacecraft – as small as 3-unit cubesats – to provide commercial quality services. These smallsats could, of course, also be launched at much less expense. These new "outside-the-box" thinkers thought in terms of deploying many more spacecraft to provide updated information and global coverage more quickly. They also emphasized data analytics and new ways to manufacture spacecraft more quickly and at less cost. They created different approaches to testing and developed new ways of updating their designs and engineering models much more rapidly.

The "NewSpace" entities focused on the deployment of many more small satellites in lower Earth orbit constellations. This in turn led to a different approach to sparing and restoration of service planning and practices. In many ways these new enterprises gave birth to thought processes and business concepts that were much more akin with the computer industry and the types of innovation that came from Silicon Valley. Indeed many of these new initiatives came out of this area or from university student design exercises. Much of the approach and culture was indeed "foreign" to the aerospace and defense industries and governmental satellite networks that had grown out of the so-called World War II military-industrial complex.

Today governmental civil and defense space organizations and research institutes are seeking to find ways to use these new capabilities to respond to their needs. This was a new type of situation quite different from the historical patterns of the past. Instead of these governmental and defense entities developing and driving these smallsat constellations, they were suddenly placed in the mode of responding to innovations arising from these new commercial satellite networks.

The governmental response tended in three prime directions. One was to explore ways to use smallsats to carry out research in a more efficient way in terms of both time and money. The second way was to use these new networks to carry out ongoing missions and increase the market use of these new commercial networks. The third way was to embrace small satellite technology and constellation to design and deploy small satellite constellations to meet government or defense requirements.

4 Use of Government and Defense Smallsats for the Pursuit of Research Activities

NASA, ESA, and the US Air Force are just some of the governmental agencies that have found that smallsats could be used to pursue key space science and applied research objectives. They have found that projects at the microsat, nanosat, and picosat level could produce solid and useful research results and do so while saving on the cost of the spacecraft and the cost of the launch. This has happened in a variety of ways. The US Air Force, for instance, has funded a University Nanosat Program, it has used hosted payloads to undertake research projects, and it has contracted with commercial aerospace companies to build small satellites for both space research scientific missions as well as to undertake proof of concept for new operational systems.

The University Nanosat Program began with the 2004 launch of the 3-CornerSat (a project of Arizona State University, New Mexico State University, and the University of Colorado (Boulder)). This microsat-type experiment was a sophisticated test, and demonstration of stereoscopic imaging, distributed operations, and virtual formation flying operations and communications was the first in a series that continues today. This program is funded under the US Air Force Office of Scientific Research (AFOSR), and it operated from the Air Force Research Laboratory (AFRL) through its Space Vehicles Directorate (RV) (Fig. 2).

Subsequent projects have included the Fastrac microsat project built by students at the University of Texas (Austin) and launched in 2010. This project had the goal of demonstrating autonomous high-precision real-time relative navigation using innovative GPS technologies (Fig. 3).

Subsequent spacecraft developed under the US Air Force UNP included the launch of four more projects in 2013 with research spacecraft projects from Cornell University and the University of Colorado (Boulder) and from the University of Hawaii and two spacecraft from the University of St. Louis. There was another launch of a project from the University of St. Louis in 2015. Another smallsat experiment was developed by the University of Florida in 2018 and launched. For more university spacecraft were launched in this program in 2019 with at least six more scheduled for launch.

Fig. 2 The 3-Corner smallsat experiment was the first in the University Nanosat Program (UNP). (Graphic courtesy of the US Air Force)

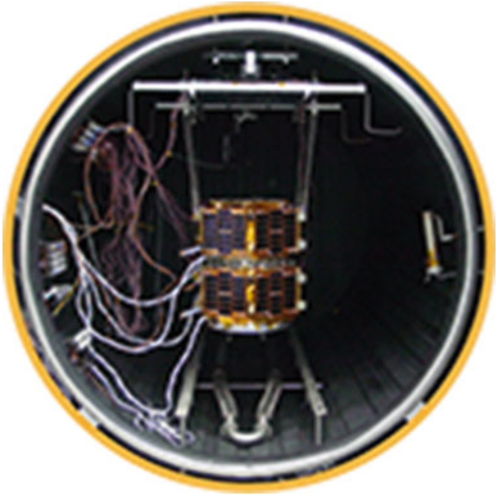


Fig. 3 The Fastrac project out the University of Texas (Austin) in 2010. (Graphic courtesy of the US Air Force)

The US Air Force explains that this program is not only to carry out serious research projects but also to train young people to design, build, and operate small satellites for the future. In the first few years, only two small satellites were launched, but since 2013 over 15 of these sophisticated research satellites have been launched or committed to be launched shortly (University Nanosat Program 2019).

The Air Force has also addressed new ways that it would undertake mainline research and development for their next generation of satellite systems. In particular it decided to commission the construction of two 3-unit cubesats to test sensors and GPS position determination to be used in its next generation of meteorological satellites. It contracted with Boeing to build two SENSE nanosatellites. These small satellites had a mass of only 4 kg and measured 30 × 10 × 10 cm in size. These two experimental and proof-of-concept satellites were launched on the ORS-3 mission in 2013 (Sondecker et al. 2012).

These SENSE smallsats were designed to collect and transmit weather data, but its software for transmitting this data did not work properly, and Boeing had to be given a supplemental contract of $400,000 to correct the software problem (Gross 2015).

Each of these SENSE nanosats contained a sensor and GPS receiver. These SENSE nanosats were designed to gather data that could be combined to make accurate weather predictions and to do so with greater accuracy. These smallsats had miniature S-band transceiver to downlink data at one megabit per second. The hope was to find a low-cost way to test new technology before it is included in operation weather satellites with new types of sensors and more sophisticated locational accuracy (see Fig. 4).

ESA and NASA, among other civil space agencies as well as the US Defense Advanced Research Projects Agency (DARPA), have also carried out a number of smallsat research projects in the past decade.

European Space Agency: ESA has set up a "CubeSat Systems Unit" to develop and expand European competency to create smallsats for high-quality research.

Fig. 4 The 3-unit cube satellite SENSE experimental project for US Air Force. (Graphic courtesy of the US Air Force)

Under this program, there are active programs to test rendezvous and docking and to explore near-Earth asteroids. During 2018 there was a successful ESA-funded CubeSat GomX-4B project. This smallsat tested precision micro-propulsion controls and intersatellite radio links for rapid data relay that could be used on research satellites as well as commercial telecommunications satellites. There were three ESA cubesat mission in 2019 for technology verification related to taking measures related to atmospheric reentry measurements, another for ozone monitoring and yet another for solar radiation studies. In addition there are a range of other small satellite projects that are under development by other ESA directorates. The economics that perhaps a dozen cubesat or smallsat missions can be conducted for the cost of one large spacecraft mission has been a powerful force to support the development of these type missions (Space Daily 2019).

European Union and a Consortium of Research Partners: One of the more innovative small satellite research projects has been the RemoveDEBRIS project undertaken by the European Union; the Surrey Space Center; Surrey Space Technology Ltd. (SSTL); Airbus Defence and Space (Germany, UK, and France/Toulouse); Airbus Safran Launchers (France); ISIS (Netherlands); CSEM (Switzerland, Inria (France)); and Stellenbosch University (South Africa). This 100 kg smallsat project was launched on a Falcon 9 to reach the International Space Station (ISS). It was then deployed into space by the NanoRacks' new Kaber system now operational on the International Space Station.

This innovative small satellite project was designed to test a number of methods for removing space debris from orbit (Remove Debris 2019). Rather than attempting to engage in actual active debris removal (ADR) the experiment with a simulation of such an activity with tests of capturing a small satellite with a net, a harpooning of a derelict satellite, active test of a laser ranging instrument, and effectiveness of a passive dragsail device designed to increase atmospheric drag. There were also two research cubesats aboard. The complex series of experiments were all compressed into a single 100 kg smallsat that was deployed by the Kaber deployment system operated by NanoRacks in 2018 (Clark 2018) (Fig. 5).

Fig. 5 The RemoveDEBRIS small satellite in orbit. (Graphic Courtesy of Surrey Space Centre)

NASA Space Satellite Research Program: NASA now has a very active smallsat research program underway. It has selected, via its Solar System Exploration Research Virtual Institute (SSERVI), ten small satellite missions for solar and planetary research. These missions which are a part of its planetary deep space studies program vary in size from cubesats up to 180 kg (400 pounds) in size. NASA's Jim Green, now Chief Scientist, in announcing these ten projects said: "These small but mighty satellites have the potential to enable transformational science. They will provide valuable information to assist in planning future Announcements of Opportunity, and to guide NASA's development of small spacecraft technologies for deep space science investigation." (NASA Selects Cubesat, Smallsat Mission Concept Studies 2011).

There are many other small satellite research projects now underway around the world that are being pursued by JAXA, ISRO, Roscosmos, the Chinese National Space Agency, and the US Defense Advanced Research Projects Agency (DARPA) and by smaller space agencies such as in Brazil, Swiss space research institutes, etc. Many of these efforts are discussed elsewhere in this handbook. The main point being made here is that hundreds of small satellite research projects are underway as mainstream research and technology demonstration activities by all the space agencies around the world as well as by defense space agencies. These activities have now become mainstream and are no longer mere student cubesat exercises.

5 Governments as Clients for Smallsat Constellations

There are governmental activities involving smallsats that go beyond research projects and demonstration of new technologies. Governments find many of the new operational small satellite programs to be a viable and cost-effective ways to contract for ongoing services. Below are just some of the examples of how governmental entities are using operational smallsat systems as a way of obtaining ongoing services. These various functions are in such areas as law enforcement, coastal monitoring, aircraft and shipping safety, agricultural and forestry monitoring, and various forms of economic development. These uses of commercial systems are already sufficiently prevalent that an exhaustive listing is really not possible. The examples cited below are noteworthy because of their originality and unique new capabilities.

6 Governments as Clients for Smallsat Constellations

There are many reasons why governments, law enforcement agencies, agricultural or forestry officials, or transportation or other safety personnel might find new smallsat constellation services to be of critical importance. Here are a few case studies.

6.1 New Zealand and Hawkeye 360 Smallsat Constellation

The Hawkeye 360 smallsat constellation provides a new type of radio-frequency (RF) geolocation service. This is accomplished by using a smallsat constellation to triangulate the exact location of all RF spectra use around the globe. The technical functioning of this smallsat constellation is described more fully elsewhere in this handbook (Wrne 2019).

The interesting aspect of this smallsat constellation is that governments such as that of New Zealand have signed a contract to obtain data from this system for law enforcement to seek to identify those that might engage in illegal fishing, smuggling, unauthorized entry, or other activities that might utilize unauthorized radio communications, especially for illicit purposes. This is a new way of undertaking law enforcement that could not otherwise be provided for a low-cost annualized fee.

6.2 Governmental Needs and Smallsats Providing Internet of Things and Automatic Identification System

There are a number of smallsat systems that are now providing or planning to provide shortly automatic identification system (AIS) plus machine-to-machine (M2M) data services. The growing demand for data relay system is now being driven by the demand for Internet of Things (IoT) data relay from remote areas. These smallsat constellation systems, planned or operational, include such networks as the Else Constellation, the Eutelsat LEO Objects (ELO), Kepler, Kineis (to replace the Argo network), Orbcomm, and Spire. Again these networks and their service offering are described in other sections of this handbook. The services provided by these smallsat networks are supported by many commercial clients, but governmental support and use of these networks are extensive and growing in number and volume of use (The Economist 2019).

6.3 New Smallsat Constellations and Their Support of New and Expanded Governmental Needs

And the future synergies between governmental requirements and large-scale LEO constellations will continue to unfold and expand in future years. The ability of the many new constellations designed to provide broadband telecommunications and networking services, remote sensing, and data analytics will produce new and expanded support to a wide range of governmental services in coming years. The dual use of these systems for commercial and governmental services (including those for defense agencies) can be expected to expand and grow. These networks will be able to provide broadband services by governments to rural and remote areas. These will include educational, healthcare, agricultural, forestry, and mining-related technical support services, economic development support, and many other governmental services.

7 Conclusion

The very first satellites that were launched in the late 1950s and 1960 were small satellites. But the mainstream development in the years that followed was to design and produce larger and larger satellites and launch vehicles to support more and more ambitious space services and programs. Many of these developments were closely allied with the needs of defined military- and defense-related services and the established aerospace companies that supported these efforts.

When the “smallsat” and “cubesat” efforts began along with miniaturization of digital processors and sensors, it was largely seen as an educational and training exercise for university students to learn about satellite technology and get some experience with satellite technology and design processes. The mainline focus by governmental and defense-related agencies, mainline large aerospace companies, and many commercial space services continued to be on large satellites, largely in GEO orbit and some MEO and polar orbit systems such as for GNSS and remote sensing. Smallsats were seen as largely as a cross between hobbist activities and training, such as the project of the ham operators volunteers that built the OSCAR satellites.

But innovative university students and faculty plus entrepreneurs with start-up ventures designed and managed to get funding for new commercial smallsat ventures. Activities in the smallsat field and the growing “NewSpace” arena began to become more real and commercially serious. New “smallsat” space systems and ventures such as Spire, Planet Labs, and Skybox, emerged. The bankruptcy associated with Iridium, Globalstar, ICO, and Orbcomm were overcome, and the viability of these systems began to become clear.

The result has been a resurgence in the design, manufacture, and deployment of smallsat constellations. Many things have supported this development such as new lower-cost commercial launch systems, new ground stations with electronic tracking capability, improvement in miniaturized components and digital processors, new levels of support and financing from the computer and networking world, and new approaches to the manufacturing of small satellites and how they are tested, deployed, and operated as well as new approaches to the sparing philosophy used in large-scale networks.

Today everybody – established aerospace corporations, civil space agencies and defense agencies, launch service providers, and service providers for networking, remote sensing, and other services – are taking "smallsats" seriously. The backers of many of these systems are in a number of cases coming from new sources. Organizations such as Google, Amazon.com, Facebook, and others from the world the Internet and Silicon Valley are seeing the value-added aspect of small satellite systems. It seems almost overnight the world of "NewSpace" has exploded to bring new vitality and interest to the field of space technology, systems, and services. What has started as largely a US phenomenon has exploded worldwide. The accessibility of smallsat technology and capital financing has fueled this interest. Governmental space agencies that 20 years ago saw small satellites as a sideline have increasingly embraced the use of this new technology and have sought to utilize it in new and an expanding range of ways. They continue to fund and support ways for students and universities to use this technology and bring innovations to the space field. They are developing programs and missions to accomplish research, technology demonstration, and operational programs. And they are beginning to buy new and important space services from the growing number of commercial service providers that are developing and deploying smallsat networks.

8 Cross-References

- ▶ Precision Agriculture and Forestry: Bytes for Bites
- ▶ Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently
- ▶ Small Satellites and Governmental Role in Development of New Technology, Services, and Markets
- ▶ Small Satellites and New Global Opportunities in Education and Health Care
- ▶ Small Satellites and Risk management, Insurance, and Liability Issues
- ▶ Small Satellites, Law Enforcement, and Combating Crime Against Humanity
- ▶ Smalls Satellites and the 17 United Nations Sustainable Development Goals

References

S. Clark, Clark, "Launch Log". Spaceflight Now. April 6, 2018

M. Gross, U.S. Air Force hopes to wring some utility from Balky SENSE nanosats. Space News, April 14, 2015. https://spacenews.com/us-air-force-hopes-to-wring-some-utility-from-balky-sense-nanosats/

NASA Selects Cubesat, Smallsat Mission Concept Studies (2011). https://sservi.nasa.gov/articles/nasa-selects-cubesat-smallsat-mission-concept-studies/

Remove Debris. https://www.surrey.ac.uk/surrey-space-centre/missions/removedebris. August 2, 2019

G. Sondecker, P. LaTour, L. Abramowitz, SENSE: the USAF SMC/SR nanosatellite program for space environmental monitoring, in *The 27th AIAA/USU Annual Small Sat Conference,* 2012. https://pdfs.semanticscholar.org/8375/7f8497c87066ecd4141d06b003466170cbc1.pdf

Space Daily, ESA's Cobesat Central fpr smaller missions into space. Space Daily, April 3, 2019. http://www.spacedaily.com/reports/ESAs_Cubesat_central_for_smaller_missions_into_space_999.html

The Economist, A new business in small satellites orbiting Earth. The Economist, June 15, 2019. https://www.economist.com/science-and-technology/2019/06/15/a-new-business-in-small-satellites-orbiting-the-earth

University Nanosat Program. https://universitynanosat.org/missions/. Last accessed 1 Aug 2019

D. Wrne, Hawkeye 360 satellites pinpointing signals. Space News February 26, 2019. https://spacenews.com/first-hawkeye-360-satellites-pinpointing-signals/

Smalls Satellites and the 17 United Nations Sustainable Development Goals

Joseph N. Pelton

Contents

Abstract

The United Nations General Assembly at the time of the new millennium approved a set of developmental goals known as the millennium goals that were to be strived to be accomplished by 2015. Although progress was made toward those goals on a global basis, there remained a great deal more to be accomplished. In 2015, a new set of expanded goals were approved known as the sustainable development goals. These new objectives were set to be accomplished by 2030.

There are many ways that satellite technology and various types of space applications can be applied to reaching the 17 United Nations Sustainable Development Goals (SDGs). This is especially true with regard to small satellite

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_59

technology and services. "Smallsats" can contribute to the accomplishment of those goals in many ways. This is because "smallsats" can reduce significantly the cost of deploying and operating satellites as well as reducing launch costs. The use of off-the-shelf components can in many ways make "smallsat" technology more accessible to developing countries. The UN COPUOS has also established a working group on "Space 2030"agenda that will seek to define and develop space capabilities, including small satellite systems and applications, that can further the UN Sustainable Development Goals. This process will start in 2020 and will continue to report on progress achieved.

The following chapter discusses the various ways that small satellites, individually and in constellations, can be employed to work toward achieving these 17 UN Sustainable Development Goals.

Keywords

Clean energy · Committee on the Peaceful Uses of Outer Space · Communications satellites · Economic growth · Employment · Environmental sustainability · General Assembly · Global food supply · Global navigation satellite services (GNSS) · High-altitude platform satellites (HAPs) · Improved health and education · Infrastructure · Justice and equality · Meteorological satellites · Poverty reduction · Precise navigation and timing · Remote sensing · Solar power satellites · Sustainable cities and communities · Sustainable development goals · United Nations

1 Introduction

For many years, the activities of the space-faring nations such as the United States, the USSR/Russia, China, Japan, Canada, the European Space Agency, and India have been seen as very expensive and highly technological undertakings that were primarily focused on exploring the outer space and developing high-technology rocketry. These activities, such as sending astronauts to the Moon, or sending research probes to the Sun, Venus, Mars, or other planets, or deploying space stations in orbits, were correctly seen as scientific missions that had little to do with the social and economic needs of the average citizens and virtually nothing to do with the needs of the developing world.

What is not as widely reported is that for the past 50 years, there have been important developments in the field of applications satellites that are increasingly providing vital services that are critical to humans across the globe. These application satellites are responsible across the globe for communications, broadcasting, networking, remote sensing, navigation, position location, smart agriculture, fishing, forestry, forest fire prevention, law enforcement, mapping, weather forecasting and storm alerts, national defense, and much more. This chapter seeks to explore the many ways that satellite applications, and especially small satellites and smallsat constellations, are now, and even more so in the future, providing a wide range of vital services that will be critical to progress against the United Nations 17 Goals for Sustainable Development for 2030.

At the 2017 Manfred Lachs Conference at the McGill University Air and Space Law Institute, the attendees from all over the world sought to identify and assess how space applications could contribute to meeting the United Nation's Sustainable Development Goals for 2030. (Summary Report of the Working Group of the "Space 2030" Agenda of the Committee on the Peaceful Uses of Outer Space A/ AC/C 195/C.1 WG 2030/2019/L.1.) At the end of this section, in Table 3 there is a chart prepared by the author, which seeks to identify by specific type of satellite services the various ways that can be utilized by satellites, including small satellite systems, to support these 17 goals or which might be able to assist in achieving these goals in the future.

The following analysis seeks to indicate the ways that small satellite systems might be particularly able to provide new or expanded capabilities to meet specific UN sustainable development goals.

2 Historical Use of Satellites for Education and Healthcare Services

The idea of using satellites to bring educational and health-related services to areas of the world where such services are greatly lacking is certainly not a new idea. Arthur C. Clarke envisioned that satellites could be used to provide low-cost and global communications to the world when he first wrote of this technology even back in 1945. NASA's early experimental satellite program known as the Applications Technology Satellite series sought not only to develop the technology but to test out new applications in rural and remote areas. The ATS-6 satellite was the first application to have an unfurlable antenna. This high-gain antenna was tested first in Appalachia and then in rural India's SITE experiments to provide remote educational and health services in the 1970s (NASA – ATS; see Fig. 1).

These experiments subsequently led to Indian Space Research Organization's INSAT program to provide rural education to villages in rural India. This program today provides education and health services to over a million students using tele-education-based systems. In the mid-1980s, the Intelsat satellite system started a Project SHARE initiative. In this case SHARE stood for Satellite Health and Rural Education. In order to carry out the international Project SHARE activity, a partnership was created with the International Institute for Communications (IIC), the Education Secretary of the British Broadcasting Corporation was recruited to help in the design and execution of projects, and an international advisory council was formed. These international partners from over a dozen countries helped to make the Project SHARE initiative a success.

Ultimately some 70 international projects were approved to test satellite-based educational and health services. These projects, in terms of time scale, ranged up to the large-scale multiyear Chinese satellite TV initiative with extensive television programming developed by the Chinese Department of Education and China Central Television. They also involved "one-off" events such as "The Day of Six Billion" television show that reached some 140 different countries and nearly one

Fig. 1 The NASA applications technology Satellite-6 with its antenna unfurled that carried out educational experiments in India and Appalachia in the 1970s. (Photo courtesy of NASA)

hundred countries provided programming for this event that was organized by CNN.

This Chinese satellite television educational and health distribution programming started with only a few dozen remote TV receive-only (TVRO) terminals but was eventually operationalized on Chinese domestic coverage satellites (Chinasats) and expanded to provide educational and health education programming that was provided to many thousands, and eventually as many, ten million students. This ambitious Chinese initiative was designed to extend a remote television instructional system to eventually cover the most remote parts of China. There were also projects that involved experiments involving the University of the South Pacific and the University of the Caribbean plus many scores of other projects around the world. Many of these programs were designed to provide educational programming directly to remotely located students. Others such as the ambitious program organized by the Miami Children’s Hospital organized a tutorial by some of the world’s leading experts on the AIDS pandemic to be distributed over all of South and Central America, North America, Europe, the Middle East, and Africa for an audience of over 65,000 doctors, nurses, and healthcare providers. This multi-continent event involved three interconnected Intelsat satellites (Report on Project Share, Intelsat, Washington, D.C. 1987).

3 Small Satellites for Communications and Networking

A great number of small satellite constellations are now licensed to be deployed in the next few years to provide expanded communications and networking services, and especially this is the case for underserved regions of the world in developing economies. Three founders of the so-called OneWeb small satellite constellation left Google to start the WorldVu company that became OneWeb. These entrepreneurs were Greg Wyler, Brian Holz, and David Bettinger. Greg Wyler had also previously started a medium earth orbit (MEO) satellite system known as O3b (short for Other Three Billion – or the residents of the equatorial regions of the global that were underserved for communications and networking) (History, One Web Satellite Network https://en.wikipedia.org/wiki/OneWeb_satellite_constellation#History (last accessed Feb. 4, 2019)).

Greg Wyler had first planned to provide new telecommunications and networking capability in rural Africa using fiber-optic networks in underserved countries, but none of the business models worked. He first organized and got backing for his O3b medium earth orbit (MEO) in partnership with the SES satellite system of Luxembourg. The success of the 16-satellite MEO system led him to found WorldVu with his two partners from Google. This led him to come up with the design of a 900-satellite low earth orbit (LEO) network that would blanket the world but provide particular coverage of Africa, South and Central America, and Asia with very low latency (or transmission delay). This design was optimized so that it would be possible to provide cellular phone or Internet services in most underserved regions of the world. As of December 2018, however, OneWeb has scaled down the size of its initial constellations from 900 to 600 (Henry 2018).

In discussions with Greg Wyler during the Arthur C. Clarke award ceremonies, he explained that he wanted to bring broadband services to underserved countries at low cost and with minimal delay that is important both to cellular services and Internet connection. He also explained that he saw advantage in non-GEO satellite systems because of the much-reduced path loss and thus higher effective power levels from smaller satellites. The other advantages were much-reduced latency or transmission delay, the reduced gain needed for ground systems, and the lower production costs and launch costs for small satellites. His first approach was the simpler and lower-cost MEO system that he called O3b. When this MEO system deployed along the equator that consisted of 4 satellites, then 8, then 12, and eventually 16 (although only 13 are now operational) proved financially viable, he sold out his interest to SES that took over full ownership of the O3b and focused on a truly large-scale LEO satellite system. This started out as WorldVu and then transitioned to the pioneering OneWeb small satellite network.

Most entrepreneurs are focused on making money, but Greg Wyler is an unusual businessman, who has put social objectives ahead of his financial goals. He has let that drive to come up with unusual schemes to make his OneWeb system viable. One of his key objectives has been to make his suppliers of both the satellites and the launch services also key financial investors. Thus Airbus and Arianespace are both suppliers and investors. The enthusiasm for the OneWeb system by Wyler to meet social goals is hard to miss. In conversations with him and in other public statements, he has confirmed his belief that OneWeb can at least help to reduce poverty (Goal 1), improve farming efficiency and thus reduce hunger (Goal 2), improve health services and education via tele-services (Goals 3 and 4), and support economic growth and industry innovation (Goals 8 and 9). The argument could be made that if more effective, higher-quality, and lower-cost education and health services can be achieved via more extensive and lower-cost communications and networking, this will ultimately increase prosperity and knowledge and aid in the achievement of all 17 UN Goals.

Nor is the OneWeb small satellite system unique. Indeed, most of the pending or proposed small satellite systems around the world will offer the possibility of lower-cost, lower-latency, and perhaps higher-power access to mobile communications and Internet connectivity. In short, many of the proposed smallsat networks will provide potential aid toward meeting at least several of the UN Sustainable Development Goals. The Geeks Without Frontiers is a nongovernmental organization that has been established to leverage the new infrastructure that smallsat constellations offer to bring broadband connectivity to the developing parts of the world through their "Community Connect" project. This NGO is currently sponsored by EMEA Satellite Operators Association (ESOA), the Arthur C. Clarke Foundation, the Asia-Pacific Satellite Communications Council (APSCC), Telesat, Intelsat, the Space and Satellite Professionals International (SSPI), the International Space University (ISU), the International Institute of Space Commerce (IISC), the Danish Telecom Industry Association, the Satellite Industry Association, and the American Institute of Aeronautics and Astronautics (AIAA) (Community Connect).

GEEKS' co-founder Michael Potter has explained the mission to bring broadband communications to the developing world in the following manner: "The Community Connect vision is to enable 100% availability of broadband communications services everywhere, providing businesses, governments, hospitals, schools, NGOS, individuals and others with access to broadband services, wherever they are located. This will help to bring the educational, healthcare, social, economic and e-government benefits to communities everywhere and facilitate and accelerate the achievement of the UN's Sustainable Development Goals (SDGs)" (Geeks Without Frontiers Releases Its 'Community Connect' Global Broadband Initiative at the Geeks "Connectivity is the Revolution!" Thought Leadership Forum, October 19, 2017 https://globenewswire.com/news-release/2017/10/19/1150375/0/en/Geeks-Without-Frontiers-Releases-Its-Community-Connect-Global-Broadband-Initiative-at-the-Geeks-Connectivity-is-the-Revolution-Thought-Leadership-Forum.html).

The initial role out of this project is to provide broadband connectivity to some 80 communities using satellite technology to demonstrate the fundamental approach. The stated plan is to use this initial beta test as the best way to prove the viability of the plans. Certainly an actual test with actual communities and actual users appears a wise way to prove the strengths and weaknesses of this rural networking plan before it is scaled up for a much larger-scale implementation. This seems wise for several reasons that include (i) understanding practical problems of rural users (this might include based on other rural projects an identified need to train new users how to use telephones and computers to access these networks or access to reliable and continuous local power at modest cost); (ii) proving the soundness of the concept and levels of use to potential investors in larger-scale projects; (iii) understanding the problems and issues involved with ground segment facilities to access the new satellite facilities; and (iv) testing practical aspects such as the billing and collection of fees associated with these new digital satellite and wireless networks.

Fig. 2 The Broadband for the Next Billion campaign foresees use of smallsats and fiber-optic networks

Although this Community Connect initiative is not exclusively tied to satellite technology, its business plan is generally based on use of new satellites being deployed to provide network connectivity for developing countries such as O3b, OneWeb, and other small satellite constellations now planned. Certainly these new "smallsat" constellations currently appear to be one of the prime ways for current goals and objectives of the "Geeks Without Frontiers" and their "Community Connect" and "Humanity Connect" projects to be accomplished. One of the elements of the overall program known as "Dig Once" does indeed include plans to use fiber-optic networks as part of the overall telecommunications development plan and is indeed seen as an element in the "Geeks Without Frontiers" strategic plan to create their ambitious ultimate goals of "Broadband for the Next Billion" campaign (see Fig. 2).

The "Geeks" may find in their current beta trials with the 80 trial communities that there is an additional need to create more Wi-Fi hotspots or other terrestrial wireless systems to supplement the satellite architecture. Likewise they may find that they need to develop improved and lower-cost earth station facilities capable of tracking LEO smallsats and which can also be acquired at lower cost and with reduced tariffs.

In the past many satellite projects for rural services have concentrated on the space segment and found that the problems actually focused on such issues as earth station costs and related tariffs, access to power at the local level, or other "last mile services" issues (Geeks Without Frontiers Launches 'Humanity Connect!' To Empower Displaced Persons Through Connectivity-Driven Solutions for Disaster Preparedness and Refugee Relief https://globenewswire.com/news-release/2018/08/20/1553736/0/

en/Geeks-Without-Frontiers-Launches-HumanityConnect-To-Empower-Displaced-Persons-Through-Connectivity-Driven-Solutions-for-Disaster-Preparedness-and-Refugee-Relief.html (Last accessed Feb. 6, 2019)).

The "Connect Humanity" initiative by the "Geeks Without Frontiers" is a most commendable initiative, but it will face many challenges that have been faced by a number of past initiatives that have sought to address the issue of rural telecom and networking access.

In the 1980s, there was the Afrosat initiative boosted by the International Telecommunication Union (ITU) that envisioned a high-power satellite optimized to work to 3 m earth station to provide rural services for the entire African continent. This system never came into being for a variety of reasons. These included political differences among the African nations, differences between Intelsat, the ITU, European countries with interests in Africa, plus the high cost of acquiring very small aperture antennas and installing them with the necessary power supplies and maintenance and repair staff.

On top of these problems, there were difficulties presented by the tariffs on these ground systems by the African nations for imported equipment that might be in the 50% to 100% level. There were in many instances in many African nations a lack of skills, training, and access to telephones or telecommunications facilities such as telex or fax machines that might be easily used by rural populations in villages across Africa.

Over a decade later, the Afristar radio services satellite was deployed to offer radio broadcast channels for the entire African continent in 1998. This direct audio broadcasting satellite provided the opportunity for commercial and educational and health-related radio channels and even nighttime downloads of video educational programming. There were many reasons why this effort, in its original commercial form, failed commercially. One of the prime reasons was that the low-cost satellite radio receivers that were then available at $50 apiece attracted a 100% tariff (Afristar).

In other rural development projects around the world, new telecommunications facilities were installed, but usage remained very low. When studies were made, it was found that one of the reasons for initial low usage was that no one had taught villagers how to dial telephones or to find telephone numbers. The bottom line conclusion is that extending telephone and digital networking capabilities into rural and underserved areas is more than just a matter of extending networks, but that there are other key elements that must be addressed as well.

Training as to how to use such networks, access to telephones, computers, radios, or fax machines, tariff-related issues, and educational, health, and governmental services programs that teach remote users the value of using such rural networks, must be a part of the overall implementation program. Other aspects such as computer software that is available in locally used languages can also be key. Many of these of the studies of telecommunications development in rural and remote areas show similar results. These studies show that the economic multiplier effect of such infrastructure development can be high as in four to one or even higher but that training in the effective use and applications of such systems is critical to achieving successful use of such systems. Instructions in local languages and educational and health-related programming that is adapted to local culture, customs, and language can be critical to success (Pelton 1987; http://glovis.usgs.gov; https://neo.sci.gsfc.nasa.gov/; http://arthexplorer.usgs.gov; http://cophub.copernicus.eu; http://search.earthdata.nasa.gov; www.class.noaa.gov; http://coast.noaa.gov/digitalcoast; www.ipums.org/IPUMSTerra.shtml; http://lance.modaps.eosdis.nasa.gov; http://earthdata.nasa.gov/lance; https://vito.be/en).

4 Mobile Satellite Service Satellites Vs. New Small Satellite Constellations for Rural Services

There are several small satellite networks that have been deployed, beginning in 1997 and 1998, that were designed to provide mobile satellite services. These included Iridium and Globalstar that deployed smaller satellites in low earth orbit (LEO) constellations. Also there were Thuraya and Inmarsat I-Phone service that utilized larger satellites in GEO orbits. These various systems provided truly global coverage including equatorial regions of the world and could thus service to rural and remote areas.

The problems that arose for these networks in providing rural service to most remote communities were severalfold. The consumer handsets were costly and priced well above $1000 dollars (US). The usage charges were high and beyond the means of most low-income residents in these remote areas with rates around $0.50 to $1.00 a minute. Further there were other practical problems such as access to electrical power for the satellite phone chargers or no place to purchase these expensive phones or laptop-size consumer terminals. Further these satellite phones were typically subject to high tariffs that steepened the cost even more. The Iridium and Globalstar LEO smallsat constellations were engineered to provide telephony-type services for higher-end users and provided only very low data rates. Thus these smallsat networks were not really adequate to provide Internet access-type services.

Although attempts were made to create remote stations that were in essence village pay phones, these did not prove to be commercially viable. Thus in remote areas, smallsat constellations for mobile satellite services were essentially used by military personnel, representatives of multinational organizations, and aid relief workers for nongovernmental organizations.

The second-generation satellite constellations for Globalstar and Iridium (Iridium Next) are actually larger than what most would classify as “smallsats” and remain geared to the needs of the military and multinational users traveling to remote areas rather than the indigenous population. The challenge is to find the suitable architecture for the satellites and the user terminals and perhaps intermediate distribution Wi-Fi systems that can allow villagers to use simple low-cost cell phones to access the new generation of LEO satellite constellations and to do so via access fees that are consistent with the incomes of the users in remote villages. In some cases GEO satellites working to and from low-cost VSATs and then Wi-Fi networks may be able to provide economical services. The problem of transmission delay or "latency," however, remains as a problem for Internet- or data-based services.

5 Remote Sensing Satellite Services Helping to Achieve UN Sustainable Development Goals

The field of remote sensing via satellites has been perhaps the most adept at achieving success in providing assistance in meeting a number of goals of the UN for sustainable development. The uses of remote sensing keep expanding as the range of sensing technologies and applications continue to expand on one hand and have become more affordable and available on the other. Small satellite systems that are now in the cubesat range such as Planet and Spire, in particular, are supplementing and expanding the remote sensing that was previously carried out by much larger and expensive Earth observation satellites (see Fig. 3).

The uses of small satellites to accomplish the UN Sustainable Goals can be found in virtually all of the 17 goal areas. Nevertheless, there are 11 out of the 17 goal areas as noted below where remote sensing and Earth observation satellites make substantial contributions to the UN objectives. Indeed many of these goal areas cannot be addressed accurately and synoptically without these technologies (Table 1).

The technology involved with the design, manufacture, and deployment of smallsats for remote sensing and Earth observation continues to allow these spacecraft to become more capable of whole shrinking in volume and mass. Satellites such as "Doves" by Planet and cubesats by Spire continue to improve. Recently it was confirmed that cubesats can not only provide high-quality sensing but that three to six unit cubesats are capable of hyperspectral imaging. Hyperspectral sensing across many bands can much more accurately allow the detection of specific diseases in

Fig. 3 A 3-unit cubesat by Planet imaging the Earth

Table 1 Ways that remote sensing satellites can assist in achieving UN goals (Source: Author compilation)

UN sustainable development goals where "smallsat" remote sensing can be most impactful	
UN goal	Positive impact area
SCG 1: No poverty	Improved farming productivity, economic growth
SDG 2: Zero hunger	Smart farming, disease spotting, and agricultural productivity
SDG 3: Good health	Better crops, improved pollution monitoring
SDG 6: Clean water	Monitoring of water pollution, more efficient farming, mining, forestry
SDG 7: Clean energy	Solar research, wind current research
SDG 8: Economic growth	More efficient farming, fishing, and forestry, new clean energy industry and jobs
SDG 11: Sustainable communities	Earth observation to monitor human growth, urbanization, pollution, etc.
SDG 12: Responsible consumption/production	Monitoring of industrial plant-generated pollution, fish and wildlife population monitoring
SDG 13: Climate action	Constant monitoring of weather, climatic changes, ice cap sizes, thermal changes, desertification, clean water supplies, etc.
SDG 14: Life below water	Continuous survey of oceans and polar regions, ocean pollution, thermal changes, hurricanes, monsoons, thunder storms
SDG 15: Life on land	Remote sensing of entire land areas, farms and forests, aridity, sensing of changes to clean water supplies, snow fall, crop yields, weather, heat, etc.

The 11 goal areas noted above are areas where remote sensing satellites are making prime contributions. Satellite telecommunications, networking, Earth observation, and precise navigation and timing satellites can, of course, be used to support many of the UN SDGs as well

crops and accurately assess which nutrients might be missing in specific farming areas. In short smallsats that can carry out hyperspectral sensing or even carry out active radar sensing with clusters of spacecraft as small as 500 kg suggest that smallsats are not only highly capable but are increasingly able to perform tasks once reserved for much larger spacecraft.

The key to the future is not only proving that smallsats can conduct remote sensing and Earth observation with sufficient resolution and sophistication to prove useful. Perhaps the most important key lies with the idea that processed satellite data can be made widely available to users around the world on an ever more rapid basis. Below is a guide to satellite-based remote sensing that can be accessed via the Internet after the user gains access via a proper registration procedure. Today many of these data bases as operated by NASA, the European Space Agency, and other providers have data that derives from very large-scale and highly capable satellites. But the future seems likely to be more and more driven by highly capable smallsats that can duplicate the capabilities of satellites that might have weighed several tons, but are now being replaced by satellites that only have the mass of a few kilograms. (See Table 2 for a listing of websites providing access to remote sensing and Earth observation data.)

Table 2 Free web sites to support remote sensing services

Key free web sites providing information about remote sensing via satellite	
Description of web site	Web site URL
GloVis: The US Geospatial Service Global Visualization Viewer. This provides a search and order tool for information about the US Earth observation data. Registration is required in order to use this data base	http://glovis.usgs.gov
NASA Earth Observatory (NEO): This NASA web site allows access to more than 50 datasets on atmosphere, land, ocean, energy, environment, and other additional information. This website requires registration in order to use it	https://neo.sci.gsfc.nasa.gov/
USGS Earth Explorer: This site is perhaps the most comprehensive website that provides free access to data from many different US sources, including both aerial and satellite-based sensing. This web site requires registration	http://arthexplorer.usgs.gov
Copernicus Open Access Hub: This site provides free and open access to data from the Sentinel 1, 2, and 3 satellites as well as process and specifically derived user products. This web site requires registration to use it	http://cophub.copernicus.eu
NASA Earth data: Earthdata search, as of January 1, 2018, became the primary means for searching and discovering NASA Earth observing data. The Reverb data search and the discovery system that NASA Earthdata replaces are no longer operational. Registration is required to use this database	http://search.earthdata.nasa.gov
NOAA (National Oceanic and Atmospheric Administration) CLASS: This website stands for the Comprehensive Large Array-data Stewardship System. The CLASS website provides data from the US Department of Defense (DoD), Polar-orbiting Operational Environmental Satellite (POES), Environmental Satellite (GOES), and other sources. Registration is required in order to use this database	www.class.noaa.gov
NOAA Digital Coast: This database is focused on data from coastal regions. Data is organized by infrared, radar, and true color composites that can be downloaded. Registration is required in order to use this data base	http://coast.noaa.gov/digitalcoast
IPUMS Terra: This database is operated by Integrated Population and Environmental Data. This organization integrates population census data from around the world with global environmental data. Also see a web site known as Terraclip. Registration is required	www.ipums.org/IPUMSTerra.shtml
The Land, Atmosphere Near real-time Capability for EOS (LANCE): This web site is a component of NASA's Earth Observing System Data and Information System (EOSDIS). Registration is required	http://lance.modaps.eosdis.nasa.gov http://earthdata.nasa.gov/lance
VITO Vision: This website is operated by the Flemish Research Center. VITO stands for Vision on Technology for a Better World. This website provides information about various broad areas of vegetation from such sources as PROBA-V, SPOT-Vegetation, and METOP. Registration is required	https://vito.be/en

This listing of the ten internet websites that, with registration, provides a great amount of free Earth observation. It was prepared by Scott Madry with assistance by Joseph N. Pelton. It is licensed for this publication. All rights reserved

6 Other Small Satellites Providing Support to Achieving UN Sustainable Development Goals

The satellite services that provide the greatest level of support to achieving the UN Sustainable Development Goals (SDGs) are clearly those related to distributing information related to health and education, providing interactive telecommunications and networking, as well as Earth observation, meteorological, and remote sensing applications. The flexibility that “smallsat” technology and systems offers worldwide and especially for developing economies continues to be examined and new applications and services developed.

Cubesats and even smaller nanosats and femtosats can be used to test new sensors, components, or instruments that can provide valuable proof of concept for experimenters and even student projects around the world. Scientific experiments by researchers in developing economies can now become much more affordable. The tiny processors that now weigh only a gram or two have many times the processing speeds of computers that were quite large and massive several decades ago. This miniaturization of processing power and high-quality sensors can unlock many new capabilities for scientific and engineering programs around the globe.

And exactly what is a “smallsat” continues to be posed around the world? Its definition actually continues to evolve as new capabilities become possible. Another element that keeps evolving is in the arena of “smallsats” is, in fact, hosted payloads. Initially the idea of hosted payloads involved putting a small experimental payload on a large satellite. Intelsat in partnership with Cisco placed an experimental router on one of its large Intelsat 18 satellites for instance. Now a large satellite might fly over a dozen small experiments or proof of concept as part of a mission. The latest iteration of what a hosted payload might mean includes the idea of placing a whole “small sat” constellation onboard a larger constellation. The Iridium Next generation is now almost fully deployed. Onboard this constellation is riding the Aireon packages for precise airline navigation, or more precisely a global air traffic surveillance system for air safety.

This Aireon system as deployed on the larger Iridium satellite provides a space-based Automatic Dependent Surveillance-Broadcast (ADS-B) network. This is an air traffic surveillance technology that relies on aircraft broadcasting their identity, a precise Global Positioning System (GPS) position for each aircraft in the sky every half a second, plus other information derived from the aircraft’s onboard system. This system will be used by Air Traffic Controllers (ATCs) to identify and separate aircraft in real-time. Space-based ADS-B extends the same ADS-B technology currently received on ground-based receivers to space and provides much more extensive global coverage.

This system can be used to enhance air safety and track hijacked planes and could be extended to ships at sea and other vehicular transport systems. This type of hosted payload approach could be used in a variety of ways by others to create other types of global services such as to monitor air and ocean pollution, etc. This approach not only saves costs, launches, and orbital debris but also could be seen as a way to reduce congestions of space.

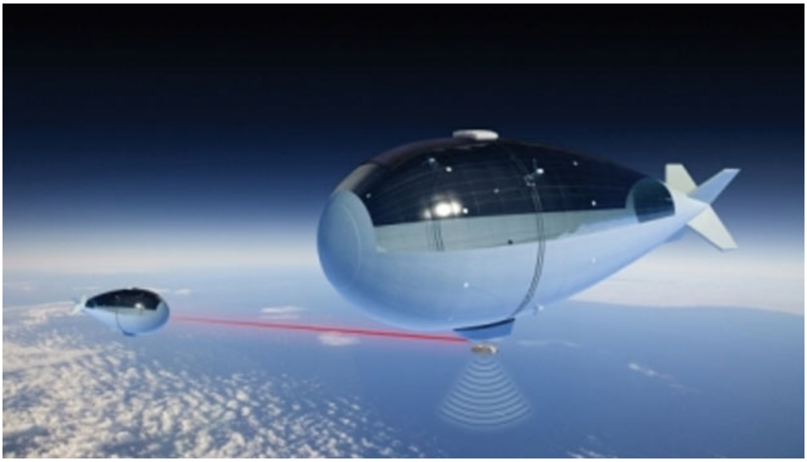


Fig. 4 HAPs can assist with UN SDGs related to health, education, and land and sea pollution and more. (Graphic courtesy of Thales)

Another area where innovation may be coming in future years is to have smallsat payloads at lower altitudes that are not satellites at all. These are, in fact, high altitude platform systems (HAPS). The advantage that a satellite provides is wide-area coverage. A HAPS at an altitude of 21 km or 12.5 miles provides complete coverage for island countries such Jamaica or Aruba, and it offers much less path loss or latency for communications or television broadcasting. Companies such as Thales Alenia Space are now offering services via what it calls “Stratobus,” and this technology could be used to provide telecommunications, networking, Earth observation, or remote sensing services to a number of counties in future years that are very much akin to those noted above for communications or remote sensing satellites (see Fig. 4).

7 Analysis of Space Systems Potential to Meet UN Sustainable Development Goals

The potential of space systems of all types and dimensions to meet the UN Sustainable Development Goals for 2030 is considerable as summarized in Table 3. A fuller explanation of the UN Goals for 2030 is presented in fuller details in Part 14 of this Handbook.

8 Conclusion

The UN Sustainable Development Goals are quite ambitious. The details of the goals are provided in chapter ▶ “UN Sustainable Development Goals for 2030.” Unfortunately the measured progress to date against these 17 objectives indicates that few

Table 3 Key areas where small satellite systems can help achieve UN sustainable development goals

Space-based services that aid UN goals for sustainable development
Prepared by Joseph N. Pelton for the Manfred Lachs conference in Montreal in 2017 in preparation
For the UNISPACE + 50 conference in 2018

Goal	Telecom and networking sats and HAPs	Broadcasting sats and HAPs	Remote sensing sats	Meteorological sats	Navigation and timing sat	Solar power sats
No poverty (Goal 1)	New jobs via telework, opportunity for remote services, training in remote villages	Broad distribution of information on birth control, nutrition, vaccines, etc.	Improved information to support fishing, farming, forestry, mining, etc.	Reduced losses of crops, housing, infrastructure	Improved farming and fishing via precision geolocation	*In future* Lower-cost clean energy to rural and remote locations
Zero hunger (Goal 2)	More efficient agricultural and fishing markets	Broad distribution of information on nutrition and birth control	More productive farming and lower-cost food	Less crop loss due to storms, flooding, typhoon, hurricanes	Improved farming and fishing via precision geolocation	TBD
Good health and well-being (Goal 3)	Tele-health and remote medical service	Broad distribution of information on birth control, nutrition, vaccines, etc.	Detection of crop or tree disease	Detection of solar flares and ozone holes	Ability to precisely track spread of disease and pandemics	TBD
Quality education (Goal 4)	Quality tele-education programs, remote testing programs	Educational radio and television, access to global news	TBD	Less destruction of schools and educational infrastructure	Cost savings on school transportation	*In future* Clean energy to remote locations for tele-education
Gender equality (Goal 5)	Tele-educational programming	Global news and TV broadcasts	TBD	TBD	TBD	TBD

(continued)

Table 3 (continued)

Space-based services that aid UN goals for sustainable development
Prepared by Joseph N. Pelton for the Manfred Lachs conference in Montreal in 2017 in preparation
For the UNISPACE + 50 conference in 2018

Goal	Telecom and networking sats and HAPs	Broadcasting sats and HAPs	Remote sensing sats	Meteorological sats	Navigation and timing sat	Solar power sats
Clean water (Goal 6)	Tele-education on water purification and sanitation	Broadcasts on water purification sanitation	Detection of polluted water. Passable road access info for water trucks after disasters	Better protection of water reservoirs against storms	Locate polluted waters, storms with acid rain, etc.	TBD
Affordable and clean energy (Goal 7)	Tele-education, internet access to create solar, wind, tidal, geothermal energy systems	Broadcasts on energy savings and building clean energy systems	Aid in finding good locations for wind farms, geothermal energy, and tidal energy	Aid in finding good locations for wind farms, geothermal energy, and tidal energy	Assist in location of renewable energy systems	*In future* Lower-cost clean energy to cities and rural and remote locations
Decent work and economic growth (Goal 8)	Telework, village training, tele-banking, tele-services	Open univ. training	Aid to more productive mining, fishing, farming, forestry, and transport	Support to new construction and design of infrastructure related to climate change	Support to new construction and design of transportation systems	In future Lower-cost clean energy to cities and rural and remote locations
Industry, innovation, and infrastructure (Goal 9)	Tele-education, internet-based innovation, internet-based technology incubators, protective security for infrastructure	Educational radio and television, access to global news	Aid to more productive mining, fishing, farming, forestry, and transport	Support to new construction and design of infrastructure related to climate change	Support to new construction and design of transportation systems	*In future* Lower-cost clean energy to cities and rural and remote locations

Reduced inequalities (Goal 10)	Tele-education, internet-based learning and data bases	Educational radio and television, access to global news	TBD	TBD	TBD	TBD
Sustainable cities and communities (Goal 11)	Substitution of tele-services for physical transportation, telework reduced transportation and cleans environment	Educational radio and television, access to global news	Key topographic information for transportation, water, and sewer planning	Key info related to protection of city infrastructure from violent storms	Improved traffic and transportation control	*In future* Lower-cost clean energy to cities and rural and remote locations
Responsible consumption and production (Goal 12)	Tele-education, tele-services, services can be provided worldwide	Broadcasts on telework, conservation, on energy savings and building clean energy systems	Monitor hazardous waste locations, atmospheric pollution, oil spills, garbage scows, etc.	Note changes in weather and climate due to industrial activities	Accurately pinpoint sources of pollution	*In future* Lower-cost clean energy to cities and rural and remote locations
Climate action (Goal 13)	Tele-education, telework, sat services, services can be provided worldwide	Broadcasts on telework, conservation, on energy savings and building clean energy systems	Track ice-cap and glacier melting, measure ocean temperature, atmospheric temperatures	Track changes in atmospheric temps, intensity of storms, solar activity	Pinpoint location of atmospheric and oceanic sensors	*In future* Lower-cost clean energy to cities and rural and remote locations
Life below water (Goal 14)	Tele-education, global internet access. Track location of endangered species	Sat broadcast TV and radio can strengthen education, civic activism, and knowledge of law	Detection of water and ocean pollution, coral bleaching, fish depletion, etc.	Track Ocean storms and hurricane	Exact location of sensor and ocean buoys	TBD
Life on land (Goal 15)	Tele-education, global internet access. Track location of endangered species	Sat broadcast TV and radio can strengthen education, civic activism, and knowledge of environmental law	Used to track animals and endangered species	Monitor violent storms and provide flood and high wind warnings	Exact location information re earthquakes, volcanos, rescue ops	TBD

(continued)

Table 3 (continued)

Space-based services that aid UN goals for sustainable development
Prepared by Joseph N. Pelton for the Manfred Lachs conference in Montreal in 2017 in preparation
For the UNISPACE + 50 conference in 2018

Goal	Telecom and networking sats and HAPs	Broadcasting sats and HAPs	Remote sensing sats	Meteorological sats	Navigation and timing sat	Solar power sats
Peace, justice, and strong institutions (Goal 16)	Low-cost sat telecom and internet access can strengthen education, civic activism, and knowledge of law	Sat broadcast TV and radio can strengthen education, civic activism, and knowledge of law	Time-stamped remote sensing data has been used to prosecute crimes against humanity			TBD
Partnerships for the goals (Goal 17)	Satellite manufacturers and service providers can help promote telework, tele-education, tele-health	Satellite manufacturers and sat broadcasters can help promote telework, tele-education, tele-health				TBD

Prepared and copyrighted by Joseph N. Pelton, All rights reserved. Printed with the permission of the author of the quantitatively defined aims will be achieved by 2030. Nevertheless many of the pathways forward to achieve these demanding goals, in numerous cases, will depend heavily on space-based systems. Furthermore, achievement of these goals in areas related to healthcare, education, reduced poverty and hunger, economic development, environmental protection, etc. will likely be heavily dependent on small satellite technology in particular.

Yet, small satellite technology is not a panacea. In fact, if the orbital space debris removal problem is not resolved soon, then very large-scale LEO constellations could create serious "space pollution" problems that could limit future safe access to space. The accelerated launch schedule required to orbit as many as 20,000 new satellites in a span of over only a few years carries with it very serious environmental concerns. Thus it is a difficult balancing act to note the many benefits that small satellite systems can bring to meet the longer-term objectives of the UN Sustainable Development Goals for 2030 against the hazards of potential increases in orbital space debris.

9 Cross-References

- ► Precision Agriculture and Forestry: Bytes for Bites
- ► Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently
- ► Small Satellites and Governmental Role in Development of New Technology, Services, and Markets
- ► Small Satellites, Law Enforcement, and Combating Crime Against Humanity
- ► Small Satellites and New Global Opportunities in Education and Health Care
- ► Small Satellites and Risk management, Insurance, and Liability Issues

References

Afristar., https://en.wikipedia.org/wiki/AfriStar. Last accessed 16 Feb 2019
Community Connect., http://geekswf.org/initiatives/communityconnect/. Last accessed 4 Feb 2019
C. Henry, One web scales Back constellation by 300 satellites. Space News, December 13, 2018. https://spacenews.com/oneweb-scales-back-constellation-by-300-satellites/
NASA – ATS., https://www.nasa.gov/centers/goddard/missions/ats.html. Last accessed 2 Mar 2019
J.N. Pelton, *Project Share Report* (Intelsat, Washington, DC, 1987)

Smallsats, Hosted Payload, Aircraft Safety, and ADS-B Navigation Services

Sanat Kaul

Contents

Abstract

The role of small satellites in the future of aviation safety is large and growing in importance.

There are many advantages that can come from the use of small satellite constellations as well as hosted payloads on small satellites to accomplish new capabilities related to aircraft navigation and safety. One of these ways is to provide

---

S. Kaul (✉)
International Foundation for Aviation, Aerospace and Drones, New Delhi, India
e-mail: sanatk@dofe.in; sanatkaul@gmail.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_96

more precise tracking of aircraft on an entirely global basis. This chapter describes how the hosted payload system, known as Aerion, is now deployed on the Iridium NEXT System. This innovation is just one of the ways that small satellite constellations and host payloads on these systems can provide new capability in such important ways as air safety and air traffic management. Aerion is just one example. More new companies to provide ADS-B services will develop in time. Other small satellite demonstrations of ADS-B such as the CAN-X7 are now launched, and GomSpace has a small satellite designed to carry out ADS-B services. New and improved ADS-B capabilities will continue to develop, and it seems likely that these will evolve using advanced small satellite design concepts.

This chapter will trace the history of development of what is formally called automatic dependent surveillance-broadcast (ADS-B). In particular it will explore the use of small satellite systems and hosted payload technology to prove this vital new service and to implement a fully functional program around the world. This new approach to air navigation and exact location of aircraft in the sky will be predominately using small satellite technology and systems for reasons explained in this presentation. This new technology can in time change the entire concept of air traffic management (ATM) and enhance air safety.

Keywords

Airborne collision avoidance systems/traffic collision avoidance (ACAS/TCAS) · Aireon · Air navigation service providers (ANSP) · Air traffic management (ATM) · Automatic dependent surveillance-broadcast (ADS-B) · Aviation safety · Aviation navigation · CAN-X7 · Chicago Convention · Communications, navigation, and surveillance/air traffic management (CNS/ATM) · Flight information regions (FIRs) · GomSpace · Global navigation satellite services (GNSS) · Hosted payloads · Instrument landing system (ILS) · International Civil Aviation Organization (ICAO) · National Aeronautical Service Providers · Paris Convention · PROBA-V · Universal access transceiver (UAT) · Unmanned traffic management (UTM)

1 Introduction

For reason of economy and pervasiveness of comprehensive global coverage, the use of small satellites will play a critical role in accomplishing the deployment of this new air navigation and safety program.

This chapter will also describe how small satellites are no longer just used for experimental projects and proof of concept but can increasingly serve a key and useful purpose in the deployment of critical and fully operational systems in the world. The uses of small satellites for such purposes as telecommunications, networking, and remote sensing have been demonstrated and are now being widely accepted, but new applications as RF geolocation, aircraft navigation and air safety, and other new applications are just starting to be realized.

2 Background

The growth of aviation, especially commercial aviation, has been phenomenal in the last century. The Paris Convention was signed in October 1919 and is formally known as the Convention Relating to Regulation of Aerial Navigation. This was the first attempt at regulating the growth and safety of civil air traffic on a global basis. On this occasion, 26 countries which represented the predominant number of countries operating ongoing aerial operations at the time signed on this convention. As part of this process, they endorsed the idea that each nation would assume exclusive control over the airspace above their own territory. The convention sought to address in a comprehensive matter administrative, organizational, and operational aspects of civil aviation and established processes that would apply to private air travel as well. This convention provided the broad areas of control of civil aviation for the next 25 years (Convention Relating to the Regulation of Aerial Navigation 2019).

This was followed by the Chicago Convention of 1944. This key and comprehensive air safety and navigation convention for civil aviation remains in effect until this day. It is one of the most significant conventions ever achieving international agreement and has perhaps served a large number of lives through improved aviation navigation and safety (Convention on International Civil Aviation – Document 7300 2019).

It was this convention that finally led to the formation of the International Civil Aviation Organization (ICAO) that coordinates international approaches to air traffic management and aeronautical navigation and safety. This specialized agency of the United Nations, which is headquartered in Montreal, Canada, coordinates and helps to improve civil aviation safety, navigation, and air traffic management standards (ICAO 2019).

The preamble of Chicago Convention of 1944 states:

> WHEREAS the future development of in international civil Aviation can greatly help to create and preserve friendship and understanding among the nations and peoples of the world, yet its abuse can become a threat to the general security; and
>
> WHEREAS it is desirable to avoid friction and to promote that cooperation between nations and peoples upon which the peace of the world depends;
>
> THEREFORE, the undersigned governments having agreed on certain principles and arrangements in order that international civil aviation may be developed in a safe and orderly manner and that international air transport services may be established on the basis of equality of opportunity and operated soundly and economically. (See Convention on International Civil Aviation above.)

It has been these principles that have guided the actions of the ICAO staff and leadership to seek to enhance international cooperation through improved standards, processes, and equipment to enrich civil aviation safety and navigation.

3 ICAO and Air Traffic Management (ATM)

The seamless growth of commercial aviation can truly be attributed to the work done by ICAO. Since the formation of ICAO, air traffic has increased from a few commercial aircrafts to the present day of flying many billions of international passengers each year. Air safety has been increased via the Standards and Recommended Practices and other guidance material produced by ICAO. These standards that are now followed by all commercial airlines and private operators have truly allowed civil aviation to be transformed into the safest form of travel. This has been brought about not only by regulatory standards and actions by ICAO but also the innovation that has taken place in aircraft design and manufacturing plus all allied subjects related to safety including navigation.

However, air traffic management (ATM) today is becoming increasingly challenged with the limitations of existing navigational and positioning technology. The radars used today were developed in the twentieth century and involved designs that were used extensively in the Second World War. They still remain the most popular technology for aviation traffic management. Important improvements in radar-based technology have come over the years. These have included instrument landing systems, rotating radars, Doppler positioning systems, secondary radars, and airborne collision avoidance/transportation collision avoidance systems (ACAS/TCAS). The advent of global navigation satellite services (GNSS) which is also known as precision, navigation, and timing (PNT) service has moved to a different type of approach. The latest innovation known as automatic dependent surveillance-broadcast (ADS-B). ADS-B represents an important innovative technology in air traffic management (ATM). The US Federal Aviation Administration (FAA) has made it compulsory for all aircrafts flying in US airspace to have ADS-B instruments installed in the aircraft by 2020. It is likely that ADS-B equipment will be installed in all civil aircraft around the world in the coming years.

The ICAO Council President has stated at the global CANSO Conference in 2018: “Today’s incredibly rapid rate of technological progress is now forcing us to acknowledge that a revolution is underway, with Unmanned Autonomous Systems (UAS) navigating residential and urban environments for a wide range of purposes at one end of the spectrum, and high-altitude balloons, RPAS, and super- or hypersonic aircraft jetting across the stratosphere at the other. . .Airspace design and management would be changing dramatically in the years ahead as more and more aircraft enter into service which fly higher, lower, faster, and much slower than those we manage today.”(ICAO Council President Dr. Olumuyiwa Benard Aliu speaking at CANSO’s Sixth World Air Traffic Management (ATM) Congress in Madrid, Spain, on March 2018).

To handle this dramatic growth, air traffic management must shift to deliver a more scalable model. This must be a digital system that can monitor and manage this increased level and diversity of activity. That system is what is now being called *unmanned traffic management*, or UTM. The UTM team at Airbus, for instance, has spent months executing research and tests to determine its recommendations on the best approach for a future UTM. Other aircraft manufacturers around the world are conducting similar research.

Further, the ICAO Council President has also drawn attention to the fact that new space-based automatic dependent surveillance-broadcast (ADS-B) technology should eventually serve as a truly global aircraft positioning solution, redefining how seamlessly modern ATM will function and deliver important efficiency and emission reduction advantages.

"We do not yet have a global ADS-B mandate, however by 2020 a number of States and regions will be ADS-B capable and many commercial aircraft will be equipped with suitable transponders"(Ibid). He went on to say that this new capability will be needed as (ADS-B) technology eventually serves as a truly global aircraft positioning solution. This new capability will redefine how seamlessly modern air traffic management (ATM) will function and deliver important efficiency and emission reduction advantages (Sixth World Air Traffic Management Conference CANSO Conference, March 2018).

4 Air Surveillance Over High Seas and ICAO's Responsibility

While the issue of improving air surveillance for aviation was taking place, the new GNSS-based technology made available by ADS-B services had been discovered. This technology could be applied to meeting needs of gaps in coverage over the high seas.

Under Chicago Convention, Article 12, Rules of the Air, states:

> Each Contracting State undertakes to adopt measures to insure that every aircraft flying over or manoeuvring within its territory and that every aircraft carrying its nationality mark, wherever such aircraft may be, shall comply with the rules and regulations relating to the flight and manoeuvring of aircraft there in force. Each Contracting State undertakes to keep its own regulations in these respects uniform, to the greatest possible extent, with those established from time to time under this Convention. Over the high seas, the rules in force shall be those established under this Convention. Each Contracting State undertakes to insure the – prosecution of all persons violating the regulations applicable.

In light of this, responsibility for surveillance over high seas as such falls on ICAO. ICAO has divided the airspace over the high seas into flight information regions (FIRs) and as needed has allotted responsibility to adjoining countries for implementation without giving any rights.

5 ICAO: Every Minute Tracking Signal Device Development Needed

On March 8, 2016, the ICAO Council adopted new provisions aimed at preventing the loss of commercial aircraft experiencing distress in remote locations. In this regard, ICAO announced new amendments to Annex 6 of the Chicago Convention (*Operation of Aircraft*) which were to take effect between then and 2021. These changes related primarily to the requirement for aircraft to carry autonomous distress tracking devices which can autonomously transmit location information at least once every minute in distress circumstances. Some other issues were also listed. These included the requirement for aircraft to be equipped with a means to have flight recorder data recovered and made available in a timely manner and extending the duration of cockpit voice recordings to 25 h so that they cover all phases of flight for all types of operations (Montréal, March 8, 2016, press release: ICAO).

These developments are consistent with the findings and recommendations of the multidisciplinary ad hoc working group ICAO formed after Malaysia Airlines MH370 went missing on May 2014. Dr. Olumuyiwa Bernard Aliu, ICAO Council President, explained at the time the importance of these changes. "They directly support the concept of operations for the Global Aeronautical Distress and Safety System (GADSS) which was proposed by ICAO at that time, and will now greatly contribute to aviation's ability to ensure that similar disappearances never occur again" (States Make Further Progress through ICAO to Help Avoid Recurrence of MH370-Type Disappearances March 8, 2016: Speech of Dr. Olumuyiwa Benard Aliu, ICAO Council President.icao.int).

The provisions relating to 1-minute distress tracking are performance-based, meaning that airlines and aircraft manufacturers may consider all available and emerging technologies which can deliver the 1-minute location tracking requirement specified.

The new flight recorder data recovery provisions are also performance-based. This means that related technology solutions may or may not entail the need for deployable flight recorders. Taken together, these new provisions will ensure that, in the case of an accident, the location of the site will be known immediately to within six nautical miles and that investigators will be able to access the aircraft's flight recorder data promptly and reliably. They will also contribute to greatly improve more cost-effective search and rescue operations.

6 ADS-B

By September 2014, ICAO published an ADS-B Implementation and Operation Guidance Document and by July 2018 it published an ADS-B Implementation and Operations Guidance Document (CNS SG/22 Appendix K to the Report 2018).

7 What Is ADS-B

ADS-B, in brief, is a GNSS/GPS-based technology. ADS-B provides many benefits to both pilots and air traffic control that improve both the safety and efficiency of flight. The prime advantages are listed below:

1. The pilot – When using an "ADS-B In" system, a pilot is able to view traffic information about surrounding aircraft if those aircrafts also are equipped with "ADS-B Out" capability. This information includes altitude, heading, speed, and distance to aircraft. (In addition to receiving position reports from ADS-B out participants, it can provide position reports on non-ADS-B out-equipped aircraft if suitable ground equipment and ground radar exist.)

2. Weather – Aircraft equipped with universal access transceiver (UAT) ADS-B In technology will be able to receive weather reports and weather radar through flight information service-broadcast (FIS-B).
3. Flight information – Flight information service-broadcast (FIS-B) also transmits readable flight information such as temporary flight restrictions (TFRs) and NOTAMs to aircraft equipped with UAT.
4. Expense – ADS-B ground stations are significantly cheaper to install and operate compared to primary and secondary radar systems used by ATC for aircraft separation and control.

In the USA, unlike some alternative in-flight weather services currently being offered commercially, there will be no subscription fees to use ADS-B services or its various benefits. The aircraft owner will pay for the equipment and installation, while the Federal Aviation Administration (FAA) will pay for administering and broadcasting all the services related to the technology.

The ADS-B system is comprised of multiple parts, including ground stations and aircraft installed equipment (Adam Krumbein: Introduction to ADS-B Technology for Enhanced Aviation Tracking and Safety: SWA southwestantennas.com dated Nov. 21, 2016).

Under the requirements for the NextGen air traffic system, all aircraft which fly within US airspace will be required to transmit “ADS-B Out” information to ADS-B ground stations and other ADS-B equipped aircraft by 2020. This information includes aircraft identification, altitude, speed, and velocity. The ADS-B equipment package installed on the plane includes a GPS unit for providing location information, processing hardware, and antennas for transmitting and receiving the ADS-B signals. “ADS-B In,” on the other hand, means “ADS-B In” is the receiver part of the system. “ADS-B In” equipment allows aircraft, when equipped properly, to receive and interpret other participating aircraft’s “ADS-B Out” data on a computer screen or an electronic flight bag in the cockpit.

As the aircraft flies over individual ADS-B receiver ground stations, these pick up the “ADS-B information broadcast by each aircraft, which can then be used by air traffic controllers as a supplement to radar-based tracking.

Airspace safety should improve with ADS-B by giving pilots and air traffic controllers additional information about exactly where each aircraft is in the system, helping to prevent midair collisions or close calls during takeoff and landing. Existing flight corridors over land will be able to safely handle an increasing number of daily flights with ADS-B, adding accuracy and redundancy to the existing airline tracking systems. The addition of a global satellite system coverage will greatly expand the abilities for all aircraft to connect to the ADS-B system.

8 Acceptance of ADS-B by ICAO and Other Governments

As early as 2003 at the 11th ICAO Air Navigation Conference it was recommended that States recognize ADS-B as an enabler of the global ATM concept bringing substantial safety and capacity benefits. It also supported the cost-effective early implementation of this new capability. They urged ongoing effort to ensure that it would be harmonized and made compatible and interoperable with operational procedures, data linking, and ATM applications (ADS-B Implementation and Operations Guidance Document: Introduction CNS SG/22 Appendix K to the Report (2018)).

ADS-B is, therefore, a new surveillance technology designed to help modernize the air transportation system. It provides foundational technology for improvements related to **NextGen** (Next Generation Air Transportation System) and **SESAR** (Single European Sky ATM (Air Traffic Management) Research Program). NextGen refers to the effort of the US FAA (Federal Aviation Administration) to transform the ATC (air traffic control) system to support a larger volume of airplanes more efficiently. SESAR is a similar effort in Europe in which EC (European Commission) and EUROCONTROL are its founding members.

For NextGen and SESAR, ADS-B is one of the most important underlying technologies in the plan to transform ATC from the current radar-based surveillance to satellite-based GPS (Global Positioning System) surveillance. In addition, the FAA states that ADS-B will serve as the cornerstone for this transformation, bringing the precision and reliability of satellite-based surveillance to the nation's skies (eoPortal Directory ADS-B 2019).

Modern Mode-S transponders on board of aircraft transmit the flight position and other information by so-called extended squitter messages (1090ES) on the 1090 MHz SSR-Mode-S downlink frequency (ADS-B Out). In the future, radar systems will be complemented or even replaced by less costly ADS-B ground stations, which will be integrated in the existing surveillance infrastructure. The European ADS-B Implementing Rule requires that new aircraft heavier than 5700 kg or faster than 250 knots will be equipped with "ADS-B Out" from 2015 onward when flying IFR (instrument flight rules), and for already operational aircraft, a retrofit was made mandatory from end of 2017 on. In 2020, ADS-B surveillance shall become operational.

Yet there remains a key issue with ADS-B coverage for long-distance and overseas flights. In these instances, usefulness of radars and even ADS-B is limited as these technologies depend upon ground-based stations. Thus with only ground-based stations, ADS-B is therefore unable to provide coverage over oceans which, in fact, is 70% of the airspace. Further, there is also the issue of difficult terrains like polar regions or high mountains where ground stations cannot be installed. Therefore, shifting from radars to GNSS-based technology like ADS-B offers much greater quality of air traffic management over land surface. This service needs to be extended to satellites to provide truly global coverage.

9 The Case of Missing MH370 Flight Over High Seas

Perhaps the defining moment for the global adoption of ADS-B was the case of flight MH370 which has now become infamous as the flight which took off from Kuala Lumpur to Beijing and became untraceable. The flight disappearance of MH370 in

2014 was truly a momentous moment for the aviation industry comparable even to hijacking of civil domestic aircrafts from Boston airport in the USA in 2011 and thereafter suicidal attack on various iconic buildings including the twin towers of the World Trade Center in New York in 2001. While the incident of 2001 led to security awareness in commercial aviation, the disappearance of MH370 over the South China Sea was an eye opener for safety of civil aviation and in particular surveillance of aircrafts over high seas.

Shortly after the disappearance of Malaysia Airlines flight MH370, a special Multidisciplinary Meeting on Global Flight Tracking (MMGFT) was convened at the ICAO Headquarters in Montréal, Canada, to propose recommendations for future actions. One of the main decisions taken was the need for operators to pursue global tracking of airline flights at a faster pace.

10 Shortcomings of ADS-B

So, while ADS-B as a technology has gained great advantage and acceptance over traditional secondary radar as it gives its location, speed, direction, etc., it still suffers from a major flaw. This is because it needs ground stations to reflect the messages which come from aircrafts which makes its coverage over high seas impossible via ground stations. The shortcomings of the old radar system of air navigation and the newly emerging technology of ADS-B had a clear common denominator. This was the inability of either of these systems to provide surveillance and navigation over high seas or difficult terrains like polar regions where ground stations cannot be installed. This is where the use of small satellites to provide ADS-B connectivity enters the picture as the solution.

11 Use of Small Satellite Constellations to Provide Global Safety to Aviation: ADS-B Over Satellites

Perhaps the greatest shortcoming of existing technology for air navigation surveillance (ANS) using radar is the absence of air surveillance over high seas, polar regions, as well as difficult terrains which are quite challenging. The missing MH370 flight in 2014 over high seas was a challenge to ICAO and the aviation community. While the lack of air surveillance over high seas and polar regions had started bothering aviation experts, it was fortuitous that a year earlier in 2013 the German Space Agency DLR had started experimenting on the same subject. DLR had already by 2013 experimented with a hosted payload on a European Space Agency's satellite PROBA-V′ on May 23, 2013, to test whether ADS-B can work from satellites instead of ground stations. On switching on for the first time, it recorded over 12,000 ADS-B messages within 2 hours at an altitude of 820 km (ADS-B over Satellite – first aircraft tracking from space, June 13, 2013, DLR News).

DLR's experiment proved that signals even from a height of about 800 km would be comparable to signals from ground stations. The advantage would, of course, be that the satellites could cover the entire oceanic air space as well as the polar regions and areas where ground stations cannot be installed. The satellites would, however, have be a constellation to cover the entire globe because the signals only had a range of 800 km and thus would be too weak for MEO- or GEO-based satellites to capture.

The DLR experiment of "ADS-B over Satellite" proved successful and was the successful proof of concept needed to move to the next stage. "Worldwide, this is the first experiment ever of this kind – and now we have evidence that this concept works," says DLR Project Manager Toni Delovski. The project team detected over 100 aircrafts during the first pass over the British Isles, East Asia, and Australia when the receiver was switched on. "For some aircraft, we were able to determine multiple positions over time, which allowed us to reconstruct their flight paths"("ADS-B over Satellites: The World's Fastest ADS-B receiver in Space"; T. Delovski, K. Warner, T. Raw like, J. Benrens, J. Bredemeyers, RWendel. DLR-Institute of Space Systems, Robert-Hooke Str7, 28359 Bremen Germany; Toni.delovski@dlr.de).

ADS-B signals are broadcast by aircraft every second; they include aircraft position and velocity information. Currently ADS-B equipment is being introduced on aircraft as a supplementary data source to the ground-based radar to monitor air traffic. The problem with radar is that its coverage is restricted. Once out of the range of terrestrial radar stations, the continuous air traffic surveillance stops. "For example, aircraft travelling from Europe to Brazil disappear from the radar over the Atlantic and will only be detected again by terrestrial radar shortly before reaching South America," explains Delovski (Ibid).

There is currently no continuous air traffic surveillance by terrestrial radar over oceanic airspace or in regions with limited air traffic surveillance infrastructure. But tracking from space could close this gap. ADS-B over Satellite was a joint project of the DLR Institute of Space Systems and the DLR Institute of Flight Guidance, in cooperation with the Luxembourg partner SES Techcom Services (Convention Relating to the Regulation of Aerial Navigation 2019).

12 PROBA-V Test Results and Considerations

The ADS-B receiver test results were limited by the fact that this was the first onboard satellite experiment of its kind, receiving 1090ES ADS-B squitter signals that were being transmitted from aircraft. Therefore, the experimenter could not build on experiences or any previous evaluation results. The assessment could not be completely definitive of the achieved results when one takes into account the constraints under which this experiment was conducted, due to limitations in cost and time as limited power and geometric coverage areas.

The reception of 1090 extended squitter ADS-B messages on board of the PROBA-V satellite was mainly affected by the following issues, which may lead to a loss of ADS-B information:

- RF signal loss due to the low signal level resulting from the distance between the receiving satellite at an altitude of approximately 820 km and the transmitting aircraft at an altitude that varied between 0 and 12 km.
- RF signal loss due to the shapes of the satellite antenna vertical radiation pattern and the aircraft antenna vertical radiation pattern.
- Corruption of messages by garbling, when several messages arrive at the ADS-B antenna onboard of the satellite and, at the same time, due to overlap and thus cannot be decoded by the ADS-B receiver.
- The ADS-B receiver on board of PROBA-V is a hosted payload, while the main mission is the vegetation scanner. So the antenna mounting position was a compromise in order not to disturb the main mission and the other payloads
- Speed of the satellite of about 27,000 km/h, which leads to a limited time of observation for each detected aircraft of about 3 min maximum (ADS-B over Satellite Global Air Traffic Surveillance for Space: Conference Paper 2014: http://www.researchgate.net/publication/286240589).

13 Hosted Payload and ADS-B Over Satellite

One of the most interesting aspects of this experiment was that the in-orbit test of ADS-B over Satellite using a hosted payload and the finding that this service does not necessarily require independent satellites. The ADS-B instrument is light and can be hosted as a payload on any satellite or for that matter even on a high rising balloon. The quality of antenna and receiver sets does become critical in terms of requiring to be posted on a free-flying satellite.

14 Automatic Dependent Surveillance-Broadcast (ADS-B) Over Satellites

Automatic dependent surveillance-broadcast (**ADS-B**) **over satellite** is a surveillance technology in which an aircraft determines its position via satellite-based navigation without the help of ground-based equipment. The aircraft also periodically broadcasts the signals, enabling it to be tracked, and various information as to location, speed, and bearing to be relayed to the satellite coverage. This allows the information to be ultimately received by the air traffic control without ground stations, and no interrogation signal is needed from the ground. It can also be received by other aircraft to provide situation awareness so that the pilot can be fully aware of other objects in the sky around him if they are equipped with ASD-B equipment.

ADS-B is “automatic” in that it requires no pilot or external input. It is “dependent” in that it depends on data from the aircraft’s navigation system. Further, this information as to speed and position heading is sent regardless of the action of the pilot or the functioning of the engine. It can, therefore, be put on a pilotless aircraft or unmanned autonomous vehicle (UAV) or even a balloon or drone. ADS-B is therefore a possible replacement of a secondary radar. However, a primary radar is different in function as it detects an unknown object in the sky, while ADS-B has no detection capability and is not a substitute for primary radar.

15 Advantage of ADS-B Over Satellites Over Normal ADS-B

There are several advantages of ADS-B over Satellites compared to ground station ADS-B.

The most obvious advantage is, of course, that ADS-B operates seamlessly over the high seas and polar regions. What is not so obvious is that it also covers certain land areas where it is difficult to put up ground stations like forests or mountains or large lakes. Some countries that are also not equipped to operate ADS-B ground stations can also benefit from it.

There are also other advantages such as:

- Search and rescue operations over high seas and areas out of range of ground stations become trackable via its ADS-B signals. This feature could have been used in the case of MH370.
- New air routes over high seas can be formed which will be more direct and save money for airlines.
- Another advantage of ADS-B over Satellites is that it will save energy and, therefore, fuel burn and lower greenhouse gas emissions.
- The satellites to be used can be small and deployed in low Earth orbit and even be designed as hosted payloads. This can make them lower in cost.

Today, there are other in-orbit tests underway. Canada has launched its CAN-X7 test satellite to experiment with ADS-B service. The small satellite designer and manufacturer GomSpace has developed a design for an ADS-B system.

Perhaps the most significant and first commercial venture has already started under the name of Aireon. This company is pioneering the commercial offering of an ADS-B service for air traffic management (ATM).

Aireon is backed by NAV CANADA, the Canadian Government Air Navigation Agency, with support beginning in 2014. Aireon LLC is a joint venture between NAV CANADA, IAA (Irish Aviation Authority), ENAV (Ente Nazionale per l'Assistenza al Volo, Italy), NAVIAR (Navigation Via Air, Denmark), and Iridium, which is hosting the Aireon payload on board the Iridium NEXT LEO constellation of 66 operational satellites. This Aireon system, now fully deployed, is actively providing a global system for tracking and monitoring aircraft anywhere in the world by using spaceborne ADS-B receivers.

Aireon is pioneering what many would characterize as next-generation aviation surveillance system. These are deploying the latest ABS-B technologies that were formally ground-based and, for the first time ever, are now operating globally. The objective of the Aireon hosted payload packages is to significantly improve efficiency, enhance safety, reduce emissions, and provide cost-savings benefits to all stakeholders interested in aviation safety and navigational efficiency. Space-based ADS-B surveillance covers oceanic, polar, and remote regions and can also augment, or in some case replace, existing ground-based systems.

In this effort, Aireon is working in partnership with leading air navigation service providers (ANSP) from around the world, like NAV CANADA, the Irish Aviation Authority (IAA), ENAV, NATS, and NAVIAR, plus others that will be recruited to join this network initiative. Iridium Communications Inc. that operates the Iridium NEXT satellite network for global voice communications and hosts the Aireon packages is also a partner.

Iridium Communications Inc. (formerly Iridium Satellite LLC) is a publicly traded US company. Iridium operates a constellation, a system of 141 active satellites used for worldwide voice and data communication from handheld satellite phones and other transceiver units. This is a combination of first- and second-generation satellites. The Aireon payloads are only on the 66 Iridium NEXT satellites.

The current Iridium network covers the whole Earth, including poles, oceans, and airways, with 95 satellites, with the remaining 46 acting as active backups. With the help of "Iridium NEXT," Aireon is hosting its specially developed receivers and is providing a global, real-time, space-based air traffic surveillance system, available to all aviation stakeholders. Aireon's space-based global surveillance system is thus the first globally deployed automatic dependent surveillance-broadcast (ADS-B) service. Instead of utilizing traditional radio receiver towers on the ground, Aireon has redesigned them into flexible and highly effective space-grade receivers. This allows for 100 percent global surveillance using the same ADS-B signal that aircraft already transmit. Iridium NEXT's low-latency, 66 cross-linked low Earth orbit (LEO) satellites meet the technical demands of global air traffic surveillance and tracking (Aireon 2019).

Iridium Communications Inc. is, therefore, a major partner of Aireon and has launched under its "NextGen" scheme 66 satellites of about 860 kg in mass. Each includes the ADS-B package. The network is deployed at a height of 780 km above the Earth. Of these, 60 satellites will provide the ADS-B services, while 6 will be in-orbit spares ready for providing service if one of the other packages should fail. Iridium NEXT's low-latency, 66 low Earth orbit (LEO) satellites are well suited in altitude, power, and coverage to meet the technical demands of global air traffic surveillance and tracking.

A "hosted payload" is the term now commonly used in the space industry to describe packages that are "piggybacking" on a larger and more powerful satellite. Such a module can be attached to a commercial satellite with communications circuitry that operates independently of the main spacecraft but which may share the satellite's power supply and even their transponders for transmission of communications signals. The concept has been also been referred to as "hitchhiking" in addition to "piggybacking."

Iridium NEXT is hosting the Aireon system and is currently the only commercial satellite constellation with the global coverage capability and universal reach to enable global air traffic surveillance due to its polar orbital configuration. The Globalstar mobile satellite communications network has service only up to 55°

latitude north and south and thus does not cover the polar regions. It also does not have inter-satellite links to allow transfer of data to reach ground control facilities. The polar orbiting configuration provides complete global coverage and inter-satellite relays. With these combined features, it could potentially eliminate the need for ground stations. Ground-based redundancy helps to make the total system more resilient.

ADS-B information broadcast from the aircraft will be received by a hosted payload (AHP), which transfers aircraft data from satellite to satellite via cross links down to Aireon's ground-based Teleport Network (TPN) and Aireon Processing and Distribution (APD) system. With the assistance of a partner, Harris Corporation, the APD decodes and verifies the data and delivers the data to the appropriate stakeholder facilities that have subscribed to the Aireon service.

16 The Aircraft Antenna for ADS-B Service

In order to ensure reliable satellite reception, an A1 class transmitter and top mount aircraft antenna (commonly found on most commercial aircraft and private jets) is required due to the space-based nature of Aireon's receivers. Aircraft with a traffic alert and collision avoidance system (TCAS) to help prevent midair collisions are typically equipped with both top and bottom mount antennas (see Fig. 1).

Fig. 1 Operational configuration between aircraft and Aireon packages. (Graphic courtesy of NAV Canada)

A paper titled “Low-Earth orbit satellite constellation for ADS-B based in-flight aircraft tracking” by Thien H. Nguye, Naomi Tsafnat, Ediz Cetin, Barnaby Osborn, and Thomas F Dixon (Nguyen et al. 2019) presents a parametric study that seeks to define an optimum design for a custom ADS-B satellite constellation.

The number of satellites, inclination, and altitudes of each satellite were varied to examine their effect on coverage. The aim was to design an alternative low-cost satellite constellation providing equal or better ADS-B coverage than that provided by ground stations/antennae. To evaluate the ability of a constellation of LEO satellites to provide ADS-B coverage in the absence of land-based ADS-B receivers, popular flights over the Atlantic and Pacific Oceans were simulated.

Thus, different satellite constellations were simulated and the link-budget data for each test case was analyzed. For the purpose of parametric analysis, three flight path possibilities were defined, and one flight from each modeled flight path was used for the optimization analysis.

The results from this simulation show that if there had been only 18 satellites in a constellation, they would have provided coverage to almost continually track the MH370 during its flight. Had the ADS-B transponder remained operational during the flight, the probable crash and debris locations area would have been quite small for the search. The parametric study suggests that a larger number of satellites at higher altitude provide more reliable ADS-B coverage for the transoceanic flights of interest. Geometrically, a 60° inclination was the most coincident with the flight paths of interest and provided the most optimal coverage of the inclinations tested. This was only a theoretical analysis, and other factors such as coincidence with an actual constellation, such as Iridium, might prove to be a more important consideration.

17 Aireon Results to Date

The Aireon experience: The use of small satellites in Leo for air traffic surveillance and management is yet another important use of small satellites.

In terms of the performance results, the performance was in many ways better than expected. Of the 113 million ADS-B reports received on April 2019, all arrived within the target 8-second update rate, with some as low as 3–4 s. The average time it took for those position reports to reach a controller was just 0.17 s against a target of 2 seconds. This shows the quality of real-time information given the journey that data makes from the aircraft, through Aireon’s satellite network and Iridium inter-satellite, and then to its ground station before reaching the ATM system.

Further, this data is now being used for allowing low-latency, real-time surveillance, thereby reducing the distance between aircrafts. This capability offers airlines that were previously assigned fixed speeds and heights the opportunity to take advantage of more flexible flight paths and optimum trajectories, that is, reducing fuel use and greenhouse gas emissions and helping them maintain their operating schedules (https://nats.aero/blog/2019/06/operational-trial-of-aireon-service-shows-potential-for-big-benefits/14 June 2019).

18 Conclusion

The European Aviation Safety Agency has certified Aireon as a new air navigation service provider (ANSP) for its space-based ADS-B surveillance, the first of its kind certification ever issued by the civil aviation regulator.

The FAA has engaged the Harris Corporation to interconnect space-based ADS-B to FAA infrastructure in support of advanced surveillance enhanced procedural separation (ASEPS). Further, is has sought further trials and information so as to achieve the following:

- Added independent validation with time difference of arrival.
- Flight test the service capability.
- Perform continuous monitoring
- Update interval (UI) result from FAA flight test is 8.05 s for oceanic holding pattern.
- Space-based ADS-B routing to any service delivery point within the FAA network connecting to ATOP/MEARTS/ERAM to be considered equivalent to ground-based ADS-B.

The Airports Authority of India has signed a memorandum of understanding (MoU) with Aireon for implementation of space-based automatic dependent surveillance-broadcast (ADS-B) data services for the oceanic regions of the Indian flight information regions (FIRs):

- Aireon has signed data service agreements (DSAs) with 11 aviation organizations, making up 28 countries. These include NAV CANADA, NATS, ENAV, IAA, NAVIAR, DC-ANSP (Curacao), Air Traffic Navigational Services Co. Ltd (South Africa), the Civil Aviation Authority of Singapore, Seychelles Civil Aviation Authority, ISAVIA (Iceland) and Aerial Navigation Safety in Africa and Madagascar (ASECNA – Western Africa and Madagascar).
- In reference to other aviation stakeholders, Aireon and FlightAware have announced a partnership on September 2016. Together, they created a product called GlobalBeacon. GlobalBeacon is a first of its kind product and a turnkey solution for airlines to be in compliance with the International Civil Aviation Organization's (ICAO) Global Aeronautical Distress Safety System (GADSS). This controls Global Beacon system that enables airlines of all sizes to proactively position themselves to respond in the event of an emergency.

Small satellites and the early operational experience of the Aireon hosted payload on the Iridium NEXT satellite have shown the way forward – both for the ICAO and National Aeronautical Service Providers. Thus, it has been shown that ADS-B over Satellite provides reliable information on aircraft location with precision and a new level of accuracy. Many believe that ADS-B services offered by small satellites can provide the answer to the lack of accurate aeronautical navigational and positioning services in many areas of the globe. There have previously been areas where there has been limited or no positional surveillance over the high seas, polar regions, and some difficult terrains. This new technology supplied via the use of small satellites in a global constellation appears to represent a game changer and an important new small satellite application of significance.

There is value beyond its critical new safety and navigational accuracy service. There is also the additional opportunity to help with better and tighter flight management. This can help to save fuel and limit greenhouse gas emissions. This can also, perhaps, reduce or eliminate future dependence on the Second World War Technology of outdated radar technology for CNS/ATM. In some cases, outdated ground equipment can be replaced and phased out of service. The longer term question remains with regard to the resilience of these systems and to what degree is there a need for greater redundancy of such systems. Operational experiene will verify the longer-term ability of such systems to avoid major outages and help address concerns such as solar storms or other possible sources of system failure.

19 Cross-References

- ► Precision Agriculture and Forestry: Bytes for Bites
- ► Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently
- ► Small Satellites, Law Enforcement, and Combating Crime Against Humanity
- ► Small Satellites and Governmental Role in Development of New Technology, Services, and Markets
- ► Small Satellites and New Global Opportunities in Education and Health Care
- ► Small Satellites and Risk Management, Insurance, and Liability Issues
- ► Smalls Satellites and the 17 United Nations Sustainable Development Goals

References

Aireon. www.aireon.com resources. Last Accessed 20 Aug 2019

Convention on International Civil Aviation – Document 7300. https://www.icao.int/publications/pages/doc7300.aspx. Last Accessed 20 Aug 2019

Convention Relating to the Regulation of Aerial Navigation Journal of Air Law and Commerce. https://scholar.smu.edu/cgi/viewcontent.cgi?article=3588&context=jalc. Last Accessed 19 Aug 2019

eoPortal Directory ADS-B.: directory.eoportal.org. Last Accessed 20 Aug 2019

ICAO. https://www.icao.int/Pages/default.aspx. Last Accessed 20 Aug 2019

T. H. Nguyen, N. Tsafnat, E. Cetin, B. Osborne, T. F. Dixon, Low-Earth orbit satellite constellation for ADS-B based in-flight aircraft tracking. http://www.techno-press.org/?journal=aas&subpage=7. Last Accessed 20 Aug 2019

Small Satellites and Risk management, Insurance, and Liability Issues

Chris Kunstadter

Contents

Abstract

Space insurance is the financial protection and risk-sharing regime that protects those involved in space activity from loss of assets, business interruption, and third-party liability for bodily injury and property damage. The first space insurance policy was written in 1965, to protect COMSAT, the US signatory to INTELSAT, from liability arising from their involvement in deployment of the earliest INTELSAT satellites. Since then, space insurance has expanded to become a critical resource that enables innovation and investment in space activity, as well as unlocking the economic potential and providing an economic safety net for the risks associated with space activity.

Keywords

Actual financial loss sustained · Ancillary coverage · Asset protection · Business interruption · Fortuity · Indemnification · Insurance coverage · Insurance exclusions · Insured vs. uninsured launches · Launch insurance · Launch risk

---

C. Kunstadter (✉)
AXA-XL, New York, NY, USA
e-mail: kunstadter@gmail.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_60

guarantee · Liability claims · Low-value launches and satellites · Market dynamics · Pooling · Risk · Satellite failure · Satellite value chain · Space insurance · Underwriting criteria · Underwriting process · Warranty payback coverage · Wrap-around coverage

1 Introduction

Risk can be defined as the intentional interaction with uncertainty. The risk management process involves identification of the perils faced; assessment of the hazard – or impact – of those perils; and treatment of the consequences. Treatment options include avoidance (don't do the risky thing), reduction (incorporate protection from perils), retention (acceptance of the risks), and sharing (e.g., insurance). Risk has many aspects. Table 1 diagrams the many key dimensions of risk.

Three principles of insurance play a significant role in space insurance:

- Pooling: "Losses of the few are paid by the many." Unlike automobile insurance, where millions of drivers pay insurance premiums to cover the losses of those few who have accidents, the small number of launches and satellites results in potential volatility, as a single loss can wipe out an entire year's space insurance premium.
- Fortuity: "Losses must be unanticipated." When a failure occurs, the cause tends to be a random "escape" resulting from errors in design, workmanship, or process. The intense scrutiny that space programs receive is designed to eliminate those risks that can be foreseen or anticipated.
- Indemnification: "Claims are paid for the actual loss sustained." Insurance not being a source of profit, claims reimburse the insured party for the actual financial loss sustained, e.g., the asset value, loss of income, or payments for liability to third parties.

2 Space Insurance

Space insurance provides coverage for satellite owners, operators, users, manufacturers, launch service providers, and other space operators during launch, initial operations, and on-orbit operations, through the life of a satellite or payload.

Table 1 Key elements of risk critical to the space insurance enterprise

Key elements of risk	
Definition	Risk is the intentional interaction with uncertainty
Risk management process has three stages	Identification → assessment → treatment
Treatment options	Avoidance, reduction, retention, and transfer (insurance)
Principles of insurance considers these three aspects	Pooling, fortuity, indemnification

In addition, ancillary coverage is available for pre-launch risks (e.g., assembly, integration, testing, transportation, pre-launch processing), end-of-life deorbiting and reentry, financial consequences (e.g., political risks and credit risks), and other risks. Space insurance includes virtually all technical risk from launch onward, and covers all risks, with few exclusions. The cost of space insurance is typically the third largest cost for a space program, after the satellite and the launch services.

The global insurance market generates about $4 trillion of premium each year – it is a major contributor to the financial economy. While space insurance has traditionally contributed only $400 million to $1 billion of annual premium into the insurance market (i.e., 0.01–0.025% of the global insurance premium), losses in space insurance are often dramatic and highly publicized. Thus, insurance company managements pay close attention to this low-frequency/high-severity corner of the market.

The first space insurance policy was written in 1965, to protect COMSAT, the US signatory to INTELSAT, from liability arising from their involvement in deployment of the earliest INTELSAT satellites. Since then, space insurance has expanded to become a tool that enables innovation and investment in space activity, as well as unlocking the economic potential and providing an economic safety net for the risks associated with space activity.

Unique challenges drive the cost and terms of space insurance:

- Rapidly evolving technologies, smaller satellites, new launch vehicles, satellite constellations, custom-built satellites, generic anomalies, and the space environment are key technical issues that differentiate space insurance from other lines of insurance.
- The small number of launches and satellites drive a large variance in annual results, while the low frequency and high severity of losses drive potential volatility of in those results. Furthermore, the large range of insured values – from a $50,000 CubeSat to an $800 million launch of two large satellites – drive capital requirements that generate stiff competition among the insurance companies engaged in space insurance.
- The short "tail" (i.e., if a launch fails, it will occur in the first minutes or hours of when the insurance attaches), high cash flow (i.e., premium for a launch is paid prior to the launch), and uncorrelated risks (losses in space insurance do not overlap with losses in other lines of insurance) make space insurance attractive to insurance companies, increasing competition.

3 Insurance Coverages

Space insurance coverages for asset protection represent the vast majority of space insurance premium. Business interruption, liability, and ancillary coverages contribute less than 5% of the total annual premium. Nonetheless, as commercial human spaceflight emerges, insurance for this new market will grow quickly.

Coverage for asset protection is generally viewed as three separate phases – launch vehicle flight (from launch to separation of the satellite in orbit), initial

Table 2 Phases of space insurance coverage

Phase	Insurance coverage	Duration
Launch vehicle flight	Launch vehicle flight only: Covers launch vehicle flight phase, from	The launch flight only can be combined with post-separation into a launch plus one year policy
Post-separation (initial operations)	Post-separation: Covers initial operations phase (orbit raising, deployments, testing) and in-orbit	Post-separation can be covered in a Launch-Plus One Year Policy
In-orbit life	In-orbit: Covers in-orbit life for one year at a time. Renewed annually based on satellite health.	

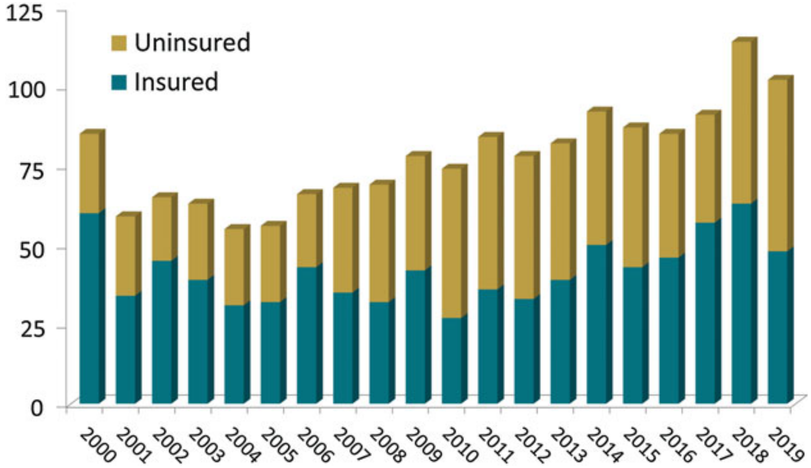


Fig. 1 Insured versus uninsured launch coverage since 2000. (Graphic courtesy of AXA-XL)

operations (post-separation activities such as orbit raising and testing), and in-orbit operations (ongoing mission operations through the life of the satellite) (see Table 2).

While policies can be written for any one or a combination of these periods, the most common policies are "launch plus one year" (i.e., launch vehicle flight, initial operations, and in-orbit operations through one year from launch) and "in-orbit" (i.e., covering mission operations on an annual basis, renewed each year based on health review from the end of the launch plus one year policy).

Coverage is typically procured by the satellite owner/operator, though any party with a financial interest can protect their exposure with insurance. The pattern of coverage or "self-insurance" has varied over time since the practice of launch insurance started in 1965. Figure 1 shows the variation in the market since 2000 (see Fig. 1). Many government launches are uninsured.

Some launch service providers may provide a "launch risk guarantee" (LRG) which will provide the satellite owner with a free relaunch or refund in the event of a launch vehicle failure that results in loss of the satellite. The LRG does not cover the value of the satellite, so the owner will need to buy “wrap-around” coverage for the satellite during launch vehicle flight.

Under satellite procurement contracts, some satellite owners will withhold a portion of the contract value to be earned by the manufacturer over the satellite’s life, based on successful performance. These contract “incentives” or “warranty payback” payments can, likewise, be insured by the satellite manufacturer.

Some insurance policies, such as homeowners insurance, cover only specific “named perils,” such as fire, windstorm, burglary, etc. Space insurance policies, as well as some other commercial lines of insurance, are written as “all-risks” policies – any loss is covered, no matter what the cause, unless it is explicitly excluded. Space insurance policies typically exclude war and terrorism, as well as several other intentional acts. Any cause that is not excluded is covered, whether design, workmanship, environmental (e.g., solar activity, micrometeoroids, space debris), or other causes.

4 Underwriting Process

The process of underwriting space risks involves understanding and analyzing complex technologies and long-term business plans. As such, insurance companies constantly track the space industry to review and anticipate developments in applications and markets. When a new program is ready to be insured, the client (e.g., the satellite owner/operator) will contract with an insurance broker to act as their agent in approaching the insurance market (the 30–35 insurance companies around the world who have the appetite to write space insurance). The broker’s role includes shepherding the client through the process of briefing the insurance market, designing the insurance coverage to ensure it is tailored to the specific technical and business needs of the client, negotiating the policy wording and pricing with the market, and, in the event of a loss, helping ensure that the claim is settled in a timely manner.

The underwriter assesses the risk, negotiates the terms and conditions of the insurance policy, and determines the appropriate premium to charge for the risk provided. The process can be quick or extended. An in-orbit renewal on a healthy satellite can be done in 1 day, while a complex launch insurance program on a constellation may take up to a year to finalize.

Underwriting criteria are the basis of the coverage design and risk analysis and include:

- Design: mission requirements, concept of operations (CONOPS), mission timeline, operating environment, system architecture, subsystem design, redundancy, margins, budgets, new technologies, unit-level qualification status and flight heritage, assembly, integration, and test flow
- Experience: operator experience, manufacturer experience, launch provider experience, anomaly resolution (ground and flight, investigation process, anomaly attribution, root cause, corrective action, cross-program issues)

- Contracts: spacecraft purchase agreement, launch services agreement, performance specifications, interface control document (ICD), qualification and test plan
- Commercial: business plan, contractual obligations, exposure analysis, asset valuation, loss calculation, insurance policy terms and conditions
- Pricing: statistical analysis, historical failure rates, quantification of potential loss scenarios, loss frequency vs. severity, insurance market conditions

5 Market Dynamics

Launch activity has increased dramatically in the past 15 years, from a low of 55 launches to orbit in 2004 to 114 launches in 2018. Likewise, the number of satellites launched has increased from 77 in 2004 to 520 in 2019. This increase is directly tied to the commercialization and globalization of space activity and has created both opportunities and threats to the space insurance market.

In 2018, 60% of launches carried some insurance, up from 36% in 2010. From 2014 through 2018, over 800 satellites were insured during launch, more than in the two decades prior to that, combined. 85% of the satellites insured during launch between 2014 and 2018 were small satellites. Only 120 were large GEO communications satellites that have traditionally generated most of the premium in space insurance. The smaller satellites generally carry low amounts of insurance. Even when 100 or more of these small satellites are carried on a single launch, the total amount of insurance on the launch is still well below the insured value of a launch carrying one or two large GEO satellites.

The relative insurance coverage of GEO satellites and LEO SmallSats is shown in Fig. 2. Clearly launch insurance coverage for GEO continues to outweigh that of LEO satellites, but coverage for LEO systems represents the area of largest growth, while coverage for GEO systems is now relatively stable (see Fig. 2).

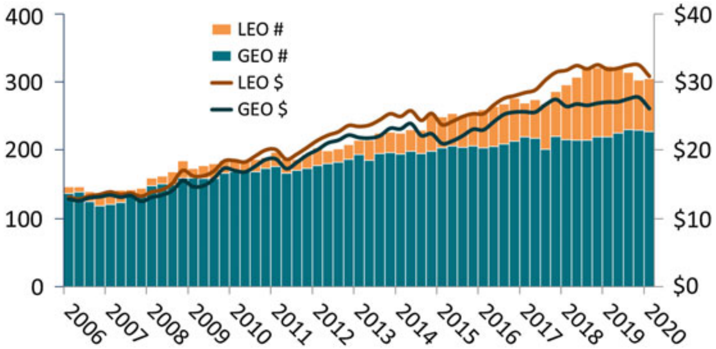


Fig. 2 The relative space insurance coverage for GEO and LEO satellite systems globally. (Graphic courtesy of AXA-XL)

Clearly the type of satellites in terms of their orbits, size, and value are changing rapidly in the global marketplace. These changes in the numbers and types of satellites being launched are in turn changing the nature and coverage profile of the global launch insurance market (see Fig. 3).

Insurance companies allocate their capital to space insurance based on the maximum amount that could be lost in any one accident. This would typically be on any one launch or on any one satellite in orbit. To accommodate the insurance needs of a large GEO launch which may carry two or more large satellites, the insurance market has provided up to $800 million of capacity to cover the value of the satellite(s) and launch. Capital is allocated by insurance companies with the expectation that it will generate premiums sufficient to cover the losses expected to occur in a year.

As the price of insurance is directly correlated with the available market capital, the excess of capital for smaller risks had pushed insurance premiums to their lowest levels in history by mid-2019. This is simple supply and demand – as long as market capital (along with its requirements for a return on investment) remained high, insurance pricing stayed low. With the significant insurance claims in space activity in 2019, some insurance companies curtailed their space insurance lines of business, either withdrawing completely, imposing severe restrictions, or decreasing their capital allocation. As a result, the $800 million of capital available to insure the largest risks has been reduced to around $650 million, and the number of insurance companies who offer space insurance coverage has decreased from 40–45 to 30–35.

Meanwhile, the increasing number of low-value launches and satellites means that the insurance companies in the space insurance market are competing for every risk, whether large (e.g., the $800 million launch) or small (e.g., a single $50,000 CubeSat). An individual insurance company rarely provides more than $50 million

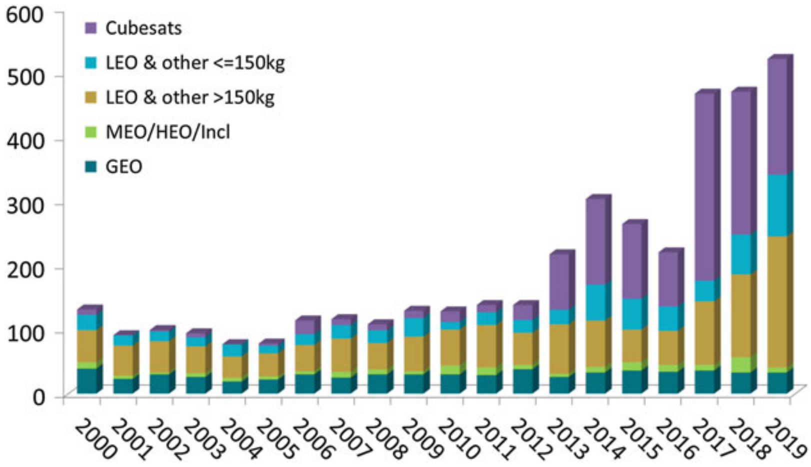


Fig. 3 Changes in the types of satellites being launch by orbit and size shown from 2000 to 2019. (Graphic courtesy of AXA-XL)

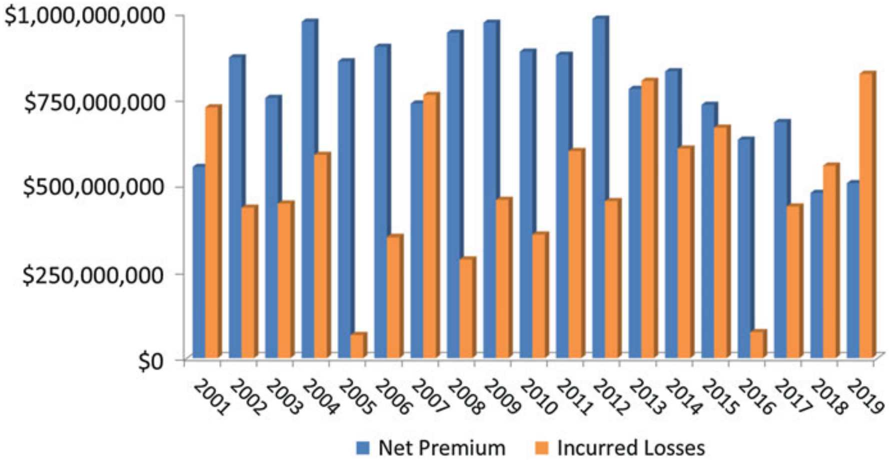


Fig. 4 Market annual premiums and claims. (Graphic courtesy of AXA-XL)

to $75 million per risk (e.g., per satellite or per launch), and some provide only $1 million per risk. As a result, a large insurance placement will be provided by a number of insurance companies. A specialized insurance broker, as an agent of the client (e.g., satellite owner), will work with the whole space insurance market to get the required capacity for a risk, whether large or small.

In 2018 and 2019, six major insured losses, as well as eight smaller losses, accounted for over $1.38 billion in space insurance claims. This level of claims was offset by only $980 million in premium, for a loss ratio (claims/premium) of over 140%. Insurance companies generally require a loss ratio on volatile lines of business of 50% to 70%. This "insurance cycle," where a soft market hardened, last occurred in the early 2000s, following a number of large space insurance losses as well as the insurance losses following the terror attacks of 9–11. Figure 3 shows the worldwide trend of net premiums paid versus incurred losses. The worldwide claims for 2019 represent the first time since 2001 where claims were very substantially larger than the incoming premium payments (see Fig. 4) (Williams and Walsh 2016).

6 New Technologies

Space insurers track space activity such as launch vehicle and satellite successes and failures. New technologies, such as the introduction of new launch vehicles and new satellite technologies, present challenges for insurers. Newly developed launch vehicles have historically experienced failure 25% of the time on their first launches and the same failure rate on their second launches. The learning curve typically

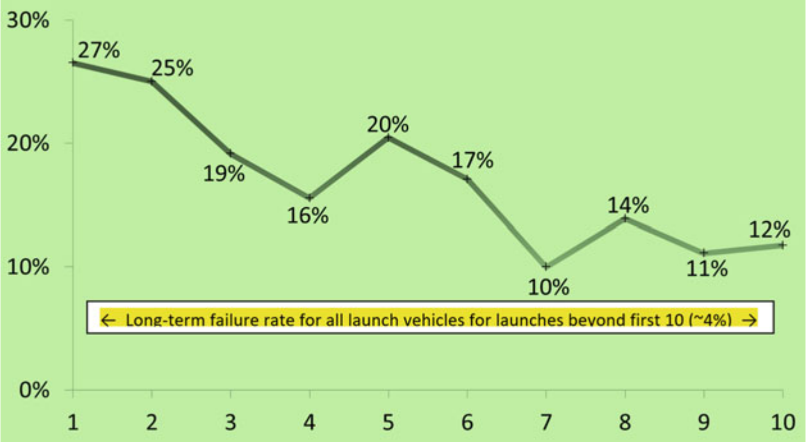


Fig. 5 Launch vehicle failure rates for first ten launches of a new launch vehicle. (Graphic courtesy of AXA-XL)

develops to a baseline failure rate after 6 to 12 launches, with the long-term cumulative launch failure rate being around 4–5% (see Fig. 5).

Likewise, new satellite technologies present challenges. Since 2000, the average mass of geostationary (GEO) communications satellites has increased by 33%, while the average payload power has increased by 100%. This increase in "energy density" of satellites is brought about by miniaturization of components and process improvements in manufacturing. Nonetheless, this increase in energy density has resulted in more satellite anomalies occurring within the electrical power system. Fully half of the anomalies on GEO satellites that resulted in loss of capability have come from the electrical power system. The cause of failure in satellites based on statistics for GEO satellites since the year 2000 can be broken down among various failure modes as follows: (a) batteries and electrical systems, 55% (these include battery cell failures, electrical harnesses, circuitry, mechanical aspects of electrical systems such as switches, etc.); (b) chemical and electrical propulsion systems, 18%; (c) other bus component failures, 16%; and (d) failure of payloads, 11%. This indicates that 89% of the failures relate to the spacecraft bus and only 11% are due to the payload and its instruments and functional units (AXA-XL, Causes of Losses, Feb 9, 2020).

With the growth of commercial satellite constellations and production-line manufacturing of satellites, the phenomenon of "generic anomalies" has arisen. Generic (or systemic) anomalies occur when a fault (either design, workmanship, or piece part) is introduced into a number of satellites, but not discovered until those satellites have been launched. In such a case, numerous similar on-orbit failures may be encountered, resulting in large space insurance claims. To avoid this, satellite operators will typically launch a small number of satellites to test them before deploying the full constellation.

7 Space Sustainability

Space insurance companies have taken active roles in promoting space sustainability and responsible space activity. Insurers have incentivized operators, manufacturers, launch service providers, governments, and institutions to implement technologies, processes, and operations that minimize risk to the space environment. Such "best practices" include improving Space Situational Awareness (SSA), introducing space traffic management (STM), and supporting on-orbit servicing (OOS). Specific types of OOS that can benefit space insurers include on-orbit inspection, repair, and refueling. As an example, over 80 GEO satellites launched since 2000 that have had significant anomalies would have benefitted directly from OOS, whether re-orbiting/deorbiting, inspection, repair, or life extension. This is in addition to a number of satellites that reached the end of their operational life and were unable to be satisfactorily re-orbited out of the heavily trafficked GEO belt.

Over 50 organizations (e.g., industry groups, advocacy organizations, governments, institutions, and satellite and launch operators) are working to develop efforts in responsible space activity. While not all efforts are coordinated, and some have opposing agendas, the development of guidelines, standards, regulations, and even rating systems will pressure all space actors to design and operate with sustainability as a core principle.

Specific technologies that can aid in Space Situational Awareness (SSA) include beacons for tracking, propulsion for orbital maneuvering, and even cameras for self-inspection. All of these technologies reduce the risk of collision and debris generation in space.

8 Conclusion

Space insurance is an enabler of innovation and investment. Financing of space activity requires large capital investments, and investors rely on insurance to protect them from catastrophic losses. Space insurance companies have adapted to the changing technical, commercial, and policy environments to continuously develop new types of insurance coverages and to lead efforts to maintain a healthy and sustainable space environment.

9 Cross-References

- ▶ Precision Agriculture and Forestry: Bytes for Bites
- ▶ Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently
- ▶ Small Satellites and Governmental Role in Development of New Technology, Services, and Markets
- ▶ Small Satellites and New Global Opportunities in Education and Health Care
- ▶ Small Satellites and Planetary Defense Initiatives

▶ Small Satellites, Law Enforcement, and Combating Crime Against Humanity
▶ Smallsats, Hosted Payload, Aircraft Safety, and ADS-B Navigation Services

References

AXA-XL statistics, Causes of Losses, GEO Satellites Launched since 2000, Feb 9, 2020

R. Williams, K. Walsh. Covering the increased liability of the new launch markets. Paper presented at the 32nd space symposium, technical track, Colorado Springs, Colorado, 11–12 April 2016

Small Satellites and Planetary Defense Initiatives

Joseph N. Pelton

Contents

Abstract

The issue of cosmic hazards and planetary defense is often associated with coping with asteroids impacting Earth and missions going into space to set off nuclear weapons in a last ditch effort to save the world as popularized in movies. There are many initiatives that can be undertaken to address cosmic hazards such as asteroids, coronal mass ejections from the Sun, and other similar threats. Many of these threats might well be addressed through small satellite initiatives. This chapter seeks to identify several types of cosmic hazards and small satellite-related initiatives that might be able to address such threats to people and global infrastructure that might be addressed via small satellite programs. This includes some projects that have already been tested in space as well as possible initiatives that are still being considered at a conceptual or design engineering level. The main thrust of this chapter is to highlight ways in which small satellite activities might be able to provide useful protective capabilities for planet Earth if these activities can be initiated at an early stage and various types of threats detected

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_101

sufficiently in advance so as to allow the use of small-scale and much less expensive space missions.

Keywords

Cubesat · Coronal mass ejections · Cosmic hazards · Global risk scale · Electromagnetic pulse (EMP) · Infrared space telescopes · International Asteroid Warning Network (IAWN) · “Laser Bees” · Minor Planet Center · Near Earth Objects (NEOs) · Palermo Threat Scale · Risk assessment · Potentially hazardous asteroids (PHAs) · Small satellites · Solar flares · Solar storms · Solar wind · Space Missions Planning Advisory Group (SMPAG) · Space Security Index · Space weather · Vital infrastructure

1 Introduction

The space age has unlocked a great deal of new scientific information about the characteristics of the Earth, the solar system, and nature of the cosmos. There is today a much greater understanding of the Earth’s vulnerabilities from potentially hazardous asteroids and comets as well as the dangers from space weather and solar eruptions. As the number of humans has increased, as urban centers have expanded so that nearly 55% of the world’s population now live in cities, and as humans are more dependent on modern infrastructure, vulnerabilities have expanded exponentially. Two of the greatest dangers come from potentially hazardous asteroids and comets and from solar eruptions, known as coronal mass ejections.

Geologists have now declared that humans now live in a new geological age known as the Anthropocene Age. The prime shaper of the world’s geology is human activity. The lesser known fact is that urbanization, modern human lifestyles and employment, and dependence on key infrastructure have made humans much more vulnerable to natural disasters – prime of these vulnerabilities are pandemics, infrastructure failures, and natural and human-caused disasters. Among these disasters that could give rise to mass-destruction events are very large cosmic objects impacting Earth (i.e., potentially hazardous asteroids and comets) and solar events called coronal mass ejections. This chapter addresses these two cosmic hazards in some details and address ways that small satellite technology might be deployed to help avoid truly devastating loses from cosmic hazards. In short this chapter addresses how new types of small satellite missions could represent a viable means of addressing a new strategy of planetary defense.

2 Asteroid Threat Assessment

A precise threat assessment of the likelihood of a major asteroid hitting Earth is not an exact science. We know that there are a significant number of asteroids that are known as Near Earth Objects (NEOs). The following chart represents a current

Table 1 Estimated threat levels for different sizes of asteroids

Ground impact	Probability/year	Diameter	Blast radius	Deaths	Ground damage	Interval within lunar orbit (i.e., within 400,000 km)
5 megaton asteroid impact	$1.67E^{-03}$	44 m	About 20 km	About 200	About 1200 km^2	1/20 years
100 megaton asteroid impact	$1.00E^{-04}$	120 m	About 60 km	About 19,500	About 10,000 km^2	1/80 years
1000 gigaton asteroid impact	$2.00E^{-06}$	3 km	About 500 km	Unknown	About 800,000 km^2	1/600 years

Note: The above estimates as to likelihood of occurrence of various sizes of asteroid strikes should only be considered rough order of magnitude figures. The actual results would be expected to vary significantly depending on actual point of contact and many other factors such as proximity to inhabited areas, air-burst or land or water impact, etc.

projection of various sizes of Near Earth Objects in terms of their mass, their probability of impacting Earth, their blast radius and ground damage area, and possible fatalities (see Table 1) (Pelton, Space Security 2019).

This is all based on known probabilities and the latest data. The results are acquired data from sensors located on the NAVSTAR satellites that constitute the Global Positioning Satellite (GPS) system and other U.S. governmental satellites. These sensors are placed on these satellites in order to detect nuclear explosions, but they can also detect asteroid and larger bolide impacts. The data from these sensors have documented the fact that impacts are at least three times – and perhaps as much as ten times – more common than previous thought. This assessment of greater likelihood was provided by former Astronaut Ed Lu, Head of the B612 Foundation that has as its main mission the detection of and assessment of threat levels associated with asteroid strikes on Earth (Blast Sensors, April 4, 2014).

Another way of assessing asteroid threat is based on the energy released from actual impacts and the creation of a graphic that connects the data collected from the aftermath of actual events. Figure 1 shows the estimated energy release from three different strikes. These range from the smallest in the form of the Chelyabinsk strike in 2013, up to the much more devastating Tunguska impact in 1908 in the early days of the twentieth century, and finally to the so-called Chicxulub catastrophic event that occurred over 75 million years ago along the coast of Mexico that wiped out the dinosaurs and led to the K-T mass extinction. This chart shows that the Chelyabinsk event released the equivalent of 75,000 tons of TNT. The Tunguska event which involved the equivalent of a 40 m asteroid involved an event equivalent to an 8 megaton atomic bomb. Finally the true mass extinction event has been calculated

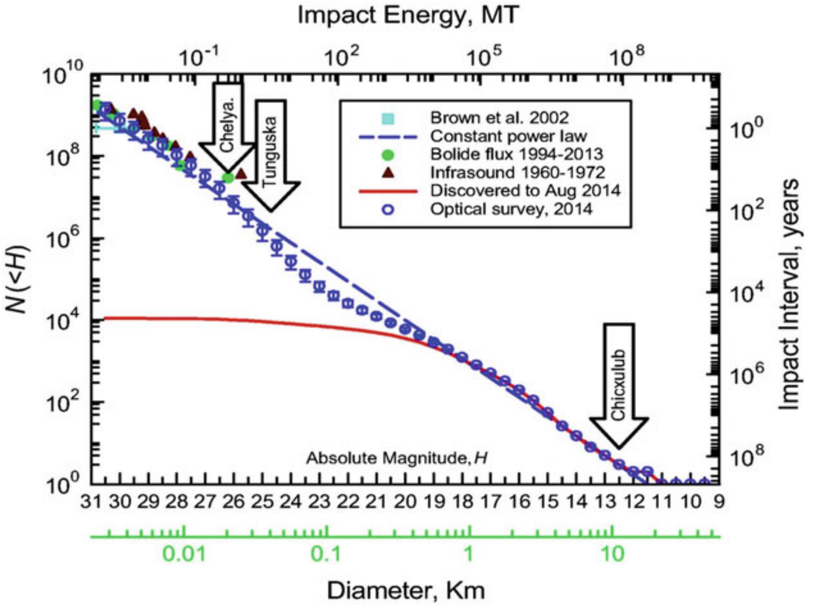


Fig. 1 The estimate energy release from various meteor and asteroid strikes on Earth. (Graphic courtesy of Jet Propulsion Labs/NASA)

to have involved an energy release equivalent to a 100 million megaton nuclear weapon (see Fig. 1). The problem with the current process of seeking to identify potentially hazardous asteroids as undertaken by NASA is that the official practice is to chart all such objects that are 140 m and larger in diameter. Yet the Tunguska event that released the equivalent of an 8 megaton atomic weapon destroyed the area equivalent to the San Francisco Bay Area.

This means that Tunguska-sized bolides are true city-killers but that the NASA search process is only looking for asteroids that could wipe out an area equivalent of the State of New York. The B612 Foundation has called for the development of infrared space telescope that could track Near Earth Objects (NEOs) and particularly potentially hazardous asteroids (PHAs) down to a size of 35 m. Estimates are that there are more asteroids of this size than the metric of estimated asteroids that are 140 m in diameter. Indeed there are estimated to be at least an order of magnitude more of potentially hazardous asteroids that are of the 35 m size compared to those over 140 m (Pelton, Introduction to the Handbook 2015).

The inventory of Near Earth Objects (NEOs) as conducted by NASA has now identified some 10,000 asteroids that are registered with the Minor Planet Center and the International Asteroid Warning Network (IAWN). The United Nations Committee on the Peaceful Uses of Outer Space and the General Assembly have increasingly recognized the significance of a major asteroid or comet hit on a world with ever-increasing human population and increasing urbanization. They approved the creation of the global initiative to create an

International Asteroid Warning Network (IAWN) and perhaps even more importantly the creation of a Space Missions Planning Advisory Group (SMPAG). These units, although endorsed by the United Nations General Assembly, are composed of independent scientific personnel. The SMPAG would recommend a global response in the event that a major potential strike by an asteroid or comet on planet Earth were identified as a major threat (Near Earth Objects Status, Feb. 2017).

The discussions of options that might be used against incoming potentially hazardous asteroids or comets have typically focused on what can be done to avert a catastrophe in the context of a short-term threat. These options involve the use of massive amounts of information that might be associated with a nuclear blast detonated on the incoming object in space, the use of very high level directed energy beams that are considered space weaponry, projectiles launched by a rail gun system, engineering a collision between the PHA and an asteroid placed in lunar orbit as a defensive system, or other techniques involving a great surge of energy. Clearly if incoming asteroids of great size were to be discovered just before impact is to occur, only a very high energy diversion would be necessary. Something as large as a 5-km-diameter asteroid that caused the K-T mass extinction would be very hard to divert indeed without many months if not years of warning (see Fig. 2).

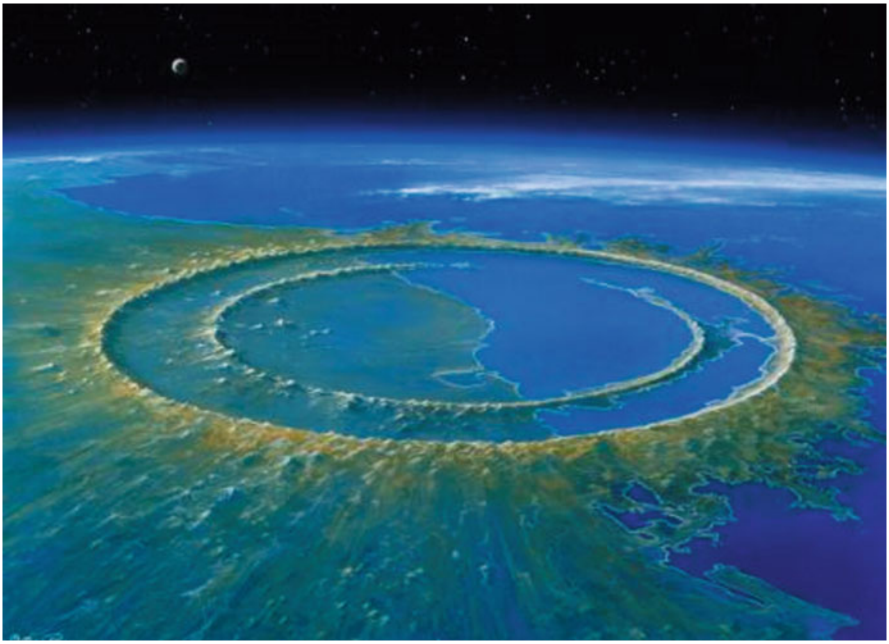


Fig. 2 Crater from the Chicxulub asteroid that was estimated to be 5 km in diameter. (Graphic courtesy of NASA)

3 Small Satellites and the "Laser Bees" Approach to Diverting Asteroid Orbits

There are ongoing efforts to create new capabilities to track potentially hazardous asteroids with greater precision so that dangerous NEOs could be identified years in advance so that missions to divert these objects to new, much less dangerous orbits might well advance. The trick is to accomplish the diversion with only minor energy thrust or velocity deltas sustained over a long period of time. The B612 Foundation has been dedicated to create new infrared space telescope to detect much smaller potentially hazardous asteroids (PHAs) and a much greater inventory of these dangerous Near Earth Objects (NEOs), but unfortunately has not obtained the funding to do so.

The Planetary Society has on the other hand pursued new concepts and design constructs that could create small orbital diversions to avert asteroids hitting Earth if there are years of advance warning. This project started out on the basis of what was called "mirror bees." The idea was to create a series of small satellites with mirrors on them to flex sunlight that would heat the asteroid and help to divert its path. After conceptual evaluation, the new idea was developed to replace mirrors with lasers that could heat the asteroid sufficiently to create small jets of materials ejected from the asteroid to create thrust that could divert the asteroid's orbit over time.

This newly dubbed "Laser Bees" project that would deploy a swarm of small satellites has been described in the following manner:

> "This technique involves many small spacecraft – each carrying a laser – swarming around a near-Earth asteroid. The spacecraft could precisely focus their powerful lasers pumped by sunlight onto a tiny spot on the asteroid, vaporizing the rock and metal, and creating a jet plume of super-heated gases and debris. The asteroid would become the fuel for its own rocket – and slowly, the asteroid would move into a new trajectory." (What is a 'Laser Bee'? 2019)

This idea when compared to that of using a nuclear weapon to blow an asteroid apart and into a new orbit has the advantage of involving a much lower cost since the rocket carrying the nuclear weapons would be much larger, particularly if manned by astronauts to place and activate the nuclear explosion. From a safety viewpoint, the new orbit would be controlled and would not create the risk that parts of the asteroid blown apart might still hit Earth. Finally agreement on the deployment of a swarm of "Laser Bees" would be much less controversial and would not be considered a "space weapon," or launching a nuclear weapon into space (Bruce Betts, What are Laser Bee Projects 2013; Fig. 3).

There was an intended NASA Asteroid Redirect Mission planned for 2025 that was canceled by the President Trump Administration in late 2017. The intent of this mission was to develop a robotic spacecraft with a large robotic arm. This mission, known as Asteroid Redirect Mission (ARM), was canceled by means of White House Space Policy Directive-1 on Dec. 11, 2017, that refocused efforts on sending crewed missions to the Moon and then to Mars. The key elements of this mission would have been to visit a large Near Earth Asteroid, not yet identified, with the purpose to collect a multi-ton boulder from its surface by means of a robotic arm. It

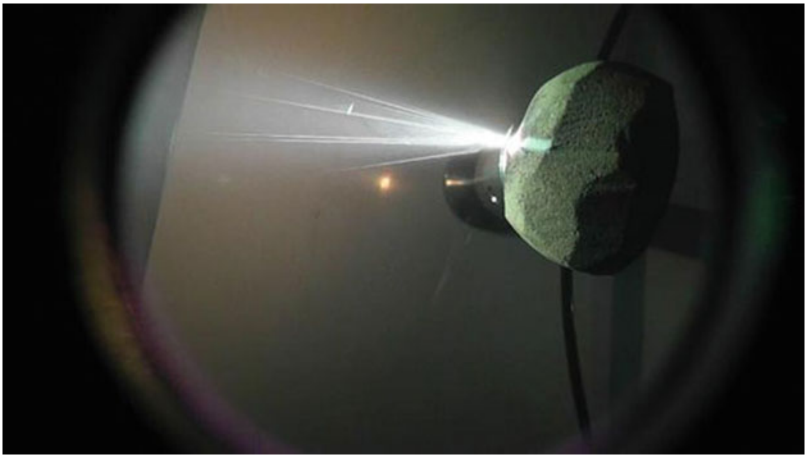


Fig. 3 A laser ablating a sandstone rock in a lab in Scotland to create a jet stream. (Graphic courtesy of the Planetary Society)

was also intended to test the concept of solar-electric propulsion (Asteroid Redirect Mission 2019).

The most sensational aspect of the mission would have been to redirect the boulder into a stable orbit around the moon, known as a distant retrograde orbit, where astronauts could have explored it and also returned to Earth with samples. Elements of this mission still remain under study. Any mission of this kind, if re-established, would also include an experiment with perhaps five or six cubesat size satellites equipped as “Laser Bees” that would be able to experiment with redirecting the asteroid at the mission’s end (NASA’s Asteroid Redirect Mission Cancelled Dec. 11, 2017).

The laboratory tests that have been carried out in Scotland under funding from the Planetary Society of “Laser Bees” as an approach to the redirection of asteroids have produced encouraging results that this approach, given enough advanced warning, could be nearly as effective as high-powered nuclear energy release. This is due to three reasons: (i) the laser-heated materials from the asteroid are providing the propulsive fuel rather the need to bring fuel along with the mission; (ii) the asteroid’s mass lessens over time and thus accelerates more rapidly; and (iii) the power for the lasers is to be supplied by solar energy that was not provided on board the small satellite itself. Thus Newtonian physics, itself, supplies three sources of mission efficiency, and over a year’s time this could significantly alter an asteroid’s orbital parameters. Thus it is hoped that any renewed asteroid redirect mission would include “Laser Bee” experiments at 1% to 2% add-on to the total mass of the overall project. Again it may turn out that small satellite technology with something like 3 unit to 6 unit cubesatellites might provide a powerful longer-term means to redirect a potentially hazardous asteroid.

There is, as is almost always the case, more than just new technology development involved here. There is also a matter of space policy and regulation. The idea that one might just reposition and asteroid’s orbit, or perhaps even place a repositioned asteroid or a boulder snipped off of an asteroid into a “distant retrograde orbit” around the Moon, is a matter of unsettled international law. There are elements of space law that address staking a claim of sovereignty over celestial objects, but there is no established space law about who might have the right to move celestial objects about in their orbit or place them in new orbits around the Earth or Moon. Again this is new territory that envisions new technological capabilities that were not anticipated when the Outer Space Treaty and its subsidiary international agreements were negotiated and agreed. It would seem that the Space Mission Planning Advisory Group (SMPAG) might at least be consulted about any such asteroid redirect mission and their expert advice be sought before such missions are contemplated and executed (Space Mission Planning... 2019).

For the longer term some form of national and international guidelines or perhaps even a treaty agreement should be developed in this area. Perhaps this might be done in conjunction with agreements worked out for space operations and rendezvous and proximity operations.

4 Small Satellites and Protection of Earth and Mars Against Coronal Mass Ejections (CMEs)

The other key areas where small satellites might play a key role in protecting Earth against a major space hazard might well be in the area of dangerous solar storm events. This would be, in particular, in the case of a catastrophic coronal mass ejection that has a devastating impact on vital global infrastructure on which billions of people depend. Fortunately Earth has an iron core and a natural protective shielding in the form of a geo-electromagnetic field that surrounds this small six sextillion ton planet. Mars, for instance, is not so fortunate. Mars’ lack of an electromagnetic shield is why it has such a minimal atmosphere. The solar wind and coronal mass ejections are stripping away its atmosphere relentlessly year after year.

There are a number of different types of solar occurrences that impact life on Earth. First of all the Earth is totally dependent on the Sun for energy. The Sun is the basis of all energy used in our world today. Oil, natural gas, trees and vegetation, wind, and any other energy source that is used today are all merely stored energy that initially came from the Sun. Without the Sun Earth and all life forms would die. Fortunately the Sun provides more energy than human’s use by a huge margin and will do so for eons to come. But not all solar energy is beneficial. Solar flares of radiation in the ultraviolet range, X-rays, and above can be dangerous. Without the Earth’s ozone layer, there would be much greater problems with cancer and genetic mutation.

About half the time where solar flares of radiation occur, there is another phenomenon known as coronal mass ejections (CMEs) that involve the spewing of many quadrillions of ions out into space. This is actual mass that travels at millions of kilometers/hour. The magnitude of the mass ejections varies greatly in terms of the

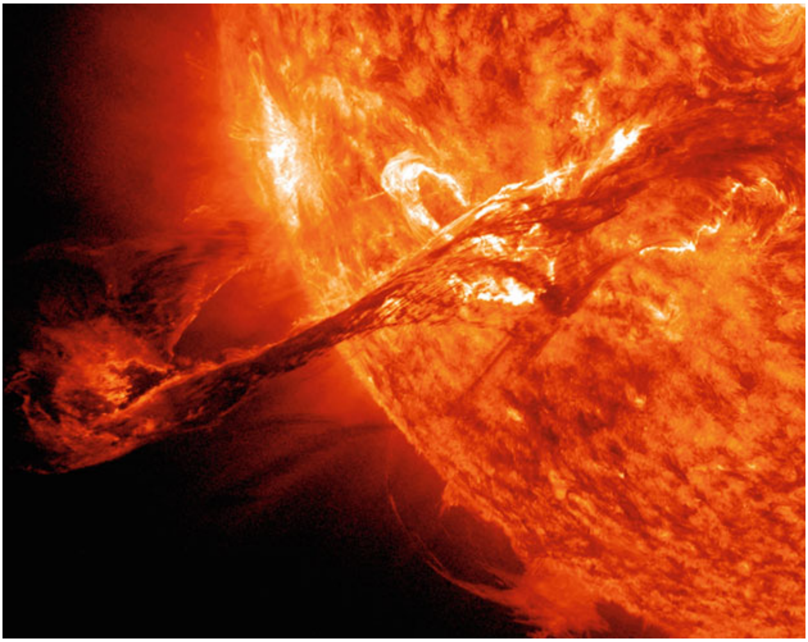


Fig. 4 Massive solar coronal mass ejection event of 2012 narrowly missed Earth. (Graphic courtesy of NASA)

number of ions released and their velocity that determines their destructive force. Fortunately most of these ejections miss Earth and thus go harmlessly into outer space. The ion ejection captured on a NASA solar observation satellite was hundreds of thousands of meters long (see Fig. 4). This ejection occurred in 2013; however, it narrowly missed Earth, and thus its very deadly stream of particles was not able to burn up transformers in electrical grids, SCADA controls on pipelines, disable telecommunications networks, perhaps destroy satellites, and bring the synchronization of the Internet to a halt (see Fig. 4).

The biggest of these solar events seems to occur about once in a hundred and fifty years. The so-called Carrington Event of 1859 occurred at the very start of the electrical age. When this massive CME event occurred, telegraph offices caught on fire as paper ignited. The so-called Northern lights came down to Cuba and Hawaii and lit up the skies. There are Chinese records of a similar solar event that occurred very early in the eighteenth century. In the eighteenth and nineteenth centuries, this type of event had little lasting impact on society. But today electrical grids, the Internet, vital communications networks, and vital satellites might be lost. The residual or collateral results could be trillions of dollars of economic losses, and a huge number of people might lose their jobs, starve to death, or otherwise suffer from such an event today. One study carried out by Lloyds of London has projected a loss of over 2 trillion dollars associated with the loss of the North American electrical grid with a hit similar to the Carrington Event (Solar Storm 2013).

And these events actually occur rather frequently at a lower level. The Montreal event of 1989 took out much of the power grid from Chicago to Montreal when this CME event occurred. The Halloween event in Scandinavia early in the twenty-first century knocked out power in a wide region as well. The Sun goes through an 11 year cycle from solar minimum to solar max. During the period of solar max, there can be as many as 15 coronal mass ejections in a week. The growing concern is that Earth, based on probabilities, is overdue for a Carrington Event-type hit by a very high-powered CME.

And there is now a serious further concern. This is that the Earth's magnetic poles are shifting from North to South. At this point it seems that magnetic North has moved down to Siberia, while magnetic South has moved up toward Australia. As the magnetic shift occurs as it has happened many dozens of times throughout Earth's history, the magnetic field that is manifested in the Van Allen belts will begin to break up in very odd ways. Some computer modeling has suggested that the protective shielding of the Earth's electromagnetic field will lose much of its effectiveness. One model that is shown in Fig. 5 suggests that the effectiveness of the natural shielding will be reduced down to only 15% of its current levels. This is to say that its protective shielding might be some seven times less than it is today (see Fig. 5).

The loss of vital infrastructure such as electrical grids, transformers, telecommunications networks, SCADA controls for traffic signals, pipelines for natural gas, petroleum, water and sewage, satellites, and more could be devastating to the global economy, and the collateral loss of life could mount into millions. It could be that the most vital space infrastructure of all time might well be the design and

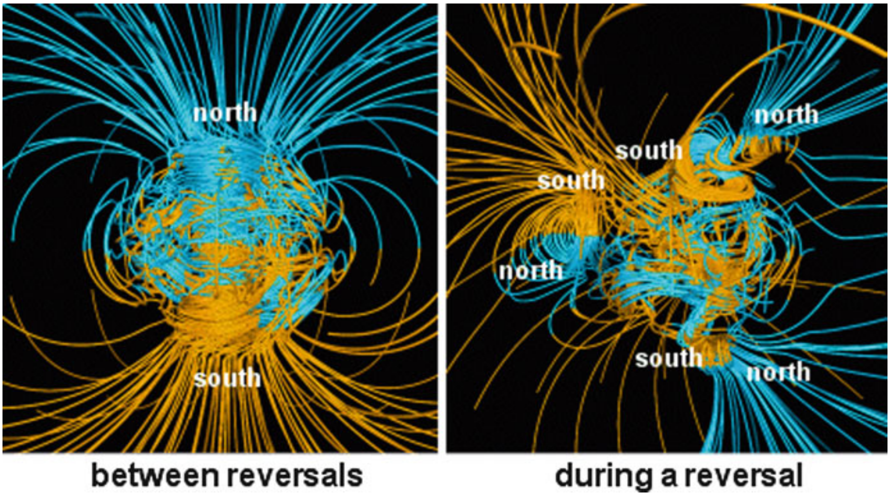


Fig. 5 The projected impact on the Earth's electromagnetic field shielding that will occur during magnetic polar shift. (Graphic courtesy of Global Commons)

implementation of satellites to form an artificial electromagnetic shield to protect Earth against a massive coronal mass ejection.

To date none of the world's space agencies have accepted the strategic mandate of making planetary defense a top priority. Today many space agencies are involved in relevant areas of research. These activities include seeking to create an inventory of Near Earth Objects and especially potentially hazardous asteroids, to examine technologies that could redirect asteroids, and to better understand solar flares, coronal mass ejections, and the Earth's electromagnetic shielding. Nevertheless they have not actively set planetary defense as a top strategic priority. They have not created units that might actively design and deploy systems that might protect Earth against asteroids or an extremely powerful coronal mass ejection.

The time has come to recognize that planetary defense is both technically possible and should be actively undertaken as a top priority for space agencies cooperating together. There have been some initial thoughts about how this might be done. Some of the first thoughts have focused on the creation of a very large shield system that would be deployed at Lagrangian Point 1. This is the point where the gravitation fields of the Sun and the Earth essentially are equal, and thus a satellite could be positioned there with very little stabilization force. This location and the gravitational effects that cancel one another out are shown in Fig. 6.

The problem that has arisen has been that of a "tailing" effect where the blast of ions is initially stopped but that the ions would then swirl around the field and then continue to hit Earth with great force.

The alternative idea of not creating a single electromagnetic field to block the flow of ion thus arises. The alternative would be to create a matrix of smaller satellites with lower levels of magnetic field strength that would be more like a sieve. This would allow some of the ions to come through but others to be diverted so that they would miss Earth. This might be built in tiers so that if the first wave of ions were not stopped then the second layer might provide a slowing or diversion of

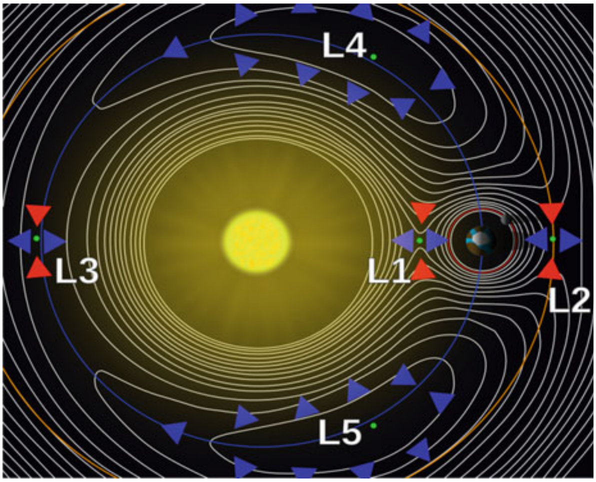


Fig. 6 The Lagrangian points of gravitational stabilization and location L1 for a CME shield. (Graphic courtesy of the global internet commons)

the ions. The key issue is whether a large matrix of small satellites could be designed with inflatable materials that could hold a charge as high as one Tesla that could be smaller in mass and lower in cost to provide an effective electromagnetic shield for Earth and deployed at a reasonable cost.

Another intriguing question is whether the existing electrical grid system operators of the world (both governmental and commercial) can be organized to contribute sufficient monies toward such an on-going protective shielding project. This would require sufficient monies to sustain the design, building, deployment, and on-going operation of such a matrix of small satellite units. Today no one knows clearly what design of such a protective matrix of small satellites would be needed to help to protect Earth from a future lethal torrent of CME ions that can be expected to come toward Earth with catastrophic effect in coming years.

The first step would be to seek to test the magnetic blocking capability against high speed ions provided by a single small satellite designed for this purpose. Or perhaps to test a cluster of three or four small satellites. A key question would be to test whether a distributed matrix of small satellites would be more effective and less costly than a single very large magnetic field satellite. A subsidiary question is whether such a matrix of small satellites could be also designed so as to modulate solar radiation so as to forestall climate change effects until greenhouse gas emissions might be greatly reduced or other longer-term solutions might be found.

One further aspect of an electromagnetic space shield has now occurred. This is the idea that such a shielding system could also be applied to Mars. Mars has no natural electromagnetic shielding because it has no iron core. As there is warming on Mars and frozen ice on the Red Planet released as water and water vapor, this too will be stripped away by the solar wind. If it were possible to create a solar shield for Earth, it would be much easier to contemplate doing it for Mars. Mars is much further away from the Sun and it is also much smaller than the Earth. Thus NASA chief scientist James Green has suggested that a solar shield for Mars could be much smaller in size with less electromagnetic field force (Green et al. 2017). This is just one of the ideas that have derived from the original concept of creating a solar shield and first designated by the author as a LAPSE (Lagrangian Protector against Solar Ejections) (Pelton and Green 2017).

5 Conclusion

The world of small satellites today is focused on such uses as education, training, technology verification, and practical space applications such as telecommunications, remote sensing, meteorological and climate change monitoring, space navigation, RF geolocation, real-time data relay, and other practical applications. Increasingly it has been recognized that small satellites can play a key role in scientific space investigations and deep space exploration. Small satellites have been used to measure changes in the Earth's electro-magnetosphere and to probe the Sun's characteristics and other deep space phenomena. This chapter suggests that small satellites could be used in efforts to divert threats from potentially hazardous asteroids through the use of so-called Laser Bees and might be used in a matrix of smallsats to create an artificial magnetic shield described by the author as Lagrangian Protector against Solar Ejections (LAPSE).

6 Cross-References

- ▶ Precision Agriculture and Forestry: Bytes for Bites
- ▶ Small Satellite Systems to Manage Global Resources, Energy Systems, Transportation, and Key Assets More Efficiently
- ▶ Small Satellites, Law Enforcement, and Combating Crime Against Humanity
- ▶ Small Satellites and Governmental Role in Development of New Technology, Services, and Markets
- ▶ Small Satellites and New Global Opportunities in Education and Health Care
- ▶ Small Satellites and Risk management, Insurance, and Liability Issues
- ▶ Smallsats, Hosted Payload, Aircraft Safety, and ADS-B Navigation Services

References

Asteroid Redirect Mission, NASA. https://www.nasa.gov/mission_pages/asteroids/initiative/index.html. Last accessed 21 Oct 2019

Blast Sensors Detect More Asteroid Strikes than Expected, NBC News, April 4, 2014. https://www.nbcnews.com/science/space/blast-sensors-detect-more-asteroid-strikes-expected-n72486

Bruce Betts, Laser Bee Projects, July 11, 2013. https://www.planetary.org/blogs/bruce-betts/20130711-laser-bees-papers.html

J.L. Green, J. Hollingsworth, D. Brain, V. Airapetian, A. Glocer, A. Pulkkinen, C. Doug, R. Bamford, A future Mars environment for science and exploration. in Planetary Science Vision 2050 Workshop 2017 (LPI Contribution N. 1989) (2017)

NASA Asteroid Redirect Mission Cancelled Dec. 11, 2017. https://www.nasa.gov/content/what-is-nasa-s-asteroid-redirect-mission. Last accessed 21 Oct 2019

Near-Earth Objects Status report by the International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG), A/AC.105/C.1/2017/CRP.25∗2 February 2017, Committee on the Peaceful Uses of Outer Space Scientific and Technical Subcommittee, Fifty-fourth session Vienna, 30 January-10 February∗Agenda item 11

J.N. Pelton, Introduction to the handbook of cosmic hazards and planetary Defense, in *Handbook of Cosmic Hazards and Planetary Defense*, ed. by J. N. Pelton, F. Allahdadi, (Springer Press, Cham, 2015), pp. 583–590

J. Pelton, Space security in the context of cosmic hazards and planetary defense, in *Handbook of Space Security*, (Elsevier, New York, 2019)

J.N. Pelton, J. Green, *“Saving Earth and Terraforming Mars” Science and Technology Track* (World Future Society, Washington, DC, 2017)

Solar Storm Risk to North American Electrical Grid, Lloyd’s and Atmospheric and Environmental Research 2013. https://www.aer.com/news-events/resource-library/solar-storm-risk-north-american-electric-grid/

Space Mission Planning Advisory Group. https://sdg.esa.int/activity/space-mission-planning-advisory-group-smpag-4311. Last accessed 21 Oct. 2019

What are Laser Bees, The Planetary Society. https://www.planetary.org/explore/projects/laser-bees/. Last accessed 20 Oct 2019

Part XI

Current Innovative Small Satellite Projects

Planet's Dove Satellite Constellation

Mike Safyan

Contents

Abstract

Planet Labs Inc. ("Planet") designs, builds, and operates the world's largest fleet of remote sensing satellites and sells the imagery data and derived products to a wide variety of government, commercial, academic, and nonprofit customers. Planet utilizes an Agile Aerospace approach to take advantage of improvements in commercial-off-the-shelf technologies, increased access to launch opportunities for small satellites, and readily scalable cloud-based IT infrastructure. This chapter describes the development of the Flock constellation, Planet's medium resolution fleet comprised of Dove satellites, and the surrounding infrastructure required to operate this innovative system.

M. Safyan (✉)
Planet Labs Inc., San Francisco, CA, USA
e-mail: mike@planet.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_64

Keywords

Planet · Cosmogia · Satellite · Cubesat · Smallsat · NewSpace · Remote sensing · Satellite imagery · GIS · Dove · Flock · Constellation · Earth Observation · Venture capital funding · Piggyback launch · Commercial-off-the-shelf

1 Introduction

In 2010, Planet Labs Inc. or “Planet” (known as “Cosmogia” at the time) was founded by former NASA scientists and engineers Chris Boshuizen, Robbie Schingler, and Will Marshall. The plan for the company was to build and operate a large fleet of small satellites capable of imaging the entire Earth’s landmass every day. Although space-based remote sensing systems had been flying for decades and a number of commercial satellite imagery companies were already in operation, nobody had previously attempted to build and deploy a large enough fleet to be able to achieve those levels of global coverage and timeliness of revisit. The co-founders took advantage of a handful of emerging technological trends while simultaneously identifying a commercial need in the market and available venture capital (VC) funding to finance the endeavor.

2 Planet’s Dove Satellite Constellation

2.1 Emerging Trends

At the time of Planet’s founding, several trends were emerging to create the perfect conditions for a new approach to satellite systems. The three major trends were (1) advances in commercial electronics, (2) the Cubesat standard and increased access to launch, and (3) cloud storage and computing.

Advances in the commercial electronics industry were making consumer electronics more and more powerful while continuing to shrink the size and power requirements of those devices. Even in 2010, smartphones already carried most of the systems needed for a satellite including a fast processor, large data storage, efficient batteries, a variety of attitude sensors, radios for communication, GPS, and a camera system. Planet’s founders had demonstrated as much while at NASA Ames with the “PhoneSat” project.

PhoneSat was a 1 kg satellite with an Android smartphone as the “brains” of the satellite. The PhoneSat satellites successfully demonstrated basic telemetry communication and transmission of low-resolution Earth imagery captured by the phone’s camera from space (Marshall et al. 2011). Although there were several challenges encountered in modifying a smartphone to behave as a satellite, the early PhoneSat missions were intended as proof of concepts. Commercial electronics, which in some cases were more advanced than their space-grade alternatives, could indeed be used in space within certain mission parameters. Going forward, it wasn’t necessary to use an actual smartphone on a satellite to take advantage of those benefits. Instead, a revolution was emerging from the act of utilizing the technologies, components, and fabrication techniques coming from the commercial electronics industry to custom-build satellites.

When the Cubesat became a commonly accepted satellite standard, it significantly lowered the barrier to entry for small satellite missions. At that time, most Cubesats were being built and operated by university teams and research institutes, but the principles of constraining a satellite design to fit within a standardized launch envelope equally applied to a commercial satellite. By conforming to the Cubesat specification, a standardized launch adapter and deployment system could be used, greatly simplifying the coordination requirements between satellite operators and launch providers. Standard Cubesat deployer systems also allowed for the number of Cubesats on a given launch to easily scale up or down depending on the launch capacity available. One Cubesat could be easily swapped for another within minimal impact to the launch provider. This helped enable a growing number of "piggyback" launch opportunities that easily allowed Cubesat customers to ride along on larger rockets going to Low Earth Orbit (LEO). And because Cubesats are so small, a large number of them could be launched either on a single rocket or across multiple rockets, but at a fraction of the total cost of a typical, large satellite mission.

And finally, the **growth of cloud computing and storage services** from companies like Amazon and Google revolutionized data management. Even small satellites are capable of generating massive amounts of data (think of how quickly a smartphone would run out of storage if it took a picture every second for 3 years). Storing and processing the data requires a significant amount of IT infrastructure. Cloud services eliminate the need for companies to build the infrastructure themselves and allow for that capacity to seamlessly scale at an efficient price point.

Taking into account the above trends, the co-founders wrote out a list of all the possible missions that could be enabled by this novel architecture – which is composed of many low-cost, small satellites that benefit from advancements in commercial electronics. The list was quickly narrowed to missions that had clear commercial value, and finally a remote sensing mission was identified as the optimum balance of feasibility, uniqueness of capability, and significant market potential.

2.2 The Remote Sensing Market

Satellite remote sensing systems can be categorized by a handful of key characteristics (Satellite Imaging Corporation 2017):

1. *Spatial Resolution*: The pixel size of the smallest feature able to be resolved in an image.
2. *Temporal Resolution*, or *Frequency of Revisit*: How often a satellite system can image a specific point on the Earth.

3. *Coverage*: How much of the Earth's surface is captured by the satellite system over a given duration.
4. *Spectral Bands*: The portion of the electromagnetic spectrum that the satellite system is remotely sensing.
5. *Spectral Resolution*: The number of spectral bands captured by the satellite system and the quality of spectral information being captured.
6. *Radiometric Resolution*: The amount of detail expressed in each pixel, also known as bit depth.

Two basic types of optical remote sensing satellites were flying at the time: (1) *high spatial resolution*, *low coverage* and (2) *low spatial resolution*, *high coverage*.

In the first category, commercial companies such as DigitalGlobe and Airbus were flying satellites with very high-resolution systems (<50 cm per pixel). Spatial resolution is directly related to the size of the satellite's telescope, and thus a high-resolution satellite is usually the size of a small school bus. These satellites might have a mass of several thousands of kilograms, which directly impacts the cost and complexity of the system. The size of the satellite also greatly impacts the launch cost, which roughly scales on a per kilogram basis. The result of such high-cost, complex systems is that a company can only afford to launch and operate at most a handful of very high-resolution satellites at any given time.

These very high-resolution satellites are operated in a "tasking" or "point and shoot" mode, and the Area of Interest (AOI) must be determined ahead of time. Using off-nadir imaging, a very high-resolution satellite system may be able to capture the same AOI multiple times within quick succession, but that comes at the expense of being unable to image other targets. A useful analogy is to think of these systems as if they were capturing imagery through a soda straw; certain locations will be imaged in great detail, but most of the Earth's surface will be missed. It can be said that such systems optimize for *spatial resolution* at the expense of *coverage* and *temporal resolution* (on a global scale).

In the second category, the joint NASA-USGS Landsat mission is considered. For example, Landsat 8 is operated in "monitoring" mode (as opposed to "tasking") with a very large Field of View (FOV), periodically sweeping its imager across the entire Earth's surface. Landsat 8 images the same point on the Earth's surface approximately once every 16 days and captures a total of 11 spectral bands, with visible imagery at 30 m per pixel. It can be said that such a system optimizes for *coverage*, *spectral bands*, and *spectral resolution* at the expense of *spatial* and *temporal resolution*. A further challenge is that optical satellites cannot see through clouds, so it may take several months to get a cloud-free image of an area since the satellite is passing overhead so infrequently.

Taking the above into account, Planet's co-founders recognized a gap in the remote sensing market. A system optimized for *temporal resolution* and *global coverage*, with adequate *spatial resolution* and *spectral bands*, would provide a highly differentiated product with substantial commercial value. With this knowledge in hand, the co-founders were able to round up a group of investors to help fund the early stages of the company (Fig. 1).

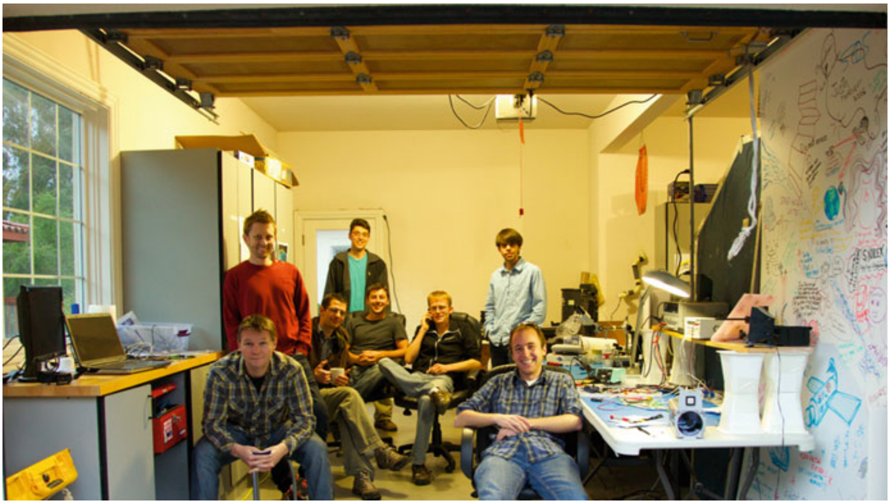


Fig. 1 Planet's founding team (known as "Cosmogia" at the time) posing with the first Dove prototype in the Cupertino garage. (Image © 2011 Planet Labs Inc., licensed for one-time publication)

Rather than show up to investor meetings with slick PowerPoint presentations, the founders would carry around the Dove prototype in a Pelican case and show with real hardware how much progress had already been made on a shoestring budget. Being based in Silicon Valley meant that there were many risk-tolerant funding sources available, so the co-founders were able to be more selective with the types of VCs they wanted to work with. Planet's co-founders wanted to make sure their investors understood the nuances of building a space company and were aligned with Planet's mission to do good in the world with Earth Observation data. Investors like DFJ (now "Threshold"), who invested early in SpaceX; Capricorn, a fund focused on social impact and sustainability; and Yuri Milner, an early investor in Facebook and a space enthusiast were some of the early investors that provided the capital to get the company off the ground.

The co-founders and investors agreed that the traditional approach of using small numbers of large, expensive satellites would be unfit for the job. Planet's first reference mission, dubbed "Mission 1," would be to launch and operate 100+ medium resolution satellites into a morning-crossing Sun-Synchronous Orbit (SSO) in order to image the Earth's landmass every day. To achieve this, a different approach to satellite design would be required.

2.3 Early Dove Satellite Design

The Cubesat specification defines a "U" as a $10 \times 10 \times 10\ \text{cm}^3$, and at that time 3U Cubesat deployers (accommodating $10 \times 10 \times 30$ cm satellites) were the most common deployer sizes being flown. The Planet team identified the biggest telescope

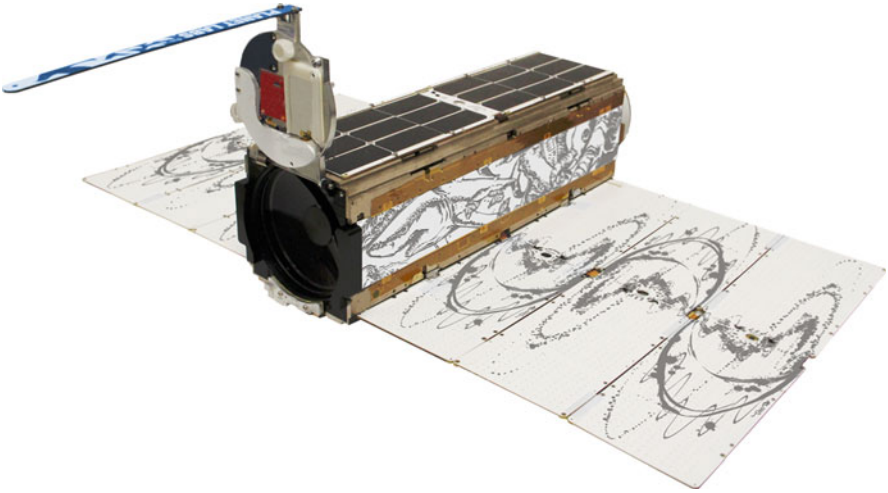


Fig. 2 Planet's Dove satellite in flight configuration with antenna flap and solar panels deployed. (Image © 2015 Planet Labs Inc., licensed for one-time publication)

that would easily fit within a 3U and began to design the satellite around that. In fact, Planet's earliest satellite models used a Questar telescope, originally designed for backyard amateur astronomy, which neatly fit within the 3U envelope and was readily available at the local hobby shop. Such a telescope would produce imagery at 3–5 m per pixel when matched with an appropriately sized camera sensor and flown at altitudes between 300 and 500 km. The 3U envelope also had enough volume to support the required focal length of the imaging system and all the supporting avionics. And finally, the Planet team wanted to give the satellite a name that conveyed the intended peace-bringing nature of the mission, and thus the "Dove" satellite was born (Fig. 2).

The total mass of the Dove satellite was approximately 5 kg and also featured a small, cylindrical compartment in the rear (sometimes referred to as the "tuna can") to house the camera sensor, which took advantage of the available volume inside the pusher spring of the Cubesat deployer. Although the Dove did not strictly adhere to the official Cubesat standard (the "tuna can" and a handful of other minor modifications were outside the official Cubesat specification), it was close enough to a 3U to make no difference to a launch provider. Each Dove satellite also featured artistic designs or inspirational quotes wherever there was spare surface area. It was Planet's way of showing that not only did the satellites have immense commercial value; they could also be fun and inspirational as well.

The first Dove prototype was built in a garage in Cupertino, California, where the company was founded. The idea was to keep the system as simple as possible, utilizing commercial-off-the-shelf components or custom-ordered elements that could easily be manufactured at scale. Aerospace suppliers were typically avoided as they often could not meet the size, cost, performance, order quantity, or turnaround time requirements. In fact, the only aerospace-grade component currently used on the Dove satellites is the solar cells. Due to the small size of the satellite, high-efficiency aerospace solar cells are required to meet the mission's power requirements, while all other components on the satellite are either off-the-shelf or custom-designed.

At the outset, the Planet team did not have sophisticated test facilities available, so they improvised as needed. To test the imaging system, engineers pointed the telescope from the Cupertino garage across a clear line of sight to a mountaintop observatory approximately 20 miles away to verify the focus and camera settings. The first "clean room" Planet ever built was a modified greenhouse tent purchased at a local hardware store, dubbed the "clean enough room."

Rather than build the perfect satellite from the outset, Planet borrowed Silicon Valley's approach to iterative software design and developed what is now called Agile Aerospace, a philosophy of spacecraft design that supports building the best satellite with what's available at the time, learning from that process to see what failed or what could be improved, and then immediately building the next iteration with those lessons learned. This was a capabilities-driven approach, rather than a requirements-driven one.

Because launch schedules were unpredictable, Planet would often take advantage of launch delays as an opportunity to advance the satellite design. It made no material difference to the launch provider since the satellite still maintained adherence to the Cubesat deployer, and Planet always ended up launching the latest technologies. With the satellite components being relatively low-cost and easily available at scale, each engineer could have a satellite (or satellite subsystem) sitting right on their desk, greatly parallelizing development. A new generation or "build" of the Dove satellite was produced roughly every 3–6 months.

As a further effort to keep the satellite system simple, the Dove satellites do not have onboard propulsion but rather use a technique called "differential drag" for limited orbital maneuvering. At the lower altitudes where the Doves operate, there is enough atmosphere to impart an appreciable drag force on the satellite. This drag force varies depending on the surface area of the satellite that is presented towards the velocity vector, and when the Dove's solar panels are fully deployed, there is an approximately 10:1 difference in surface area depending on if the satellite is oriented to fly at maximum drag ("face-on") or minimum drag ("edge-on"). When properly orchestrated, the varying attitude states give the satellites some limited maneuvering capability. Using differential drag techniques enables the initial phasing of the satellites so that they can be equally spaced around an orbit after launch, and differential drag is also used to maintain the relative phasing of the satellites over time as their orbits naturally drift and decay, all without the need for a propulsion system (Foster et al. 2018) (Fig. 3).

Unlike traditional satellite systems with lifetimes upwards of 15 years, the expected Dove satellite lifetime is between 2 and 3 years, usually limited by the long-term survivability of the onboard commercial electronics in the high radiation

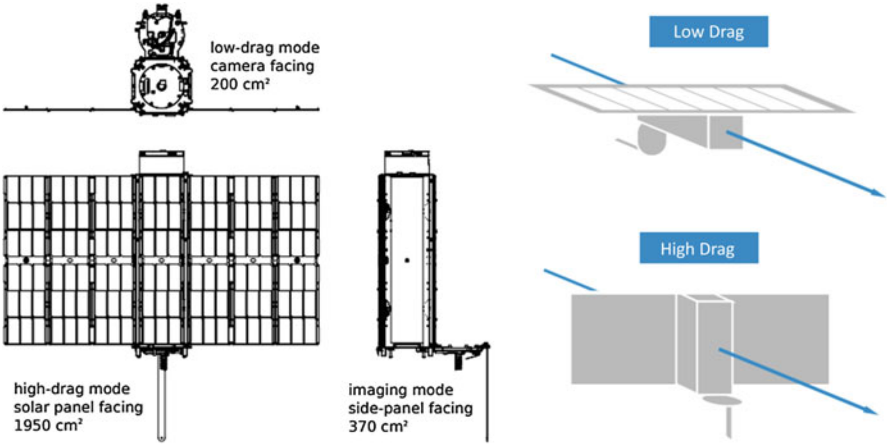


Fig. 3 Various drag orientations for the Dove satellite that enable differential drag maneuvering. (Image © 2018 Planet Labs Inc., licensed for one-time publication)

environment of LEO. Planet launches enough Doves such that if a percentage of the satellites fail, the system in aggregate is unaffected. This approach of shorter lifetime coupled with failure tolerance at the constellation level comes with several advantages:

1. **Planet is always flying the latest and greatest technologies**. Continued advancements in commercial electronics, such as faster processors and better camera sensors or more efficient batteries, are readily folded into the Dove satellite design as they become available. Planet avoids the need for radiation-hardened parts, which are typically bulkier and more expensive compared to their commercial counterparts.
2. **Planet is able to react to the market**. Customer feedback and industry trends can be quickly accounted for in subsequent generations of the satellite design.
3. **Many of the subsystems need only to be single-string**. While some of the critical subsystems such as communications and attitude control do have onboard redundancy, a majority of the Dove satellite systems are single-string, keeping the mass of the satellite low and reducing complexity. Redundancy is accounted for across the entire fleet with the numbers of satellites being flown, rather than focusing on the performance of any single satellite. It was found to be much easier to account for spare satellites rather than attempt to achieve an additional decimal place of reliability on each satellite.

Shorter lifetime of the satellites also comes with some disadvantages, such as the recurring need for constellation replenishment (and associated launch costs), but the simplicity of the approach and the aforementioned advantages greatly outweigh the disadvantages and still cost significantly less than the traditional satellite approach.

2.4 Doves 1–4

The first launch contract Planet ever signed was via Spaceflight Industries for the launch of one Cubesat, Dove 1, on the maiden flight of the Antares rocket (which was called Taurus II at the time). When the contract was signed, the launch was scheduled for December 2011 and would carry a Cygnus mass dummy as the primary payload. Although launch schedules are notorious for delays, maiden flights can be particularly egregious, and month after month the Antares launch date kept slipping. The team used the additional time to improve the satellite design, and Planet signed a second launch contract via Spaceflight for Dove 2 to launch on a Soyuz as a follow on to Antares. If all went to plan, Dove 1 was to launch sometime in 2012, giving enough time for those learnings to be folded into Dove 2, which was to be launched about a year later. The thinking was that at the very least, having two launch contracts on two separate launch vehicles would mitigate schedule risk and launch failure risk, especially recognizing that the maiden flight of a rocket also has a higher-than-average risk of failure. As luck would have it, Dove 1 and Dove 2 ultimately launched 2 days apart.

When time came to deliver the satellites for each respective launch, the Planet team was faced with two very different scenarios. On the one hand, the Antares rocket had a statistically higher likelihood of failure, and even if it was successful, the drop-off altitude was very low (approximately 250 km altitude), allowing for only a week of operations before the Dove orbit would decay due to drag and the satellite would burn up in the atmosphere. On the other hand, the Soyuz rocket was one of the world's most reliable launchers and would drop off the Dove at a much higher altitude (approximately 575 km), giving the satellite several years of orbital lifetime and plenty of time for the Mission Operations team to run through its mission objectives. Planet also had two satellite types ready to be launched at the time: a Build 4 Dove, which was thoroughly tested and considered a stable design but also carrying lower-performing subsystems, and a Build 6 Dove, which was newly released with higher-performing subsystems but had not undergone as much long-term testing and was considered experimental. The team decided to match risk with risk, and so the stable Build 4 design was assigned to the low-risk Soyuz launch (Dove 2), and the experimental Build 6 design was assigned to the high-risk Antares launch (Dove 1).

Dove 2 successfully launched on April 19, 2013, and Dove 1 successfully launched 2 days later on April 21, 2013. Due to the extremely low drop-off altitude of Dove 1, the Mission Operations team worked around the clock for a week straight to commission the satellite and run through its test objectives, which were to turn the satellite on, gather some basic telemetry, schedule a series of camera activities, and download at least one image over the X-band radio. To further complicate matters, Planet only had one X-band capable ground station available at the time located in Chilbolton, UK, meaning there were only a handful of opportunities to get things right before the satellite permanently deorbited. The Mission Operations team's tireless efforts paid off and Dove 1 was able to capture and downlink an image of a forested field just outside of Portland, Oregon. This was an incredibly important milestone for the company. Despite extensive development on the ground, Planet's approach had thrown out most of the aerospace industry's playbook in building the satellite, so the outcome of the mission was uncertain until the last moment. After seeing that first clear image from Dove 1 finally appears on the ground, the team deemed Dove 1 a resounding success. This gave Planet confidence in the viability of the Dove design, which helped enable further rounds of fundraising for the company. Six days after launch, Dove 1 deorbited, and the Mission Operations team turned its full attention to Dove 2, which was also able to successfully capture and download several clear images over its slower S-band radio system. Dove 2 also gave the Mission Operations team experience with more sustained operations and was better able to test the in-house built UHF radio and attitude control system.

The launch of Dove 3 and Dove 4 followed shortly after, successfully launching on a Dnepr rocket on November 21, 2013. Dove 3 and Dove 4 were both Build 7 versions, but Dove 3 was housed inside an ISISpace ISIPOD deployer (same as Dove 1 and Dove 2), while Dove 4 was housed inside the UniSat-5 satellite. Dove 3 would be immediately deployed once the Dnepr reached orbit, whereas UniSat-5 would wait several days after it was released from the upper stage until deploying Dove 4. Dove 3 deployed without issue, but unfortunately UniSat-5 suffered an in-orbit anomaly and was unable to deploy Dove 4. Planet's risk mitigation strategy of utilizing two different deployment systems on a single launch resulted in at least one satellite being deployed, and Dove 3 was able to successfully complete its mission. At the time of writing, UniSat-5 remains nonoperational in orbit with Dove 4 trapped inside.

2.5 Flock Launches

Following the successes of the early Dove missions, the next phase of building up to Planet's Mission 1 was to launch Planet's first fleet, or "Flock," of Dove satellites to prove Planet's ability to operate a constellation. Planet's manufacturing capability underwent a major upgrade, and many of the improvements between the subsequent Dove builds were focused on ease of manufacturing and ease of testing, in addition to improving the performance of the various subsystems, so that the satellites could be more easily manufactured at scale. Planet's manufacturing output grew from several days to build the first prototypes to about a dozen satellites per week and now stands at over two dozen per week, fully environmentally tested and ready for launch (Fig. 4).

In addition, each time a batch of satellites needs to be delivered for an upcoming launch, the manufacturing team would "overbuild" by a certain number of satellites to allow margin for error. For example, if 20 Dove satellites were scheduled for launch, 25 satellites would be built and tested. If any of those satellites experienced issues during the assembly or testing phase, those satellites would be "red-tagged" and set aside for future investigation. Since Planet is usually launching as a secondary payload, the team does not have the ability to delay a launch for production issues, so the strategy of "overbuilding" always guarantees a minimum number of

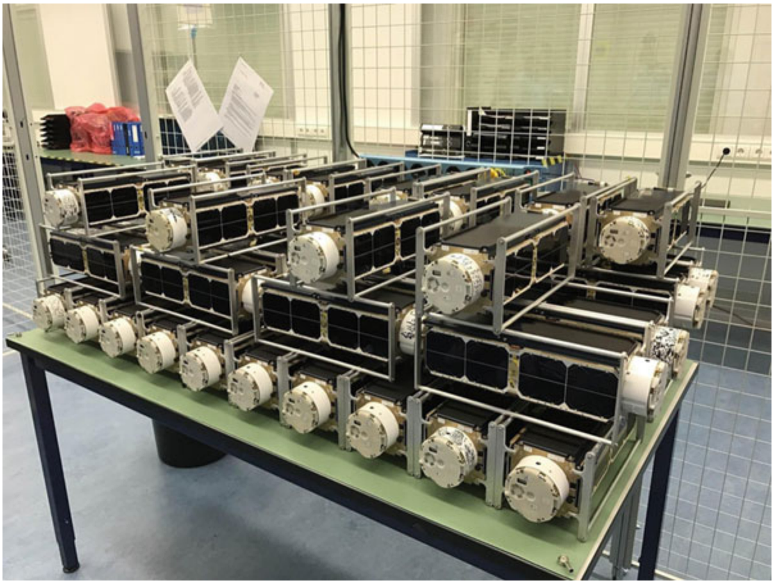


Fig. 4 A flock of Dove satellites ready for launch. (Image © 2017 Planet Labs Inc., licensed for one-time publication)

satellites ready for each launch. During the lulls in between manufacturing runs, the manufacturing team can take time investigating any issues discovered on the satellites left behind and will either keep those satellites as ground spares or scrap them for parts for future builds.

Flock 1, comprised of 28 Dove satellites, was launched on January 9, 2014, as cargo inside the Cygnus capsule to the International Space Station (ISS) on an Antares rocket and deployed into orbit 45 days later through an ISS airlock. Planet's Agile Aerospace approach required many iterations to refine the satellite design over time, and launching via the ISS had several advantages. There was a steady cadence of cargo launch opportunities to the ISS (roughly every 3–6 months, aligning with Planet's design iteration cadence), the low deployment altitude of approximately 400 km resulted in slighter better imaging resolution, and the launch environment was relatively benign due to the satellites being snugly packed inside of cargo bags. The low deployment altitude also meant that the satellites naturally deorbited after about a year of operations, making it a "self-cleaning" orbit.

After a series of successful ISS launches, on October 28, 2014, Planet suffered its first launch failure when the Antares rocket, carrying 26 Dove satellites bound for the ISS, experienced a catastrophic breakup only a few seconds after lifting off the pad. For most companies, the loss of 26 satellites would be equally catastrophic, but Planet's Agile Aerospace approach kicked into high gear, and it only took 9 days after the Antares failure for the manufacturing team to produce two additional Dove satellites and deliver them for launch integration on the next available launch. Those two satellites were launched on a Falcon 9 ISS cargo mission less than 3 months later on January 10, 2015, demonstrating just how quickly both NASA and Planet could recover from a launch failure. The Antares rocket was completely destroyed, but because those Dove satellites were housed inside of their deployers, which were further protected from the blast by being inside the Cygnus cargo module, almost a dozen Dove satellites survived the Antares failure and were later recovered near the site of the accident. Those surviving Doves now sit as proud museum pieces in Planet's headquarters in San Francisco.

Although ISS launches were frequent and dependable, the delivery timelines on ISS launches were often 60 days or more before launch, as opposed to the typical 30-day delivery timeline on direct launch opportunities. In addition, once the cargo reached the ISS, astronaut time had to be allocated to unpack the cargo bags and load the Cubesat deployers onto the deployment pallet. Cubesat deployments had to compete for airlock access with other ISS experiments and activities, and finally, visiting vehicles such as the Soyuz, Cygnus, or Dragon had to be clear of the ISS before Cubesat deployments could be initiated. NanoRacks, Planet's ISS partner, advocated as best they could with NASA and the partner space agencies for crew and airlock resources, but in many cases it took several months after Planet's satellites reached the ISS before they could be deployed. These delays greatly hindered Planet's Agile Aerospace design loops, but the ISS was the most reliable and consistent path to orbit at that time. In fact, of the 144 Dove satellites launched in 2014 and 2015 across 9 launches, 133 of the Doves were sent to the ISS, and only 11 of them were sent to the Mission 1 reference orbit of SSO. There simply weren't very many SSO launch opportunities available during that time, so Planet mostly made do with the ISS.

Sun Synchronous Orbit (SSO) is ideal for optical imaging satellites. The near-polar inclination allows satellites to see the entire Earth's landmass, and with respect to the sun, the orbit processes in such a way that the satellites consistently cross overhead at the same local time of day. This creates consistent shadow angles in the imagery, greatly easing the task of automated imagery analysis algorithms, and makes it easier to compare imagery from one day to another. The ISS orbit, on the other hand, is at 51° inclination. The non-SSO inclination of the ISS orbit means that the satellites only see $\pm 51^\circ$ latitude on the Earth's surface. It also means that the effective local time of day when the satellite crosses overhead drifts over time, resulting in "blackout" periods when the satellites don't have the right illumination conditions to successfully capture imagery.

After 2015 the launch market began responding to the growing demand from small satellite companies like Planet and offered more opportunities to SSO. Even more critically, in 2016 the US Government began to allow commercial US companies to launch on Indian rockets, which were regularly flying to SSO. Planet was able to transition from its R&D phase utilizing ISS launches to the company's operational phase with its fleet in SSO. The Polar Satellite Launch Vehicle (PSLV) turned out to be a critical launch vehicle for Planet. Between Soyuz and PSLV launches in 2016 and 2017, Planet launched an additional 148 Dove satellites to 500 km SSO, providing enough actively imaging satellites in orbit to achieve Mission 1 imaging the entire Earth's landmass every day.

2.6 Flock Operations

Flock operations are intentionally simple to keep the satellite fleet manageable. In nominal operations, each Dove satellite runs on an automated schedule capturing nadir-oriented imagery at a regular interval while in daylight. The imagery and telemetry data are stored onboard until downlinked to a ground station, and then the process repeats. The Mission Operations team at Planet is small but mighty; the number of Dove satellites flying greatly exceeds the number of satellite operators.

Mission Operations primarily focuses on improving automated operations and responding to anomalies, rather than having humans actively track every activity on each satellite. The team is split between Planet's US headquarters in San Francisco, California, and Planet's European headquarters in Berlin, Germany. Operators can also log in to the Mission Operations system via a secure, remote VPN, allowing operators to perform satellite tasks from home if needed. Most days, each team is able to maintain a "9 to 5" workday, with the differing time zones between California and Germany helping to spread the workload. If a Dove satellite experiences an anomaly during off hours, the Mission Operations team is usually able to wait until working hours to address the issue given that there are enough active satellites operating in Planet's fleet to withstand temporary individual outages (Demir et al. 2018) (Fig. 5).

The Dove onboard software is regularly updated for performance improvements and bug fixes. The software is first deployed to a ground spare satellite and tested extensively and then uploaded to a small handful of on-orbit Doves for further testing before being deployed to the entire fleet. Maintaining version control over the various Dove builds flying in orbit with different hardware builds, hardware states, and software versions can be a challenge, but the benefits of continuous improvement of the satellites outweigh the costs.

2.7 Ground Station Network

Planet's ground station network is comprised of about a dozen sites around the world and is a hybrid model of leased antennas and Planet-owned antennas. Because of the sheer number of satellites operating in orbit, the ground station antennas are active for most of the day, and many of the ground station sites have several antennas in a single location to account for when several Dove satellites are in view. Planet takes a similar approach to its Mission Operations strategy and runs the ground station network in a highly automated, hands-off fashion. The ground stations are unmanned during operations and monitored remotely, which again is overseen by a very lean team.

The ground network uses two communications paths to establish contact with the Dove satellites: low-speed Telemetry, Tracking and Control (TT&C) over UHF and high-speed communications over S-band (uplink) and X-band (downlink). The UHF ground systems utilize broad-beam Yagi-Uda antennas, and the S-band/X-band

Fig. 5 A Planet Mission Operations operator commanding satellites from her laptop with a Dove model in the forefront. (Image © 2018 Planet Labs Inc., licensed for one-time publication)

system uses parabolic dish antennas typically 5–7 m in diameter, although a handful of Planet's ground stations have antennas with all three frequency capabilities combined into a single parabolic dish.

The UHF system is especially important during the satellite commissioning phase right after launch when the Doves are traveling in a cluster and might easily be mixed up from the ground. Planet's UHF Low-Speed Transceiver (LST) radio is used both on the Dove satellite and on the ground station and has the ability to quickly establish communications, identify which Dove satellite is which, and even refine satellite positioning estimates using radio ranging. Planet has a 100% success rate in contacting every Dove satellite ever deployed over the UHF LST radio, usually within a timespan of a handful of orbits. The smallsat community has historically struggled with post-launch satellite tagging, tracking, and communications, especially on large cluster launches, which is why Planet open-sourced a version of its LST radio called the OpenLST for other satellite missions to take advantage of.

The S-band/X-band radio system was also designed in house and utilizes the DVB-S2 communications protocol to achieve amazing downlink rates. The latest generation of the Dove satellite can downlink imagery data at speeds better than 1 Gbps over X-band by using advanced DVB-S2 modulation and coding, improvements in the satellite antenna, and dual-polarization transmissions.

2.8 Space Stewardship

Orbital debris mitigation and responsible space stewardship is a top concern for Planet, especially considering the numbers of satellites in Planet's fleet. (At the time of this chapter's writing, over 350 Planet satellites have been successfully launched and deployed into orbit.) Planet was the first company to launch in such large numbers, and the company wanted to make sure it was being a good space stewards and leading by example. Planet developed the following principles to abide by:

1. No intentional junk: Never intentionally release any debris, including during deployment of actuated systems (e.g., the Dove's fold-out solar arrays).
2. Launch low: Planet aims to launch the Dove satellites between 400 and 600 km in altitude, with a target orbit of 500 km. This has dual benefit: the satellites will naturally decay from orbit well within the 25-year deorbit guideline (in most cases the deorbit lifetime is 5 years or less), and the Doves also avoid the most congested region of LEO between 700 and 1000 km, thus reducing the risk of collision with other space objects.
3. Share data: Planet openly publishes its most up-to-date satellite positioning data so that other satellite operators can more accurately assess any potential conjunctions. Many of the conjunction warnings issued to satellite operators turn out to be false positives due to the large uncertainties in the propagated estimates of satellite positions. By using the Dove's UHF transceiver for radio ranging along with the onboard GPS, Planet can provide more accurate position data to other satellite operators and help filter out false positives.

Although Planet currently operates the world's largest satellite fleet, those numbers will likely soon be eclipsed by the communications "megaconstellations" being developed by SpaceX, OneWeb, and others. Regardless, Planet is committed to continuing to advocate for responsible space operations, especially as the space environment evolves over time.

2.9 Current Status

In addition to the Flock constellation, Planet also owns and operates two other satellite fleets: the five RapidEye satellites, which produce medium-resolution imagery of similar quality to the Doves, and the constellation of SkySat satellites, which produce sub-meter, high-resolution imagery and HD video. The RapidEye satellites are expected to be retired in 2020 as they have been operating since 2008, and equivalent imagery capabilities are being produced by the latest generation of the Dove satellites. The SkySats, on the other hand, have an expected lifetime of several years to come. The SkySats, in combination with the Flock fleet, produce a combined dataset not available anywhere else at such scale.

After the milestone Flock launches in 2017 and the acquisition of the SkySat satellites that same year, Planet transitioned from a space-focused company to a product-oriented company. The company's primary focus is on developing Planet's imagery platform, easing the integration of Planet's imagery to other existing platforms and workflows, and enabling the development of imagery analytics to automatically extract features and insights such as automated road and building detection from the raw imagery. Planet's imagery is already being adopted on a global scale by a variety of different users, including government agencies, agricultural and forestry industries, environmental nonprofits, prominent media outlets, and academia. The user base continues to steadily grow as industries not typically used to relying on remote sensing data begin adopting Planet's unique dataset.

In parallel with Planet's imagery product developments, the company's space efforts are also steadily advancing. Planet recently announced the SuperDove platform, the next-generation Dove-series satellite that will feature a total of eight spectral bands in the visible and infrared spectrum and improved performance across multiple subsystems. In addition, improvements are being made to Planet's high-resolution platforms as the company continues to push the boundaries of what can be done with large networks of small satellites. Planet's ultimate goal of using space to help life on Earth by providing best-in-class imagery capabilities remains the company's top priority, with many more exciting developments expected in the future.

3 Conclusion

In the span of less than a decade, Planet went from a handful of engineers tinkering in a Silicon Valley garage to a company that operates the world's largest fleet of remote sensing satellites producing a dataset that is unmatched in its global coverage and frequency of revisit. Utilizing the Cubesat standard, commercial off-the-shelf-components, and cloud computing and storage services, the company took a radical new approach to satellite design, manufacturing, and operations. Planet has now set its focus on developing more powerful imagery analytics tools and the commercial adoption of its imagery data across a variety of industries and markets while still pushing forwards its space-based capabilities to remain at the forefront of the remote sensing industry.

4 Cross-References

- ► An Overview of Small Satellite Initiatives in Brazil
- ► The Kepler Satellite System
- ► The OneWeb Satellite System
- ► The Spire Small Satellite Network

References

I. Demir, D. Doan, D. Nelson, Not your mom's mission control: satellite automation at scale. Presented at the Grace Hopper Celebration, Houston, 2018

C. Foster, et al., Differential drag control scheme for large constellation of planet satellites and on-orbit results. Originally presented at the 9th International Workshop on Satellite Constellations and Formation Flying, Boulder, 2017; paper published in 2018

W. Marshall, et al., PhoneSat: a smartphone-based spacecraft bus. Paper presented at the 62nd International Astronautical Congress, Cape Town, 2011

Satellite Imaging Corporation, Characterization of Satellite Remote Sensing Systems (2017), https://www.satimagingcorp.com/services/resources/characterization-of-satellite-remote-sensing-systems/. Accessed 20 Oct 2019

The Kepler Satellite System

Shane Laverty, Wen Cheng Chong, Jeffrey Osborne, Mina Mitry, and Vanessa Lewis

Contents

Abstract

The advances of the NewSpace movement have acted as a wellspring for the field of entrepreneurial space. Made possible by these developments, Toronto-based Kepler Communications is working to lay down the telecommunications infrastructure of the next century by using its low Earth orbit (LEO) constellation as a cellular network for spaceborne assets. Kepler emphasizes taking small steps toward its goal, using its LEO network first to deliver Earth-based services to the global VSAT market and to the burgeoning industrial IoT ecosphere. With careful observance of historical lessons, Kepler has developed a robust business strategy to navigate the minefield of private space. With its plan in hand and a laundry list of bleeding-edge technological innovations, Kepler is placing one foot in front of the other on its path to build what it calls the "Internet in Space."

S. Laverty (✉) · W. C. Chong · J. Osborne · M. Mitry · V. Lewis
Kepler Communications, Toronto, ON, Canada
e-mail: slaverty@kepler.space; wchong@kepler.space; josborne@kepler.space; mmitry@kepler.space

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_65

Keywords

CubeSats · Internet of Things · IoT · Machine2Machine (M2M) · Competitive satellite market · NewSpace · Spectrum · Intersatellite links · Internet in Space · Ku-band · Nanosatellite · Software-defined radio · Kepler · Satellite communications · Low Earth orbit · LEO · Private space · Telecommunication

1 Introduction

Kepler Communications was founded in 2015 by a group of University of Toronto graduates with the mission to build the space infrastructure for the next century. In doing so, it joins a long legacy of people to pursue lofty goals in space – many of whom have stumbled along the path. Their activities can provide the basis for understanding Kepler's emergence, as well as its early success. To be clear, a small, private company like Kepler could not have existed for most of space development history. Space has traditionally been an arena that only the largest, most advanced economies could ever hope to step into. Fortunately for Kepler, much has changed.

The beginning of the satellite communications industry is often attributed to the visionary author Arthur C. Clarke who, for an article in *Wireless World*, described that relay satellites could be used for distributing television programs in a 24-h orbit (Clarke 1945). Some 13 years later in 1958, the USA launched the world's first purpose-built communications satellite SCORE (Signal Communications by Orbiting Relay Equipment) (Smithsonian 2019a). SCORE was primarily built as a response by the USA to the Soviet launch of Sputnik 1 and 2. It survived in orbit for only a few months, with its most well-known achievement being a broadcast of a Christmas message from President Eisenhower. Both US and Soviet endeavors highlight the enormous feat of space access, which had been closely held within government superpowers.

Kepler's first true predecessors were Telstar 1 and 2, a set of commercial telecommunications satellites launched in 1962 through a multinational private-public consortium comprised of AT&T, Bell Telephone, NASA, the British General Post Office, and the French National Post, Telegraph, and Telecom Office (today, commonly known as the company Orange) (Smithsonian 2019b). The technology aboard each of the Telstar satellites was primitive relative to today. Firstly, each satellite was spin stabilized, meaning it was constantly rotating. This invoked the need for low-gain, omnidirectional antennas, limiting the bandwidth that could be supported. The technology at the time meant that enormous facilities such as the Andover Earth Station (a 177-foot horn antenna housed in the equivalent of a 14-story building) needed to be built to receive Telstar's faint signals (Maine 2019).

Like Kepler's own network, these satellites were launched into a non-geostationary orbit, which meant that the signals could only be received and transmitted intermittently from the ground as the satellite passed overhead. Nevertheless, Telstar enabled the world's first transatlantic television feed, a remarkable feat for the time.

Its use marked a shift toward the commercial use of space, away from government-exclusive activity. Although some parts of the world saw this restriction persists for decades (e.g., China), the seeds of early space commerce had been planted in North America and Europe.

Kepler's family tree started to grow. As Telstar and other early satellite systems such as Relay and Syncom were operating successfully in space, commercial satellite communications companies began to form. The Communications Satellite Corporation (COMSAT) was formed in 1963 as a result of the Congressional signing of the Communications Satellite Act of 1962, thus becoming the first government-initiated satellite communications company (COMSAT 2019). COMSAT then formed the International Telecommunications Satellite Consortium (now known as Intelsat) and in 1965 formally kicked off the global satellite communications industry with the launch of Intelsat I (nicknamed Early Bird). National governments around the world soon began to take notice of the benefits of satellite communications. In 1969, the Canadian government formed the Crown Corporation Telesat, which then went on to launch the world's first domestic satellite in 1972, called "Anik" (Telesat 2019). In 1977, 17 European countries set up the European Telecommunications Satellite Operator (now known as Eutelsat) (Eutelsat 2019). In 1979, 28 countries within the International Maritime Organization (IMO) established the International Maritime Satellite Organization (now known as Inmarsat) (Inmarsat 2019). SES (Société Européenne des Satellites*)* was established in 1985 by the Luxembourg government (SES 2019), and Thuraya was established by the United Arab Emirates (UAE) government in 1977 (Thuraya 2019).

All of these companies had been initiated in some way by a government-led initiative. Government support had been instrumental in these early years because of the inherent risks associated with building, launching, and operating satellites, as well as the national need in providing these communication services. But as time passed, many of them returned to private sector ownership. Telesat was the first to make this transition, being sold by the Canadian federal government to Bell Canada in 1998. Inmarsat followed suit in 1999, when the company was privatized. Both Intelsat and Eutelsat were then privatized in 2001. SES today maintains the Luxembourg government as a major shareholder, and Thuraya is now owned by Yahsat.

As technical risks were gradually mitigated and the needs for connectivity began to take shape, the late 1980s into the 1990s saw a wave of the first truly private initiatives. These new ventures represent Kepler's closest historical relatives and included Teledesic, Skybridge, ICO Global Communications, Iridium, Globalstar, and Orbcomm. Teledesic was certainly one of the most well-known ventures at the time. The company was conceived in 1990 by cellular industry pioneer Craig McCaw. Its original plan called for a constellation of 840 satellites to be deployed in LEO at 700 km altitude. Over time, the plan was scaled back to 300 satellites at 1400 km and then to 30 satellites in a higher medium Earth orbit. Nevertheless, the company was able to attract impressive investors, including Bill Gates, Saudi Prince Al-Waleed bin Talal, Boeing, and the Abu Dhabi Investment Co. (Chan 2002). Another well-known private initiative was Iridium, designed to provide global cellular services. Its constellation was initially envisioned in the late 1980s, and design effort began in earnest in the 1990s, financed by Motorola. Its primary objective was to target the mobile phone market for international business travelers. Iridium progressively launched its 66-satellite constellation between 1997 and 2002, with all satellites needed to be operable before commercial services could begin (Bloom 2016).

Each of the other ventures – Skybridge, ICO, Globalstar, and Orbcomm – had their own unique history, but all of the private initiatives would later find themselves in the same place, declaring bankruptcy. Teledesic, Skybridge, and ICO folded before being able to offer any commercial services. Iridium, Globalstar, and Orbcomm got their constellations off the ground first before conceding the same. The latter constellations specifically were able to later emerge from bankruptcy by either restructuring their debt or being acquired in an asset sale. Their fates did not bode well for the hopes of private space industry.

At this point, history had clearly indicated that the only successful satellite communications companies had either relied on governmental support or had been purchased out of bankruptcy for a fraction of their invested value. This begged the question, would private space companies ever be able to survive on their own? How might they do it? Early on, Kepler took the opportunity to learn from these stories, hoping to use them to navigate the treacherous road to private space independence. And although the world of space remains as harsh as it ever was, fresh water has slowly trickled into the landscape, bringing with it the possibility of life. The NewSpace movement of the mid-to-late 2000s bore a number of innovative developments that have allowed capital-limited groups to start placing and proving inexpensive products in space.

One of the great nucleators of this NewSpace movement was the CubeSat standard, developed as an attempt to simplify the construction of satellites and reduce their overall cost through standardization. Kepler's satellites use this very standard. The satellites of old were always built to-order, designed, and assembled by teams of highly specialized engineers with extreme material and construction standards. CubeSats are made up of multiples of $10 \times 10 \times 10$ cm "units," and their fixed design allows manufacturers to optimize their essential parts (like batteries, solar panels, and antennas) such that they can be sold as commercial-off-the-shelf components. These can then be purchased by any up-and-coming university or NewSpace satellite startup. In conjunction with the optimizations and cost reductions provided by the CubeSat standard, the miniaturization of many payload technologies progressed in parallel, often developed as the primary focus of these startups and universities. Kepler was one such group, and its goal of building an advanced telecommunication network led it to channel its efforts into developing the cornerstone technology it would need for its mission – a custom software-defined radio (SDR).

Kepler's SDR payload was built in accordance with the CubeSat specifications, allowing it to leverage available commercial-off-the-shelf products for the rest of the spacecraft and save costs. Furthermore, the development of a standard form factor also brought with it a reduction in launch complexities. Launch providers suddenly were working with an industry-shared specification that let them easily incorporate disparate satellites onto their rockets. This allowed them to aggregate multiple customers on the same vehicle, dramatically reducing the cost of launch to space. The days where a single rocket was built to launch a single satellite were over. This further acted to renew government interest in commercial space, penning new legislation and regulations to provide a catalyst for the growth of NewSpace companies. All of these factors have allowed low-capital upstarts like Kepler to not only build and launch their own satellites, but to do so in as short time as 12 months! Kepler and companies like it and were suddenly free to dream of a compelling future in space, and now they had the tools to achieve it.

2 Kepler's Approach to Internet in Space

From the building of the aqueducts that powered the Roman Empire, to the development of railroads that helped settle the western frontier, and to the construction of the cell towers that underpin our digital ecosystem, the initial laying of infrastructure is essential for the building of economies. This was the strongly held belief at the root of Kepler's foundation. Drawing parallels to these forms of essential infrastructure, it was clear that for humanity to sustainably expand into space there needed to be a new form of development – an underlying vision that united Kepler's founding team.

In pursuit of this vision, Kepler focused on the increased usage of low Earth orbit (LEO) and the ever-growing demand for spaceborne data. Recognizing the deficiencies in existing satellite communications infrastructure, Kepler set out to design a network of small satellites in LEO that would operate much like network routers, but in space. These routers would form the backbone of a space-based Internet infrastructure, moving data in both directions between assets operating in LEO to Earth and beyond.

Kepler then patented an initial architecture for its eventual space network, one designed to be particularly useful in solving the connectivity problems of LEO spacecraft. When fully deployed, Kepler's network will comprise of a constellation of 140 satellites working in concert, spread equally among 7 different orbital planes. Each of the planes was set up in what is called a Sun-synchronous orbit, which is precisely calculated such that satellites will pass over the same parts of Earth at the same time each day. Furthermore, the constellation would carry on-orbit spares (designed to quickly replace active satellites that might fail) and could provide the capacity to support a broad array of data streams not only for customers in space but also for those on Earth. But such a large network of spacecraft and a diverse array of services brought with it unique challenges. For one, unlike more traditional geostationary satellites (which can retain sight to a single teleport year-round), Kepler's constellation would need to be supported by a geographically dispersed ground station network spanning multiple continents. Further, Kepler's constellation would be too big to monitor with human eyes alone. It would need to develop autonomous software systems that could manage satellite health and orbital collision avoidance on their own.

Such a large-scale network plan required new forms of thinking at the company level to ensure risk tolerance procedures and good aerospace practices were properly adapted. Both spacecraft design principles and company-wide operations carry a higher degree of risk tolerance to achieve the desired timelines where redundancy is sought in number of satellites. Every 3 to 5 years, Kepler will upgrade its network of satellites, bringing the latest advancements to space and mimicking the pace at which modern terrestrial wireless infrastructure is upgraded.

At the time of Kepler's founding, early indicators suggested that the need for in-space connectivity was not so distant. Satellite launches were growing at 30% year-on-year. Barriers to space access had been readily declining from regulation to technology, ultimately leading to a proliferation of NewSpace companies. These businesses were poised to capitalize on renewed space access and provide services including de-orbiting, maintenance, Earth observation, and manufacturing. Despite the excitement within the space industry, Kepler recognized that in-space connectivity was a new product in a new market, and it would be years before adoption would take shape. This ignited the thinking on how to establish the envisioned constellation of satellites that could serve as the future of in-space connectivity.

3 How to Build the Internet in Space

The exploitation of space has always been a harsh and trying arena. Even the well-funded Big LEO projects of the 1990s failed to survive its punishing environment. An awareness of this has been embedded in Kepler's business philosophy since its infancy. If Kepler was to succeed, it would have to draw from all of the lessons of the past.

One of the most crucial lessons came from looking at companies that had misunderstood their opening market. For example, Iridium had based their product development strategy on one such market – the international business traveler – which never materialized. The company's fall was tied to its inability to compete with the ever-growing terrestrial cellular providers of the time. When the service went live in the early 2000s, their handsets cost $2000 and airtime was $2–4 per minute – orders of magnitude higher than the cost of cellular. The number of Iridium subscribers after their first year selling service was 10,000, a far cry from the 500,000 that all the development plans had designed to serve (Bloom 2016).

A similar market misreading was done by Webvan, the online home grocery delivery service and darling of the dot-com era. At its height, Webvan appeared as an exemplar company, seemingly executing its business plans with flawless efficacy. They invested in delivery trucks, built a state-of-the-art warehouse with automated sorting, employed a seasoned CEO with savvy investors, received great reviews from early customers, and generated promising early revenue. The company raised nearly $800 M USD across a number of private rounds and their IPO in November 1999. But like Iridium, they overestimated the readiness of their market. Shortly after first product shipment, they were selling 2000 orders per day, a mere quarter of what the initial business plan had called for. Their entire product development, infrastructure, and staffing rollout had been built around an assumption of 8000 daily orders! Fundamentally, both Iridium and Webvan fell victim to premature scaling. They ramped up all of their costs (marketing, sales, facilities, recruiting, production, etc.) to support a planned revenue model that never materialized to their expectations. When this happens, burn rate increases without revenue in-tandem, and companies enter into a downward spiral.

Webvan, Iridium, and many other ventures that have failed this way (read Segway, Apple Newton) employed a similar product-focused, "build it and they will come" business strategy, and each of them was struck by its Achilles heel. They went through the motions to envision, pitch, develop, and produce their project before they ever tested the target market. This approach leaves market engagement as the last step that the business performs in the product development cycle. As history shows, it can have fatal consequences.

In contrast, Kepler employed what might be called a "customer-focused" strategy, one that puts market testing earlier in the development cycle. In this way, customer feedback is often directly incorporated into the conceptual stage of the product itself. The essence of this method is to *first recognize the problem and then devise the solution*. To mitigate risk the progression of the product should proceed gradually, beginning with the recognition of smaller, manageable customer problems that can be solved in the near term.

Frankly, startups do not have the resources to develop a product for mainstream or mass-market customers with many requirements and high standards. It is much better to start with a smaller customer subset wrestling with a very specific problem. This way, early product generations can be validated in market *at the same time* that they are being designed. Only after the solution is demonstrated to be viable should the company seek to find a broader customer base. These activities act to slowly pour the foundation for the business. After the concrete has settled, focus can shift to increasing spending on things like infrastructure costs, improved reliability, and product robustness.

Critically, small satellites are uniquely suitable to this *customer-focused* strategy, especially in comparison to larger satellites. First, their development cycles and costs are substantially less. A nanosatellite can be designed and constructed in 1 year, whereas a new, large geostationary satellite will require 5 to 10. Second, a design pivot for a nanosatellite might cost the developers months of effort; for a large GEO, this can potentially cost years. These things make it far easier for nanosatellites to test new market hypotheses. If first service requires a \$100 M investment (as is the case for large satellites), then it is imperative that your market hypothesis is correct. Such undertakings are not risk tolerant. But if first service merely requires a \$1 M investment to deploy (as is often the case for small satellites), then it is possible to make a few changes to your business plan without incurring fatal setbacks. The value of this ability to dynamically test risky markets cannot be understated. It is a potent tool that, when combined with the wave of technological advancements being made in the small satellite industry, might be enough to give private companies the energy they need to survive in space. First, Kepler would have to solve its own technical challenges.

4 New Problems Demand New Solutions

Ultimately, Kepler recognized that new technology would be needed to make its constellation a commercially viable platform. Over time, it could progressively add new capabilities to its satellites, thereby paving the way for new types of devices to join the network. Each of these successive service offerings could act as a stepping stone to the next, allowing Kepler to iterate on the technologies that would be useful for its final in-space connectivity vision. Further, each of them would raise unique challenges, some of which have never before been explored by industry, government, or academia. And so without knowing either the market need or the timeline in which it could be realized, Kepler's early years of work focused on solving problems that were certain to be required for the build out of this infrastructure.

It was recognized early on that key to any large-scale data infrastructure is a central processing node that can manage and carry traffic throughout the network. This line of thinking (combined with an exhaustive survey of available technologies in the market) provided the impetus for building Kepler's core payload – a proprietary SDR and high-gain antenna. This focus on payload development allowed Kepler to differentiate its business from others and take full advantage of the recent NewSpace trends, including commoditized satellite components and plummeting launch costs.

When evaluating desirable payload characteristics, Kepler came across the need to select its operational frequency band. Fortunately, Kepler's early development was done in Seattle, home of the infamous Teledesic-failed satellite venture and a myriad of technical talent that had been through similar experiences. This access allowed Kepler's founders to attain a clear understanding of how the International Telecommunications Union (ITU) regulations had been changed as a result of Teledesic's efforts and the availability of Ku-spectrum for non-geostationary high-bandwidth data services. Understanding the history and justifications for how this scarce, complicated resource was allocated became essential for Kepler to obtain coveted access to the Ku-band and provided clear guidance on how to further develop its network. Kepler prioritized this effort early on, quickly filing its system characteristics with the ITU and applying for Ku-band licenses in Canada, Europe, and the USA.

Kepler's first two prototype satellites (named KIPP and CASE after the companion robots in Christopher Nolan's *Interstellar*) were launched in January and November of 2018, respectively. They host Kepler's first iterations of its high-gain Ku-band passive array antenna and custom SDR. When launched, these satellites were the first commercial telecommunication satellites in LEO to operate in Ku-band. In alignment with its *customer-focused* strategy, Kepler opened its network to the first type of customer – the remote VSAT market. As a niche market consisting primarily of a small number of high-value enterprises, Kepler was immediately able to offer useful, high-throughput services with KIPP and CASE.

5 High-Throughput Service

This high-throughput offering in Ku-band was eventually named the *Global Data Service* (GDS). To begin customer validation, Kepler started by identifying niche markets that could benefit from its offering and that were underserved by incumbent networks.

As it happens, sun-synchronous LEO networks are uniquely suited to provide connectivity to the poles, which themselves are utterly underserviced by terrestrial networks. This is primarily because the population density is so low – a killer for economies of scale. The simple solution: lower the cost of the orbital infrastructure. Kepler was able to loft KIPP and CASE into orbit with only a seed funding of US $5 M, a 12-month timeline, and a team of around ten. These satellites are capable of *moving tens of GBs per month* for customers above the 60th parallel. In particular, GDS offers store-and-forward (i.e., non-real time) connectivity at reduced cost, which remains useful for data-heavy demands from remote polar vehicles/facilities. A critical customer base is in maritime, including scientific, industrial, and shipping vessels operating in and around the Arctic. Earnings from GDS are then reinvested into the R&D necessary to allow Kepler's follow-on services to be developed.

To deliver GDS successfully, Kepler's high-gain antenna needed to support plenty of bandwidth and still fit on a 3U CubeSat bus. Part of the reason why Ku-band was selected as its operational frequency was because it had just the right balance that was needed. The narrow beamwidth achieved by the 3U-size Ku-band antenna was enough to make full use of the state-of-the-art pointing capabilities available for CubeSats at the time (controlled pointing to within $<5°$). In addition, Ku-band had sufficient bandwidth available under international regulations to enable the data rates that the business model demanded. With the antenna specifications selected, Kepler searched for a commercially available SDR to perform the necessary digital signal processing. Its search turned up empty, finding zero available Ku-band SDRs available to the CubeSat component market. If Kepler was to move forward, it would need to build its Ku-band SDR from scratch.

Kepler's custom SDR is powered by a special chip known as a field-programmable gate array (FPGA), a clever bit of engineering wizardry first developed in the 1980s that can *efficiently simulate discrete hardware components*. Unlike your granddad's radio (which would have built using a concoction of mixers, filters, amplifiers, modulators, and other separate components), an FPGA-powered SDR can simulate the effects of many such subcomponents to produce a *virtual* radio that can operate nearly as efficiently as the real thing. Critically, SDRs allow radio operators to change their center frequencies, bandwidths, modulation types, bit rates, and output powers dynamically via sensing, autonomously via schedule, or manually via telecommand (useful when trying to avoid interference with other systems). SDRs can also support certain advanced interference mitigation methods, such as "cognitive" radio, where a network of SDRs can dynamically communicate with each other to collectively determine the optimal use of a shared frequency and minimize overall spectrum use and therefore interference. Further, FPGAs can be reprogrammed on the fly, effectively “shape shifting” their virtual component layouts. This ability allows Kepler to keep its satellites up to date merely by patching their software throughout the entirety of their orbital lifetimes. KIPP was the first commercial Ku-band CubeSat system placed in orbit globally, and its specialty characteristics have allowed it to set the CubeSat uplink speed record, demonstrating ~150 Mbps with theoretical capability as high as 300 Mbps. Further still, the SDR is capable of operating using instantaneous channel bandwidths anywhere between 1 kHz and 250 MHz, a feat that analog radios would be hard pressed to replicate.

At the end of the day, KIPP and CASE were important proving grounds for Kepler as a company. They enabled Kepler to field-test and mature its core antenna and radio technology, build out its gateway network, develop compatibility with existing Ku-band user terminals, secure and bring into use the spectrum necessary for operation, and generate early revenue – an immensely powerful milestone for a startup in its infancy. The next step would be to extend the reach of Kepler’s network into the world of small data. The 2010s had seen great excitement for the mass deployment of the “Internet of Things” (IoT), and many of these small, portable devices could be ideally served by satellites in LEO.

6 Low-Throughput Service

In combination with the high-throughput capabilities in Ku-band, the expansion into IoT would mean Kepler’s network might one day reliably provide connectivity services for devices demanding anywhere between 10 kB/month and 500 GB/month. Meanwhile, IoT market growth predictions dwell in the stratosphere, with expectations that related technology spending will increase from the US $151B spent in 2018 to over US $1.5 T in 2025 (Leuth 2018).

A number of other NewSpace companies are aiming to get into the IoT market, but most of them are constraining their targetable devices to narrow specifications. To capture a broader share of the satellite-accessible market and to differentiate from competitors, Kepler’s plan for IoT is to support a swath of low- and medium-data rate applications. This is a technical challenge to be sure, but unlike many other NewSpace IoT companies, Kepler is working to greatly optimize its fixed costs by vertically integrating the ground and satellite sides of its network. To that end, all production-class satellites (i.e., non-prototype) are to be designed, assembled, tested, and staged for deployment in-house at Kepler’s Toronto HQ. All aspects of satellite design from power generation, onboard software, thermal management, and payload operations are managed by a team that effectively works on a single floor. This control is mirrored for Kepler’s user terminals. Kepler has designed its GDS customer modem from the bottom up; and it builds, assembles, and tests each finished product in-house. Powering the GDS modems is a derivative of the same custom SDR technology used on its satellites, a shortcut that saved substantial amounts of non-recoverable engineering time on their design. Lastly, Kepler fields its own technicians to install its GDS user terminals on-site. This level of control begets an enormous amount of flexibility, allowing Kepler to cohesively optimize all aspects of its service from launch to customer product. This approach will be extended to the development of a similar user terminal for IoT. In this case, the terminal will be a small transceiver module capable of direct-to-satellite communication.

These kinds of connectivity modules are useful when attached to sensors and trackers that operate in remote areas or over disparate cellular networks. Examples include animal trackers, whose subjects' migration patterns often lead them away from cell coverage, or rail/marine shipping container monitors that frequently cross borders and travel through poorly connected areas. Such devices are often designed to operate on a single battery charge. To be economical, they must be low cost, use little bandwidth, and be capable of operating for 3–5 years without maintenance, thus requiring low-power transceivers as well. Further, communications must be bidirectional, so that they can receive commands and updates from Kepler's network operations center. Kepler's IoT module has been designed to fit precisely these customer requirements. To handle the simultaneous traffic of thousands of co-located devices, ground and space devices employ an advanced spread-spectrum code division multiple-access scheme. The nature of these IoT devices mean that under international regulations that are categorized as *mobile*. This classification carries some regulatory implications, one of which is that Ku-band cannot be used to service them. Instead, frequencies are available in VHF, L-band, and S-band, requiring Kepler to develop a completely new antenna system.

Lessons learned from the development of the IoT module will further inform the rest of the development of Kepler's network in space. Advances in low-power hardware and communication protocols can be directly extended to Kepler's satellites, where every milliwatt counts. The multi-access scheme developed to manage transmissions from thousands of IoT modules at once can inform Kepler's approach to intersatellite links. Tapping into new revenue streams allows the funding of subsequent waves of satellite deployment.

Because "IoT" is a broad term that encompasses everything from simple thermometers to fully networked cars, device connectivity demands will vary. Thinking back to the location tracker application, such devices need only transmit their location data – a few bytes at most at a time. In contrast, a network of environmental sensors may need to transmit tens to hundreds of kBs. It is important that connectivity options capable of supporting this wide variety are available to customers. Many NewSpace IoT entrants have tailored their technology to focus on one type or the other, but Kepler's ability to leverage both high- and low-throughput data streams will allow its network to support the full breadth of terminal types that span the consumer landscape (Table 1).

Never before has a commercial satellite service been able to offer this level of flexibility. Each technology borrows from the others, mitigating risk and saving R&D expense. The ability to include increasingly diverse devices on its network allows Kepler to build its business gradually, paving the way to the stability that evaded Big LEO. After the foundation is laid, Kepler can pivot to deliver its final aspiration: laying the groundwork for the Internet in Space.

Table 1 Breakdown of consumer business models

Name	Monthly data rate	Cost of deployment	Description
IoT service	~10 kB	<$100	Small, independent remote devices
Small aggregator	100 kB–1 MB	$1000	To support local networks of ~10 devices
Large aggregator	1–100 MB	$5000	To support local networks of ~1000 devices
GDS	1–1000 GB	$30,000	VSAT backhaul

7 The Internet in Space

It has been over six decades since Sputnik first broke the barrier of orbit, but the commercial in-space economy has yet to emerge from gestation. Recently, the launch industry has seen incredible progress with SpaceX pioneering the advent of reusable launch vehicles and paving the way for others to follow. With every dollar that costs-per-kilogram to orbit plummet, the door to the final frontier opens a little wider. Within two decades, non-geostationary orbit will see a flurry of new activity made possible by cheap, ubiquitous access, and Kepler hopes to co-host the welcoming party. All major historical industrial developments are preceded by the laying of infrastructure. Where launch providers lay the tracks, Kepler hopes to raise the towers that bring our connected world beyond.

Visions aside, few outside the space industry are aware that objects in orbit are already plagued with connectivity challenges. In fact, non-geostationary satellites all suffer from one main issue commonly referred to as the *downlink problem*. Simply put, you cannot communicate with a satellite that you cannot see, and non-geostationary satellites are by their nature not always visible. Therefore, you cannot communicate with a non-geostationary satellite unless you have a ground station that can see it at any given time. This problem has dogged satellite operators since the space race, and the simplest way to solve it is to use an intersatellite relay. Such relays handle satellite traffic using the same principle that cell towers do with mobile signals. For Kepler, this task will be the final function of its orbital network.

An excellent example of the downlink problem can be observed in the current business of Earth observation satellites. These suffer from an embarrassment of riches – there is simply too much imagery data being collected for the supporting communications infrastructure to handle. The reality of getting your data back from space is operationally complex, expensive, and oftentimes the bottleneck that restricts a system's capabilities. LEO satellites, like those used for Earth observation, must send their wealth of imagery data back to Earth by contacting a "ground station" whenever they are in sight. Even when leveraging established ground networks, opportunities to send information to an Earth-based station are typically available for less than 40% of the day. With such limited access time, operators can find themselves generating more information than they could ever hope to send back to Earth! In these cases, they are forced to throw away valuable excess data and, in doing so, miss the business opportunities it could have served. Further, this problem of intermittent connectivity, by its very nature, prevents real-time communications between LEO satellites and users on the ground.

Historically, when an entity commissioned a space program, they would also be responsible for developing their own ground stations to "downlink" their information. By analogy, imagine the expense if every mobile phone user in the world had to purchase their own cell towers and operate their own network just to communicate. The individual buildup of this infrastructure may have been a viable solution in the past, but the market landscape of today has greater demands. The lack of a scalable communications system for LEO satellites limits the commercial use of hardware that has already been launched, and as the number of satellites in LEO grows, this acute communications problem will only become more pronounced.

Some companies today are building and operating ground station networks as a service – eliminating the need for customers to build their own facilities. One approach is to aggregate the unused capacity of existing satellite ground systems around the world and make them available to network subscribers. This would allow the owners of those grounds stations to maximize traffic on their networks. Others are building their own ground station infrastructure outright and selling the capacity to customers directly. But even with expansive commercial ground networks, achieving constant visibility is a momentous challenge, requiring dedicated antenna systems to be installed across the entire globe, including the oceans.

Until the Space Shuttle era, governments had largely been forced to accept this problem. Alongside the building of the International Space Station (ISS) and the Space Shuttle, the USA deployed a national space network to solve the communications problem. Investing nearly $5 billion, they launched 13 geostationary satellites that would relay traffic between customer satellites and a visible ground station, allowing them to maintain an always-on connectivity. This system, called TDRSS (Tracking and Data Relay Satellite System, pronounced *tee-driss*), is now more than 20 years old and costs $100 M/yr to maintain. With no line of sight to renew the system, other initiatives have been proposed, such as Europe's EDRS (you guessed it, the European Data Relay System). However, where TDRSS uses radio signals to communicate, EDRS plans to use lasers to transmit data at significantly greater speeds. This presents its own set of challenges, requiring satellites hoping to connect to the system to carry onboard a power-hungry 160 W, 60 kg terminal, which alone is almost 12 times the entire mass of KIPP! Furthermore, TDRSS and EDRS are government infrastructure and as such are burdened with red tape. This is made apparent by the fact that TDRSS users must both fall in line with the priority queue for government users and be approved through a formal process to get access to the service. Once granted, the astronomical cost of connecting satellites sits at a whopping $136 *per minute*.

As Kepler's constellation grows, it will tackle the downlink problem by using its own constellation as a giant relay. Each satellite will act as a mesh node, forming connections with adjacent Kepler satellites to connect orbital customers to the ground in real time. Together, the satellite nodes will form an interconnected network capable of relaying low-power transmissions from nearby spacecraft. These intersatellite links (ISLs) however come with their own technical challenges. One of the largest problems with orbital communication is dealing with "Doppler shift," a phenomenon that causes the frequency of radio waves transmitted between two moving objects to change in proportion to their relative positions (this effect is made particularly strong at orbital velocities). It is the same phenomenon that causes sound waves emanating from a car to change pitch as it passes you on the road. Kepler's satellites travel at over 7 km/s, and attempting to send and receive signals to customer satellites moving at similar speeds in different directions can result in some very distorted radio waves indeed. Kepler has patented its proprietary network architecture that deals with this complex issue. Today, it already operates software on KIPP that manages Doppler shift. This works by tracking the drift in its transmission center frequency as seen from a stationary receiver on the ground. Successive iterations of this functionality will be necessary for establishing reliable ISLs.

Another striking problem is determining the best path that information should take when traveling between satellite nodes. Kepler has devised an algorithm to solve this issue that routes data packets along a node pathway to the closest available ground station in the shortest amount of time. Before all 140 satellites are deployed, however, there may not always be a direct pathway available at any given moment. In the meantime, the network supports delay-tolerant transfer (packets are stored temporarily before being transmitted at the next available opportunity).

Kepler's constellation is to be deployed gradually in several phases. The first includes its *Interstellar*-themed prototype satellites. Its first production-class systems will launch shortly thereafter, beginning with a batch of approximately 16 satellites that will deliver commercial Earth-based connectivity services while also testing future on-orbit technologies. The subsequent generation will sport 50 new satellites, followed thereafter by the full 140-satellite deployment that will come equipped with all of the technologies it needs to support the Internet in Space.

Space is the new commercial frontier. The recent "entrepreneurial space race" has brought with it unprecedented levels of access and opportunity. Upstarts are constantly imagining new uses for the benefits that spacecraft in LEO and beyond can provide. By building a communication network in accommodation of this exciting new economy, Kepler is continually making new discoveries and deriving valuable insights on the promising new world of private space.

8 Conclusion

The satellite communications industry at large has seen widespread transformation over its 60-year lifetime. In the time of Sputnik, space was tightly controlled by government agencies; today it is increasingly dominated by commercial activity. As technology and regulation become more accessible, space networks will continue to transition away from government-led initiatives into private enterprise. Standardization has been the largest catalyst to improving space access in the last two decades, not only for well-funded government organizations but also for entrepreneurs. The dramatic advancements in launch cost and commercial-off-the-shelf components mean that the cost of building a satellite communications business today is equivalent to that of a software-as-a-service company. This, along with new developments in SDR technology and reduced barriers to space, is what has ultimately made Kepler's existence possible.

Kepler's vision is rooted in a long-term view of the needs of this emergent commercial space sector. History has shown that the greatest industrial and economic developments of the past were first preceded by the laying of critical infrastructure. Its aspiration to build the Internet in Space was directly informed by these patterns. Kepler holds the founding belief that the establishment of ubiquitous space connectivity will be required to sustain this nascent, future economy. With this in mind, Kepler has formulated the design of an orbital network of 140 satellites with the line-of-sight to support the communication needs of the future, from Earth to LEO and beyond. Its network was specifically designed for gradual scalability. By incrementally providing services to Earth-based markets, it can navigate many of the revenue pitfalls faced by prior satellite communications businesses. Starting with a high-throughput service to the remote VSAT market in Ku-band, Kepler uses its own proprietary SDR technology to move large quantities of data for users that are otherwise underserved/unserved today. As the number of spacecraft in orbit increases, the network can continually both increase capacity and provide better revisit times for its terrestrial users. Further, its orbital architecture naturally lends itself to support the globally expanding market of remote IoT devices, especially where their terrestrial connectivity is bogged with regulatory restrictions, patchy infrastructure, or cross-border incompatibility. In the long term, this service diversity provides Kepler the ability to overcome challenging market adoption timelines and sustainably grow its business.

With the limited capital expenditure required to set up the network and the ability to refresh its spacecraft technology on a rolling 3–5-year basis, Kepler is well-poised to rapidly advance the state of satellite communications. This progress will be actualized by the variety of technological upgrades added to its network over time, including the pioneering of intersatellite optical communications, to the substantial increase of on-orbit processing capabilities. Each of these technologies will be introduced incrementally to the network and immediately tested in-market, each helping to pave the way to the Internet in Space.

9 Cross-References

- ▶ An Overview of Small Satellite Initiatives in Brazil
- ▶ Planet's Dove Satellite Constellation
- ▶ RF and Optical Communications for Small Satellites
- ▶ The OneWeb Satellite System
- ▶ The Spire Small Satellite Network

References

J. Bloom, *Eccentric Orbits: the Iridium Story* (Grove Atlantic, New York, 2016)

S.J. Chan, The birth and demise of an idea: Teledesic's 'Internet in the sky'. (The Seattle Times, 2002). http://community.seattletimes.nwsource.com/archive/?date=20021007&slug=teledesic070. Accessed 1 Oct 2019

A.C. Clarke, in *Wireless World*, vol 51 (Dorset House, London, 1945), p. 305

COMSAT, About COMSAT. https://www.comsat.com/about-comsat/. Accessed 1 Oct 2019

Eutelsat, History. https://www.eutelsat.com/en/group/our-history.html. Accessed 1 Oct 2019

Inmarsat, Journey into History. https://www.inmarsat.com/news/journey-into-history/. Accessed 1 Oct 2019

K.L. Leuth, State of the IoT 2018: number of IoT devices now at 7B – market accelerating (IOT Analytics, 2018). https://iot-analytics.com/state-of-the-iot-update-q1-q2-2018-number-of-iot-devices-now-7b/. Accessed 1 Oct 2019

Maine Memory Network, Telstar Earth Station, Andover, ca. 1962. https://www.mainememory.net/artifact/26106. Accessed 1 Oct 2019

SES, Our History Highlights. https://www.ses.com/about-us/our-history-highlights. Accessed 1 Oct 2019

Smithsonian National Air and Space Museum, Communication Satellite, SCORE (2019a). https://airandspace.si.edu/collection-objects/communications-satellite-score. Accessed 1 Oct 2019

Smithsonian National Air and Space Museum, Telstar (2019b). https://airandspace.si.edu/collection-objects/communications-satellite-telstar. Accessed 1 Oct 2019

Telesat, History & Industry Firsts. https://www.telesat.com/about-us/telesat-history. Accessed 1 Oct 2019

Thuraya, Who We Are. https://www.thuraya.com/who-we-are. Accessed 1 Oct 2019

The OneWeb Satellite System

Yvon Henri

Contents

Abstract

The majority of the world still does not have access to the Internet, and this "digital divide" is not only an issue in developing countries. Unconnected populations exist in every country, and it is important to find ways to provide universal access to the Internet. Furthermore, the demand for connectivity (Internet and data) is growing exponentially, and existing terrestrial solutions likely will be insufficient. OneWeb is building the world's first global communications network in space to deliver high-throughput, high-speed services capable of connecting everywhere to everyone with new satellite technology and meaningful

---

Y. Henri (✉)
OneWeb, London, UK
e-mail: yhenri@oneweb.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_67

solutions with low latency. OneWeb, by launching the first large-scale mass-produced constellation of satellites in low Earth orbit at 1,200 km altitude, is committed to the sustainable values that will shape the world to help bridge the digital divides that exist so nobody gets left behind.

This large OneWeb constellation of about 650 satellites was scaled down to 288 satellites to restructure its capital financing in 2019, but after having launched 74 satellites it filed for bankruptcy in May 2020. New financing as of July 2020, to be provided by the UK Government and by the Indian mobile network operator Bharti Global, of $1 billion, will apparently allow this system to recover from bankruptcy and still be deployed. The 2021 start of service date mentioned in this article has been delayed due to the bankruptcy.

Keywords

Satellite · Broadband · Latency · Responsible space · Innovation

Abbreviations

GSO	Geostationary satellite orbit
IoT	Internet of Things
ISPs	Internet service providers
ITU	International Telecommunication Union
LEO	Low Earth orbit
LTE	Long-term evolution
Mbps or Mb/s	Megabits per second
MEO	Medium Earth orbit
ms	Millisecond
NDC	Network data center
NGSO	Non-geostationary satellite orbit
PoP	Point of presence
SNP	Satellite network portal
SOC	Satellite operation center
UT	User terminal

1 Introduction: Internet Access Everywhere, for Everyone

Almost half the entire human population is not yet connected to the Internet and when connected the access is limited, both in developing and developed countries. At the same time, the global demand for data, especially mobile data, is growing exponentially, and terrestrial solutions alone cannot keep up. Indeed, new applications will drive continued consumption growth – autonomous cars, virtual reality, and artificial intelligence. Today aviation and maritime mobility are also hampered by the lack of connectivity in the skies and at sea – many areas still underserved, indeed:

- Forty-eight percent of the world's population is not connected to the Internet (ITU's Measuring the Information Society Report 2018). Terrestrial solutions cannot reach everybody economically.
- Growth rate of people connecting for the first time has slowed (M-Lab 2019). The gap in society of digital haves and have-nots is widening.
- Expected increase in IoT connected devices from 8 billion in 2017 to 13 billion in 2020 (GSMA Intelligence Global IoT Connections 2019). High demand for existing connectivity to be faster.
- Seventy-six percent of enterprises looking to cloud applications and platforms to accelerate IT service delivery (IDG Cloud Computing Study 2019). Prioritization of public cloud is happening fast.

2 New Satellite Technology Can Meet the Increasing Data Demand

Only space-based infrastructure can ever provide true geographic ubiquitous coverage of the world. The satellite industry has gone through game-changing transformation in the last decade, not only creating high-throughput satellites for use at the traditional geostationary satellite orbit but, more importantly, developing non-geostationary satellite systems (NGSOs) that are much closer to Earth, thus cutting the latency (delay) in communication to a tenth of what it used to be. With latencies of under 150 ms, these NGSOs are designed to revolutionize wireless broadband coverage for the entire world.

OneWeb's high-speed, low-latency, and global solution are well-positioned to win in these markets.

3 OneWeb's Mission: To Provide Global Satellite Internet Coverage

OneWeb is building the world's first global communications network in space to bring unparalleled high-quality broadband access, low latency, redundancy, security, ubiquity, and opportunity to everyone by:

- Launching roughly 650 mass-produced satellites into the first mass-produced low Earth orbit constellation at 1,200 km altitude
- Initiating seamless global coverage, with customer demonstrations in late 2020 and launch of commercial services in late 2021
- Serving fixed and mobility markets including maritime, aviation, enterprise, cellular backhaul, land mobility, government-civilian, military and humanitarian, and consumer broadband sectors
- Building sustainable practices and environmental stewardship into the business model

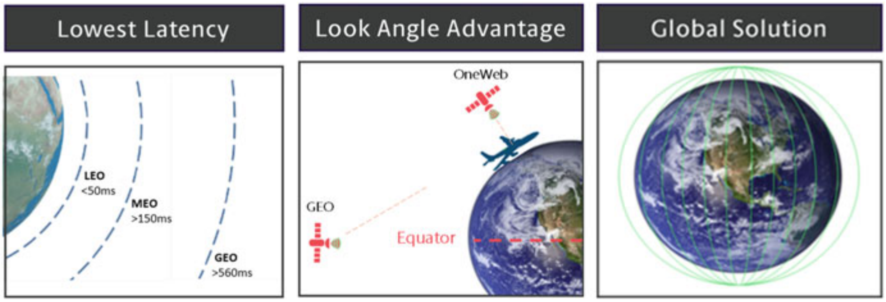


Fig. 1 OneWeb value proposition (graphic courtesy of OneWeb)

To provide global availability, high performance, and low latency (under 50 ms), OneWeb has partnerships to provide low-cost, easily manufactured satellites (with Airbus) and strong partners who are leaders in their respective fields (such as Qualcomm, Softbank, Coca-Cola, Hughes, Grupo Salinas, and Intelsat).

4 OneWeb Value Proposition

Low Latency: OneWeb's network is 30 times closer to Earth than traditional satellite systems, providing services on par with or faster than optic fiber or cable. Most of today's in-demand applications require low latency.

Global Coverage: OneWeb's polar orbiting satellites are designed to logically interlock, creating a coverage footprint over the entire planet. Global coverage means connectivity everywhere: land, sea, or air and even over the poles.

Applications: Machines do not care about latency, but people do. OneWeb's combination of high speed and low latency enables everybody to use all the interactive applications while unlocking totally new applications (Fig. 1).

5 OneWeb System Architecture

The OneWeb satellite system will consist of an initial constellation of 650 or more operational low Earth orbit (LEO) satellites with circular orbits at an altitude of 1,200 km inclined to polar in 12 orbital planes spaced around the equator, with 49 or more satellites evenly spaced in each orbital plane (650 satellite constellation: 588 satellites in service + spares at the beginning). The constellation is scalable as demand increases (Fig. 2).

The system performance with global coverage will provide:

- Terminal download speeds up to 195 Mbps
- $>$ 99.7% availability
- End-to-end latency ideal for real-time applications such as cloud gaming

Fig. 2 OneWeb global coverage (Graphic courtesy of One Web)

- 16-beam "Venetian Blind" pattern per satellite
- Beams are 1,600 km in longitude and 65 km in latitude
- Wi-Fi/2G/3G/LTE/4G/5G experiences

operating in full compliance with the United Nations' International Telecommunications Union (ITU) regulations in:

- User links in Ku-band (10.7–12.75 GHz and 14.0–14.5 GHz)
- Gateway links in Ka-band (17.8–18.6 GHz, 18.8–19.3 GHz, 27.6–29.1 GHz, and 29.5–30 GHz) (Fig. 3)

6 OneWeb Organization and Network Infrastructure

OneWeb headquarters are located in London, UK, along with one of two satellite operation centers (SOCs); the other SOC is in Virginia, USA. There are also ground stations positioned around the world for monitoring and controlling the satellites. Initial locations include Norway, Canada, and Sicily. More than 40 ground stations (satellite network portals/gateways) will be responsible for monitoring the entire OneWeb constellation once it is fully launched. OneWeb will be tracking the positions of each satellite constantly, using automated processes to efficiently manage complex tasks, as well as to predict any potential interference.

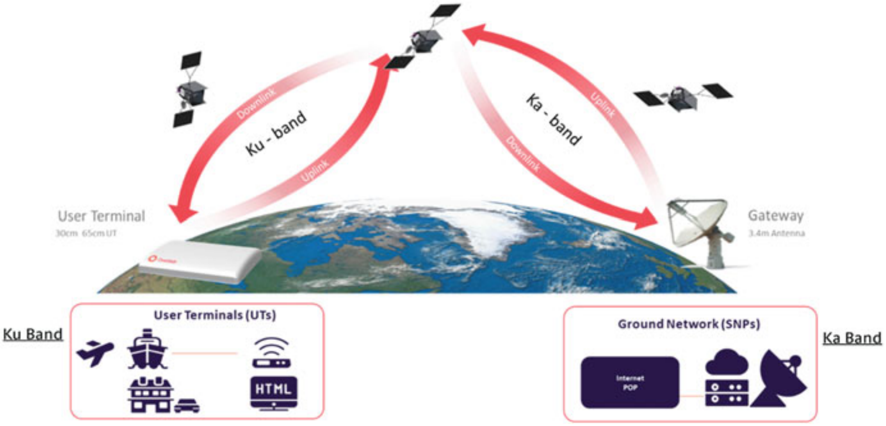


Fig. 3 OneWeb architecture (Graphic courtesy of One Web)

The network infrastructure is deployed in three layers:

- Network data center (NDC): the NDCs will be deployed in key global locations. The data centers will host the authentication, authorization, policy, and user terminal databases.
- Point of presence (PoP): the PoP will connect the OneWeb network to the Internet. PoP will be deployed at key Internet peering points.
- Satellite network portal (SNP): SNPs are the ground stations, deployed to maintain connectivity to the LEO satellites. SNPs are mostly in remote locations that allow large antenna farm arrays. Each site requires between 7 and 30 full motion antennas (16 on average) with 3.5 m Ka-band, circular polarization feed, 2.5 GHz bandwidth, and 2 polarizations (Fig. 4).

The first batch of six satellites was successfully launched on February 27, 2019; a massive launch campaign is on track and has begun with the successfull launch of 34 satellites on February 7, 2020 and with continuing monthly launches of more than 30 satellites per launch with Soyuz (Arianespace) over the next 2 years; commercial service is expected to be launched at the end of 2021.

7 OneWeb User Terminals

The OneWeb user terminal (UT) consists of a satellite antenna, a receiver, and a customer network exchange (CNX) unit, easily deployable and cost-effective intended to be located outdoors in view of the satellites and directly on customer locations. The CNX connects the UT to the customer's network which in turn connects to end-user devices including laptops, smartphones, sensors, and more. These terminals will have fixed antennas that employ phased array antenna technologies or steerable dish antennas to track the moving OneWeb satellites. For security

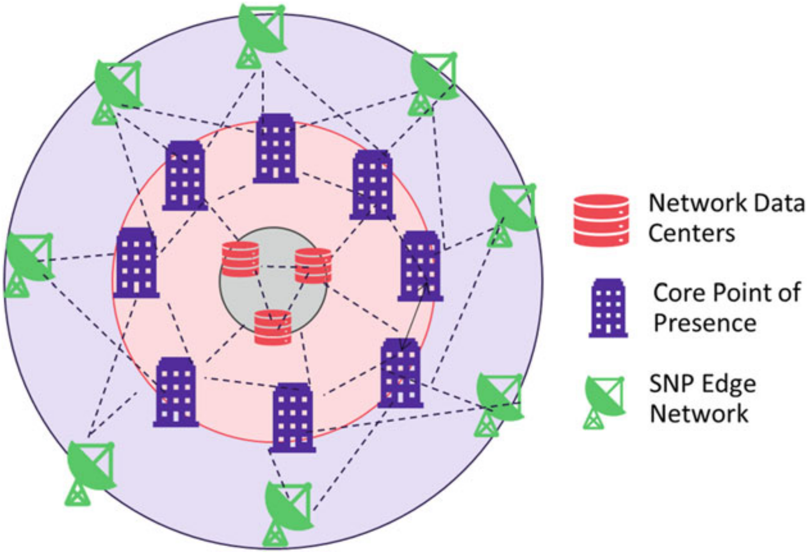


Fig. 4 Network infrastructure (graphic courtesy of OneWeb)

Fig. 5 User terminals (Graphic courtesy of OneWeb)

reason, user terminals on ground are installed at fixed locations, and they are GPS locked; meaning that once installed, it will only work at the installed location. If the location changes, the user terminals will be deactivated.

OneWeb is working with leading vendors to provide a portfolio of high-performance UTs that can be easily self-installed and which will be customized for specific applications within the aviation, maritime, enterprise, cellular backhaul, government, and consumer broadband sectors (Fig. 5).

8 OneWeb Satellites

OneWeb Satellites – a joint venture of OneWeb and Airbus – has found a way to change the economics of space with the opening in July 2019 of the world's first high-volume, high-speed, advanced satellite production facility in Florida (USA).

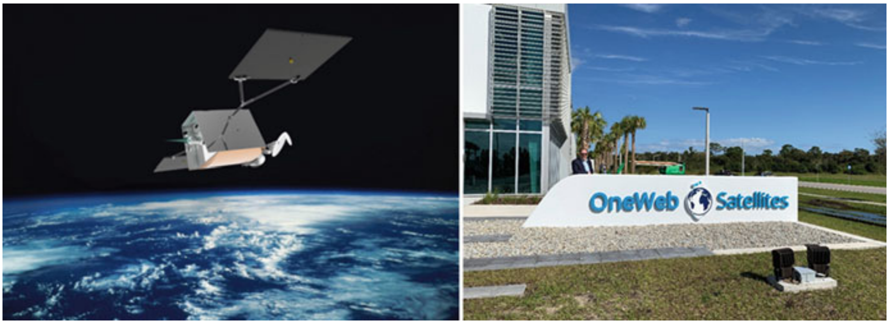


Fig. 6 Satellite and satellite factory (Graphics courtesy of OneWeb)

The factory is designed to produce small, highly efficient satellites at a rate of two per day, at approximately 1/50th of the cost of a traditional manufacturer. The total spacecraft mass is about 150 kg, payload mass about 60 kg with electric propulsion (Xenon HET). The design life of the first satellites to be launched will be greater than 7 years in a 500 km orbit and greater than 5 years in a 1,200 km orbit.

Historically, satellites are individually custom built, costing tens of millions of dollars to build, and it takes more than a year to produce a single one. The OneWeb Satellites facility is the first to employ industrial-scale mass production techniques for satellites, enabling dramatically reduced costs and production times that can deliver one satellite per production shift or two a day, making space technology far more accessible (Fig. 6).

9 OneWeb Market Sector

OneWeb's satellites will provide global connectivity and networking solutions that can influence and enable digital transformations that will change society, industry, and global enterprise.

9.1 Maritime

OneWeb is powering the digital transformation of vessels at sea by providing networking solutions tailored to any need, at any level, replacing one-size-fits-all connectivity with a full spectrum of tailored, customizable broadband channels. The high-throughput, low-latency global network is delivering unprecedented flexibility, lowering the barriers to high-quality maritime connectivity, minimizing environmental impact, and enabling the fleets of the future on all world routes, including the Arctic ones.

9.2 Aviation

OneWeb's vision-led global communications network provides Internet access everywhere, creating new use cases and opportunities for both business and commercial aviation. Business jet passengers consider high-performance bandwidth, speed, and coverage area of onboard connectivity essential for inflight office and travel time. Commercial airlines want to provide ever-improving service quality and incremental value to reflect loyalty. Passengers boarding commercial airlines with mobile devices switched on want a reliable, safe, fiber-like Internet experience in the sky for seamless and uninterrupted access to their emails, social media networks, online games, or applications.

9.3 Enterprise

Enterprise information systems and business functions that once were relatively constant are becoming more agile as organizations turn to more dynamic, digitally powered, cloud-enabled applications to accelerate their IT delivery. OneWeb's connectivity will enable this digitalization process within the enterprise sector, streamlining ISP solutions with low-latency, secure fiber-like connectivity everywhere that offers a competitive advantage, more intelligent interactions, a more skilled and connected future workforce, and operational capability across a wider geographical region.

9.4 Government

OneWeb's global communications network will deliver the levels of reliable and secure throughput that government applications require. The high speed and low latency create new use cases that will enhance decision-making and security to connect those who protect. These include breakthroughs in the commercial mobile communications sector such as increased GPS capability, improved persistent FMV (full-motion video) relay for unmanned aircraft systems, and increased reliance on mobile ad hoc networks. OneWeb's global network also creates new solutions for civil government applications such as border forces, maritime security, disaster management and recovery, and government-funded nonprofit social initiatives in areas such as education.

10 Responsible Space

OneWeb is the only LEO satellite communications company to embed sustainable practices into all corners of its operation, across company culture, production lines, launch processes, and orbit. The term Responsible Space describes practices that drive sustainability within the space industry, to minimize harm and build operations that work for everyone.

OneWeb uses the term Responsible Space to describe a far-reaching framework of principles and best practices on which the company, and other space industry participants, can build a shared commitment to sustainability in space. The fundamental premise is that space is a shared, natural resource which, if used responsibly, can help transform the way people live, work, and interact. Responsible Space also builds on and strengthens work already being done within the broader space community to address this important issue. OneWeb applies the principles and values of Responsible Space into all areas of the business, into design and operational practices, technological innovation, and collaborative partnerships. In this regard, OneWeb announced in December 2019 that a low-cost, advanced grappling fixture shall be installed across the OneWeb constellation that can support a variety of capture techniques for satellite servicing and disposal.

"OneWeb's Responsible Space framework informs who we are and where we are going as a company. With OneWeb's monthly satellite launch campaign beginning at the beginning of 2020 and commercial services starting in 2021, we are committed to seeing the continued advancement and discussion of the issues at stake for the Space community" (Adrian Steckel 2019).

11 Conclusion

The OneWeb satellite constellation is in many ways a game-changing space-based network building the world's first global communications network in space to deliver high-throughput, high-speed services capable of connecting everywhere, to everyone, for low-cost, low-latency access to the Internet. Many of the unique aspects of the architecture, responsible space practices, and aspirations for this new large-scale low Earth orbit (LEO) constellation that is currently being deployed are summarized and described in this chapter.

12 Cross-References

- ▶ An Overview of Small Satellite Initiatives in Brazil
- ▶ Planet's Dove Satellite Constellation
- ▶ RemoveDEBRIS: An In-Orbit Demonstration of Technologies for the Removal of Space Debris
- ▶ The Kepler Satellite System
- ▶ The Spire Small Satellite Network

References

ITU's Measuring the Information Society Report, 2018. https://www.itu.int/en/ITU-D/Statistics/Pages/publications/misr2018.aspx

A. Steckel, CEO of OneWeb, OneWeb Announcement, 2019

The Spire Small Satellite Network

Jeroen Cappaert

Contents

Abstract

This chapter provides a detailed description of the Spire small satellite network from a technical, services, financial and network perspective. It first describes how the Lemur-1 cubesat demonstrated the feasibility of this innovative new system that led to deployment of the Lemur-2 network and the current deployment of a global network of over 80 three-unit small satellites. It also explains how it has evolved through the raising of capital through venture capital rounds of financing.

It describes Spire's complex, diverse, and growing range of services and data analytics as they have evolved to date. These various services include: (i) a range of maritime Domain awareness products; (ii) a variety of critical weather and

---

J. Cappaert (✉)
Spire Global, Glasgow, UK
e-mail: jeroen@spire.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_93

space weather data and products; (iii) innovative air traffic data services including ADS-B automatic dependent surveillance-broadcast (ADS-B) air safety services; (iv) global weather prediction data analytics; and (v) consulting and other support services that helps other get small satellite payloads into orbits. Further, it describes the global ground systems that are designed, deployed, owned, and operated by the Spire smallsat network.

Keywords

Automatic Dependent Surveillance-Broadcast (ADS-B) · Automatic Identification Systems (AIS) · Maritime domain awareness · Cubesat · European Space Agency (ESA) · Global Navigational Satellite Service (GNSS) · Global weather prediction · High frequency launch schedule · LEMUR · Nanosatellites · National Geospatial Administration (NGA) · National Oceanic and Atmospheric Administration (NOAA) of USA · Predictive analytics · Software defined technology · Space-as-a service · Spire small satellite network · Weather prediction data analytics

1 Introduction

Spire is a data and analytics company that collects data from space to solve problems on Earth. Owning and operating one of the largest satellite constellations in the world, Spire identifies, tracks, and predicts the movement of the world's resources and weather systems so that businesses and governments can make smart decisions (e.g., see Fig. 1 for an example data set).

Spire offers a suite of RF sensing products, including AIS-based maritime data and associated predictive analytics products, ADS-B aviation data, and radio occultation-derived weather, atmospheric and ionospheric data. The company operates an expanding constellation of 84 nanosatellites and 31 ground stations. Spire's space operations, data processing, and distribution network are born in the cloud and dynamically scalable.

In addition to RF collection capabilities, Spire offers a space-as-a-service product suite, Orbital Services. This program allows customers to either integrate third-party sensors as hosted payloads or develop custom payloads, leveraging Spire's high-frequency launch schedule and infrastructure to deploy satellites on orbit within 6–9 months of project kick off.

2 Brief History

Spire Global Inc. (previously known as NanoSatisfi Inc.) was founded in 2012 in the USA and opened an office in San Francisco. Spire started work on its first 1U CubeSat satellites, named "ArduSat," which were partially co-funded through the crowdfunding platform KickStarter and had mainly educational applications. The first ArduSats were launched in August 2013 as one of the first Cubesat deployments from the International Space Station (see Fig. 2) and the first commercial satellite

Fig. 1 Example Spire dataset, AIS + ADS-B. (Graphic courtesy of Spire, ©Spire Global)

deployment. ArduSat and the educational applications were later spun out to focus solely on educational technology.

After successful launch and operation of the ArduSat technology demonstrators, Spire built and launched a 3U CubeSat technology demonstrator, LEMUR1, in 2014 as a precursor to its production satellite series, LEMUR2. LEMUR1 had early versions of Spire's AIS and GNSS payloads on-board and validated critical technology elements needed for further production satellites. In the meantime, Spire also opened offices in Singapore and Glasgow, UK.

In 2015, the first LEMUR2 satellites were launched, which kicked off the build-out of the LEMUR2 constellation. As the constellation reached critical mass and more capabilities were added, such as ADS-B in July 2018, data and analytics products were rolled out in the various markets Spire operates in. Spire has since been providing data and services to a large swath of customers, including many commercial entities, NGOs, and government partners (e.g., NGA, NASA, NOAA, ESA, UKMet Office). Since then, Spire has opened further offices in Boulder, CO, Luxembourg, and Washington DC.

Spire has raised multiple rounds of venture funding since its inception from top-tier financial and institutional investors such as BVP, RRE, Promus, Qualcomm, Luxembourg Future Fund, Mitsui, Itochu, GPO, and many others.

3 Business Overview

3.1 Strategic Direction

All of the products that Spire has developed or is developing follow the three strategic pillars the founders have set out from the beginning:

Fig. 2 ArduSat Satellites being deployed from ISS. (Credit: NASA)

- **Use of Software-Defined Technology**: Spire truly believes software is eating the world and collects data with sensors that are programmable and re-programmable in orbit. It is applying Moore's Law to space, making sure Spire's sensors are as up to date as the latest cellphone.
- **Focus on global and timely coverage**: Spire collects data where no one else can, capturing radio frequencies in remote and inaccessible locations where ground-based receivers cannot reach. Whether it is AIS, ADS-B, GNSS-RO, Total Electron Content (TEC), or other types of measurement – Spire monitors signals that can only provide value being detected en masse from space.
- **Quantity over size**: Spire collects data where the number – not the size – of sensors matters most. Each LEMUR satellite can hold multiple sensors in one 3U bus. By using many satellites and payloads rather than just a few, data is updated more often and delivered to the customer in a more timely fashion. Spire makes physics work in its favor.

3.2 Businesses

Spire currently has five main business lines (see Fig. 3):

- **SENSE:** Spire SENSE provides maritime Domain awareness products.
- **STRATOS**: Spire STRATOS provides critical weather and space weather data and products
- **AIRSAFE**: Spire AIRSAFE provides air traffic data for
- **GVM/Weather**: Spire GVM provides innovative global weather prediction fueled by its data
- **CUSTOM/Orbital Services**: Spire Orbital Services provides the opportunity for others to take advantage of the infrastructure Spire's built over the years and get payloads operating in space rapidly.

The business lines are explained in more detail below.

3.2.1 SENSE: Maritime

Spire Maritime uses satellite AIS data and sophisticated APIs to provide maritime awareness solutions for vessel tracking, ship monitoring, and for viewing historic AIS data and predicted positions.

Spire has one of the largest satellite constellations in the world. Spire Sense Cloud gives you access to this industry-leading AIS data. The Standard and Premium APIs let you access AIS data that has been cleansed: data where the noise and redundancies have been removed. For advanced analytics and planning, the cleansed data is much better than the raw AIS feed, which can be full of errors.

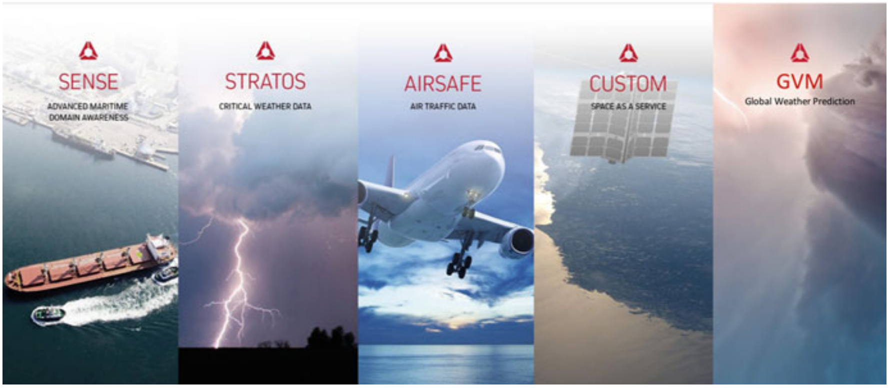


Fig. 3 Spire business lines. (Graphic courtesy of Spire, ©Spire Global)

Spire maritime is pioneering entirely new technologies that are already changing the way maritime data is collected and analyzed. Some examples of Spire Maritime's research and development projects:

- **Predictive analytics**: forecasting ship locations and routing. This is unique, first-in-market technology and is constantly improving.
- **Decollisioning**: Separating AIS signals in high-traffic zones directly from space, improving speed and allowing for more real-time analysis.
- **Weather integration**: Spire's Stratos Cloud is pioneering next-generation weather observation. Fused with Sense Cloud, weather data can increase fuel efficiency and routing among other benefits. Spire maritime also aids the National Oceanic & Atmospheric Administration (NOAA) with their research.

Each of Spire's satellites hosts satellite-based automatic identification system (AIS) receivers (S-AIS) that capture both Class A and B transponder messages, working to ensure global coverage. Spire's geographical focus is on areas generally 50 miles or greater from shorelines, areas outside the range of traditional existing Terrestrial AIS (T-AIS) receiver towers. Spire focuses collection over open ocean and polar regions – areas that are impossible to cover without S-AIS capability – and enhances their S-AIS data with third-party T-AIS data.

3.2.2 STRATOS: Weather Data

The Spire Stratos sensor, which uses signals from global navigation satellites, gathers data about our atmosphere, ionosphere, ground, oceans, and magnetic fields.

GNSS-RO harnesses the power of global navigation systems to capture weather data. As Spire's LEMUR satellites orbit the Earth, they pick up signals from GPS satellites rising and falling on the horizon. These signals, which scrape through the atmosphere, are bent by the moisture that they encounter. Once analyzed, the bent signals tell us a great deal about the temperature, pressure, and humidity of the air on our planet.

Spire is the only commercial entity in the world with the expertise to process raw radio occultation data into measurements to be placed into weather forecasts. Each profile is collected with a Spire satellite and analyzed using Spire's cloud-based processing system. The system is able to scale from thousands to hundreds of thousands of profiles processed per day.

Spire's GNSS receivers continuously track multiple dual-frequency GNSS satellite signals to increase accuracy of their data. Spire tracks all major GNSS constellations, with a 50 Hz frequency of collection. The neutral atmospheric data collected through GNSS-RO has been validated by multiple trusted third parties to be as good or better than that produced by NOAA's COSMIC 1 system, the golden standard in radio occultation.

Spire's GNSS-RO sensor-equipped satellites collect 256 evenly distributed slices of atmospheric data per occultation, measuring from the ground to an altitude of 80 km. In whole, the constellation produces 5000 profiles per day at the time of writing and is still increasing production levels rapidly, collecting both rising and setting occultations.

Spire computes its atmospheric and weather measurements leveraging RO observables including GNSS signal excess phases, bending angles, refractivity profiles, as well as dry and wet temperature and pressure measurements. RO data is collected from antennas in the velocity and antivelocity direction, resulting in a vertical sounding resolution of about 100 m, along-track resolution of about 200 km, across-track resolution of about1 km, and an accuracy of about 0.5 km.

In addition to RO data, Spire collects TEC observations. Spire estimates its ionospheric data to determine TEC to a level comparable to that of COSMIC. The spatial resolution of the associated ionospheric data is estimated to be at about 10 km.

Spire is currently developing a GNSS-Reflectometry (GNSS-R) product that will be supported by two satellites and incorporated into its suite of STRATOS weather products by 2020, as part of a collaboration with the European Space Agency. Through GNSS-R, Spire's satellites will be able to capture and measure GNSS signals that have been reflected off the Earth's surface.

Over oceanic regions, GNSS-R data will provide estimates of sea surface roughness (mean square slope), sea surface wind speed, sea surface heights (altimetry), and sea surface ice extent maps. Over land surfaces, GNSS-R data will provide soil moisture estimates, as well as flood inundation/wetlands extent maps.

3.2.3 AIRSAFE: Aviation

Spire Aviation provides precise position data over land and fills gaps in remote areas of the world that are out of reach of existing ADS-B data collection.

The positional data is enhanced with flight schedule information, aircraft information, and more. With large volumes of position reports every day from over land and sea, Spire Aviation is solving the needs of industries in Aviation and Logistics. Spire's satellites are positioned in areas lacking traditional radar coverage such as over open-ocean, polar regions, and data deserts.

As of July 2018, every new LEMUR satellite is equipped with this capability. Spire is currently working towards growing its ADS-B capable fleet to provide global coverage and performance complying with international regulations.

Spire currently captures four million ADS-B messages from 40,000 aircraft daily but estimates 30 to 40 million per day at FOC. Captured data includes Aircraft Identification (ICAO Address), callsign, speed over ground, vertical rate, latitude and longitude coordinates, barometric altitude and/or GNSS height, aircraft status/operational status/target state, and emergency status.

3.2.4 Weather Prediction

Spire also offers an analytic product referred to as the Spire Operational Forecast (SOF). This is Spire's own global Numerical Weather Prediction (NWP) product which processes its current weather observation data with computer models to form a weather forecast and provide weather prediction alerts. This NWP uses Spire's own proprietary models and input from other global weather models to create an optimized prediction called the SOF. SOF has been specifically developed to meet the needs of commercial and government clients. Spire plans to initially address the weather forecasting requirements of underserved geographic regions and developing nations.

In addition to incorporating Spire's own GNSS-RO data, SOF also incorporates third-party data from NOAA and ECMWF including wave height, sea surface temperature, ocean currents, and sea ice. The model collectively offers the following outputs: surface temperature and winds, accumulated precipitation, cloud cover, land surface temperature and moisture, as well as wind, temperature, and humidity throughout the troposphere and lower stratosphere.

Spire weather forecasts are provided to end users through a set of APIs aimed at allowing the customer to download and manipulate the data on their systems.

3.2.5 CUSTOM/Orbital Services: Space as a Service

Spire works with businesses and government to co-create and deploy customizable data collection satellites within just 6 months. This provides secure, near real-time data from custom payloads fitted to a customer's needs. Spire launches on average every 6–8 weeks and the satellites are built at a rate of up to two per week.

Spire is working with the ESA to demonstrate the power of Space Mission Providers (SMP). As part of the program, Spire is engaging in several demonstration missions that show how Space as a Service can put new payloads in space quickly and at an incredibly reasonable cost.

Spire builds both its own LEMUR satellites, as well as customizable satellites for customers at its facility in Glasgow, United Kingdom. As a supplement to this capability, Spire also offers integration of third-party RF sensors as hosted payloads on its own LEMURs.

Due to Spire's consistent launch schedule and build rate, it can quickly iterate on and deploy satellite capabilities for its customers. Specifically, Spire reports it can deploy a custom satellite within 6–9 months.

4 LEMUR2 Constellation

Spire's constellation consists of 3U LEMUR2 Cubesats. At the time of writing, 84 LEMUR2 platforms are in operations, with a total of over 100 satellites built and launched across over 20 launch campaigns. Twelve satellites have naturally deorbited, and ten were lost in a launch failure in November 2017.

Additional satellites have been shipped to various launch providers, are awaiting launch, or are in the build stages, for a total of about more than 120 LEMUR2 satellites built by Spire's team.

The first LEMUR2 satellites were launched in September 2015 and the most recent ones were deployed in July 2019 (at the time of writing). Seven more launches are manifested in the near future. The Spire constellation has taken advantage of a large number of launch opportunities over the years, working with most of the

Table 1 Spire Launch History

Date (DD/MM/YYYY)	Vehicle	Launch	Orbit
03/08/2013	H-IIB	HTV-4	ISS
09/01/2014	Antares	CRS-1	ISS
19/06/2014	Dnepr	Deimos2	SSO
28/09/2015	PSLV	AstroSat	Equatorial
22/03/2016	Atlas-5	OA-6	ISS
17/10/2016	Antares	OA-5	ISS
09/12/2016	HII-B	HTV6	ISS
14/02/2017	PSLV	Cartosat-2D	SSO
18/04/2017	Atlas-5	OA-7	ISS
23/06/2017	PSLV	Cartosat-2E	SSO
14/07/2017	Soyuz	Kanopus	SSO
11/11/2017	Antares	OA-8	ISS
28/11/2017	Soyuz	Meteor	Failed
12/01/2018	PSLV	Cartosat-2F	SSO
20/01/2018	Electron	Still testing	83°
01/02/2018	Soyuz	Kanopus 2	SSO
20/05/2018	Antares	OA-9	ISS
11/11/2018	Electron	Launch #3	85°
29/11/2018	PSLV	C43	SSO
26/12/2018	Soyuz	Kanopus V	SSO
01/04/2019	PSLV	C45	SSO
05/07/2019	Soyuz	Meteor	SSO

industry's launch brokers and launch service providers. A comprehensive launch history is listed in Table 1.

Due to the constellation being built mostly using rideshare launches, the satellites over a heterogeneous set of LEO orbits, between 400 and 600 km in altitude (see Fig. 4), and between equatorial and SSO inclinations, to form a nearly global coverage pattern (see Fig. 5).

This yields a constellation with excellent revisit time and data latency (e.g., average revisit time over 24 h shown in Fig. 6). Orbit spacing is managed using differential drag techniques.

5 Satellite Engineering and Manufacturing

5.1 LEMUR2 Satellite

Spire's LEMUR2 satellites are flexible multisensor platforms built to operate a variety of in-house and hosted payloads. As mentioned above, Spire currently also commercializes this platform through a "Space-as-a-Service" offering with aerospace and defense customers.

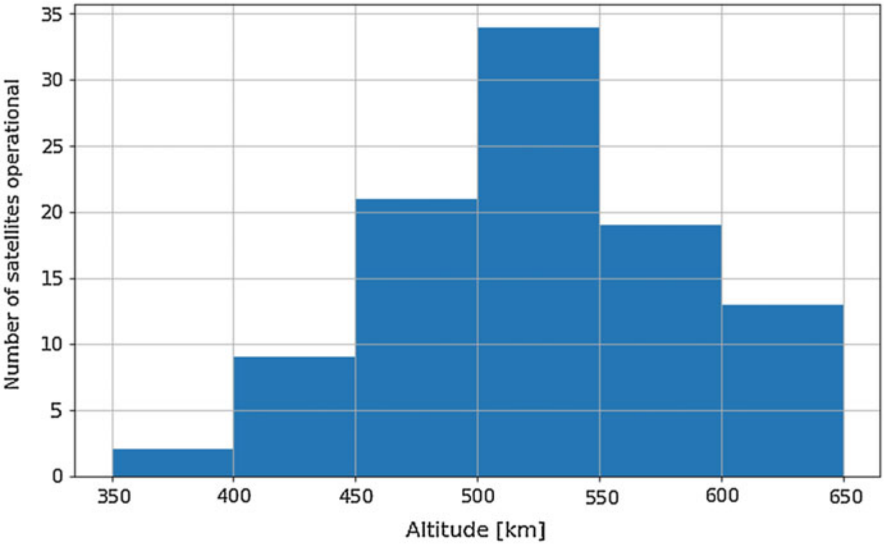


Fig. 4 Current LEMUR2 altitude distribution. (Graphic courtesy of Spire, ©Spire Global)

Spire designs, builds, and tests all of its satellites in-house at its Glasgow offices. The company uses adapted COTS electronics to ensure access to the latest technologies, increase iteration speed, and reduce cost. The satellites are placed in low-Earth orbit and are scheduled to be retired and replaced every 2–3 years. Spire adheres to internationally recognized guidelines for disposal of old satellites.

The satellites are multisensor and carry multiple payloads per vehicle. Spire's production satellite carries all three of its main payloads: AIS, ADS-B, and GNSS sensing. Spire also launches other versions of satellites with more experimental payloads, or to demonstrate critical new technologies, such as a set of satellites with GNSS reflections (GNSS-R) technology, or satellites with a GPU-based parallel computing payload on-board.

The LEMUR2 platform (Fig. 7) is a 3U cubesat, with multiple deployable antennas and solar arrays. LEMUR2s operate on UHF, S-band X-band frequencies. Spire has built over 20 versions of its platform, through four major generations.

As a perk in Spire, employees are each allowed to name one LEMUR2 satellite, which sometimes results in satellite names with interesting stories connected to them, such as "LEMUR-2-CUBECHEESE," "LEMUR-2-SPIREMINIONS," or "LEMUR-2-BROWNCOW."

5.2 Systems Engineering Approach

Spire borrows heavily from agile software methodologies in the ways it thinks about satellite iterations and system engineering. It is a more cyclical and iterative model than is usual in the aerospace industry (see Fig. 8).

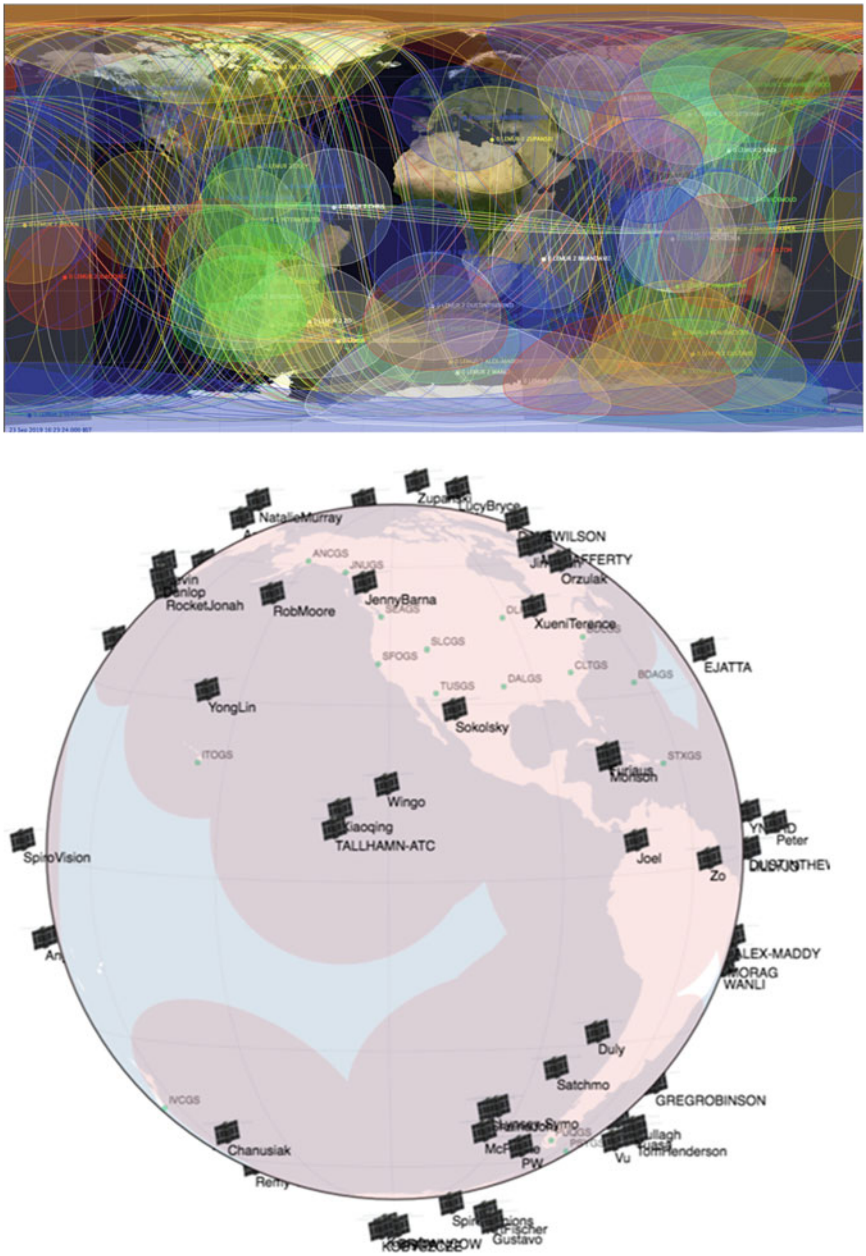


Fig. 5 Current LEMUR2 constellation overview. (Graphic courtesy of Spire, ©Spire Global)

Spire engineering is not afraid to try something new and keeps only as long as it helps to achieve the goals. If something's working, it stays. If it is not working, or not providing progress, the process should be cut out – to not hold on to something just

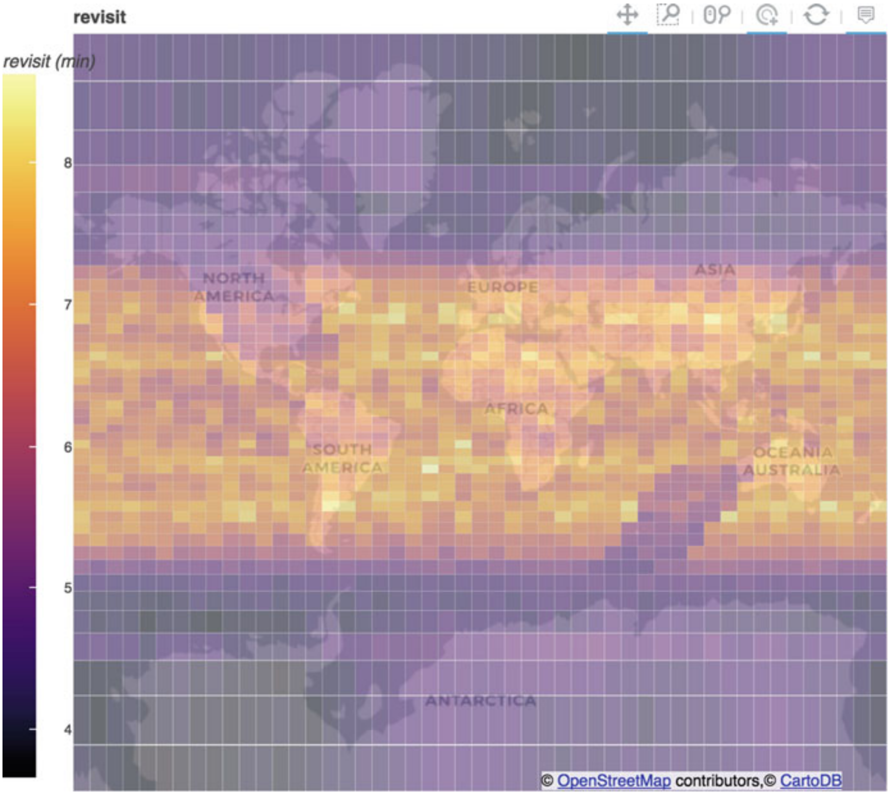


Fig. 6 Example revisit time distribution for LEMUR2 constellation. (Graphic courtesy of Spire, ©Spire Global)

because it has been done in a certain way for a long time. There is nothing sacred about the process itself, only what the process lets us accomplish.

As new feature ideas enter the satellite pipeline following a customer request or need, or following engineering-driven improvements, a standard scope of work is prepared and the systems engineering process is kicked off for the new version of satellite.

At the mission level, the inputs to the process are the mission requirements and objectives. High-level trade-offs are done to determine mission feasibility and overall scope of change to the LEMUR satellite platform. This includes verifying the design budgets (i.e., mass and volume budget, RF budgets, power budget, data budget), any necessary constellation analysis or simulation, high level subsystem trade-offs, and cost and timeline trade-off evaluation. Based on the output of these trade-offs, a high-level feature list is compiled for the satellite system level. If any requirements need to be placed on any of the ground systems (e.g., operations, ground stations), those are identified at this stage as well.

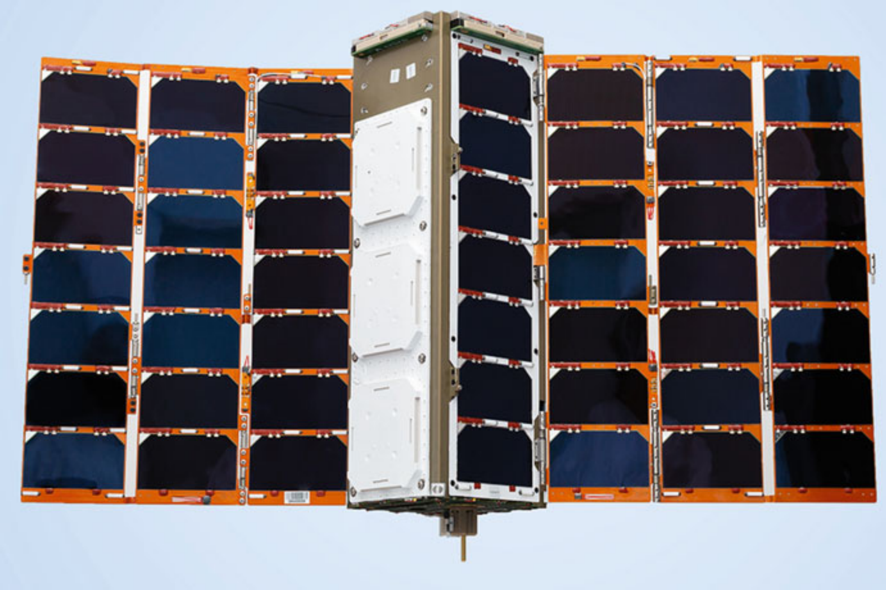
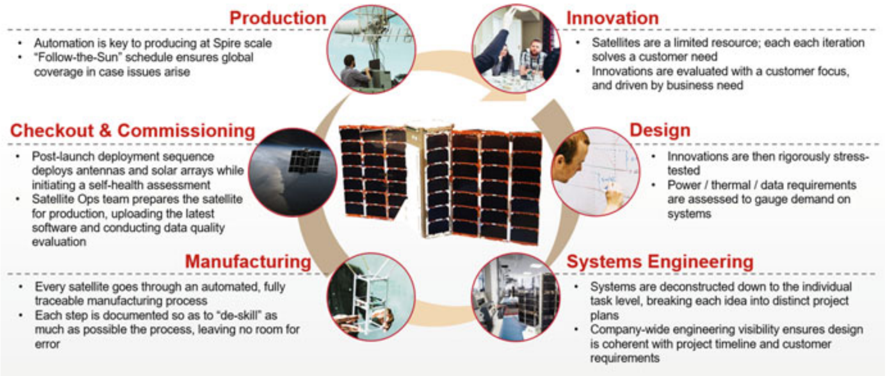


Fig. 7 Spire LEMUR2 satellite. (Graphic courtesy of Spire, ©Spire Global)



Innovation

- Satellites are a limited resource; each each iteration solves a customer need
- Innovations are evaluated with a customer focus, and driven by business need

Design

- Innovations are then rigorously stress-tested
- Power / thermal / data requirements are assessed to gauge demand on systems

Systems Engineering

- Systems are deconstructed down to the individual task level, breaking each idea into distinct project plans
- Company-wide engineering visibility ensures design is coherent with project timeline and customer requirements

Manufacturing

- Every satellite goes through an automated, fully traceable manufacturing process
- Each step is documented so as to "de-skill" as much as possible the process, leaving no room for error

Checkout & Commissioning

- Post-launch deployment sequence deploys antennas and solar arrays while initiating a self-health assessment
- Satellite Ops team prepares the satellite for production, uploading the latest software and conducting data quality evaluation

Production

- Automation is key to producing at Spire scale
- "Follow-the-Sun" schedule ensures global coverage in case issues arise

Fig. 8 Systems engineering approach. (Graphic courtesy of Spire, ©Spire Global)

Once the mission requirements are translated into the system level in the form of a high-level satellite feature list and a set of budgets, the satellite deep-dive review is held with the satellite design team. The output of this review is a detailed requirements list for all satellite subsystems and a list of actions for the system level design. The satellite qualification plan is put together at this stage, as well as the subsystem qualification plans.

Based on the detailed design requirements, the necessary subsystems are (re) designed and go through thorough design reviews. The subsystems all have individual qualification plans that are defined based on the overall satellite qualification plan and the subsystem requirements. Subsystem prototype hardware is acquired and put through the qualification plan.

Then, based on the qualification test report, a go/no-go decision is made to either make alterations to the subsystem design or proceed to acquire flight hardware for the design. In the subsystem qualification stage, all the documentation and test hardware and software needed to hand off the designs to the satellite manufacturing team is completed.

Once all subsystem qualification tests have passed and the necessary prototype hardware is in house, a qualification model (QM) is built. The QM is a full equivalent of what will later be the flight model (FM). The qualification model serves two purposes: it will be used for integrated testing against the satellite qualification plan, and after passing the satellite qualification review the QM will remain on the ground as the representative ground test platform for that satellite revision. At that point the QM is handed over to the satellite operations team.

After the qualification tests have passed, the designs are handed off to the manufacturing team and flight hardware can then be acquired by the supply chain team as necessary for the satellite builds. Each satellite goes through functional and environmental acceptance testing before delivery. At the end of the test campaign, a Certificate of Compliance (CoC) is produced that is signed off by the satellite design team, the manufacturing team, and the satellite operations mission director.

Based on the CoC, a mission readiness review is held before deployment to ensure the satellite operations team is ready to put the satellite into production. The output is a list of action items to prepare the ground systems and satellite operations teams. After initial checkout and commissioning, satellite operations produce a postdeployment checkout report, which indicates the performance of the satellite in orbit and describes any issues found against the checkout procedures.

5.3 Manufacturing and Vertical Integration

Spire does all of its satellite systems design, subsystem design, and satellite manufacturing in-house (e.g., see Fig. 9). Early on, Spire's identified that one of the keys to success in building out a rapidly changing production constellation was owning a much of the supply chain as possible.

Owning almost all of the steps in the satellite value chain has yielded three main benefits:

- **Speed:** Vertical integration enables a higher speed for various reasons: systems knowledge resides in-house allowing faster iteration and issue resolution, test facilities do not need to be booked weeks in advance with no transport required, etc.
- **Reliability:** Insight in all the design aspects and details guarantees the ability to address issues that arise on any level of the design. This enables the ability to guarantee the reliability of the spacecraft to the desired level. For example, the

Fig. 9 LEMUR2 satellites in the Spire cleanroom. (Graphic courtesy of Spire, ©Spire Global)

exact batch of chips assembled onto a printed circuit assembly, or the exact piece of software running on a critical system is always known. While high levels of reliability can eventually be targeted, the immediate benefit is in repeatability and traceability.

- **Control:** This enables faster iteration on all aspects of the chain, across hardware and software, allows fast scaling, and bolsters innovation. It enables the ability to build and include new features very quickly.

The combination of these factors results in the fastest path to high-quality satellites with the lowest amount of risk possible.

While not the main driver, cost is also drastically reduced due to vertical integration. Spire still works with selected vendors and partners, but ensures there is a relationship that is mutually beneficial and often exceeds just a vendor-buyer relationship.

In addition, bringing AIT facilities in house has further sped up the manufacturing cycle, to the point where it is possible to build and test satellites in just a few days (see Fig. 10).

Spire has access to vibration testing, thermal (vacuum) testing, solar testing, magnetic testing, and RF/EMC testing in-house (e.g., see Fig. 11).

To keep track of all the design and manufacturing flows, Spire has developed a comprehensive software suite that allows us to not only track all designs and

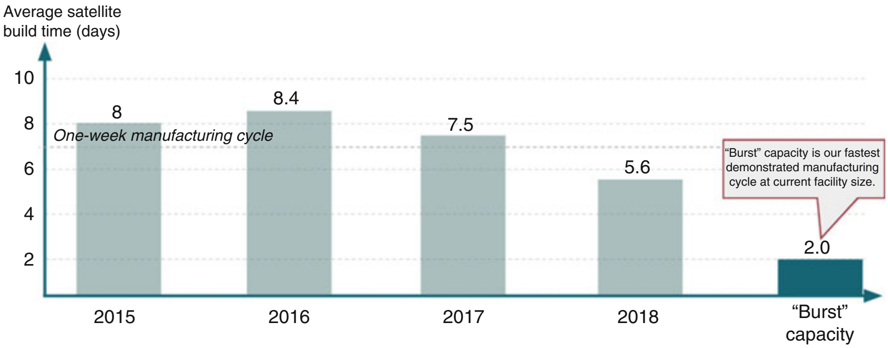


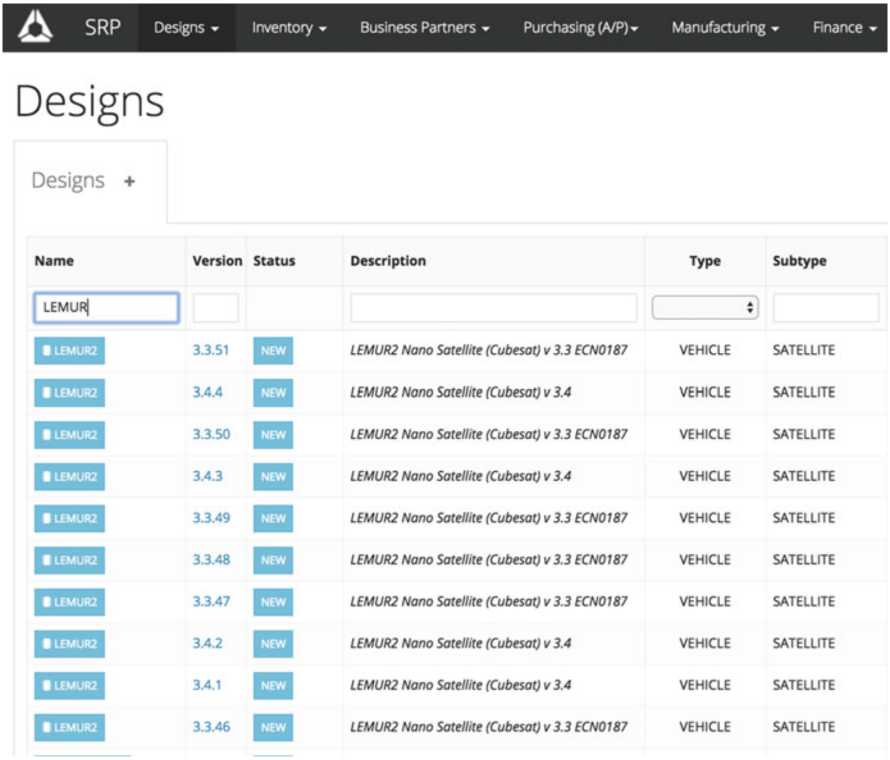
Fig. 10 Spire's build cadence over the years. (Graphic courtesy of Spire, ©Spire Global)

Fig. 11 A Spire technician manipulates a LEMUR2 satellite in Spire's EMC chamber. (Graphic courtesy of Spire, ©Spire Global)

processes but also to ensure all documentation needed to produce satellites is present.

The "Spire Requirement Planning" (SRP) tool (screenshot shown in Fig. 12) provides us with features commonly found in PLM, ERP, and MRP systems, allowing us to effectively bring all design data, supply chain and finance data, and manufacturing data together in the same place.

Design data is kept in the system for all items that are present on the satellite's Bill of Materials (BOM). Detailed design information is made available for the different types of designs (e.g., schematics, mechanical drawings). When new designs are entered in the system, all information for the design items is gradually populated throughout the design cycle, until everything is present, at which point it can be handed over to supply chain to order components and to manufacture satellites. Once hardware is built, it is also tracked in this system, along with all performance and test



Name	Version	Status	Description	Type	Subtype
LEMUR					
LEMUR2	3.3.51	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.3 ECN0187*	VEHICLE	SATELLITE
LEMUR2	3.4.4	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.4*	VEHICLE	SATELLITE
LEMUR2	3.3.50	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.3 ECN0187*	VEHICLE	SATELLITE
LEMUR2	3.4.3	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.4*	VEHICLE	SATELLITE
LEMUR2	3.3.49	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.3 ECN0187*	VEHICLE	SATELLITE
LEMUR2	3.3.48	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.3 ECN0187*	VEHICLE	SATELLITE
LEMUR2	3.3.47	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.3 ECN0187*	VEHICLE	SATELLITE
LEMUR2	3.4.2	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.4*	VEHICLE	SATELLITE
LEMUR2	3.4.1	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.4*	VEHICLE	SATELLITE
LEMUR2	3.3.46	NEW	*LEMUR2 Nano Satellite (Cubesat) v 3.3 ECN0187*	VEHICLE	SATELLITE

Fig. 12 Spire manufacturing backend software. (Graphic courtesy of Spire, ©Spire Global)

data, such that later when satellites are in orbit, there is complete traceability to the subsystem and component level. This is data often used in debugging on-orbit issues or anomalies.

6 Ground Systems

6.1 Ground Stations

Since its founding, Spire has also owned the ground system element of the space data chain. To fully enable flexibility in acquiring data and operating the constellation, control of the ground station network was necessary from day one.

For a constellation operator, it is paramount to have access to every opportunity for a groundstation contact, regardless of whether it is eventually used or not. For us, having the flexibility to schedule (or not) a ground station to optimize constellation contact time is important and would be much harder with only limited windows of opportunity at certain stations, or having to schedule windows well in advance. As a

Fig. 13 Spire Groundstation Network. (Graphic courtesy of Spire, ©Spire Global)

side benefit, it also results in a lower cost given due to only having to guarantee compatibility with Spire's constellation.

Starting with a single groundstation site in San Francisco in 2012, the network has expanded to over 30 sites across the world, with hardware deployed to all 7 continents (current coverage illustrated in Fig. 13).

The network consists of a combination of UHF, S-band, and X-band groundstations (some examples in Fig. 14).

The groundstations operate in bent-pipe mode, which means that no data is ever left un-encrypted on a groundstation. The groundstations are deployed, maintained, and monitored by Spire's own field team. A similar iterative approach to groundstation design as utilized by the spacecraft team is used by the groundstations team.

In addition to the Spire-run groundstations, surge-support ground stations from partner groundstation networks are also used if needed.

6.2 Constellation Management

Operating a large cubesat constellation comes with a few challenges:

- The iterative design approach yields a heterogeneous constellation, where every launched batch might at best have slight hardware differences and at most completely different payloads.
- As satellite software is often updated, various satellites will run different versions of software, even within a single launch batch.
- Each satellite usually develops its own "personality," given the specific hardware it has on board
- Operational priorities can shift based on customer demand.

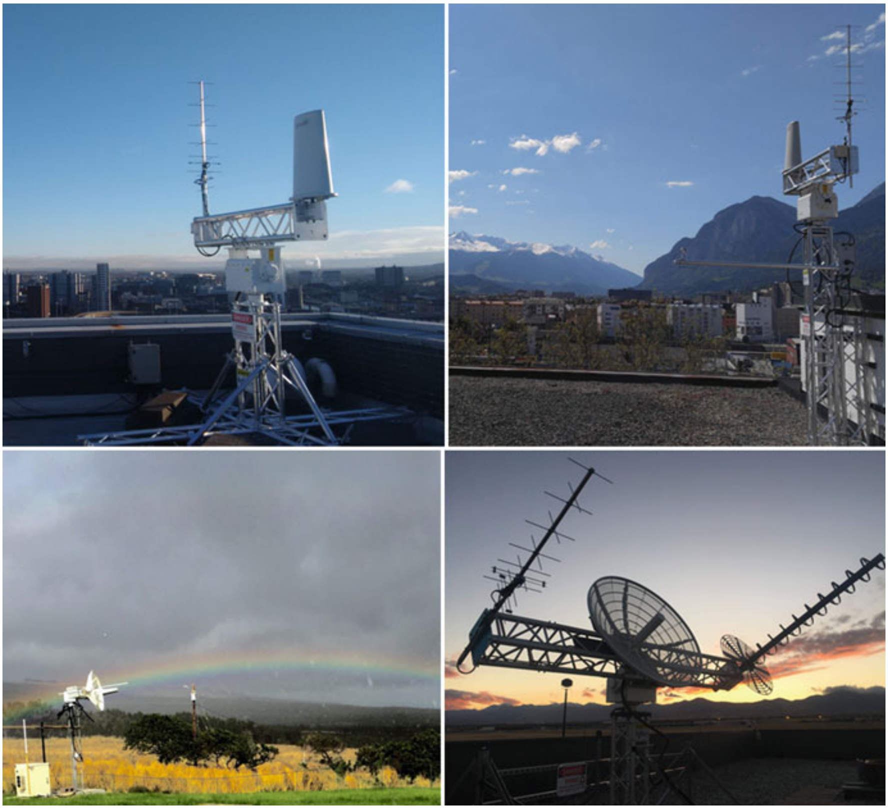


Fig. 14 Spire Groundstation Examples. (Graphic courtesy of Spire, ©Spire Global)

Additionally, all of the above issues are also present for groundstations.

So to be able to operate efficiently a number of backend systems are required.

6.2.1 Per-satellite Configuration

As indicated above, each satellite usually ends up having a unique personality, resulting in the need for a per-satellite configuration database. This database keeps track of things like satellite frequency configuration and licensing jurisdiction, status of subsystems, status of watchdogs, timestamps of the last time maintenance procedures were executed, software interface version, ADCS control mode, telemetry alerting limits, etc. Whenever missions are scheduled and executed, the satellite configuration database is used to determine how to interact with a specific satellite and what software interfaces to use.

In addition, the database also contains groundstation characteristics, so the scheduler (see below) knows which satellites are compatible with which groundstations.

6.2.2 Scheduling, Automation, and Data Management

Managing a few satellites can be done by hand by a team of operators. Managing 20 satellites can be done with a little bit of scripting and simple automation. Managing more than 50 satellites requires a completely different level of automation. Satellites can no longer be thought of as individual assets, but rather the constellation has to be considered as a whole. Assets need to be continually optimized to provide maximum product value.

Two major software systems support this. In space, satellites run a suite of automation software. This software knows for each task that the satellite has to perform the actions it has to take on-board to complete this task and present the resulting data over the next groundstation contract. On the ground, a central scheduler optimizes the schedule for satellite/groundstation contacts as well as for payload operation windows. As the schedule gets synchronized to the constellation, satellites capture the data they are instructed to collect and downlink it as they pass over groundstations (either self-initiated or initiated by uplink commands). As time progresses, based on feedback from the constellation on how captures are being executed, the schedules can be adapted to optimize for customer value. If no major issues arise, no human interaction is required for this system to run and deliver data to APIs.

After the data is downlinked, it is pushed to a downstream processing or analytics system based on the data type, after which it is made available in a customer facing APIs.

6.2.3 Incident Management

Given the level of automation present, the main job of the satellite operations team is not to directly command or task the satellites, but rather to monitor the constellation for any anomalies that might occur, and manage those appropriately. To be able to do this effectively, an incident management system is required, that can link back to operational data, on-ground test results, and any other information that can help resolve the issues at hand. The satellite operations team can then feed this information back to the satellite engineering team as new satellite versions are being developed.

7 Conclusion

Spire's multisensor CubeSat constellation approach has enabled it to quickly build out a suite of diverse and high-quality data and analytics products. Fueled by vertical integration and constant iteration and innovation, it is able to improve data volumes and quality. Turning a proof of concept into a large-scale reliable production system requires a lot of systems and work behind the scenes, which Spire has built over the past 7 years. With all of this in place, Spire is now in the middle of commercializing its product suites and attacking new markets.

8 Cross-References

- ▶ An Overview of Small Satellite Initiatives in Brazil
- ▶ Planet’s Dove Satellite Constellation
- ▶ RemoveDEBRIS: An In-Orbit Demonstration of Technologies for the Removal of Space Debris
- ▶ The Kepler Satellite System
- ▶ The OneWeb Satellite System

An Overview of Small Satellite Initiatives in Brazil

Rodrigo Leonardi and Adriana Elysa Alimandro Corrêa

Contents

Abstract

This chapter presents an overview of past and ongoing small satellite-related initiatives in Brazil and discusses the importance of these initiatives on several fronts such as education, training, research, science, applications, and business opportunities in the context of the Brazilian space sector. For this purpose, a brief history of early initiatives in the 1990s is provided together with a description of recent national small satellite projects, from mini down to pico-space objects, and an examination of synergies with other space activities in Brazil. This compilation of the major facts about the use of small satellites in Brazil is a helpful contribution for professionals interested in space activities in the country and in South America.

R. Leonardi (✉) · A. E. A. Corrêa
Directorate of Satellites, Applications and Development, Brazilian Space Agency (AEB), Brasília, DF, Brazil
e-mail: rodrigo.leonardi@aeb.gov.br; adriana.correa@aeb.gov.br

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_68

Keywords

Brazilian small satellites · South American small satellites · Brazilian space agency · INPE · Brazilian multi mission platform · Amazonia-1 · Nanosatellites · STEM

1 Introduction

Early studies and efforts to develop small satellites in Brazil can be traced back to COBAE, which was a commission, created in 1971, with the purpose of providing advice for the Brazilian government about the development of space activities in the country. COBAE activities were important to enable the very first satellite developed entirely in Brazil – more specifically at the Brazilian National Institute for Space Research (Portuguese: *Instituto Nacional de Pesquisas Espaciais*; INPE) – named SCD-1, a small satellite with a mass of 115 kg, that was launched into space by a Pegasus rocket in 1993 with the mission of receiving and retransmitting environmental data, from ground and ocean automatic data collection platforms, to tracking ground stations.

But the very first Brazilian small satellite launched into space was actually an initiative of one single individual. The small satellite Dove-OSCAR 17 was a Brazilian educational and an amateur radio satellite developed by Mr. Júnior Torres de Castro, an engineer from the state of São Paulo, using resources of his own. Dove-OSCAR 17 had a mass of about 13 kg and was launched in 1990 by an Ariane 4 launch vehicle as a piggyback of the French satellite Spot 2. It carried on-board a Digital Orbiting Voice Encoder designed to transmit synthesized voice messages and telemetry data. Although it was proposed and executed by a Brazilian engineer, the project took place at AMSAT Labs, Colorado, USA. Nonetheless, it is considered a Brazilian space object indeed by the United Nations Office for Outer Space Affairs.

These two small satellite projects, SCD-1 and Dove-OSCAR 17, followed very different paths and approaches to fulfill their missions. SCD-1 was a government planned and executed mission using national engineering and resources – what one would refer these days as the traditional approach – while Dove-OSCAR 17 was a bottom-up mission of opportunity with enormous support from international partners and with some elements of what one would refer these days as lean approach. But both were definitely pioneers of the small satellite category in Brazil and, back then, very innovative projects. And after them, Brazil embarked on other space projects, although did not maintain a constant flow of small satellite missions, as can be seen in Table 1 that displays a timeline of Brazilian space objects, under 500 kg, launched into space.

Meanwhile, Brazil established its space agency in 1994, and, since then, the Brazilian Space Agency (Portuguese: *Agência Espacial Brasileira*; AEB) is the civilian entity responsible for the country's space policy and program. Besides, in the aftermath of the tragical Alcântara VLS Brazilian launch vehicle accident in 2003, Brazil actually prioritized medium (e.g., China-Brazil Earth Resources

Table 1 List of Brazilian space objects under 500 kg in reverse chronological order of launch

Object	Year	Launch vehicle	Main organization	Mass [kg]
FloripaSat	2019	Long march 4B	UFSC/AEB	1
Itasat	2018	Falcon-9	ITA/AEB	5.2
Tancredo-1	2017	H-2B	Escola Tancredo Neves/INPE/AEB	0.7
Serpens	2015	H-2B	UnB/AEB	4
Aesp-14	2015	Falcon-9	ITA/AEB	1
NanosatC-Br1	2014	Dnepr	INPE/UFSM/AEB	1
Unosat	2003	VLS[a]	UNOPAR	9
Satec	2003	VLS[a]	INPE	65
Saci-2	1999	VLS[a]	INPE	80
Saci-1	1999	Long march	INPE	60
SCD-2	1998	Pegasus	INPE	117
SCD-2A	1997	VLS[a]	INPE	115
SCD-1	1993	Pegasus	INPE	115
Dove-OSCAR17	1990	Ariane 4	Eng. Torres de Castro	13

[a] The satellite was lost due to a launch failure

Satellite CBERS) and large (e.g., Geostationary Defense and Strategic Communications Satellite SGDC) space objects initiatives. But, recently, after more than a decade without expressive results on space objects under 500 kg, there is again a small satellite trend gaining visibility and importance in the Brazilian space sector. This chapter offers a compilation of the major facts about the use of small satellites in Brazil as a helpful contribution for professionals interested in space activities in the country and in South America.

The chapter is organized as follows. Section "Multi Mission Platform" contains a description of the basic elements of the Brazilian Multi Mission Platform for mini satellites. Section "Amazonia-1" presents the satellite Amazonia-1, scheduled for launch in 2020, and the associated technological challenges and gains. Section "Brazilian Nanosatellites" summarizes the current scenario of nanosatellites in Brazil. Section "Launch Vehicle for Small Satellites" reports some Brazilian initiatives that aim to provide access to space for small satellites. Section "Educational Initiatives" provides comments on the importance of small satellites for science and technology education. Lastly, section "Conclusions" offers a view of future opportunities and conclusions.

2 Multi Mission Platform

The Multi Mission Platform (MMP) is a generic platform for mini satellites developed in Brazil (e.g., (INPE)). Its service module – a satellite mounting platform with a mass of 250 kg – provides all necessary resources to support the operation, in orbit, for payloads up to 280 kg. The project is a joint effort of INPE and AEB, and it is one of the most important initiatives Brazil has carried out in the field of small satellites. Its propulsion, solar generator, thermal control, and mechanical structure subsystems were completely developed and manufactured in Brazil. The attitude and orbit control and on-board supervision subsystem were developed in cooperation with Argentina, and the power supply was designed in Brazil using hardware available in the international market. One of the main drivers of the MPP project is to allow the reduction of costs and development time of small satellites that adopt its service module as a reliable solution for their mission (the MMP serves primarily as a platform for small objects, but it is also suitable for satellites with a mass slightly above 500 kg). The MMP is planned to be qualified in space through the Amazonia-1 mission. Additionally, INPE and AEB have already carried out conceptual studies for future uses of the MMP such as Synthetic-Aperture Radar (SAR) applications and Ocean monitoring. The MMP is a project with considerable participation of Brazilian space companies. Figure 1 displays a schematic view of the MMP.

3 Amazonia-1

The Amazonia-1 is the first Earth Observation satellite based on the MMP, and it was designed, integrated, and tested in Brazilian facilities (e.g., (INPE da Silva et al. 2014; Chagas and Lopes 2014)). INPE and AEB are working together to ensure success of this Sun synchronous (polar) orbiting satellite that aims to generate images over the Brazilian territory in order to observe and monitor the Amazon rainforest, especially deforestation in the region, as well as the diversified agriculture throughout the country with a high revisiting rate – 5 days – working in synergy with existing environmental INPE programs and Amazon deforestation databases such as PRODES and DETER. In addition, it is expected that Amazonia-1 data would be useful as well for monitoring coastal zones, reservoirs, forests, and disasters.

For this purpose, it carries on-board a wide-view optical imager capable of observing a range swath of approximately 850 km with 60 m resolution in four spectral bands – visible and near-infrared. The high revisiting rate is extremely valuable in applications for deforestation monitoring and alert in the Amazon, as it increases the likelihood of capturing useful images in the face of cloud cover in the region. The Amazonia-1 satellite consists of two independent modules: a service module, which is the MMP, and a payload module, which houses imaging cameras and equipment for recording and transmitting image data. The MMP has the purpose of bringing together in a single platform all the equipment that performs functions necessary for the maintenance of a satellite – pointing, power generation, thermal control, data management, and communication service.

The Amazonia-1 satellite is a very important milestone for the Brazilian space sector, and it is scheduled for launch in 2020 on a PSLV launcher. Figure 2 shows the Amazonia-1 through AIT at INPE and some subsystems developed and

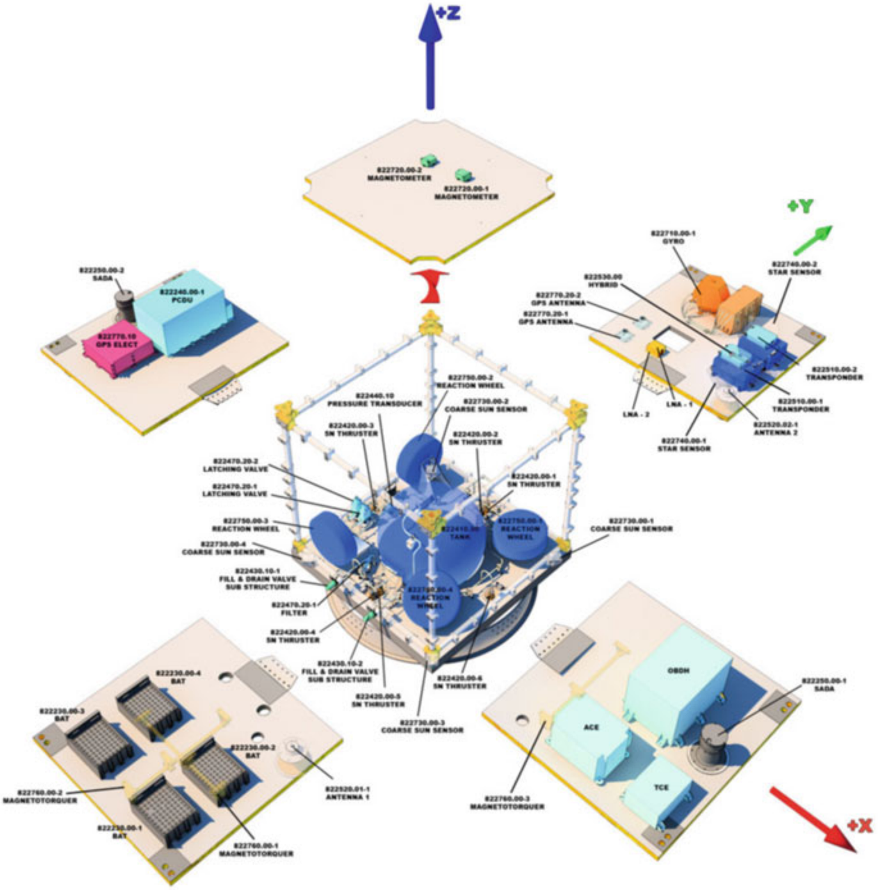


Fig. 1 Schematic view of the Multi Mission Platform embedded in a Cartesian coordinate system. On top (+Z), two magnetometers are positioned as part of the Attitude Control and Board Supervision Subsystem – ACDH. The ACDH also contains the On Board Data Handling (OBDH) computer (+X), the Attitude and Orbit Control System (AOCS) computer, propulsion control electronics (−Z), Sun sensors (−Z), star sensors (+Y), gyros (+Y), reaction wheels (−Z), magnetorquer (+X and Y), GPS receivers (−X), and on-board control and control systems software, embedded in their computers. The propulsion subsystem is positioned at the bottom (−Z) and contains thrusters, valves, filters, propellant tank, pressure transducer, and pipe assembly. On the +Y side also are positioned the antennas, part of the telemetry and remote control subsystem (TT&C), and the transponders. On the Y side are positioned other antenna and the batteries, part of the power supply subsystem. The power supply subsystem also contains the power distribution and conditioning unit (PCDU), positioned at -X side, and the solar generator drive group (SADE and SADA), at X and + X sides. During the nominal operation mode, the -Y face would be always pointed to Earth. In emergency mode, the satellite attitude control would point -Z facing the Sun, in order to warm up the propulsion subsystem elements, and two rotations per orbit would be imposed around the Z axis, in order to distribute external heat loads equally on the lateral panels. (Courtesy image from INPE)

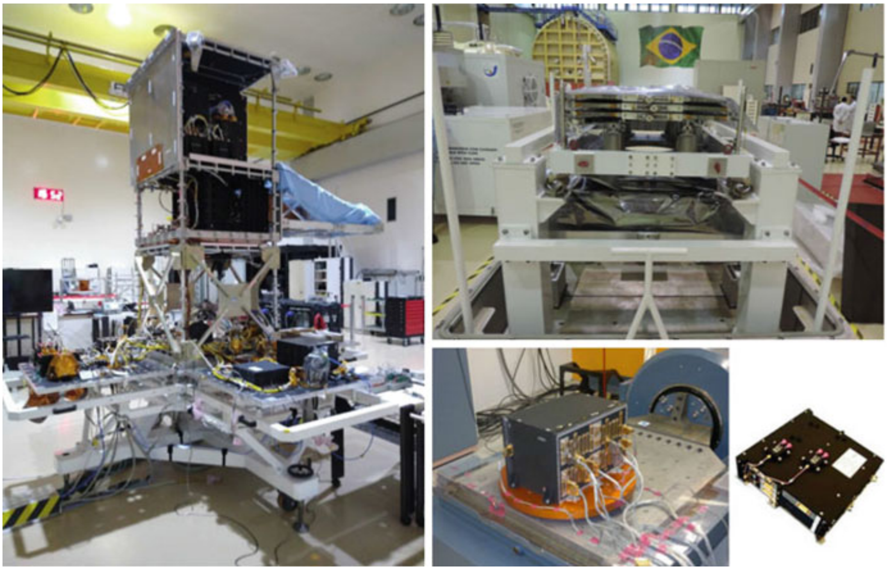


Fig. 2 *Left*. The satellite Amazonia-1 through AIT at the INPE Integration and Testing Facility in São José dos Campos. *Upper right*. The solar generator subsystem of the MMP fully developed and manufactured in Brazil. *Bottom center and right*. Components of the MMP attitude and orbit control and on-board supervision subsystem developed in cooperation with Argentina. (Courtesy images from INPE)

manufactured in Brazil and in South America. This important mission is driven by Earth Observation demands and an agenda that places national industry participation and national capacity building in strategic technologies among the central objectives of the Brazilian Space Program. About 60% of the budget resources destined to the development of the Amazonia-1 satellite were destined to contracts signed by the national industry for the development and manufacture of subsystems and equipment. More specifically, the following equipment/subsystems were developed by Brazilian companies: service and payload module structure (Cenic Engenharia), solar generator (Orbital Engenharia), propulsion (Fibraforte), WFI Camera (Equatorial & Opto), X-band antenna and remote terminal unit (Omnisys Engenharia), digital data recorder (Equatorial Sistemas), and DC/DC (AEL Sistemas). The main technological gains for the Brazilian space program resulting from the Amazonia-1 mission are:

- The qualification of the MMP as a space system, improving reliability and significant reductions in schedules and costs for the development of future satellite missions based on this platform.
- Consolidation of the knowledge in Brazil of the complete cycle of development of stabilized satellites in three axes, also gaining maturity in the activities of integration and satellite tests.
- Development of the propulsion of the attitude and orbit control subsystem in the national industry, although using parts acquired abroad.
- Development in the national industry of the opening mechanisms of the solar panel.

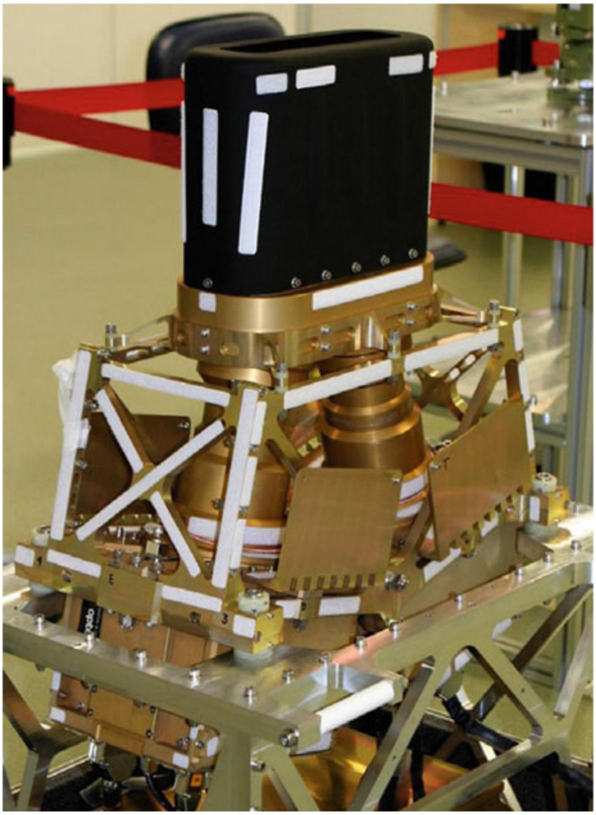


Fig. 3 Wide Field Imager (WFI) Camera developed in Brazil. (Courtesy image from INPE)

- Country capacity to carry out Launch and Early Orbit Phase (LEOP).
- Reliability, as future missions will benefit from project maturity.

Together with the satellite itself, the payload subsystem was also developed and manufactured in Brazil. The Amazonia-1 imager is a Wide Field Imager (WFI) Camera developed and used in the CBERS Program, therefore, an equipment already with flight heritage. The design, assembly, integration, and testing of signal processing electronics and mechanical and thermal design, assembly, integration, and testing of the camera were all performed in Brazil. Figure 3 shows the Amazonia-1 WFI payload camera.

4 Brazilian Nanosatellites

Nanosatellites represent an important technology trend of the global space segment and – in this satellite category – CubeSats are a good tracer of the growing demand for small satellite space applications and solutions. These platforms are being used for several space applications, such as education, Earth remote sensing, science, and defense as well described and analyzed in (Villela et al. 2019).

More than a thousand CubeSats have been launched over the past two decades. And, until the end of 2019, 16 CubeSats assembled in South America – 5 of them in Brazil – have been launched into space. Brazilian universities are playing an important role in proposing and developing CubeSats in Brazil. The NanoSatC-Br1 was the first Brazilian CubeSat launched into space. It was a 1U CubeSat proposed for studying the South American Magnetic Anomaly (Schuch et al. 2019). It was followed by Aesp-14, a 1U CubeSat for testing subsystems developed in Brazil (Bürguer et al. 2014); Serpens, a 3U educational CubeSat for research university experiments (Ishioka et al. 2016); Itasat, a 6U CubeSat designed to serve as a platform for future missions as well as testing Brazilian experiments, a transponder, a GPS receiver, and a radio amateur communication device (Shibuya Sato et al. 2019); and FloripaSat, a CubeSat carrying an ITAR-free FPGA, and a single-event upset counter (Slongo et al. 2019). All these projects share the common goals of capacity building, hands-on training, and Research and Development (R&D) under university leadership. All these objects were sponsored by AEB. And the latest object in this timeline, FloripaSat, had the opportunity of being launched as a piggyback of another Brazilian satellite, the CBERS-4A – a remote sensing space object with a mass of 1980 kg – in a classic example of when the AIT activities of a CubeSat have to be synchronized with the project schedule of a much larger satellite. An illustration displaying some Brazilian CubeSats and their respective payloads is shown in Fig. 4.

And other missions are already in the pipeline getting ready for launch. The NanoSatC-Br2 is a Brazilian 2U CubeSat envisaged for studying the Earth's magnetic field. Sport is a NASA-AEB-INPE-ITA – Technological Institute of Aeronautics (Portuguese: *Instituto Tecnológico e Aeronáutica*; ITA) – joint science 6U CubeSat mission targeting space weather, more specifically, to study the preconditions leading to equatorial plasma bubbles and scintillation in the ionosphere that disrupt radio communication systems, satellite technologies, and Global Positioning System (GPS) signals (Loures da Costa et al. 2018). The United States provides the science instruments and launch, Brazil provides the spacecraft (a legacy from the Itasat mission) and the operations, and the scientific data analysis is jointly done by Brazilian and North American scientists. The Sport mission is a prime example where a nanosatellite proves to be an excellent framework for engaging in international collaboration.

Despite the fact that the number of CubeSat-based space missions in Brazil is still modest, there has been an increase of initiatives resulting in a scenario where Brazilian CubeSat missions are going beyond the goals of R&D and aim to deliver quality data for science and services. In the proceedings of the Brazilian Aerospace Congress held in 2019 (Anais 2019), there are several proposals for CubeSat-based missions and nanosatellites associated technology: Raiosat is an INPE 3U CubeSat mission aiming to detect and study lightning flashes; NanoMirax is an INPE initiative, in partnership with a Brazilian startup, to detect cosmic explosions in X-ray with a CubeSat platform; and Conasat is an INPE proposal for putting in place

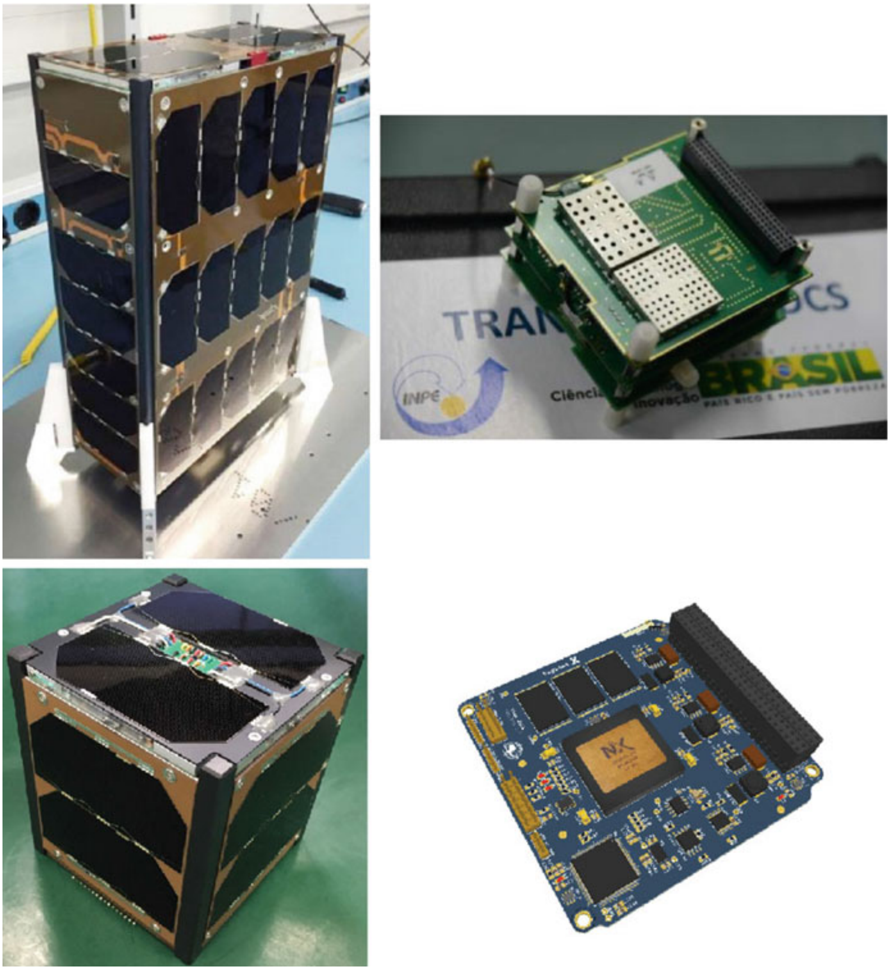


Fig. 4 Latest Brazilian CubeSats launched into space as displayed in Table 1. *Top row.* A picture of the 6U Itasat protoflight model and one of the payloads, a Data Collection Transponder. *Bottom row.* A picture of FloripaSat and one of the payloads, a board for testing an ITAR-free FPGA. (Courtesy images from ITA, INPE, and UFSC)

a CubeSat constellation for environmental monitoring. Furthermore, a few other missions are being proposed by different Brazilian stakeholders, for instance, Garatéa-L is a private enterprise to send a CubeSat to the Moon; Alfa Crux is an university initiative to establish a CubeSat constellation to provide communication links in regions of difficult access; and Brisa is a CubeSat proposal, from a Brazilian think-tank organization, for SWIR applications. Although a complete list of proposals being discussed in the Brazilian community is beyond the scope of this overview, it can surely state that these missions are a driver for further small satellite-related research and development. Just browsing (Anais 2019), one would find ongoing research in Brazil on nanosat as, for example, battery and solar panels, UHF and S-Band antennas, space tethers, transponders, and payloads.

A survey carried out for the United Nations/Brazil Symposium on Basic Space Technology (Creating Novel Opportunities with Small Satellite Space Missions, Natal 2018), co-organized by the United Nations Office for Outer Space Affairs and the Government of Brazil, identified a Brazilian network of 253 colleagues contributing to the field of nanosatellites. Half of them held a PhD, 24% held a MSc, 23% were grad students, and 3% were high school students. This statistic clearly shows that students are a significant part and a driving force in the Brazilian nanosatellite community.

In parallel, the Brazilian industry is also investing efforts to explore nano-platforms for offering their services and products. For instance, the Vcub is the first CubeSat proposed, designed, and developed by a Brazilian company, Visiona, a joint venture between Embraer and Telebrás, in search of a sustainable business model, precision agriculture, for instance, based on nanosatellites. Some other Brazilian companies (e.g., Criar Space Systems) and startups (e.g., Cron *Sistemas e Tecnologias* Ltda) are also taking a chance in the nanosatellite segment.

5 Launch Vehicle for Small Satellites

Brazil has a long and successful tradition with sounding rockets (e.g., VSB-30). But the country has not yet developed a national launch vehicle for inserting space objects into a stable orbit. This is in part a fallout of the Alcântara – Maranhão State – accident in 2003, when an explosion, caused by the accidental ignition of 1 of the 4 engines of the Brazilian rocket VLS, conceived for inserting small satellites into orbit, caused the tragical death of 21 people, together with the loss of the rocket, 2 small satellites, and the surrounding infrastructure, and resulting in a setback to the plans of a Brazilian launcher. Subsequently, a launch vehicle cooperation between Brazil and Ukraine did not deliver results as expected, turning it into a complicated situation to deal with. But Brazil efforts of developing a national launcher continues.

Nowadays, the Brazilian Aeronautics and Space Institute (Portuguese: *Instituto de Aeronáutica e Espaço*; IAE) is developing a Microsatellite Launch Vehicle named VLM. In order to achieve this objective, Brazil has developed and qualified a solid rocket motor, named S-44, with a performance of about 38kN of average thrust and 277 s of vacuum specific impulse, and is qualifying a solid rocket engine, named S-50, designed to have about 440kN of average thrust and 266 s of sea level specific impulse. Considering the current status of development of the S-50 solid rocket motor, some concepts for a Brazilian launch vehicle configuration to deliver small satellites to low-Earth orbit – from the Alcântara Launch Center, Brazil – would be capable of sending payloads in the range of 350–750 kg in a variety of orbit inclinations, as described in details in (da Cas et al. 2019). If Brazil succeeds in this endeavor, the strategic importance of small satellites for the Brazilian space program would be greater than ever.

Similar to what happens to nanosatellites, new stakeholders are also taking a chance in the launch vehicle segment. For instance, the Acrux Aerospace Technologies is a Brazilian startup proposing a rocket for small satellites.

Additionally, Brazil and the United States have celebrated in 2019 a technology safeguards agreement (TSA) in order to allow commercial launch activities from the Alcântara Launch Center. There is expectation that with this TSA in place, Brazil would play a part in the launch market, including offers of access to space for small satellites.

6 Educational Initiatives

Small satellites are an excellent venue for promoting space science and technology education, and AEB has been exploring them to conduct STEM activities, organize workshops and events, as well as continuously promote human capacity building for national space activities.

In 2017, AEB inaugurated in Natal, a space camp named CVT-E – Space Technological Vocational Center (Portuguese: *Centro Vocacional Tecnológico Espacial*; CVT-E) – located in the *Barreira do Inferno* Launch Center (Portuguese: *Centro de Lançamento da Barreira do Inferno*; CLBI) (Goncalves and Gurgel Veras 2016). The CVT-E has proven to be an important vector for educational social inclusion through space science and STEAM activities. Through hands-on activities based on interdisciplinary core principles, students have the opportunity to learn about the importance of space activities for the country and the world. In addition, they can know a little about the last projects developed in the space area and about what are the first steps to specialize in this area in the future. Some activities performed at CVT-E are rover workshops, CanSat (development, assembly, testing, clean room, operation, etc.), planetary sessions, and studies about space transportation, launch centers, astronomy, astronautics, and other relevant subjects. Over 3000 elementary and high school students have attended the CVT-E experience throughout 2018 and 2019. An example of an educational outcome of this center, a CanSat kit developed by CVT-E students, was presented at the second International Academy of Astronautics Latin American Symposium on Small Satellites (Guedes et al. 2019).

Another important educational initiative is a picosatellite developed by students from the Tancredo de Almeida Neves public school in Ubatuba, São Paulo, with technological support from INPE. The project has seen encouraging results toward promoting students interest in engineering, science, and technology, especially in Aerospace Engineering, by the assembly, integration, testing, coding, and launch of a picosatellite. This also promotes teamwork among different levels of education because some activities are being developed by elementary school students, others are planned for technical students, and some are even within the scope of grad students. The project has received recognition from the national and international scientific community. Tancredo-1 is the first picosatellite of the UbatubaSat project, and it is a compact tube-shaped picosatellite with a mass of less than 0.6 kg based on

TubeSat kit from Interorbital Systems (IOS). It was successfully launched in 2016 toward the Japanese Kibo module of ISS – International Space Station. Once at Kibo, deployment and final ejection were performed in January 2017 followed by ground operations. The picosat carries an educational voice recorder and an experimental Langmuir probe from INPE's Ionosphere research group on Plasma Bubbles (Tikami et al. 2017). The UbatubaSat project is already preparing a second object named Tancredo-2.

It is also worth mentioning that the Amazonia-1 has been providing hands-on learning toward fostering qualified professionals. Since 2016, about 130 professionals have had an opportunity to get involved in activities of integration and testing, space project management, and product assurance, through satellites being integrated at INPE.

7 Conclusions

The miniaturization of space devices is changing in profound ways how space activities are approached and conducted worldwide, and the Brazilian space sector is no exception. A case in point of size reduction is clearly seen when we track the evolution of transponders for a long and continuous Brazilian demand for environmental data collected with space systems. In order to attend this demand, the SCD-1 carried an analog transponder of 3.8 kg mass needed for fulfilling its mission of collecting data from platforms distributed over the Brazilian territory. Twenty-five years later, Itasat embarked a digital transponder of just 0.3 kg, developed by INPE, for the same task. More recently, INPE has developed another digital transponder, named Environmental Data Collector, of just about 75 g, for the exact same task onboard the Conasat mission. A small payload getting even smaller. A reduction in mass of 98% with respect to the very first device for targeting the same objective.

AEB is exploring synergies between small and large satellites. The SGDC – a more than 5 tonne satellite – has provided spin-offs through a transfer of technology from France to Brazil that allowed six Brazilian companies, AEL Sistemas, Cenic Engenharia, Equatorial Sistemas, Fibraforte, Opto Space & Defense, and Orbital Engenharia, to improve and advance industry know-how on satellite-related technology such as panels for optical instruments, propulsion system for attitude control, thermal interface material and control systems, solar panels, electric power, on-board systems, and optical instruments for Earth Observation. This transfer of technology is an investment and an asset for future small satellite missions, in a moment when there is growing demand in Brazil for small satellites, and a handful of future Brazilian space missions is prospecting the use of small platforms – Equars (space weather), Carponis (remote sensing), Lessonia (SAR), and Atticora (communications).

AEB has put in place a set of initiatives – from general-to-specific with an end-to-end approach – to promote small satellites, starting with space science activities toward middle/high school students and teachers (e.g., CVT-E); space research toward university professors and students (e.g., CubeSats); and hands-on learning in Brazilian space projects toward fostering qualified professionals (e.g., Amazonia-1).

This chapter has provided an overview of past and ongoing small satellite-related initiatives in Brazil. As discussed through the chapter, there is growing demand in Brazil for small satellites, especially those that attend qualified demands. Small satellites have also plenty to offer in terms of continuous human resources training. New stakeholders (universities, industry, startups, think-tank) are contributing to the advancement of the field (services, applications, innovation), as well as promoting international partnerships. Last but not least, small satellites are an important driver for a Brazilian launch vehicle development effort.

8 Cross-References

- ▶ Planet's Dove Satellite Constellation
- ▶ RemoveDEBRIS: An In-Orbit Demonstration of Technologies for the Removal of Space Debris
- ▶ The Kepler Satellite System
- ▶ The OneWeb Satellite System
- ▶ The Spire Small Satellite Network

Acknowledgments The authors thank Dr. Adenilson Roberto da Silva, INPE, Brazil, and Jośe Machao, Telecom Argentina, for useful discussions and insights for this chapter and thank Bernardo dos Santos Veras, Fernanda Muro, and Renato de Brito do Nascimento Filho, AEB, for helping with formatting figures and double-checking facts. Although R. Leonardi and A. E. A. Corrêa are directly involved in some of the initiatives reported in this overview chapter, the authors acknowledge that this summary is mostly a compilation of third-party studies and work and express their gratitude for the Brazilian space community that support and carry on small satellites activities in the country. Finally, the authors thank Dr. Joseph N. Pelton for motivating them to share some aspects of the Brazilian space activities among colleagues and people interested in the field.

References

Anais do 2° Congresso Aeroespacial Brasileiro, in *Proceedings of the Second Brazilian Aerospace Congress*, Universidade Federal de Santa Maria, 2019

E.E. Bürguer, G. Loureiro, P.T. Lacava, D.H.Z. Carrera, C.T. Hoffmann, in *The CubeSat Aesp-14 and its Systems Engineering Development Process*, 1st Latin American IAA CubeSat Work-Shop, 2014

R.A.J. Chagas, R.V.D.F. Lopes, Seasonal analysis of attitude estimation accuracy for the Brazilian satellite Amazonia-1 under normal and faulty conditions, in Proceedings of the 24th International Symposium on Space Flight Dynamics, Laurel, 2014

P.L.K. da Cas, C.A. Gurgel Veras, O. Shynkarenko, R. Leonardi, A Brazilian space launch system for the small satellite market. Aerospace **6**, 123 (2019)

D.F. da Silva, I. Muraoka, E.C. Garcia, Thermal control design conception of the Amazonia-1 satellite. J. Aerosp. Technol. Manag. **6**(2), 169 (2014)

E.S. Goncalves, C.A. Gurgel Veras, Brazilian Space-Tech Vocational Center, in *54th AIAA Aerospace Sciences Meeting*, San Diego, 2016

M.D. Guedes, P.J.A.A. Gil, A.B..D.N. Soares, J.M.A. Nascimento, Cansat as an educational tool for basic teaching, in *2nd International Academy of Astronautics Latin American Symposium on Small Satellites: Advanced Technologies and Distributed Systems*, Buenos Aires, 2019

INPE; *Amazonia-1*, Retrieved Dec 2019 from http://www.inpe.br/amazonia-1/

I.S.K. Ishioka, G. Figueiró de Oliveira, C. Cappelletti, B.G.R. Amui, N.P. Lôpo Júnior, P.L. Kaled da Cás, D. Nodar, A. González, F.A. Agelet, A Vázquez, Serpens AIT activities, in *2nd IAA Latin American CubeSat Workshop*, 2016

L.E.V. Loures da Costa, L.H. Shibuya Sato, M.A. Abdu, V. Carrara, P. Albuquerque, H. Santos, L. Santos, E. Oliveira, D. Guilgim, A.C. Jeronymo, J. Bianchini, J. Azevedo, B. Crucioli, J. Spann, L. Krause, S. Nash-Stevenson, E. Eberly, C. Swenson, O. Durão, C. Denardin, J. Costa, R. Heelis, R. Bishop, G. Le, The Scintillation Prediction Observations Research Task (SPORT): a spacecraft development for an international mission, in *32nd Annual AIAA/USU Conference on Small Satellites,* 2018

N.J. Schuch, O.S.C. Durão, M.R.D. Silva, F. Mattiello-Francisco, J.B.D.S. Martins, A.P. Legg, A.L. D. Silva, E.E. Bürguer, The NanoSatC-Br, CubeSat development program – a joint CubeSat program developed by UFSM and INPE/MCTIC – space geophysics mission payloads and first results. Braz. J. Geophys. **37**, 95 (2019)

L.H. Shibuya Sato, L.E.V. Loures da Costa, J.B. Fulindi, H.A. Santos, L.S. Paula, E.H.S. Oliveira, J.G. Azevedo, B.A. Crucioli, D.G. Vieira, V. Carrara, A.C.I. Jeronymo, R.B. Januzi, D.H. Makita, W.G. Santos, P.K. Albuquerque, M.F. Mattiello-Francisco, The ITASAT – the lessons learned from the mission concept to the operation, in *Small Satellite Conference, 2019, Logan. 33rd Annual AIAA/USU Conference on Small Satellites*, 2019

L.K. Slongo, J.G. Reis, D. Gaiki, P.V.H. Seger, S.V. Martínez, B.V.B. Eiterer, T.G. Pereira, M.B. Neto, M.D.S. Frata, H.D. Hamisch, A.M.P.D. Mattos, J.P.F. Mera, K.V.D. Paiva, M.B.H. Mantelli, L. Dilillo, E.A. Bezerra, Pre-flight qualification test procedure for nanosatellites using sounding rockets. Acta Astronaut. **159**, 564 (2019)

A. Tikami, C.O.D. Moura, W.A. Dos Santos, First on-orbit results from the Tancredo-1 Picosat mission, in *1st IAA Latin American Symposium on Small Satellites: Advanced Technologies and Distributed Systems*, Buenos Aires, 2017

T. Villela, C.A. Costa, A.M. Brandão, F.T. Bueno, R. Leonardi, Towards the thousandth CubeSat: a statistical overview. Int. J. Aerosp. Eng. **2019**, 5063145, 13 pages (2019)

RemoveDEBRIS: An In-Orbit Demonstration of Technologies for the Removal of Space Debris

G. S. Aglietti

Contents

This chapter is based on material from within: Aglietti, G., Taylor, B., Fellowes, S., Ainley, S., Tye, D., Cox, C., Zarkesh, A, Mafficini, A., Vinkoff, N., Bashford, K., Salmon, T., Retat, I., Burgess, C., Hall, A., Chabot, C., Kanani, K., Pisseloup, A., Bernal, C., Chaumette, F., Pollini, A., Steyn, W. (2020). RemoveDEBRIS: An in-orbit demonstration of technologies for the removal of space debris. The Aeronautical Journal, 124(1271), 1-23. © Royal Aeronautical Society 2019, published by Cambridge University Press, reproduced with permission.

The Author would like to acknowledge all the co-authors of the original, above-mentioned article.

G. S. Aglietti (✉)
Space Institute, University of Auckland, Auckland, New Zealand
e-mail: g.aglietti@auckland.ac.nz

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_107

Abstract

The RemoveDEBRIS mission has been the first mission to successfully demonstrate, in-orbit, a series of technologies that can be used for the active removal of space debris. The mission started late in 2014 and was sponsored by a grant from the EC that saw a consortium led by the Surrey Space Centre to develop the mission, from concept to in-orbit demonstrations, that terminated in March 2019. Technologies for the capture of large space debris, like a net and a harpoon, have been successfully tested together with hardware and software to retrieve data on noncooperative target debris kinematics from observations carried out with on board cameras. The final demonstration consisted of the deployment of a drag-sail to increase the drag of the satellite to accelerate its demise.

Keywords

Active Debris Removal · Space debris · Harpoon · Net · Vision based navigation · Drag sail · In-orbit demonstration · Deorbiting · End of life disposal · Cubesats

1 Introduction

Over 60 years of activities in space have produced great benefits for the world population, from the SatNavs in cars, to satellite communications/broadcasting, as well as weather forecasting, environment monitoring, and the list could go on. There are literally hundreds of devices for everyday use and applications that rely on satellite technologies. When the satellites that deliver these services reach the end of their life and stop working, they are normally left in-orbit. In 2018 there were almost 3000 dead satellites still in-orbit, not to mention the final stages of the rockets that were used to put satellites into orbit, as well as fairings and other hardware. In addition to intact objects, there are also millions of fragments that have been produced by the degradation of these bodies from flakes of protective materials to shrapnel produced by explosions and collisions (Bonnal and McKnight 2017). Altogether, a mass of over 8000 tons of debris is currently orbiting the planet, posing as a threat for operative satellites.

Activities in space have not yet triggered the nightmare scenario known as the Kessler syndrome (named after the scientist who first investigated this phenomenon (Kessler and Cour-Palais 1978)) which is when fragments formed by a collision hit other objects producing further collisions creating new fragments that will hit other objects. This would result in a cascade effect that grows exponentially which would rapidly increase the density of objects to the point of making particular orbits unusable. Furthermore, the space sector cannot be complacent and simply continue to put more satellites in-orbit ignoring this problem, as collisions with space debris have already occurred (see for example (Wang 2010)). Almost routinely, the ISS and other satellites have to perform maneuvers to avoid being hit by other orbiting objects. There are guidelines to try to mitigate the growth of the debris population (Inter-Agency Space Debris Coordination Committee 2007) – these have been produced by the Inter-Agency Space Debris Coordination Committee (IADC), which is an international forum of governmental bodies (e.g., national Space Agencies), for the coordination of activities related to the issues of man-made and natural debris in space. Some Agencies and government bodies have adopted these guidelines and complemented them with further regulations. Perhaps the most quoted guideline is that satellites should be de-orbited, or re-orbited (putting them in a graveyard orbit) within 25 years from their launch. However, although these guidelines have been in place for some time, they are just "guidelines" and not enforceable regulations. Various countries, for example, have tested ground-launched anti-satellite missiles, hitting their satellite target in-orbit producing step increases in the space debris population. Hence, for a variety of reasons, from political to technological, to constrain the growth of the space debris population has proven to be challenging. There is consensus among the experts in the field that to stabilize the debris population, in view of the growing number of launches, the active removal of some debris from some of the most utilized orbits is necessary (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100017146.pdf; Liou and Johnson 2009), although the quantification of the benefits strongly depends on the modeling assumptions (White and Lewis 2013).

Various researchers and organizations have investigated the field of Active Debris Removal (ADR) (White and Lewis 2014a; Bonnal et al. 2013), and various methods have been proposed to address this issue (Shan et al. 2016; White and Lewis 2014b),

The European Space Agency has probably been the most active international participant in the space sector that is addressing this issue with its Clean Space Initiative (Innocenti 2016; https://www.esa.int/Our_Activities/Space_Safety/Clean_Space/The_Challenge). This is articulated in the area of EcoDesign (embedding environmental sustainability within space mission design), CleanSat (developing technologies to prevent the creation of future debris), and in-orbit servicing/ADR (removing spacecraft from orbit and demonstrating in-orbit servicing of spacecraft) to embrace all the relevant domains. The French space agency (CNES) has also been very active and has funded studies including OTV that takes into account different ADR mission scenarios (Pisseloup et al. 2013). Similarly the UK Space Agency has funded studies and issued guidelines applicable to UK crafts. The German Space Agency (DLR)'s DEOS (Deutsche Orbital Servicing Mission) aimed to progress towards ADR, designing a system for rendezvous with a noncooperative and tumbling spacecraft by using a robotic manipulator system incorporated within a servicing satellite (Reintsema et al. 2011).

In the industrial sector, Airbus focused on the capture technologies including a robotic arm, a net (Astrium Space Transportation 2003) and harpoon demonstrators (Pisseloup et al. 2016), as more cost effective capture technologies. Aviospace has also recently participated in some ADR studies such as their capture and de-orbiting technologies (CADET) studies (Chiesa et al. 2016) as well as the Heavy Active Debris Removal (HADR) (Bicocca 2014). The company D-Orbit has proposed solid rocket de-orbitation for the S-SAT mission (Antonetti 2016) and other methods have been proposed, for example, Ion-beam Shepherd, Gecko adhesives, and polyurethane foam

(Merino et al. 2011; Parness 2015; Trentlage and Stoll 2015), just to name some of the most relevant proposals. A very popular de-orbiting system has been dragsails, which attracted significant research attention and has already produced working devices (Hobbs et al. 2013; Kingston et al. 2015; Underwood et al. 2019).

It is acknowledged that for any new proposed space technology, in-orbit demonstration is a significant stepping stone to de-risk the final implementation. The RemoveDEBRIS, mission discussed in this chapter and other publications (Forshaw et al. 2016, 2017a, b; Taylor et al. 2018), has been the first mission to perform successfully in-orbit demonstrations of a series of technologies for ADR thus de-risking their future industrial implementation.

2 Mission Overview

The purpose of the mission was to perform in-orbit demonstrations of technologies for the active removal of large space debris. These are typically old satellites which were no longer working, upper rocket stages, and large fairings. More specifically, the technologies that were tested were: two technologies (a Net and a Harpoon) for the capture of the debris: a technology for the observation of a debris (a LiDAR camera & software) in order to automatically determine parameters such as distance, spinning rates, which would be essential during the rendezvous and debris capture, and finally a technology for the de-orbiting at the end of life, the Dragsail.

The need to perform in-orbit demonstrations stems from the impossibility to perform fully representative tests on the ground, and the need to increase TRL of the devices, reducing development risks before embarking in a real industrial ADR mission.

As seen in the infographic of the mission shown in Fig. 1, the satellite was put into orbit in two stages. Firstly it was taken to the International Space Station during one of the Space X periodic resupply missions and secondly, from the ISS, using the airlock in the Japanese module, the satellite was transferred outside the ISS and released in-orbit by the ISS robotic arm.

The actual RemoveDebirs mission was then performed, and in terms of hardware this consisted of a mini satellite platform (mothercraft) of approximately 100 kg mass that hosted the payloads performing the demonstrations. Once in-orbit, the platform released two 2 U cubesats that acted as space debris, targets for the Net capture and VBN technology demonstration. The Harpoon functioning was demonstrated by firing the Harpoon from the mothercraft at a target (the size of a table tennis bat), which was held at the end of a deployable boom at a distance of about 1.5 m from the platform.

Finally, the dragsail was supposed to be deployed from the mothercraft, and this consisted of an inflatable 1 m long mast supporting a mechanism that deploys radially four booms, that extending, unfurl 4 quadrants of sail. Once fully deployed, the sails form a square of approximately 3 × 3 m, with the deployable booms as diagonals. The inflatable mast holds the assembly from the center, at 1 m distance from the mothercraft (see Fig. 1). As the craft is in a Low Earth Orbit, the residual

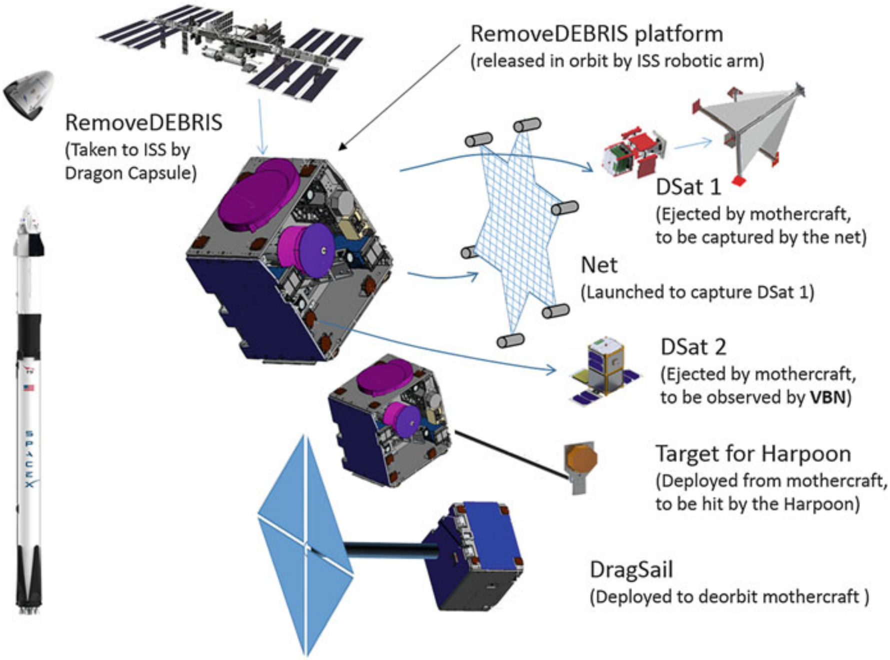


Fig. 1 Infographic of the RemoveDebris Mission

atmosphere allows the sail to produce drag that slows down the satellite, significantly accelerating the de-orbiting process.

2.1 Mission Team

The mission, whose design started in 2014, was performed by the team described in Table 1, led by the Surrey Space Centre at the University of Surrey. The overall cost of the mission was approximately 15 M euros. This was supported by a grant from the European Commission, part of its Framework Severn research funding round, and provided a 7 M euro contribution to the cost of the project, with the remainder self-sponsored by the partners.

2.2 Launch and Early Orbit Phase

At the end of the Assembly Integration and Testing activities, carried out in the SSTL cleanroom in Guildford, UK, the satellite, appropriately packaged (with protective panels, in a foam clamshell that was contained in a box which was finally put in the transportation case), was shipped to Cape Canaveral for launch. Once at the launch site, the external transportation/casing was removed, leaving the craft with its

Table 1 RemoveDebris mission team

Partner	Country	Business	Roles in the project
SSC (coordinator)	UK	University (research)	Project management CubeSats, Dragsail, Harpoon target Assy
SSTL	UK	Satellite prime	Platform provider, satellite operations
Airbus D&S	D	Prime for space transportation and satellites	Payloads: Net
Airbus D&S	F		Mission & system Eng., P/oads: Vision-based Nav. & VBN algorithms
Airbus D&S	UK		Payloads: Harpoon
Ariane Group	F	Prime for space transportation and satellites	Mission & System Engineering
ISIS	NL	SME, nanosatellites	Payloads: CubeSat deployers
CSEM	CH	Research institution	Payloads: LiDAR camera
INRIA	F	Research institution	Payloads: VBN algorithms
STE	South Africa	University (research)	Payloads: CubeSat avionics

protective panels in the protective foam clamshell. In this configuration, the craft was put in the cargo transfer bag and finally into the Dragon capsule.

The launch, on the 2 April 2018, was nominal, with the Dragon capsule propelled into orbit by the SpaceX Falcon 9 Rocket and the craft arrived at the ISS 2 days later as planned. The craft was then kept stored until mid-June, waiting for its scheduled time slot for unpacking and deployment into orbit. The unpacking consisted of removing the foam shell casing and protective panels, and the craft then was mounted on the sliding table in the Japanese module airlock. No other servicing operations were required form the ISS crew to make the craft operational. Once on the external side of the airlock, the craft was handled by the ISS robotic arm equipped with the NanoRacks Kaber Microsat Deployer, and released in orbit on the 20th of June 2018. Figure 2 shows the craft a few minutes after its release from the ISS.

The craft was released completely switched off in compliance with the ISS safety requirement, and contact was made during the first pass after power up, over the SSTL ground station in Guildford, UK.

The telemetry showed that the spacecraft was performing nominally, for example, Battery was fully charged, and temperatures as expected and commissioning progressed with switching on the spacecraft On Board Computer. Next, the craft was de-tumbled from the slow initial angular rate and brought to a controlled attitude state. Attitude and Orbital Control System commissioning progressed until the platform was in a coarse Nadir pointing mode.

All other platform checks, to verify health and functioning of the key modules not already checked were successfully performed.

The spacecraft then performed a series of maneuvers to verify its performance against the requirements for the various demonstrations.

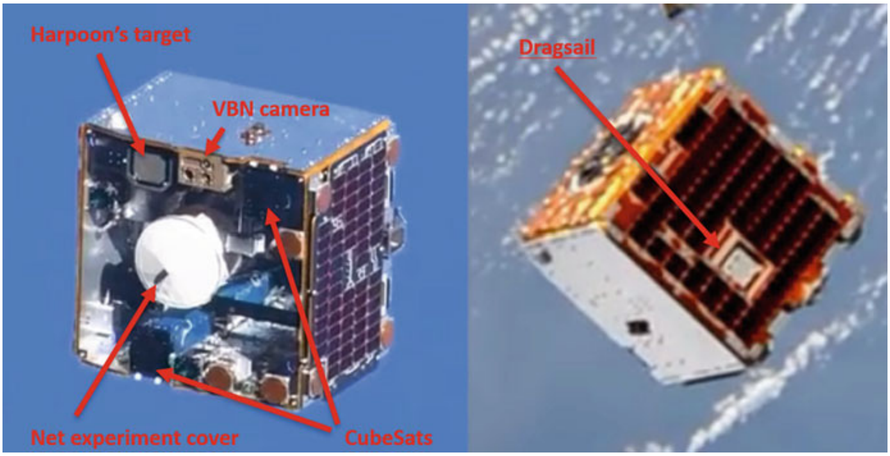


Fig. 2 RemoveDebris in flight, pictures taken from ISS

The final phase was the calibration and characterization of the cameras and VBN were tested over a range of exposures and frame rates which were planned for use on the experimental demonstrations and related parameters were adjusted.

By mid-September, the craft was ready to start the demonstrations with the Net capture scheduled as the first experiment. This was to be followed by the VBN demonstration, Harpoon firing and finally de-orbit sail deployment, with the series of experiments planning to take approximately 6 months.

3 Net Capture Technology Development and Demonstration

The first demonstration planned, was the Net capture. For this demonstration, the first cubesat had to be released form the mothercraft and while this slowly drifted away (planned separation speed 5 cm/s) and reached an appropriate distance (approx. 7 m), the Net had to be launched from the mothercraft to capture the cubesat. After the cubesat release from the mothercraft, and before this is captured by the Net, the cubesat deploys some inflatable structures to increase its original size (from the 10 × 10 × 20 cm dimension of a 2 U CubeSat, to approximately 1 m side length pyramid structure (see Fig. 3)). This is in order to be more representative of the size of a larger space debris and produce a situation more representative of the Net capture dynamics. The Net is held in a container/canister (see Fig. 4), and is deployed by launching 6 masses simultaneously, that are attached along the perimeter of the Net. The masses are cylindrical, with a push off spring at the base, and contained in 6 barrels located on the internal wall of the canister (see Fig. 4). A lid closes the canister pushing the masses down their barrels, compressing their push off spring. Once the lid of the canister is ejected, the masses are pushed out by their springs along trajectories that funnel out from the

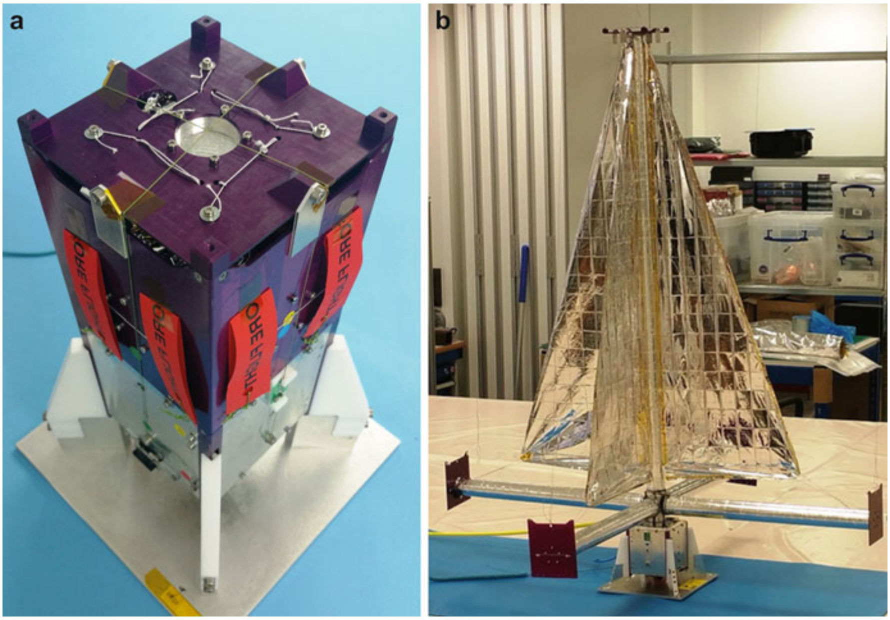


Fig. 3 Debrisat 1 (**a**) stowed configuration (**b**) deployed configuration

longitudinal axes of the canister in order to drag the net out from the central volume of the container, progressively stretching it open (see Fig. 5). During its deployment, initially the net will take the shape of a six-pointed star with each of the masses pulling one of the vertices of the "star," and eventually when fully deployed, the perimeter of the net should take approximately a hexagonal shape with vertices on a 5 m diameter circle. Once the target has been captured, the masses are naturally pulled towards the longitudinal axis by the Net, and each of the masses draws a string that runs along the perimeter of the net in order to close it, like a drawstring bag. The closure of the net is performed to ensure the retention of the target, as otherwise, after the initial capture, the net might open up and release the target. The activation of the drawstring is commanded by a timer, and the whole demonstration was planned to be filmed by two supervision cameras, starting recording just before the release of the target cubesat.

The design of the hardware has been supported by extensive experimental test campaigns, as both, the target cubesat and the Net launching device, have complex dynamics. For example, the cubesat presents the challenge of the inflatable booms that deploy the sail quadrants, and whose inflation/deployment is almost chaotic, and similarly the deployment of the net, from tightly packed in the container to fully open is difficult to model mathematically with good reliability. Even the cubesat deployer required significant testing to verify the very low ejection speed that was required.

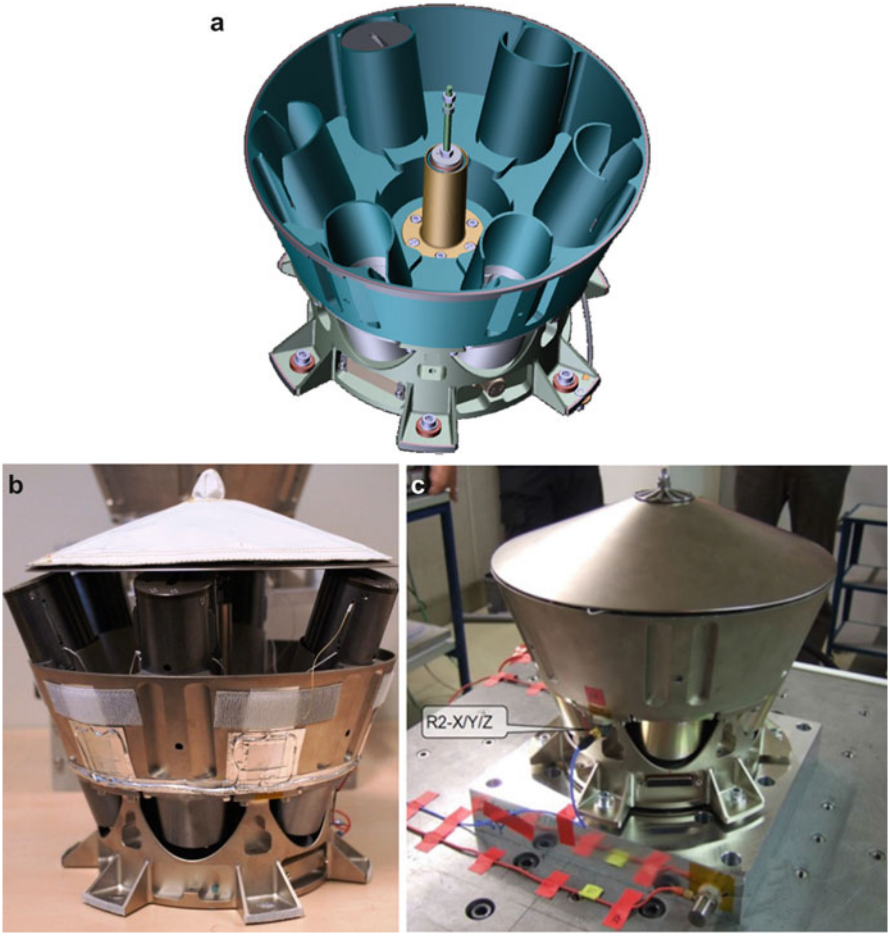


Fig. 4 Net capture device (**a**) CAD model of the container, (**b**) hardware, container with masses partially inserted in the barrel, and lid resting on the masses (**c**) container closed and ready for vibration testing

3.1 Hardware Ground Testing

The functioning of the net device was verified during ground test of increasing complexity. From simple packing and unpacking tests with people pulling the corners of the net out of the container to make sure that there were no snags during deployment, to functional tests in zero-g and vacuum in the drop tower (these tests only allowed us to verify the first second of the net deployment process), to tests during parabolic flights, to verify the closure of the net. Although these tests could give confidence in particular aspects of the design, none of the tests could verify the whole capture of a free floating non-cooperative target in space, with hardware that was similar to what would be required to capture a real piece of large space debris.

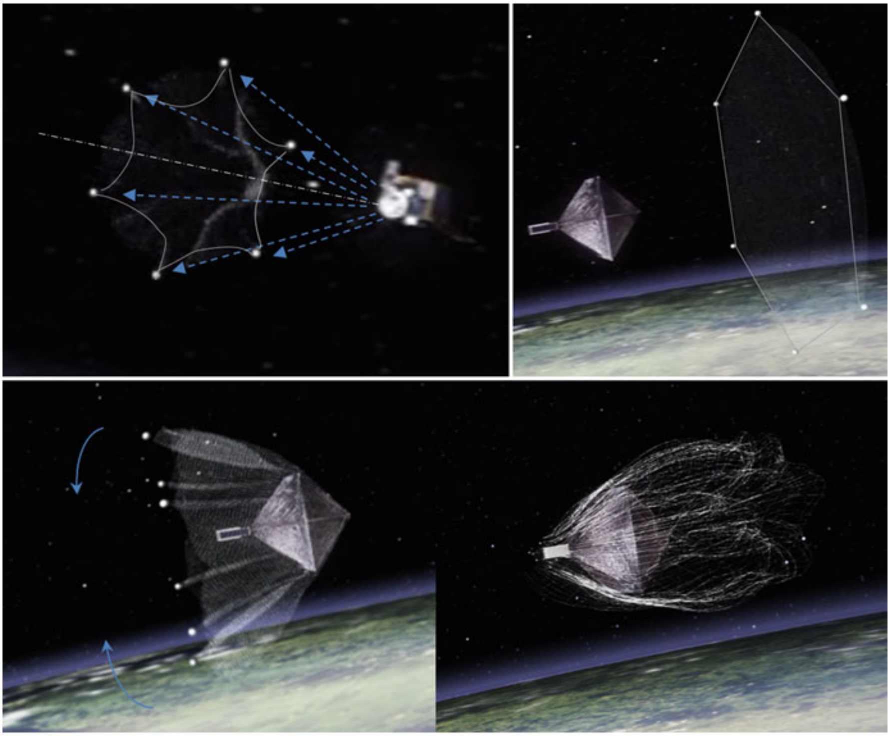


Fig. 5 Sequence from video animation of the Net ejection and DSAT#1 capture

Hence, the in-orbit demonstration was necessary to give full confidence in the design and reduce the risk of the further scaling up that will be necessary to utilize this technology in real ADR missions to capture an object a few meters in size.

Concerning the target cubesat, a significant test campaign was carried out to consolidate its design. From the initial baseline that included a 6 boom deployable structure as shown in Fig. 6, which gave substantial challenges in terms of its capability to withstand a harsh vibration environment, the design evolved into a 5 boom configuration visible in Fig. 3. The inflation is driven by two Cool Gas Generators; however, during most of the testing activities, to allow several repetitions and limit cost, compressed air was used.

The main challenge for the cubesat deployer used to eject the cubesats from the platform was to achieve a very low ejection speed, as in a realistic scenario there would be a very low relative speed between a debris and the spacecraft that is capturing it. This was achieved by implementing a two-stage deployer system illustrated in Fig. 7. The first stage pushes the cubesat out if its container using a typical large compression spring system that at the end of its run keeps the push plate flush at the opening of the container, with the base of the cubesat retained by the push plate. The second stage is the cubesat release system. This separates the

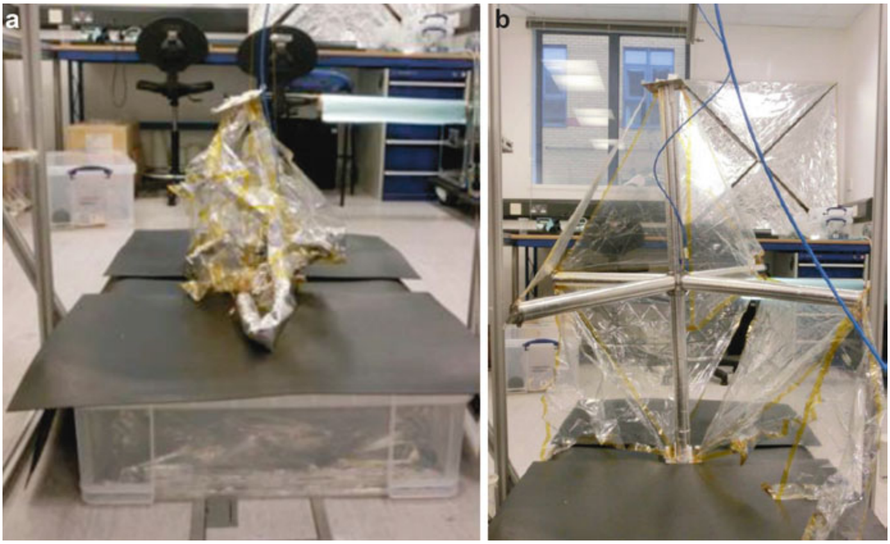


Fig. 6 6-DSat inflation testes, 6-boom configuration (**a**) during inflation (**b**) fully inflated

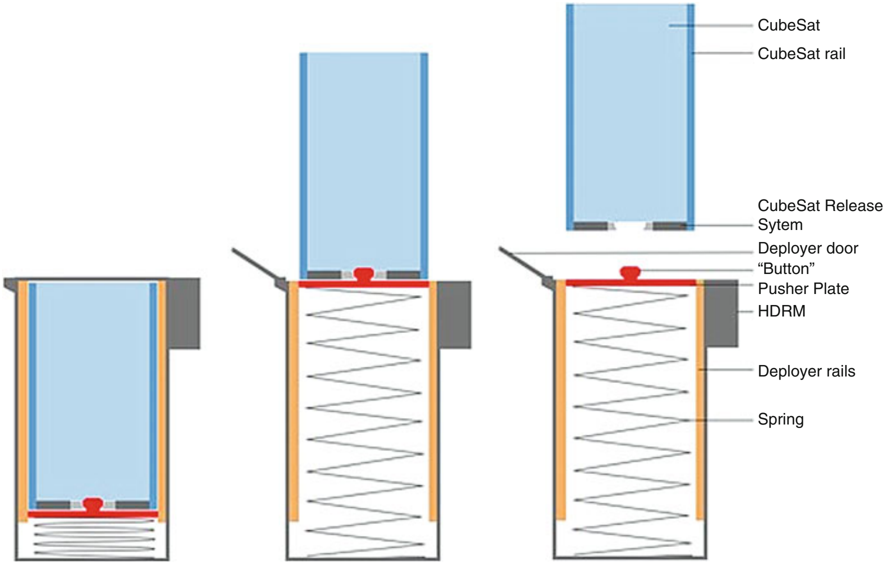


Fig. 7 Schematic of the CubeSat Ejection system

cubesats and gently pushes it away using low stiffness springs. The performance of this mechanism was verified in the lab using a long pendulum system for gravity compensation and a high speed camera to measure the release speed of the cubesat (see Fig. 8).

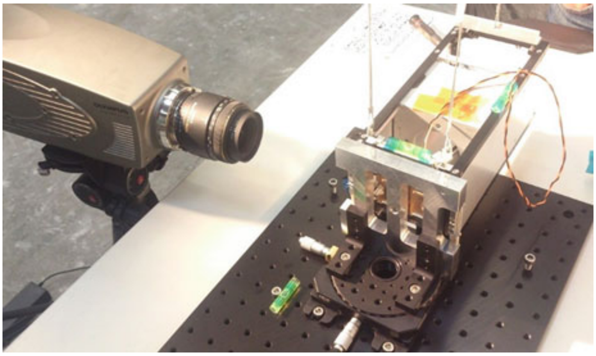


Fig. 8 Deployer and CRS: Detail of the Velocity Testing Setup. 2 U CubeSat suspended on pendulum and high speed camera

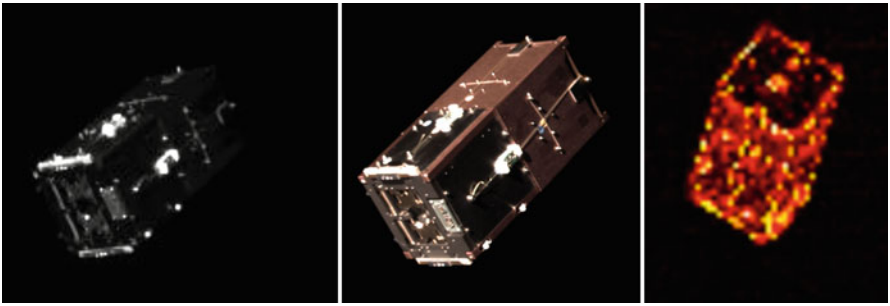


Fig. 9 Standard supervision camera, VBN digital camera, VBN Lidar camera

3.2 In-Orbit Demonstration

The in-orbit demonstration (16th of September 2018) was filmed by the two supervision cameras on the platform as planned. In addition, it was decided to use this opportunity to test also the functioning of the VBN cameras (i.e., a digital camera and a Lidar system that will be further discussed in the next section), and therefore, the demonstration was filmed by a total of 4 cameras. The type of imagery is visible in Fig. 9.

From the imagery, it is possible to see the cubesat drifting away from the mothercraft at a velocity slightly higher than planned (approximately 7.5 cm/s) and then inflating two of the four inflatable booms making the base of the pyramid (see Figs. 3 and 14). The inflation of the longitudinal boom is also visible, as the net captures the cubesat (see Fig. 15).

As the booms inflated, the cubesat started spinning, and this was most likely due to a gas leak from the two booms not correctly inflating, acting as a thruster and generating a moment to the cubesat. As the net was travelling towards its target (Fig. 15), pulled by the 6 throw masses, it assumed the shape of a 6 point star (each point pulled by one of the masses). However, the central area of the net remained

Fig. 10 DSAT#1 with lateral inflatable booms deployed

slightly tangled together preventing a full stretch of the mesh. It is estimated that the net opened to approximately 4 m diameter and then hit the spinning target wrapping itself around it. The capture itself happened at a distance of approximately 11 m, and the distance was estimated from the knowledge of the camera field of view and the size of the target. As the Net wrapped itself around the target, the imagery did not allow us to determine whether the drawstring mechanism worked properly. Although it was clear that the net achieved its main purpose (i.e., to capture the target). From the way it tangled itself around the cubesat and its deployable structures, it is very unlikely that, later on, the cubesat could unwrap itself and escape from the net. All the telemetry (Two Line Elements), from the moment of the capture to the complete de-orbiting of the cubesat (2nd of March 2019) enveloped by the net, is consistent with a single object.

In a real operational scenario, the net would be tethered to the motehrcraft, so that after the capture of a debris the mothercraft can tow it down and de-orbit together. However, this would require the mothercraft to have a very capable propulsion system and sophisticated AOCS which would significant impact on the mission budget, and this was considered to be beyond the scope of this demonstration.

Besides propulsion, to deploy this technology on an industrial scale to capture real large space debris, the technology will need scaling up, but there is nothing in the current design that could prevent an increase in size to enable capture of debris that could have dimensions of a few meters (Figs. 10 and 11).

4 Vision Based Navigation

The second demonstration to be carried out tested the performance of two cameras for VBN and related software. The two cameras were a standard high quality digital camera and a flash imaging LiDAR system, whereby the target is illuminated by flashes of laser whose reflections are captured by a sensor, enabling the measurement of the distance of the target.

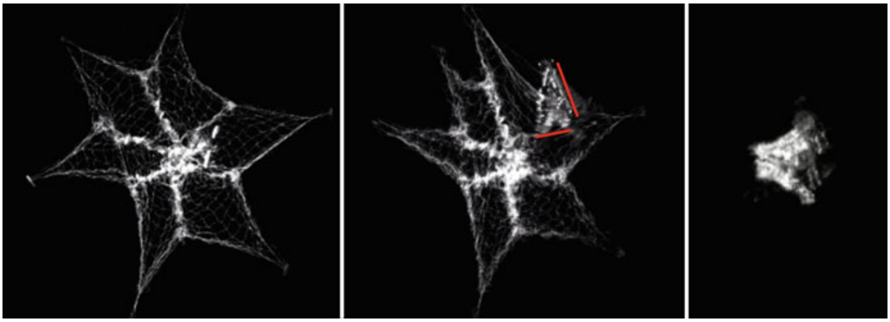


Fig. 11 Left – before the capture, two lateral booms visible. Center – Moment of the Net capture of DSAT#1, one of the satellite sails is shown, between the lateral and longitudinal booms –Right – after the capture, DSAT#1 tangled in the net

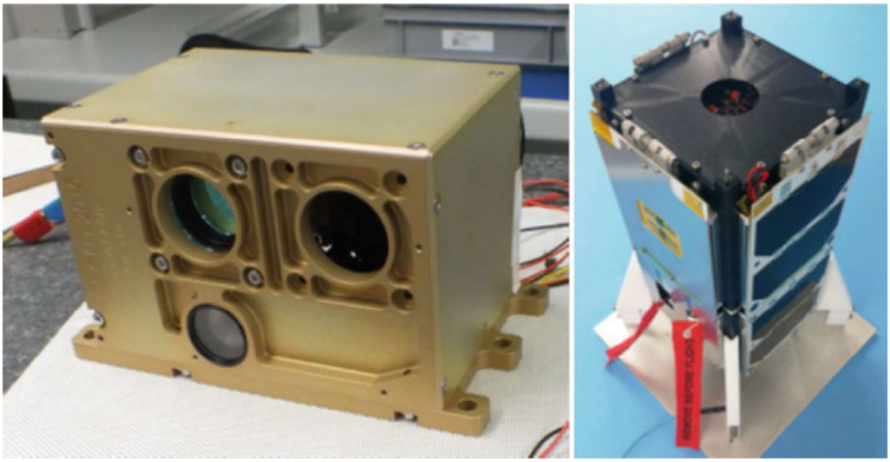


Fig. 12 Left: Vision Based Navigation payload, Right: DS-2 target in deployed state

The purpose of this demonstration was to test the hardware and to assess the state-of-the-art of Image Processing (IP) and navigation algorithms based on real flight data.

The device is shown in Fig. 12, together with the cubesat that was released by the mothercraft in order to be observed by the two cameras. The imagery from the cameras enables the reconstruction of the object and its dynamics (shape, distance, and spinning rate) that can be used for rendezvous algorithms for relative navigation.

4.1 In-Orbit Demonstration

The cubesat target for the VBN was released by the mothercraft on the 28th of October 2018, pushed away with a velocity of 2 cm/s, released by the same type of

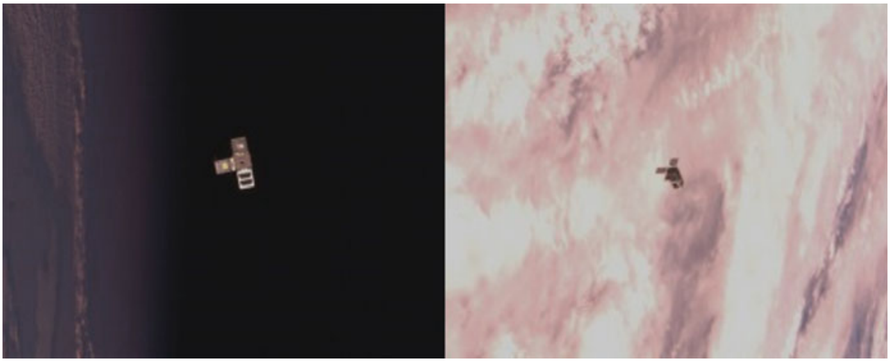


Fig. 13 DSAT#2 with different backgrounds

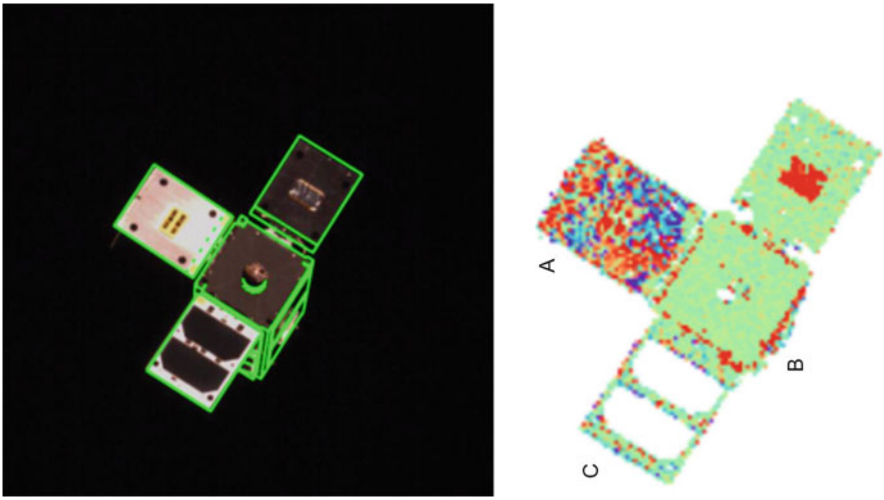


Fig. 14 Left: View of DSAT#2 with shape contours, Right: image from LiDAR camera

separation mechanism as that used for the first cubesat but with lower push off spring energy.

One of the challenges addressed by this experiment was to recognize the target independently from the background (see Fig. 13), and this demonstration provided a wealth of real data to assess the performances and robustness of the VBN algorithms. If a model of the geometry of the object being observed is available (e.g., a CAD model), the software can combine it with the sensor's measurements and improve the overall estimation of the kinematic of the object and its visualization (see Fig. 14). If other physical data of the target is available (i.e., inertia matrix), the estimation can be further improved including the equation governing the dynamics of the object in the algorithm.

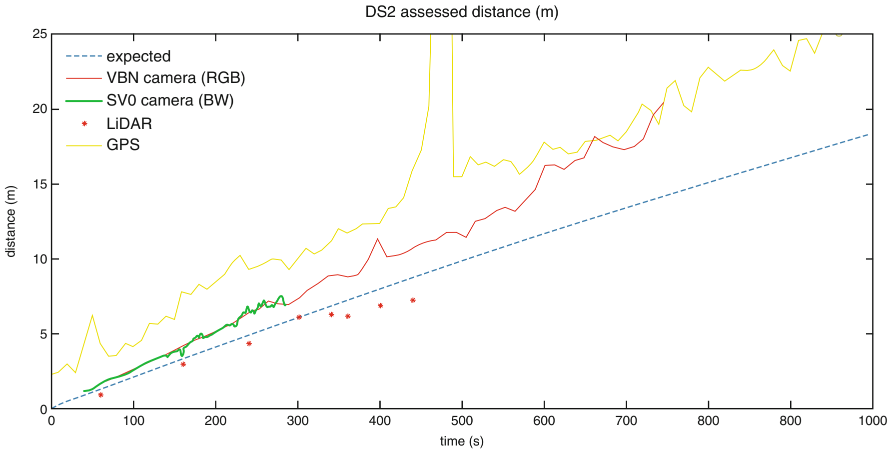


Fig. 15 Comparison of distance measurements using different systems

In this experiment, the measurements obtained by the Lidar system (target distance and spinning rates) were compared with the information obtained by the GPS on board the CubeSat, which were transmitted to the mothercraft via an inter satellite link.

Figure 15 shows a comparison of the measurements of the relative distance between mothercraft and cubesat, using raw data from the various sensors while the target was tumbling and also the background was changing, therefore varying the level of noise during the experiment. As knowledge of the physical characteristics of the target can improve significantly the estimation, further work in this direction is currently being carried out.

Downloading all the data from the experiment took a few weeks, as the videos were very large files and contact to download the data could only be made for a few minutes every day when the satellite was passing in view of the ground station in Guildford.

5 Harpoon

The next experiment to be performed was the Harpoon capture, and this was executed the 8th of February 2019. The demonstration starts activating the frangibolt that retained the target pressed against the mating structure of the chassis Harpoon Target Assembly (Aglietti et al. 2018) (see Fig. 16). After the target has been freed, the deployable boom that supports it starts to uncoil/deploy moving the target to a position 1.5 m away, in front of the harpoon firing device (Fig. 17).

The deployment of the target is recorded on video by the mothercraft supervision camera. Once the video has been downloaded and reviewed to confirm that the target is correctly deployed, the harpoon can be fired. Before firing the harpoon its safety

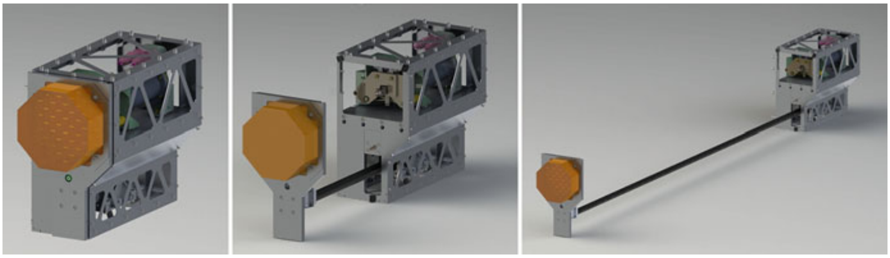


Fig. 16 Harpoon Target Assembly. Left – stowed configuration, the target is held against the chassis of the device by a frangibolt. Center – Once free, the target is moved into position by the deployable boom. Right – device fully deployed with target in its final position

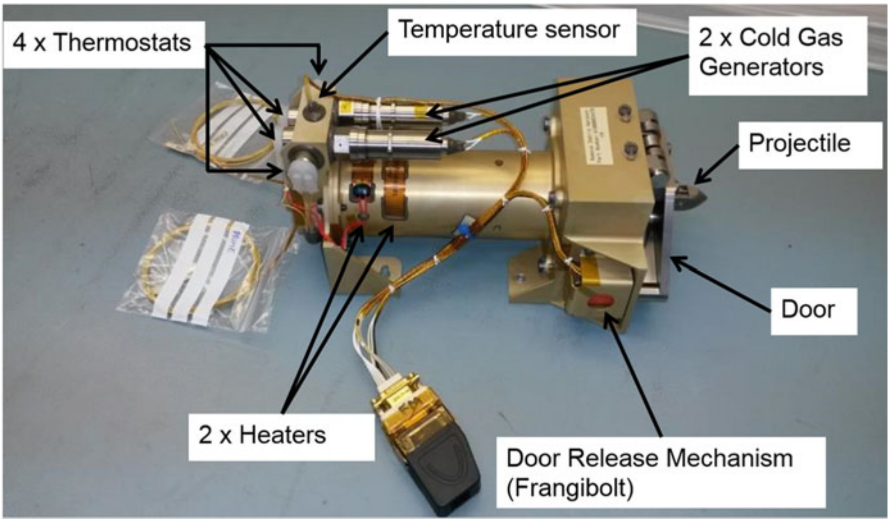


Fig. 17 Harpoon firing device

door, kept closed by two frangibolts, has to be opened to free the harpoon/bullet. The harpoon is launched using compressed gas produced by two Cool Gas Generators, and it is tethered to the mothercraft using a line whose length is significantly longer than the harpoon distance (see Fig. 18). A total of 27 harpoon firing tests were conducted to verify various aspects of the design and in particular the behavior and strength of the tether system, as it was mandatory to demonstrate the capability to retain the harpoon under any conditions (including missing the target). Early in the program, considerable attention was also given to the design of the tip of the harpoon and the barbs, with various design iterations, shown in Fig. 19, to improve its capability to imbed itself and lock on the target (Fig. 20).

The target, roughly the size of a table-tennis bat, includes an aluminum honeycomb panel of contraction representative of an old satellite structure that has to be struck by the harpoon.

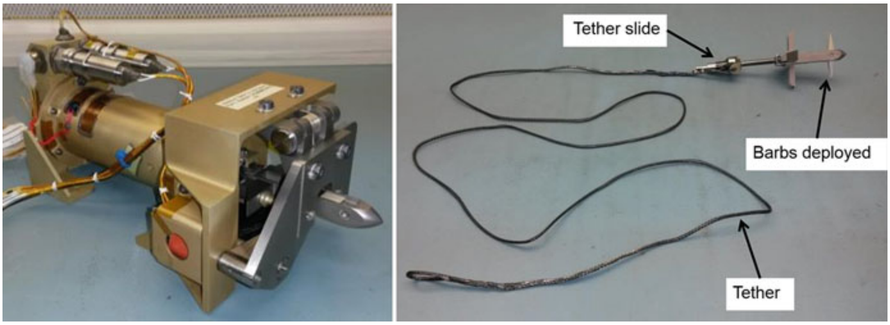
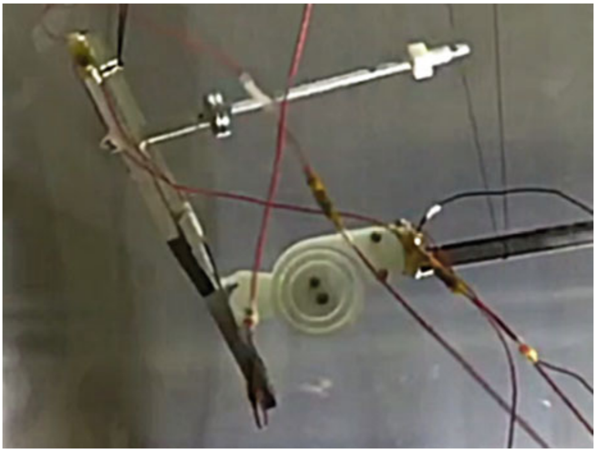


Fig. 18 Harpoon firing device, projectile, and tether

Fig. 19 Harpoon tip and barbs design iteration

Fig. 20 Harpoon target support implementing "shock absorber"



The deployable boom that supports the target is a lightweight CFRP with a U cross section and a series of holes along its length that engage a gear used for the deployment the boom.

During ground testing it became apparent that the high energy of shock of the harpoon hitting the target was sufficient to snap the target off the boom. Consideration was given to include a system, similar to a clock spring to reduce the amplitude of the mechanical shock upon the harpoon impact, and related stress on the structure. However, as after the impact the harpoon would effectively retain the target, the possibility of the target breaking off the boom was not deemed a particular concern and therefore the shock absorber was not implemented in the flight model.

5.1 Harpoon In-Orbit Demonstration

After the boom was deployed, the imagery was downloaded and examined to verify the status of the system before proceeding with the demonstration. This showed a significant oscillation of the target (see Fig. 21) with rotations of up to +/−17 deg and translations of the target central area of a few centimeters. This was due to the fact that the target was supported in a cantilevered configuration by a boom with relatively low stiffness and damping. Excited by the microvibrations generated by the equipment on board the platform, the system resonated, producing large oscillations of the target. As the main source of the platform microvibration was the actuators of the attitude control system, the issue was resolved performing the

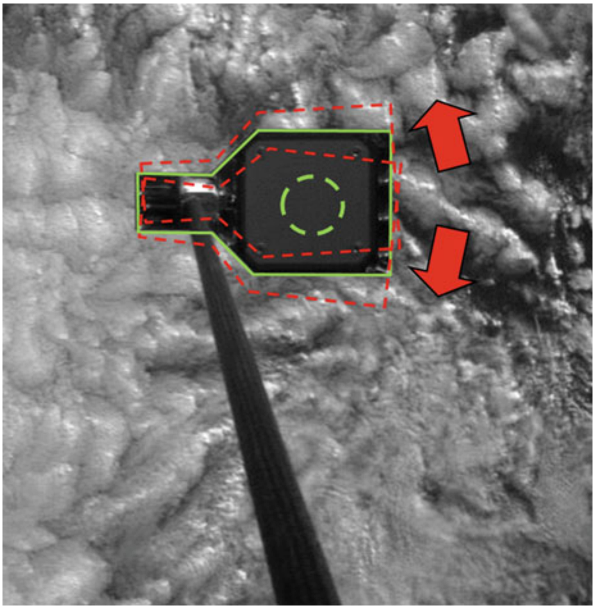


Fig. 21 Target deployed at the end of the boom, in green the nominal position and in red the positions at the extreme of the oscillations whose direction is indicated by the red arrows

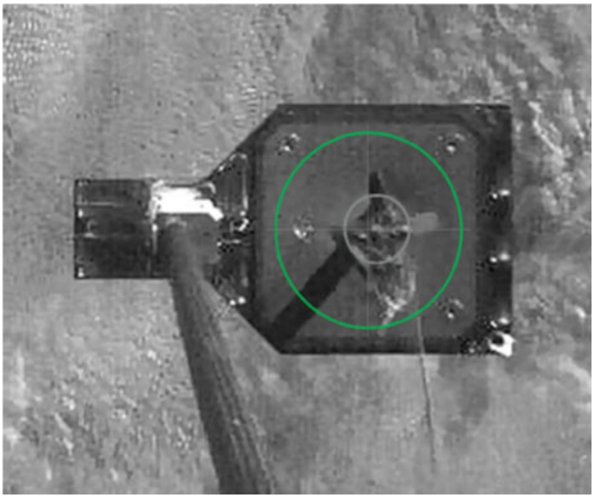


Fig. 22 Harpoon imbedded in the target

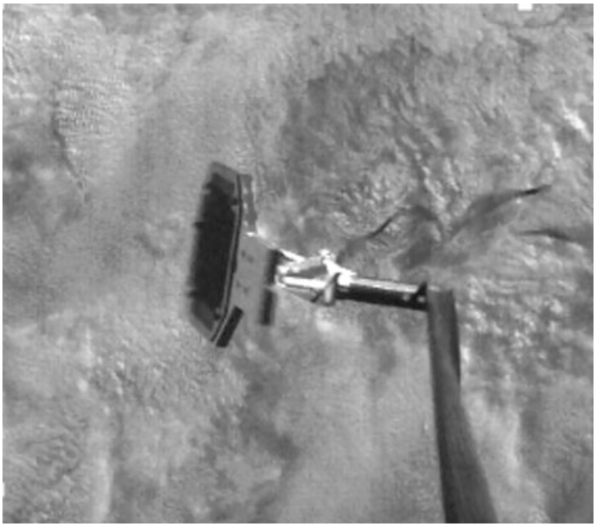


Fig. 23 Target snapping off the end of the boom

experiment in a mode of operation where the actions of the attitude control system had been minimized.

In this new mode of operation, it was verified that the target was stable, and it was possible to fire the harpoon. As visible in Fig. 22, the dart hit the target in the center and due to the mechanical shock the target snapped off the boom (Fig. 23), and floated away tethered to the mothercraft via the harpoon tether. After some time floating around the platform, the target retained by the harpoon tether wrapped itself around the boom (Fig. 24).

Fig. 24 Target retained by harpoon tether wrapped around the boom

6 Dragsail and De-orbiting

The final phase of the mission consisted of an accelerated de-orbiting of the craft, triggered by the deployment of a drag-sail. The concept of operation of this device is that deploying a sail like that shown in Fig. 25 in low earth orbit, where there is still some residual atmosphere, increases the drag, reducing the velocity of the satellite, so it de-orbits more quickly. The graphs in Fig. 26 show the improvement in the de-orbiting time which can be produced by this kind of system. In this case, the prediction showed that deploying the sail could have reduced the de-orbiting time to approximately 10% of its natural de-orbiting time.

The initial configuration of the craft had all the experiments mounted on the same side of the satellite in order to be monitored by the surveillance cameras. However, as the dragsail was the last device to be operated, possible malfunctions of the previous experiments (e.g., incapability to retract the boom supporting the harpoon target after its demonstration) would have impeded its deployment. In one of the last design iterations, to avoid any possible interference with the previous demonstrations, it was therefore decided to mount the dragsail on the opposite side of the satellite (see Fig. 2). Unfortunately, this did not allow us to video the operation of the dragsail, and successful deployment would have been confirmed mainly by the more rapid de-orbiting of the craft. Other indicators, such as changes/reduction in power generated by the solar panels due to shadowing of the sails, changes in telemetry

Fig. 25 Drag-sail system

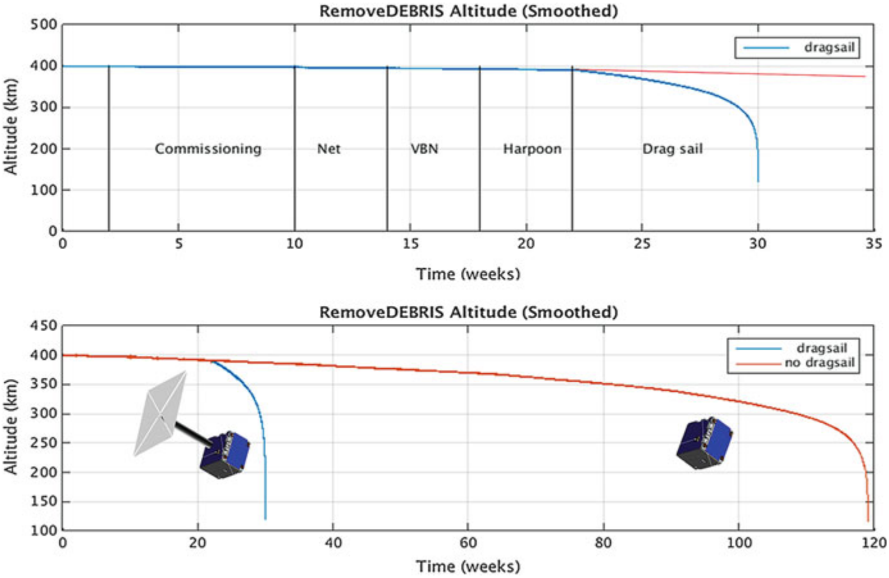


Fig. 26 RemoveDebris de-orbiting performance prediction with and without dragsail

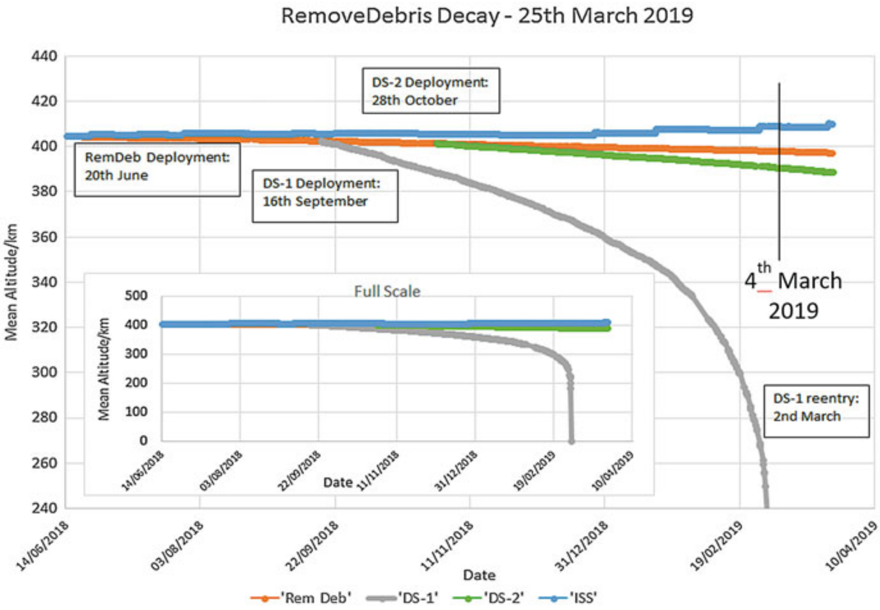


Fig. 27 Decay of the various RemoveDEBRIS objects

from the sun sensor, and observation from the ground (significant increase in brightness of the object), would have confirmed the successful deployment.

A command to deploy the dragsail was given the 4 March 2019. In the following days, some changes in the brightness of the object were reported, but no significant changes in the de-orbiting trajectory or in any of the other indicators could be detected. Figure 27 shows the altitude of the mothercraft, which is naturally de-orbiting (expected time for complete de-orbit is approximately 2.5 years), but no significant change occurred from the 4th of March. Note that the first cubesat, wrapped in the net, de-orbited in less than 6 months and the second cubesat is also de-orbiting at a faster rate than the mothercraft.

At this stage it has not been possible to confirm the nature of the anomaly in the operation of the dragsail, although most of the data is consistent with an issue with the deployment of the inflatable mast that supported the sails. However, the lesson learned in the development of the RemoveDebris drag-sail has been put into practice in the development of two new dragsails that have been supplied to the Space Flight Industries for their the SSO-A mission, and all the telemetry available for that mission has confirmed a successful deployment.

As the purpose of the RemoveDebris demonstrations was to pave the way to industrial exploitation of the various technologies that were tested, the dragsail experiment also fulfilled its purpose (Fig. 28).

Fig. 28 Ground testing of the DragSail for the SSO-A mission

7 Conclusion

The RemoveDebris mission has been the first successful in-orbit demonstration of a series of technologies for ADR.

Both the Net and Harpoon have been proven viable methods to capture large space debris. Indeed these devices will need scaling up, possibly up to one order of magnitude in terms of the size of the hardware, in order to be used in a real industrial scenario, for example, to capture large defunct satellites. However, none of the technologies implemented in the systems have features that would prevent their increase in size.

The VBN demonstration, besides verifying the functioning of the hardware and software, collected a wealth of data that will be useful for years to come.

The development of the dragsail and the anomaly in its operation, although disappointing at the time, has provided important lessons that have enabled the successful manufacturing and operation of a new generation of drag-sails. Most importantly the use of inflatable structures in space still poses significant challenges, and alternative solutions seem to deliver higher reliability. In the case discussed in this chapter, also the need for extensive testing, implementing a higher level of quality control in the whole MAIT process, has certainly contributed to achieving success in the new generation of drag-sails.

Once again, this project reconfirmed that the systems that underwent extensive ground testing performed better than those that relied on a small number of tests.

Overall, from a programmatic perspective, one important lesson learned was that in case of launches via the ISS, an earlier engagement with the ISS safety review process is very beneficial. In-fact in comparison to standard launches, where the craft is put directly in orbit, transiting through the ISS requires a higher level of safety. This is relatively easy to implement directly in the design if this is done at an early stage, rather than having to add modifications or carry out further unscheduled test activities to achieve compliance.

Still from a programmatic perspective, another peculiarity of the project was the "loose" contractual control of the interfaces between partners. This derived from the fact that the whole project was set up as a research collaboration between members of a consortium led by the SSC (the consortium coordinator) and with responsibilities described at top level in a research proposal subsequent description of work. Such consortium configuration was rather different from the typical contractual arrangement used to deliver space missions (e.g., a satellite development would normally be led by a Prime Contractor which leads a group of Subcontractors with responsibilities that are specified in detail in their subcontracts). While on one hand this enabled flexibility in the interfaces to optimize, from a technical perspective, the interface, and distribution of the work, it created some challenges from a project management perspective. The key for the successful delivery of this kind of project was to maintain top level alignments of the overall objectives and the partners' willingness to absorb some extra (unscheduled) work deriving from adjustments of the interfaces.

Besides its technical success, this project attracted significant media attention, which was welcome, as it raised the awareness of the issue of the space debris in the general public.

8 Cross-References

- ► An Overview of Small Satellite Initiatives in Brazil
- ► Planet's Dove Satellite Constellation
- ► The Kepler Satellite System
- ► The OneWeb Satellite System
- ► The Spire Small Satellite Network

Acknowledgments This research was supported by the European Commission FP7-SPACE-2013-1 (project 607099) "RemoveDebris – A Low Cost Active Debris Removal Demonstration Mission", a consortium partnership project consisting of: Surrey Space Centre (University of Surrey), SSTL, Airbus GmbH, Airbus SAS, Airbus Ltd., Ariane Group, Innovative Solutions in Space (ISIS), CSEM, Inria, Stellenbosch University.

The authors would also like to acknowledge the help and support of the launching agent NanoRacks as this has been crucial to successfully deliver this mission.

References

G.S. Aglietti, J. Forshaw, A. Viquerat, B. Taylor, An overview of the mechanisms and deployables on the Removedebris ADR mission, in *European Conference on Spacecraft Structures Materials and Environmental Testing ECSSMET*, Noordwijk, 28 May–1 June 2018

S. Antonetti, D-SAT mission: An in-orbit demonstration of autonomous decommissioning capabilities in changing space debris mitigation requirements scenario, in *CNES 4th International Workshop on Space Debris Modelling and Remediation*, Paris (2016)

Astrium Space Transportation, ROGER phase-A final report executive summary, Tech. Rep. ROG-SIBRE-EXS, Astrium Space Transportation (2003)

M. Bicocca, Debris capture technologies overview, Tech. Rep., Aviospace (May 2014)

C. Bonnal, D. S. McKnight, IAA situation report on space debris – 2016. International Academy of Astonautucs. (May 2017)

C. Bonnal, J.M. Ruault, M.C. Desjean, Active debris removal: Recent progress and current trend. Acta Astronaut. **85**, 51–60 (2013)

A. Chiesa, G. Gambacciani, D. Renzoni, G. Bombaci, Enabling technologies for active space debris removal: The CADET (CApture and De-orbiting Technologies) project, in *CNES 4th International Workshop on Space Debris Modelling and Remediation*, Paris (2016)

J.L. Forshaw, G.S. Aglietti, N. Navarathinam, H. Kadhem, T. Salmon, A. Pisseloup, E. Joffre, T. Chabot, I. Retat, R. Axthelm, S. Barraclough, A. Ratcliffe, C. Bernal, F. Chaumette, A. Pollini, W.H. Steyn, Removedebris: An in-orbit active debris removal demonstration mission. Acta Astronaut. **127**, 448–463 (2016)

J.L. Forshaw, G.S. Aglietti, T. Salmon, I. Retat, M. Roe, C. Burgess, T. Chabot, A. Pisseloup, A. Phipps, C. Bernal, F. Chaumette, A. Pollini, W.H. Steyn, Final payload test results for the RemoveDebris active debris removal mission. Acta Astronaut. **138**, 326–342 (2017a)

J. L. Forshaw, G. S. Aglietti, T. Salmon, I. Retat, A. Hall, T. Chabot, A. Pisseloup, D. Tye, C. Bernal, F. Chaumette, A. Pollini, W.H. Steyn, The RemoveDebris ADR mission: Launch from the ISS, operations and experimental timelines, in *International Astronautical Congress*, Adelaide, 25–29 Sept 2017 (2017b)

S. Hobbs, J. Kingston, P. Roberts, C. Juanes, R. Sewell, B. Snapir, F. Robinson, J. V. Llop, J. Hobbs, M. Patel, De-orbit sail design for techdemosat-1, in *Proceedings of the 6th European Conference on Space Debris*, ESA SP-723, Darmstadt, 22–25 Apr 2013 (August 2013)

L. Innocenti, Clean space – An overview, in *ESA Clean Space Industrial Days*, (ESTEC, Noordwijk, 2016)

Inter-Agency Space Debris Coordination Committee, IADC space debris mitigation guidelines, IADC-02-01, Revision 1 (September 2007)

D.J. Kessler, B.G. Cour-Palais, Collision frequency of artificial satellites: The creation of a Debris Belt. J. Geophys. Res. **83**, 2637–2646 (1978)

J. Kingston, S. Hobbs, P. Roberts, C. Juanes-Vallejo, F. Robinson, R. Sewell, B. Snapir, J. Llop, M. Patel, Use of CYPRES™ cutters with a Kevlar clamp band for hold-down and release of the Icarus de-orbit sail payload on TechDemoSat-1. Acta Astronaut. **100**(1), 82–93 (2015)

J.-C. Liou, N. Johnson, A sensitivity study of the effectiveness of active debris removal in LEO. Acta Astronaut. **64**(236), 43 (2009)

M. Merino, E. Ahedo, C. Bombardelli, H. Urrutxua, J. Pelaez, L. Summerer, Space debris removal with an ion beam shepherd satellite: Target-plasma interaction, in *47th AIAA Joint Propulsion Conference & Exhibit*, San Diego (2011)

A. Parness, Orbital debris removal with gecko-like adhesives; technology development and mission design, in *66th International Astronautical Congress*, Jerusalem (2015)

A. Pisseloup, T. Salmon, C. Cougnet, M. Richard, ADR concepts from CNES funded study OTV, in *64th International Astronautical Congress*, Beijing (2013)

A. Pisseloup, S. Estable, K. Pegg, E. Ferreira, R. Delage, J.-M. Pairot, T. Salmon, A. Ratcliffe, M. Frezet, Airbus defence and space's vision and activities in active debris removal and on-orbit servicing, in *CNES 4th International Workshop on Space Debris Modelling and Remediation*, Paris (2016)

D. Reintsema, B. Sommer, T. Wolf, J. Theater, A. Radthke, W. Naumann, P. Rank, J. Sommer, DEOS – The in-flight technology demonstration of German's robotics approach to dispose malfunctioned satellites, in *ESA 11th Symposium on Advanced Space Technologies in Robotics and Automation*, (ESTEC, Noordwijk, 2011)

M. Shan, J. Guo, E. Gill, Review and comparison of active space debris capturing and removal methods. Prog. Aerosp. Sci. **80**, 18–32 (2016)

B. Taylor, G. Aglietti et al. The RemoveDebris mission, from concept to orbit, in *Proceedings of the SmallSat Conference*, SSC 18-I-03, Logan, 4–9 Aug 2018

C. Trentlage, E. Stoll, The applicability of gecko adhesives in a docking mechanism for active debris removal missions, in *13th Symposium on Advanced Space Technologies in Robotics and Automation, ASTRA 2015*, (ESTEC, Noordwijk, 2015)

C. Underwood, A. Denis, A. Viquerat, B. Taylor, B. Sanders, B. Stewart, C. Massimiani, C. Bridges, D. Masutti, G. Aglietti, M. Schenk, R. Duke, S. Fellowes, InflateSail de-orbit flight demonstration results and follow-on drag-sail applications. Acta Astronaut. **162**, 344–358 (2019)

T. Wang, Analysis of debris from the collision of the Cosmos 2251 and the iridium 33 satellite. Sci Glob Secur **18**, 87–118 (2010). https://doi.org/10.1080/08929882.2010.493078. Copyright C Taylor & Francis Group, LLC, ISSN: 0892-9882 print 1547-7800 online

A.E. White, H.G. Lewis, Quantifying the benefits of active debris removal in a range of scenarios, in *Proceedings of the 6th European Conference on Space Debris*, ESA SP-723, Darmstadt, 22–25 Apr 2013 (August 2013)

A.E. White, H.G. Lewis, The many futures of active debris removal. Acta Astronaut. **95**, 189–197 (2014a). https://doi.org/10.1016/j.actaastro.2013.11.009

A.E. White, H.G. Lewis, An adaptive strategy for active debris removal. Adv. Space Res. **53**(8), 1195–1206 (2014b)

Part XII

Economic, Legal, and Regulatory Issues, Standards, Constraints, and Opportunities

Small Satellites Market Growth Patterns and Related Technologies

Frank A. Robert, Maxime Puteaux, and Alexandre Najjar

Contents

F. A. Robert (✉)
Kearney Consulting, Melbourne, VIC, Australia
e-mail: Frank.Robert@atkearney.com

M. Puteaux · A. Najjar
Euroconsult, Paris, France
e-mail: puteaux@euroconsult-ec.com; anajjar@euroconsult-ec.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_109

Abstract

This chapter discusses small spacecraft technologies and trends, e.g., propulsion systems, additive manufacturing, AI, standardization, launch solutions, miniaturization, and high-level design systems behind smallsat market growth, as well as forecasts related to the manufacture and launch of small satellites over 2019–2028.

Keywords

Small satellite · CubeSat · Smallsat · Satellite market · Satellite technology · Launch · Earth observation · Communications · Constellations · Small satellite market · Micro-launcher · Launch broker · Applications

1 Introduction

The exponential advancement of capability for small systems of all types is transforming the satellite industry in very powerful ways. In 2018, two tiny National Aeronautics and Space Administration (NASA) CubeSats, MarCO A and B, affectionately known to their controllers as Wall-E and Eve, accompanied NASA’s InSight mission to Mars and relayed photos of Mars and diagnostic data back to Earth from the entry, descent, and landing (EDL) of the primary spacecraft via the Mars Reconnaissance Orbiter (MRO), becoming the first CubeSats active in deep space (i.e., beyond Earth orbit). This begins the era of “bring your own communications relay” to science missions and is a considerable evolution in terms of value compared to previous missions, which required large/heavy/costly systems. The spacecraft, despite being the size of a shoe box, navigated to Mars independently of the main spacecraft, and their phased array X-band antennas and associated processing systems accomplished the relay flawlessly.

Many of these innovations are starting to arise beyond traditional places such as the US Space Coast and Pasadena, coming from new centers for small spacecraft development ranging from Glasgow, Scotland, where over 130 space companies are now located, to Adelaide, Australia's new Space Precinct (South Australia estimates over 80 space companies which now call it home), and to hundreds of universities across the world which may for the first time develop space hardware thanks to the low-cost CubeSat form factor.

In more common near-Earth communications applications, three Sky and Space Global CubeSats (10 × 10 × 30 cm) in 2017 successfully relayed 56 Kbps sessions/phone calls across Africa, a technology milestone. Future launches to bring the constellation to 200 satellites have been intended to be via air launch, on Virgin Orbit's LauncherOne, but funding appears uncertain at this point, putting the project at risk. This is just the very tip of the iceberg: far more massive constellations are now planned by several industry stakeholders, such as OneWeb (~650 smallsats), Elon Musk's SpaceX (up to tens of thousands of smallsats according to its various filings), and Jeff Bezos' Project Kuiper (3,236 satellites), raising hopes for inexpensive global internet but also raising concerns for astronomy observations and orbital debris mitigation, due to the significant risk increase in terms of orbital collisions.

In this chapter the technologies supporting small satellite market growth by enabling more and more capabilities within the smallsat form factor are discussed, capabilities which previously were only feasible on large, heavy, and expensive spacecraft with costs often valued in hundreds of millions to a billion dollars. The second part measures, breaks down, and analyzes smallsat industry growth over 2009–2018 and provides a market forecast and insights into market developments expected over 2019–2028. This exhaustive market analysis (all regions, all orbits, all operators and operator types, all launch service providers, all mass categories, etc.) covers all major satellite applications, from telecommunications in broadband and narrowband to provide worldwide connectivity services to Earth observation for civilian (climate change monitoring, resources management, agriculture, forestry, etc.) and military purposes, as well as navigation satellites, security satellites, technology demonstration spacecraft, science and space exploration missions, and many other types of small satellites, with various applications.

2 Small Satellite Technologies Driving Growth

Several advances in technology in particular have been responsible for the dramatic increase in small satellite capabilities and market expansion, ranging from the miniaturization of chips and propulsion systems to miniaturization of payloads, the advent of electric propulsion, more standardization and the availability of affordable commercial off-the-shelf (COTS) components lowering hardware costs, an evolving ground segment ecosystem, as well as a broader range of access to space solutions coming online (at both ends of the mass spectrum, from the launch of hundreds of satellites on heavy launchers to dedicated launches of a few kilograms of satellites) and reducing the launch bottleneck, facilitating and/or reducing the cost of access to space. The advent of AI and flat panel antennas are also playing a key role by greatly facilitating smallsat constellation operations and orbital coordination, driving important growth in telecom and Earth observation smallsats to be launched.

Miniaturization and technology improvements offer smallsat customers the choice between increasingly lighter satellites (at equivalent performance) and more capable but heavier satellites, due to the addition of improved capabilities (lifetime, propulsion, payload, etc.). Thanks to these improvements, CubeSats are now capable of delivering operational services, while, in the heaviest mass category, 250–500 kg satellites can now perform better than some >500 kg non-smallsat satellites.

These technological advancements translate into a rapidly growing number of small satellites. The space industry is on the verge of significant expansion and is undergoing profound changes both on technological and business terms, as dozens of new entrants and established stakeholders alike prepare for the 2020s. The smallsat industry is gearing up for significant expansion in terms of capabilities and demand, with the number of satellites to be launched growing sixfold over 2019–2028, compared to the previous decade. The next 10 years of the smallsat market will be defined primarily by the rollout of multiple constellations, which are estimated to account for 83% of smallsats, mainly for commercial operators (Fig. 1).

Much of the funding financing this technological progress and advancement stems from a boom in private investment in space start-ups. Over 400 start-ups have been funded with over $18 billion from over 500 venture funds since 2009, when SpaceX had its first successful launch, and this trend is accelerating (Fig. 2).

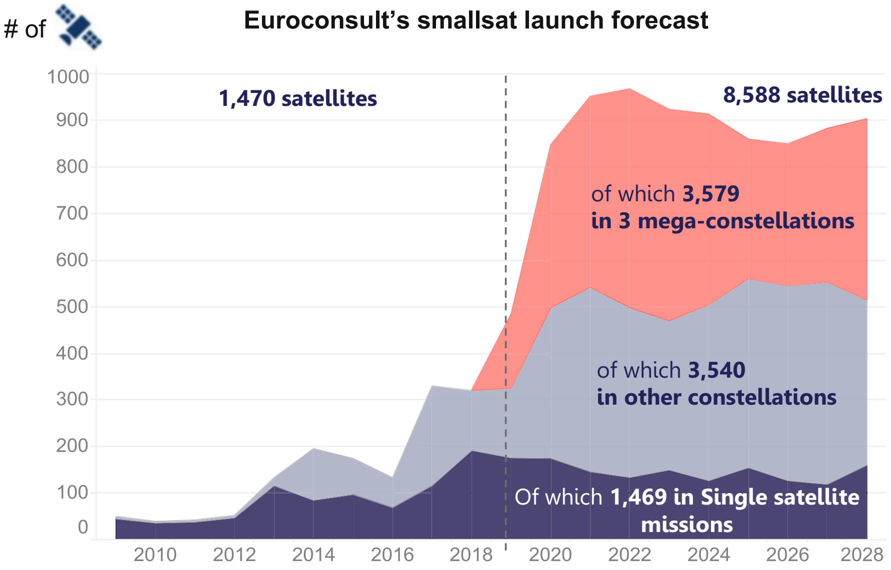


Fig. 1 Euroconsult's comparison of two decades for the smallsat market: the past (2009–2018) and the forecasted future (2019–2028). (Source: Euroconsult 2019. All rights reserved to Euroconsult; this figure is licensed to Springer to publish in the Handbook of Small Satellites)

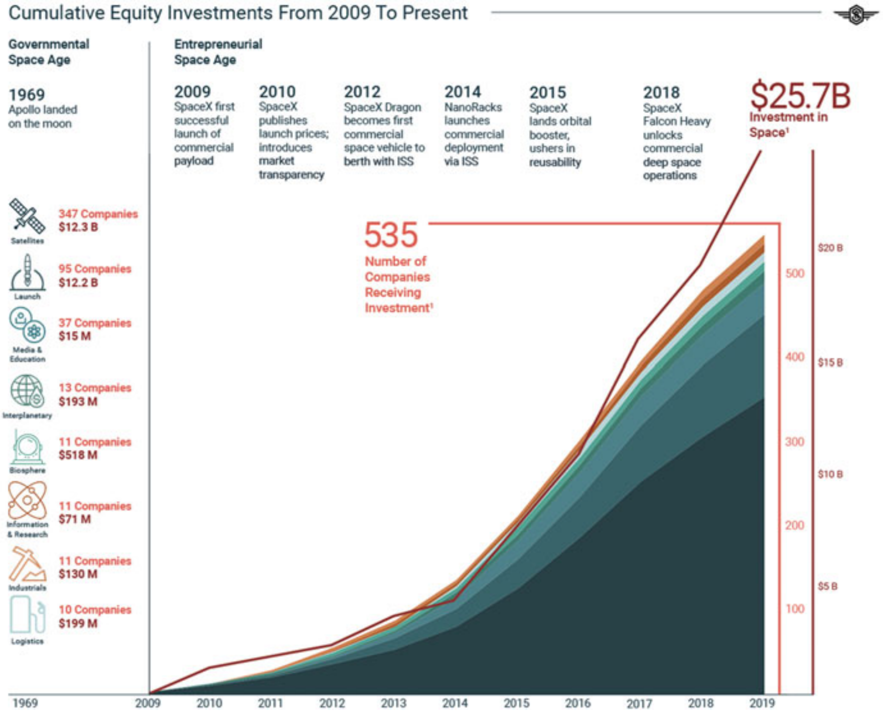


Fig. 2 Investment in space start-ups since 2009 (Investment in Space Startups 2009). (Source: © Space Angels Space Investment Quarterly, Q4 2019, copyright permission given via Creative Commons License; no changes have been made. All rights reserved to Space Angels, this figure is licensed to Springer to publish in the Handbook of Small Satellites. Note: this chart is not specific to smallsats nor to the satellite industry and covers the entire space industry)

2.1 Capability Growth and Manufacturing: Launch Costs Decline

Capability of ICs of course has increased to where a watch has many times the power of a 1980s mainframe computer (device counts per CPU rising from 1000 in 1970 to circa 50 Bn in 2018), and though they are susceptible to gamma rays and other radiation damage on orbit, they are now so small, light, and power-conserving that multiple fail-over backups are feasible in a tiny package. Onboard processing can drastically reduce the amount of data to transmit on the downlink for Earth observation systems, while on-orbit intelligence can also adapt missions to new requirements once launched. This capability increase of roughly 50 million times from the days of the design of Voyager of course does not apply to all onboard systems, but many have come down dramatically due to their reliance on electronics.

Launch prices are key to this also and launch costs to Sun-synchronous orbit (SSO) range from $5,000/kg to ~$60,000/kg. The dispersion in launch prices reflects the differences between launch vehicles in terms of launch capacity (performance – kg to orbit – and launch rate); production and operation costs (as a result of differences in hardware, labor cost, and currency valuations); and versatility (i.e., the ability to accommodate and launch multiple payloads of various masses and volumes). However, prices advertised by providers and per kilo prices are not representative of invoiced prices, which are usually higher than advertised. This is because specific prices are calculated on the assumption that a launcher launches at full capacity (100% fill rate), an extremely rare scenario. Partially filled vehicles thus mean higher specific prices.

For now, launch competition remains driven by price with other factors such as on-time launch and injection precision as secondary considerations. Falcon 9 is the only launcher with a specific price as low as 5,000$/kg but for an entire Falcon 9, until in 2019 a new set of rideshare to SSO opportunities as early as 2021 was announced, starting at 5,000$/kg. The service aims to leverage first stage reutilization to provide yearly rideshare opportunities. Another launcher, India's Polar Satellite Launch Vehicle (PSLV), is also widely seen to be one of the most available and cost-effective. The Indian Space Research Organisation (ISRO) charged between 28,000$/kg and 38,000$/kg for 3 U CubeSats in 2018 and between 12,000$/kg and 16,000$/kg for heavier smallsats. Its Small Satellite Launch Vehicle (SSLV) is a new dedicated micro-launcher scheduled for a 2020 maiden flight and is expected to reduce price as low as 7,000$/kg and capture significant market shares. It theoretically combines the flexibility and reactivity of micro-launchers with the lower cost of a rideshare on a larger vehicle. The other small vehicles in development are by design more expensive than heavier solutions but allow for a shorter time to orbit. Prices from Rocket Lab, Virgin Orbit, and Firefly all have increased in recent years, ranging from 24,000 to 50,000$/kg. With a need to generate revenues and limited dedicated launch options available, prices are expected to stay at the current levels before increased global competition leads to lower prices. Moreover, the arrival of Chinese start-ups with competitive prices (e.g., 10,000$/kg for Kuaizhou-11) will push for mass production and high launch rates, eventually putting pressure on prices. The pricing of launch brokers comes at a premium as they act as a one-stop shop, giving access to multiple launch solutions, but they provide effective solutions for many players and improve utilization of launchers. Spaceflight Services, the only launcher broker with public prices, charges regardless of the launcher used, from $26,000 (for a 300 kg satellite) to 35,000$/kg (for a 50 kg satellite).

Cost declines driven by the availability of COTS components (for both hardware and software) and mass reduction for spacecraft which retain the same level of capabilities are also driving growth in value per dollar for small satellites. Combined, these trends show a dramatically rising value per dollar spent on spacecraft and launch to date, and these are expected to accelerate. This drives an increasingly robust market for small spacecraft and their services.

2.2 Propulsion Systems, Including the Electric Propulsion Paradigm Change

The small size and mass of CubeSats present challenges for adding propulsion, and most often they are so far launched without it. For missions in which rapid time to orbit and/or a maneuvering capability is required, standard chemical thrusters or solid propellant motors are often the best choices for larger spacecraft. However, many smallsats are too small for chemical propulsion systems, which are expensive in terms of volume, mass, and cost, in addition to the increased complexity of the small satellite. Therefore, given the volume, complexity, and cost of chemical propulsion systems, many smallsats did not have any propulsion capability in the past. Adding electric propulsion (EP) significantly improves the potential of the smallsat form factor, by enabling propulsive capabilities and autonomous maneuvers, which previously were limited to the largest smallsats and came at a high cost. In addition, most CubeSats share launch vehicles: this often subjects them to rules against the use of propellants such as hydrazine, or pressurized tanks in general. In consequence, today the majority of smallsats either tends toward electric propulsive capabilities or no propulsion, as the mass and cost of chemical propulsion remains prohibitive for most smallsats. Only smallsats in heavier mass categories may opt for a chemical propulsion system, often based on hydrazine. Green monopropellants are being developed as potential replacements to hydrazine, which is highly toxic.

The propulsive mass efficiency of propulsion systems is defined by their specific impulse (ISP). While chemical propulsion systems have specific impulse (ISP; a measure of fuel effectiveness), in the 250 s range, electric propulsion can reach ISPs of 4000 s and above, allowing a spacecraft to go much further per kg of propellant. The transition in larger satellites to electric propulsion, generally using Xenon or Krypton fuel ionized in a magnetic field and accelerated out the back of Hall-effect thrusters at very high speeds (typically up to 80 km/s), is only just reaching CubeSat-sized smallsats. In large spacecraft such thrusters can turn 1.35–10 kW of input power into thrust of 40–600 millinewtons for up to 8,000 s specific impulse at efficiency in the range of 45–60% (Choueiri 2009).

Today, smallsats can benefit from a growing range of propulsion types, currently available on the market or at various stages of development, from early research to the in-orbit validation of prototypes. Examples include cold gas thrusters, with an ISP around 80 s, solid fuel motors with an ISP around 210 s, water propulsion with ISP around 175 s, plasma (water) propulsion with ISP up to 750 s, and electric propulsion with ISP up to 6000 s. Bradford Space's ECAPS company developed a range of high performance green propellant (HPGP)-based thrusters enabling a 6% increase in ISP compared to hydrazine propellants (in addition to toxicity reduction), which have been adopted by a wide array of smallsat operators. Green propulsion systems using fewer toxic propellants from Ball Aerospace will also be tested on NASA'S Green Propellant Infusion Mission (GPIM).

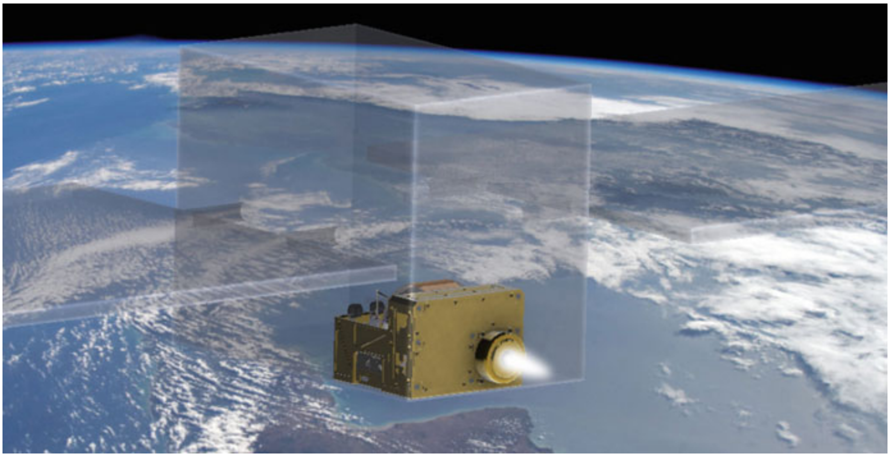


Fig. 3 Artist rendering of CubeSat radio frequency electric propulsion system. (Image: © Phase Four, 27 June 2019, All rights reserved to Phase Four; this figure is licensed to Springer to publish in the Handbook of Small Satellites)

Electric propulsion (EP) features many different subcategories undergoing parallel development, with a wide range of new entrants, many of which are spun-off from academia. Among the various types of electric propulsion are resistojets, electrosprays, ion engines, pulsed plasma thrusters, and Hall-effect and RF thrusters. Electric solid-state propellants also are under development to control ignition and extinguishment voltage. Hall-effect thrusters, for example, are under development by Accion, Phase Four (USA, shown in Fig. 3 below), ThrustMe (France), Clyde Space (UK), and Neumann Space (Australia), among others, most of which are targeting in-orbit demonstration within the year. Neumann Space aims for a 10 K second specific impulse ion thruster which can use a variety of fuels, and in 2019 Phase Four unveiled Maxwell, a CubeSat radio frequency plasma thruster capable of delivering up to 10 mN of thrust and up to 1,400 s of specific impulse, with total impulse of up to 14,000 newton-seconds. It is intended for satellites of 20–500 kg with 300–500 W power budgets.

The main impact of EP on satellite operations is an improved time to orbit as well as an optimized satellite lifetime. For geostationary Earth orbit (GEO) missions, the trade-off is often a slower orbit raise compared to chemical propulsion (4 months vs 1 week), which means delayed revenue generation, in exchange for a smaller, less costly satellite of equal capability (as the fuel mass saved can be replaced by either additional payload mass or significant savings on launch costs). However, when considering EP for low Earth orbit/Sun-synchronous orbit (LEO/SSO) operations, there are many variables to consider. Smallsats launched via ridesharing tend to be released as secondary payloads into the orbit of the main payload. While this is the least expensive access to space option for smallsats, it is also the least practical. EP thus enables them to perform orbital maneuvers such as orbit raising, plane changes (i.e., modifying the inclination of an orbital plane, effectively accessing another orbital plane), and constellation phasing (i.e., spreading the satellites along an orbital plane), allowing the satellites to autonomously reach their final orbit.

Considering that satellites in LEO have relatively short lives, some satellite operators take this to the extreme and forgo propulsion altogether (e.g., Planet, Spire). If low enough, satellite phasing can be achieved by altering the orientation and drag profile of each satellite (or its solar panels) thus modifying the orbit without propulsion. In 2019, the use of EP for attitude control of a smallsat was demonstrated by Morpheus Space, which flew NanoFEEP thrusters on the UWE-4 technology demonstration 1 U CubeSat.

In 2019, the Federal Communications Commission (FCC) released new regulations meant to streamline licensing procedures for small satellites. However, only satellites up to 180 kg, within a limit of 10 satellites (i.e., constellations under 10 spacecraft) and with 6 years of orbital lifetime, would be eligible for this fast-track licensing regime. Application fees would be reduced from \$450 k to \$30 k for eligible satellites. The applicant would have to prove that he mitigates the risk of creating new space debris. If the orbit is above 600 km, a propulsion system is required to ensure a secure end-of-life removal and to enable collision avoidance maneuvers. Satellites would also be required to carry a telemetry marker so that ground teams are able to distinguish it from other satellites. This specific regime does not apply to mega-constellations or to CubeSats with a 1 U form factor.

2.3 Standardization and Commercial Off-the-Shelf (COTS) Hardware Lowering Costs

Standardization is now a strong growth factor for smallsats. In the past, initial missions used to be one-off custom efforts. With a focus on rapid and low-cost development, standardization facilitates compatibility and interoperability and removes the obstacles related to legacy technology by allowing the simultaneous use of upgraded components and software.

Standardization is even more critical at subsystem level than for the satellite itself. The 1 U CubeSat standard (10 × 10 × 10 cm) established in 1999 aimed to facilitate design and manufacturing by research institutions using non-space-graded hardware. It was later adopted by commercial operators for operational services. The CubeSat form factor is so far the only standardized platform bringing agility to launch services with their ability to swap launchers on short notice thanks to CubeSat dispensers, booked by launch brokers who buy unused capacity from launch providers.

Seeking to replicate the success of the CubeSat form factor, the Aerospace Corporation proposed another launch standard, Launch-U, in August 2018. This standard for larger smallsats (45 × 45 × 60 cm; 60–80 kg), if adopted by the industry, would provide the same platform agility as the CubeSat form factor. One Launch-U equals roughly 96 units. Rocket Lab's Electron and Virgin Orbit's LauncherOne would, for example, be capable of hosting up to two and seven Launch-U's under their fairings, respectively.

In heavier mass categories, platform diversity is driven by mission diversity. Several platforms are compatible with the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring payload adapter enabling piggyback launch options. No other comprehensive initiatives have yet materialized in a single format. Further initiatives envision satlets, or easily stackable modular spacecraft that can be connected depending on mission requirements, with the involvement of the Defense Advanced Research Projects Agency (DARPA) and NovaWurks.

The multiplication of dedicated suppliers was key to the development of the industry. Commercial off-the-shelf (COTS) hardware, miniaturization, electronics integration, and sometimes non-space-graded components allow reasonably similar performance at smaller size and lower cost. Low development costs and short manufacturing times are key advantages of smallsats, in addition to large-scale manufacturing economies of scale and continuous iteration in product development. CubeSat platforms are now a commodity allowing operators to focus on the design of their payload or on their business of selling satellite services. Online procurement is now common to build CubeSats. Smallsat manufacturers are positioning themselves as “one-stop shop” suppliers, offering simulators and payload development tools in addition to satellite platforms plus turnkey services (testing, regulatory compliance, insurance, launch procurement, ground control).

Larger small satellite platforms have yet to become truly recurring products, and modifications are often needed to adapt to each mission’s requirements. Regarding mechanisms, the development of microelectromechanical systems (MEMS) helps with the miniaturization of some subsystems, enabling them to fit into smaller form factors. Oxford Space Systems, for example, develops deployable antennas and solar panels, stored energy hinges, and extendable booms. This also allows avoiding the use of pyrotechnic devices wherever possible, due to their potential hazards, so other release mechanisms such as springs or sophisticated MEMS are used. In 2019, NSLComm launched a constellation prototype designed to test its deployable antenna reflector using built-in shape memory polymers, which could result in throughputs as high as 1 Gbps; an impressive feat for a 6 U Ka-band CubeSat.

2.4 Directed Beam Telecoms for Small Satellite Systems

Directed beam flat panel array antennas and associated processing systems both on the spacecraft and on ground terminals are expected to soon have a major impact on small satellite and ground segment capabilities. As small satellites tend to be in low Earth orbit, tracking antennas on user terminals are required to keep one or more spacecraft in the receive beam of the terminal. Medium Earth orbit systems like O3B also require tracking, and early commercial terminals are so far primarily using physically moving dishes, but flat panel phased arrays are currently being developed by many stakeholders seeking to profit from the important forecasted markets for flat panel antennas.

The flat panel antenna system used onboard MarCO A and B is still beyond the budget of most CubeSat builders, but flat panel phased array antennas on satellite terminals with associated processing to track LEO orbiting CubeSats appear to be incoming, to be followed by commercial flat panels orbiting on smallsats themselves (thereby eventually able to create multiple beams toward ground terminals).

In support of developing economical CubeSat-flown flat panel arrays, NASA/JPL has proposed the Integrated Solar Array and Reflectarray Antenna (ISARA) mission. It is intended to test the integration of a flat reflector into the solar array used to power a CubeSat, thereby raising data rates from the 9.6Kbps now typical in CubeSat links using high frequency band radio (3–30 MHz) to over 100 Mbps at Ka band (26.5–40 GHz, further discussed below), without adding the size and mass of a separate flat panel array antenna to the spacecraft (JPL CubeSat).

On the user terminal end of CubeSat space segment communications, Kymeta Corp. of the USA began shipping its metamaterial electronically steered flat panel antennas to customers in 2017, although for now these are intended mostly for systems using larger satellites and come at a high cost per unit. The ground terminals are thus mostly reserved for yachts, commercial ships, tractors, and first responder vehicles. ThinKom Solutions, also in the USA, also produces commercial phased array antennas for aircraft and motor vehicles that are expected to work with future low and medium Earth orbit constellations. Meanwhile, Phasor is testing low-profile electronically steered broadband antennas for buses, ships/yachts, and aircraft. Many more products are coming, including entries from Isotropic Systems, Alcan Systems, C-Com Satellite Systems, SatixFy, AvL Technologies, Ball Aerospace, Rockwell Collins, and Viasat (SpaceNews 2018).

2.5 Use of Additional Spectrum Bands by Small Satellites

Spectrum represents one of the top requirements for all satellite operators, and CubeSat systems tend to be able to afford less while needing more than traditional systems. Traditional communications satellites in geosynchronous Earth orbits (GEO) have historically used C band at 4–8 GHz, now coming into use also for 5G mobile, Ku band at 12–18 GHz, and recently Ka band at 26.5–40 GHz for their space segments to fixed terminals. Ku and Ka are named for being under and above the 22.24 GHz water vapor resonance which absorbs radio waves strongly. For mobile satellite services, the prized lower spectrum bands include L Band at 1-2GHz in mixed mobile and fixed use and S band at 2–4 GHz (though portions of both bands are reserved for terrestrial mobile communications).

The use of Ku and Ka band by LEO smallsats is relatively new and was allegedly inaugurated by two Canadian companies, Telesat and Kepler Communications in 2017 and 2018, respectively (however, OneWeb and SpaceX claim they were first for primacy rights on spectrum, which are given on a “first come first served” basis at the FCC). Further applications for these bands have been made by more than eight other LEO operators.

Some large new constellations are using a wide variety of bands outside of the mainstream, such as China's Galaxy Space launch of a Q/V band prototype for a potential future constellation in 2020, and some systems are using newly efficient algorithms to separate thousands of terminals' signals from one another in a very narrow bandwidth. An example of the latter is Australia's Myriota, whose constellation of polar orbit nanosatellites will use a tiny sliver of L band to collect data from terrestrial Narrowband Internet of Things (NB-IoT – a primary terrestrial IoT standard) environmental sensors outside of mobile network coverage. Limited to 24 bytes every 4 h in one direction only, no panoramas of the bush are feasible, but very inexpensive sensor data collection is, such as whether cattle have enough water in a given spot. This is a truly tiny sliver of usage compared with the "Internet Everywhere" constellations discussed below, and supports very small terminals with very long battery lives by comparison, as well as economizing on spectrum.

2.6 Militaries Across the World Show Substantial Interest in Smallsat Constellations

Whether through hardware failure, debris impacts, or aggressive external action, the premature loss of a satellite has extensive repercussions, due to its replacement cost and to the loss of significant projected benefits/revenues during its expected lifetime. Smallsat constellations, on the other hand, are designed with redundancy and resilience at heart. When the size of the constellation is sufficiently large, the loss of even a handful of satellites may have little to no impact on the final service offered to end users. Additionally, ground spares can be launched much more easily and rapidly than for larger satellites, and many constellations plan in-orbit spares for maximum reactivity, i.e., satellites "standing by" in case of failures and ready to provide a service. The US military, for example, is more and more involved in the smallsat industry, as low-cost, expendable, and distributed assets such as smallsat constellations are far more resistant to enemy action and a strong advantage in any conflict.

Defense agencies have supported smallsats since the 2000s but have been reluctant to use them beyond in-orbit demonstration. Increased threats in the space environment, coupled with budgetary realities and the flexibility and resiliency of smallsats, make small satellite ventures inherently well positioned to meet those needs. The Blackjack program, led by the DARPA in collaboration with the Rapid Capabilities Office, is an architecture demonstration intending to show the utility of global LEO constellations and mesh networks of lower size, weight, and cost based on commercial smallsat platforms to the military. In the meantime, Viasat was awarded a demonstration contract for a tactical LEO comms demonstrator using Link 16, a NATO communication protocol. The newly created Space Development Agency released in 2019 an RFI for agile and responsive architectures aiming to leverage industry solutions.

The world's military organizations are also suddenly interested in the development and launch of LEO constellations, both for telecommunications (global coverage, low latency, resiliency) and Earth observation (surveillance, monitoring of enemy activity and conflict zones, border security, etc.). Part of the rationale for this is the capability to detect the ionized exhaust trails of hypersonic cruise missiles while remaining difficult for anti-satellite (ASAT) weapons to take out, unlike large single spacecraft which are vulnerable to ASAT weapons. Russia claims to have flown a hypersonic cruise missile, the Avangard, from the stratosphere over the Ural Mountains in Eastern Russia to hit a target on Kamchatka Peninsula on its Pacific coast 6,000 km away, at Mach 27, a speed very close the Space Shuttle's reentry velocity. This was launched by a rocket and thus would have been visible initially to existing anti-ICBM systems but would have become effectively invisible during its cruise phase, in which it reportedly remained fully maneuverable. Another Russian hypersonic cruise weapon, Kinzhal, is reported capable of Mach 10 under its own power, with no rocket boost phase, and hence would be invisible to current detection satellites. Russia claims operational deployment of its initial hypersonic systems. China also tested its Xingkong-2 "Waverider" hypersonic cruise missile in 2018. This weapon also reportedly demonstrated full maneuverability through the stratosphere at Mach 6, described by the China Academy of Aerospace Aerodynamics as able to "break through any current generation anti-missile defense system," hence the development priority for new smallsat-based defense systems.

In light of these announcements, the USA and its allies have raised focus on catching up and begun greater financing of this effort, with the USA reportedly allocating circa US$1B per year to it. France and Japan also are joining the race, France to launch hypersonic weapons in 2022 and Japan in 2026 (per the U.S. Congressional Research Service, 2019). Hypersonic vehicles also experience ionization envelopes, essentially like the impenetrable ones enveloping the Space Shuttle on its reentry as their speeds approach Mach 17. This makes communicating with these weapons challenging, and new satellite systems may facilitate circumventing this problem also.

The race to be able to detect and deflect these weapons is on for real now, undoubtedly funded in most countries capable of developing them. Detection of hypersonic weapons' flight paths and intended targets, as well as communicating with anti-hypersonic missile systems which will be built to respond, requires satellite systems, and the advent of anti-satellite weapons tested successfully by the USA, Russia, China, and India up the ante on required resilience of such systems. Likely responses will therefore entail large LEO constellations, a step function in military demand for such systems.

The USA, for example, considers launching hundreds of small satellites with sensors capable of tracking heat sources an order of magnitude cooler than rocket boosters, making them hard to take out by deploying many of them. The satellites would also be used to help guide US hypersonic weapons. The full Hypersonic and Ballistic Tracking Space Sensor network could be up and running by 2030 (Stone 2020a) (Fig. 4).


Pentagon's New Space Agency Seeks $10.6 Billion Over Five Years Bloomberg, 4 Oct 2019

The US launched its Space Command and Pentagon Space Development Agency in 2019, and France announced it is arming its new satellites.

This raised serious fears of Kessler Syndrome from cascading Orbital Debris impacts.

More additional countries are expected establish or expand military forces in space in 2020

Space Development Agency Head Fred Kennedy Presentation, April 9, 2019

Fig. 4 Beyond these commercial constellations, military ones are also expected. (Source: Fred Kennedy, Space Development Agency, image in public domain)

2.7 Small Spacecraft Onboard Processing via AI and Machine Learning

James Lovelock, at 100 years old, in his recent book *Novacene*, postulates a rapid evolution to a benevolent AI/Human stewardship of our planet. He notes: "The sea bird, with its graceful flight, took more than 50M years to evolve from its lizard ancestors. Compare this with the evolution of today's airliners from the string-bag airplanes that flew a mere 100 years ago. Such intelligent, intentional selection appears to be a million times faster than natural selection. By moving beyond natural selection, we have already enrolled as sorcerers' apprentices.[10]" His prediction may be considered to be reflected, among many places, in AI for small Earth observation spacecraft.

CubeSats and large data flows do not mix well, as high data rates require large communication systems to operate. Initial examples of AI in small satellites are therefore focused around drastically reducing the data stream required for remote sensing/Earth observation satellites. On the upcoming Federated Satellite System Catalunya (FSSCat) mission by the European Space Agency proposed by Spain's Universitat Politècnica de Catalunya, AI technology will fly on one of the two CubeSats (federated over a radio and optical intersatellite link) that make up the mission – the mission consists of two 6 U (i.e., 6 of the 1 U volume of 10 × 10 × 10 cm) CubeSats working together in support of the Copernicus Land and Marine Environment service. Sensors will include a Global Navigation Satellite

System (GNSS) reflectometer, an L-band radiometer, and a multispectral optical payload to measure soil moisture, ice extent, and ice thickness and to detect melting ponds over ice. One of these spacecraft, dubbed PhiSat, will have the ability to decide for itself which images are worth sending back to Earth for further analysis.

Raw data is generated in orbit and transmitted to Earth ground stations, after which it is processed and analyzed. Satellite throughput is limited by bandwidth, and ground stations as well as data centers are costly, particularly for new entrants, and often saturated. With terabytes of data being routinely generated, and much of it commercially unviable, the costs associated with data downlink, storage, and analysis can become too much to bear and an important barrier to entry. So far, few players have sought to address this inefficiency, which increases in direct relation with the increase in data generation.

Onboard processing reduces the amount of unused data while improving accuracy and pertinence of received data, as it allows satellites to perform initial autonomous data analysis in orbit. Only relevant data is downlinked back to Earth, reducing the need for storage, making data easier to find, and reducing the final cost per GB of data. Human interaction with the data is refocused onto decision-making rather than analysis.

This trend will lead to improvements in satellite design, ease strain on the value chain, reduce operating costs, and improve profitability. In 2018, the HyperScout CubeSat mission demonstrated this capability in orbit, and the OVERPaSS consortium, led by Earth-I and including Surrey Satellite Technology Ltd (SSTL), was founded to develop onboard data processing capabilities.

2.8 New Design and Manufacturing Methods

The processes used for initial design of small spacecraft and the constellations they will form are accelerating along with the rapid tailored fabrication and mass production of the satellites.

Increasingly, new high-level system design is being supported by modular, shared Digital Twin modelling generally referred to as concurrent design. A burgeoning example of this method is used by the Australian National Concurrent Design Facility of the University of New South Wales (UNSW) Canberra. In this system, modules of simulation code have been built around core spacecraft simulation software from France's National Centre for Space Studies (CNES). This has adapted the system to smaller missions and enabled a real-time high-level design process in which technology specialists use design elements for power/solar arrays, propulsion systems, launch weight and distribution of mass, thermal balance, communications link and spacecraft bus loadings, etc (Fig. 5).

Design beyond individual spacecraft, to the constellation level with orbital dynamics overlaid on link budgets; intersatellite communications and shared processing; Telemetry, Tracking, and Command; and traffic carrying links to Earth stations, is next up for this process. Other concurrent design facilities are used by

Fig. 5 Australian National Concurrent Design Facility at UNSW Canberra. (Image © UNSW Canberra. All rights reserved to UNSW Canberra; this figure is licensed to Springer to publish in the Handbook of Small Satellites)

major prime contractors and NASA (e.g., the Goddard Space Flight Center and Integrated Design Center for Concurrent Engineering).

2.9 Improved Access to Space Reducing the Launch Bottleneck

The market entry of SpaceX and Rocket Lab and the capacity to deploy CubeSats from the International Space Station (ISS) have greatly improved access to space for small satellites in recent years, combined with the launch of hundreds of smallsats of Indian and Russian launch vehicles. This is just the beginning. On the launch side, future developments include new and established players that seek to challenge SpaceX on the launch cost side, or by seeking to provide a different value proposition (e.g., a better time to orbit, premium services via dedicated launches, more flexibility, etc.). In 2019, SpaceX dramatically undercut its smallsat launch prices by offering lowest pricing in the industry, with regular rideshare opportunities into subsynchronous orbits for $5,000/kg of payload, a substantially lower price, competitive even with the cheapest Indian and Chinese launch solutions, starting in 2020/2021. Rising companies capable of challenging SpaceX to look forward to include Blue Origin with its New Glenn launch vehicle (with a massive performance to LEO and a 7-m fairing capable of launching hundreds of smallsats at once, in addition to partial reusability with first stage recoveries and reuse) and Relativity Space (which seeks to additively manufacture launch vehicles in a matter of weeks instead of months, at a very low cost; See Fig. 6). SpaceX itself is not staying idle

Fig. 6 Relativity Space Stargate Printer. (Image: © Relativity Space; All rights reserved to Relativity Space, this figure to be licensed to Springer to publish in the Handbook of Small Satellites)

and is trying to improve its own capabilities through the development of Starship, a very ambitious fully reusable and super heavy-lift launch vehicle which would be the largest launch vehicle operational, if SpaceX demonstrates its technical, financial, and legal feasibility. As it is fully reusable and expected to be capable of launching dozens, if not hundreds, of times, its marginal launch cost would be limited to refurbishment operations and refueling activities (which Elon Musk has said to be as low as $900 k), totaling about $2 million per flight (i.e., less than the cheapest and smallest launch vehicles, despite a massive payload capability). This is however uncertain/remains to be proven.

Other more exotic and “nonconventional,” low-TRL (technology readiness level) technologies are being introduced despite their lower credibility and higher risk, such as SpinLaunch, a start-up funded to develop a centrifugal force “space catapult,” succeeding at multiple major fund raisings despite a widespread skepticism about its technology.

Furthermore, online procurement is now common to build CubeSats, and smallsat manufacturers are positioning themselves as “one-stop shop” suppliers, offering simulators and payload development tools in addition to satellite platforms plus turnkey services (testing, regulatory compliance, insurance, launch procurement, ground control). Launch brokers and micro-launchers are now offering online booking systems to simplify procurement. With dozens of micro-launchers in development, smallsats are poised to benefit from more launch flexibility for reaching specific orbits and to reduce time to launch, at the cost of a premium in $/kg compared to a rideshare launch on a heavier vehicle. Micro-launchers aim to launch every couple of weeks or even days, although such responsiveness and launch rates have yet to be demonstrated (Figs. 7, 8 and 9).

2.10 Launch Brokers: A Middleman Business Model Providing Flexibility

Launch brokers optimize payloads across multiple launch systems and, in doing so, offering customers easier/cheaper and wider access to orbit. This service allows for

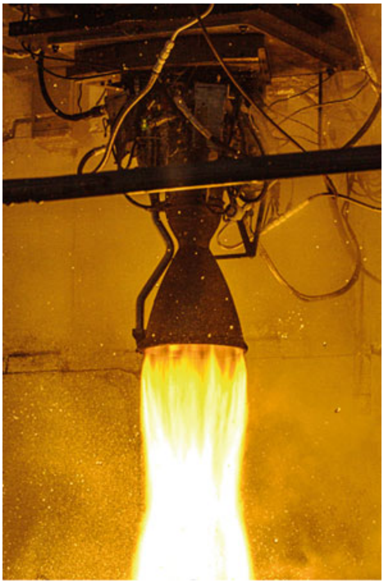


Fig. 7 Rocket Lab 3D printed Rutherford engine firing. (Image: © Rocket Lab; All rights reserved to Rocket Lab, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

Fig. 8 SpaceX Starship. (Image: © SpaceX; All rights reserved to SpaceX, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

significant cost savings for operators compared to buying an entire launch, which may be either unaffordable or impractical because their satellite weighs only a few kilograms. Aggregators offer a comprehensive service through aggregating and marketing excess payload space and assisting in integration and overall logistics. The logistical support of brokers for mission preparation and integration may also be essential for small operators not familiar with these activities. The business model of the launch brokers is complex: as they aggregate unused payload space on multiple launchers, they must accommodate the schedules of the launch provider, the primary

Fig. 9 Virgin Orbit LauncherOne/Cosmic Girl. (Image: © Virgin Orbit; All rights reserved to Virgin Orbit, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

mission, and the secondary passengers. They also must include the margin of the launch provider into their costs. Launch brokers include Spaceflight Services and NanoRacks LLC in the USA, which democratized access to space via the ISS, as well as ISIS (Netherlands), Exolaunch (Germany/Russia), Precious Payload (USA), and Space BD (Japan), which has access to Japan's Kibo module on the ISS, and which early-on specialized in ISS launch, but is now branching out and has contracts as far away as Australia.

2.11 An Evolving Ground Segment Ecosystem

The ground segment is evolving to adapt to the growing smallsat market, in anticipation of significantly higher volumes of data expected to be downlinked in the coming years. Ground stations for data transmission and reception represent significant capex investments, especially for new entrants with less resources to expend. Due to the need for multiple stations to ensure global coverage, it can be too costly to implement for most emerging players. Companies such as RBC Signals, Spaceflight Networks, Infostellar, Leaf Space, and Amazon Web Services (AWS) propose access to their ground station networks with pay-as-you-go customized services ("space as a service"). Customers can adapt their contracts to their needs (e.g., continuous or sporadic data downloads). AWS's market entry is likely to disrupt other players, as the company will enable important synergies with its data storage and analytics capabilities. It seeks to operate a global network of Lockheed-built ground stations, starting with 12 locations and 8 publicly disclosed customers, including Capella Space, Spire, Maxar's DigitalGlobe, Myriota, D-Orbit, NSLComm, Open Cosmos, and Thales Alenia Space.

2.12 Resulting Mega Constellations

Advanced systems with greater bandwidth and very large numbers of satellites, enabled in part by the above technology advances, are now being proposed, developed, and launched in the case of the most advanced players (Starlink and OneWeb). Some are seeking to employ nontraditional bands, often for the first or nearly the first time. SpaceX's Starlink constellation, for example, intends to use Ku and Ka for early generations of satellites and is reportedly considering using V band and optical intersatellite links in later generations of satellites. Starlink will reportedly use phased array antennas at Ku and Ka bands on 260 Kg spacecraft initially at 550 km orbits, as well as on consumer ground terminals "with flat antennas the size of pizza boxes." Initial Starlink and OneWeb launches have lacked optical intersatellite links, but these are planned for in later generations. Due to the high cost of laser terminals (a very early stage technology), it is likely that SpaceX will try to internalize their design and production for more vertical integration and cost synergies. The satellites will use more traditional Hall-effect thrusters with Krypton fuel, cheaper than the Xenon in widespread use for electric spacecraft propulsion on larger spacecraft, and more traditional than other electric small spacecraft propulsion systems discussed here. This constellation has filed for licenses to grow from its existing 300 satellites (as of March 2020) to over 12,000, and possibly 42,000, but this remains highly unlikely due to the cost of manufacturing and launching the satellites. SpaceX itself has said that less than 2,000 satellites would be sufficient to start an operational service, and the high figures are likely to include several generations of replacement satellites, as their lifetime is limited to about 5 years.

Amazon's Kuiper constellation FCC application ("APPLICATION FOR AUTHORITY TO LAUNCH AND OPERATE A NON-GEOSTATIONARY SATELLITE ORBIT SYSTEM IN KA-BAND FREQUENCIES") describes a system of 3,236 satellites in 98 orbital planes, at altitudes between 366 and 391 miles, to serve "tens of millions of customers" with internet over Ka band (17.7–20.3 GHz, primarily for customer connections, and 27.5–30.0 GHz primarily for gateway connections). The system is intended to be sold through mobile network operators to reach customers outside their coverage areas. Initial targets mentioned in the FCC application include mobile services to aircraft (where initial trials have exceeded 600 Mbps), maritime vessels, land vehicles/first responders and fixed services to homes, schools, businesses, hospitals, and government agencies. The system will use software-defined networking (SDN) control and new technologies for spectrum sharing and control being developed by Amazon, building on its drone work.

One of the most mysterious constellation plans, most of which remain highly uncertain, is that of Facebook, which filed a small satellite experimental application in 2018 via its subsidiary PointView LLC. The project, as reported by IEEE and Wired, is to be called Project Athena, and early concepts imagine up to 1100 LEO satellites. Little information is available on the project, but Facebook and PointView LLC have been experimenting with optical laser links and with the exotic E-band (71–76 GHz for downlinks and 81–86 GHz for uplinks) which is said to be capable of 10 Gbps downlinks and 30 Gbps uplinks, a massive improvement over tradional alternatives. It however remains to be demonstrated, and the launch of its first Athena prototype has been delayed to 2020 due to the 2019 Vega launch failure. Facebook is probably waiting for demonstration results to take a go/no go decision for a constellation, particularly as it would be very late to market. It remains to be seen whether the technology works as expected and whether it makes economic sense.

Apple also has hired senior satellite executives and engineers and is thought to be at least tentatively considering a direct-to-handset service and/or seeks synergies with its autonomous vehicle business.

These and other main large planned constellations are summarized in Fig. 10 below. The list is not exhaustive and only includes some of the most credible players. Not all will be funded and launched.

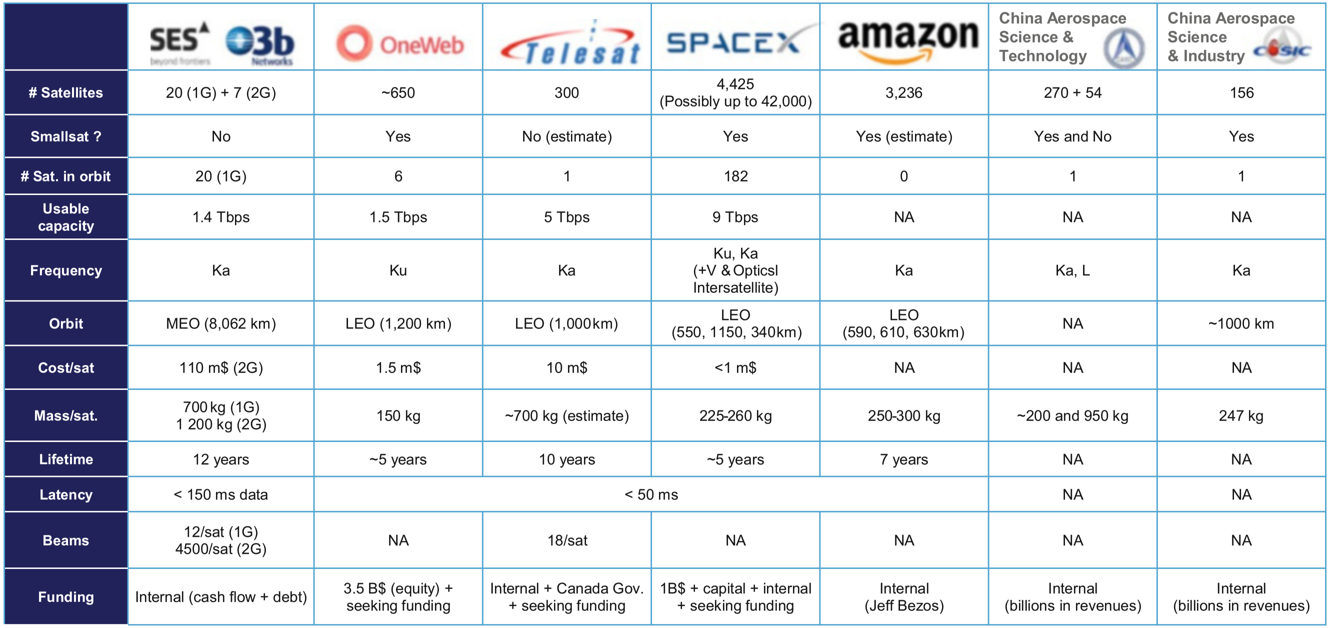
3 Small Satellite Market Growth Patterns

A total of 1,470 smallsats was launched from 2009 to 2018, i.e., an average of about 147 units per year. Most of them (53%) were launched over 2015–2018, mainly for Planet and for academic purposes. The dominant smallsat applications were technology demonstration and Earth observation with proof-of-concept missions seeking to demonstrate platforms and payloads and the deployment of the first smallsat constellations. In the future, smallsats will continue to be used for Earth observation, however second to satellite communications, as several constellations will launch for broadband and narrowband communications.

Over the next 10 years (2019–2028), Euroconsult anticipates that about 8,600 smallsats will be launched, at an average of 835/year by 2023, growing to an average of 880/year by 2028. Euroconsult's 2019 forecast for the next 10 years increased by 22% over the 2018 estimates, highlighting the untapped demand potential for several applications in some regions of the world and new entrants such as Amazon's Project Kuiper constellation. The future smallsat market will be driven by the rollout of several constellations, mainly by commercial operators for broadband communications, Earth observation, and data collection services. Constellations are anticipated to account for 83% of the 8,600 smallsats to be launched. The constellation market is cyclical with strong year-to-year variations driven by their initial deployment in batches within a short period of time in order to begin services as early as possible, followed by waves of replacement satellites. The market for single-satellite missions (about 1,470 units) is more evenly distributed over time.

Most future smallsats (circa 70%) will be launched into LEO. Telecom constellations in LEO seek to enable wide or even global connectivity at lower latencies. Meanwhile, Sun-synchronous orbits (SSO) will be the main destination for most Earth observation satellites. Geostationary transfer orbits (GTO), not a traditional smallsat destination despite new small GEO satellite projects, are increasingly being used as an injection orbit for science/exploration missions beyond Earth orbit.

The smallsat market is going through significant expansion in terms of both capabilities and demand. While 2018 did not exceed 2017's record, the number of



	SES O3b Networks	OneWeb	Telesat	SPACEX	amazon	China Aerospace Science & Technology	China Aerospace Science & Industry CASIC
# Satellites	20 (1G) + 7 (2G)	~650	300	4,425 (Possibly up to 42,000)	3,236	270 + 54	156
Smallsat ?	No	Yes	No (estimate)	Yes	Yes (estimate)	Yes and No	Yes
# Sat. in orbit	20 (1G)	6	1	182	0	1	1
Usable capacity	1.4 Tbps	1.5 Tbps	5 Tbps	9 Tbps	NA	NA	NA
Frequency	Ka	Ku	Ka	Ku, Ka (+V & Opticsl Intersatellite)	Ka	Ka, L	Ka
Orbit	MEO (8,062 km)	LEO (1,200 km)	LEO (1,000km)	LEO (550, 1150, 340km)	LEO (590, 610, 630km)	NA	~1000 km
Cost/sat	110 m$ (2G)	1.5 m$	10 m$	<1 m$	NA	NA	NA
Mass/sat.	700 kg (1G) 1 200 kg (2G)	150 kg	~700 kg (estimate)	225-260 kg	250-300 kg	~200 and 950 kg	247 kg
Lifetime	12 years	~5 years	10 years	~5 years	7 years	NA	NA
Latency	< 150 ms data	< 50 ms				NA	NA
Beams	12/sat (1G) 4500/sat (2G)	NA	18/sat	NA	NA	NA	NA
Funding	Internal (cash flow + debt)	3.5 B$ (equity) + seeking funding	Internal + Canada Gov. + seeking funding	1B$ + capital + internal + seeking funding	Internal (Jeff Bezos)	Internal (billions in revenues)	Internal (billions in revenues)

Fig. 10 Major commercial LEO constellation plans. (Source: Kearney Analysis, Euroconsult Analysis; All rights reserved to Kearney and Euroconsult, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

satellites launched remained stable (322 compared to 330 in 2017), at a 93% increase from the 167 units average observed over 2014–2016. The past and current years are critical for the smallsat industry with the launch of the first operational satellites for telecom mega constellation ventures, and the maiden flights of several micro-launchers, with contrasted outcomes. Moreover, mass production facilities are becoming operational and are expected to further lower the manufacturing cost of smallsats.

In the last 2 years, numerous companies have developed satellite solutions, largely based on constellation projects, to deliver better services and reach out to new users. These solutions are supported by new ventures and entrepreneurs investing in the so-called "new space" or "adaptive space" environment. The objectives of the numerous low-cost constellations in development are to provide global, low-latency connectivity from a single system (telecom segment), high-frequency change detection (Earth observation segment), and low data rate/narrow-band data collection services from ground sensors such as remote devices and connected vehicles (information segment). The information segment is critical for the emerging Internet of Things (IoT) and Machine to Machine (M2M) communications sector, as well as for air and sea traffic monitoring systems including space-based automatic identification system (AIS – ship locations), automatic dependent surveillance – broadcast (ADS-B – aircraft anti-collision system), and radio frequency (RF) monitoring. The market is aided by advances in satellite systems miniaturization, permitted by new technologies in space and space-related sectors, particularly in computational technology and data analytics. As a result, smallsats are now providing operational services that were previously only achievable through heavier satellites.

The 1,470 smallsats that were launched between 2009 and 2018 have an estimated total market value of $12.6 billion (manufacturing and launch combined). The 8,588 smallsats that are due to be launched over 2019–2028 are valued at $42.8 billion, i.e., almost a quadrupling decade-to-decade. Market value is expected to grow more slowly relative to the number of smallsats, reflecting the growing penetration of low-cost smallsats for (Euroconsult 2019) CubeSats and nanosats below 50 kg of launch mass and (Investment in Space Startups 2009) large-scale constellations with a satellite cost of $1 to 1.5 million per unit. This is also representative of the expected decrease in the average cost per kg of smallsat expected in the coming decade, as more affordable platforms and payloads will be introduced on the market and increased competition driven by new entrants will lead launch service providers to lower their prices.

Smallsats <10 kg (mostly 3 U CubeSats) alone will only account for an estimated 2% of future total market value over 2019–2028, due to their low manufacturing and launch value compared to larger smallsats.

Satellite manufacturing is expected to represent 70% of the $42.8 billion future market, i.e., $30.1 billion, with the remaining 30% dedicated to launch services. Most of the smallsat manufacturing market value is placed with large or small integrators that are independent of the satellite operator. In-house manufacturing remains the rule for most satellites below <50 kg and for academic CubeSats;

however larger smallsats tend to favor outsourcing production to third-party integrators.

Three broadband mega constellation projects (SpaceX's Starlink, OneWeb, and Amazon's Project Kuiper) concentrate most of the demand, in terms of number of satellites, launch mass, and market value. However, they are not representative of the industry as a whole, which is highly diverse due to the variety of operators, start-ups, universities, and emerging countries accessing space for the first time, thanks to the growing affordability and capabilities of smallsats.

3.1 Launch

The 1,470 smallsats launched between 2009 and 2018 were not equally distributed among countries of the smallsats' operators and those of the launch services providers. Only 11 countries own autonomous access to space capabilities and have launched smallsats for their own needs but have also launched on behalf of 65 other countries as they export their launch services capabilities. However, countries with autonomous access to space are not always able to retain domestic demand, and local smallsat operators may procure a launch service abroad, if a better value proposition is found elsewhere. This happens when domestic supply is not available, not compatible with the mission, or not sufficiently affordable for the satellite operator (Fig. 11).

The concentration of dedicated micro-launchers under development in the USA is not a surprise but a consequence of inadequate launch supply in the USA as 35% of smallsats operated by US operators were launched by either India or Russia over 2009–2018. Upcoming dedicated launch suppliers are looking to capture this demand with attractive solutions and are lobbying the US government to prevent this demand drain from a regulatory point of view, claiming that they will soon be able to offer domestic access to space solutions for smallsats. For example, launching on India's PSLV is not forbidden to US operators, but it is frowned upon, and operators still need to solicit a waiver from the government. On the other hand, US smallsat operators emphasize their current needs to be launched as soon as possible, regardless of the launch provider's country of origin, as being prevented from launching, or a delayed launch may endanger their business (Fig. 12).

From 2009 to 2018, the small satellite launch market remained concentrated with four launch providers, representing 58% of the revenues. With $586 million, Arianespace dominated the market with its Vega and Soyuz launch vehicles. The French-based company is closely followed by SpaceX at $544 million, Chinese national launch provider China Great Wall Industry Corporation (CGWIC), which commercializes a wide range of launch vehicles and is in charge of deploying most Chinese small satellites ($491 million), and Northrop Grumman (which includes Orbital ATK since its acquisition) using former intercontinental ballistic missiles (ICBMs) Minotaur and Taurus, as well as Pegasus and Antares (International Space Station (ISS) cargo resupply mission), at $443 million.

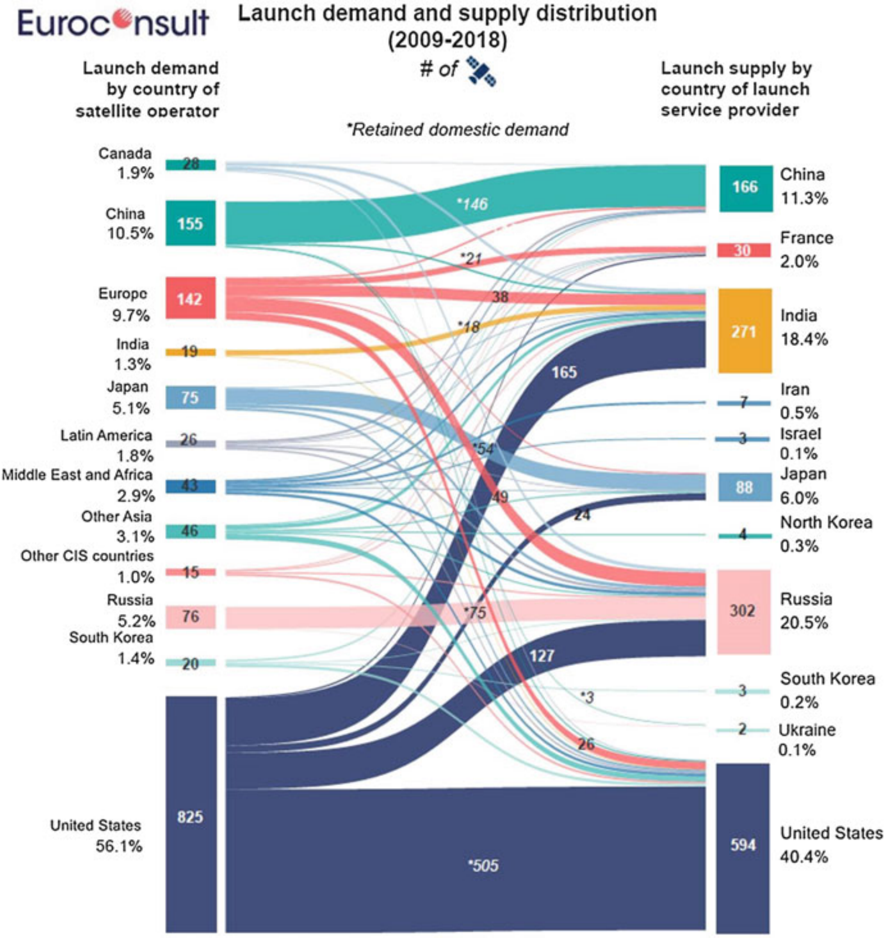


Fig. 11 Launch demand and supply distribution per country of satellite operator and launch provider for the 1,470 small satellite launched over 2009–2018. (Source: Euroconsult 2019; All rights reserved to Euroconsult, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

The profiles of launch revenues were very different from one launch service provider to another. Arianespace has generated an average revenue of $33 million per launch with a total of 30 satellites over 10 years, mainly due the relatively high prices of dedicated Vega missions. In the meantime, SpaceX and Northrop generated on average $12 million and $23 million per launch, respectively, with a total of 163 and 210 satellites each, respectively, over 2009–2018, reflecting the average form factor difference between the providers, as they launched large numbers of low-mass CubeSats during ISS cargo flights.

An estimated $3.5 billion in revenues were generated by smallsat launches over 2009–2018, out of the $12.6 billion manufacturing and launch total market value.

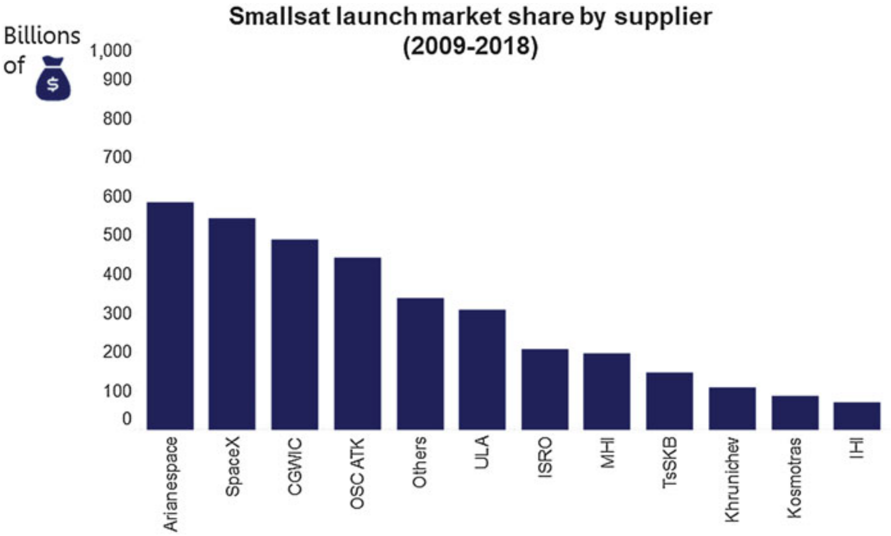


Fig. 12 Smallsat launch market share by launch service provider over 2009–2018. (Source: Euroconsult 2019; All rights reserved to Euroconsult, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

Annual variations ranging from $206 to $864 million were experienced, depending on mission readiness and launch vehicle availability. Over 2019–2028, launch services are expected to generate $12.7 billion, a + 260% increase over 2009–2018. The expected growth in launch cadence and volume (from 1,470 to 8,858 smallsats to be launched), combined with anticipated long-term reductions in average access-to-space costs, are the leading launch market growth drivers.

Different trends affect the two ends of the mass spectrum: <10 kg smallsats will witness a slower average cost per kilo decrease from $45 k to $37 k (−18%) as a consequence of the higher specific prices of dedicated micro-launchers; average >250 kg smallsat launch costs will fall from $45 k to $8 k (−82%). This is a result of super heavy-lift capabilities arriving on the market, such as SpaceX's Falcon Heavy and Blue Origin's New Glenn, which are expected to leverage partial reusability and batch launches to cut prices.

Heavier (51–500 kg) smallsats generate more revenue, as they use more of a launcher's capacity, filling launch vehicles more quickly than lighter satellites. This mass category should generate $11.5 billion in launch value over 2019–2028, a + 281% increase over the previous decade, driven by the three communication mega constellations (Starlink, OneWeb, Kuiper). This mass category accounts for 91% of launch market value over 2019–2028. Mega constellations also affect targeted orbits for the >51 kg mass category, as communication smallsats destined for LEO account for much more mass and value than Earth observation smallsats to be launched into SSO (most of which are <50 kg, hence the stable value shares for that mass category). SSO's share is therefore expected to fall from 42% to 18% of the

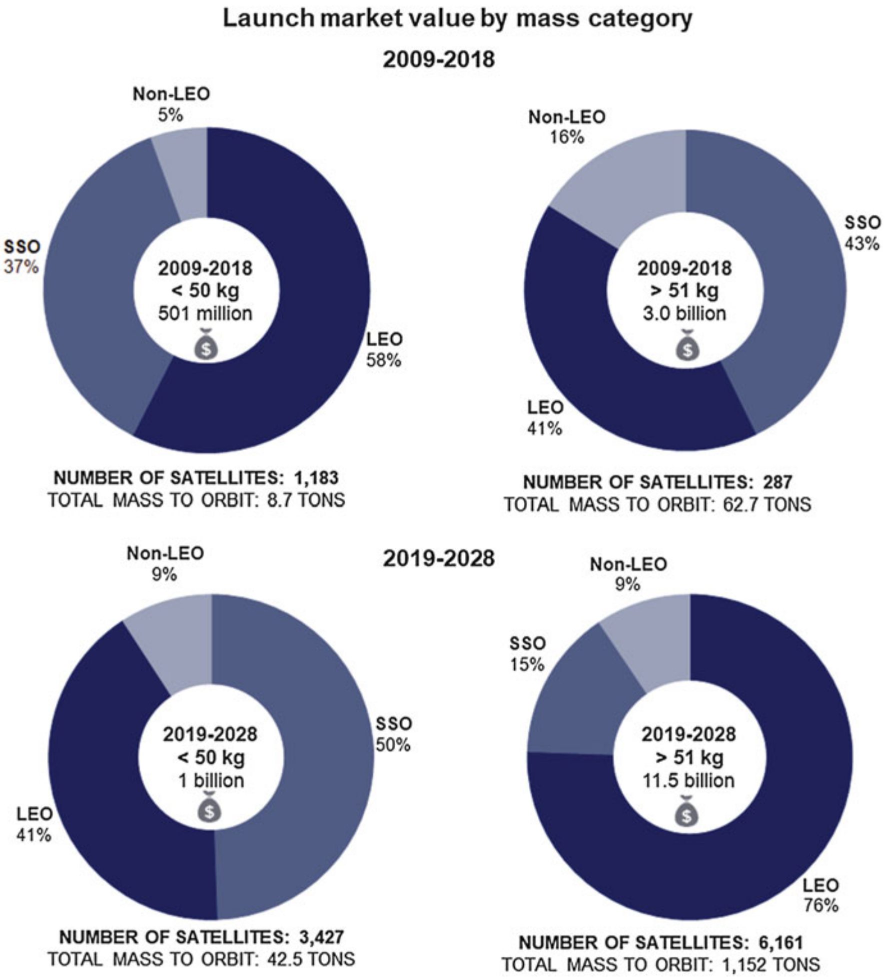


Fig. 13 Launch market value by smallsat mass category over 2009–2018 and 2019–2028. (Source: Euroconsult 2019; All rights reserved to Euroconsult, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

$12.6 billion. Satellites with a launch mass <50 kg will generate $1.5 billion in launch revenues, accounting for only 9% of the 2019–2028 small satellite launch market. 50% of this will be generated by launches into SSO, while LEO is expected to account for 41% of the $1.5 billion in launch revenues (Fig. 13).

New, dedicated launch service providers are working on various systems to capture the growing small satellite market. Value propositions vary by solutions. Dedicated micro (<500 kg in LEO) and small launchers (<2 t in LEO) aim to provide affordable and responsive access to space by flying small satellites as their primary payload (as opposed to relying on ridesharing, etc.). With these new launch solutions, the price per kilogram may not be the only appropriate metric to compare

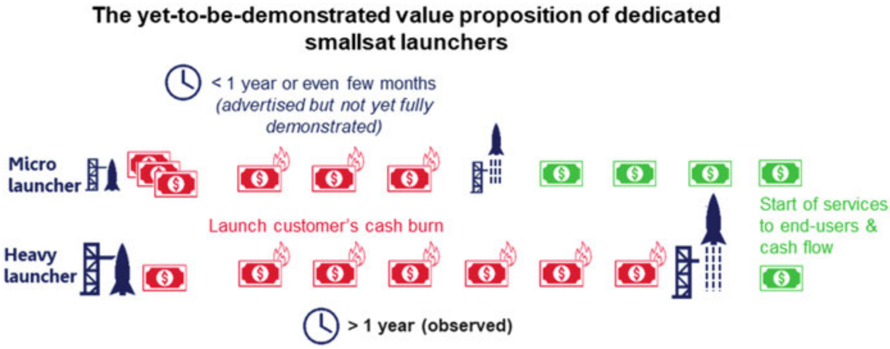


Fig. 14 A better time to orbit: the value proposition of dedicated micro-launchers. (Source: Euroconsult 2019; All rights reserved to Euroconsult, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

vehicles, as these micro-launchers come with a premium in price in terms of $/kg of payload. With more vehicles becoming available, operators could be more selective, using different launch service KPIs to assess performance, such as time to orbit, launch schedule reliability, and services associated with payload integration as additional parameters in their decision-making. This could lead them to prefer dedicated solutions. Among these new suppliers, a few air-launch systems are under development, such as Virgin Orbit and Stratolaunch (which cancelled its plans to develop a micro-launcher in 2019). Air launch can increase the performance of the vehicle by up to 30%, enabling a wider range of launch azimuths and more flexibility as it can be operated from airports. However, existing carriers have a limited payload capacity and come at a relatively high price/kg (Fig. 14).

About 100 companies claim to develop dedicated launch systems as of 2019. Rocket Lab's Electron and iSpace's Hyperbola-1 excepted, both of which successfully reached orbit in 2018 and 2019, respectively, no privately funded small launcher has yet conducted successful orbital missions. Landspace and OneSpace both failed as they attempted to be the first orbital privately funded launcher in China in 2018 and 2019, respectively. The most advanced systems have already secured contracts, including multi-launch agreements, but this does not prevent business failures, as Vector had to put its activities on hold when a key investor stopped financing the company, before filing for bankruptcy in 2019. The status of dozens of projects is unclear, and several have been terminated since the early 2010s. It is likely that many more small launch ventures will fail to reach the market, considering the major barriers to entry (technical, financial, and legal). Even once operational, the sustainability and profitability of micro-launchers are questionable. Micro-launchers have higher costs/kg than larger launch vehicles. Their market acceptance still must be demonstrated beyond initial customers, and the economics of higher launch price vs. reduced cash burn while awaiting launch has yet to be validated.

For constellations, the deployments of hundreds of satellites into multiple orbital planes require the most cost- and time-effective launch solutions to reduce capital expenditures over time and start services as soon as possible to generate revenues.

This favors medium and heavy launchers for full-scale deployments of the constellations. The phasing of launch demand for constellations varies greatly depending on their life cycle and orbital architecture. Micro-launchers can contribute to proof-of-concept (i.e., the launch of prototypes and demonstrators) and limited replenishment (i.e., replacement satellites), or deployment into underserved orbits, provided their reliability and responsiveness are demonstrated. Kleos Space, for example, aims for a 37° inclination for higher revisit frequency on the most populated areas and therefore wishes to deploy its constellation through dedicated launchers, the only solution to cover such low inclinations.

3.2 Manufacturing

2019–2028 is expected to witness a large increase in supply from 1,470 satellites to 8,588 satellites. North America will continue to account for an important share of the supply with almost half (48%) of satellites (4,157) as it concentrates the manufacturing of three mega constellations (Starlink, OneWeb, and possibly Amazon will be manufactured in the USA) (Fig. 15).

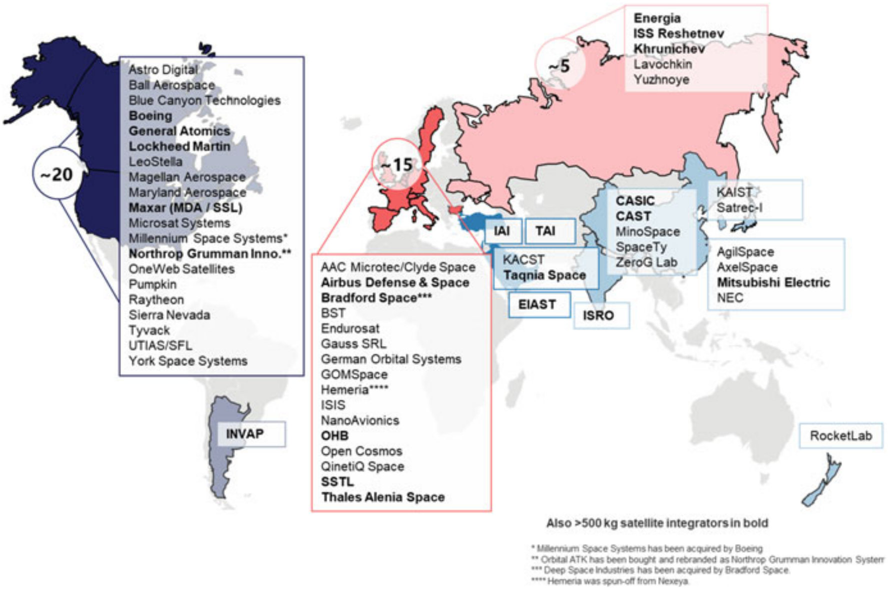


Fig. 15 Main small satellite integrators around the world. (Source: Euroconsult 2019; All rights reserved to Euroconsult, this figure is licensed to Springer to publish in the Handbook of Small Satellites. *Note: the map above does not include satellite integrators which have not launched a satellite into orbit to date and does not include in-house manufacturing. It is a list of the main satellite integrators that are commercializing their manufacturing capabilities. For example, SpaceX and Planet are not featured on the map despite being the two largest satellite operators as of early 2020, as they only manufacture satellites for themselves and do not seek to commercialize manufacturing services to third parties*)

Asia is expected to have a sizeable market share, with 17% of satellites over 2019–2028. Europe is expected to experience substantial growth in number of units (+204%) but will lose market share (from 17% to 9% in the next decade) as it is expected to grow more slowly than North America and Asia.

Satellites for which an integrator has not yet been selected, i.e., the open market, are expected to account for 24% of the 8,588 smallsats to be launched over 2019–2028. As such, each region's market share relative to other regions may grow if that region captures more of the open market than others. Satellites which are captive of their own manufacturing industries (e.g., government smallsats from countries with an established industry) are part of the respective regions of their governments.

Russia and Central Asia's share of smallsats to be launched is expected to decrease from 6% to 1%, although the region will see a marginal increase in number of satellites manufactured from 89 to 118 units in the next decade (Fig. 16).

At the satellite supply level, high fragmentation of the market is expected. Planet accounted for the largest single share (24%) of the manufacturing supply over 2009–2018 but only addressed its own needs as a vertically integrated company (Terra Bella excepted, sourced from SSL, formerly Space Systems Loral). Universities accounted for large shares of the supply with 27% of satellites being manufactured by an academic institution in the past decade. The remaining manufacturing supply was highly fragmented with no company owning more than 5% of the demand in terms of units. Circa 26% of the supply was addressed by about 268 organizations manufacturing up to three orders each. 23% of the supply was addressed by 57 companies manufacturing between 4 and 10 units. Following a merger between AAC Microtec and Clyde Space, the new company accounted for 5% of the past supply with about 70 units, mostly for Spire before it brought production in-house.

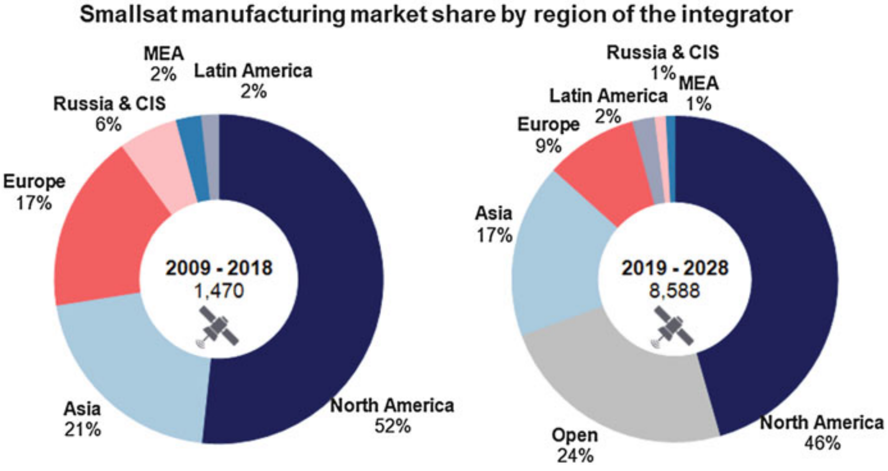


Fig. 16 Smallsat manufacturing market share (in units) by region of the integrator over 2009–2018 and 2019–2028. (Source: Euroconsult 2019; All rights reserved to Euroconsult, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

This supply fragmentation here only considers supply at the satellite level. Since some of the companies are also providing subsystems and components, their market share is expected to be higher than figures presented here due to the associated additional revenue. This is the result of commoditization and standardization allowing satellite operators to combine hardware from various suppliers.

The smallsat manufacturing market, which was valued at $9 billion over the past decade, is set to grow by +232% to about $30 billion over the next 10 years, mainly driven by the multiplication of constellation projects from both commercial and government stakeholders. In countries where an established supply chain and integration capabilities exist, civil government and military demand are assumed to be captured by domestic industry, meaning that contracts are not open to foreign bidders. This is the case for the USA, Canada, Europe, China, India, Japan, Russia, South Korea, Israel, Iran, and North Korea, and it may soon be the case of Saudi Arabia and Qatar. On top of that, considering that Starlink and OneWeb already have identified integrators, only a small market value share (12%) remains commercially open. Furthermore, this 12% share of open market features Project Kuiper, which has yet to select a third-party integrator or prefer in-house production and which is not considered as captive to North American integrators.

Asia is expected to experience substantial growth over the next decade (+45%), second only to North America in market value. The next decade will see Asia account for 14% of the total manufacturing market value, compared to 32% for North America. This is a consequence of local manufacturers winning notable contracts from the government, such as the Hongyan and Xingyun constellations by the China Aerospace Science and Technology Corporation (CASC) and the China Aerospace Science and Industry Corporation (CASIC), respectively. North America is expected to grow by +182% from $3.4 billion to $9.5 billion due to its established industry base, mega constellations, and commercial new entrants in the USA and Canada.

Europe’s market share is expected to decrease from 15% to 7% over 2019–2028. Despite growth in absolute terms, driven by constellations such as Iceye, Astrocast, and Hiber, Europe will grow more slowly than Asia and North America and therefore account for a smaller market share relative to those markets. The manufacturing contracts from Russia are largely won by local primes to support government civil/defense missions (led by Russian Research and Production Enterprise Pan-Russian Research Institute for Electromechanics (FSUE NPP VNIIEM) and Information Satellite Systems Reshetnev (ISS Reshetnev)). Manufacturing market value is set to increase across Latin America, driven by the Satellogic constellation.

In addition to contracted manufacturing market shares and 12% open market, 30% of 2019–2028 manufacturing market value is captive to specific regions. The captive market mostly includes government-operated single-satellite missions and constellations from countries with an established manufacturing base, which are not open to be addressed by foreign manufacturers. This market remains to be competed for but only by local integrators (Fig. 17).

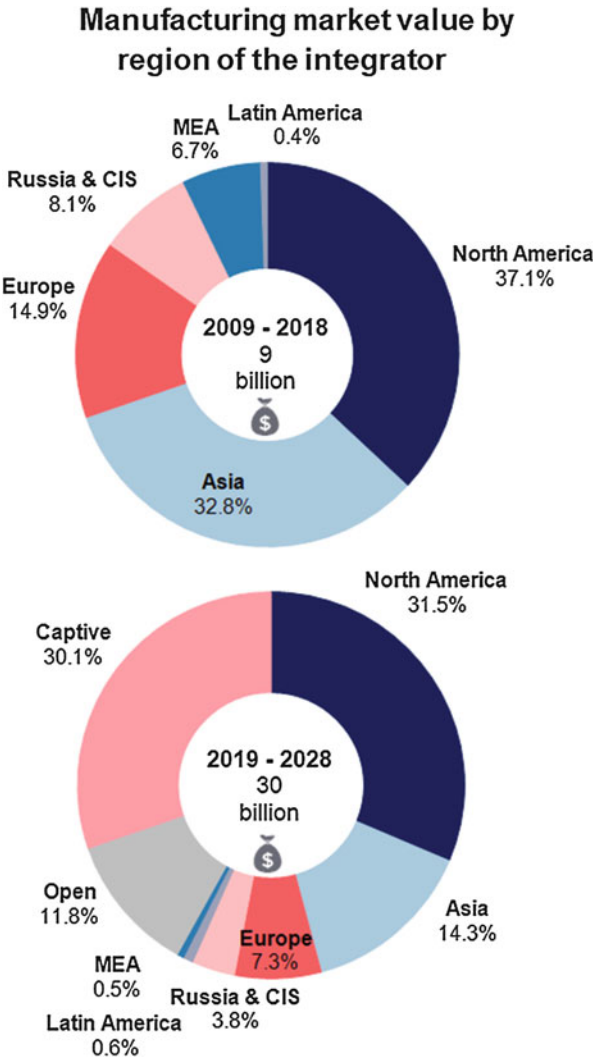


Fig. 17 Smallsat manufacturing market share (in value) by region of the integrator over 2009–2018 and 2019–2028. (Source: Euroconsult 2019; All rights reserved to Euroconsult, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

4 Constraints to Manage and Upcoming Challenges

The market growth discussed here represents an integer multiple expansion of the number of spacecraft on orbit. This suggests managing the hazards, and downsides of this proliferation will be required to assure this proves feasible and desirable. Good practices and stewardship must be advocated for in order to ensure the sustainability of the space environment and prevent Earth orbit from becoming a new “wild west” and hypervelocity junkyard.

Looking forward, an important challenge for smallsat constellations will be the mitigation of their impact on the space environment. As for any specific environment back on Earth, conservation and sustainability measures should be implemented to ensure that future generations may benefit from the same opportunities. Without looking too far into the future, in-orbit failures or collisions could have dire consequences in orbits populated by hundreds of satellites, threatening entire constellations and their business models.

Licenses to launch around the world entail an increasing element of specific commitment to mitigating the rise of on-orbit debris, spawning technologies to support this. Systems are becoming multilevel, and many orbital altitudes will become occupied with large numbers of small spacecraft. Some of these higher orbital levels will push into the Van Allen radiation belts, bringing the spacecraft using them into the realm of charged particles confined there, including those arising from nuclear explosions on-orbit past and potential. This section explores these hazards and challenges, and means for their mitigation.

4.1 Orbital Debris Mitigation

Most smallsat systems discussed here operate as constellations and many without the propulsion systems required to perform collision avoidance maneuvers. Even smallsats equipped with propulsion do not necessarily have the sufficient delta-V generation capability to enable performing collision-avoidance maneuvers: this is generally the case of electric propulsion, which does not enable “last minute maneuvers” due to its low thrust. The numbers of such spacecraft expected to launch shortly will dwarf the total number of satellites currently on-orbit, so mitigating their potential to generate orbital debris is a high priority for system designers and governments.

As of today debris below 10 cm in diameter cannot be tracked. Researchers have been trying to raise awareness of the fact that often it is now actually not known what object is being tracked. This means that anything below 10 cm in diameter is essentially invisible and of significant risk to space operations. NASA/US Space Surveillance Network estimates, as shown in Fig. 18 below, that >20 K debris objects of 10 cm diameter or larger currently are in orbit. The estimated number rises to 0.5 million objects of 1 cm or larger and in excess of 100 million objects 1 mm or larger. To illustrate the power of small bits of debris, a 1-cm-aluminum sphere moving at a LEO typical 10 km/s carries the same impact as a 200 kg safe moving at 150 km/h (Fig. 18).

LeoLabs, a commercial Space Situational Awareness (SSA) company based in California, seeks to improve the industry’s understanding of the population of orbital objects, active satellites, and space debris combined. Currently, the company tracks >10,000 orbital objects 10 cm or larger using its existing two ground-based radars, in Texas and Alaska. With a new higher-frequency radar coming online in New Zealand, it expects to grow its database by a factor of 10 to 25 by being able to see objects down to 2 cm in diameter. In August 2019, LeoLabs unveiled a LeoTrack, a

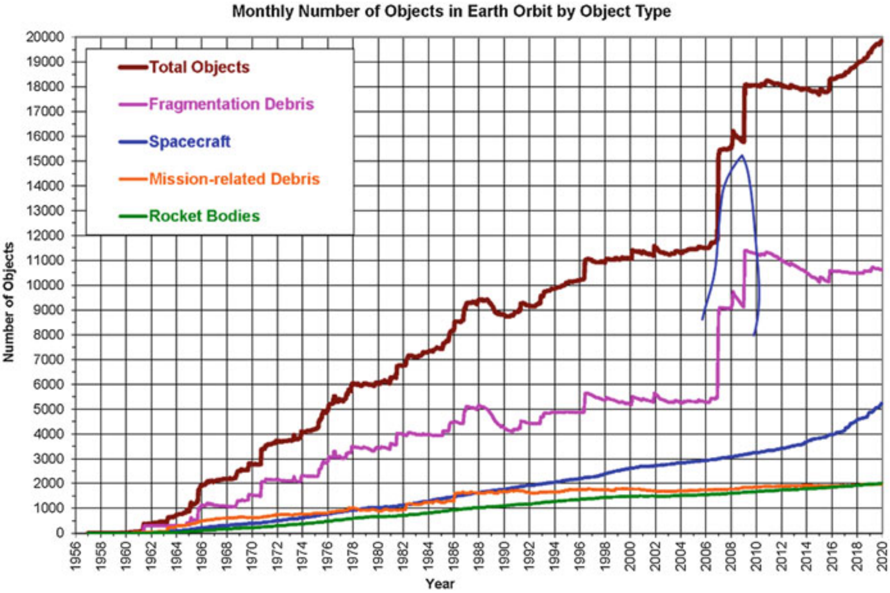


Fig. 18 Growth of orbital debris 1957–2020. (Image NASA. Source: J.-C. Liou, PhD, NASA Chief Scientist for Orbital Debris Personal Communication; not subject to copyright)

commercial satellite tracking service targeting small satellite operators. Sold via a monthly subscription at $2,500 per month per satellite (with possible discounts for large constellations), this software will provide several services such as smallsat tracking, orbital state vectors, predictive radar availability, scheduled passes, and visualization tools. LeoLabs expects to be able to identify satellite positions within a hundred meters, a factor of ten improvement compared to the current kilometer-level precision of the Joint Space Operations Center (JSPOC). Several smallsat players have already subscribed to the LeoTrack service, including BlackSky, Maxar Technologies, Planet, and Swarm Technologies (which is known for operating 0.25 U CubeSats which are harder to track).

As regulation by governments and agreements in the UN are tightening restrictions on Orbital Debris Risk Mitigation licensing requirements, companies building CubeSats are increasingly required to plan for deorbit mechanisms.

4.2 Radiation in Higher Orbits Could Present a Risk for Smallsats

Radiation from debris/missions poses its own hazards, including that from the 1962 US "Starfish" test of a ¼ megaton nuclear bomb in space, and similar tests by the Soviet Union, possibly soon to be joined by a North Korean high-altitude weapon test and perhaps others. High-energy electrons and other charged particles from these blasts killed the first communications satellite, Telstar, and a number of other spacecraft. A substantial proportion of these electrons are now known to be still trapped in the Van Allen radiation belt, as indicated by NASA's Van Allen probe missions (2012 to 2019). A military spacecraft is now in-orbit, and two more are planned for 2020, to take the first steps to analyze the potential for radiation belt remediation (RBR).

In 2019, the US Air Force launched the DSX dipole antenna, described as the largest robotic mission structure ever launched. It will transmit very low frequency (VLF) radio into the Van Allen belts to cause charged particles to deorbit, and will measure what is hoped will be particles falling out of orbit as a result. In 2020, a team from Los Alamos and NASA's Goddard Space Flight Center will launch a second experiment in VLF precipitation of charged particles. This suborbital mission will loft the Beam-Plasma Interactions Experiment, a miniature accelerator that would create its own high-energy electrons, would generate VLF waves, and cause precipitation of charged particles. Finally, a second suborbital mission will launch a few months later: The US Naval Research Laboratory plans to launch the Space Measurements of a Rocket-Released Turbulence mission. The mission will spread 1.5 kg of barium atoms. When ionized by sunlight, the barium becomes a moving plasma, emitting radio waves.

The missions should help validate effectiveness of these techniques and enable determination of which, if any, of these three approaches to RBR system is most feasible.

It is not known however, and won't be from these tests, what side effects might result from a wide deployment of such technologies. Energy released into the atmosphere could rival that of coronal mass ejections and impair communications and navigation. Some potential by-products could damage the ozone layer (e.g., oxides of nitrogen and hydrogen), so additional research would be needed before deployment (Stone 2020b). Most notably, low-cost smallsats built without space-graded, rad-hard components would be at risk.

4.3 Concerns for Astronomical Observations

Perhaps of little direct financial effect but with an important impact on public perception of the satellite industry, LEO constellations may cause interference with astronomical observations. Satellites in LEO are already visible to the naked eye, and the first generation of the Iridium constellation (66 satellites) was known for its "Iridium flares," i.e., a visible phenomenon caused by the reflective surfaces of satellites (which could be antennas, Synthetic Aperture Radar (SAR), or solar panels), reflecting sunlight toward Earth. Ranging up to −9.5 magnitude, some Iridium flares were so bright that they could be seen in the daytime and occasionally disturb astronomy observations. Iridium took these considerations into account for the design of its second generation, which does not flare. However, considering the thousands of constellation smallsats expected to be launched in the decade, light pollution has the potential to become an important issue if not considered.

Relatively simple changes such as changing the albedo to reduce satellite reflectivity may be sufficient to mitigate this risk. Following the first Starlink launch, SpaceX was

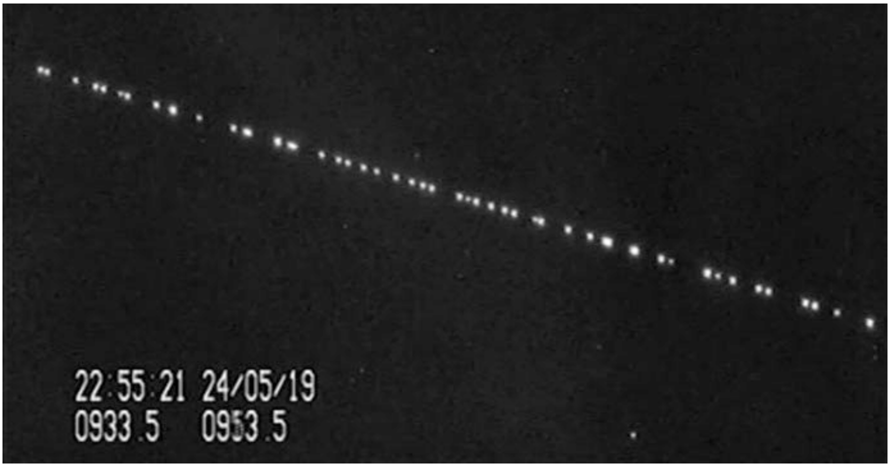


Fig. 19 Starlink satellites released from launcher. (Image © Marco Langbroek via SatTrackBlog; All rights reserved to Marco Langbroek, this figure is licensed to Springer to publish in the Handbook of Small Satellites)

highly criticized even before its satellites were raised to their operational orbits, and agreed to take steps to avoid this in the future, including launching darkened prototypes on subsequent launches to assess the difference from initial versions.

In 2019, PepsiCo explored the possibility of advertising from space using “orbital billboards” made of a constellation of highly reflective smallsats, due to be visible from the ground. It quickly backtracked due to public outcry and criticism. While there may not yet be any laws regulating the light pollution caused by LEO constellations, federal law in the USA does indeed prohibit the use of “obtrusive space advertising.” Similarly, the Humanity Star reflective payload launched by Rocket Lab in 2018 was largely seen as an “act of vandalism” on the night sky (Fig. 19).

Interference to radio astronomy is also a significant concern, with many constellation satellites radiating in bands in or close enough to those used for celestial observations that side lobes of the signals will likely interfere.

4.4 Satcom Constellations Need to Secure Landing Rights to Enable Commercialization

While successfully financing, manufacturing, and launching a satellite constellation qualifies as a major engineering feat, it is not sufficient to guarantee its commercial success, as the Iridium bankruptcy in the 1990s can attest. One of the main challenges for communications (broadband or narrowband) constellations will be to successfully secure landing rights (i.e., the authorization from the government or telecom regulating authorities to commercialize satellite capacity in a given country) in dozens of countries around the world. Negotiating with dozens of governments remains a challenge for most countries, let alone emerging space companies with no experience in dealing with foreign countries.

Securing partnerships with established satcom operators for capacity commercialization in foreign countries could be a way to mitigate this, and fast-track this critical negotiation phase. It would however negatively impact margins, as such an operator would take away a share of revenues in exchange for access to its existing network of distributors. This was part of the rationale behind the aborted merger between OneWeb and Intelsat.

Furthermore, geopolitics also play an important role, as access to the Chinese and Russian markets is far from guaranteed for US-based constellation operators and vice versa. OneWeb, for example, has repeatedly been denied access to the Russian market, due to fears of espionage and fears of losing control over the nation's communications from the Russian government.

4.5 Consumer Ground Segment Costs Drive Adoption Rates

Home antennas for GEO satellites are a simple matter and can be obtained for as little as $50. The cost of this piece of hardware is so low that it is often part of the subscription price of TV/Internet bundles. However, antennas for LEO broadband constellations face the difficult task of maintaining a link with rapidly moving targets in low orbits, seamlessly switching targets once a satellite is out of range.

Electronically steered flat panel antennas (FPA) are accepted to be the technological solution to this problem; however their cost remains prohibitive and does not permit the broadband constellation business case to succeed at current costs levels, as they remain unaffordable by the public despite improvements. A few years ago, consumer-grade antennas were estimated to cost ~$20 k per unit and have dropped to ~$1.5 k per unit today. Companies aim to bring this cost down to <$1 k, with some companies aiming for antennas as cheap as $300 to $500. Such prices however remain to be achieved.

This satcom-centered rationale also applies to Earth observation constellations but with the number of ground stations for data downlink rather than consumer terminals, which do not apply to Earth observation. The more important the amounts of data collected and the data downlink requirements, the more ground stations are required. The capex to establish a significant ground station network across the world quickly rises. One way to mitigate this is to work with ground station "as a service" providers, renting antennas on a "pay-as-you-go" model, favoring OpEx over CapEx.

4.6 Antenna Production and Distribution (Supply Side)

Consumer affordability is key if smallsat constellations are to reach their projected revenues and market adoption objectives, which will define success or failure. However, developing the ability to produce and deliver a sufficient number of antennas is just as serious an issue as the cost to produce them. Several million FPAs must be shipped over the future decade to keep up with projected market forecasts; however production of affordable antennas has yet to start. Companies are, reasonably enough, focusing on enabling mass production to leverage economies of scale.

Production and distribution of consumer-grade FPAs however is a chicken and egg problem, as market demand is required for mass production to begin and mass production at consumer-friendly costs requires an established and sustainable market demand. A new wave of FPA-focused venture capital and/or government financial backing could be required to bridge this gap; however uncertain ROIs mitigate the interest of investors.

Until then, business-/enterprise-grade antennas will remain the norm, with FPA companies already commercializing the more expensive antennas for ships, emergency response vehicles, and aircraft.

It may be that captive production such as that of SpaceX could solve this, given sufficient capital.

5 Conclusion

5.1 New Business Models and Smallsats as a Service (SSaaS)

From building hardware and integrating it into satellite operations, ground stations, and analytics, the smallsat ecosystem is maturing and evolving. More and more private companies are establishing niches and specializing, while others are moving into the “Smallsats as a Service” business model. For an entity looking to launch a payload into orbit, reactivity, lower costs, ease of operations, accessibility, and operational simplicity are in high demand. Whereas in the past it may have been difficult to find platform providers, launch providers, and even facilities for testing and qualification, these can now all be procured online. While not yet as simple as ordering hardware online, that point is quickly approaching. This increased accessibility benefits new entrants and organizations which are new to the space sector. The SSaaS business model removes complexity and barriers to entry, facilitating market entry for newcomers. Additionally, this new granularity offers a level of transparency over the value chain which improves the confidence of industry outsiders. SSaaS allows the customer to step out of the satellite value chain entirely and rely exclusively on managing its core business, whether that is data analytics, scientific research, or something else. The SSaaS customer can now have as much or as little input into the life cycle of its satellite as desired. While SSaaS may not always meet the needs of all customers (as in cases of specialized orbital and hardware requirements), it addresses the most common market needs in a clear fashion.

5.2 Turnkey Satellite Missions

More integrated value propositions are emerging as companies propose full solutions from system integration to data delivery, allowing their customers to concentrate effort on value added services. Examples of this include Tyvak, York Space Systems, and Open Cosmos. Open Cosmos provides a hardware mock-up of its satellite to its clients, so that they can build their payload into it. Once the payload is ready, it is quickly integrated into a real platform, and all other aspects of licensing and launch campaign management are then managed on behalf of the customer. Tyvak on the other hand actively seeks upstream companies outside of the space sector, to propose solutions and explore how its capabilities can meet their needs.

5.3 Increased Modularity and Standardization of Spacecraft "Blocks", i.e., Subsystems

One early indication of future directions for small satellites is the increasing modularity of small satellites which can be logically combined over robust intersatellite links while orbiting separately, or physically combined using a common bus, like electronic Lego. This subject has seen an increase in interest recently, starting with NovaWurks' "satlets" mentioned previously (NovaWurks was acquired by Saturn Satellite Networks in 2019), the generic name of its HISat spacecraft, which are modular "Lego-like" spacecraft elements capable of independently performing all satellite functions (i.e., propulsion, payload, power storage and generation, etc.). In theory, each of these elements is capable of operating as its own spacecraft and provides redundancy in case of failure, as every "satlet" is capable of taking over the functions of another "satlet" that has failed. To date, several prototypes have been deployed on various orbits for technology demonstration purposes. The US military has long been interested in this concept (NovaWurks was contracted as early as 2012 by DARPA to participate in its Phoenix project) due to its interest in redundant assets that are highly resilient in the face of failure or direct attack from an adversary. DARPA is supporting NovaWurks through the sponsoring technology demonstration missions, and operational agencies within the US government will surely become customers when the technology is more fully proven in orbit and made available commercially. The National Reconnaissance Office, which operates US surveillance satellites, is taking a similar approach, experimenting with small standardized systems to which engineers can attach instruments.

5.4 Hosted Payloads

Hosted payloads may also play a role, albeit a niche one, in the future. Launching a payload without a dedicated satellite is a tested means of getting to orbit with little hassle. In past offered by companies such as SES (formerly Société Européenne des Satellites) and Iridium, hosted payloads are being offered by new and established companies such as Loft Orbital and Spire. Spire provides "space as a service," allowing third-party payloads on the back of its own satellites. In 2019, it announced a deal with a defense contractor, KeyW Holding Corp, to host its reconnaissance payloads on its satellites. It previously offered to fly 20 payloads on its satellites within 12 months for €10 million. Loft Orbital offers "mission as a service," with a plug and play "condo" housing that is designed to receive parallel hosted payloads. It has announced partnerships with stakeholders all across the smallsat value chain.

5.5 Quantum Navigation Systems

New ultra-accurate/ultra-stable quantum inertial navigation systems seeking to offer positioning without the need for access to a Global Navigation Satellite System is also likely to be adopted by MilSat constellations once sufficiently miniaturized. (e. g., M Squared/Imperial College London's "Quantum Compass" system).

5.6 The Beginning of Deep Space Science and Exploration Smallsats

In science missions too, the success of the MarCO CubeSats has spurred mission planners to include more interplanetary CubeSats on missions to the outer solar system, starting with Europa. China's Chang'e 4 lunar landing on the far side of the Moon in the early 2019 was supported by Queqiao, a small satellite (425 kg) communications relay probe, to enable live connectivity with the far side. Exploration and science missions, traditionally burdened with high costs and long development times, are increasingly looking at smallsats to provide operational services at a fraction of the cost associated with space exploration in past decades, and the Queqiao and MarCO successes have demonstrated the smallsat form factor's great potential for science and exploration missions.

5.7 Bright Prospects Ahead for Small Satellites

A similar positive feeling is permeating the space industry, as space agencies, commercial stakeholders, and military entities alike realize the game-changing potential that smallsats are bringing to the space sector. Small spacecraft can indeed be said to be taking over the industry as of this writing. Furthermore, the cost reduction supported by smallsats means new entrants, previously hampered by the cost of developing and launching space assets, may enter the space sector, driving more synergies with other industries such as software and IT, electronics, power management, thermal and material sciences, etc. which will in turn enable further growth prospects in the future.

6 Cross-References

▶ Deorbit Requirements and Adoption of New End-of-Life Standards
▶ Financial Models and Economic Analysis for Small Satellite Systems

- ▶ Legal Issues Related to the Future Advent of Small Satellite Constellations
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ▶ "Rules of the Road" for Launch and Operation of Small Satellites and Related Issues
- ▶ Small Satellites and Their Challenges to Space Situational Awareness (SSA) and Space Traffic Management (STM)
- ▶ Space Finance for 'New Space' and Small Satellites
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit

References

E.Y. Choueiri, New dawn for electric rockets. Sci. Am. **300**, 58–65 (2009)

Euroconsult, *Prospects for the Small Satellite Market*, 5th edn. (Euroconsult, 86 Boulevard de Sébastopol, 75003 Paris, France). (2019)

Investment in Space Startups since 2009; Source: Space Angels Space Investment Quarterly, Q3 2019

JPL CubeSat, Integrated Solar Array & Reflectarray Antenna (ISARA)

A.T. Kearney, Euroconsult

J.-C. Liou, PhD, NASA Chief Scientist for Orbital Debris Personal Communication (public domain)

J. Lovelock, B. Appleyard, *Novacene* (Allen Lane, Penguin Random House, London). ISBN 978-0-241-39936-1

Marco Langbroek via SatTrackBlog; All rights reserved to Marco Langbroek

Phase Four, 27 June 2019

SpaceNews, Does the satellite industry have antenna deficit disorder? by Caleb Henry and Debra Werner – October 17, 2018

R. Stone, Need for speed. AAAS Sci. **367**(6474), 134–138 (2020a). https://doi.org/10.1126/science.367.6474.134

R. Stone, U.S. military tests radiation belt cleanup in space. AAAS Sci. **367**(6473), 9 & 10 (2020b)

U.S. Congressional Research Service report July 2019

Financial Models and Economic Analysis for Small Satellite Systems

Henry Hertzfeld and Joseph N. Pelton

Contents

H. Hertzfeld (✉)
Director, Space Policy Institute, Elliott School of International Affairs, George Washington University, Washington, DC, USA

Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA
e-mail: hrh@gwu.edu

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_69

Abstract

The well-established terrestrial satellite applications markets have been generating revenues and producing very substantial earnings in the billions of dollars for many decades. These major markets include the telecommunications and broadcasting services: fixed satellite services, mobile satellite services, and broadcasting satellite services and the Earth observation/remote sensing/meteorological satellite services. Also very important to commercial customers is the global navigation satellite services (GNSS) also known as precision navigation and timing services. In the case of GNSS, at least in the United States where the actual satellite system is government-owned, most of the revenues come from the manufacture and sales of user equipment and services rather from operation of the satellite systems themselves.

There have been profitable businesses associated with the development and manufacturing of satellites. These include the manufacturing of satellites, ground antennas that support these various space-based applications, the launch services industry that launches these systems into orbit, and the space insurance industry that can safeguard companies against risks associated with the launch of the satellites, possible liability claims, and even the loss of revenue from satellites or from in-orbit failures.

The status and nature of these well-established space systems are currently in a state of upheaval and change. One of these changes in satellite telecommunications is that new quite efficient high-throughput satellites (HTS) are challenging less efficient satellites that operate at lower speeds and are much less cost-efficient. There is also rapid technological innovation of new more cost-efficient launcher systems, applications satellites, and ground systems that will increase the competitiveness of all commercial uses of space.

Major technological innovations and cost-reducing trends provide a stimulus to all sorts of space-based services. However, they also create a sense of confusion in understanding the economic and financial impacts that come from the so-called “NewSpace,” “Space 2.0,” and “small satellite” revolution. In actuality, not only are “small satellites” cheaper to manufacture and launch, but also the large geosynchronous high-throughput, high-efficiency satellites can, and are, being designed, built, and launched more efficiently as well in terms of net cost per rate of digital throughput for data, voice service, or video channels.

Current economic analyses have generally concluded that it is too early to measure the economic performance of small satellite constellations in relation to new high-efficiency geosynchronous satellite networks. Further the economics and design innovations are different for remote sensing satellites than satellites that are providing communications services, making any comparisons more difficult. And there are many risks in space systems that are different from terrestrial operations and need to be understood better. Despite these market analysis limitations, this chapter seeks to assess the relative economics of small satellite systems deployed in LEO and MEO orbits, versus the most efficient of GEO applications satellites.

Keywords

Artificial intelligence · Big data · Bleeding edge technology · Cash flow · Competitive modeling · Component parts · Commercial off-the-shelf (COTS) · Constellation expansion strategies · Crowdsourcing · Data analytics as a space market · Hosted payloads · Investment capital · Investment rounds · Kickstarter · Landing licensing requirements · Launch arrangements · Launch costs · NewSpace industries · Phased expansion of constellations · Risk · Start-up companies · Self-insurance · Sparing philosophy · Supply and demand · Suppliers as investors · Technology innovation · World Trade Organization

1 Introduction

Regardless of which part of the commercial space industry is being analyzed today, they are all characterized by continuous and dramatic change. There are new satellite applications products and services, launcher options, types of ground systems, and antenna designs that are designed, manufactured, and sold incorporating technological innovation, manufacturing process changes, and speed of design and production. Much of these innovations are associated with the companies and entities involved in “NewSpace,” “Space 2.0,” and the world of small satellite innovation coupled with new launch vehicles providing access to low Earth orbits.

It should be clearly noted that there is nothing really “new” in “NewSpace”. All companies, whether new or traditional, have market and technology innovation and making a profit as prime motivators. All successful corporations must seek innovation to survive and to introduce new products and/or services to sustain themselves. In the United States, the government space agencies have relied on the private sector to manufacture most space equipment from beginning of the space era in the mid-1950s. Some of the more recent changes, however, are the aggressive initiatives of the government to stimulate private innovation and new entries from the computer, digital services, social media, investment banking and venture capital firms, and especially entrepreneurial start-ups.

However the rise of a multitude of new companies does not mean that the conventional space system manufacturers, service providers, and launch providers are going to fail in light of these changes (Rapp et al. 2015). They will face increasing competition. Indeed these industries are already quickly adapting to this new world of more rapid innovation. And the more traditional aerospace companies have adopted new practices that have come from rapid prototyping and new manufacturing techniques such as additive manufacturing and use of advanced analytics and artificial intelligence being used across the spectrum of the aerospace industry. These innovations are stimulated by continued public and private research and development as well as a growth in consumer demand.

The current small satellite revolution has also broken down some of the barriers to starting a new space enterprise. New types of initial capital formation such as small start-up funding through crowdsourcing and other Internet programs as well as large investments from wealthy individuals and venture capital companies have led to a renaissance in space industry innovation.

None of these providers of new funding guarantees any assurance of eventual economic success in the market place. The bottom line is that space enterprise is an attractive yet risky type of business that will be characterized by some significant new economic successes but can also lead to a significant rate of business failures. The SpaceX Ansari Prize contest from the early 1990s to 2004, which had the aim to create a viable space plane prototype, produced only one winner. Along the way there were close to two dozen start-up ventures that ultimately failed as ongoing business ventures. Today, challenges from both government and private initiatives have produced parallel results. What is important is that investors now view space as more than government missions and are willing to invest in space ventures. And, some government agencies themselves view space, particularly in low Earth orbit, as an opportunity for economic development and are providing significant incentives, both financial and regulatory, to these new private ventures. This has been particularly true in the United States, Luxembourg, New Zealand, the United Arab Emirates, France, and even somewhat unlikely locations such as China, Denmark, etc.

Over the past two decades, GEO system operators and space insurance companies have been developing a large storehouse of knowledge about how to deal with the unique aspects of risk and insurance coverage for space assets and applications. Newer companies that are operators of LEO small sat constellations do not have the same knowledge base and history. This creates new challenges for these companies, but in some cases it allows for more innovative concepts and new industrial and technology processes to flourish.

In summary, commercial space systems, particularly those in low Earth orbit, are rapidly evolving and changing. New associated challenges and risks are yet to be solved. During this transition phase, there will be winners and losers; neither can be easily predicted. But what is clear is that the role of private space actors is growing and the future rewards are likely to be very lucrative for those that survive and thrive matching the market demand for existing and new services to the regulatory, production, and global sales challenges that will be inevitable.

2 The Demand for New Space Products and Services

The rise of the large successful aerospace enterprise was stimulated in the United States by the post-World War II "Cold War." The result was a very large military-industrial development funded by the US government and built and operated in close association with private companies. The companies were therefore dependent on the multimillion dollar government contracts generated by defense-related demand. These organizations were awarded contracts to carry out research and to develop weapons systems and the underlying related technology that supported weapons systems. It should be noted that many scientific and engineering breakthroughs were created from that research that enabled mission success with improved manufacturing productivity, new materials, and new products and services for business and consumers.

Space capabilities were one direct objective of this government investment, and today's space capabilities are a legacy of the era of the 1950s and 1960s. Along with those space successes and terrestrial applications were the dominance in the industry of very large firms with close government connections on both the civil and security side.

Of course, this large government investment was the major source of market demand for space applications. Unlike normal consumer goods like food, clothing, housing, travel, etc., where the price of the product is the market signaling mechanism for economic choices, government purchase decisions are often made for other reasons such as security, defense, and social welfare. Normal economic models do not account very well to those non-price-based purchases, and other non-market factors such as the oligopolistic structure of the aerospace industry also separate traditional space supply and demand from most other free-market industries.

Many space applications are now transitioning from government purchases for government use to consumer purchases with the government buying services alongside at prices determined by market forces. As barriers and disincentives to these previously "closed" markets begin to deteriorate, the space sector and its commercialization will also begin to be more price-sensitive and more "mainstream" in terms of industrial organization. The real test is in the future and will be driven by more traditional capitalist decisions. An open question is whether and how fast the large traditional space companies can and will adjust to these changes.

It should be noted that the telecommunications market is the oldest commercial space service, dating back to the 1970s. It was then a heavily regulated industry and government space telecommunications satellites, although built and operated privately, were dominant. By the 1990s the trends were clear and slowly private, and competitive telecommunications satellites were permitted, and by the early 2000s, with the privatization of Intelsat, the transition was fully in progress. Today, it is a regulated market because of limited spectrum availability, but relatively open to price competition both domestically and internationally. No other space application is both as open and as lucrative as are telecommunication and direct radio and TV broadcasting.

New markets for telecommunications and other space services are developing and growing. How fast and how effective they will be is yet to be fully determined, but the prospects for a growing market are stimulating innovation and investment in space applications. It should also be noted that there is no real demand for launch vehicles themselves. That demand is fully dependent on how we find uses for space and therefore launch vehicles is the transportation artery for those uses rather than a "use" of space themselves.

No longer does one have to be a multibillion dollar aerospace industry such as Boeing, Lockheed Martin, Airbus, Thales Alenia, NEC, Mitsubishi, CAST of China, etc. to enter and prosper in the world of space hardware manufacturing, space application services, or space launch services. But, the barriers to entry remain relatively high, and the ultimate road to success remains difficult. Many new ventures falter if they cannot find or generate the demand for their products or services, or cannot generate enough progress to support a second or third round of equity funding. Sometimes they will be rescued by strategic mergers. Other ventures will find incentives to get started, but also within a year or two, the most likely outcome will be organizational breakdown, discontinued support from a start-up incubator, bankruptcy, or acquisition, Only a few will accomplish the long shot success of continued rounds of funding to finance the growth needed to reach financial viability. The road has been paved with numerous companies that no longer exist and with others that have been extremely successful.

3 The Demand for Money (Financing) for New Space Products and Services

The world of digital innovation that grew up in Silicon Valley and elsewhere led to increases in available capital for new enterprises. Venture capital firms and other investors worked with research universities, inventors, and others with bright ideas. Thus, coupled with the growth of the Internet and social media, a number of new financing mechanisms evolved such as crowdsourcing and Kickstarter, along with traditional funding from banks, investment houses, and friends and families. These were responsible for getting the new ventures off the ground sufficiently to later obtain larger rounds of subsequent financing.

The financial evolution and roadmap to true large-scale viability of the SPIRE system, in some ways, might be considered an ultimate roadmap that other start-up organizations might follow in years to come. The SPIRE constellation has now launched over 100 satellites into orbit and is providing data analytics to a growing range of customers (Howell 2019). It started small, but its ultimately leap forward came when it concluded a multibillion dollar 25-year contractual arrangement with the European Union/European Space Agency's Galileo system for predictive weather analysis and future space-based analytic services (Michael and CNBC News n.d.). (See Fig. 1 of a SPIRE cubesat.)

A key strategy has now emerged in terms of financing new small satellite constellations by raising capital funds through contractors that were willing to invest in the project. This has been particularly successful in the case of the One Web large-scale small satellite constellation. In lieu of payment, or at least in lieu of some portion of the payment, the suppliers have become investors and partial owners of the One Web system. Airbus, which is the main supplier of the satellites for the constellation, is a partial owner of the system. Although the One Web satellites with a mass of 150 kg are about a hundred times more massive than a SPIRE cubesat, they are nevertheless still considered to be "minisats." (See Fig. 2.)

Similar arrangements have been made with Arianespace and Virgin Galactic as launch service providers that also become capital investors in the new LEO constellation. Qualcomm, which is another indirect supplier, is another investor. Most striking of all is the investment in the new LEO system by GEO satellite operator Intelsat. (At one point Intelsat and One Web were to go a step beyond with a merger

Fig. 1 The latest generation of SPIRE cubesat shown next to an apple to demonstrate scale. (Graphic courtesy of SPIRE)

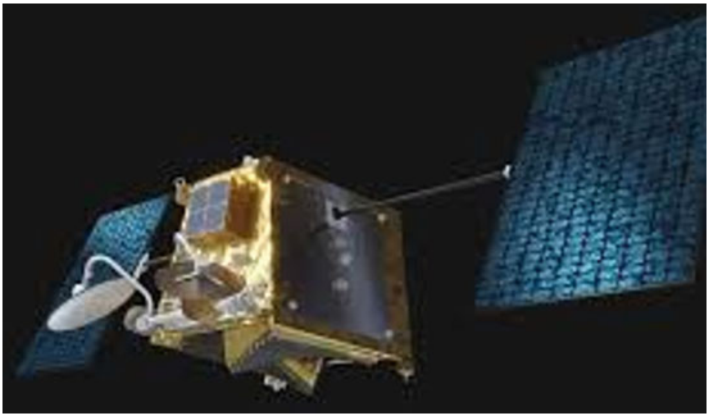


Fig. 2 One of 650 One Web satellites that will be in this LEO small sat constellation that may eventually expand to 4000. (Graphic courtesy of One Web)

of the two systems that would have been financed by SoftBank of Japan. These arrangements were never finalized.) Currently, three rounds of investments, which have been led by SoftBank of Japan, have raised $3.4 billion in investments. Of all the new large-scale constellations, this project has come closest to completing the full financing of their system as of July 2020. This financing would include the latest

$1 billion of new financing from the U.K. government and from the Indian mobile network operator Bharti Global that would lift the system from bankruptcy which was declared in May 2020. Thus this new OneWeb system will be the first of the new large-scale systems to be deployed and will be the first to deploy what can be described as a new 5G ready satellite network for global networking services (Henry 2019).

This type of financing arrangement, which is based on the supplier also becoming an investor, has the potential to be applied for much smaller scale small satellite constellations. At least in theory, this would be result in less costly manufacturing and launch costs for potentially cash-starved new entrants into the industry.

In concept such arrangements create incentives for all of the suppliers to work with extra zeal for the success of the new enterprise. A final dimension of such an arrangement is to have the bank that is providing the financing for the new system to likewise become an investor in the project. Indeed, in the case of One Web, it was the initial investment made by SoftBank that led to the other investments that followed.

In the case of an investment bank direct involvement in a new small satellite constellation, there are multiple options that might apply such as reduced financing rates, deferred loan repayments, or pledging future streams of revenues to the financial bank. The arrangements for the One Web supplier as investment arrangements are confidential, but the basic types of bartering arrangements are rather straightforward.

4 Risk and Financing

One possible concern is that a supplier that offers “bartered services” for an investment in a satellite system but continues to be a supplier to other competitive or potentially competitive satellite services could be subject to conflicts of interest charges, particularly if some unlikely misadventure should occur. For example, an organization such as Arianespace that offers launch services to a large number of satellite operators might make special contract arrangements against a liability claim. In any event all such suppliers should be well advised to set up entirely blocked lines of communications between the part of the organization that holds the investment in a company where they are supplying a service and the part that is actually delivering the satellite or the launch service. In theory these should be completely separate divisions.

The traditionally engineering GEO satellites for telecommunications such as those operated by Intelsat, Via Sat, Echostar/HNS, Telesat, and Eutelsat are today quite large, multi-ton spacecraft that may cost upward of a quarter of a billion dollars (US) each. Since it takes only a few of these satellites in order to serve the entire globe, in-orbit spares are also deployed to back up the operational capabilities. Although there might be incremental revenues derived from this type of spacecraft that provide these backup services that may be subject to interruptions from preemption options, this provision of in-orbit spares is quite expensive for GEO-based communications and broadcast satellite services. The same high expense applies to providing on-orbit spares for GEO-based Earth observation and meteorological satellites. In the case of full size remote sensing satellites in sun-synchronous orbit, the backup and resilience costs are not as high as for the larger GEO orbit satellites, but they are still quite substantial.

The very large-scale newer LEO orbit constellations for communications, networking, or remote sensing incur backup costs that are relatively modest. Constellations for mobile satellite communications such as Globalstar or Iridium could work around a single failure even with a LEO network of 50 to 70 satellites. This is particularly the case with Iridium that have inter-satellite links. In the case of very large networks of a 1000 or more, this problem should not prove to be an issue unless there were a major series of collisions that trigger multiple additional satellite conjunctions and a proliferation of space debris. In such a case, the problem then would become a much larger space environmental issue.

Unusual sunspot activities and actual coronal ejections of ions can be quite dangerous to satellites in orbit. Some areas of natural risks (e.g., high magnitude solar X-Class or above flares are easier for GEO systems to manage in comparison to MEO or LEO constellations. There are global warning systemsin place, and the timely and very quick powering down of GEO satellites coupled with the use of heavy-duty circuit breakers can be protective actions for a fleet of three to a dozen GEO satellites. Protective action for constellations with as many as 7500 satellites in a global constellation may be much more complicated. Further installation of heavy-duty switches and other types of radiation hardening measures may not be considered economically feasible in the design and engineering for constellations of small satellites.

The bottom line is that considerations related to risk, risk management, and insurance against loss of satellites as well as the consequent risk of lost revenues are considerably different for those engaged in GEO-based satellite services and those deploying large-scale small LEO satellite constellations. The management question is whether one engineers and protects against satellite failures and provides for in-orbit space for Geo-based systems or does a company simply provide a few more LEO satellites in a large constellation. The assumption is that there is a reasonable cycle of failures will be worked around until the next batch of small satellites goes up in a non-ending renewing cycle. Some of the largest constellations may well decide that self-insurance, either through GEO redundancy or through replacement small sats, will make the most sense for them rather than purchasing insurance policies that only provide a limited amount of guaranteed revenues, but not service.

Finally another thorny issue that will increase risk is becoming apparent. New small satellite constellations by ESA and NASA (ESA's Swarm satellite configuration of three small satellites and NASA's MMS configuration of four small satellites) have confirmed that the Earth's magnetic poles are shifting with magnetic North now slipping down to Siberia and magnetic South now moving up toward Australia (Swarm Mission Overview 2019). (See the ESA small satellite constellation pictured in Fig. 3.)

The Earth's magnetic poles currently hold into shape the so-called Van Allen belts of radiation. These belts of ionized particles actually protect Earth and especially LEO satellites from solar storms. As this newly discovered shift occurs, satellites,

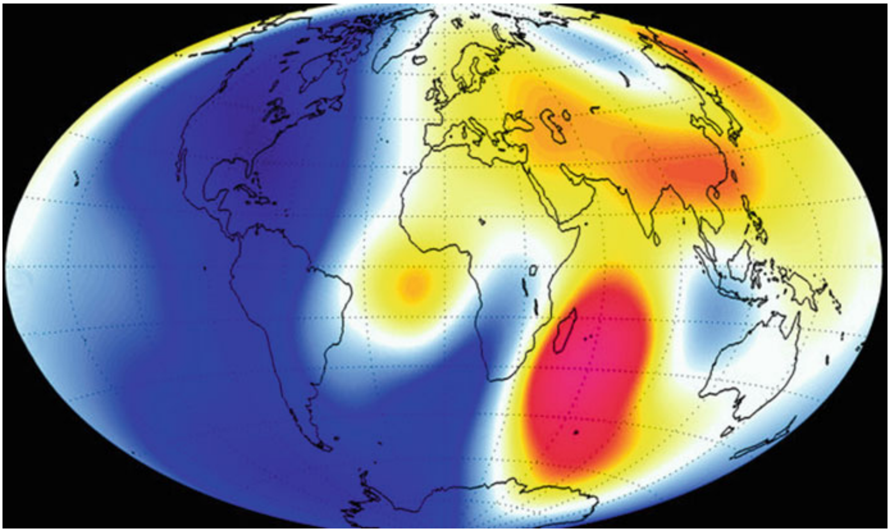


Fig. 3 The Earth's changing magnetosphere with the magnetic North pole moving down toward Siberia and magnetic South moving up toward South Africa (as depicted in red). (Graphic courtesy of ESA)

electronic grids, pipelines, and other infrastructure will be exposed to higher levels of risk. These are new risks that satellite engineers and insurance companies will need to take into account going forward.

5 The Supply Side: Innovation and New Technological Developments

The entrepreneurial innovations that are concentrated in California's Silicon Valley have been generated by people with a special drive focused on all types of new technological discoveries. Some are the result of university research, some are new businesses built on ideas nurtured in garages or maxed out credit cards, and some are attributed to larger companies expanding their R&D efforts. This has largely come from the computer, telecommunications, artificial intelligence, software, and Internet-based digital economy, although some have come from the world of bio-technology, medical research, or other sciences and applications.

There are today a number of new space ventures that got started by such innovative means. The SPIRE constellation discussed elsewhere in this handbook got started by raising funds for its first experimental test satellite via crowdsourcing. A well-crafted appeal made via the Internet allowed this fledging enterprise to launch its very first cubesat experimental prototype. This success led to a number of other rounds of investment that followed a more conventional path forward of seeking several rounds of investment by angel investors (https://www.SPIRE.com/en/SPIRE/about-SPIRE (Last accessed June 10, 2019)). (See Fig. 1 above.)

Nor is the successful bootstrapping upward of a start-up to financial viability in the case of SPIRE a unique story. The Skybox venture was started by four graduates from Stanford University that managed to get sufficient start-up capital to get their small refrigerator-sized 1 meter cube satellites to orbit before being bought out by Google. Planet Labs was started by graduates of the International Space University that based their efforts largely on the sweat equity of a number of college graduates from Silicon Valley. Today Planet, the owner of Planet Labs, Terra Bella, and other assets, is managing hundreds of remote sensing satellites in what is now a highly successful business (Schingler n.d.).

6 The Supply Side: Costs of Production

The manufacturing of satellites and space equipment has seen major improvements, both in quality, performance, and lower costs over time. Some of these improvements can be traced to moving up the "learning curve" as companies gain experience in production techniques. Some are traced to improved technology and components within the satellites. And, some are the result of taking advantage of scale economies and larger orders that are required for mega-constellations of small satellites, standardized components, and more experienced production workers. In addition, although the manufacturing of single-unit large R&D satellites often required by government specifications is more expensive since each satellite is unique, the design and components often use new breakthrough technological improvements that then spill over to the commercial satellite production arena, contributing also to more efficient production of all satellites.

One successful innovation often leads to a chain reaction generating many new ideas and innovations. One of the main components of the current patent and the intellectual property system is that the technical information behind the invention is recorded and available publically. Although the invention is protected from being copied for a specified period and royalties or licensing fees are paid to the holder of the intellectual property during this period of time, others can seek to extend the knowledge and create new ideas or devices that go beyond the original invention. Some of the entrepreneurs that have engaged in developing small satellite technologies that are now building and operating small satellite systems are downstream beneficiaries of these earlier inventions.

6.1 Life Cycle Cost Analyses

The manufacturing facilities for large satellites that are very capable but few in number do not lend itself to mass production techniques or to large-scale economies and consequent large per unit reductions in manufacturing costs. They are designed for long lifetimes of 15 years and beyond and do not need frequent replacement.

Further they do not generate a large demand for launches and launch services. With the possible near-term development of effective satellite servicing, their life may even be extended for a longer time if such developments prove cost-effective.

The advent of swarms of large constellations of low Earth orbit satellites competing with the large GEO satellites for similar terrestrial uses and services may also be advantageous to the mass production of cheap (on a relative basis) and lightweight satellites. One factory could conceivably produce thousands of these satellites at a rate that would take advantages of scale economies and, like the revolution in the manufacture of automobiles almost a hundred years ago, make these small units quite inexpensively. And, since they are small and light in weight, they also may be able to be launched on smaller and cheaper vehicles. Finally, they are easily replaceable, and there would be no need for many, if any, spares in orbit.

That sounds like a very attractive business life cycle plan compared to the current methods. And it is a different model for the industry. But, the conclusion that these new techniques are better and cheaper has not been proven and may not be realized. There are many reasons for this. First, there are still no operating systems of swarms of satellites in space that effectively “talk to each other” and operate as one “big” satellite. Second, for some applications such as remote sensing, they are incapable in design of having a large aperture and producing equivalently good Earth observations. Third, the large number of satellites may also increase space environment risks from difficulties of managing all the new “traffic” in space (Werner 2019).

On the manufacturing end, there are other questions for which there are as yet no answers. First, these satellites will use components and materials from all over the world. A guarantee of a continuous and constant supply chain to make them could easily be subject to large fluctuations from political, economic, and availability issues, not to mention export control issues. Any disruption of a supply chain can add large costs to manufacturing and selling these satellites competitively. Second, as these small satellites age, new ones need to be launched. There is no model at present for a smooth production line that will keep the production line active at a fairly constant basis over time. It is quite possible that the life cycle costs of a mega-constellation of small satellites could end up with profit points being less than those for the services provided by the legacy large GEO satellites.

Other questions are also unanswered. How many mega-constellations are needed (i.e., can a terrestrial market support)? What are their vulnerabilities? Is the business model solid? It appears that the cost and size of each small satellite is increasing due to the desire and ability to have each one do more and more complex tasks; will this trend continue and significantly increase the total investment and cost of the systems? It is too early to predict the outcomes. But the present time does require that these difficult questions be posed.

6.2 Hosted Payloads

The idea of hosted payloads has evolved and also contributed to economic advantages in the development of new satellites and services. Some of the operators of satellite systems had technology or components that they wished to deploy on future spacecraft that they would like to test in space. Thus they simply attached an experimental package to one of their current generation of spacecraft for verification testing. For example, Cisco Systems developed a new router that it wanted to test in space. They approached and got permission from Intelsat to put this as a test package on an Intelsat 9 spacecraft. The Inmarsat Express satellite, a multi-ton satellite in a more recent launch, contained over 30 experimental packages.

In short, the operator of satellite systems recognized that the residual margin between their satellite mass and the maximum lift capability of their launch rocket had value and offered launch opportunities in the form of a "hosted payload." The extent of these opportunities were recognized that led to the formation of a "Hosted Payload Alliance" that assisted in matching up those seeking a launch opportunity for a small payload with someone who was launching a larger spacecraft. This was, in part, the reason why the Inmarsat Express ended up with so many experimental packages included in this launch.

In the case of small satellite constellations, the opportunities for so-called piggyback launches expanded in a significant way. Instead of a one-off launch of a hosted payload attached to a single launch, the opportunity expanded to the possibility of a hosted payload that could fly on a fully deployed satellite network and could thus achieve in this manner a completely operational global system. The first to achieve such a complete global network is the Aireon hosted payload network that is deployed on all of the Iridium Next satellite system for mobile satellite communications. This Aireon package and antenna system is deployed on all 66 plus spare satellites in the second generation of the Iridium satellites that is now fully complete and functional. The Aireon package provides a broadcast beacon for this new space-based Automatic Dependent Surveillance-Broadcast (ADS-B) that is sent to all aircraft equipped with the new antenna system built by the Harris Corporation. In this case the Aireon service is a joint venture between Iridium and Harris (Aireon Technical Specification 2019). There are clear economic advances that come with the ability to combine two satellite missions together on a single spacecraft, especially if this can be done on a complete constellation of satellites. (See Fig. 4.)

6.3 Matching Supply and Demand

The communications satellite industry has learned long ago that matching system capacity supply in orbit to market demand is good for bottom line profitability. This means not only that additional satellites are launched when demand dictates but also that the use of the most efficient digital coding systems is a way to provide market demands in the most efficient ways. Ten years ago transmission efficiency rates of 1 bit per Hz to 2 bits per Hz were common. Today systems typically operate a efficiency rates of 4 bits per Hz to 6 bits per Hz. Satellite system that have gone from 1 bit per Hz to 6 bits per Hz can thus send six times as much information through the same satellite and thus increase efficiency up to six times.

Fig. 4 The Iridium Next 66 satellite LEO constellation as it was in deployment

Such coding efficiencies are not possible to maintain at all times. Coding efficiencies and greater dwell times may become necessary in high noise environments and particularly in conditions such as very high rain rates and associated rain attenuation. Efficient system design with the latest encoding systems can make satellite much more efficient.

Those that are planning to implement large-scale constellations need to consider the economic risks of deploying a very large number of broadband systems without the corresponding market demand being firmly in place. There is a clear logic to the decision by the One Web constellation to deploy only the first 600 satellites and leave until later to launch of the next 300 or so satellites until later. Likewise is seems reasonable to wait until this part of the system is responding to real market demand before seeking to move to the ultimately envisioned 4000 satellite network for the longer term.

The O3b medium Earth orbit constellation that preceded by 6 years the One Web network was also launched a new four satellites increment in April 2019. Thus it has gradually built this constellation in size up to 20 satellites in MEO constellation and incrementally responded to consumer demand (O3b Satellites Roar into Space 2019).

As the next stage of this evolutionary growth, SES has now contracted to create a new MEO constellation of seven satellites to be launched starting in 2021. This new constellation is known as the mPower network. This constellation will have a combined capability to create a total of 30,000 spot beams and attain a total system throughput capacity of 10 terabits/second. Thus it would have the throughput capacity equivalent to a very high capacity fiber optic network. These would no longer by “small satellites,” but there is the ability in the satellite field to scale up capability by deploying more and more satellites in a constellation or to scale up the size of the satellites to increase capacity. (See Fig. 12.5 for a representation of the SES mPower network.) (O3b mPower 2019).

It is the concern about matching in-orbit satellite capacity to established needs that gives particular concern to the proposed SpaceX system of over 4500 satellites followed by a network of over 7500 satellites. This now proposed volume of satellite launches gives concerns about oversupply of satellite capacity, the SES mPower network, and other proposed systems that are noted in the handbook that seem to create the likelihood of a satellite service provider global “price war.” The current spate of proposed filings of communication satellite networks in the mid to late 1990s brings back vivid recollections of past market over calculations as represented by the Teledesic, Iridium, Globalstar, Orbcomm, and ICO networks that experienced bankruptcies in the late 1990s. Finally it concerns about not only the deployment of so many satellites but also the issue of how to effectively deorbit these many satellites at end of life as well as to deploy replacement satellites, perhaps as quickly as on a 7-year cycle.

6.4 Shared Support Systems and Associated Risks

In this way power, tracking, telemetry and command, mission control staffing costs, and clearly launching costs can be efficiently shared. As long as both the primary satellite and hosted payload perform as expected and all launches are successful, then the joint project is also economically efficient. Even the end of life removal of the satellite and the hosted payload has efficiency as long as both the system and subsystem reach their intended lifetime and perhaps exceed it.

The downside can come, of course, if things should go wrong. Perhaps the classic problem would be if the power systems on the Iridium satellites developed a design flaw such that it could support the primary mission, but would not be able to provide power for the ADS-B safety surveillance subsystem. Clearly such types of problems should be considered carefully before such system-wide sharing of resources are pursued. Even in a partnership arrangement, legally binding language needs to spell out a series of “if-then” contingencies of things that might go wrong and how the problem would be addressed. In the case of the Iridium Next and Aireon partnership, there were serious delays due to problems with the Falcon 9 Launch services, but currently all systems are successfully deployed, and no major issues have emerged after the constellation was fully deployed. Of course in the future, other joint projects and hosted payloads may not be as successful.

7 Looking Ahead: Demand and Supply in the Future

The concept of hosted payloads is not the only spin-off idea that has come with the small satellite constellation and “NewSpace” revolution. Another idea that is getting serious attention today is the idea of deploying high-altitude platform systems (HAPS) or so form of stratospheric platform or long-endurance aircraft that might provide communications, remote sensing, fire detection, or other services for a particular area such as an island country.

There has even been serious consideration of a constellation of as many as 15 HAPS that would provide telecommunications and broadcasting coverage of all of Japan on a continuous basis. There have also been ideas that have included solar- and battery-powered HAPS, automated jet aircraft that could stay aloft for as long as 7 days, and even beamed energy systems that could power and keep in position a high-altitude craft. Instead of an orbited satellite, the application platform would be the equivalent of a GEO satellite, but instead of being up at 35,870 km, it would be stationed at about 20 or 21 km in altitude. This could provide high gain services for communications, broadcasting, fire detection, or remote sensing with very negligible path loss.

In this case there have been more than a half dozen initiatives that have been seriously proposed as well as so-called aerostat projects that have been pursued but none have as yet proved technically and financially viable.

Quite recently Facebook, which was providing funding for a HAPS projects to support networking services, pulled out of one such project. Currently Amazon which is now backing a small satellite constellation known as Athena was seriously considering attaching data relay united to high-altitude meteorological balloon that would drift around the equatorial region to support remote Internet access. This project was known as deploying "Loons." Perhaps one of the more serious initiatives at this stage is the Stratobus initiative by Thales Alenia. This is a fully prototyped system that would operate for long duration missions up to an altitude of perhaps 20–21 km. This kind of stratospheric operation that would fly up to the region sometimes call near-space, sub-space, or Protospace is addressed elsewhere in this handbook of small satellites.

There are also manufacturing risks that can have more severe consequences for space equipment than terrestrial equipment. For example, a satellite series that had used the same batch of computer chips that contained a contaminant that in time disabled the satellites. Fortunately this problem was discovered to affect only a limited number of satellites. If such a problem had involved contaminated chips installed in thousands of small satellites, the economic consequences could run into billions of dollars, and the losses in revenue for services not performed could likely bankrupt the service providers.

Thus while risks for small satellite constellations might be minimized, and providing spares is more easily done, there are some other high level engineering and reliability risks for small satellite constellations. This can occur if a key component in thousands of small satellites were found to be defective after the satellites are placed into orbit and the result could be the cause of a catastrophic failure. In the case of an automobile manufacturer, if there is a faulty component in large production run, the component can be replaced in a local dealership. In the case of thousands of satellites deployed in space, there would not be any easy answers.

In summary, new mass production systems that may be developed for large clusters of almost identical small satellites face many risks that are different from the mass production of terrestrial equipment. They may also face other economic risks and costs. It is not a foregone conclusion that the mass production of these satellites is any cheaper or less risky than producing large LEO or GEO satellites that currently serve markets that are similar to those projected for small satellite clusters.

8 Regulatory Concerns

When entities are first engaged in planning the deployment of a new satellite system for telecommunications, networking, remote sensing, or other such applications, the initial thoughts are typically focused on the space segment, i.e., all the efforts that are directed toward the design and manufacture of the satellites, intersystem coordination of satellite spectrum usage through the International Telecommunication Union (ITU) procedures, making arrangements for the launch services for deploying the satellites in orbit, and controlling the network in orbit.

Besides a good assessment of market conditions, often overlooked are regulatory procedures and national licensing and landing rights for the countries where the satellite services are to be marketed. One of the largest single factors that led to the bankruptcy of the Iridium mobile satellite system was a recognition of the costs and pricing implications for their services in the countries where there services were planned. In many countries, particularly developing countries with limited access to hard currencies, international telecommunications is a key source of supply of key overseas monetary resources.

The idea that an Iridium satellite, or a Globalstar or ICO satellite, might be able to have its own “country code” and thereby allow users in their country to avoid using national telecommunication carriers and share revenues with the country in question was considered a very big problem indeed. Country after country demanded that cost of a “landing license” to operate in their country was a share of the entity’s revenue stream. The initial projected costs for the Iridium international cellular voice service – as well as the other systems such as Globalstar and ICO – was well under a $1.00 a minute, but when the total costs of getting landing licenses; coordinating frequencies, taxes, or tariffs; sharing of revenues with local telecommunications companies and governments; and ground equipment were all added, the actual price was much greater ($3 to $10 a minute).

How the various new small satellite constellations relate to national regulatory bodies is thus a very important issue. Some systems are opting to download their remote sensing data via data relay systems. This can speed up their download capabilities to near real time and avoid issues such as tariff fees for ground equipment and perhaps other forms of taxation.

Satellite networks that are seeking to provide telecommunications and networking services have more limited options. In the case of local networking and Internet services, they might be able to make commercial arrangements with nationally based Internet service providers to upgrade their service capabilities. Different countries will have different regulatory practices and legal constraints. In the age of broadband IP-based streaming of movies and video services, radio programming, and voice over IP, these small satellite constellations that are seeking to provide networking services may still be required to obtaining “landing licensing” and may very well be subject to revenue sharing arrangements. The world of telecommunications, broadcasting, and networking is now almost completely intertwined. The argument that a “networking” system is not competing for telecommunications services, either locally within a country or for international services, is unlikely to be accepted by national telecommunications licensing authorities.

The economic effects that are associated with “NewSpace” enterprises are evident in many different ways. Launch costs for lightweight small payloads are much less, mainly driven by their size and capability to be launched not only on small launch vehicles but using excess capacity on large vehicles. Companies as diverse as SpaceX, Blue Origin, Rocket Labs, Virgin Galactic, and Vector have begun to revolutionize the launch industry by adding such capabilities as reusable first-stage rocket engines, vertical integration of their rocket production, new materials, lower cost ground or air launch operations, true small launchers geared to the small satellite markets, and more. These lower cost and more flexible launch operations have not only made it easier to launch for small satellite enterprises. The lower cost not only enabled the creation of new satellite constellations for established satellite applications, such as telecommunications, networking, and remote sensing, but also opened the door to new commercial space services.

One of these new types of networks is the Hawkeye 360 system that is now offering RF Geo-location services. This new cubesat constellation is now monitoring frequency use on a global scale and does so with a precise identification of the RF users and their location.

There were at least two firms that are intending to offer commercial data relay services to support remote sensing services and rapid data analytics. These two companies are Audacy and Theia. The Audacy effort though is currently seeking financial support to continue operations. Nor do the new satellite services offered by innovative small satellite ventures stop there. There are likely to be in the future a number of firms that will seek to offer on-orbit servicing and perhaps also active debris removal. Firms that have developed, or are seeking to develop such capabilities, include McDonald-Dettwiler (MDA), Orbit Fab, SSL, Northrop Grumman Innovation Systems, Vivasat, and Conesat (Pelton 2015).

However, there are still many problems to be resolved, particularly in the area related to on-orbit services (OOS) and satellites that engage in so-called rendezvous and proximity operations (RPO). There is the question of nation-state liability if such close approach operations in space should go wrong. The resultant accident could result in a significant amount of new debris, and major liability claims might be created against the launching state as well as civil claims against the on-orbit operator. National security aspects and diplomatic problems are also likely consequences. No regulatory system now addresses these issues, and a new liability regime may be needed for in-orbit activities.

9 The Reshaped World of Commercial Satellite Services and the NewSpace Launch Services Industry

The world of commercial space is continuing to be reshaped in almost every dimension. There has been a major reshaping of design processes, innovation, and manufacturing cycles for satellites, and in many cases the size and mass needed for the satellites to perform many of their missions have decreased in major ways.

Likewise the design and cost efficiency of launcher have also dramatically changed. There are many new start-up companies in the world of commercial space. There tends to be a whole new cost structure that relates to many aspects of space operations and services. These relate to not only "NewSpace" commercial operations, but the impact is increasingly broad in terms of military and governmental satellite activities and in terms of the business practices and operations of well-established aerospace corporations.

It is no longer governmental space agencies and military ministries that are dominating space-related procurements. The dominant role of the "military-industrial complex" where procurements, especially in the United States, Canada, Europe, Australia, and Japan, largely came from governmental or defense agencies and largely went to the largest and longest established space agencies is tending to change. Commercial organizations rather than governmental and defense agencies dominate procurements. Contracts are less likely to be cost-plus arrangements with specific design specifications. Instead contracts are likely to set performance standards and establish a fixed price and delivery schedule for space-based equipment and systems.

So-called NewSpace practices have rippled through government space agencies and defense agencies and large aerospace corporations. Space agencies are sponsoring commercial competitions. Defense and governmental agencies are commissioning small satellites for many projects. Large aerospace companies are acquiring innovative start-up companies. Boeing is building cubesats for the US Air Force. Air Bus has purchased Surrey Space Technology Ltd. and also building small satellites for One Web. Northrop Grumman has acquired Orbital ATK. But some of the scale start-ups such as Sierra Nevada, Planet, Via Sat, SpaceX, Blue Origin, and SPIRE have become truly major aerospace corporations. Everywhere there is change and innovative design, and new corporate practices will evolve from many sources.

10 International Trends in "NewSpace" Service Industries

Many people attribute the so-called "NewSpace" revolution to the growing world of computers and digital systems. The idea of seeking 50% or 100% improvements in efficiency, design, or process rather than a 5% or 10% improvement is clearly what "Silicon Valley" innovation has been all about as new generations of products or systems have forged ahead with remarkable speed. Moore's law of a doubling of performance every 18 months has characterized the world of digital innovation for decades, but now the aerospace world is seeking to innovate in this fast pace way as well, even as the digital improvements may be increasing at a slower pace now.

The source of this type of "NewSpace" thinking may have come in part from Silicon Valley, but it has certainly spread worldwide. The world of cubesats, commercial launch vehicle design, and new aerospace innovation is now global in scope. There are more than a dozen new Chinese commercial launch vehicle companies and space satellite designers and manufacturers. The many companies that are designing and manufacturing new launchers, small satellites, and new flat panel antennas and starting new space-based service companies may still be predominantly in the United States, but there are a growing number of these innovators that are located in scores of countries around the world. Canada is also a powerhouse of new initiatives. Innovations are coming from countries like India, China, Taiwan, Australia, New Zealand, Luxembourg, Russia, Ukraine, Spain, Denmark, Italy, the United Kingdom, South Africa, South Korea, the Malaysia, United Arab Emirates, Chile, Brazil, and many other sources as well.

11 Conclusion

The purpose of this chapter was not to compare and contrast conventional designers and operators of large GEO satellite networks with small satellite networks in MEO or LEO orbit in precise terms of economic efficiency or market viability. This is much too early in the deployment process for small sat LEO constellations to reach any definite conclusions. The nature of these competitive systems and the evolution of related technology in terms of satellite design, new ground equipment design, new market demand, and new launcher systems will sort themselves out in the coming decade. Successes and failures for both types of systems seem likely to occur.

It may become apparent that the number of new systems is much limited by the expected amount of new types of demand for space-based services fueled by broadband Internet to rural and remote areas, 5G backhaul, and M2M messaging services associated with interactive IoT units. It is also quite possible that new innovative land-based systems may also compete with space services. It is thus not possible to predict the longer-term future, but it is clear that there are economic factors that encourage new and more efficient space systems just as there will always be competition from innovative non-space systems.

This chapter instead was oriented toward examining the economic consequences and trends that are inherent in all markets where there is rapid rate of technological change. Clearly there is alteration in space business models that are being driven by all of the new LEO and MEO small satellite constellations that are now planned with perhaps up to 20,000 satellites now planned for deployment. Nor are all the forces of change entirely market or technology driven. The vulnerabilities that could come from orbital debris collisions, small satellite deployment or defunct satellite removal, or even a gigantic solar storm that disables a large number of these new types of satellites – either high-throughput satellites in GEO orbit or small satellites in LEO or MEO – could have huge economic and market impacts that could affect the viability of many companies providing commercial space services.

The practices of governmental agencies, defense ministries, start-ups, and conventional aerospace companies are all changing, both in the United States and across the world. This chapter has examined how the developments of the past decade have enabled the creation of new types of space services, especially in telecommunications, remote sensing, and Earth observation, but also have spurred innovation in all sectors of the space industry with these broader effects being seen on in the years and perhaps even decades in the future.

12 Cross-References

- ▶ Deorbit Requirements and Adoption of New End-of-Life Standards
- ▶ Legal Issues Related to the Future Advent of Small Satellite Constellations
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ▶ "Rules of the Road" for Launch and Operation of Small Satellites and Related Issues
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit
- ▶ US Space Policy Directive-3: National Space Traffic Management Policy

References

Aireon Technical Specification. http://www.aireon.com. Last Accessed 15 June 2019

C. Henry. One Web raises $1.25 billion from returning investors. *Space News*, 18 Mar 2019. https://spacenews.com/oneweb-raises-1-25-billion-from-returning-investors/

E. Howell. Satellite company SPIRE sees high growth amid a crowded market. Forbes, April 5, 2019. https://www.forbes.com/sites/elizabethhowell1/2019/04/05/satellite-company-SPIRE-sees-high-growth-amid-a-crowded-market/#4ba522444f52

S Michael, CNBC News. SPIRE Global lands deal with ESA's Galileo satellites for predictive weather data. (n.d.) https://www.cnbc.com/2018/12/11/SPIRE-global-gets-2point7-billion-weather-data-partnership-from-galileo.htmlStart-up

O3b mPower. https://www.ses.com/networks/networks-and-platforms/o3b-mpower. Last Accessed 2 June 2019

O3b Satellites Roar into Space, Scaling SES's Constellation. April 4, 2019. https://www.ses.com/press-release/o3b-satellites-roar-space-scaling-sess-meo-constellation

J.N. Pelton, *New solutions for orbital debris problems* (Springer, New York, 2015)

L. Rapp, V.D. Santos, A. Martin, Satellite miniaturization: Are new space entrants about to threaten existing space industry, in *Manfred Lachs International Conference on NewSpace Commercialization*, (Institute of Air and Space Law, McGill University, March 16–17, 2015)

R. Schingler. Planet Launches Satellite Constellation To Image The Whole Planet Daily. https://www.planet.com/pulse/planet-launches-satellite-constellation-to-image-the-whole-planet-daily/

Swarm Mission Overview, European Space Agency. https://earth.esa.int/web/guest/missions/esa-eo-missions/swarm/mission-overview#Swarm_Mission. Last accessed 20 June 2019

D. Werner. Suppliers scramble to keep up with constellation demand, RUAG/Space News, March 2019

Space Finance for 'New Space' and Small Satellites

Joseph D. Fargnoli

Contents

J. D. Fargnoli (✉)
New York Space Alliance, New York, NY, USA
e-mail: jfargnoli@NYSpaceAlliance.org

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_70

Abstract

This chapter will look at how various classes of new space and satellite projects which may have capital requirements that can go from as low as under a $1M up to well into the billions of dollars are now able to come to fruition leveraging novel financing models which are being constructed. It is clear that for "New Space" to mature and reach its fullest potential, mastering the ability to drive large-scale infrastructure level investment into the sector is required. The financing mechanisms change as one progresses to new support service companies or small satellite ventures operating at the cubesat level, to satellite constellations of larger and larger size, to very ambitious space projects involved with building the cislunar architecture and beyond which may take decades to realize. A smaller space business might start with family and friends financing, angel investors, or even crowdsourcing on the Internet via such sites as "Kickstarter." The next step involves venture capital financing that might end with an initial public offering (IPO) or merger/acquisition. Finally, there are very long-term and ambitious space ventures that may involve various forms of public-private international financing arrangements which have been used in the past for large collective projects which are now being framed and envisioned for new space applications. In this chapter, all these mechanisms will be explored with the greatest emphasis and most lengthy discussion related to demystifying the venture capital financing process for new space actors since this is perhaps one of the most common approaches used. Other mechanisms exist such as spin-offs from established corporations or equity-based loans, but these are not addressed in any detail because they are unusual mechanisms which are available to entrepreneurial projects and small satellite venture startups but not often used.

The goal in this chapter is to help the budding space entrepreneur make their case for the right investment type and to help them to propose a structure based on a better understanding of the different investment classes and vehicles. There is also some consideration of how to posture their enterprise based on the longer-term future at a time when space industries will represent a multitrillion dollar sector. When one thinks of some of the larger projects described later in this chapter, it is important to see them in historical perspective. Although the numbers presented here for long-term space infrastructure projects seem large, they need to be seen in light of other infrastructure projects such as the original US Interstate highway system which is estimated to have cost $500 billion (in 2008 dollars) and the upgrade costs alone for the emerging 5G network which are estimated to be $200B *per year*. It is clear that when the case is made properly, the investment dollars are available. Currently, NASA's FY 2020 budget was nearly $22.629B in order to address their very ambitious mandate, and the capital requirements for some of the larger new space infrastructure projects are way beyond the political will that exists to support the kinds of budget expansions that would be needed if all space-related fundings were to come from the government. What can thus be seen is that to really make financial room for truly innovative, capital-intensive, and longer-term new space projects, there is a need for a new transnational investment model whereby there can be a pooling of the resources of international partners, corporations, high-net-worth individuals and family supporters, and other forms of private equity (PE) along with venture investors. It is clear that these future projects will not only involve venture capital and governments, but there will be a need to involve more of the capital community, coordinated in a way that supports competition and innovation which will allow these new space enterprises to keep learning and improving. All of this needs to be done while respecting and abiding the laws set by each sovereign nation to address their own national security concerns arising from non-controlling investments involving foreign parties.

It is important to keep in mind that as far as the investment community is concerned, investing in space has the same business risks as many other fields of endeavor – execution, technology obsolesce, and regulatory risk plus an additional set of risks due to operating in the space environment which magnifies the difficulty of executing the business plan and getting a return to the investors who ultimately want to make money and will compare this investment opportunity to many others. Although space investors are often motivated by a highest set of principles involving mankind's advancement in space, one of the main challenges that the space entrepreneur faces is finding innovative ways of buying down risk to create a level playing field with other capital investment opportunities available to the investor.

Although successful space missions are hard, financing space missions can be harder because in addition to the high and uncertain capital needs and high-risk levels of any space venture, space entrepreneurs also face immature and uncertain markets in terms of price points and market behavior. It is hoped that this chapter helps to equip the space entrepreneur on this journey to bring forward concepts which will enable the continuing progress of humanity in space for the advancement of a sustainable prosperity for all humankind.

Keywords

Angel investors · Capital financing · Crowdsourcing · Endowments · Exit strategy · Family and friends financing · Kickstarter · Initial public offerings · Limited partnerships · Outer space private investment corp (OSPIC) · Private equity (PE) · Public private partnerships (P3s) · Publicly traded · pass-through shares (PTS) · Space prize competitions · Term sheet · Venture capital (VC)

1 Introduction

The commercial exploration of space should be seen among the historically great projects that mankind has conceived and pursued over time. In most instances, success for these projects has been dependent on finding an appropriate means of financing. From the pyramids to the voyage of Columbus to the construction of the American railway network, Interstate highway system, and telecommunication network – each project has lived or died on finding the right means of financing. Often this has depended on whether there has been public or private financing or some combination thereof. Although space finance is rather new, the concept of venture capital investing to achieve new worlds and new opportunities is not. It is sometimes said that Queen Isabella of Spain was the first true venture capitalist (VC) by backing an entrepreneur named Christopher Columbus with capital in the form of money, ships, supplies, and crew to do something that most people at the time thought was insane and certain to fail. This investment was made in exchange for a portion of the to-be-earned profits of the voyage, but at the start, such a project was seen as unlikely to succeed yet with an asymmetric payoff compared to at the capital at risk.

The following quote concerning Columbus's quest for financing his mission portrays the insatiable appetite for exploration and difficult quest for achieving a truly challenging goal that fuels the entrepreneurial zeal of mankind:

> Columbus arrives as a supplicant at the court of Queen Isabella of Spain, hoping for cash and three tall ships. When the Queen asks him what he desires, he bows over her hand and murmurs, "Consummation." The Queen is offended. Columbus becomes known at Isabella's court for his colorful clothes and excessive drinking. The Queen plays with Columbus, permitting him familiarities, then banishing him to the stables and piggeries for forty days. "The search for money and patronage," Columbus says, "is not so different from the quest for love." . . ..He dreams that Isabella is herself having a dream, in which she sees that all the known world is hers, but that she will never be satisfied by the possession of the known. Isabella's heralds arrive and tell Columbus that she has summoned him for his voyage–she saw a vision, and it scared her. (The New Yorker, June 17, 1991, p. 32)

Another era of similar entrepreneurial zeal took place in the USA during the 1800s in the whaling industry when outfitting to go out for the hunt was very expensive and risky but highly profitable when successful. The New Bedford agents would raise a pool of capital from corporations and wealthy individuals (today's limited partners) to fund ship captains (entrepreneurs) to launch a whaling venture (startup company) in search of asymmetric returns that were heavily skewed to the top agents yet often plagued with failure. Similarly, in 1878, J.P. Morgan would act as a "venture capitalist" to Thomas Edison financing the Edison General Electric Company. Today, VCs do not exist by royal treasuries or monopolistic titans of industry but by the grace of sets of limited partners who invest their own funds into specific VC funds to maintain a diverse portfolio to produce good returns relative to a specific market index.

In this section, the objective is to present ideas that can accompany and empower the next generation of modern space entrepreneurs, or existing ones, looking to take their businesses to the next level while attempting to create a new space infrastructure for both public good and private profit. The focus is on the challenge of raising the amount of capital needed to develop "new space" architectures for projects such as small satellite constellations, new launcher systems and related sub-systems, or even cislunar architectures, infrastructure, and space settlements. Such undertakings are typically defined as the following along a certain magnitude of capital need and the associated timing to achieve breakeven and profitability:

1. **LEO/MEO/GEO Satellite Systems or Supporting Services** – These might be for remote sensing, communications and networking, data relay, RF geolocation, solar power satellite systems, science and technology demonstration, or other applications. They also might involve a subsidiary activity to develop new encoding software or to develop and manufacture key subsystem components. The range of funding in this regime can be as low as a million dollars for a supporting service or to create a new satellite service using PocketQube picosats. However, this could also represent the need for billions of dollars of capitalization for a visionary large LEO or MEO constellations or GEO-based infrastructure. This "New Space" market is alive and well today, and many such satellite systems are already deployed, in development, or on the drawing board with significant engagement at all phases of the financing life cycle. Typical time to viability and profitability: short (3–5 years) to medium term (10 years), depending on the scale of the project.
2. **New Launcher Systems** – This may be a new development of a small-scale launcher, or it might be a new larger-scale launcher by an established launch service provider. Other possibilities are to serve as a launch aggregator or in developing a small satellite dispenser. Typical time to viability and profitability: short (3 years) to medium term (10 years), depending on the scale of the project.
3. **New Venture to Manufacture Small Satellites or Subsystem Components** – The key is not only to be able to manufacture small satellites and components but do so efficiently with the latest technology for additive manufacturing, with properly skilled employees, and suitable facilities but also with the right ability to integrate and test these systems with a high degree of commercial success. Typical time to viability and profitability: short (2 years) to medium term (5 years), depending on the scale of the project.
4. **The Cislunar Infrastructure (CLI)** – The focus here is on getting to the Moon and the developing a cislunar (between the Earth and the Moon) infrastructure for satellite communication servicing, establishing propellant depots, manufacturing, lunar logistics, aquaculture, tourism/settlement, and space mining-related capabilities. Although there is some activity starting up in this area today, there is likely to be an acceleration and maturation of such efforts which has been estimated to be about 20 years out. The build out of the CLI will also serve as an initial stepping-stone to take humanity to Mars which is the ultimate goal for space settlement with very large capital needs.
5. **Moon Colonization and Exploitation** – Once humanity gets back to the Moon on a manned mission in the next 5 years or so, the focus is then going to shift to working and investing to stay sustainable and in supporting larger and larger populations. There will be the need for businesses that focus on mining, processing, settlement, and tourism. Once this is established, such base will immediately serve as a stepping-stone to Mars perhaps as soon as the 2050

time frame where larger and larger populations of planet Earth will be able to be supported. The need for a new capital infusion at a much larger level (i.e., over $50B) will be required before real progress is made in creating a sustainable ecosystem.

This is not an exhaustive list of new space ventures that might seek new capital financing, but it represents the dynamic range of relatively small levels of backing that might be needed to launch up to the truly large new space ventures that could require vast sums to succeed.

2 Valuation of New Space Markets

Space enthusiasts know that there will be a market for many of their ideas, but the key question is how big it might be and when it might come to fruition. The uncertainty in answering this question places a tremendous amount of market risk than more traditional deals that investors might come across. It is challenging at this early stage to predict the value of longer-term projects such as water on the Moon or on Mars or how one should price communication services from the Moon or Mars back to Earth.

Space is still very much the "Wild West" in many ways, but when the West was settled, property rights were recognized. However, international space law is still in a state of flux so staking a claim and defending it are not yet an established practice. As of this writing, no individual, corporation, or nation can own a piece of the Moon, Mars, or even an asteroid, so for many business plans, fundraising must be done in a risky environment without being able to show material collateral such as acquired property so new ways of raising money are required. Even Columbus could offer the promise of new lands conquered for the Queen in exchange for the risk in funding the mission. A new model is required which will replace property rights with things that still allow money to be raised. The bottom line is that investing in space is not like investing in the next great software company so neither can anyone expect the funding mechanism to be.

3 New Sources of Funding for New Space Ventures

Long-term space infrastructure projects require new sources of long-term and very patient capital committed to realizing the vision of building space infrastructure. Most venture capital (VC) or private equity (PE) firms expect a 3–7-year return on their high-tech projects. However, many space infrastructure projects may require 10–20 years to see sizable returns. The challenge to bringing these forward is not the technology or the political, corporate, or social will in the USA, other countries, companies, and individuals since all of this actually exists. What is needed is to develop the correct finance plans to fund these audacious businesses. Silicon Valley VC investing despite all its successes has generally created a world with relatively impatient investors with short investment horizons due to the quick returns that have been available in the software and internet markets. This is not mentioned to be critical but rather to identify that there have been relatively quick return opportunities presented in the world of digitalization, and this is not usually so in the world of space.

Venture investment firms have made many hundreds of investments in roughly the last 5 years in early-stage space-related entrepreneurial firms mostly from the USA and Silicon Valley but also Japan, the EU, UAE, India, and some others. These firms are typically raising rounds as low as $1M but usually no higher than around $50–100M. The pipeline is full of entrepreneurial firms with great dreams that have been funded in this manner. Yet what is required is an effective way to winnow down the many hundreds of aspirational projects to a smaller set of truly viable ventures that might be able to raise hundreds of millions or even billions of dollars needed to fully realize their dreams to deploy this new space infrastructure. In the next few years, there may be significant shakeout of companies that cannot make it to this next level of serious rounds of capitalization. There is a need for considerable consolidation through mergers and acquisitions (M&A) to get to the levels of scale which can attract the needed investors. It will take time and new forms of consolidation or acquisitions before it will be possible to get down to a smaller group of companies that have the capability to raise both capital and execute their business plans.

Although the venture firms have been very impactful, the future of new space ventures cannot really rely on them alone given their charter and their scale. There is a need to get to the billions of dollars per year scale that will be required to really enable the needs of capital financing associated with many larger new space infrastructure needs. One key method will be the private equity (PE) industry which does have the financial depth required. There is probably $1T in PE funds around the world, but today, there is not much interest among these fund managers to invest in new space because these markets are still seen as being very uncertain and unpredictable. PE firms like to have predictable markets in order to raise debt capital so they can leverage their investments, but because of the uncertainty in the space markets, we are not yet there so their pools of capital are still on the sidelines. Similarly, many traditional aerospace industry companies are making investments in commercial space partially to service their government customer (and this is likely to increase), but they can only do so only while keeping an eye on quarterly earnings so excessive long-term risk does not fit their model. Likewise, the debt markets, with trillions in capital, are also on the sidelines with the exception of a few such as SoftBank of Japan. In general, one cannot expect much money from this class of investor in the near term until there are businesses with assets that can be used as collateral. It must be noted that the space industry has had previous period of high-yield financing when the IPO window opened in the late 1990s and bankers raised $15B for commercial sat companies some of whom made it while others went bankrupt or consolidated.

A chapter on space financing cannot be written without mentioning the great deal of money which was invested in Iridium Generation I, Globalstar, Teledesic, and even Orbcomm. These failures and bankruptcies took away naive ideas of "build it in space and they will come." The ideas of building the infrastructure and waiting for the demand failed miserably, so it is very hard with investors to bring that model back. It is not just space projects that face this challenge, one can look at several other commercial terrestrial infrastructure projects (such as the Chunnel) which were not financed properly, hit hard times but eventually came back to viability. Although there is certainty that mankind's future in space is bright, a careful analysis of timing and financing is required to ensure that some of the errors of the past are not repeated. This will require new and innovative ways of building space infrastructure and especially new ways to find ways to fund it sensibly in a manner which can be shared with government, corporate, and private investments resulting in benefits going to both private industry and the public sector. Some of these domestic space projects, such as Iridium, Globalstar, and Orbcomm, eventually became successful and have become great assets for many years once demand caught up with the capability offered by the infrastructure. The same challenge will be true for new space infrastructure now planned or being envisioned.

The key to successful space entrepreneurship lies not only in having a solid idea for the delivery of a product or service but also in finding patient investors with the right long-term vision. Space agencies are funding a lot of technology development and demonstrations with program such as Commercial Lunar Payload Services (CLPS) for delivering science and technology payloads for NASA, including payload integration and operations, launching from Earth and landing on the surface of the Moon. They have a long-term vision but are underfunded compared to the total amount of capital needed. Unfortunately, governments in general are proven to be unreliable because each administration brings an altered set of priorities and initiatives, so some programs are cut, while new programs are created with each administration. A lot of the investment community will not even invest alongside the government because they have been burned so many times because of examples where funding for programs has been cancelled.

Although the government has not been a reliable long-term partner, this can change by creating new public private partnerships (P3s) that do work. A prime example of this is the ISS cargo delivery program created by NASA which shared the cost of the development by buying down the development risk with capital that was non-dilutive to the investors. The government did not sit on the boards and try to direct the execution of the business plan; instead they bought down about half of the cost of developing the infrastructure, and once this was proven and deployed, they gave a big multiyear contract to deliver to the space station. This guaranteed and quantified the demand at a fixed level for a fixed number of years. With these two things in place, they were able to create a vibrant and competitive delivery service that helps keep the ISS going, supports commercial crew, and helps fund SpaceX and Northrop Grumman Innovation Systems to build rockets to buy down the cost of commercial satellite launches. This has had tremendous effects throughout the industry starting with NASA designing a P3 structure that checked off all the boxes for investors.

There are other patient large pools of capital that can wait years for a positive return such as sovereign funds which have many billions of dollars to invest and are becoming increasingly interested in space to help modernize their country's economy by getting involved in new space projects. To date they have not yet made significant investments from these funds, but this is expected to change if they are able to invest in profitable small satellite constellations from which they might also consider investing in activities on the Moon or in going to Mars. There are also substantial funds within family offices and a small number of billionaire space enthusiasts backing Virgin, Blue Origin, Bigelow Aerospace, and SpaceX, but there are 100–1,000s of other businesses with large wealth owners that can be attracted into this sector if the right case is made. Right now, most private investors worldwide are more concerned with preserving family wealth rather than increasing it, so they must be approached as a way to build long-term wealth in their families. This is a sector that will be a huge part of the economy in 10–50 years, and the message is that they need to invest now, to avoid missing out because it will become a lot more expensive to invest later down the road. Space entrepreneurs must do a better job of explaining the proposition to this group and attracting capital. Governments could also continue to support space billionaire initiatives, as well as encourage startup entrepreneurs by helping to buy down risk.

The range of financing mechanisms for new space ventures is thus quite large with the possibilities running the gamut from (i) small startups backed by "family and friends," angel investors, and "Kickstarter" crowdsourcing (these are often efforts used for spin-offs from a university cubesat project); (ii) various types of venture capital-backed projects ranging from modest projects up to very large venture capital initiatives that ultimately lead to initial public offerings (IPOs) for new public corporations and major new space organizations; and (iii) public-private initiatives that might be used to create global consortia and might be the core of longer-term space initiatives associated with space stations, settlements, and space projects on the Moon or Mars or even things such as planetary defense mechanisms.

4 Financing Concepts for the Smallest of Space-Related Startups

The "new space" revolution and the development of cubesat technology and systems that can provide commercial services have led to a whole new school of thought. New companies such as Spire, PlanetIQ, exact Earth, Capella, ICEYE and many more have shown that space industries can start without a multibillion dollar capitalization. Even smaller firms can be started to create components for small satellites, develop software, or analyze information from small satellite constellations to provide "data analytics" to customers. Such space services or component manufacturers can start with even smaller capitalization.

The smallest levels of capitalization for entrepreneurial new space companies have come from three types of funding. The first is simply known as "families and friends." There is someone who develops a new design for a component, a new software for encoding or encrypting signals, or something else that can be brought to market for perhaps as little as a few hundred thousand or a million dollars.

The innovator develops a prototype or working model or demonstrates how the new software will work with sufficient skill that they can go to their family, friends, work colleagues, and college associates to offer them investment shares in a basic corporate structure that perhaps an attorney friend will draw up and file incorporation papers. There might even be a first round of $100,000 of funding and a second round of $500,000 to get the project off the ground. In many cases, the project may fail, and the family and friends may lose $10K or even $25K, but if the project succeeds, then all of the early investors can end up profiting from such a low key launch.

The second approach would be to seek “angel investors” to invest. Although investors can put their money into a venture capital fund and then let professionals find the best investment opportunity, they can also qualify based on their net worth and income to become investors in new startup corporations. This can be a high-risk type of investment, but it can payoff handsomely if a new space corporation truly succeeds. There are actually many options here, and there can be individuals who are knowledgeable in the space industry that can identify new projects of note which they can recommend to angel investors. These “intermediaries” serve a useful role that VC firms perform in a much more structured way. The venture capital route has been the key route for the computer and web-based companies, and it is now a viable route for space-related startups to get their financing.

The third and newest type of approach to new space ventures is through crowdsourcing. The most notable site in this regard is the Kickstarter site. It is through this process that Spire funded its first cubesat experimental launch. The successful launch of this first trial demonstration satellite let Spire proceed to a series of venture capital rounds of financing and then have an IPO and go public. This, however, is a rare success in moving from a Kickstarter-funded initiative and then move all the way to a public corporation with quite substantial assets.

5 Entrepreneurial Capital Financing in the Here and Now

These next sections are for entrepreneurs interested in applying venture capital to fuel their space dreams and to help create a global system of sustainable prosperity to create new jobs and continue the path of global economic growth. This practical path of financing is “here and now” for most space entrepreneurs to secure early funding to get a space venture off the ground. It is the aim to demystify how this crucial part of the startup ecosystem works specifically for the space industry vs software, biotech, or any of the others in vogue in Silicon Valley, New York, or beyond.

The first step is to take a quick look at the space VC startup life cycle from every angle including how VC decision makers decide where to invest and how best to approach VC firms. This chapter also seeks to supply some legal and financial details and where to seek help in forming and growing a space startup. This information can help to reframe the relationship between space startups and their investors. If properly followed, this can lead to a true partnership aimed at advancing the future of space progress which requires that new ideas can come to fruition to fuel the future from a wider range of entrepreneurs with the goal of helping to clarify the world of space VC so new entrants can succeed in it.

Overall, the perspective that is offered here is that barriers to entry to space entrepreneurship are being reduced everywhere thanks to the new space revolution, the rise of globalization, and the influx of new talent into every industry and sector. It needs to be recognized that venture-backed companies overall account for nearly half of the entire R&D budget for US public companies while making up a fifth of the total market capitalization of public companies while employing over 4M people in high-tech industries. In a growing number of countries in Europe, these numbers and ratios are not too greatly different. Yet new space needs more entrepreneurs engaged, and the following sections will identify the incentives and systems behind VC investment strategies in order to help space entrepreneurs navigate the maze of venture investors and to help decipher behaviors and explain why and how the system works.

Venture firms use a formula to determine how much money to allocate to different types of space investments, and the current reality is that the amount of resources invested in innovation, space, or otherwise is based on the percentage of assets that need to be invested according to a formula rather than the number of investable opportunities that exist. When too much money is chasing too few deals, prices rise rather than funding the kinds of organizations that are needed. There are currently not enough quality space startups that are wide-ranging enough to build the kinds of companies needed for rapid continued expansion of new space industries, so they are more high-quality talent constrained than capital constrained. Although each space startup is unique, together they all have the common purpose to shape a better world in which everyone is represented and served well by the companies and systems that are created. This path requires the participation of policy makers, academic, government officials everywhere, civic leaders in space startup hubs around the world who are already helping to democratize startups geographically, as well as people who work in corporate innovation who might want to look to VCs for inspiration on how to fund and grow space-related projects within their organizations.

6 The World of Venture Capitalism (VC)

In the world of VC, there are no authoritative formulas, but there are many nuances to the field of space investing with lots of different firms that invest at different stages, under different investment theses, with different portfolio constructions and with different return expectations. Also, space entrepreneurs have their own perspectives, and their ideas come with a unique set of opportunities and challenges and conditions to be navigated. The story of space venture capital is a subset of the story of space entrepreneurship, and the space entrepreneur needs to recognize that VCs raise funds from a broad range of limited partners (LPs) such as endowments, foundations, pension plans, family offices, and fund of funds which is then invested into great space entrepreneurs with breakthrough ideas. VCs invest along the spectrum from early stage where the startup is little more than an idea and a couple of people to growth-stage startups, where there is some decent revenue coming in and the focus is on effectively scaling the business. A space company generally leaves the venture ecosystem via initial public offering (IPO), a merger or acquisition, or bankruptcy and a wind down. A good VC/space entrepreneur relationship involves more than just writing a check, and a good firm will help identify talented employees and executives to bring into the company or existing companies that can serve as live customer test sites. They will work with the team throughout the company building life cycle over long periods of time and multiple investment rounds spanning 5–10 years or longer while often serving on the board and providing strategic advice, contacts, and whatever it takes to make the company successful.

Just as entrepreneurship is essential to the innovation in many national economies, the same is true with the emerging space economy. Successful venture-backed companies have had an outsized positive impact on the US economy and many other industrialized countries, and the same is hoped for with space ventures. In the USA, nearly half of all initial public offerings (IPOs) since the mid-1970s were venture-backed companies, while US-based VCs have invested over $100B in R&D and are responsible for creating over $4T in market capitalization or about two-thirds of the total market capitalization of public companies formed in the USA having a tremendous impact on the net jobs created. This is hard evidence that for the space economy to flourish and expand, there is a need for new ideas to flourish. In order for startups to succeed and expand, the key to this success will be for space entrepreneurs to be able to access capital and present their unique ideas to capital markets as democratically as possible.

All entrepreneurs need to ask themselves if they are ready for VC financing and if venture financing is right considering the benefits and risks of this source of capital and as to whether their space business is appropriate in scope and type to raise venture financing. Key questions to be addressed are whether the intended chunk of the space market size is big enough that the business, when it achieves scale, has a reasonable prospect of being a home run and whether the proposed new space business moves the needle for a venture capitalist in terms of the overall fund returns. One must also keep in mind how to manage the balance of economic and governance terms with a VC and the tradeoffs and the downstream implications when needing to raise subsequent capital and how the board, with VC representatives in place, will work effectively to achieve the long-term goals of the business.

Typically, space VCs have lots more experience in these dealings than space entrepreneurs, so there is a need to level the playing field to eliminate the information asymmetry that can affect what should be a long-term, sharing and reasonably equal relationship. Care should be taken that information asymmetry doesn't pollute the foundation of a relationship that should last 10 years or more. VCs are typically seeking investment opportunities with asymmetric upside payoff potential (and capped downside), so they are interested in seeking to build industry changing businesses.

It is key to be able to ask the right questions of space VCs throughout the process to make informed decisions about how best to proceed each step of the way. Right up front, the term sheet is a big part of the VC financing process and defines the economic and governance rules under which they will operate. Once funding is in hand, the founders will need to be able to operate within the economic and governance constraints that they agreed to with the assistance of the board of directors to help steer the ship under the various well-defined legal constraints. VCs will also look at exits and how money that comes into the company goes back to investors in the form of an initial public offering (IPO) or an acquisition or merger. Although timing isn't everything, it is something to consider. Bad timing can be a big reason why ideas that failed in one era become successful businesses decades later as market conditions change and business models that failed can become viable. One might ask why this is the time right for this space startup idea to come forward not and if there are already too many new space projects of a particular type being backed by VCs or if it might be too late to seek VC assistance. Things to consider carefully are:

(i) Whether the amount of capital required to start a space company has begun to decline to the point that they are in an investment class and size comparable to software startups.
(ii) How can a space startup leverage space incubators which are basically a startup school where cohorts or entrepreneurs go through a series of tutorials and mentorship sessions over a 3-month period to see what might come out the other end. This has educated a whole range of space and other entrepreneurs on the process of starting a company of which raising capital is an integral part thus cracking the code of the VC industry and illuminating entrepreneurs in the process of startup company formation and capital raising creating a true community of entrepreneurs which can share their knowledge and views on company building and their experiences working with VC firms tipping the balance of power in favor of the entrepreneur.
(iii) How to look to a space VC firm for more than a check. A good firm with space experience can help a CEO with tasks that include technical recruiting, executive recruiting, PR and marketing, sales and business development, corporate development and regulatory affairs, and the most important assistance might be to coach the CEO to be world class.

7 Space Venture Capital and How Is It Unique

If one looks at the five largest market capitalization companies today (Apple, Microsoft, Facebook, Google, Amazon), all of them were funded by venture capital, but also many successful non-technology businesses have been venture capital funded; how this success can be translated to the space community will be examined here. Venture capital is a source of funding for companies that are not otherwise good candidates to get funding from other, more traditional financial institutions such as banks which have traditionally been the lifeblood of new company formation. However, loans are not always the best form of financing for all companies because they are not part of the permanent capital structure of a company (which means that they must be paid back with interest). Whereas a loan is well suited for a business that will be generating near-term cash flow sufficient to pay the interest and principal, this model only works for the most established space companies in the most predictable markets. This is why equity in the form of financial investment in exchange for an ownership interest is permanent capital, and there is no set time frame over which it must be paid back. The equity holder is making an implicit bet at the time of investment that the value of the equity will grow commensurate with the financial progress of the business and that it can be sold at a profit at some future date. Founders are often faced with the decision of debt or equity, but if a space venture can generate near-term cash flow, or if it is possible to reduce investment in some area of the business to make available cash to pay interest and ultimately principal on the debt, then bank lending may be the best source of capital allowing company management to retain control of their business. However, almost all space-related startup businesses do not have a near-term ability to generate cash flow or do not want to have nonpermanent capital in the business, so they have to choose equity financing in exchange for giving up some portion of ownership to equity holders. Equity-based financing is often the better choice for businesses that are not generating near-term cash flow, are risky, or have long illiquidity periods. Many angel or seed early-stage investors often will invest in companies via convertible notes which have distinguishing characteristics that make them look more like equity where the initial investment looks like debt with an interest rate and a date by which the principal amount of the debt is expected to be repaid, but the conversion feature is the mechanism by which the investor can convert the debt into equity in lieu of getting the principal back. This conversion feature turns nonpermanent capital into permanent capital, and it often tied to an equity-based financing for the company.

8 How Might Early-Stage Space VCs Decide Where to Invest?

The investing world is dramatized on TV and in the media, but in reality, not many people are really in tune with what drives space VC decisions. The challenge is that for early-stage venture, investing raw data is hard to come by, and there is rarely a rearview mirror that accurately portrays the future space market in a predictable way. The entrepreneur needs to develop the skill of qualitative space market evaluation as well as quantitative ways to model the potential future returns of an investment. However, typically, there are not enough financial space metrics to meaningfully model future potential returns for a business that is speculating on a future market such as space applications. This is especially true in new area such as RF geolocation, solar power satellite systems, or on-orbit servicing. But in the experience of many VC firms, there are qualitative high-level factors that they use to evaluate the prospects for an investment which fall into three categories: people, product, and market.

A typical space startup is little more than a very small collection of individuals with an idea, so the quality of the people and team built around them is key. Since ideas are not necessarily proprietary, the ability of the team and particularly the founders to quickly establish their vision and market plan is key. It can be expected that the VC firm will seek to delve into the background of the founders and their team for clues of their effectiveness in executing their idea. So when putting a team together, it is important to have a good dynamics among the founders, so think long and hard about the quality of the people recruited and whether they will convince a VC that the assembled team has the right market unique stuff to carry out the vision in what will likely end up being a tight market for good ideas. Another big area of investigation for VCs focuses on the founder's leadership abilities to determine if the founder can create a compelling story around the mission to attract a great team as well as customers to buy the product and later-stage investors to help with growth stage.

An investor then examines if the space product or service will solve a fundamental need in the market such that customers will pay real money to purchase it. These new products need to be ~10X better or cheaper than current best in class to compel companies and consumers to adopt.

Lastly, market size is the third leg of the stool used to evaluate an early-stage space investment opportunity. What matters most to VCs is the ultimate size of the market opportunity that is being pursued. Big markets are good and leave lots of room for error, while small markets are bad. VCs fear getting the company right but never being in a market big enough or failing to invest in a company that does become the next behemoth. VCs are looking to invest in big market opportunities where fortunes can be won or lost based on their ability to understand the market size and think creatively about the role of that specific new technology can be employed in developing these new markets.

What's key is that as a space entrepreneur and consumer of VC dollars, one needs to be aware of the time constraints imposed where a VC will push for an exit to generate liquidity which is a function of how the company is doing and where the firm might be in its fund life cycle and how the rest of the companies in the fund are performing. A key factor to be aware of and to ask a potential VC partner is how old the fund is, where one is receiving capital from, and to find out where they are in their life cycle. If they are early in the fund, they should have less pressure to return capital putting less pressure on the startup business. If they are later in the fund cycle and haven't generated sufficient liquidity from other investments, the pressure for a more near-term exit could be much more intense.

9 Forming a New Space Startup

Great space company founders are innovative, brave, inspiring, and visionary, and their ideas can be groundbreaking and world changing. It is critical to get the company off on the right foot beginning with a visit to a lawyer's office to work out things like tax and governance to understand how to set up the business. There are several firms out there who have special practices and years of depth of experience in space, and it is possible to find many of them at some of the premier space conferences held around the country. Some law companies are equipped to provide legal services for equity or at least deferred compensation.

10 Raising Money from a VC

Although raising money from a VC is all the rage for many space startups, one should start by asking if venture capital is right for the company and, if the project is just starting, whether other mechanism such as family and friends, angel investor, or some form of crowdsourcing is perhaps the better answer. If the project has matured to the stage where VC financing is realistic, then the next question is the amount and valuation at which funding should be raised. If one does decide to go forward, the simple guide is to raise the highest valuation possible in order to give the startup as much runway to grow the business. The right time to raise capital is when it is available. But, if the ultimate size of the opportunity isn't big enough to create a stand-alone, self-sustaining business of sufficient scale (such as being a profitable, high-growth, several-hundred-million-dollar revenue business over 7–10 years which will support a capitalization of sever billion dollars), it may not be a candidate for venture financing because it does not have sufficient scale to move the needle on the fund's overall economics. The next step might be to think about taking a different approach to financing such as looking to smaller VC funds which will look to exit sooner through acquisitions or even considering banks for debt financing. Another big factor in determining whether VC is right is determining if one can live with sharing equity ownership, board control, and governance in a relationship that will last 8–10 years. If one decides to go ahead with VC financing, there is a need to set about to raise as much money as possible to safely achieve the key milestones to show de-risking. This will be key for next investors who will be convinced that they are willing to put new money into the company at a price that appropriately reflects the progress that has been made since the last round of financing. Most early-stage companies raise new capital every 12–24 months reflecting the time frame over which reasonable business progress can be made. The milestones that are set should match the funding that is raised with some margin of error built in if things do not go according to plan. Since it will not be possible to raise all of the money that is needed right up front, this practice of setting milestones will be critical to phasing fundraising and setting milestones. By spreading the capital raised, the startup retains the benefit of increases in the valuation as the company "de-risks" the opportunity and the VC can size their investments based on achievement of these milestones so that if the objectives laid out at the time of the first round are reached, the next investor will pay for that success in the form of a higher valuation. Also, having too much money can be the death knell for early-stage startups since lack of financial constraints actually limits the need for creativity and innovation and creates dangerous dynamics amount the team.

Finding the right valuation at each successive round of financing is key but difficult. If there is overvaluation at any stage, then this raises the stakes and makes it more difficult to be able to achieve an even higher valuation for the next round, while if the current valuation is high or low, it is likely to reach a point of balance over the successive rounds. Prevailing market conditions can also have an impact on the valuation of a startup from round to round. But one must avoid falling into the trap of raising too little money since this can leave a startup without the financial resources needed to be able to achieve the business goals required to safely raise the next round of financing above the current round's valuation. It should also be mentioned that creating a competitive environment around potential investors helps as well which means keeping valuation expectations attractive to a range of potential participants. Also, keep in mind that employees often judge the success of the business at least in part on the external measure of valuation in a financing round compared to other companies that have raised money recently whether or not they serve as relevant benchmarks. Keeping the valuation moving up and to the right is key – not raising or raising at a valuation lower than the last round are the last things to do.

11 The Art of the Space Startup Pitch

Angel or seed investors are upstream of a VC in that they are typically investing at an early stage in the company's development than might a traditional VC. Many VCs develop symbiotic relationships with angel and seed investors since VCs are interested in a curated pipeline of opportunities and angel or seed investors are looking to see additional capital attracted to their company. Law firms tend to be important avenues into venture firms and are often upstream of the VCs since lawyers are motivated to introduce their best startups clients to VCs to help drive more resources to their firms. It is useful to find creative ways to get to the VC by finding someone who knows someone who has some relation to a VC. A suggestion for the VC pitch is to "be natural" and believe in the idea that is being presented with strong commitment. Communicate the commitment and responsibility of bringing this new space product or service it to the world indicating the wonderful opportunity that is being offered to the sponsor to join in on this journey avoiding the mindset that the meeting is just about "raising money" to fund the entrepreneurial team. The mission is to communicate that here is a chance to change the world, and the honor of the visit and presentation is truly theirs, not the team making the presentation. The VC should see the confidence and value the fact that this unique team is presenting to them a unique and breakthrough concept.

12 The Content of the Pitch

VCs are incented by their limited partners (LPs) to produce outsized returns relative to the alternative uses for which the LPs might invest that capital, so they are expected to lockup their capital for 10 years or more to give the VC the time to realize those returns in the form of acquisitions or the IPO of portfolio companies. Most of what the VC returns will not yield much, but those few home runs that return

10–25 times or more of the capital invested will make or break the business, and the pitch to a VC is to provide a convincing case that this new space startup has the potential to be one of those outliers. There are many ways to structure a pitch, but one is Guy Kawasaki's 10/20/30 Rule of PowerPoint which says that a PowerPoint presentation should have ten slides, last no more than 20 min, and contain no font smaller than 30 points. This rule is applicable for any presentation to reach agreement, for example, raising capital, making a sale, forming a partnership, etc. Ten is the optimal number of slides in a PowerPoint presentation because a normal human being cannot comprehend more than ten concepts in a meeting, and venture capitalists are very normal humans. The ten topics that a venture capitalist cares about are:

1. Problem
2. The solution
3. Business model
4. Underlying magic/technology
5. Marketing and sales
6. Competition
7. Team
8. Projections and milestones
9. Status and timeline
10. Summary and call to action

Of these 10, the focus will be on the 5 pitch essentials which are market size, team, product, go-to- market, and next round planning.

12.1 Target Space Market Sizing

The primary job of this chapter is to show the potential size of the market that is being addressed after painting the picture to show the VC audience that if they invest in the company, and the business is successful in the market, then the business can be big enough to really drive an outsize return to the fund and will it materially allow the VC to accomplish the objectives of his fund. Sometimes it is not obvious how big a market for a new technology or service can be. Thus, one cannot always use the current models as a proxy for market size or make assumptions of what this unique idea could accomplish, and instead one will need to make the case for a much broader line of thinking by considering the effect of adjacent technologies as a way to scale the definition of market size and a way to foresee a much larger addressable market than what might be perceived right now. This may be the single most important exercise that the entire team needs to master. One can also look at the network effect of the new space business and think about the new milieu that is to be addressed. For example, considering that once launch costs drop and regulations are relieved, then the conditions are right for a new space business. Network effects do not exist in every case when addressing an existing market which might be quite large already. In this case, one needs to show how the new space service can address that market and explain the macro trends which are evolving in that market. There is a need to show a clear vision of how the market will develop, and one needs to illustrate as clearly as possible the position of the new space startup's product or service within the market that develops as a result of a new technology. There is a need to rigorously prove the basic assumptions that the space platform, product, or service will become dominant. For a VC firm to take this "one giant leap," they must be convinced that there is a real potential of there being a pot of gold at the end of this space rainbow.

12.2 The Team

The long and the short of it is that the composition and quality of the startup team matter. There is a need to answer the question of why the VC should back this particular team vs waiting for the next set of "space wantrepreneurs" who might pitch the same or similar idea. Ideas about new space products and services are a "dime a dozen," and it is execution which sets the winners apart from the pretenders. At early stages, there is not a lot for a VC to undertake in terms of "due diligence" because so much of the analysis is qualitative, but the team can be examined closely. The pitch needs to talk about the strengths of the CEO and the rest of the team to explain what makes this particular team uniquely qualified to win the space products or services market allowing the VC to learn about the unique set of skills. This chapter should discuss prior accomplishments or experiences relative to the current business that is being pitched and why past success supports the likelihood of success in the current venture. The entire team needs to show the full range of competence including a deep technical understanding of the problem to be solved, coupled with the knowledge of how best to develop the right regulatory, sales, and marketing strategy ("go-to-market") capabilities. This means to show that the team represents ideal founders to back in this space initiative with a short but convincing story as to why this unique team is the best fit to start this company in a competitive market. Doing this requires a combination of skills to tell stories in a compelling way to articulate a vision that is likely to lead employees, customers, and financiers to want to come along for the ride. Think about what skills and advantages the team uniquely possesses that will prove valuable to the ultimate development of the new space business. Once the VCs are convinced of the market scale and the market opportunity to be exploited, it is equally important to sell the team as competent to build the company with the overall competence to succeed. The CEO and key leader for the project must also be effectively sold as well, and there must be a clear explanation as to what makes that person a natural born leader, or learned technology leader, who will cause people to quit their jobs and come work for the startup and cause customers to be willing to buy the products or services, or cause business development partners to want to help to sell the new company's wares and penetrate new markets and cause funding partners to want to provide the capital to do these things. If the main presenter or members of the team are successful repeat entrepreneurs, this is a large help. If this is not the case, then it is important to explain other leadership-like opportunities that are indicative of an executive or charismatic CEO leader. Storytelling skills, that ability to captivate an audience and get them commit to a new enterprise, are a good indicator or potential success in an entrepreneur. True storytelling is a critical talent. Presenting a vision for the opportunity that will make people want to be a part of the company building process will require the same skills that will help to land VC financing partners.

12.3 Product

This chapter is where to present a clear product plan and the data from the market showing how this product is clearly better or cheaper than existing alternatives. It's expected that the product or service plan is likely to pivot in the actual market when there is the ability to test a real product offering against real market needs. A VC wants to be comfortable that the process of evaluating the market needs is robust enough to enable the company to adapt appropriately to changing market demands. This chart should walk them through the thought process, the rigor of the analysis, but also show the ability to adapt to the changing needs of the market while continuing to learn from the product development experience.

12.4 Go-to-Market

In this chapter, there is the critical need to show how the company will acquire customers and that the business model supports profitable customer acquisition. Even if the current funding round does not get meaningfully into the market, it's important to include this aspect in the pitch since it is foundational to the long-run viability of the business. Instead, address things like the plan to build a sales force and the average selling price of the product or services. There is a need to explain how customers will be acquired, i.e., through brand marketing, partnerships and alliances, online interest acquisition, etc. Even if there is not yet a robust financial model at this stage of development, there should at least be a framework that gives a VC a warm feeling and understanding that there is clear thinking around customer acquisition. Walk the VC through the "go-to-market" strategy to show them an understanding of the target audience. As an entrepreneur at an early stage of development, no one expects that all of the precise and correct answers have already been figured out, but there need to at least be theories grounded in reasonable assumptions against which one can apply real-world experience. A hallmark of startup companies is that they often "pivot" which is to change an aspect of the business and try again when the original product or go-to-market did not quite work out the way that was expected. A pivot can be minor or a wholesale change of direction. VCs understand that despite the best intentions, most business go through some set of pivots along the way whether small tweaks or almost complete restarts. At the time of the presentation to the VC, one is not expected to be clairvoyant. It is well-known that things will not materialize as initially forecast. The objective is to demonstrate to the VCs that the team constituting the startup knows in great detail the ins and outs of the space business in a way that shows depth of preparation and conviction. Present a thoughtful engaged discussion on how key conclusions were reached and also be willing to listen to the feedback and incorporate it into future thinking, as appropriate.

12.5 Planning for the Next Round of Fundraising

In the final part of the pitch to VCs, one should clearly articulate the milestones intended to be accomplished with the money to be raised in this round. A VC is likely projecting ahead to the next round of financing to gauge the level of market risk that they are taking by funding the project at this stage. Show that in this round, enough money is being raised to accomplish the milestones set out such that the next investor will be willing to invest new money at a substantially higher valuation (roughly 2X) than the current round. This kind of momentum will be well received by both the current investors and all employees. If the VC firm feels that at the time the milestones are presented there is too much risk, then it is likely for there to be a discussion about raising more capital at the current round. Another option would be to lower the valuation or find other ways to increase the confidence interval around forecasted progress. Every VC knows that they will not be the only investor through the course of the company's life cycle which is why VCs care about the achievability of the milestones that are being presented. They know that they don't want to be or can't be the only capital provider at the next round of financing. Thus they are trying to estimate the risk of the startup they are funding may get stranded at the next round. The bottom line is to convince a VC that the business has a chance to be one of those outsize winners that will make them look like heroes in front of their limited partners (LPs) whose money is, in fact, being invested.

13 Term Sheet Economics

After doing a great job in the pitch to the VC and receiving initial interest, the next step will be to review the term sheet. The term sheet is usually the place where the asymmetry between VCs and founders comes into play the most because VCs have been through the process many times as opposed to the founder who likely has not. The term sheet has two big elements to it – economics and governance. *Economics* includes information on the size of investment, valuation, anti-dilution treatment, liquidation preference, the size of the employee option pool, vesting options, and founder shares. *Governance* deals with who gets a say in what happens in the company. The following is a review of the salient points on the term sheet along with and a few pointers to help with this process.

Usually, the first item defined in the economics section of the term sheet is a description of preferred shares. A benefit of being a C corp is that one can have different classes of shareholders with different rights. A VC will typically purchase Series A preferred shares of the company which are distinct from common shares (which is what the founders and employees typically hold), and they are also different from potential future series of preferred stock (which will be labeled "Series B," "Series C,"etc.). The reason for creating a new class of stock is to give it "preferred" economic and governance rights relative to those enjoyed by the common shareholder.

The section on aggregate proceeds will describe how much will be invested for what percentage ownership of the company, and it will also specify that any debt outstanding in connection with this investment of notes which will convert into equity under the terms of this financing. Notes (i.e., debt) are senior to equity so if a VC invests, they do not want other monies to be ahead of them in the event of a potential liquidation. This forces all notes to convert into equity in this round ensuring that everyone is in the same position with respect to the distribution of proceeds in the event of an exit.

Convertible debt is often raised at the seed stage for cost and simplicity reasons allowing both the entrepreneur and the seed investor to defer (until the Series A) on the question of valuation at this early stage of company development. Standard convertible debt documentation is pretty simple and don't require much legal time and expense. In its most basic form, the debt converts into equity at the same price at which the Series A investors purchase equity and is referred to as an "uncapped" note meaning that the valuation at which the note converts is not restricted and will be determined based upon the Series A equity price – this is not generally sought after by investors because they are taking on additional early risk yet receiving the same reward and the Series A investor. Because of this, most convertible debt is "capped" to establish a ceiling on the maximum price at which debt will convert into equity and a conversion discount (with or without a cap), so the cap sets a valuation limit for the debt to convert to equity. A conversion discount simply provides the note holder with a fixed conversion discount relative to the established Series A financing valuation wherever it may end up, and typically, this is employed up to the point where the cap comes into bear. Convertible debt financings can have multiple rolling closings, whereas an equity financing typically has only one. One word of caution is to be very careful of how much debt is raised in this manner since the long-term consequences of the founders' percentage ownership at Series A can lead to a situation where one can end up with less control than thought. The key is to ensure that all interests concerned stay aligned with the company's success. Be mindful as an entrepreneur and founder of the constant tradeoff between raising the capital needed to grow the business and minimizing the dilution of the shareholdings owned by the founders and other employees and early investors who are along for the journey. Thus it is important to be clear on the impact of every VC dollar on the existing crew of people involved.

The term sheet also says important things about what the market is willing to pay for the investment. First is the "post-money" valuation which is the valuation of the company once the VC has invested their money. The "pre-money" valuation is the valuation before the investment is made. Pre-money + amount invested = post-money, so if an investor offers \$1M and the post-money is \$5M, then they own 20%. Post-money valuation has two key elements. Any shares that convert as a result of prior convertible debt have to be included in this valuation. Debt gets taken into account as part of the valuation the VC is willing to pay, and this often provides full accounting of how much dilution has been created. Valuation also includes employee option pool because when all shares are added up, they cannot exceed the post-money valuation

When performing valuation, the comparable company analysis method requires that other publicly traded comparable companies are found whose valuations and financial metrics are publicly known that resemble the space startup. The object is to establish a reasonable value by looking at how those companies are valued as a function of certain financial metrics such as multiples of revenue. This analysis is hard when applied to a space startup which is quite often unique, and the ability to forecast revenue is unpredictable or at least quite difficult.

Over the long run, the value of a space company equals the present value of future cash flows. Whatever annual cash a company can generate in the future, if one discounts that cash to present-day values, an investor should be willing to pay no more than the current value of that future cash stream. The problem with this for a new space company is that it requires that one build out a financial forecast for their company estimating annual cash flow into the future and then discounting that back to the present day using a "discount rate" which is a way of saying the opportunity cost for a company's investments. Of course, this analysis makes good sense for mature companies with predictable future results based on past financial performance, but for early-stage companies, particularly early-stage space companies, this is a huge challenge.

The predominant question is how does an early-stage space startup company determine its valuation? The answer is found in a simple conceptual analysis since for very early-stage companies, there are no real financial metrics with which to value a company. There is a need to ask what would need to happen for a certain level of valuation to be achieved and justified or what would have to go right with the business for that to happen? Is the market size big enough to support a company with a certain level of revenue and what are all of the things that could cause the company to fail and how does one assess the probability of each of those nodes on the decision tree toward success or failure? As startups get more mature and have financial statements that are more reliable, later-stage venture capital deals will adopt more traditional metrics such as looking what has to happen to receive a 10X ROI from a sale or for the company to trade at a certain metric over revenue.

It should be noted that the valuation of a company includes the unallocated employee option pool ownership which is not diluted by adding this later but should be sufficient to handle the expected employee hiring until the next round of financing. The CEO should generate a head count growth plan for the next 12–18 months and estimate how much stock is required to grant those planned hires while keeping the pool as small as possible so that the current rounds don't dilute the company while the VC firm will want it as large as possible, so future hires don't dilute them after they invest.

The term sheet will also address the unlikely event that the board decides to pay a dividend to preferred shareholders (investors)before common shareholders (founders and employees), and this section of the term sheet specifies the amount in order to prevent founders from "dividending" out money to themselves at the expense of the preferred shareholders. Thus, if founders want to pillage cash, they have to pay the VCs first.

The liquidation preference section specifies who gets their money back under certain circumstances called liquidation events (company is sold or wound down). Liquidation preferences can be structured as some factor of the original investment the investor received back first but no more. For most startups, they are never taken over 1x. However, when a company is at a later stage of investment, an investor may request more than a 1x preference since they are entering later into the growth cycle and their chance to grow to a point where its value is some greater multiple of the valuation paid in the financing round. "Nonparticipating" means that the investor gets a choice to take liquidation preferences or convert preferred shares into common shares and take the equity value of her percentage ownership of the company. "Participating" means that not only does the investor get their original investment back, but they can also convert shares into common and participate in any leftover proceeds as with any other shareholder.

Redemption rights address the fact that the whole idea of seeking investment is so that it can become permanent capital upon which the company can be built, so an early-stage space startup should not entertain discussion of redemption nor allow the investor to give back stock in order to get their money back. An investor looking to exercise their redemption rights would put the company in dire financial situation so it simply must be stipulated that the investment is not redeemable. Given that the whole idea of raising capital is to keep it permanently to build the company, redemption would allow an investor to give back their stock in exchange for getting their money back and most likely any redemption rights, if granted, would come into play at the worst time possible for the company. In fact, most state laws restrict the ability of investors to exercise their redemption rights if doing so would put the company in a dire financial situation, so the suggestion would be to keep things simple by just stating that the investment is not in fact redeemable.

A section on Conversion/Auto-Conversion addresses investors who obtained preferred shares and at some point may want to (or the founders may want them to) convert into common shares since preferred has so many more rights over common. Often to go public, the capital structure of the company is cleaned up to bring everyone to common stock. On the IPO, it is possible to have "dual class" stock with high voting class and lower voting class, but preferred shares need to go away at the time of IPO. VCs will want to be sure that an IPO is of sufficient size relative to their initial investment to ensure trading liquidity so they can sell their shares into the public market. An IPO conversion term indicates that the IPO will be of a certain minimum size to avoid a low-trading volume small-cap stock where any appreciable effort to sell shares would result in a deflation in stock pricing. Most companies sell between 10% and 20% of the company at IPO, and minimum IPO thresholds will increase with later financing rounds. Another variety of autoconvert is to put in place a specific price per share or ROI threshold to force conversion. In the case of a voluntary conversion, a vote of the majority of the preferred stock is another way to convert preferred into common.

The anti-dilution protection provides some element of safety in the event that the company raises money in a "down round" which is at a valuation below that at which an investor invested which is highly dilutive to everyone's ownership stake. A broad-based weighted average as an intermediate form of anti-dilution protection is often used, but a "full ratchet" protects the VC from getting diluted at all by a down round of financing, but the founders and employees will not have such protection and will be diluted on their end. The more VCs get anti-dilution protection, the more diluted common shareholders can get as well.

Lastly, the term sheet addresses voting rights where each share of both common and preferred has only one vote. Some companies will have different classes of shares with different voting rights when they go public but rarely if ever when they are still private. Founders like to have a high vote stock that applies to their shares only so they keep enough voting power to control any actions, and one could stipulate that founders have 10X the voting rights, but this has not been implemented, and some founders will ask investors to enter a "voting proxy" where their voting rights go to the founders.

14 Term Sheet Governance

Governance is an important topic in the term sheet because it basically defines who gets a say in what happens in the company. Board composition is critical since it will vote on major corporate actions such as raising money and choosing the CEO and M&A decisions. Protective provisions determine what corporate actions the preferred shareholders get to have a say in as these serve as checks to the CEO's ability to take corporate actions as well as understanding auto convert, drag along, and voting structure. The key role of the board of directors is the hiring and firing of the CEO and is typically composed of an odd number of people to avoid deadlock. Series A preferred will appoint one board member as well as the major investor in an early-stage financing. The "lead" investor drives the negotiation of the term sheet with the CEO and typically invests half of the total amount of the round and will likely be the board representative for that set of preferred investors. The **second** seat is reserved for the common shareholders and designated to be the CEO. Sometimes the founding CEO asks to have the board seat designated to them directly. This could lead to the founder remaining a board member even after being removed as CEO so it is probably best if a board seat remains with the founder as long as they remain CEO but that they lose the seat when the position is lost or resigned from. The **third** seat is reserved for an independent person not affiliated with the company as an investor or officer and must be approved by two other board directors.

The term sheet sets the rules for the vesting of both employees and founder shares where a standard approach is for 25% of employee stock to vest 1-year anniversary of their hire ("1-year cliff vest"), and the remaining 75% vests in equal monthly increments over the next 3 years. Double-trigger acceleration has two triggers to the founder getting their acceleration. The first trigger is the acquisition itself, and the second trigger is the founder getting terminated by the acquirer other than for cause or good reason. This allows the acquirer to retain the founder without having to worry about options automatically vesting. If the acquirer doesn't want to retain the founder, then it's fair for their shares to vest on an accelerated basis.

From signing the term sheet to closing the investment typically takes 2 weeks to a month. The "no-shop" is a 30-day period in which the company is tied up preventing the disclosure of the term sheet to other parties or to pursue a deal with somebody else. When negotiating a term sheet, the space CEO must be forward thinking about what might be agreed to in the current term sheet as it will have implications for subsequent financings.

15 The Art of the Exit

It is said that one should always enter any endeavor seeing the end in the beginning. After one has mastered the many struggles of creating a space startup, the point will arrive where it is key to think about options to transition or exit the investor ownership structure or business profitably. Venture- financed space companies typically exit through being acquired by another company or by going public and holding an initial public offering (IPO). Whereas the company itself enters a new chapter of its life as a public company, the early investors typically exit their ownership positions in the company after having grown the equity value of their initial investment and thus providing a return capital to their LPs.

16 Creating a New Space Corporation

It is interesting to note the ratio of acquisitions to initial public offerings (IPOs) today has gone down so that the overall market is now seeing about 80% of exits coming via acquisition, but before the dot-com adjustment that occurred around the year 2000, the ratio had been at 50%. Every space startup should be planned to be acquired from day 1 and every day after that by building business development partnerships with companies that might have existing sales channels into some of the markets that the company is planning to enter since these relationships can often lead to acquisition offers. What is key here is that in order to have the option to be acquired, the company needs to be intentionally nurturing these relationships and considering some key issues. Although price is an important consideration, often the acquirer will propose to exchange its shares for the shares of the acquired company, and such a deal should only be considered after having a careful professional valuation analysis performed on the acquirer's stock, and any space company should consider requesting price protection for what could be a lengthy due diligence period in the event that the acquirer's stock exceeds an upper or lower bound as an insurance policy. Liquidity of the stock is also key – a publicly traded stock can be sold immediately, but sometimes the acquisition stock can take some time before it can be sold. Another element of being acquired is to look at how employee options are affected by the acquisition. Unvested options could be eliminated by the acquirer or replaced by new options and new terms or even accelerated. Typically, special equity grants are made available to retain key employees, and a closing condition may require that some percentage of key employees need to stay on. There may also be closing conditions regarding voting approvals that the seller is required to get with the threshold being set by the acquire such as requesting that at least 90% of the shareholders vote in favor of a deal to reduce the potential for some to seek legal redress. Also, usually 10–15% of the purchase price is placed in escrow to cover potential surprises over representations, litigation for actions pre-closing, and any ownership or IP claims some 12–18 months after the deal closes. Also, indemnification protects the buyer from claims that may arise post-closing. There will also likely be a request for an exclusivity period which will prevent shopping the term sheet with other investors or soliciting their interest for a period of time typically 30–60 days (determined as required by the due diligence and legal documentation period).

The second major form of exit for venture-backed space companies is the IPO which on average today has risen to take about 10 years and typically occurs for any number of reasons. The first and most obvious is to raise capital beyond what might be expected to be raised from private space investment markets, but in recent years, those markets have stepped up to larger investments in some cases. IPOs can also help a space company get recognized as having a higher profile, hopefully driving business. Such an offering also represents a liquidity event whereby employees can sell stock in the company once shares are registered. Human nature also dictates that being a public company can help customers feel more comfortable in dealing with a space company, and going public also makes it much easier to make acquisitions to keep a company's innovations stream fresh perhaps by using publicly valued and traded stock as part of the transaction.

Going public is no different for a space company than any other, and there are plenty of investment banks (underwriters) that can be considered based on several factors. First, one should choose a bank with the appropriate domain experience in the space industry considering the research analysts that will interact with and help educate institutional investors who will perform follow-up research. Another key element to look for is the strength of their ability to place the resulting founding stock with institutional investors to create the proper trading environment. The biggest effort will be to work with lead and co-underwriters to create the prospectus to provide all relevant disclosures to potential investors detailing the risk that they agree to take on by buying the stock. It is key to accurately portray the risk to avoid the potential of a class action lawsuit from investors who relied on this data when agreeing to invest.

As a new space company, revenues will be less than $1B and therefore qualify as an emerging growth company (ECG) which can help to streamline this process. In fact, ECGs offer a range of other benefits such as being able to meet with accredited investors to get feedback ahead of an IPO road show to give them more time to evaluate the opportunity to invest. The ECG allows one to file the initial prospectus confidentially and provides for lighter regulatory requirements (such as only 2 years of financial history) and disclosure requirements in the prospectus and after the IPO. The net result is that qualifying as an ECG as defined in the US Jobs Act of 2012 made it less burdensome to become a public company. In any case, once the prospectus is complete, the road show presentations will begin, and the underwriters of the offering will try to get an idea of how much demand there will be at different prices so they can determine how many shares to sell and what the initial selling price will be. Once the SEC declares the prospectus effective, the underwriter can start the public trading of the stock. Investors are generally required to execute a lockup agreement to restrict their ability to sell stock for the first 6 months post-IPO and even after that to set time intervals over which officers and directors can trade to allow for price stabilization. Two last points to consider are how one handles VCs who want to exit after the IPO and employees who may have just experienced a significant personal liquidity event. The concept of a secondary offering of shares can be an orderly and disciplined way to allow a VC to exit placing their shares in friendly institutional hands. Dealing with newly minted employees will give rise to separate questions such as the true focus of the acquired employees and their dedication to the mission of the new created entity as well as how they feel they will be are able and willing to continue to contribute. If a space startup is among the very few that successfully crosses over into a public entity, then the results will include both huge rewards and significant challenges. It is hoped that this chapter has at least begun to outline a means of navigating this opportunity.

17 Developing Patient Capital Investment for New, Longer Range, and Highly Capitalized Space Ventures

Other solutions to the patient capital or longer-term return investors must be considered as well. Many have tried to solve this problem in order to fund new space, and a possible model is publicly traded, pass-through shares (PTSs) which are used in some countries to help their mining industry. Mining horizons are similar to space in many regards in that they can take 10–12 years from exploration to mature exploitation. This structure allows all losses to be deducted from the income taxes all through the long development period. One could envision the creation of PTSs to support the development of space infrastructures where investors get trading liquidity and one could use multiple years of early loses to shield current taxable income.

Also, intergovernmental organizations (IGOs) have been used so all countries of the world could participate in building the space systems required to transmit signals across the ocean which was too big of an investment for any one country to take on. This effort resulted in the creation of Intelsat to provide communication to the ground and Inmarsat to provide communication services to ships on the ocean in a manner such that every country that wanted to join could do so by delegating a signatory to the IGO. The US created COMSAT as its signatory, while most countries used their public monopoly Telcos as theirs. Once in place, they raised billions of dollars to fund a fleet of satellites, and for many years, they were a monopoly where each country paid based on their use and most dividends were reinvested. This model worked very well to get this segment moving, and then in the 1990s, PanAmSat and SES sought to privatize the industry, and now, there are a multitude of private- as well as state-sponsored satellite communication companies in operation. This laid out a path to bridge from a worldwide intergovernmental organization (IGO) to a worldwide private industry with competitive systems that now realize hundreds of billions of dollars in revenues from providing services. One might foresee that today the same thing could be done in forming space IGOs (SIGOs) where national signatories' own shares would be commercially run but remain during this startup phase as a nonprofit entity with national investments based on historical utilization percentages or resulting services just like Intelsat and Inmarsat operated before privatization. Another model that has been proposed is the creation of a "Fannie Mae" for space which would allow long-term mortgages associated with the financing of such activities as small satellite constellations where there would be an implied government guarantee behind them. This created a vibrant mortgage market and could be applied to create an infrastructure finance market in space. Yet another approach would be to support a service fee model which could create a universal space service fee (USSF) applied to all commerce that occurs in, from, and to space to help cover the government's part of any P3 for space. Although this might in some cases burden the users, it could if properly designed create an overall benefit.

The last model might involve the creation of an Outer Space Private Investment Corp (OSPIC) like the Overseas Private Investment Corporation (OPIC) which is the US government's development finance institution mobilizing private capital to help solve critical development challenges and in doing so advancing the foreign policy of the USA and national security objectives. It would be hoped that OSPIC could find an effective way to work with US private sector to help US space businesses gain footholds in emerging markets, catalyzing revenues, jobs, and growth opportunities both at home and abroad. An OSPIC could achieve its mission by providing space investors with financing, political risk insurance, and support for private equity investment funds when commercial funding cannot be obtained elsewhere for a worthy space project. Such a fund needs to be set up so investors would be willing to wait 10–20 years for a profitable return. This model has been a huge success in over 100 countries where OPIC makes profits that go back to the treasury. As an agency of the US government established in 1971, it now operates on a self-sustaining basis at no net cost to the American taxpayer as part of the US Development Finance Corp (DFC). The discussion has been to just replace overseas with "outer space" (or space) and create a stand-alone OSPIC entity making space new "emerging market." By changing "overseas" to "space," it would be possible for new space ventures to be treated as a developing market with tremendous potential. It would also be hoped that other countries would follow suit. Thus OSPIC could be foreseen as carrying the following charter for space development for any country:

The Outer Space Private Investment Corporation (OSPIC) is a self-sustaining government agency that helps national businesses invest in emerging space markets providing businesses with the tools to manage the risks associated with space investment, fostering economic development in space markets, and advancing national foreign policy and national security priorities. OSPIC helps national businesses gain footholds in new space markets, catalyzes new revenues, and contributes to jobs and growth opportunities both at home and abroad. OSPIC fulfills its mission by providing space businesses with financing, political risk insurance, and advocacy and by partnering with private equity investment fund managers.

Another interesting example that is currently being discussed is the International Lunar Development Authority (ILDA) under design by Michael Castle Miller and the NSS Policy Committee. This model goes past the IGO model, and it would not only share the cost of developing new space systems or infrastructure but create a virtuous cycle that keeps building on the value that is developed to bring more and more capital. The key principles are that numerous countries (40 or more) and commercial companies capitalize ILDA as shareholders with the USA as lead and lunar land rental prices are set by auction, plus utilization fees operating for profit to reinvest in common cislunar infrastructure. The benefits of this approach are that this would align profit incentive with public good and allow for higher returns on investment rather than by relying upon infrastructure usage alone to allow for development financing without land ownership. This prevents the occurrence of the "tragedy of the commons" which is a situation in a shared resource system where individual users, acting independently according to their own self-interest, behave contrary to the common good of all users by depleting or spoiling the shared resource through their collective action.

The space debris problem is an example of this. The idea would be to have a commons with shared infrastructure that everyone helps to pay for and improve by having a large consortium create this authority that would be made up of nations, space agencies, corporations, and wealthy individuals. They would all be in a public benefit corporation model that would seek to run the settlement to create profits to support the common infrastructure by having auctions to lease parcels of land near the common infrastructure where the highest bidder gets to use it on a non-interference basis to do their lunar mining, establish a power plant, communications node, etc. Over time they will add value to their land, and the commons increase in value which will make the whole more valuable drawing in more investors to develop more parcels of land. Having this global consortium providing a long-term lease and giving the exclusive right to operate on this properly for a long period of time establishes that they are giving their collective approval and that they have all agreed to do this. Corporate governance of this lunar authority model structure is still in development and must still be figured out as well as the need to operate on a noninterference basis.

Lastly, one should not forget about the power of prizes and challenges. When a bold challenge like the X-prize is put out there, it excites human nature resulting in a lot of response. If this works for small prizes of $1M or less, one might envision that significant additional investment would be attracted if larger prizes like the Google Lunar X Prize or the Bigelow challenge were to be offered by governments at truly large levels, then truly exciting space initiatives might be accomplished, but clearly, it would be very hard to get this appropriated through a national legislature.

This chapter has hopefully provided the macro vision of the challenge of space finance and both the need to solve the patient equity problem to get to new space industry investment and a few concepts and new structures which could collectively be worked upon to get there. Although the ideas presented to this point are new, they are powerful and will be needed to really help take the next giant leap.

18 Conclusion

This chapter has aimed to provide some information about financing options related to new space entities in order to help promote the growth and expansion of new space industries. Choosing the right finance model and executing it with the right finance partners will be key to success. There are many approaches that might be taken for starting new space ventures starting from the most basic which can begin with angel investors, friends and family, and even crowdsourcing websites such as "Kickstarter" to capitalization through venture capital (VC) funds that lead to formation of corporations, often leading to acquisition or initial public offerings (IPOs). There are also other longer-term major new space initiatives that may be developed to enable the very large capitalizations which may be needed. These types of multibillion dollar projects may require new forms of public-private financing, and some of these longer-term and visionary approaches have also been addressed. There is no question that the future of space financing is best described by the Latin proverb "audentes Fortuna iuvat" which means "fortune favors the bold." For the future of space finance to keep up with the technical potential, bold new sources of space finance will be required. It is hoped that this chapter has provided some illumination on the road ahead while opening up thought channels for future space finance entrepreneurs to pursue and expand.

19 Cross-References

- ► Deorbit Requirements and Adoption of New End-of-Life Standards
- ► Financial Models and Economic Analysis for Small Satellite Systems
- ► Legal Issues Related to the Future Advent of Small Satellite Constellations
- ► Long-Term Sustainability of Space and Sustainability Requirements
- ► Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ► Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ► "Rules of the Road" for Launch and Operation of Small Satellites and Related Issues

▶ Small Satellites and Their Challenges to Space Situational Awareness (SSA) and Space Traffic Management (STM)
▶ Small Satellites Market Growth Patterns and Related Technologies
▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit

Acknowledgments Lastly, this acknowledges the direct and indirect contributions to this chapter based on conversations with Hoyt Davidson of Near Earth LLC who has been promoting the expansion of capital into space finance for many years as well as references with consent from Scott Kupor (managing partner, Andreessen Horowitz) from his book *Secrets of Sand Hill Road: Venture Capital and How to Get It* by **Scott Kupor** and Eric Ries who have pioneered the effort to democratize access to venture capital to great numbers of entrepreneurs to enable economic growth and the realization of the dreams of more and more startups. Also, the tireless efforts of the New York Space Alliance should be mentioned as they labor to help lobby for and advance many of the new investment vehicles called out in this chapter particularly with regard to crossing the chasm of new space investment into the private equity community so that space can access the immense capital that will be needed to bring about these many visions. Through their investment community advocacy, a broadened understanding of the potential is being appreciated and recognized among traditional investors.

References

S. Kupor, *Secrets of Sand Hill Road: Venture Capital and How to Get It* (Penguin Random House, New York, 2019)
The New Yorker, June 17, 1991

Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations

Audrey L. Allison

Contents

Abstract

Like their larger counterparts, small satellites require assured access to radio-frequency (RF) electromagnetic spectrum from their orbital positions to support their operations and to fulfill their missions. This mission requirement applies equally to the smallest nanosatellites or picosatellites launched by academic institutions for research to the relatively small commercial satellites that are increasingly being launched into non-geostationary orbit into very large – or "mega" – constellations to provide telecommunications services. While not perhaps the first item contemplated by a designer of small satellite missions, assured access to the invisible natural resource of RF spectrum from space can prove to be a critical and long lead item, and the wise prospective operator plans accordingly. Use of RF spectrum, even from space, is a heavily regulated, highly

---

A. L. Allison (✉)
International Space University, Strasbourg, France

The Boeing Company, Arlington, VA, USA
e-mail: Audrey.allison@boeing.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_71

competitive, and increasingly congested necessary resource. Obtaining assured access to RF spectrum is often a high-risk, complex, and time-consuming task.

This chapter will briefly describe the evolving legal and regulatory regimes that face small satellite operators in terms of RF spectrum and associated orbits and will highlight recently adopted treaty provisions by the International Telecommunication Union's (ITU) 2019 World Radiocommunication Conference (WRC-19). These actions range from streamlining the regulatory requirements to facilitate entry of a broader range of operators of the smallest satellites, such as those launched by academic and other nonprofit institutions, to adding an entirely new regulatory approach for managing the small satellites that comprise emerging large constellations in non-geostationary satellite orbit to provide commercial telecommunications services.

Keywords

Federal Communications Commission (FCC) · International Telecommunication Union (ITU) · ITU Radiocommunication Sector (ITU-R) · Radiocommunication Bureau · Radio frequency (RF) spectrum · Master International Frequency Register (MIFR) · Radio Regulations (RR) · Radio Regulations Board (RRB) · 2015 World Radiocommunication Conference (WRC-15) · 2019 World Radiocommunication Conference (WRC-19) (20 max.)

1 Introduction

To ensure mission success, one of the many requirements of a successful satellite operation is assured access to radio-frequency (RF) spectrum from the satellite's position in space. Satellites utilize spectrum for communications with the earth (and potentially other satellites) for mission-essential purposes, such as telemetry, command and control, station keeping, payload communications, and scientific observations. Assured access means that the satellite will be able to reliably complete its radiocommunication links for the lifetime of its planned operation, free from radio interference that seriously degrades the performance of the link. While being able to confidently expect to have its operations protected from harmful interference, the satellite operator has the reciprocal obligation to ensure that its own operations do not cause such harmful interference to any other operator who possesses superior rights to use of that spectrum at that location. Obtaining rights for assured spectrum access as well as the relative responsibilities relating to spectrum use is the subject of a series of interlocking national and international regulations, as well as coordination agreements among states and operators of potentially affected systems. Knowledge of this complex web of regulations is essential for satellite system designers and operators, including operators of satellites both large and small.

This chapter briefly describes the evolving radio regulatory landscape for small satellite operators from the smallest CubeSats to those that are part of mega-LEO commercial constellations.

2 Regulation of Small Satellites: Radio-Frequency and Orbital Resources

Albeit invisible, radio-frequency spectrum is a sovereign natural resource, and its use within the territory of a nation-state is subject to regulation by that nation. A national government typically requires a license for transmission of radio waves within its territory and has laws and regulations setting technical and operational limits for such operations, such as allowable frequencies and bandwidths, power limits, antenna, and emission types, to ensure interference-free operations for other authorized operators in that territory. This requirement applies to everything from FM radio and television broadcasting stations, to mobile phone services, to fixed microwave systems, and to satellite space and earth station operators. Moreover, there are likely further regulations concerning the categories of services which may be offered using spectrum in particular frequency ranges, as well as numerous other requirements to advance national policies of a nontechnical nature.

National regulators need to be confident that the radio systems they authorize are able to operate free from harmful interference from other authorized radio operations, including the operations of other nations (a requirement of the International Telecommunication Union's Constitution and Radio Regulations). Many nations have bilateral agreements with their neighbors to this end, but that alone would not suffice to address all sources of potential radio interference. Some radio operations are inherently international, such as maritime, aviation, and space operations, and thus require a broader approach. Accordingly, multilateral mechanisms of cooperation and regulation have been developed to assure interference-free operation of radio stations within and without national territories.

The International Telecommunication Union (ITU) is an intergovernmental organization founded in 1865, originally as the International Telegraph Union, to facilitate the interconnection of telecommunications systems across national borders. Today, it performs a broad range of tasks to advance and promote the extension of all forms of telecommunications, including satellite-delivered communications, to the world's populace. As radio-based services began operating in the dawn of the twentieth century, the need swiftly arose for management of destructive radio interference to domestic services through national regulation of radio use and international cooperation. This led to the adoption of national radio regulatory regimes and ultimately to the creation of the International Radiotelegraph Union in 1906, which merged with the ITU in 1932, and became part of the United Nations (UN) system in 1947 following World War II. As space technologies developed in the 1960s, the ITU's remit expanded to address the management of radio stations in space to encourage deployment of new space-based services by managing interference to and from space-based stations (and their earth stations), to provide international recognition to space-based operations, and to ensure equitable access to spectrum and orbital resources for all countries.

As satellites operate beyond national territories in outer space, their operations are also subject to the broader outer space legal framework arising out of the 1967 Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer

Space, including the Moon and other celestial bodies (the "Outer Space Treaty") which codified the principles that outer space is the province of all mankind and that it shall be free for exploration and use by all countries on a basis of equality and in accordance with international law; and it is not subject to national appropriation by means of use or exclusive occupancy. The Outer Space Treaty, together with the other UN outer space treaties of that era, established that activities in outer space are to be carried out by state parties who bear international responsibility and liability for their actions there, including activities by the nongovernmental entities that they authorize. Activities of such nongovernment entities require continuing supervision by the authorizing state (United Nations 2002).

The ITU fulfills the international legal mandates of the outer space treaties through periodic conferences of its Member States which promulgate international law in the form of a Constitution, Convention, and Radio Regulations (RR). The ITU's Radiocommunication Bureau carries out processes for rationalizing the use of radio-frequency spectrum and orbits. These activities directly advance the non-appropriation and free exploration principles of the Outer Space Treaty.

Under the ITU's Radio Regulations, Member States are required to license the transmitting radio stations of satellite operators and represent them (including "nongovernment entities") as "notifying administrations" in the ITU's regulatory processes. The ITU's Constitution requires that "[a]ll stations, whatever their purpose, must be established and operated in such a manner as not to cause harmful interference to the radio services or communications of other Member States or of recognized operating agencies, or of other duly authorized operating agencies which carry on a radio service, and which operate in accordance with the provisions of the Radio Regulations" (ITU Basic Collection of Texts 2019a, p. 50, Art. 45). In cases of harmful interference, Member States must "exercise the utmost goodwill and mutual assistance . . . to the settlement of problems of harmful interference [and] Administrations shall cooperate in the detection and elimination of harmful interference" (ITU Radio Regulations Vol. 1 2016, p. 237, Nos. 15.22, 15.25).

The ITU's Constitution also extends "equitable access" to the electromagnetic spectrum and associated orbital resources by all countries:

> Member States shall endeavour to limit the number of frequencies and the spectrum used to the minimum essential to provide in a satisfactory manner the necessary services. To that end, they shall endeavour to apply the latest technical advances as soon as possible.
>
> In using frequency bands for radio services, Member States shall bear in mind that radio frequencies and any associated orbits, including the geostationary-satellite orbit, are limited natural resources and that they must be used rationally, efficiently and economically, in conformity with the provisions of the Radio Regulations, so that countries or groups of countries may have equitable access to those orbits and frequencies, taking into account the special needs of the developing countries and the geographical situation of particular countries. (ITU Collection of Basic Texts, p. 49 Art. 44)

The above general legal framework applies to all satellite operators, no matter whether they are tiny CubeSats or large communications satellites operating in geostationary orbit. However, as small satellites have proliferated, the applicability of some of the elements of these legal regimes and processes that were originally designed for larger geostationary satellites have become increasingly criticized as being overly burdensome and unworkable for the operators of the smallest satellites, particularly for noncommercial entities, with disproportionate impact on developing countries who may be embarking on their first space-faring activities. As a result, greater numbers of spacecraft are being launched into orbit outside of the Radio Regulations process and therefore lacking the protections afforded by regulatory status, ultimately contributing to increasing risk of unsustainability of the low Earth orbit.

3 Streamlined Procedures for Small Satellites with Short-Duration Missions

In light of the legal requirements for use of radiofrequencies in outer space, satellite operators must seek authorization, usually in the form of a space station license, from a national regulator in advance of their launch. An operator will select radiofrequencies, usually from existing satellite spectrum allocations, based on its mission requirements, the technical parameters of its spacecraft, and local regulatory requirements. Small satellites intended for commercial communications projects as part of non-geostationary satellite constellations typically have very different requirements than small satellites for research projects or scientific missions. One defining difference between the two types of missions is the length of the mission. Commercial satellite projects generally extend much longer than 3 years and have an expectation of replenishing their constellations with new satellites following their end of life. Another difference is that the commercial small satellites operate in the radio frequency allocations typically used to provide communications services – mobile-satellite service (MSS), fixed-satellite service (FSS), or broadcast-satellite service (BSS); are usually subject to coordination requirements of ITU Radio Regulations (RR) Article 9; and tend to have a greater impact on the overall spectrum environment.

For small satellite operators of short-duration missions, there are a wide range of frequency bands that are allocated, or agreed by regulators to be prioritized for satellite use, that may be used to support such operations, including the earth exploration-satellite service, meteorological-satellite service, space research satellite service, amateur-satellite service, and space operation service. Typical frequency bands downlinks and uplinks include 137–138 MHz, 144–146 MHz, 148–150.05 MHz, 399.9–400.05 MHz, 401–403 MHz, 435–438 MHz, 449.75–450.25 MHz, 460–470 MHz, 902–928 MHz, 2020–2025 MHz, 2025–2110 MHz, 2390–2400 MHz, 2400–2450 MHz, 5830–5850 MHz, 8025–8400 MHz, and 25.5–27 GHz (FCC Small Satellites Notice 2018, at p. 4161, para.18).

In the United States, for example, the Federal Communications Commission (FCC) has been authorizing small satellite operators by three methods: as commercial satellite operations under Part 25 of its regulations (with long processing times and very high filing fees); as experimental operations (limited to short-term, noncommercial operations with no regulatory status); and as amateur satellite operations (noncommercial operations for limited purposes). In 2019, in an effort to support and encourage innovation and deployment of small satellites with short-duration missions, the FCC adopted streamlined licensing procedures for qualifying small satellites featuring a simplified application form, faster processing times, and lower application fees (US $30,000). To qualify for these streamlined procedures, the proposed operation must satisfy a long list of criteria:

- Ten or fewer satellites under a single license
- Maximum in-orbit lifetime of any individual satellite is 6 years, including deorbit time
- All operations completed within 6 years.
- Maximum mass of any individual satellite will be 180 kg, including propellant.
- Deployment below 600 km altitude unless have capability to perform collision avoidance and de-orbit maneuvers using propulsion.
- Satellite(s) will release no planned debris.
- Satellite operator has assessed and limited the probability of debris being generated due to an accidental explosion resulting from the conversion of energy sources on board the satellite into energy that fragments the spacecraft.
- Probability of in-orbit collision between any satellite and large objects is 0.001 or less as calculated using current NASA software or other higher fidelity model.
- Any individual satellite is 10 cm or larger in its smallest dimension.
- Satellite(s) will have a unique telemetry marker.
- Probability of casualty resulting from uncontrolled atmospheric re-entry of any satellite is zero, as calculated using current NASA software or other higher fidelity model.
- Licensees must have the capability to eliminate harmful interference when necessary . . . [and] satellites must have the capability for immediate cessation of emissions on telecommand.
- Radiofrequency operations will be compatible with existing operations in the requested frequency bands and not materially constrain future operations of other satellites in those frequency bands. (FCC Small Satellites Order 2019, p. 8, para. 19)

In designing these streamlined national processing rules, the Commission deliberately limited the class of eligible small satellite operators to those with short-duration missions (1–3 years) and not requiring “full-time, uninterrupted availability of assigned spectrum” as compared to small satellites comprising “traditional” large commercial non-geostationary MSS constellations such as Iridium or the proposed new FSS constellations such as OneWeb and Starlink (FCC Small Satellites Notice 2018, at 4154, para. 4).

In addition to obtaining an authorization from its national regulator, small satellite operators are required to act through its administration to notify their planned use with the ITU’s Radiocommunication Bureau, a 7-year long process set forth in RR Articles 9 and 11. Application of the ITU coordination and notification procedure is required if the proposed satellite operation is capable of causing harmful interference, is planned to be used for international radiocommunication, is subject to the coordination procedure of Article 9 or if it is seeking international recognition for protection from harmful interference.

The ITU's coordination and notification procedure generally applies to all satellites, large and small, geostationary and non-geostationary, that will operate in frequency bands that are not subject to a priori plans (where spectrum/orbital resources are reserved for use by administrations to ensure equitable access). These "first come-first served" procedures for spectrum not set aside under the plans include advance publication, coordination, and notification. Acting on behalf of the satellite operators, notifying administrations electronically submit filings to the Bureau containing general and system characteristics as required by RR Appendix 4 which are then published by the Bureau for review by administrations and other operators for potential impact on planned or existing systems. Successful completion of the procedure, including coordination and payment of ITU cost recovery fees, results in international recognition of the satellite network or system via recording of the assignment in the Master International Frequency Register (Master Register). There are defined regulatory deadlines for each of these steps in the process. The ultimate deadline is that the frequency assignments must be "brought into use" by the end of the 7-year regulatory time period, which begins when the advance publication information is received by the Bureau. Failure to meet the regulatory deadline results in cancellation of the assignment and thus loss of regulatory status of the operation.

These procedures are subject to improvement and updating every 3–4 years by World Radiocommunication Conferences (WRC) convened by the ITU. WRCs may adopt or amend the Radio Regulations in response to proposals of Member States which are typically informed by the results of studies performed by the ITU Radiocommunication Study Groups, the recommendations of the ITU's Radiocommunication Bureau and Radio Regulation Board (RRB), and the input from the national regulators and satellite operators.

In 2015, a group of several countries from the Southern African region (SADC) requested the ITU to "examine the regulatory procedures for notifying space networks and consider possible modifications to enable the deployment and operation of nanosatellites and picosatellites, taking into account the short development time, short mission time and unique orbital characteristics" and that the 2019 World Radiocommunication Conference (WRC-19) consider "possible modifications to the existing regulatory procedures for notifying satellite networks to facilitate the deployment and operation of nanosatellites and picosatellites" (Angola 2015, p. 3). Although the ITU Member States were reluctant to consider creating a separate regulatory regime for small satellites, they acknowledged that the current procedures could be reviewed and possibly updated to better accommodate them. In the meantime, the ITU's 2015 Radiocommunication Assembly adopted Resolution ITU-R 68, "Improving the dissemination of knowledge concerning the applicable regulatory procedures for small satellites, including nanosatellites and picosatellites," and instructed the Radiocommunication Bureau to develop material that would help to improve knowledge of the applicable procedures for submitting filings of satellite networks to the ITU.

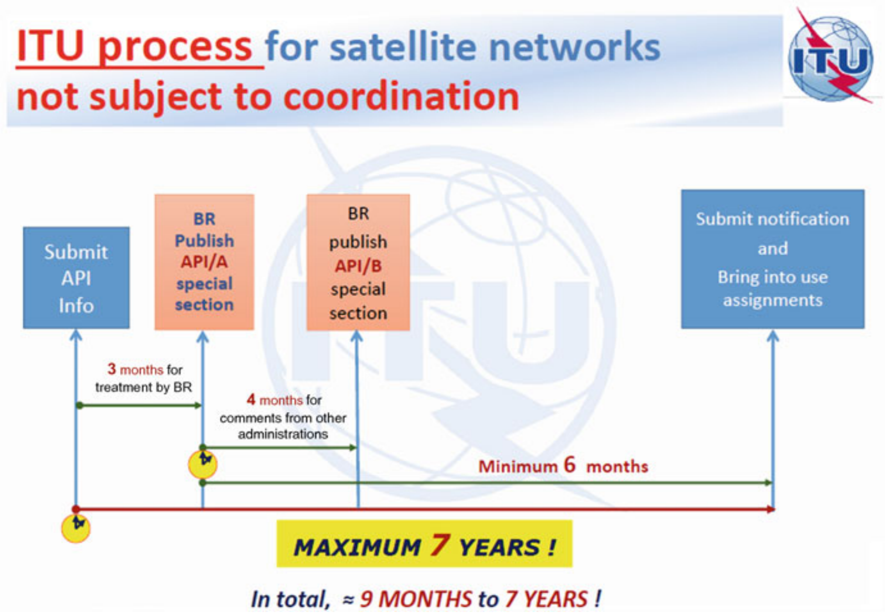


Fig. 1 Pre-WRC-19 ITU Procedure for most small satellites with short-duration missions (ITU Regulatory Procedures for Small Satellites 2018)

During the ITU-R preparatory studies for WRC-19, participants agreed that the procedures for coordination and notification, including the data elements of RR Appendix 4, are particularly difficult for small satellite operators with short-duration missions. For one thing, the overall procedure is too long relative to the length of their missions (Fig. 1). Once the notifying administration submits the Advance Publication Information (API) for the small satellite operation, the Bureau has up to 3 months to publish it. Administrations then have 4 months to review and submit comments. Then there may be additional time for administrations to reach agreement as to the acceptability of the filing. In any event, the Radio Regulations required a minimum of 6 months between publication of the API data and the submission of notification before the process can be completed – a minimum timeline of 9 months to completion. Another procedural challenge for small satellite operators is their inability to provide all the system characteristics required by RR Appendix 4 for API and notification within the required timeframes. For example, many operators do not know their orbital characteristics in advance of the actual launch of their satellite(s).

The ITU-R studies concluded that "given their short development cycle, short lifetimes, and typical missions, a modified regulatory procedure for the advance publication, notification and Master Register recording of non-GSO satellite systems with short duration missions may be beneficial for these systems . . .. [They] may require regulatory procedures that take account of the nature and timing for deployment of these systems" (ITU CPM Report 2019c, p. 595). Proposed remedies included shortening the regulatory time periods and changing the data requirements. The results of these studies formed the basis for Member States' proposals to WRC-19.

In November 2019, the 162 nations participating in the 2019 World Radiocommunication Conference, held in Sharm el-Sheikh, Egypt, agreed to provide relief to small satellite operators (and their notifying administrations) by adopting changes to the Radio Regulations to improve the regulatory situation for small satellites with short-duration missions. As recommended by the studies, WRC-19 adopted targeted amendments to the Radio Regulations and a streamlined procedure in Resolution 32, "Regulatory procedures for frequency assignments to non-geostationary-satellite networks or systems identified as short-duration mission not subject to the application of Section II of Article 9" (ITU WRC-19 Provisional Final Acts 2019e, p. 411).

The applicability of the streamlined procedure is confined to non-geostationary satellite systems or networks identified by their notifying administrations as having short-duration missions and meeting the following criteria:

1.1 The network or system shall operate under any space radiocommunication service on frequency assignments that are not subject to the application of Section II of Article 9 [subject to coordination];
1.2 The maximum period of operation and validity of frequency assignments of a non-GSO satellite network or system identified as short-duration mission shall not exceed 3 years from the date of bringing into use of the frequency assignments (see the Annex to this Resolution for the definition of date of bringing into use for such networks or systems), without any possibility of extension, after which the recorded assignments shall be cancelled;
1.3 The total number of satellites in a non-GSO satellite network or system identified as short-duration mission shall not exceed 10 satellites (with a typical mass of each not normally exceeding 100 kg). (*Id.*)

In addition, these networks or systems are required to operate within the conditions of the allocation (frequency band and service) in which they plan to operate and to have the capability to cease transmissions immediately to eliminate harmful interference to other systems.

The Annex to the Resolution provides special instructions for the application of the provisions of Articles 9 and 11 to these non-geostationary satellite networks and systems with short-duration missions. It provides alternative timing for submission of Appendix 4 information until after the launch of the satellite. In addition, the Conference amended the data elements in Appendix 4 to tailor them for these small satellites.

The Resolution also defines the date of bringing into use for these small satellites as the launch date of a satellite in a single-satellite non-geostationary satellite system or the launch date of the first satellite in a satellite system of multiple satellites. The Resolution invites administrations to avoid heavily used frequency bands when making assignments to small satellites with short-duration missions. Administrations are further encouraged to exchange information on these networks as soon as possible and to make every possible effort to resolve interference issues.

Finally, WRC-19 made changes to the provisions of Article 9 to tighten the timeframe for the processing of all satellite networks and systems under its purview, not only small satellites. In light of advancements in the electronic tools now available for filings, the Conference reduced the minimum timeframe in RR No. 9.1 for submission of notification information following publication of the API from 6 months to 4 months. Second, it reduced the time period in No. 9.2B for the Bureau to publish API information received from 3 months to 2 months. Thus, the Conference shortened this phase of the coordination and notification procedure from 9 months to 6.

Although the preparatory studies had contemplated shortening the 4-month timeframe for administrations to respond to APIs, WRC-19 refrained from doing so based on the concerns of many administrations. Instead, a footnote was added to No. 9.3 urging administrations to consider APIs for small satellites with short-duration missions "as soon as possible" within the applicable 4-month time period and for the Bureau to promptly make any comments received available on its website.

From the foregoing discussion, we can see real progress by national and international legal authorities to streamline their regulations to enable small satellites with short-duration missions to accommodate their mission requirements while preserving the stable international environment for interference management and space sustainability. Should further reforms prove necessary, the ITU's periodic process for updating its international legal instrument, the Radio Regulations, allows for continuing incremental improvements to be made to the international regime for managing satellites and their efficient use of spectrum/orbit resources.

4 New Regulations for Small Satellites in Large Non-geostationary Constellations

Another area of active regulatory development concerns small satellites of a different nature entirely – the small satellites (relative to geostationary communications satellites) that populate large non-geostationary satellite orbit constellations for provision of commercial telecommunications services (such as broadband Internet connectivity) utilizing spectrum in the MSS, FSS, or BSS allocations. Since 2014, the ITU has received a tsunami of filings for constellations of hundreds and thousands (even tens and hundreds of thousands) of satellites for these proposed systems in the Ku, Ka, and Q/V frequency bands (see Fig. 2). The ITU's historic regulatory provisions and processing procedures never contemplated filings of this magnitude.

The Radiocommunication Bureau sought guidance from WRC-15 on how to treat these mounting very large filings. The United States and United Kingdom submitted proposals to WRC-15 on the coordination of these new constellations and how to define when they are brought into use to fulfill the 7-year implementation period established in RR No. 11.44. The Conference determined that these complex issues

Fig. 2 Recommendation ITU-R V.431-8, nomenclature of the frequency and wavelength bands used in telecommunications 2015a

Letter symbols	Space radiocommunications	
	Nominal designations	Examples (GHz)
L	1.5 GHz band	1.525-1.710
S	2.5 GHz band	2.5-2.690
C	4/6 GHz band	3.4-4.2 4.5-4.8 5.85-7.075
Ku	11/14 GHz band 12/14 GHz band	10.7-13.25 14.0-14.5
Ka	20 GHz band 30 GHz band	17.7-20.2 27.5-30.0
V	40 GHz band	37.5-42.5 47.2-50.2

required study and then could be addressed by the following Conference in 2019. WRC-15 instructed that the preparatory studies should consider the definition of bringing into use for these non-geostationary satellite systems and the possible application of a milestone-based process to these systems following their being brought into use and recording in the Master Register.

In the past, when the ITU coordination and notification processes were being overwhelmed by the exuberant filing of unrealistic numbers of satellite network filings (for geostationary orbit FSS networks) – the so-called "paper satellites" era – the ITU responded with a series of regulatory changes over a number of years and the course of several meetings and Conferences from tightening the regulatory process, including reducing the regulatory period for bringing into use from 9 years to 7 (RR No. 11.44) to introducing cost recovery fees for the processing of satellite network filings (Council Decision 482 (1999)); to adding administrative due diligence measures, including a requirement to file data identifying the manufacturer and launch provider (Resolution 49 (1997)); and to supporting additional oversight by the Bureau in monitoring and determining whether satellite networks recorded in the Master Register are "real" (RR No. 13.6) (Allison 2014). Indeed, it bears noting that the ITU Council, the governing body of the ITU between Plenipotentiary Conferences, recently acted to revise its long-standing Satellite Network Cost Recovery mechanism to include a new procedure to capture the additional costs of the Bureau's processing the filings of large non-geostationary satellite systems (ITU Council, Decision 482, Doc. C/19-143, 2019).

National administrations have employed milestone requirements and other due diligence measures to ensure that their spectrum licensees build out their authorized facilities within a limited time following the grant of the license, else face regulatory consequences such as the cancellation of the license. These domestic requirements are intended to discourage licensees from warehousing spectral and orbital resources and thereby forestalling competition from others who might have provided services using those resources. The FCC requires construction build out requirements for many of its licensed systems, including milestones for its space station licensees.

In a recent update to its regulations, the FCC adjusted its milestone requirements in light of the very large systems before it which may not be able to be fully launched within the required 6-year time period normally provided following issuance of the license. The revised rules require these non-geostationary space station licensees to deploy 50% of their authorized constellations within 6 years of their authorization. Failure to meet this milestone results in a reduction of the authorized number of satellites in the constellation to those in actual use as of the first milestone date and forfeiture of a surety bond of up to US $5,000,000. Successful completion of the milestone releases the licensee from the bond obligation. The second milestone is full deployment of the remainder of the authorized constellation within the next 3 years – for a total of 9 years to full deployment. Following completion of the milestone period, licensees are required to maintain at least 50% of their authorized constellation in use at all times or the size of their authorized constellation will be decreased. In adopting this new milestone approach, the FCC stated that its goals were to discourage applicants from applying for "oversized, unrealistic constellations" noting that "unused authorizations for spectrum-orbit resources can create unnecessary coordination burdens and uncertainty for other operators" (FCC NGSO FSS Order 2017, p. 7830, para. 66).

As national administrations were processing applications for licenses for non-geostationary orbit satellite systems, the administrations and operators were also participating in ITU-R Study Group 4 studies to prepare for WRC-19. These efforts culminated in agreed general approaches for defining the date of bringing into use for non-geostationary satellite systems and a new milestone-based framework. These new approaches raised many complex regulatory questions, and there was little agreement on the details in advance of WRC-19 as the resulting regulations would have varying impacts on the relative status of the competing satellite system projects from different nations. For example, the administration of a prospective operator that was closer to the implementation of its system might support adoption of more rigorous milestone requirements that would be applied to its later-filed competitors, whereas proponents of less mature, larger, or more technologically complex systems might be better served by longer milestones with lower deployment requirements. Many administrations and satellite operators were mainly motivated by the need to preserve the stability of the management of the spectrum-orbit regime.

4.1 Bringing into Use

Bringing into use the frequency assignments of a satellite system is a prerequisite to attaining international recognition of the system and protection from harmful interference, the status achieved from recording the system's frequency assignments in the Master Register following the successful completion of the coordination and notification procedures of the Radio Regulations. Radio Regulation No. 11.44 sets the regulatory period for bringing into use a satellite frequency assignment as

7 years. The “clock” for this 7-year period starts on the date of the Radiocommunication Bureau’s receipt of the API (or other required initial filing) and stops with the “bringing into use” of that frequency assignment.

Until WRC-19, the Radio Regulations defined the bringing into use the frequency assignments of geostationary satellite networks:

> A frequency assignment to a space station in the geostationary-satellite orbit shall be considered as having been brought into use when a space station in the geostationary-satellite orbit with the capability of transmitting or receiving that frequency assignment has been deployed and maintained at the notified orbital position for a continuous period of 90 days. (ITU Radio Regulations Vol. 1 2016, p. 217)

In the absence of a regulatory definition for bringing into use the frequency assignments to non-geostationary satellite systems, the Radiocommunication Bureau applied a working definition to enable it to process such filings in its queue until such time as the Radio Regulations could be amended by a WRC. Under a Rule of Procedure approved by the ITU’s Radio Regulations Board, the frequency assignments to a non-geostationary satellite system are considered to be brought into use “when one satellite is deployed into a notified orbital plane and capable of transmitting and/or receiving those frequency assignments” (ITU Rules of Procedure 2017, Ar. 11, p. 26). For this purpose, a satellite is considered to be deployed into a notified orbital plane when its orbital characteristics match those indicated in its Appendix 4 information, including orbit altitudes and inclination. This working definition was applied for several years to MSS and FSS non-geostationary satellite filings regardless of the number of satellites notified to comprise the system.

The Director of the Radiocommunication Bureau reported to WRC-15: “[t]aking into account of the numerous non-GSO systems received so far by the Bureau, and the possible speculative nature of such submissions that could lead to spectrum warehousing and resurgence of so-called ‘paper satellite networks,’ the conference may wish to consider redefining the notion of bringing into use for non-GSO satellite networks” (ITU Director’s Report 2015b, p. 32, Section 3.2.2.4.4).

Based on the Bureau’s long-standing practice and the discussions during the 4-year preparatory cycle for WRC-19, the WRC-19 decided to add the recommended definition for the bringing into use of the frequency assignments of non-geostationary satellite systems to RR No. 11.44C:

> A frequency assignment to a space station in a non-geostationary-satellite orbit network or system in the fixed-satellite service, the mobile-satellite service or the broadcasting-satellite service shall be considered as having been brought into use when a space station with the capability of transmitting or receiving that frequency assignment has been deployed and maintained on one of the notified orbital plane(s) [footnote omitted] of the non-geostationary satellite network or system for a continuous period of 90 days, irrespective of the notified number of orbital planes and satellites per orbital plane in the network or system. The notifying administration shall so inform the Bureau within 30 days from the end of the 90-day period [footnotes omitted] On receipt of the information sent under this provision, the Bureau shall make that information available on the ITU website as soon as possible and shall publish it in the BR IFIC subsequently. (ITU WRC-19 Provisional Final Acts 2019e, p. 66)

In sum, a 1000-satellite constellation can be brought into use and meet the ITU's 7-year regulatory deadline with the launch and operation of a single satellite. Clearly, more oversight of these systems would be required beyond the 7-year bringing into use period.

4.2 Milestone-Based Approach

In taking the action to amend the Radio Regulations to adopt a new type of regulatory mechanism to facilitate the management of the spectrum-orbital regime, WRC-19 observed that:

> [I]t would be unrealistic to expect to have all the satellites of a system, in some cases consisting of hundreds or thousands of satellites, to be deployed within this seven-year regulatory period. Therefore, the BIU [bringing into use] of frequency assignments of non-GSO systems cannot always be considered as a confirmation of the full deployment of these systems, but instead may in some cases be just an indication of the commencement of deployment of satellites capable of using the frequency assignments. (ITU CPM Report 2019*,* p. 472, Section 3/7/1)

In other words, if such a constellation is brought into use (and its frequency assignments recorded in the Master Register) with the deployment of a single satellite – perhaps the first of a thousand such satellites in the constellation – a supplemental process was needed to confirm the ultimate deployment of the other 999 satellites beyond the 7-year regulatory period in order to ensure the accuracy of the Master Register. The studies recommended adoption of a series of deployment milestones that would apply during specified periods following the conclusion of the regulatory period to confirm deployment of the notified constellation. "A milestone-based approach would balance the need to prevent spectrum warehousing, especially in congested frequency bands, and the need to recognize the technical and operational challenges associated with this type of non-GSO system" (*Id.*).

The ITU-R studies recommended the following guiding principles for the Member States' consideration in developing proposals to WRC-19 on the adoption of a new of a milestone-based process:

- The bringing into use process should be separate [from the milestone-based process].
- Appropriate time should be given to allow the completion of the deployment of non-GSO systems [beyond the seven-year regulatory period].
- [T]ransitional measures should be considered to address the implications of any new milestones adopted by WRC-19.
- The milestone-based approach should be applied to all non-GSO systems in specific space services in specific frequency bands.
- The milestone-based approach should provide incentives to notifying administrations to deploy satellites in a timely manner, as a failure to meet a given milestone for a non-geostationary system will result in consequences.

- The milestone-based approach should be developed in such a way as to not constrain the development of non-GSO systems. *(Id.* at p. 473, Section 3/7/1.3)

Moreover, it concluded, acting on these principles would advance the efficient, rational, and economical use of spectrum and orbital resources and improve the transparency of the deployment of non-geostationary satellite orbit systems.

Under this recommended approach, there would be a series of milestones separated by a specific period of years following the expiry of the 7-year regulatory period. Each milestone would require a percentage of the satellites to be deployed based on the notified size of the system in one or more of the notified orbital planes with the confirmed capability of transmitting or receiving in the notified frequency. If the filer meets or exceeds the applicable milestone requirement, the characteristics of its recorded assignment in the Master Register (relating to the number of satellites comprising the system) would remain unchanged. Failure to meet the milestone would result in regulatory consequences such as a downward adjustment to the number of satellites in the system recorded in the Master Register relating to the number actually deployed (a so-called deployment factor). This milestone-based approach would be included in a new WRC resolution. In addition, transitional measures would be required for application of the procedure to systems already submitted or notified.

After the better part of 4 weeks of intensive negotiations, WRC-19 adopted Resolution 35, “A milestone-based approach for the implementation of frequency assignments to space stations in a non-geostationary orbit satellite system in specific frequency bands and services” (ITU WRC-19 Provisional Acts 2019e, p. 423). The Resolution is a mandatory treaty obligation through incorporation by reference to the Radio Regulations in new RR provision No. 11.51. The Resolution recounts that “design considerations, availability of launch vehicles to support multiple satellite launches, and other factors mean that notifying administrations may require longer than the regulatory period stipulated in No. 11.44 to complete implementation of [large] non-GSO systems” (*Id.*). Further, the preparatory studies concluded that “adoption of a milestone-based approach will provide a regulatory mechanism to help ensure that the Master Register reasonably reflects the actual deployment of such non-GSO satellite systems in certain frequency bands and services, and improve the efficient use of the orbital/spectrum resource in those frequency bands and services” (*Id.*). The Conference noted that:

> In defining the timeline and objective criteria for the milestone-based approach, there is a need to seek a balance between the prevention of spectrum warehousing, the proper functioning of the coordination mechanism, and the operational requirements related to the deployment of a non-geostationary satellite system. (*Id.*)

The Conference limited the applicability of the Resolution to non-geostationary satellite systems in specified FSS, MSS, and BSS allocations in Ku, Ka, and V-band frequencies (between 10.7 GHz and 51.4 GHz) reflecting the allocations where the ITU is receiving the highest number of filings for the largest non-geostationary satellite systems (See Fig. 3). It decided to exclude the various science services and commercial allocations in lower frequency bands (such as L- and S-bands) that had been considered for inclusion during the preparatory studies and in some of the proposals to the Conference. Because the systems filed in these services and frequency bands simply did not raise the same level of urgency and dimension of concern regarding speculative filings, misuse of resources, and potential damage to the overall satellite coordination and notification process, they were not included in the new regulatory process and were left to the consideration of a future conference.

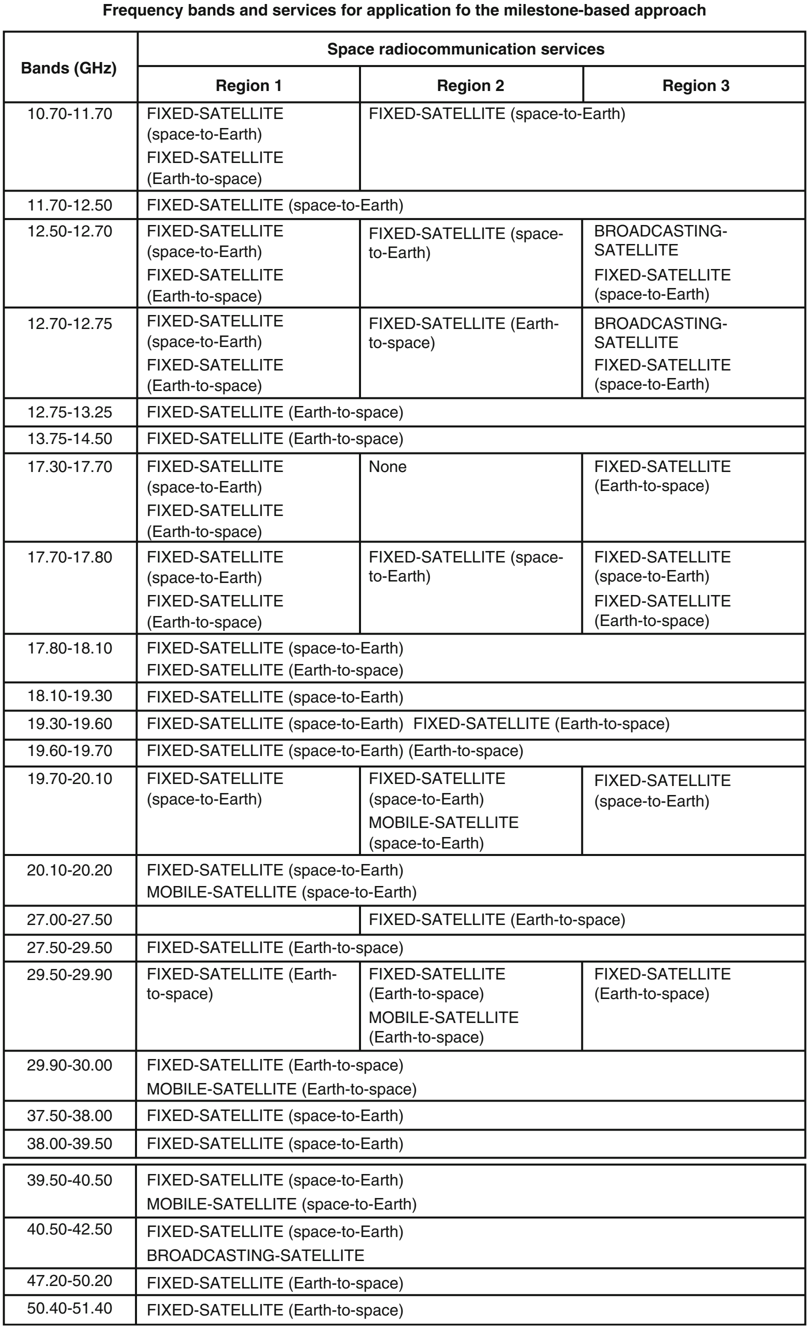
For the non-geostationary satellite systems that are subject to the Resolution having frequency assignments in the applicable allocations that will reach the end of their regulatory period on or after 1 January 2021, the first step under the new milestone-based process is that the notifying administration must submit to the Bureau deployment information no later than 30 days after the end of the regulatory period (*Id.* at 426). The deployment information required for submission is provided in Annex 1 to the Resolution:

(A) **Satellite system information**
   1. Name of the satellite system
   2. Name of the notifying administration
   3. Country symbol
   4. Reference to the advance publication information or the request for coordination, or the notification information, if available
   5. Total number of space stations deployed into each notified orbital plane of the satellite system with the capability of transmitting or receiving the frequency assignments
   6. Orbital plane number indicated in the latest notification information published in Part I-S of the BR IFIC for the frequency assignments into which each space station is deployed

(B) **Launch information to be provided for each deployed space station**
   1. Name of the launch vehicle provider
   2. Name of the launch vehicle
   3. Name and location of the launch facility
   4. Launch date

(C) **Space station characteristics for each space station deployed**
   1. Frequency bands from the notification information that the space station can transmit or receive
   2. Orbital characteristics of the space station (altitude of the apogee and perigee, inclination, and argument of the perigee
   3. Name of the space station. (*Id.* at 431–432, Annex 1)

Upon receipt of the deployment information, the Radiocommunication Bureau publishes it in the form of its receipt on its website for information. Should the deployment information indicate that the system is not yet 100% deployed, then the Bureau will add a remark to the Master Register entry (or the latest notification information) regarding the applicability of the Resolution to the frequency



Frequency bands and services for application fo the milestone-based approach

Bands (GHz)	Space radiocommunication services		
	Region 1	Region 2	Region 3
10.70-11.70	FIXED-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)	FIXED-SATELLITE (space-to-Earth)	
11.70-12.50	FIXED-SATELLITE (space-to-Earth)		
12.50-12.70	FIXED-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)	FIXED-SATELLITE (space-to-Earth)	BROADCASTING-SATELLITE FIXED-SATELLITE (space-to-Earth)
12.70-12.75	FIXED-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)	FIXED-SATELLITE (Earth-to-space)	BROADCASTING-SATELLITE FIXED-SATELLITE (space-to-Earth)
12.75-13.25	FIXED-SATELLITE (Earth-to-space)		
13.75-14.50	FIXED-SATELLITE (Earth-to-space)		
17.30-17.70	FIXED-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)	None	FIXED-SATELLITE (Earth-to-space)
17.70-17.80	FIXED-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)	FIXED-SATELLITE (space-to-Earth)	FIXED-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)
17.80-18.10	FIXED-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)		
18.10-19.30	FIXED-SATELLITE (space-to-Earth)		
19.30-19.60	FIXED-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)		
19.60-19.70	FIXED-SATELLITE (space-to-Earth) (Earth-to-space)		
19.70-20.10	FIXED-SATELLITE (space-to-Earth)	FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth)	FIXED-SATELLITE (space-to-Earth)
20.10-20.20	FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth)		
27.00-27.50		FIXED-SATELLITE (Earth-to-space)	
27.50-29.50	FIXED-SATELLITE (Earth-to-space)		
29.50-29.90	FIXED-SATELLITE (Earth-to-space)	FIXED-SATELLITE (Earth-to-space) MOBILE-SATELLITE (Earth-to-space)	FIXED-SATELLITE (Earth-to-space)
29.90-30.00	FIXED-SATELLITE (Earth-to-space) MOBILE-SATELLITE (Earth-to-space)		
37.50-38.00	FIXED-SATELLITE (space-to-Earth)		
38.00-39.50	FIXED-SATELLITE (space-to-Earth)		
39.50-40.50	FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth)		
40.50-42.50	FIXED-SATELLITE (space-to-Earth) BROADCASTING-SATELLITE		
47.20-50.20	FIXED-SATELLITE (Earth-to-space)		
50.40-51.40	FIXED-SATELLITE (Earth-to-space)		

Fig. 3 Resolution 35 (Sharm el-Sheikh, 2019d) table of allocations subject to the milestone-based approach for non-geostationary satellite systems. (ITU WRC-19 Provisional Acts 2019e, pp 425–426)

assignments. The Bureau will also include this action in its regulatory publication and post it on the website (*Id.* at 426).

If the system is less than 100% deployed, then the second step of the process applies (*Id.* at 427). The notifying administration must submit updated deployment information to the Bureau no later than 30 days after the expiration of each of the following three milestone periods as they continue to apply:

M-1	2 years after end of 7-year regulatory period
M-2	5 years after end of 7-year regulatory period
M-3	7 years after end of 7-year regulatory period

Upon receipt of these updated deployment information filings, the Bureau posts them on the ITU website. Next, it conducts an examination for compliance with the applicable milestone in terms of number of satellites deployed relative to the total number of satellites in the system (as indicated in its Appendix 4 information) rounded down to the lowest integer (*Id.* at 428–429). The percentages of required satellite deployment for each milestone are:

M-1	2 years	10% of the total number of satellites
M-2	5 years	50% of the total number of satellites
M-3	7 years	100% of the total number of satellites

Based on the results of its examination, the Bureau will modify the entry in the Master Register (or latest notification information) for the frequency assignments and publish the results (*Id.* at 428).

The third step of the Resolution's milestone-based process applies only in the case the proponent fails to meet the required deployment level of that milestone. In such case, a deployment factor is applied to reduce the size of the constellation as notified or recorded in the Master Register. The notifying administration must submit to the Bureau, not later than 90 days following the expiry of the applicable milestone period, a modification to the characteristics of its recorded or notified frequency assignments as follows:

M-1	2 years	If less than 10%, then the modified total number shall not be greater than ten times the number of space stations deployed of the total number of satellites
M-2	5 years	If less than 50%, then the modified total number shall not be greater than two times the number of space stations deployed
M-3	7 years	If less than 100%, then the modified total number shall not be greater than the number of satellites already deployed (*Id.* at 428–429)

The deployment factor for each milestone is used to scale the size of a constellation based on what has been actually deployed by the operator as of the applicable milestone date. It is intended to incentivize satellite operators (and their notifying administrations) to undertake filings with realistic parameters and to maintain the accuracy of the Master Register, thus providing a clearer picture to other operators about the scale of planned operations that need to be protected.

Upon receipt of a modification request, the Radiocommunication Bureau will retain the original date of the entry in the Master Register of the reduced frequency assignments remaining for the constellation (and thus preserve their regulatory status), provided the notifying administration submits a commitment that the modified characteristics will not cause more interference or require more protection than the original ones filed (*Id.* at 429).

The Radiocommunication Bureau is charged with sending two reminders to notifying administrations at various points in the procedure regarding the deadlines for submission of information. Should the notifying administration fail to submit the initial deployment information under the first step of the process, the Bureau will maintain the entry in the Master Register and continue to take it into account until such time as the RRB takes a decision to cancel the frequency assignments. Should the notifying administration fail to submit the required information per the second or third steps of the milestone-based process, the Bureau will suppress the notified parameters of all satellites for which the required deployment information has not been received. Any satellites whose assignments have been suppressed no longer have regulatory status, and thus they may not cause harmful interference nor claim protection from other frequency assignments recorded in the Master Register (*Id.* at 429–430).

Following the completion of the milestone-based process, the subject non-geostationary satellite orbit systems are required to maintain their operations at a level of at least 95% of the satellites notified. Should the number fall below this level in any 6-month-long period, the notifying administration is required to inform the Bureau (*Id.*). Other actions are required to resume the operation and to retain the regulatory status of the system's regulatory status. The Conference indicated that this area requires further study and regulatory development (ITU Committee 5 Eleventh Report 2019).

The Conference also decided that this new milestone-based process would have some variations for different transitional cases: for earlier-filed systems whose regulatory periods will expire prior to 2021 and for systems whose regulatory period will expire before 28 November 2024. Although ITU treaty conferences are generally reluctant to make decisions with retroactive impact to the rights of Member States (or their approved private operators), the delegations to WRC-19 were in agreement that retroactive action was necessary in this case with so many large systems in the ITU-R's processing queue and their potential impact on the spectrum-orbit resource. Moreover, there was an acknowledgment that the next World Radiocommunication Conference, which is expected to be convened in the latter part of 2023, would be in a position to review (and to take any necessary action on) this new milestone-based procedure with the benefit of the experience gained over the next 4 years. Thus, the process was purposely designed to yield specific deployment information in time for consideration by WRC-23.

In the case of systems whose regulatory period ended prior to 1 January 2021, the Conference decided to apply the milestone-based procedure but with specific deadlines for submission of deployment information and the application of the milestone periods. The initial deployment information for these earlier systems must be filed by 1 February 2021 (ITU WRC-19 Provisional Final Acts 2019 at p. 426). Second, should these networks report less than 100% deployment, then their notifying administrations must file updated deployment information for the following three milestones:

M-1 No later than 1 February 2023 (corresponding to 30 days after the expiry of the two-year period after 1 January 2021);
M-2 No later than 1 February 2026 (corresponding to 30 days after the expiry of the five-year period after 1 January 2021);
M-3 No later than 1 February 2028 (corresponding to 30 days after the expiry of the seven-year period after 1 January 2021) (*Id.* at p. 427)

The second special transitional case applies to the several (approximately 20) large constellations filed during WRC-15 whose regulatory period will expire before 28 November 2022. The Resolution affords them, on an exceptional basis, the option to avoid complying with the first milestone of the regular procedure and instead submitting by 1 March 2023 special deployment information to indicate the “realness” of their systems and to confirm their progress toward meeting the second milestone (*Id.* at 429). The special deployment information to be submitted in this exceptional case is set forth in Annex 2 to the Resolution:

1. Reference to Notification Information already submitted
2. Current deployment and operational information
3. Report indicating efforts made and detailing status of coordination with systems or networks
4. Clear evidence of a binding agreement for the manufacture or procurement of a sufficient number of satellites to meet the milestone obligation in [milestone 2]
5. Clear evidence of a binding agreement to launch a sufficient number of satellites to meet the milestone obligation in [milestone 3]. (*Id.* at 432)

Annex 2 further provides that this deployment information “shall be submitted in the form of a written commitment by the responsible administration; include manufacturer or launch provider letters or declarations, and evidence of guaranteed funding arrangements for the implementation of the project, where possible. The notifying administration is responsible for authenticating the evidence of agreement” (*Id.*).

The unprecedented scope and nature of the information requested in Annex 2 arises from the fact that it is not yet clear how these pending mega-LEO constellations in overlapping frequency bands will be coordinated with one another. The Conference discussed various approaches, including the consultation procedure in Resolution 609 (Rev.WRC-07) that has been in successfully applied to coordinate systems in the radio navigation satellite and the aeronautical radio navigation services. But more time and study are needed before such an approach can be formally adopted into the Radio Regulations for these mega-LEO satellite systems.

Upon receiving this special deployment information, the Bureau is to provide it to the RRB by 1 April 2023, so that Member States may review and submit comments in time for consideration by the RRB at its second meeting in 2023. The RRB is instructed to provide a report to WRC-23 containing its conclusions and recommendations regarding the deployment efforts. This should make for an interesting discussion at WRC-23 and during the preparatory activities leading up to the Conference.

The new milestone-based procedure of Resolution 35 is a highly complex and radically different mechanism for the ITU-R's management of the spectrum-orbit regime which has been significantly challenged by the filing of so many large non-geostationary satellite orbit constellations. It is certain to be the subject of concentrated focus and studies throughout the preparatory period for WRC-23 and beyond. The Resolution includes instructions to the Radiocommunication Bureau to report any difficulties on its implementation of the procedure to WRC-23 as well as to report on other frequency bands and services that should be examined for future inclusion into this approach. Also outstanding is the further development of post-milestone procedures. Finally, the ITU-R also needs to conduct technical studies on "the tolerances for certain orbital characteristics of the [satellites covered by the milestone-based process] to account for potential differences between the notified and deployed orbital characteristics for the inclination of the orbital plane, the altitude of the apogee of the space station, the altitude of the perigee of the space station and the argument of the perigee of the orbital plane" (ITU, Minutes of Tenth Plenary Meeting 2019b). Besides informing the date of bringing into use and evaluation of milestone compliance, this information has potential implications for space safety and the sustainability of the low Earth orbit.

5 Conclusion

The advent of the small satellite era has challenged existing domestic and international regulatory constructs in two opposite ways. The needs of operators of small satellites with short-duration missions require lighter and clearer regulatory approaches to allow them to safely operate in the neighborhood of the low Earth orbit but still meeting the fundamental requirements of the international spectrum-orbit regime to protect their own and other operations. On the other hand, small commercial satellites that comprise large (and sometimes "mega") constellations require new, more rigorous national and international regulatory approaches to ensure order in low Earth orbit and to provide international protection to those systems whose frequency assignments are recorded in the Master Frequency International Register. As it has done many times in its 155-year history, the ITU has evolved its regulatory approaches as new technologies have developed and entered into service to achieve the goals of the outer space treaties and the ITU's basic instruments. But, at least for managing these emerging mega-LEO constellations, the ITU's efforts have only just begun. The 2023 World Radiocommunication Conference will be the next opportunity for the creation of new international legal measures to continue to ensure orderly, efficient, and equitable use of the spectrum-orbit resource and the provision of satellite-delivered broadband services to the world.

6 Cross-References

- ▶ Deorbit Requirements and Adoption of New End-of-Life Standards
- ▶ Financial Models and Economic Analysis for Small Satellite Systems
- ▶ Legal Issues Related to the Future Advent of Small Satellite Constellations
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ "Rules of the Road" for Launch and Operation of Small Satellites and Related Issues
- ▶ Small Satellites and Their Challenges to Space Situational Awareness (SSA) and Space Traffic Management (STM)
- ▶ Small Satellites Market Growth Patterns and Related Technologies
- ▶ Space Finance for 'New Space' and Small Satellites
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit

References

A. Allison, *ITU and Managing Satellite Orbital and Spectrum Resources in the 21st Century* (Springer, Cham, 2014)

Angola et al., *Common Proposals for the Work of the Conference*, Doc. CRM15/130(Add.25)(Add.4) (ITU, Geneva, 2015). https://www.itu.int/dms_pub/itu-r/md/15/wrc15/c/R15-WRC15-C-0130!A25-A4!MSW-E.docx

Federal Communications Commission, *Update to Parts 2 and 25 Concerning Non-Geostationary, Fixed-Satellite Service Systems and Related Matters*, 32 FCC Rcd 7809 (FCC, Washington, DC, 2017). https://ecfsapi.fcc.gov/file/0927000146342/FCC-17-122A1_Rcd.pdf

Federal Communications Commission, *Streamlining Licensing Procedures for Small Satellites* (Notice of Proposed Rulemaking), 33 FCC Rcd 4152 (FCC, Washington, DC, 2018. https://ecfsapi.fcc.gov/file/0417247304932/FCC-18-44A1_Rcd.pdf

Federal Communications Commission, *Streamlining Licensing Procedures for Small Satellites* (Report and Order) IB Docket 18-86 (FCC, Washington, DC, 2019). https://ecfsapi.fcc.gov/file/08020582709488/FCC-19-81A1.pdf

International Telecommunication Union, *Recommendation ITU-R V.431-8, Nomenclature of the Frequency and Wavelength Bands Used in Telecommunications* (ITU, Geneva, 2015a). https://www.itu.int/dms_pubrec/itu-r/rec/v/R-REC-V.431-8-201508-I!!PDF-E.pdf

International Telecommunication Union, *Report of the Director on the Activities of the Radiocommunication Sector, Part 2*, Doc. CMR15/4(Add.2) (Rev.1) (ITU, Geneva, 2015b). https://www.itu.int/dms_pub/itu-r/md/15/wrc15/c/R15-WRC15-C-0004!A2-R1!MSW-E.docx

International Telecommunication Union, *Radio Regulations*, 2016 edn. (ITU, Geneva, 2016). https://www.itu.int/en/publications/ITU-R/pages/publications.aspx?parent=R-REG-RR-2016&media=electronic

International Telecommunication Union, *Rules of Procedure*, 2017 edn. (ITU, Geneva, 2017). https://www.itu.int/pub/R-REG-ROP-2017

International Telecommunication Union, *Radiocommunication Bureau, Regulatory Procedures for Small Satellites* (ITU, Geneva, 2018). https://www.itu.int/en/ITU-R/space/Documents/Chart%20-%20ITU%20Regulatory%20Procedures.pdf

International Telecommunication Union, *Collection of the Basic Texts of the International Telecommunication Union Adopted by the Plenipotentiary Conference*, 2019 edn. (ITU, Geneva, 2019a). https://www.itu.int/pub/S-CONF-PLEN-2019

International Telecommunication Union, *Minutes of the Tenth Plenary Meeting*, Doc. CMR15/571 (ITU, Sharm el-Sheikh, 2019b). https://www.itu.int/md/R16-WRC19-C-0571/en

International Telecommunication Union, *Report of the Conference Preparatory Meeting to the World Radiocommunication Conference 2019*, Doc. CMR19/3 (ITU, Geneva, 2019c). https://www.itu.int/dms_pub/itu-r/md/16/wrc19/c/R16-WRC19-C-0003!!MSW-E.docx

International Telecommunication Union, *Book of ITU-R Resolutions*, 2019 edn. (ITU, Sharm el-Sheikh, 2019d). https://www.itu.int/pub/R-VADM-RES/en

International Telecommunication Union, *Provisional Final Acts of the World Radiocommunication Conference 2019* (ITU, Sharm el-Sheikh, 2019e). https://www.itu.int/pub/R-ACT-WRC.13-2019/en

International Telecommunication Union, *Decision 482* (Mod.2019), Doc. C/19-143 (ITU, Geneva, 2019f). https://www.itu.int/md/S19-CL-C-0143/en

United Nations, *United Nations Treaties and Principles on Outer Space* (United Nations, New York, 2002). https://www.unoosa.org/pdf/publications/STSPACE11E.pdf/

Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis

Tony Azzarelli

Contents

Abstract

It is important to have a clear understanding of the system architecture and the business model of a satellite system before embarking on the acquisition of the requisite regulatory instruments needed for their operation (e.g., spectrum authorizations, service licenses). Getting this right may be the key to obtaining key licenses and vital authorizations and frequency allocations for a satellite network. This article provides vital information with regard to the complexity of satellite systems in general and low Earth orbit satellite constellations in

T. Azzarelli (✉)
Azzurra Telecom Limited, London, UK
e-mail: tony@azzurra-telecom.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_72

particular. This complexity also results in a quite complicated regulatory, authorization, and standards process. Successfully winning the necessary regulatory approvals is essential to operating such satellite networks in a global environment. The article that follows provides useful details as to how these regulatory requirements, radio frequency allocation, and other types of authorizations such as "landing licenses" can be met, but this must be considered only to be a broad overview of this quite difficult, complex, and demanding field. This article addresses the regulatory processes specific to communications satellite systems. Nevertheless many of the authorization processes are similar for other satellite applications as well, and thus this article can be instructive for others seeking to deploy non-geostationary systems for other purposes.

Keywords

Control segment · Cyber security · European Conference on Postal and Telecommunications (CEPT) · Earth segment · Earth station · Earth station license · European Telecommunications Standards Institute (ETSI) · Frequency allocation · Geostationary · Gateway station · Hub · International Telecommunication Union (ITU) · Interface standards · ITU Radio Regulations · Landing license or rights · Low Earth orbit (LEO) · Network authorization · Network segment · Non-geostationary · Radio frequency (RF) · Registration of the space network · Service segment · Satellite constellation · Standards · Taxes and taxation systems · Terrestrial interface · TT&C Earth station · User interface segment

1 Introduction

Below is a typical architecture of a satellite system. This might be a satellite system with a "bent pipe" or regenerative satellite payload. At each point in the communication chain shown in Fig. 1, there is at least one possible legal instrument required by one country or another.

From Fig. 1, it can be seen that the architecture of a satellite system is technically complex and that many interfaces exist between all the parts. Thus it becomes clear that there are many regulatory instruments required for the satellite operator to comply with before an entity can offer commercial services in a country.

The functional blocks (see Fig. 1) of a potential satellite network are:

- **Space Segment** – the physical part of the system related to all the spacecraft in outer space
- **Ground Segment** – the part related to the radio equipment and antennas that download and upload traffic to the space segment
- **Control Segment** – the part where the control function (with its space control center and radio antenna system) of the spacecraft resides

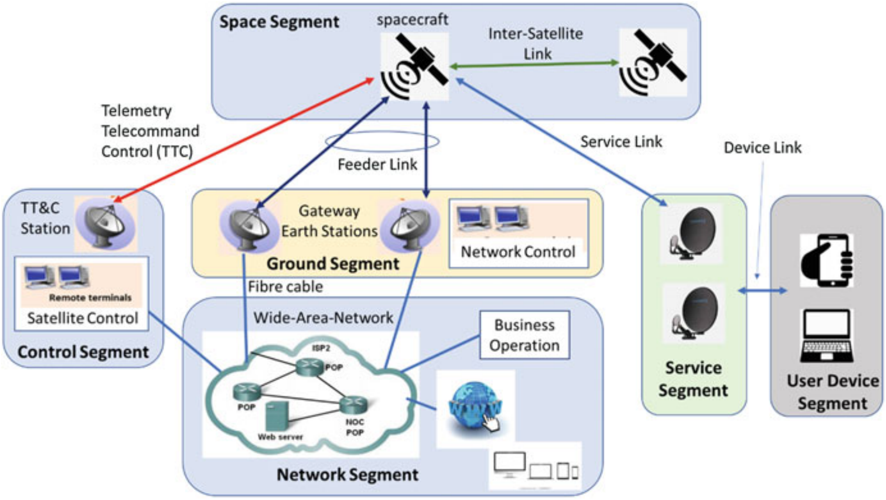


Fig. 1 Complexity of a satellite architecture. (Graphic courtesy of the author)

- **Network Segment** – the heart/core of the ground network where the global interconnections, control data functions, and people are located to run the communication network and all the data flow, including business, security, and operations functions
- **Service Segment** – the physical part of the system where the communication data flows from and to the space segment and the antenna terminals interfacing the user on Earth
- **User Device Segment** – is the physical part where the user devices such as their laptops, phones, and sensors are.

Not all satellite systems require all these functional blocks or may require additional blocks, and this depends on the business objectives/model of the system. Thus, the regulatory environment requirements may differ from system to system. What is described in this section is typical of a satellite system that provides high-speed broadband connectivity. However, some of the regulatory requirements here can extend to other types of satellite network.

1.1 The Communications Channel

Within the system architecture, Fig. 2 shows how the data flows from one end (e.g., a “web page” or a “data storage” on the Internet) to the other end (the “user”) of the system.

The data flow is transferred from one block to the other block using either cable or a radio spectrum. At each block, the data information (“1”s and “0”s) is converted

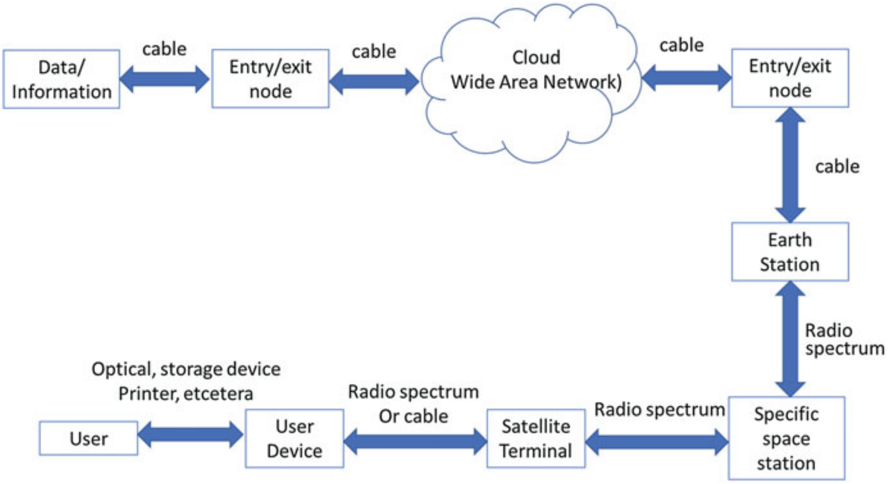


Fig. 2 The satellite broadband communication system. (Graphic courtesy of the author)

from bits of information to data or analogue signals, to be reconverted back to data information (“1”s and “0”s).

Regulatory approvals may be required as data and information transits through the communication channel. This is due to various reasons, for example:

- Crossing national borders – taxations and fees
- Control of data flow by national authorities – limited or not by law
- Using natural resources, such as spectrum – requires authorizations/license
- Control of interference when using radio frequencies
- Business transactions – taxation and authorizations to sell/buy
- Data protection and data security laws – lawful intercept

2 The Regulatory Environment for Satellite Systems

The approach taken by all countries and regulatory jurisdictions of the world are not harmonized and the regulatory requirements different from country to country or from region to region of the world.

Also, the bodies responsible for regulating the national resources related to telecommunications, radio frequencies, and space objects differ from country to country. What is the regulatory model in one country can be very different in another (see Table 1).

This makes life difficult for satellite operators that have a global reach, thus requiring large investments in resources to acquire the required approvals to access different markets around the world.

Table 1 Regulatory agencies in selected countries

	Radio frequencies	Telecommunication services	Space resources control	International representation on radio frequencies
United Kingdom	Office of Communications (Ofcom)	Department for Digital, Culture, Media and Sport (DCMS) Ofcom	UK Space Agency	Ofcom
USA	Federal Communications Commission (FCC) and NTIA	FCC	FCC Federal Aviation Administration (FAA)	FCC
Italy	Ministry of Economic Development (MISE)	MISE	Italian Space Agency (ASI)	MISE
France	Agence Nationale des Frequences (ANFR)	Ministry of Economics Agence Autorité de Régulation des Communications Électroniques et des Postes (ARCEP)	Centre National d'Etudes Spatial (CNES)	ANFR
China	Ministry of Industry, Information and Technology (MIIT)	MIIT	Chinese National Aerospace Agency (CNSA)	MIIT
India	Department of Telecommunications (DOT) Telecommunications Regulatory Authority (TRA)	Department of Telecommunications (DoT) Telecommunications Regulatory Authority (TRA)	Indian Space Research Organisation (ISRO)	DoT
UAE	Telecommunication Regulatory Authority (TRA)	TRA	National Space Agency	TRA

In addition to national regulators, satellite operators have to deal with international and regional bodies. Each of these groups have different roles and some of these are:

- **International Telecommunication Union (ITU)**: which develops international rules of engagements, through its Radio Regulations, resolutions, and recommendations. It also has the international function of registry of radio space resources (i.e., the Master International Frequency Register).
- **European Conference on Postal and Telecommunications (CEPT)**: a body representing 48 countries, under which the **European Communications Commission (ECC)** studies compatibility between systems and develops the radio decision, reports, and recommendations on how spectrum is shared and allocated, reducing or even eliminating harmful interference, and how radio equipment is regulated for circulation across European borders and licensed for the spectrum use. Thus, providing for a harmonized regional approach to licensing, whereby countries of the CEPT can adopt and ratify these decisions and recommendations into their legislations, regulations, or guidelines.
- **European Telecommunications Standards Institute (ETSI)**: which develops the radio interface standards that ensure equipment does not cause harmful interference to other radio services. Such standards can be adopted by the **European Union (EU)** as harmonized standards, which then allow free circulation and free market access for radio terminals that comply with such standards. Like the FCC mark, the EU marking (CE) is accepted by many countries around the world, as a quality assurance that such equipment does not cause harmful interference.

3 Different Satellite Links

Figure 1 shows the architecture of a typical satellite system. From this chart, it can be demonstrated that different aspects of an overall satellite communications systems can be split in functional blocks. Such blocks are interfaced or linked together using a communication link that can be either radio link, fiber, or cable transmission.

Understanding these links will help understand what kind of regulatory instruments may be required from each country or from an international institution such as the International Telecommunication Union (ITU).

The interfaces provided in Fig. 1 above are:

- **Device Link** – is the link which connects user devices to the satellite network (i.e., the satellite terminal). This can be in various forms, radio (WiFi, 3G, 4G LTE), Ethernet, or optical cable.
- **Service Link** – is the link which provides access to the space segment and where information is relayed from the satellite terminals on the ground to the satellites in outer space. This is usually a radio link, which requires to be in allocations recognized internationally by the ITU.

- **Feeder Link** – is the link that connects the space segment to the satellite ground network. This can be seen as the backhaul part of the space segment and not related to any use by the end users. Usually this is a radio link and must be recognized internationally by the ITU. Future connections could use optical/laser links.
- **Control Link (TT&C)** – this is a sensitive link which provides the control of the spacecraft through the TT&C signalling. Here TT&C means, Telemetry, Telerange and Command; i.e., through these the satellite operator will obtain the following:
  (a) **Tracking** (space-to-Earth) – for obtaining the location of the spacecraft (possibly through GPS signal received on the spacecraft)
  (b) **Telemetry** (space-to-Earth) – for obtaining the health of the subsystems of the spacecraft
  (c) **Command** (Earth-to-space) – for sending commands to the satellite to either move it in space or to command the functions of the satellite subsystems, including the payload frequencies
- **Intersatellite Link (ISL)** – it is the link between spacecrafts in outer space, and not all satellite systems use such link today. A future option is to use optical laser links. ISLs are required to transfer data from satellite to satellite before landing on the Earth, usually to avoid complex ground networks and investments on ground antennas or even avoid complex regulations. However, it provides the advantage to cut down costs and delays in delivering the date to the end user and vice versa. The radio links are also allowed under the ITU regime, but it does not require any national license to operate these.
- **Fiber/Cable Links**: these links provide connectivity to transfer data from one installation to another or even across the globe. As these are based on cable connectivity, they do not enter in the radio regulatory domain. However, other national telecoms and data security regulation may be applicable.

4 Regulatory Requirements for a Satellite System

Taking the various links and system segments described above, exploration of what might be some of the regulatory requirements for each of them is reviewed below.

4.1 Requirements for the Service Link, Service Segment, Device Link, and Device Segment

(a) The **Service Link** and **Service Segment** are the part of the system dedicated to the provision of a given telecommunication service to an end user, in a given country. As such, regulations stem from various considerations, for example:
  - Telecommunications law, which usually protects the citizens' interest
  - Radio communications regulations, which protect the sharing of spectrum and lowering of interference

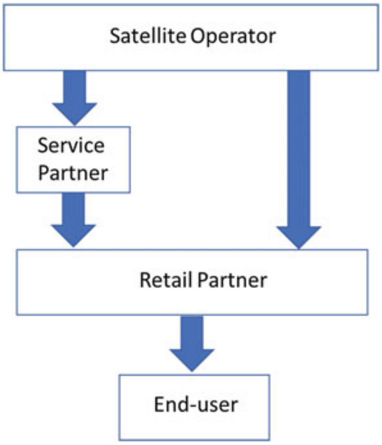


Fig. 3 Simple service provision model. (Graphic courtesy of the author)

- Taxation and duties, for services provided
- International law, for the respect of other international users

The provision of satellite services can be done in different ways, and this depends on the business model adopted by the satellite operator. A simple model is provided in Fig. 3. In this typical model, various types of requirements must be met to achieve necessary licenses and authorizations.

For example:

- Having a local company or partner
- An authorization for the sale of capacity from the satellite operators onto the service partner or the retail partner
- An authorization for the service partner or the retailer to sell the capacity it receives from the satellite operator onto the next stakeholder or the end user
- An authorization for the satellite system coverage requirement, e.g., **landing rights**, **network authorization**, or **registration of the space network**.

Under such authorization or licensing regime, there can be legal and technical conditions, such as the need for customer care services, provision of a good quality of service, lawful intercept, and more.

(b) The **Service Segment** also includes the satellite terminal provision and deployment. There are many things to consider here, but limiting this to the essential and most important things to worry about is related to ensuring that the terminals do not cause harmful interference to other services. In such case, some of the regulatory requirements are:

- **Type approval** and the related marking (e.g., CE or FCC) of the terminal are required for each terminal type and ensure that the terminal is built based on a specific standard. A qualified laboratory does the testing on a prototype and thus ensures that the terminal model does not cause harmful interference or cause harm to humans.
- **Certification** of the terminal equipment, for example, for aviation and maritime purposes. Such certification is normally related, for example, to safety

installation and aviation safety requirements. Such certification is usually obtained by the aviation or maritime authorities.

- **Authorization for satellite terminals**, which varies from country to country and regulated by the spectrum authority which ensures that the terminal equipment is operated in conformance to the laws and regulation of that country. Some countries require the licensing of individual terminals, and in others certain terminals are license exempted or are allowed to operate under a single "umbrella" license. The latter two cases are when the terminals have technical and operational characteristics which ensure that there is no harmful interference caused to other services and applications.

(c) The **Device Segment** and **Device Link** are usually outside the reach of the satellite operator, although the interface requirement between the satellite terminals and the user devices must be known and designed by the satellite operator. Typical user devices such as smartphones, tablets, and laptops can be interfaced to the satellite terminal using radio spectrum such as 3G, LTE, WiFi, or Ethernet cable. The authorization of the spectrum used and the terminal compliance to national regulations are the responsibilities of the national provider licensed or authorized for the provision of such spectrum. Hence this is outside the scope of this book.

4.2 Requirements for the Space Segment

There are several regulatory approvals that may be required at the space segment side, and these are mainly related to the spectrum used by the satellite and governed by the International Telecommunication Union (ITU) and the notifying administration of the satellite operator. Other approvals are also required and relate to the launch and space operations governed by the United Nations' Outer Space Treaty (UN OST) of 1967 and other related international law provisions.

(a) **ITU approvals**, required for satellite spectrum rights, such as:
  (i) **ITU satellite filings** are required (see Article 9 of the ITU Radio Regulations) when sending a satellite into space. Such filings describe the orbital resources required, such as the orbit type and the frequencies used by the system. Without such filings and the ITU process that goes with it, the system will not be recognized by other countries and satellite operators.
  (ii) **Frequency coordination**: after the submission of the satellite filings, the satellite operator is required to coordinate with all affected services and systems. The procedure is described in Article 9 of the ITU Radio Regulations. In particular, the date of receipt of the satellite filing by the ITU Bureau serves as a marker for the satellite operator to request coordination with all satellite systems filed before its filing. The operator has 7 years to fully coordinate the satellite filing and then to notify and bring into use the assignments of such satellite filing. Specifically to non-GSO satellite systems which operate in certain frequency bands and where

Article 22 of the ITU Radio Regulations applies, the non-GSO satellite system must comply with the equivalent power flux density limits (e.p.f.d.) which ensure that the non-GSO systems do not cause harmful interference to the GSO networks. When the non-GSO satellite system complies with such limits (the ITU Bureau has a software to check this), then the system is not required to coordinate with GSO satellite networks.

(iii) **Internationally agreed limits** are limits that apply in certain frequency bands which ensure that the emissions of a satellite system do not cause harmful interference to certain radio systems. For example, power flux density limits (see, Article 21 of the ITU RR) which protect GSO networks or terrestrial systems; off-axis antenna gain limits or e.i.r.p. density limits; interference limits; Article 22 e.p.f.d. limits. Such limits are specified in the resolutions, appendices, annexes, and the provisions of the ITU Radio Regulations. The satellite system must be designed and operated in respect of such requirements.

(iv) **Bring into use** and **notification:** before the end of the 7-year regulatory period, the assignment of the satellite filings must be notified and brought into use. This is regulated by the provisions set under Article 11 of the ITU Radio Regulations and often ITU Resolutions which regulate a particular satellite service. Once the notification has been received by the Bureau, the assignments of the satellite system or network are placed onto the Master International Frequency Register (MIFR), which is there to provide international recognition and protection from harmful interference by later filed assignments of other systems or networks.

The ITU WRC-19 has just agreed upon a milestone approach for the deployment of the satellites of a non-GSO satellite system. Such approach states that the non-GSO system must launch one satellite before the end of the 7-year regulatory period and then has to deploy the full constellation based on three milestones of length 2, 5, and 7 years from the end of the 7-year regulatory period. The percentage of the constellation that must be deployed within such milestones is 10%, 50%, and 100%, respectively. Failure to meet such milestones will have consequential penalties for the satellite constellation, such as reduction of the constellation size.

(b) **Ground coverage approvals**: As each satellite covers part of the Earth with its beams or that a full constellation may be able to cover the full globe, the landing of signals or capacity on the countries of the Earth may require a national authorization. Such authorization may take the form of a “landing right,” “spectrum authorization,” “space object registration,” or other kinds of authorization. This authorization varies from country to country. From analysis made by the authors when working with certain satellite operators, the number of jurisdictions of the world that require such authorization is limited to less than 40 countries. The author believes that such authorization is redundant because other forms of authorization are required for the operations of the satellite services on the ground, such as licensing of spectrum use and licensing of satellite equipment.

4.3 Regulatory Requirements for the Ground, Control, and Network Segments

At the ground segment side (see Fig. 1), we have large-sized antennas and electronic equipment (e.g., down-converters, filters, modems). The antenna receives signals from the satellite (and vice versa) which are then converted to data information (through the modems) that is then transmitted through fiber links to the network segment ground connections (the "ground network") to reach a particular destination. This happens through the use of a closed-circuit network, usually leased from TELCOs, by the satellite operator. At this point, certain system functions are connected to the network, such as network operations center (NOC) and billing system.

(a) For the **Ground Segment** as the corresponding Earth stations are located in certain countries, as there is use of spectrum here, and as well as there is transit of user data and information through to the core network and the World Wide Web, each national jurisdiction will require some kind of authorization. For example:
   (i) **Authorizations for the spectrum use**: by Earth stations connecting to the satellites and these will usually take the shape of a license for the use of spectrum. Such license will need to carry technical limitations which may stem from the regulations or frequency coordination which was carried out by the Earth station operator (which may be different than the satellite operator).
   (ii) **Landing rights**: required by certain countries to authorize the landing of satellite spectrum from the satellites to the Earth stations receiving/transmitting the signals. This is required by a limited number of countries, less than 40 in the world.
   (iii) **ISP license, carrier license, or equivalent**: This is a license required by a small number of jurisdictions which may want to ensure that the satellite or Earth station operators provide a service that is of good quality and that complies with certain national regulations or just for taxation purposes.
   (iv) **Lawful intercept requirements**: these stem from the national cyber security laws, which may ensure that user traffic can be monitored or filtered, for example, for policing purposes.

(b) **Control Segment**: For the purpose of regulatory approvals, authorization requirements that can be included in the above, especially (i) and (ii), also the Control Segment, which is the part of the system that sends signals (telecommand) and receives signals (Telemetry) from the satellites for the control, monitoring, and health of the spacecraft in outer space. As the **Control Link** (see Fig. 1) does not carry any user data, this part of the system is not subject to any carrier licensing or lawful intercept.

(c) The **Network Segment** (see Fig. 4) is the core of the satellite system where all the data and information flow through from users on one side of the network to users on the other side of the space segment. All telecommunication functions

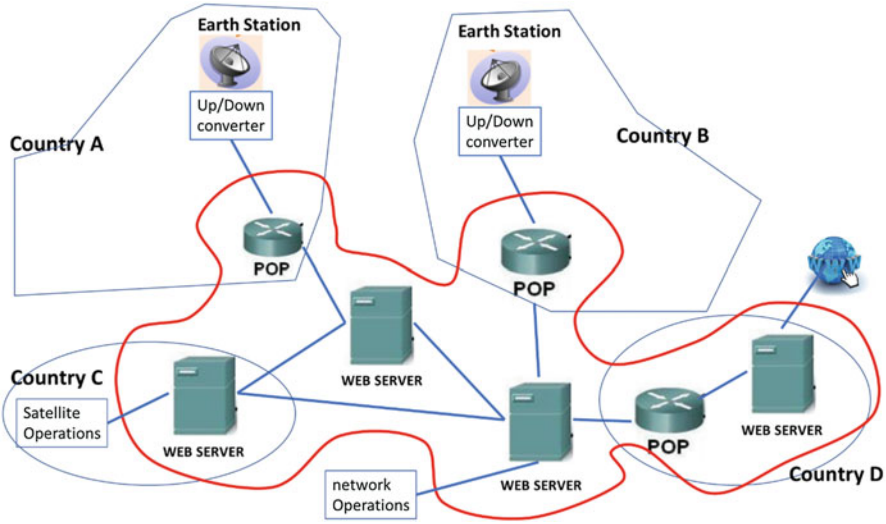


Fig. 4 Simple network model. (Graphic courtesy of the author)

of the satellite systems are practically located here, and thus it forms a very important part of the satellite system, such as:

(i) The **Point of Presence (POP)**, usually located near the Earth stations or can be isolated from these. The POP is an IP switch with related servers, where IP data flows through, controlled and monitored/filtered, and also where information of subscribers of that country or that roam in that country is also located.

(ii) The **Servers**, located within data centers scattered around the world (which are usually leased). These serve as data banks or switches, where data is processed or just switched to another server or POP.

(iii) Other functions such as switches connected to the WWW or the billing center, satellite operations, network operations, or even the server of a business client (e.g., mobile or Telco operators).

From a regulatory perspective, the pieces (e.g., POP, servers, switches) of the network segment need to be identified with the countries where these various network blocks are located. This is because the country may have special regulations and laws that apply to such functions. For example, in China the POP should be the place where data from Chinese users is processed, controlled, or filtered before it leaves or enters the country; as such the POP is captured within certain legal and technical conditions that these have to comply with. This matter will not be addressed by this section.

4.4 Other Regulatory and Legal Requirements

This section will not cover other national regulatory or legal requirements that a satellite system will need to comply with. This should not be undermined, and usually they should be discussed with a partner or a law firm of a particular country. These other requirements could be:

(a) Administrative fees such as importation duty, VAT, or taxation
(b) Universal Service Obligation tax, paid to the authorities based on revenues on that country

5 Example of Regulatory Requirements in Some Countries

It is known that regulatory requirements differ from country to country and it is no easy task to acquire authorizations and licenses for satellite services or spectrum use around the world.

It requires knowledge of the local regulations and knowledge of the satellite system and its business model. As import, the influence of geography, culture, legal system, and the country's history greatly influences the national regulations for Telecoms (Mazar 2008) and thus that for the satellite services.

Countries like France, Italy, and Spain, for example, follow formal and codified law (Napoleonic Code, or Roman Law), which sets the legal norms that authorize telecommunication services and equipment. So, any kind of telecommunication authorization for services and spectrum must be inscribed in law. In such legal environment, a ministerial department such as a ministry is required to regulate all telecommunication services, including that of satellite systems.

Other countries follow some form or another of common law (e.g., USA, UK) and thus rely on a more flexible approach to regulating telecommunication services and radio equipment.

Others still, such as those in the European Union (EU), in certain cases follow norms set by the European Parliament set to harmonize regulations for services and equipment that have a broader market access across the member states of the EU (see for example, the Authorization Directive https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Al24164). Regulations for satellite applications and equipment may follow such approach (see for example, the Radio Equipment Directive https://ec.europa.eu/growth/sectors/electrical-engineering/red-directive_en).

It is not the scope of this section to provide details on this topic; however, information of how satellite services, and in particular non-GEO constellations, are regulated in some countries and regions of the world will be provided. Information on national requirements for non-geostationary constellations will be provided below.

In addition to the national legal environment, which sets the national regulations on allowing satellite services to be operated in the country at the international level, the International Telecommunication Union (ITU) regulates through international law access to spectrum and the management of interference that can be caused to services on a global scale. The ITU's Constitution and Convention (see, https://www.itu.int/en/history/Pages/ConstitutionAndConvention.aspx) and the other instruments of the ITU, related to the radio sector (ITU-R), telecom and standards sector (ITU-T), and development sector (ITU-D), form part of the ITU treaty laws. In particular, the Radio Regulations and its other instruments are very pertinent to the proper functions of satellite systems, including those of non-geostationary satellite constellations. Some specific information on this topic will be provided below.

What is also important in this is that certain national regulations, for example, the licensing of a hub or a gateway or the landing rights in a country, will require the existence of an ITU satellite filing, which is addressed in the following section.

International law related to the launch and operation in outer space for satellites and/or constellations of satellites will not be addressed in this section. This is a topic under the responsibility of the United Nations Office of Outer Space Activities (UN-OOSA) and the related Outer Space Treaties (see, https://www.unoosa.org/pdf/publications/STSPACE11E.pdf) which regulate through international law the peaceful operations of space objects in outer space.

5.1 Satellite Filings of the International Telecommunication Union (ITU)

5.1.1 Background

The ITU is the specialized agency of the United Nations responsible for the international development of regulations and standards governing wired and wireless information and communication technologies (ICT). Since its first Radio Conference in 1906 (Berlin; see, https://www.itu.int/en/history/Pages/RadioConferences.aspx?conf=4.36), it is responsible to regulate radio spectrum at the international level. It wasn't until the late 1950s that the ITU considered initiating international discussions on space communications and then not until the ITU's Extraordinary Administrative Conference (1963; see, https://www.itu.int/en/history/Pages/RadioConferences.aspx?conf=4.89) that radio frequencies and treaty text were adopted for the various space services. However, major modifications to the ITU-R Radio Regulations and the procedures to regulate frequency allocations of space services were introduced in subsequent radio conferences, such as that of WARC 1979 (see, https://www.itu.int/en/history/Pages/RadioConferences.aspx?conf=4.101) and WARC ORB 1988 (see, https://www.itu.int/en/history/Pages/RadioConferences.aspx?conf=4.119). The latter conference was instrumental in the structuring of regulations for the geostationary space objects.

The ITU was restructured in 1992 into the ITU, and its three sectors that are known today (i.e., Radio (ITU-R), Telecom and Standards (ITU-T), and Development (ITU-D)) and the subsequent World Radio Conference have done a great amount of work in the space communications, especially starting from WRC-1992 when the first non-geostationary constellations were studies and allocations were assigned (e.g., Motorola's Iridium, Qualcomm's Globalstar, Inmarsat's ICO-P).

5.1.2 ITU Satellite Regulations

The ITU Radio Sector, or ITU-R, has legal instruments enshrined in its Radio Regulations (https://www.itu.int/pub/R-REG-RR). The preamble of these Radio Regulations provides the principles under which these are founded, for example:

> 0.3 [...] that radio frequencies and any associated orbits, including the geostationary-satellite orbit are limited natural resources and that they must be used rationally, efficiently and economically, in conformity with the provisions of these Regulations, [...]

and

> 0.4 All stations, whatever their purpose, must be established and operated in such a manner as not to cause harmful interference to the radio services or communications of other Members [...]

Hence, space objects that use any radio spectrum in frequency allocations (from 8.3 kHz to 3000 GHz) assigned to space services must conform to these regulations for two main reasons:

- Ensure the rational, efficient, and economical use of spectrum.
- Not to cause harmful interference to other services or stations in the same service.

The first point is addressed by the Study Groups of the ITU-R, which embark in studies that ensure this principle and thus develop and adopt ITU-R Recommendations that ensure compatibility between services. And the second point, also studied by the Study Groups and the Recommendation it follows, it is ensured through the active coordination between proponents and the registration of their frequency assignments into the Master International Frequency Register (MIFR).

Hence, the objectives of a satellite company at the ITU are to (1) coordinate the assignments of its satellites with other proponents and then (2) obtain international recognition for these frequencies by recording these onto the ITU's Master International Frequency Register (MIFR) (see, https://www.itu.int/en/ITU-R/terrestrial/broadcast/Pages/MIFR.aspx).

This process is regulated by Articles 8, 9, and 11 of the ITU Radio Regulations, for example:

- Article 8 "Status of frequency assignments recorded in the Master International Frequency Register"
- Article 9 "Procedure for effecting coordination with or obtaining agreement of other administrations"
- Article 11 "Procedure for effecting coordination with or obtaining agreement of other administrations"

5.1.3 ITU Satellite Filings

General Objectives of Satellite Filings

The whole process described above starts with the satellite operator requesting to file the frequency assignments of their satellite system to a member state of the ITU, e.g., the FCC in the USA for US companies, Ofcom in the UK for British companies, or MIIT of China for Chinese companies. This is done through the ITU process whereby a satellite filing must be compiled as per the ITU-R procedures under Article 9 of the Radio Regulations. How these filings are compiled and the whole process of submissions and management will not be addressed here, but what is important for the reader here is to know that such filings are a necessary step to:

- Be recognized internationally – important for investors and financing of the satellite system.
- Start the frequency coordination process under Article 9 of the ITU Radio Regulations with other filings submitted at an earlier date – necessary for limiting the interference and thus affecting the design of the satellite system.
- And ultimately, at the launch of the physical satellite(s), the notification and bringing into use of the frequency assignments of such filings can be submitted under Article 11 of the ITU Radio Regulations and be recorded to the MIFR – necessary for the interference protection from future satellite systems.

Frequency Allocations for Non-geostationary Systems

With the advent of non-geostationary satellite constellations, WRC-1992, WRC-1995, and WRC-2000 adopted certain frequency allocations for these systems.

- **WRC-1992** adopted mobile satellite service (MSS) allocations below 3 GHz for the MEO and LEO constellations providing Global Mobile Personal Communication Systems (GMPCS) (see, https://www.itu.int/en/gmpcs/Pages/default.aspx). These systems are for the personal voice and very low-speed data communications, many of whom are used for aero and maritime safety and emergency applications. WRC-1997 adopted certain feeder link allocations (C- and Ka-band) for these systems.
- **WRC-1995** and **WRC-2000** adopted Fixed Satellite Service (FSS) allocations above 3 GHz, for the LEO and MEO constellations providing high-speed broadband connectivity globally. These allocations are now being targets by the new mega-constellations of the 2010/2020s, such as OneWeb and SpaceX.

For the latter allocations, the ITU also adopted regulatory provisions in the ITU Radio Regulations which allow the non-geostationary satellite systems the operations of their constellations within the same frequency bands as that of the geo-stationary satellite systems.

Some of these provisions are footnote No. 5.484A (similar footnote provisions also exist for other FSS bands (e.g., in C- and V-bands)), which states that (see Article 5, in Volume 1 of the ITU Radio Regulations):

> **5.484A** The use of the bands 10.95–11.2 GHz (space-to-Earth), 11.45–11.7 GHz (space-to-Earth), 11.7–12.2 GHz (space-to-Earth) in Region 2, 12.2–12.75 GHz (space-to-Earth) in Region 3, 12.5–12.75 GHz (space-to-Earth) in Region 1, 13.75–14.5 GHz (Earth-to-space), 17.8–18.6 GHz (space-to-Earth), 19.7–20.2 GHz (space-to-Earth), 27.5–28.6 GHz (Earth-to-space), 29.5–30 GHz (Earth-to-space) by a non-geostationary-satellite system in the fixed-satellite service is subject to application of the provisions of No. **9.12** for coordination with other non-geostationary-satellite systems in the fixed-satellite service. Non-geostationary-satellite systems in the fixed-satellite service shall not claim protection from geostationary-satellite networks in the fixed-satellite service operating in accordance with the Radio Regulations, irrespective of the dates of receipt by the Bureau of the complete coordination or notification information, as appropriate, for the non-geostationary-satellite systems in the fixed-satellite service and of the complete coordination or notification information, as appropriate, for the geostationary-satellite networks, and No. **5.43A** does not apply. Non-geostationary satellite systems in the fixed-satellite service in the above bands shall be operated in such a way that any unacceptable interference that may occur during their operation shall be rapidly eliminated. (WRC-2000)

Thus, this footnote states that non-geostationary satellite systems:

- Are operating under the Fixed Satellite Service (FSS), thus given the same priority rights vis-à-vis any other ITU service operating in the same frequency allocation
- Must protect and must not claim protection from geostationary satellite systems. In relation to the former, non-geostationary satellite system must comply with the equivalent power flux density limits given in Article 22 of the ITU Radio Regulations (see also Resolution 76 (WRC-15) of Volume 3 of the ITU Radio Regulations)
- Must share the allocation and coordinate on the basis of the ITU Radio Regulations

WRC2019 Milestone Rules for Non-geostationary Constellations

The World Radio Conference-2019 has developed new rules for non-geostationary, constellations under the standing agenda item 7, that come into force on 1/1/2021. These new regulations, in general, can be summarized as follows (not taking into account any transitional measures adopted for satellite filings filed and brought into use before 1/1/2021):

- A satellite filing of a non-geostationary constellation can be brought into use and notified within 7 years of being submitted to the ITU by the launch of a single satellite capable to transmit the assignments notified (A filing has an expiry date of 7 years from its submission, and a satellite must be launched and reach the intended orbit before such expiry date. If the satellite is launched and reached the intended orbit on the date before its date of expiry, the notifying administration will have another 120 days (composed of a 90 days of continuous operations at the intended orbit, plus an additional administrative period of 30 days) to notify the bringing into use of the satellite(s)). At this point, when the milestone process kicks in from the date T equal to the date when the satellite filing exprires;

- Within 2 years of the end of the regulatory period of the satellite filing (i.e., time T +2 years), 10% of the satellites of the constellation must have been launched, or failing that the difference in number between launched satellites and 10% of those filed loses priority;
- Within 3 years after that (i.e., time T+5 years), 50% of satellites of the constellation must be launched, or failing that the difference in number of satellites loses priority;
- Within 2 years after that (i.e., time T + 7 years), 100% of satellite of the constellation must be launched, or failing that the difference in number loses priority.

Fees for Satellite Filings

The ITU Council in 2019 discussed and modified Decision 482 (i.e., **Document C19/143-E**, Decision 482 "Implementation of cost recovery for satellite network filings," 20 June 2019), which provides information on the cost recovery fees by the ITU-R for all satellite filing submissions and notifications (note: The ITU Council is the interim governing body of the ITU, which meets every year and operates under delegation from the ITU Plenipotentiary Conference (see the ITU Constitution and Convention at https://www.itu.int/en/history/Pages/ConstitutionAndConvention.aspx)). For example, a typical non-geostationary filing submission may generally cost the satellite operator around 25,000 CHF and notification of around 50,000 CHF (cost varies based on the number of units and submitted forms; see the above mentioned Decision 482).

The ITU cost recovery is in addition to what the notifying administration (Term used by the ITU-R for the Member States of the ITU that submit the satellite filings) charges for the management of the satellite filings. This charge (and the management of satellite filings) is different from country to country. At the national level, fees for the management of satellite filings differ, with cost for submission of filings which could range from a total of € 20,000 in France (and no annual fees thereafter) to a much higher figure of the USA of US$471,675 (with an annual fee of US$122,775). The cost will differ also from the type of satellite mission, for example, the cost for amateur, or CubeSat-type satellites will differ than that of a constellation of larger-sized satellites.

5.2 Landing Rights

5.2.1 Definition

This term is often misused and can mean different things to different people. Also, while some countries specifically mention the word "landing rights" into their regulations, others do not, but still in practice, the practice or requirement has the same objective.

For clarity, the words "landing rights" are defined as:

> any regulatory requirement, or regulations, that allow the transmission and receptions of radio frequencies or signals of a space station to land at, or be received from, a given country.

“Landing rights” are not related to the authorizations of ground equipment transmissions or receptions, although the term landing rights can be confused with this process. Ground equipment requires additional or other regulatory approvals that are to be addressed separately below.

The term “landing rights” is used differently from country to country, and this may range from:

- Landing rights in Indonesia (We understand that the FCC has announced a major reduction in fees, at least for small companies and with an expedited processing procedure; see https://spacenews.com/op-ed-streamlined-fcc-licensing-a-big-deal-for-smallsats/)
- Satellite operating license for a foreign satellite in India (see https://www.isro.gov.in/sites/default/files/article-files/indias-space-policy-0/satcom-ngp.pdf)
- Space station frequency license in China (Article 30 of the Regulations of the People’s Republic of China on the Management of Radio Operation, first published on September 11, 1993)
- Registration of foreign space objects in Australia (see Australia’s Foreign Space Object Determination, https://www.legislation.gov.au/Details/F2018C00844)
- Market Access Grant of the FCC (see Approved Space Station List of the FCC, https://www.fcc.gov/approved-space-station-list)
- Network authorization, in some other countries

Overall the objective for a national regulatory authority is to regulate foreign satellite operators that can enter their national market. Some do this to protect the local industry (e.g., USA, India) others to know what space resources are available for their national infrastructure (e.g., Australia) while others for security purposes (e.g., China).

In general, not many countries of the world require these landing rights; from the author’s regulatory experience over the past 25 years, it is known that the number of countries requiring these landing rights is less than 40 of the 220 regulatory jurisdictions of the world.

5.2.2 Regulatory Conditions for Landing Rights

Regulatory conditions for the landing rights as discussed above, in the nearly 40 countries of the world that require these, will vary from country to country. Some examples are given in the following Table 2.

5.3 Spectrum Use and Authorizations

It has been shown above that the ITU affirms that spectrum is a natural resource and that it “*must be used rationally, efficiently, and economically.*” Hence, through the

Table 2 Some countries and examples of the regulatory conditions for satellite system operation

Country	Type	Regulatory conditions	Fees	Difficulty
Australia	Registration	None	None	None
China	Frequency license	ITU coordination with all Chinese satellite operators	None	High Requires a strong national partner
India	Operating license	Of national value or lack of Indian capacity	None	Medium-high Access granted if no other Indian system is available
Indonesia	Landing rights	Local partnership	Unknown	Medium Requires a national partner
USA	Market access	Serve the public interest Open processing round for other applicants Show sharing with others	Post a surety bond (US$ 5 million) in satisfaction of FCC Part 25 rules Paid back through milestones	Medium May restrict the use of spectrum utilized

inception of national regulations, the main aim of any national authority should be to control the assignment of spectrum to national users and operators, so that spectrum is used efficiently and does not cause harmful interference. However, such process may not ensure that spectrum is effectively utilized to its fullest, and, nowadays, regulators of many countries have adopted new principles for assigning spectrum, for example, the use of market spectrum pricing approach, or even spectrum auctions.

However, for the satellite communications, whose operational reach is beyond country's borders and whose operations of satellite platforms rely on the same conditions globally, a well-defined and easily controlled spectrum management approach is still required. This is even more the case because spectrum, between satellite operators, can be shared and a market based spectrum assignment could create unnecessary monopolies detrimental to competition.

As such, the authorization regime for satellite communications still relies on a spectrum management approach licensing and at lowest fees possible.

The type of authorizations required at the ground for a non-geostationary constellation is no different than that of a geostationary, and countries are encouraged to expand their current geostationary regulations to non-geostationary. However, such approach has several problems, such as spectrum assignment, and spectrum fees are transacted on a one-to-one basis for non-geostationary platforms. This does

Table 3 Differences in approaches used by geostationary and non-geostationary systems

	Geostationary	Non-geostationary
Equipment spectrum use	10 MHz	100 MHz
Equipment data rates	1 Mbps	50 Mbps
Emitted power levels (EIRP)	60 dBW per antenna	37 dBW per antenna
Elevation angles	20° (low)	60° (high)
Business models	Usually for use by an individual user or company	Usually for a multiuser use

not work well because non-geostationary satellite systems operate at a different business model and at different operational, technical, and business models than that of the old geostationary systems.

Some examples of technical and business parameters of equipment used by geostationary versus non-geostationary systems are provided in Table 3.

Below are some additional licensing information on satellite terminals and gateway stations/hubs.

5.3.1 Satellite Terminal Licensing and Spectrum Use

As shown in Fig. 1, at the beginning of this regulatory section, there is a service segment on the ground, which provides the connectivity to end users and businesses in a given country.

The satellite equipment of this segment is what links (through radio waves) the end user devices and the satellite system.

Because the satellite equipment, such a an antenna with its receiver/transmitter unit, is a radio station utilizing radio resources it is then captured by the national regulations (or telecom law) on electronic equipment. Such regulation will form part of a national regulatory regime which may require:

- **An authorization or license** for the **sale and installation of the satellite equipment** (e.g., in India, Indonesia), which will either be under a license exemption or an individual/blanket license (In proper English the noun is spelled as "licence," while the verb is as "license," while in the US English, it is distinguishable as "license.").
- **An authorization or license for the use of the spectrum** (e.g., in certain European countries, China, India), which will either be under a license exemption or an individual/blanket license. It is usual in some countries (e.g., in Europe) that a license exemption regime exists, whereby satellite terminals do not require a license, and as such they will not be afforded protection.
- **An equipment type approval** (in almost every country of the world) **for the distribution, circulation, and sale of the equipment to the public**. In the European Union, this is governed by the Radio Equipment Directive (see, https://ec.europa.eu/growth/sectors/electrical-engineering/red-directive_en), and the type approval of the equipment will result in a marking with a "CE" symbol. Similarly for the FCC marking. Countries around the world usually recognize

equipment markings developed by other countries. However, the equipment may still require a type approval certificate from a local laboratory (e.g., China, India, Russia).

- **An associated ITU satellite filing**, which assures the regulatory authority that the satellite system exists.
- **A landing rights license** (only for certain countries).
- And sometimes the need to **coordinate the spectrum use** with terrestrial services which may share the same band. Usually if terrestrial services exist in a particular band, these will be licensed on an individual basis and thus will be afforded protection from the satellite services.

Additionally, the service provider in the country may also require additional licensing, such as a **business license** (e.g., in China. This is pretty much a requirement in many countries) which allows him to provide services to the public and businesses.

In terms of fees for these regulatory instruments, these can vary from country to country: from a zero or small administrative fee, such as is the case in certain countries (for certain satellite services and equipment) through a proper statutory instrument which exempts these from an authorization, usually by complying to specific technical requirements (usually derived from the CEPT/ECC Decisions which establish conditions for equipment and services to be license exempted) which assures the regulator that the equipment does not cause harmful interference. This is usual in the CEPT/EU, where the regime is such that equipment which complies with certain technical requirement that assures that the equipment does not cause harmful interference to other services and/or equipment. See also the EU Authorization Directive and the “general authorization” conditions, such as “The aim is to harmonise the market for electronic communications networks and services by limiting regulation to the minimum necessary. The main innovation is the replacement of individual licences by a general authorisation for all electronic communications networks or services, alongside a special scheme for attributing frequencies and numbers. Thus the provision of electronic communications networks or services may only be subject to a general authorisation without the need to obtain an explicit decision or any other administrative act by the national regulatory authority (NRA), thus limiting the procedure to just one notification for the companies concerned.” (See https://www.ecodocdb.dk/document/category/ECC_Decisions?status=ACTIVE.)

- To a large fee, usually liked to revenues generated in a country by the satellite service provider or to the amount of spectrum occupied and/or a fee for the Universal Service Obligation Fund (usually in the range of 1–2% of national revenue). This is usual in developing countries (e.g., in Asia and Africa) where certain telecommunication services or certain geographical areas of the country may require the state to intervene and invest in the infrastructure.

5.3.2 Earth Stations' Licensing

Also, from Fig. 1, the necessity to place the gateway stations (used for feeder link or TT&C purposes; also known as "hubs" for some type of services) in certain countries of the world has been shown. Such stations serve the purpose to relay the user information back to Earth and then to the cable/fiber access points in that country that relays back the information to the service operators, which usually are different than the satellite operator of the non-geostationary constellation.

As gateway stations transmit radio signals to and from the satellite(s) from a fixed location on the ground, usually through a very large infrastructure, connected to an international fiber cable, will be captured by many licensing regulations, including those for radio spectrum and radio equipment.

Unlike the satellite terminals discussed above, these Earth stations may not require the same kind of authorizations and radio technical conditions. This is because these fixed stations are fixed to the ground and are unique.

Usually the placement of these gateways is purely decided from an engineering perspective; the best location for the satellite link is where existing telecommunication sites called Teleports exist. However, the reality is slightly different, and political and national laws intervene where such Earth stations may be placed or required for specific purposes. While in most countries of the world this selection is purely based on an engineering choice, some countries will require an Earth station gateway in their country, for example, USA, Russia, India, China, and Brazil.

Licensing of Gateway Earth Stations

Putting this aside, the regulatory requirements of gateways are usually as follows:

- Landing rights
- Spectrum authorization or license
- Spurious emission limits
- Frequency coordination with terrestrial services

All of these are the same authorizations required for the satellite terminals for the service segment. Some differences exist, and these are physical and business:

- From a physical perspective, these Earth stations can be quite large, from about 3 m in diameter (in Ka-band) to even more than 30 m (for C-band frequencies). The reason lays on the purpose of these stations, being to carry all the traffic on a satellite through the feeder link, which is generated by thousands and possibly hundreds of thousands of terminals at the service link. This also means that you may not need many of such stations around the Earth. Usually one will suffice for each geostationary satellite and thus usually one per non-geostationary satellite.
- From a business perspective, these Earth stations are part of the satellite infrastructure, very much like the cables of a mobile telecommunication service, where such cables connect the radio masts to the central operating system, in satellite jargon called the Network Control Center (see Fig. 1). Hence this private-

Table 4 Differences in license fees for fixed gateway Earth Station in some countries

Country	Fee per year
UK	Based on the Earth station parameters and the amount of spectrum occupied. For a typical Earth station with a 1 GHz occupation, the fee is around GBP 5,000 (6,500 US$) per year[a]
Italy	Spectrum fees at a maximum of € 22,200 (19,645 US$) per year per site Additional administrative fees are applicable[b]
Australia	Depends on the location of the facility, i.e., for 1000 MHz of spectrum, the spectrum fee per year is: High density: 194,200 AUS (128,609 US$) Medium density: 30,500 AUS (20,198 US$) Low density: 3,200 AUS (2,119 US$)[c]
South Africa	RAND 2344 (147 US$) per MHz RAND minimum R58 596.00 (3,662 US$) per hub station[d]
USA	$325 per license $325 for each hub[e]

[a] See https://www.ofcom.org.uk/__data/assets/pdf_file/0020/27461/fees.pdf

[b] See https://www.mise.gov.it/index.php/it/comunicazioni/servizi-alle-imprese/codice-delle-comunicazioni-elettroniche

[c] See https://www.acma.gov.au/fees-apparatus-licences

[d] See https://www.icasa.org.za/pages/spectrum-licensing

[e] See https://docs.fcc.gov/public/attachments/DOC-353885A1.pdf

based infrastructure is not generating business but a pure physical part of the satellite network.

From research done by the author, license fees for gateway Earth Stations vary from country to country. A small taste of such fees is provided in Table 4.

Sharing with Terrestrial Radio Systems

From a radio perspective, these Earth stations need to be operating at certain frequency allocations, usually, in the ITU jargon, the Fixed Satellite Service. Depending on the amount of spectrum required and the design of the satellite system, Ku- and Ka-bands are quite apt to accommodate these stations, even if these bands are shared with terrestrial services.

When it comes to sharing with the terrestrial services, usually point-to-point microwave links operating under the ITU's Fixed Service, these large Earth stations will usually be able to coordinate easily with such terrestrial equipment. This is because Earth station antennas are very large, they will have extremely small beamwidth, and they are pointed to the sky toward the satellite, while microwave link antennas are also with small antenna beamwidth and will point horizontally. In such physical reality, it will be possible to operate closely without causing harmful interference to both systems.

Unlikely to the satellite terminals of the service link, gateway station license will be for an individual antenna and will be afforded protection from any radio equipment which may be deployed afterward.

Table 5 Frequency allocations for different frequency bands

Band	Receive frequency	Transmit frequency
C-band	3600–4200 MHz	5950–7075 MHz
Ku-band	10.7–12.75 GHz	12.75–13.25 GHz 13.75–14.0 GHz 14.0–14.5 GHz
Ka-band	17.7–18.6 GHz 18.8–20.2 GHz	27.5–30.0 GHz
Q/V-band (not yet commercially used but new uses are now pending)	37.5–42.5 GHz	42.5–43.5 GHz 47.2–50.2 GHz 50.5–51.4 GHz

More difficult is the sharing with terrestrial systems that are mobile, because the location of the latter is unknown a priori. However, sharing can still be possible through particular technical means.

TT&C Earth Stations' Licensing

TT&C Earth stations (see Fig. 1) are similar to the gateway Earth stations that carry feeder link data. However, as explained in the section "Different Satellite Links," their purpose is much more limited but extremely important because the control and monitoring of the satellite is done through these links.

Their licensing is similar to the gateway licensing and possibly easier because their spectral occupancy is much smaller.

Spectrum Allocations for Gateway Earth Stations for Non-geostationary Systems

The typical spectrum allocations for feeder link and TT&C Earth stations are as provided below (see ITU Article 5 of the Radio Regulations; see Table 5).

These allocations can be used for the provision of feeder link and TT&C services of non-geostationary satellite systems. Their coordination is done through the Article 9 of the ITU Radio Regulations.

6 Conclusion

This article, although it provides useful details, does not represent an exhaustive explanation of the regulatory and licensing requirements for non-geostationary satellite systems. Indeed because of the complexity of satellite networks and their regulatory frame, the rules and regulations are never static and are indeed constantly evolving. Also, it doesn't cover other complex regulations and licensing requried by outer space activities, such as the launch and the operations of satellites.

The complexity of the process to obtain frequency allocations and ensure that satellite transmissions do not interfere with other satellites, terrestrial systems, or other systems such as aeronautical-related transmissions or high-altitude platform systems is a very difficult and challenging process. And beyond the technical and operational challenges, there are regulatory requirements related to taxation and tariffs to be met. There are constantly new standards, regulations, or authorization of other types as well. These may well relate to concerns about privacy, money laundering, cyber security, policing, or national security. The basic requirements to obtain key licensing and authorizations have been covered in this brief article, but it must be noted that there are constantly emerging new regulatory requirements and the level of complexity involved only seems to increase.

7 Cross-References

- ▶ Deorbit Requirements and Adoption of New End-of-Life Standards
- ▶ Financial Models and Economic Analysis for Small Satellite Systems
- ▶ Legal Issues Related to the Future Advent of Small Satellite Constellations
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ▶ “Rules of the Road” for Launch and Operation of Small Satellites and Related Issues
- ▶ Small Satellites and Their Challenges to Space Situational Awareness (SSA) and Space Traffic Management (STM)
- ▶ Small Satellites Market Growth Patterns and Related Technologies
- ▶ Space Finance for ‘New Space’ and Small Satellites
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit

References

H. Mazar, An analysis of regulatory frameworks for wireless communications, societal concerns and risk: the case of radio frequency (RF) allocation and licensing (2008.), at https://eprints.mdx.ac.uk/133/2/MazarAug08.pdf
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Al24164
https://ec.europa.eu/growth/sectors/electrical-engineering/red-directive_en
www.itu.int
https://www.itu.int/en/history/Pages/ConstitutionAndConvention.aspx
https://www.unoosa.org/pdf/publications/STSPACE11E.pdf
https://www.itu.int/en/history/Pages/RadioConferences.aspx?conf=4.36
https://www.itu.int/en/history/Pages/RadioConferences.aspx?conf=4.89
https://www.itu.int/en/history/Pages/RadioConferences.aspx?conf=4.101
https://www.itu.int/en/history/Pages/RadioConferences.aspx?conf=4.119
https://www.itu.int/pub/R-REG-RR
https://www.itu.int/en/ITU-R/terrestrial/broadcast/Pages/MIFR.aspx
https://www.itu.int/en/gmpcs/Pages/default.aspx
https://spacenews.com/op-ed-streamlined-fcc-licensing-a-big-deal-for-smallsats/

https://www.isro.gov.in/sites/default/files/article-files/indias-space-policy-0/satcom-ngp.pdf
https://www.legislation.gov.au/Details/F2018C00844
https://www.fcc.gov/approved-space-station-list
https://www.ecodocdb.dk/document/category/ECC_Decisions?status=ACTIVE
https://www.ofcom.org.uk/__data/assets/pdf_file/0020/27461/fees.pdf
https://www.mise.gov.it/index.php/it/comunicazioni/servizi-alle-imprese/codice-delle-comunicazioni-elettroniche
https://www.acma.gov.au/fees-apparatus-licences
https://www.icasa.org.za/pages/spectrum-licensing
https://docs.fcc.gov/public/attachments/DOC-353885A1.pdf

Legal Issues Related to the Future Advent of Small Satellite Constellations

Steven Freeland

Contents

Abstract

The development of international space law within the United Nations, and specifically as negotiated through global consultations of the UN Committee on the Peaceful Uses of Outer Space (COPUOS), was largely first undertaken in the

---

Professor of International Law, Western Sydney University; Director, International Institute of Space Law. This chapter was written in September 2019 and builds on my previously published research as follows:

1. From Little Things, Big Things Grow: How Should We Regulate the Commercial Utilization of Small Satellite Technology? in George D. Kyriakopoulos and Maria Manoli (eds), The Space Treaties at Crossroads: Considerations de Lege Ferenda 65–78, 2019 Springer.

2. A Delicate Balance: Regulating Micro Satellite Technology in a Big Satellite World (2014–2015) 18:1 University of Western Sydney Law Review 1–18.

S. Freeland (✉)
Western Sydney University, Sydney, Australia
e-mail: S.Freeland@westernsydney.edu.au

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_73

1960s and 1970s. This process resulted in the negotiation and creation and implementation of the Outer Space Treaty and four additional subsidiary binding instruments. Quite understandably, these twentieth-century agreements did not anticipate many of the latest developments in space technology and systems that have arisen in the twenty-first century. One of the most significant developments in recent years is the development of small satellite technology and systems that can be designed, manufactured, and launched at much lower cost. The international space law that was agreed a half century ago is in some way not sufficient to specifically address all of the issues associated with deployment of large number of small satellites. These issues include a number of concerns related to frequency allocations and interference, removal or deorbit of small satellites at end of life, space situational awareness and space traffic control, and other concerns related to the safety of space systems in Earth orbit.

The processes of agreeing international space law are complex and are based on achieving global consensus and thus tend to be quite slow. By contrast, the current pace at which small satellites are being developed and launched is accelerating each year. This raises concerns about space safety and the avoidance of collisions in space, as well as increased levels of frequency interference. The complexities associated with achieving new levels of international agreement suggest that many of these safety, frequency interference, and improved space situational awareness and space traffic management issues will need to be addressed at the national regulatory level – especially with regard to small satellites. In this regard, issues related to the deployment of the so-called mega-constellations and removal of these satellites at the end of life are perhaps among the most urgent.

This chapter explores the background of international law and regulation with regard to the launch of satellites into Earth orbit, and especially with regard to the increasing number of small satellites that are now being launched or planned for deployment. It also suggests that national regulatory controls and safety measures to prevent the excessive buildup of space debris and increased frequency interference will be the critical near-term solution to these emerging problems. In addition, some form of "soft law" guidelines and informally agreed measures at the international level might also be helpful.

Keywords

Australian Space (Launches and Returns) Act 2018 · Barriers to access to space · Collision avoidance maneuvers · Frequency allocation and interference · Federal Communications Commission · General Assembly Principles · Liability Convention · Long-term sustainability of outer space · Mega-constellations · National space regulations · Outer Space Treaty · Small satellite constellations · Soft law · Space debris · Space traffic management · United Nations Space Treaties

1 Introduction

On 2 September 2019, the European Space Agency (ESA) performed what it referred to as a “collision avoidance maneuver” – in layman’s terms, a change of course – of its low Earth orbit observation satellite Aeolus, (https://www.esa.int/Our_Activities/Operations/Aeolus_operations 2019) in order to avoid a potentially catastrophic collision with a SpaceX Starlink satellite. This Aeolus satellite had a mass of 1.3 tons when launched in August 2018 and thus was a substantial target. The Starlink satellite is known as Starlink 44 – represents one of some 60 satellites launched by SpaceX on 23 May 2019 as the initial phase of the constellation. This satellite with a mass of 227 kg when launched is substantially less massive than the Aeolus satellite, but a collision would have created thousands of new debris elements. While such evasive actions are not unheard of, the unique aspect of this event was that it was the first time that an operator had found it necessary to undertake such a maneuver to mitigate against the possibility of a conjunction with a small satellite that is part of a small satellite “constellation.”

Small satellite (“mega-”) constellations can be thought of as fleets of hundreds and perhaps even thousands (https://www.spacex.com/sites/spacex/files/starlink_-press_kit.pdf 2019) of spacecraft working together in orbit. Typically, they will comprise “small” or “nano-’ satellites, albeit that those terms are not strictly defined and are generally thought to include space objects ranging from tiny “femto-’ satellites weighing less than 100 gm to those “mini” satellites weighing up to 500–1000 kg, and everything in between (at this stage, most small satellites seem to be at the lower end of the scale).

For various reasons outlined below, small satellite constellations are expected to become a significant feature of space activities over the next few years and thus will give rise to a disproportionately large increase in the number of space objects that operate within the Earth’s space environment.

While such objects are much smaller than the average low Earth orbiting satellite, given the required orbital velocity necessary for them to remain in space, they are still large enough to cause serious damage to other (larger) spacecraft supplying important services such as Earth observation and meteorology. This has not escaped the attention of the national and international authorities, and there is the risk of a backlash from the established players concerned about the potential increase in collision risk from the additional number of small objects in low Earth orbit.

As the number of satellites in space dramatically increases, close approaches between two operated spacecraft will occur more frequently. In contrast to potential conjunctions with space debris – nonfunctional objects including dead satellites and fragments from past collisions – these require coordination efforts between the respective operators to avoid conflicting actions and, ultimately, collision avoidance maneuvers of the type conducted by ESA in situations of high potential disaster.

The Aeolus/Starlink 44 incident will, therefore, add further fuel to the increasingly strident debate that is emerging about the risks and opportunities that this technology gives rise to. It seems that the advent of small satellite constellations is inevitable, at least from the perspective of industry, even in the absence of clear prohibiting regulation; thus it is important to understand the major relevant legal issues related to this development. These issues are discussed in this chapter.

2 The Evolutionary Events that Have Led to Small Satellite Constellations

Since the launch of Sputnik 1, the first human-made space object to orbit the Earth, there has been a breathtaking and seemingly endless development of space-related technologies. Humankind is now engaged in a multitude of space activities far beyond the contemplation of those involved at that time. The utilization of space technology now forms a crucial part of everyday society in all parts of the globe – irrespective of the (geo)political, economic, societal, and cultural characteristics of any one country.

Simply put, our reliance on space technology is such that the world would cease to function in many respects without constant and unimpeded access to space, and this imperative is likely to become even more pronounced for future generations. This has primarily been driven by the increasing “commercialization” of outer space.

Yet, as is well known, there remains a vast gulf between the space capabilities of the relatively small number of space “powers” and the rest of the world. It has been estimated that approximately up to 60–70 States currently possess some form of direct indigenous space capability, although the extent that they are able to utilize space for their own development (and other) purposes varies quite significantly. Of course, this also means that perhaps up to 130–140 States thus far do not possess *any* independent indigenous capability to directly access space themselves, despite their reliance on the technology for many aspects of their functioning and development. These countries are instead totally dependent on others for their space access, which therefore impacts upon their space independence and national security and may well also impede opportunities for creativity, innovation, industrial development, and progress among their citizens.

The reality is that their access to satellite data and the ability to utilize vital space technology in a crisis would be largely dependent on and subject to the strength and enforceability of their existing contractual relationships and political ties. Given the changing nature of international (geo)politics, it seems that reliance upon historical and traditional strategic links, or pre-agreed international arrangements, may be more prone to uncertainty and difficulties than ever before.

This invariably operates within the space arena as well – the combination of factors arising from any State’s growing reliance on space assets and space-related data and intelligence, coupled with its increasing focus on maintaining sovereign independence and capability in areas of critical infrastructure, means that any country will seek out ways in which it can be more self-reliant in its interaction with space activities.

It is in this context that the recent development and adaptation of small satellite technology potentially represents a paradigm shift in the way humankind accesses space. These satellites are usually cheaper and less complex to develop, build, and launch than conventional (large) satellites. They therefore open up the possibilities for a significantly greater degree of space access to a much larger range of States and their space "actors." Initially, groups such as university students and nonprofit organizations in both developed and developing countries increasingly have become involved in space through these means. In many countries, the development of this technology may represent an important precursor to the establishment of indigenous and independent space programs in States that previously were not in a position to consider such activities.

In effect, by eliminating some significant barriers to entry, small satellite technology may facilitate capacity building, broader collaborative opportunities and education/training programs, as well as bridging (some) technology gaps, for hitherto "non-space-faring" States. It will also open up even more diverse commercial opportunities for a much broader range of potential service providers and, generally, "bring space to more people."

But more than that, significantly, as the technology has been developed even further, it has also opened the door also to "traditional" users of outer space – including both States and private commercial entities – to utilize it for existing as well as new purposes. This has served to broaden the scope of their capability at a significantly lower relative cost, which may present some interesting and potentially lucrative commercial opportunities. Of course, this is subject to the development of feasible and achievable business cases – although the fact that several large corporations are proceeding down this path seems to suggest that this is possible.

In addition, this has and will require a mind-shift on the part of existing space actors, as they grapple with whether and how to adapt to this relatively new technology and adjust their activities to the challenges posed by the potential for new market entrants. Yet, as is clear from the announced plans of companies such as SpaceX, One Web (2019), Planet (2019), Amazon (Sheetz 2019), and others, it is an opportunity that is being embraced in significant terms.

As a consequence, the increasing advent of this technology is already redefining the landscape of many activities in space. This new space paradigm will not see the end of more traditional satellite technology since, naturally, small satellite technology will not quench our insatiable demand for all that space can provide. However, it does open up a plethora of possibilities, many of which we are simply not in a position to comprehend or even imagine at this point. In this regard, one might liken the potential of small satellites to the way that mobile phones have revolutionized terrestrial communication activities. We simply do not know where this technology might ultimately lead and what it will allow us to do. However, we can confidently expect that it will open the door to an even more expansive array of profitable commercial opportunities.

Thus, from a technological perspective at least, small satellite technology most likely represents a "win-win" possibility that enhances the momentum for change and further promotes commercial space activities. Indeed, in many respects, this has been the primary motivation for both developers and users thus far. As with many aspects related to the exploration and use of outer space, the technology continues to move forward at a rapid pace without sufficient attention being paid to the regulatory consequences and requirements. It is therefore important not to be too caught up in this wave of optimism and innovation, without at least also considering how these developments coexist with the current international regulatory framework, which has largely been designed to govern those space activities carried on through the utilization of “big” satellite technology.

Moreover, the fact that small satellite constellations allow greater access to space for more people does not necessarily translate into an adherence to responsible space behavior. Indeed, it may have the opposite effect, particularly if the regulatory regime is not specifically relevant, appropriate, and/or respected. This, of course, gives rise to immediate questions as to what the major issues are and what the current regulatory framework has to say about these. From there one has to then consider whether a sui generis set of prescriptive rules, principles, or standards should be developed and made applicable to small satellite constellations.

The purpose of this chapter is therefore to take pause and reflect on various regulatory requirements and challenges posed by the existing international legal regime in relation to the use of small satellite technology to develop constellations. While many of the users of this technology are no doubt cognizant of these requirements, it is this author’s experience that many are not; or, put another way, they do not consider the regulatory issues with the same degree of attention as they do the technical factors.

What this discussion will highlight is the fact that the existing legal framework was not designed with small satellite technology specifically in mind. As a result, further regulation will most likely be required – particularly at the national level – and this will necessitate a “balancing” of sometimes competing interests between protecting the State from potentially very significant liability on the one hand and encouraging innovation and research and development on the other.

Coupled with these considerations, the increasingly crucial notion of responsible space behavior must also play a part in determining how to address some of these specific issues. Although the discussion below focuses on the current regulatory requirements, it leads to the conclusion that the design of future legal regimes to deal specifically with small satellite technology will necessitate some fundamental policy decisions by national lawmakers and regulatory bodies.

3 The Current International Legal Framework and Regulatory Requirements

The international regulation of the exploration and use of outer space is primarily based upon a series of five United Nations Space Treaties. These are (i) 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, 610 U.N.T.S. 205 (Outer Space Treaty); (ii) 1968 Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, 672 U.N.T.S. 119 (Rescue Agreement); (iii) 1972 Convention on International Liability for Damage Caused by Space Objects, 961 U.N.T.S. 187 (Liability Convention); (iv) 1975 Convention on Registration of Objects Launched into Outer Space, 1023 U.N.T.S.

15 (Registration Agreement); and (v) 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 1363 U.N.T.S 3 (Moon Agreement).

Also of importance are several General Assembly principles: (i) 1963 Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space, United Nations General Assembly Resolution No 1962; (ii) 1982 Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting, United Nations General Assembly Resolution No 37/92; (iii) 1986 Principles Relating to Remote Sensing of the Earth from Outer Space, United Nations General Assembly Resolution No 41/65; (iv) 1992 Principles Relevant to the Use of Nuclear Power Sources in Outer Space, United Nations General Assembly Resolution No 47/68; and (v) 1996 Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries, United Nations General Assembly Resolution No 51/122.

The treaties in particular set out a number of fundamental rules, imposing various obligations on States parties, some of which are also regarded as representing customary international law (Hobe et al. 2009).

Those States that are parties to the major United Nations Space Treaties are subject to various obligations that logically point to the need to develop national space law (Freeland 2012) to regulate those private entities within their respective jurisdiction that engage or wish to engage in "national activities in outer space."(Outer Space Treaty, Article VI) More and more States are therefore promulgating national space laws to "transform" these international obligations into their respective domestic legal spheres. The status of these various national space laws as reported here are not necessarily up-to-date for those countries, nor comprehensive in its coverage. For example, in December 2017, the New Zealand Outer Space and High-altitude Activities Act 2019 came into force in that country. Quite a number of other States have also finalized or are in the process of developing their own national space legislative framework (United Nations Office of Outer Space Affairs (UNOOSA) 2019).

Given that the advent of small satellite technology presents opportunities for hitherto non-space-faring States to engage in space activities, it may well be that the development of such technology in a particular country may "pre-date" any specific applicable national laws. Thus, the possibilities of greater access to this technology may be a driving force in the enactment of a further "wave" of national space law in various countries – for example, as was the case in Austria, which enacted its national space law in late 2011 (Freeland et al. 2018). Another example is the Austrian Outer Space Act 2011, which entered into force in December of that year and was introduced largely in response to the development of small satellite programs by a number of Austrian universities, and the impending launch of two Austrian-built small satellites, which were eventually launched from India into low Earth orbit in February 2013.

In certain respects, therefore, the development of national space law represents a major growth "industry" for space professionals and government regulators.

It should be noted that, in addition to these various instruments, and possibly also to supplement any perceived "gaps," there have recently been an increasing number of "soft-law" guidelines concluded that also relate to the conduct of particular activities in outer space. This has been for several reasons, partly related to the strategic and political nature of space, which has made the finalization of internationally binding treaties more difficult to achieve (Marboe 2012). Given the current increasingly competitive geopolitical environment between the major powers, these difficulties will, if anything, be further exacerbated.

This chapter will refer primarily to existing "hard-law" regulatory requirements that flow from the United Nations Space Treaties – although reference will be made to one important set of voluntary guidelines – from the perspective of how they may relate to the use of small satellites and seek to raise some pertinent questions that arise from their applicability. It is not intended in this chapter to be exhaustive in this regard or comprehensive as to all precise details, but rather to raise the more significant issues and the challenges they pose. This will also serve to highlight the importance of properly addressing the reality of small satellite constellations by way of specifically directed regulation, given that the use of small satellite technology, and the "management" of these constellations, will most likely continue to grow exponentially into the future.

4 International Regulatory Requirements for Deployment and Operation of Space Systems

Some of these (international) regulatory requirements are as follows.

4.1 International Responsibility: Authorization and Supervision

As noted above, the regime for space activities is structured on the basis that States bear international responsibility for "national activities in outer space," including when such activities are carried on by nongovernmental entities. While there is no precise definition in the Outer Space Treaty as to what constitutes a "national" activity, the terms of the domestic space law of a particular State will clarify the scope of activities to which it refers – in essence, representing an interpretation by the drafters of that legislation as to what they regard as constituting national activities in outer space, at least for the purposes of the specific domestic law.

A review of existing national space legislation indicates that, in most cases, States have legislated for the regulation of space activities based on the "territoriality" of the activity (i.e., where an activity, e.g., a launch, involves the territory of that State), in accordance with general international law principles of jurisdiction. In addition, many States that have national space law also regulate space activities based on the nationality of the space actor (i.e., the person/entity engaged in the space activity).

For example, one of the express objects of the Australian Space (Launches and Returns) Act 2018 is:

> to establish a system for the regulation of space activities carried on either from Australia or by Australian nationals outside Australia. . .

Thus, a launch of a small satellite in Australia by any private person or entity will in all likelihood engage the international responsibility of that State under the Outer Space Treaty, as will the involvement of that person/entity in a small satellite program – for example, the QB50 program. Under this program the satellites were launched from outside Australia. In these circumstances, therefore, (international) responsibility under the Outer Space Treaty is interpreted as extending to extraterritorial activities and is applied under the general international law concept of "nationality." (One such example is the involvement of a number of Australian universities in the QB50 mission, which involved the launching in 2017 of a network of 36 "CubeSats" built by universities all over the world, with the aim of performing various scientific experiments in the lower thermosphere at an altitude of approximately 320 kilometers. Twenty-eight of these small satellites were deployed from the International Space Station in May 2017 and eight from India in June 2017.)

Article VI of the Outer Space Treaty goes on to require that the "appropriate State" – which is thought by most commentators to refer to the State whose national activity it is – undertake the "authorization and continuing supervision" of such activities. Typically, the authorization of space activities is implemented by way of a licensing regime established under national law (at least for those States with specific domestic space legislation) (Freeland 2010). This can be through the creation of a comprehensive "one-size-fits-all" license regime or, more likely, via the establishment of different forms of license, depending upon the particular space activity for which authorization is being sought.

For example, the Australian Space (Launches and Returns) Act 2018 specifies a number of different licenses to deal with specific space activities, including an "Australian Launch Permit" for launches from Australian territory and an "Overseas Payload Permit" for launches of a space object by an Australian national from outside of Australia.

In relation to the use of small satellites, there is little conjecture that their launch/deployment and use do, indeed, constitute a space activity. Moreover, the satellite itself would in most circumstances be a space object for the purposes of international space law – including for the purposes of the Liability Convention, as well as the national law of most countries. Activities involving small satellites therefore would typically fall within the scope of Article VI of the Outer Space Treaty.

This in itself is not surprising, but must be taken into account, particularly by those wishing to engage in "experimental" and "amateur" small satellite activities. When it comes to sophisticated commercial operators, particularly those that are planning to launch/deploy small satellite constellations, one must assume that they are now familiar with this requirement. In any event, the reality is that those seeking to engage in small satellite activities, irrespective of where those satellites might be launched, should take careful note of the relevant national laws and apply for the requisite license (where applicable). As noted below, this might also have added consequences in terms of financial and liability concerns, as well as other aspects of conditionality.

Moreover, the requirement of continuing supervision on the part of the State may be quite complex. There is, for example, some conjecture as to how, in practice, the need for continuing supervision might be undertaken in circumstances where the relevant space activity is a cooperative venture between institutions in a number of States, such as the case with the QB50 project. Internal arrangements between the cooperating States should be put into place to allow for each State to, in some way, exercise a degree of supervision, at least in relation to those aspects of the activity (and over its nationals who may be involved in its ongoing operation) in which it has a specific interest.

Yet, even this presupposes that the institutions or persons engaged in the space activity have informed the relevant governmental agency of their involvement and have provided specific and comprehensive details as to the scope of the program, design, payload, issues of control, etc. The recent "tardigrades" incident on the moon illustrates precisely this point – it seems that, in this instance, one of the entities involved in the Beresheet mission allegedly failed to inform other relevant stakeholders about the fact that living organisms (tardigrades) were on board the space vehicle (Johnson et al. 2019).

Another example of the difficulties that could arise with respect to the authorization and continuing supervision obligations that arise through the Outer Space Treaty, and which involved a group of small satellites, is illustrated by the "Swarm Space Bees" incident in 2018. Four very small space objects were launched (from India) into low Earth orbit even though the relevant American regulatory authority, the Federal Communications Commission (FCC), had refused to grant authorization to the operator to proceed with the launch of those particular small satellites (Howell 2018). Although the company was ultimately fined for its actions, the case highlighted the problems that can arise when a space actor fails to comply with the relevant national regulatory requirements.

This incident also gives rise to interesting questions as to the extent of, in this case, the United States' liability under the international space regulatory framework had one of these unauthorized objects caused damage to another space object. This author has had informal discussions with officials from the United States' Administration, who confirmed that, from their perspective at least, the Liability Convention regime for fault liability (Liability Convention, Article III) would not apply, given that the Administration had exercised an authorization process (and decided *not* to authorize the launch) with respect to this group of small satellites. This is an issue that will no doubt be further debated by commentators.

Adding further to the complexity is the fact that many small satellites have, to date, not been designed with control systems, and therefore cannot be maneuvered once they are launched and operative. As a result, for these small satellites, as soon as they are placed in orbit, their position cannot be altered from Earth. This may also explain why the continuing supervision requirement may often have been disregarded, leaving the responsible State in a difficult position in terms of its obligations under the Outer Space Treaty. Of course, the features of more sophisticated satellites may change when they are a part of a commercial small satellite constellation that is required to perform more complex functions.

4.2 International Liability: National Indemnity Requirements

The general international liability provisions found in the Outer Space Treaty and the more detailed regime specified in the Liability Convention impose liability on a "launching State" for certain damage caused by a space object. There are no time limitations or caps on the amount of this liability under the Liability Convention, as long as it represents "damage" by a "space object" as those terms are defined for the purposes of that instrument.

Article VII of the Outer Space Treaty prescribes the general terms that give rise to international liability for damage caused by an object launched into outer space. The scope of international liability is then elaborated in the Liability Convention.

However, even if it is not a State Party to the Liability Convention, a State would still be subject to the liability provisions in the Outer Space Treaty, as well as any other potential claims under relevant general principles of public international law. Further, the identity of the relevant launching State(s) is determined at the time of launch, with Article I(c) of the Liability Convention defining a launching State as:

> (i) A State which launches or procures the launching of a space object;
> (ii) A State from whose territory or facility a space object is launched

Finally, Article I(a) of the Liability Convention defines "damage" as:

> . . .loss of life, personal injury or other impairment of health; or loss of or damage to property of States or of persons, natural or juridical, or property of international intergovernmental organizations.

It would be difficult, given this background to seek to argue that an operating small satellite was not a space object for the purposes of the Liability Convention, even if it is not maneuverable while in operation.

In the absence of specific indemnities in relation to claims by third parties, or where various exceptions and exonerations contained in the Liability Convention do not apply, a launching State will bear this international obligation of liability (Freeland 2001) even in circumstances where the space activity is undertaken by a nongovernmental entity and perhaps also even where the State may not be aware of the activity at all. On this point, there may be an argument that, where the only possible relevant mode by which a State could be a launching State in a specific case is by "procuring" the launch, there is a minimum "threshold" test to demonstrate whether there has in fact been a procuring, at least based on knowledge of the particular activity. However, it is unclear whether such an argument reflects the correct legal position.

This represents one compelling "incentive" for States to pass domestic space law. The enactment of national space law enables States to formalize domestic legal processes that would allow them to pass on financial responsibility to and recover from their national nongovernmental entities the full amount (or part thereof) of the damage for which the State may be liable at the international level, either under the international legal and regulatory framework for space activities or otherwise under international law.

Of course, this does not remove the international obligation of liability of a launching State under the Liability Convention – this contingent liability remains in place in relation to any space object for which a particular State is deemed to be a launching State. A well-known expression that is often used by teachers of space law is: "Once a launching State, always a launching State." However, it does enable the State to put in place a domestic mechanism by which it can transfer the financial "risk" associated with this potential international liability for third-party claims. Indeed, this is precisely the practice that a number of States have followed in their national laws in relation to "traditional" satellite technology.

As a consequence, national space legislation often attaches conditionality to the issue of a license to engage in a specific space activity, the practical effect of which is to require the applicant to provide or somehow procure an indemnity to the government for damage, although the amount may be subject to specific caps under the particular national law. Although it would be relatively straightforward to simply require the applicant in these circumstances to take out appropriate commercial insurance against third-party claims to the extent of the specified (maximum) damage, this would often be impractical (given the relative lack of depth of the international space insurance market) and, more specifically in the case of some small satellite operators, disproportionally costly. Under the Australian Space (Launches and Returns) (Insurance) Rules 2019 made under the Space (Launches and Returns) Act 2018, which also came into force on 31 August 2019, certain launch and return activities require zero insurance to be procured by an applicant, while for others, the specified minimum amount of insurance required is $100 million (Rule 6). For those activities that do require a specified amount of insurance, the Australian Space (Launches and Returns) Act 2018 envisages that, in certain circumstances, rather than satisfy those requirements, an applicant could instead show "direct financial responsibility" for the relevant launch or return as an alternative (section 47(b)).

Indeed, such a requirement might make the planned small satellite activity unaffordable, thus preventing it from going ahead at all, although this will obviously not be as much of a concern for those large corporations planning to embark on a small satellite constellation program.

For the less affluent small satellite operators, however, this could conceivably give rise to difficult considerations that would require a "balancing" between the protection of the State from potential financial liability and the desirability of encouraging expertise, research, and development, perhaps as a precursor to more profitable and commercial opportunities down the track.

Such potentially conflicting interests between a need for regulation on the one hand and the provision of incentives for new innovation on the other are not unique to the situation of small satellite operators. Indeed, similar arguments have been raised in relation to the requirement for the "equitable sharing of benefits" derived from the exploitation of natural resources under the Moon Agreement. Section 3(b)(i) of the Australian Space (Launches and Returns) Act 2018 refers to the need to consider inter alia "...the removal of barriers to participation in space activities and the encouragement of innovation and entrepreneurship in the space industry...."

However, unlike the Moon Agreement, virtually every space-faring State is a party to both the Outer Space Treaty and the Liability Convention – and, in any event, the liability regime they establish arguably is also reflective of customary international law. It is therefore incumbent on all States with an (potential) involvement in space to somehow address this issue.

The ideal scenario would be for the small satellite operator to negotiate with the relevant launch service provider for the provision of insurance cover and/or an indemnity by that provider (and perhaps also the government standing behind that provider) to the launching State and the payload owner, at least in relation to certain elements of potential third-party claims (again most likely subject to a cap). This is often the case in commercial launch service contract arrangements for large satellites. Some small satellite operators contend that the position is more complicated in the case of a collaborative small satellite program such as the QB50 project. However, the point remains that many such programs have proceeded without the issue even being raised with either the launch service provider or the intermediary arranging the launch. Potential operators of small satellite constellations should be aware of this preferable negotiating course of action when discussing their commercial contracts.

Once again, this is something that should be negotiated coincidentally with the development of the technical aspects of such a program. A failure to do so potentially not only places the launching State(s) in a difficult position but might also expose the institution or corporation supporting the small satellite operators to a real and unacceptable risk of liability. Obviously, this should be of practical concern to those involved, although one would likely assume that a large corporation planning a multimillion dollar small satellite constellation program will be sufficiently abreast of this issue to address it more comprehensively.

4.3 Registration: National and United Nations Registers

The Registration Convention provides for a two-pronged regime of registers that are relevant in respect to space objects that are launched inter alia "into earth orbit."(Registration Convention, Article II(1)) The State of Registry (as defined) is to maintain a national register in which such space objects are to be included and, in addition, shall provide certain specified information in relation to those objects to the United Nations, which itself maintains a central register (*Ibid*, Article IV(1)). In accordance with the terms of the Outer Space Treaty, the registration of a space object within a State's national register also has implications with regard to the "jurisdiction and control" of that object (Outer Space Treaty, Article VIII).

In situations where a State has not, for instance, previously been involved in launching activities, it may not have in place a national register nor a mechanism for the furnishing of the required information to the United Nations. There may be a time lag associated with the establishment of the national register, which, in most circumstances, could only be implemented and maintained on an ongoing basis under national space legislation (Australian Space 2018). Once again, this will require consultation and information flows between the small satellite operator and the relevant government agency (if indeed such an agency exists).

In addition, with widespread cooperative small satellite programs that may potentially involve institutions from many countries, there will be a need for careful coordination between the various launching States as to who should be the State of Registry – it can only be one of the launching States (Registration Convention, Article I(c)). It may not, for example, make practical sense that each launching State would seek to be the State of Registry for its specific small satellites in the context of a joint program involving a large constellation of objects launched simultaneously from the one launch vehicle.

Likewise, where a large number of (identical/similar) small satellites are launched or deployed into Earth orbit as part of a constellation program, either at the same time or over a period of time, it may not be feasible or practicable to require a separate registration filing and number for each one of them. This is a practical and policy issue for each national regulatory authority to determine and has implications also for the information that is subsequently passed on to the United Nations Office of Outer Space Affairs (on behalf of the United Nations Secretary-General) pursuant to the terms of the Registration Convention (Article IV).

5 Sustainability of the Space Environment: Space Debris Mitigation

One of the major challenges for the future exploration and use of outer space and for the long-term sustainability of space activities is the growing proliferation of space debris, which represents both a major area for environmental concern but also can and increasingly will impact upon human safety. Much has been written about the exponential growth of pollution in outer space and the hazards that it poses (Bohlmann and Freeland 2013).

There are many approaches as to how the problems should be addressed, given that the whole issue of the environment of outer space is a complex one, with many interconnecting variables at play (Bohlmann and Freeland n.d.). As noted above, these variables, and the enormous financial implications that would arise from setting in motion binding requirements, have meant that, to date, only soft law guidelines, rather than hard law treaty regulation, have been agreed to address this issue.

Nonetheless, these IADC guidelines, (2007) although voluntary and expressed in general terms, are significant in that they reflect existing practices as developed by a number of States and international organizations and set (minimum) standards toward which space-faring nations should strive. By implementing the guidelines contained in these soft law instruments via national or agency policies, policy makers might ultimately contribute to the formation of a due diligence standard, assuming that international practice is sufficiently widespread and representative.

The principles underpinning the debris mitigation guidelines are that care should be taken to minimize the risk of debris “creation” in the conduct of space activities. The UN Guidelines recognize two broad categories of space debris mitigation measures: those that curtail the generation of potentially harmful space debris in the near term, through the minimization of the production of mission-related space debris and the avoidance of break-ups, and those that limit their generation over the longer term, for example, by end-of-life procedures that remove decommissioned spacecraft and launch vehicle.

The importance of accessing and using space for all aspects of our lives necessitates a diligent adherence to these standards to the greatest extent possible. It is generally recognized that it is in the interests of all space-faring States to follow these guidelines, and this is, as noted, increasingly reflected in their practices. The long-term sustainability of outer space activities is a matter of interest and importance for the international community as a whole and has been a principal focal point for UNCOPUOS over more recent years. **During its 62nd session in June 2019, UNCOPUOS adopted the Preamble and 21 Guidelines for the Long-Term Sustainability of Outer Space Activities (Long-Term Sustainability Guidelines). These provide guidance on policy and regulatory framework for space activities; safety of space operations; international cooperation, capacity-building, and awareness; and scientific and technical research and development. The problem of space debris remains as a major element among the specific issues addressed by the Long-Term Sustainability Guidelines. UNCOPUOS is encouraging States and international intergovernmental organizations to voluntarily take measures to ensure that these guidelines are implemented to the greatest extent feasible and practicable:** (UN Doc. A/AC.105/C.1/L.366 2019)

There are some potentially significant environmental challenges that arise from the use of small satellite technology, particularly the development of plans for large constellations of small satellites as has been announced by major corporations. Growing demand, the expanding range of functions, and, ultimately, the commercial services can provide point to rapid increases in the numbers of small satellites that will be placed into Earth orbit. In order to utilize this technology to achieve “global” coverage, very large constellations of small satellites will be required, and, as noted, some are now at various stages of implementation. While, at least initially, most of these satellites will be placed into a low Earth orbit, projects such as these will “populate” important orbits with a significant number of space objects and increasingly pose a potential collision risk, as well as raising other concerns as to possible future de facto “appropriation” of particular orbits.

Even with respect to less ambitious low-cost small satellite programs, the issue may still remain. Many experimental satellite programs have been exactly that “experimental.” They have often utilized existing “off-the-shelf” components, and the expectations of mission success for any significant period of time have not necessarily been high. It is fair to say that such circumstances give rise to lower perceptions of risk and a higher tolerance toward failure. For many such programs, at least in the relatively early phases of small satellite development, the process has largely been about the journey (to space) rather than the delivery of services – though of course this is now changing.

Many of these programs have relied on “piggyback” launches, which have meant that the satellites have been placed in orbits significantly higher than the very low orbits that would allow them to decay relatively quickly. For many small satellites, therefore, there is a potentially very long period (perhaps in excess of the 25-year cap suggested by the IADC Debris Mitigation Guidelines) before orbital decay, even though the satellite itself will have been functioning for only a short timeframe.

This also highlights the seeming change in risk tolerance that is occurring due to the advent of much cheaper small satellites, as compared to large and very expensive traditional satellites. The issue of an increased “acceptable failure rate” might also apply to small satellite constellations to an even greater degree in terms of numbers of inoperable space objects. It is entirely feasible to suggest that, when a “mega-’ constellation comprising thousands of small satellites is launched/deployed, there is considerable “redundancy” built into in the system, meaning that literally hundreds of objects may fail – thus rendering them inoperable and non-maneuverable – and yet the commercial goals of the operator are still achievable.

Even though operators may claim that this is not a “problem” given that those objects will descend to and burn up in the Earth’s atmosphere in a relatively short space of time, (Henry 2019) this will certainly not always be the case. In this regard, large operators have announced plans to eventually locate small satellite constellations in orbits higher than the low Earth orbits that are currently being utilized, meaning that they will almost certainly remain in space for a long time, thus posing an increased collision risk. **It has been reported that, as part of its Starlink small satellite constellation, SpaceX hopes to launch approximately 2,800 satellites at altitudes between 1,100 and 1,325 km above the Earth** (Mosher 2019).

Moreover, as noted, there are several variants of small satellite technology. While it is too simplistic to categorize them solely on the basis of their size and weight, some satellites may be too small to be picked up by conventional tracking systems. Indeed, this was the stated reason for the FCC decision not to authorize the launch of the Swarm Space-Bees, although, that assertion has been disputed (Fernholz 2018). Yet, even such low-mass objects can cause catastrophic damage in certain circumstances. The potential consequences, and therefore the potential risks, would, of course, be greatly magnified should the development of a large-scale commercial human spaceflight industry ultimately come to fruition (Virgin Galactic website 2010).

Of course, these issues are relevant to the question of potential liability raised above. They also point to the need to carefully consider how, and to what extent, the future advent of small satellite constellations can and will be undertaken, so as to as much as possible be consistent with the overarching goal of managing the long-term sustainability of outer space activities in such a way as to maximize the (commercial) benefits that can be derived while maintaining appropriate and acceptable safety standards, particularly, but not only, for missions involving humans.

In some senses, therefore, the environmental consequences relating to small satellite constellation programs have not really been properly factored into the regulatory framework. This is also a question of education and awareness but is a highly important factor to take into account when designing the future legal regime to apply to such programs.

6 Other Regulatory Considerations: Frequency Allocation/Space Traffic Management/Impact on Science

As noted, these brief comments do not purport to be comprehensive as to the relevant regulatory factors associated with the new commercial space paradigm constituted by small satellite constellations. However, the primary regulatory issues that ultimately stem from the principal requirements under the United Nations Space Treaties have been raised.

There are, of course, other equally relevant considerations that also arise. For example, as more such programs emerge, particularly offering commercial services, the issue of radio frequency usage becomes all important. As noted, the historic use of the "amateur band" frequencies by experimental and noncommercial operators will no longer be applicable and appropriate in the case of small satellite constellations developed and operated by large commercial corporations. The regulatory framework of the International Telecommunication Union (ITU) will become even more relevant.

While the ITU operates effectively to manage the use of radio spectra, it is a large intergovernmental organization and can be highly bureaucratic. Decisions about allocations of valuable (commercial) frequencies need significant periods of time and are sometimes highly political, particularly in a context where there exist increasingly competitive pressures for spectrum. While the debate regarding the 28 gigahertz frequency may not directly impact on small satellite constellation programs, it is symptomatic of an even broader concern about the apparent "depletion" of available spectrum for space-related activities (see, e.g., Caleb Henry, "Satellite operators worried about losing Ka-band spectrum", Space News, 7 May 2019: https://spacenews.com/satellite-operators-worried-about-losing-ka-band-spectrum/ (accessed 11 September 2019).

As is well known, the coordination of frequencies so as to minimize harmful interference is complex. This lengthy process does not necessarily sit comfortably with the shorter timeframes associated with the development of small satellite constellation programs. Accordingly, procedures will need to be established to accommodate this technology without compromising the important work of the ITU. This will not be an easy task.

In addition, the introduction of small satellite constellations will highlight even more the imperatives to consider the development of international traffic management systems involving space traffic, as well as its intersection with air traffic. While this issue has been discussed already for some time, and some initial steps are being taken to consider the relevant factors, there is much work to be done by all stakeholders. For example, already in early 2015, the United Nations Office of Outer Space Affairs (UNOOSA) and the International Civil Aviation Organization (ICAO) jointly sponsored an "AeroSPACE" symposium where some of these issues were discussed.

More recently, another (nonlegal) issue has been raised – the impact that the launch/deployment of large numbers of small satellites into low Earth orbit (and beyond) will have on scientific endeavors and research such as astronomy. This objection arose (coincidentally) as a result of the launch of the first 60 Starlink small satellites (Bartels 2019) – obviously it is to be anticipated that this debate will only grow louder as more small satellite constellations come into existence.

7 Conclusion

This chapter has highlighted the fact that the current international legal framework continues to apply to new and developing space technologies and systems – such as small satellite constellations – that will contribute to the further evolution of commercial space activities. The advent of small satellite technology into the mainstream of space activities, and particularly the likely eventuality of various forms of small satellite constellations comprising large numbers of space objects, is an issue that is currently being addressed by the international community. For several years already, the Legal Subcommittee of UNCOPUOS has considered as an agenda item the issue of "General exchange of views on the application of international law to small satellite activities."

Interestingly those discussions have thus far seen a diverse range of views as to whether, and if so how, a sui generis set of rules should be established to specifically regulate small satellite constellations. The UN Committee on the Peaceful Uses of Outer Space (COPUOS) operates on the basis of decision-making by consensus. In light of the divergent opinions currently held by various UNCOPUOS Member States, this means that any such new legal or regulatory regime, if it were to be developed at all, will not be forthcoming for quite a period of time. Thus, the existing international framework continues to apply to small satellite constellations in every respect.

As it stands, however, the existing law and the technology, at least at the international level, does not represent a natural fit. The international regulatory framework was not designed specifically to deal with the advent of this technology nor for the expansive range of new space actors. Moreover, these new actors, in particular, may not be completely aware of, or understand, the relevance and implications of the existing framework.

The United Nations General Assembly and its Committee on the Peaceful Uses of Outer Space (COPUOS), as noted above, are therefore conscious of the imperative to explore the potential dynamics of the small satellite industry. There is awareness of the need to address both the challenges and to promote the opportunities posed by small satellite constellations. Yet, even putting any current initiatives aside, it is clear that such shifts in space technology and new space systems require the development of appropriate regulatory standards in a relatively short timeframe. Small satellite entrepreneurs, and large constellation operators, are anxious that any real (or perceived) barriers to entry posed by national regulatory requirements are removed.

Whether or not these fears are justified in every case, what seems increasingly likely is that, in some respects, small satellite technology and systems will become mainstream means of utilizing space for commercial purposes in the future. As part of this evolution, it seems likely that in the relatively near future that a number of small satellite constellation programs involving many thousands of space objects will be implemented. Attempting to regulate this twenty-first-century technology solely by reference to twentieth-century rules, devised for other space systems and technologies, is likely to create difficulties and uncertainties and perhaps deter some who would otherwise consider engaging in these new space industries and space-based services.

In the meantime, however, there is no doubt that small satellite technology can offer great opportunities, but it also poses some significant challenges to the broader perspective of the exploration and use of outer space. The desirability of clear regulation to specifically address this technology is clear, and it thus falls on national lawmakers to consider how to provide what is required within a more expedient timeframe (Freeland and Davis 2015).

In the end, therefore, clear national policies must be formulated. National legislatures will need to come to grips with the ever-changing range of space technology, particularly if they wish to become increasingly involved in space activities. Some governments have, through their national legislation, dealt specifically with the issues that arise through the advent of small satellite technology, (Marboe and Traunmuller 2012) but there is a long way to go, particularly as the ever-increasing plans for future programs emerge. Whatever rules are put in place must find the right balance. On the one hand, there is the need for regulation of the financial, operational, and technical elements, so as to minimize the risks to an acceptable level. On the other, there is the need to facilitate research and innovation to allow for greater and more efficient access to space and the potential for commercial returns on investment.

Complex public policy questions arise as to whether, for example, to exempt small satellite operators from several of the existing national regulatory requirements that apply to their large satellite "brethren." Yet, to do so may have the ultimate effect of minimizing the "incentives" or motivation of these operators to engage in best practice or to take simple, inexpensive steps to ensure that their local stakeholders are covered by existing protections.

Naturally, this may not necessarily be the case when it comes to those large corporations that are developing small satellite constellations; however, it is suggested that the industry as a whole would not necessarily be unduly stifled by the requirement that, in all circumstances, they take proper and appropriate risk management steps. Any relaxation of the rules for the users of this technology will bring with it added risks for the regulators and the relevant State, as well as raising some of the broader questions that have been alluded to in this chapter.

These are difficult choices, and States will take differing paths, depending upon their specific circumstances. This will, unfortunately, mean that there is unlikely to be established a uniform international set of rules to specifically address the complexities of small satellite constellations, at least in the short-medium term. One possible way forward is that we might see the emergence of a soft law code of conduct at the international level, but this may not provide a sufficiently comprehensive basis to properly regulate the conduct of those new actors in the space paradigm.

This again points to the strong role that national law and lawmakers have to play. For this to be effective, it will require close consultation between all stakeholders and emphasizes the need for regulators, the scientific community, the entrepreneurs, the large corporations, and the lawyers to all talk to each other to a far greater degree than has thus far been the case. It is clear therefore that any appropriate solution to address the many and varied issues that arise with the advent of large-scale small satellite constellations will need to be carefully thought through with responsible action taken at both the national and international levels.

8 Cross-References

- ▶ Deorbit Requirements and Adoption of New End-of-Life Standards
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Financial Models and Economic Analysis for Small Satellite Systems
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ▶ "Rules of the Road" for Launch and Operation of Small Satellites and Related Issues
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit
- ▶ US Space Policy Directive-3: National Space Traffic Management Policy

References

See, as an example, the Australian Space (Launches and Returns) Act 2018, Part 5

M. Bartels, 'Astronomy Group Says Starlink and Other Satellite Constellations Could Threaten Science', *Space.com*, 4 June 2019. https://www.space.com/astronomy-group-worries-about-starlink-science-interference.html. Accessed 11 Sept 2019

U.M. Bohlmann, S. Freeland, in *The Regulation of Space Activities and the Space Environment*, ed. by S. Alam, Md J.H. Bhuiyan, T.M.R. Chowdhury, E.J. Techera. Routledge Handbook of International Environmental Law (2013), Routledge, p. 375

T. Fernholz, 'The first illegal satellite launch came with a $900,000 penalty', *Quartz*, 21 December 2018. https://qz.com/1503575/swarm-technologies-settles-illegal-launch-for-9000000/. Accessed 10 Sept 2019

S. Freeland, There's a satellite in my backyard! – Mir and the convention on international liability for damage caused by space objects. Univ. NSW Law J. **24**(2), 462 (2001)

See S. Freeland, Matching detail with practice: the essential elements of national space legislation. Proc. Int. Inst. Space Law **53**, 540 (2010)

S. Freeland, *'The Development of National Space Law', in Steven Freeland*, ed. by R. Popova, S. Passy. Contemporary Issues for National and International Space Law: Commentary and Source Materials (2012), AMG, p. 12

S. Freeland, M. Davis, 'Space treaties are a challenge to launching small satellites in orbit', *The Conversation*, 17 April 2015. https://theconversation.com/space-treaties-are-a-challenge-to-launching-small-satellites-in-orbit-37971. Accessed 11 Sept 2019

S. Freeland, V. Sim, K. Hutchison, How technology drives space law down under: The Australian and New Zealand experience. Air Space Law **43**(2), 129 (2018). See also Rocket Lab website: https://www.rocketlabusa.com/. Accessed 9 Sept 2019

C. Henry, 'Amazon lays out constellation service goals, deployment and deorbit plans to FCC', *Space News*, 8 July 2019. https://spacenews.com/amazon-lays-out-constellation-service-goals-deployment-and-deorbit-plans-to-fcc/. Accessed 10 Sept 2019

S. Hobe, B. Schmidt-Tedd, K.U. Schrogl (eds.), *Cologne commentary on space law, volume i – outer space treaty* (2009), and *Volume II – Rescue agreement, liability convention, registration convention, moon agreement*. (2013)

E. Howell, Four Cubesats Snuck into Orbit Without Regulatory Approval, FCC Says, *Space.com*, 16 March 2018. https://www.space.com/40001-four-cubesats-unauthorized-launch-fcc.html. Accessed 9 Sept 2019

See https://www.esa.int/Our_Activities/Operations/Aeolus_operations. Accessed 7 Sept 2019

See https://www.spacex.com/sites/spacex/files/starlink_press_kit.pdf. Accessed 7 Sept 2019

IADC Space Debris Mitigation Guidelines issued by Steering Group and Working Group 4 of the Inter-Agency Space Debris Coordination Committee in September 2007 (IADC Debris Mitigation Guidelines). http://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf. Accessed 11 Sept 2019; United Nations General Assembly Resolution 62/217, which (in paragraph 26) endorsed the Space Debris Mitigation Guidelines agreed by the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) (UN Guidelines)

Ibid, Article IV(1)

C.D. Johnson, D. Porras, C.M. Hearsey, S. O'Sullivan, M. Vidaurri, The curious case of the transgressing tardigrades (part 2), Space Rev. 3 September 2019. http://www.thespacereview.com/article/3786/1. Accessed 9 Sept 2019

Liability Convention, Article III

I. Marboe (ed.), *Soft Law in Outer Space: The Function of Non-binding Norms in International Space Law* (2012); S. Freeland, For better or for worse? The use of 'soft law' within the international legal regulation of outer space. Ann. Air Space Law **XXXVI**, 409 (2011)

I. Marboe, K. Traunmuller, 'Small Satellites and Small States: New Incentives for National Space Legislation'. J. Space Law **38**, 289 (2012)

D. Mosher, 'Elon Musk just revealed new details about Starlink, a plan to surround Earth with 12,000 high-speed internet satellites. Here's how it might work', *Business Insider Australia*, 15 May 2019. https://www.businessinsider.com.au/spacex-starlink-satellite-internet-how-it-works-2019-5?r=US&IR=T. Accessed 10 Sept 2019

One Web, https://www.oneweb.world/. Accessed 8 Sept 2019

Outer Space Treaty, Article VI

Outer Space Treaty, Article VIII

Planet, https://www.planet.com/company/. Accessed 8 Sept 2019

Registration Convention, Article I(c)

Registration Convention, Article II(1)

Registration Convention, Article IV

S.M. Sheetz, 'Amazon wants to launch thousands of satellites so that it can offer broadband internet from space', *CNBC Markets*, 4 April 2019. https://www.cnbc.com/2019/04/04/amazon-project-kuiper-broadband-internet-small-satellite-network.html. Accessed 8 Sept 2019

Space (Launches and Returns) Act (2018), section 3(a). https://www.minister.industry.gov.au/ministers/pyne/media-releases/atmosphere-right-review-our-space-activities. Accessed 9 Sept 2019

UN Doc. A/AC.105/C.1/L.366. Report of the Committee on the Peaceful Uses of Outer Space – Sixty-second session (12–21 June 2019), UN Doc. A/74/20, paragraph 163 and Annex II

United Nations Office of Outer Space Affairs (UNOOSA). http://www.unoosa.org/oosa/en/ourwork/spacelaw/nationalspacelaw/index.html. Accessed 9 Sept 2019

Virgin Galactic website. https://www.virgingalactic.com/. Accessed 10 Sept 2019. Also S. Freeland, 'Fly Me to the Moon: How Will International Law Cope with Commercial Space Tourism?' Melb. J. Int. Law **11**(1), 90 (2010)

The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit

Christopher D. Johnson

Contents

Abstract

The emergence and near-term bringing into use of constellations of very numerous satellite constellations raises issues of unwanted and possibly impermissible appropriation of Low Earth Orbit (LEO) or portions thereof. Currently, coordination of orbital “slots” occurs only in the Geostationary Orbit (GSO), and there

---

C. D. Johnson (✉)
Secure World Foundation, Washington, DC, USA
e-mail: cjohnson@swfound.org

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_95

are no restrictive rules preventing individual actors, including both States and private entities, from deploying very numerous spacecraft into LEO. MegaLEO constellations may utilize LEO orbits to such an extent that other actors might be excluded from using these orbits. This chapter will explore explicit rights and obligations, principles of general nature, and economic and political aspects of addressing this emerging issue.

Keywords

Constellations · Global constellations · Kepler Communications · Low Earth Orbit · Megaconstellations · National appropriation · OneWeb · Outer Space Treaty · Small satellites · SpaceX · Space law · Space situational awareness · Space traffic management · Starlink · Telecommunications law

1 Introduction

The launching of very numerous constellations of small satellites into Low Earth Orbit (LEO) seems promising, but this activity should also give us pause. While spacecraft in LEO may only be operating in space for limited amounts of time, what does it mean to occupy LEO with such overwhelming presence – where spacecraft occupy multiple orbital planes with numerous satellites, and where other potential users of those orbits might not risk trying to share those orbits? International law currently prohibits the appropriation of outer space, whether void space itself or celestial bodies. However, this fundamental principle of space law suits uneasily with the broad freedoms to access, explore, and use outer space, along with the national interests of States to foster domestic industrial space capacity and pioneering space activities.

2 Normative Background of Space Law Applicable to Satellite Constellations

Constellations of numerous small spacecraft present challenges to the current legal and regulatory regimes governing space activities. However, their emergence will not pose fundamental threats to this regime. From the lawyer's perspective, the major difference between existing space projects and very numerous small satellites projects are the following: these missions use *smaller spacecraft* than the larger, more expensive, and often unique spacecraft of previous decades. These missions involve the use of satellites in *greater numbers* than these previous space activities. These missions are often *cheaper* and *quicker* to develop and execute. Next, these missions are often *in orbit for less time* than traditional space activities. The spacecraft used *may lack propulsion* necessary for on-orbit maneuvers, and/or they *may fail at higher rates* than traditional satellites. Additionally, the organizations and individuals developing and operating these projects are different than the traditional aerospace companies and large governmental agencies.

In summary, smaller spacecraft deployed; more numerous; cheaper and quicker to get to bring into use; shorter missions; and less capable or reliable spacecraft. Additionally, younger and more diverse teams, in smaller and more agile organizations.

These are the hallmarks of the ongoing small satellite revolution, which has been successful for precisely these attractive qualities. While these differences have interesting and attractive characteristics, such as allowing startups to get to space quicker and cheaper than in previous years, these differences also pose administrative and oversight challenges to regulators, raise difficult questions regarding the interpretation and application of space law, and raise concerns and challenges regarding the long term sustainability of outer space activities. In principle, the legal regime for outer space activities is sufficiently robust to address these innovations. However, the small satellite revolution is one where oversight, control, and space sustainability issues continue to exist.

Various specific space law topics will be discussed in more detail in other chapters, but it is worthwhile to briefly highly here some basic principles and sources of law which are applicable to large constellations in LEO. While some of these principles may be said to be vague in nature, they are nevertheless applicable and serve as “guard rails” to the use of LEO by any constellations of satellites. These norms comprise the regulatory context for any discussion on whether mega-constellations violate international law by impermissibly appropriating outer space as their own.

2.1 Freedom of Exploration and Use

According to the Outer Space Treaty of 1967, States are free to explore and use outer space. Article I of the Outer Space Treaty establishes that States which are party to the treaty are permitted to access, use, and explore outer space, including the Moon and other celestial bodies. Because this is such a fundamental principle of space law, upon which all other obligations and prohibitions are balanced, it is worth quoting in full.

> The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind.
>
> Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies.
>
> There shall be freedom of scientific investigation in outer space, including the Moon and other celestial bodies, and States shall facilitate and encourage international cooperation in such investigation.

In many respects, the language of Article I speaks for itself. The second sentence of Article I makes it clear that States are free to access and explore space without first seeking permission from any other State, or group of States, or from the United Nations Security Council, or any other authority or body. That States can freely explore space by themselves was not a foregone conclusion at the dawn of the space age, but was a right, negotiated among them, within the United Nations. First made clear by a lack of international resistance to the USSR's launch of *Sputnik-1*, this right to unilaterally access space was then enshrined in a declaration of principles at the United Nations in the early 1960s and then finally made a clear and explicit right under binding international treaty law with the Treaty on the Principles Governing States on the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies (also known as the "Outer Space Treaty") This treaty was negotiated at the United Nations in 1966, opened for signature in January 1967, and came into force in October of 1967. As of 2019, the Outer Space Treaty has a total of 110 States Party to the treaty (UNOOSA 2019a), including all of the other large historical space powers, emerging space powers, and many States just entering into space activities.

It is worth noting that the subject of the first sentence is "the exploration and use of outer space," rather than merely "outer space," which is deemed to be "the province of all mankind." As we shall see in the Outer Space Treaty's Article II, outer space does in fact not belong to anyone. Conversely, nor is it the property of everyone collectively. Rather, States are free to access, explore, and use it — provided such activity conforms with any and all other applicable rights, obligations, and prohibitions in international law.

2.2 Nonappropriation

Article II of the Outer Space Treaty contains the famous, or possibly infamous, prohibition on national appropriation. Just a short 30 words long, this article has caused decades of debate regarding its interpretation and application.

> Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.

This bold sentiment, that outer space is simply not a permissible subject for national appropriation, was present in even the very first discussions on outer space at the United Nations level. One of the earliest UN General Assembly resolutions on space, General Assembly Resolution 1721 A and B (XVI) of December 20, 1961, entitled 'International cooperation in the peaceful uses of outer space', first announced this principle. In 1963, the UN's Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space, which is seen as a draft precursor of the binding Outer Space Treaty negotiated just a few years later, again reiterated this principle of nonappropriation.

This prohibition, placed on States, essentially means that outer space – both void space and celestial bodies – cannot be lawfully appropriated as some sort of extraterrestrial territory ripe for annexation and possession. Drafted in an era of both Cold War tensions and rapid global decolonization, the major space powers did not want to kick off a new colonial land grab for territory outside Earth's atmosphere. Historically, unilateral sovereign claims of territory were a legitimate method for expanding a State's territory. However, such a rush to claim territory on, say, the Moon, might trigger tensions between space powers. It was better to simply say that outer space, whether it be particular celestial bodies or even particular orbits, cannot come under the direct, permanent territorial sovereign possession of any single State.

Beyond that, the nuances of this article are frankly unclear, especially in its implementation on particular activities and on how it applies to modern and emerging space missions. Some clarity is necessary regarding the structure of the phrases, however. Pared down to its subject, verb, and direct object, the sentence states that outer space (the subject) is not subject to (verb) national appropriation (direct object). From there, is lists ways that outer space is not subject to national appropriation: claims of sovereignty, by means of use, by means of occupation, or, indeed, by any other means. In other words, there is no lawful, permitted means which will legitimize the national appropriation of outer space, as space is not "subject to" or capable of "national appropriation." The list ends with the inclusive "by any other means," as a kind of a capstone to the sentence, just to make it clear that the listing of actions is not exhaustive and to prevent any loopholes. It is used out of an abundance of caution, to make it clear that outer space cannot be brought under the sovereign domain of any State, and that no State may claim exclusive rights in these areas. Consequently, there is no way for a State to appropriate space, or subsets of space, such as locations on celestial bodies or particular trajectories or orbits. Whatever they do, it does not constitute appropriation that will be recognized.

The Outer Space Treaty was negotiated on behalf of the United States of America by Ambassador Arthur Goldberg. When the treaty was finalized within the UN, and then opened for States to sign, Ambassador Goldberg returned to Washington D.C. to testify before the US Senate as to its worthiness as a treaty (US Senate 1967). In explaining Article II to the Senators before him, the following exchange occured.

> Mr. GOLDBERG: Article II is a statement that outer space is not subject to national appropriation by means of sovereignty, by means of use or occupation or by any other means, which means that outer space is the province of mankind. It is complementary to article 1.
>
> The CHAIRMAN: Any further questions?
>
> Senator CHURCH: It cannot be claimed for Ferdinand and Isabella.
>
> Mr. GOLDBERG: That is correct.

This brief exchange seems to reflect the limited extent of investigation that State legislators, in considering whether or not to ratify the treaty, investigated the limits of the prohibition on appropriation in Art. II. It seemed evident to them that the provision was meant to oppose and formally ban State appropriation of outer space.

As Article II follows directly from Article I in any direct reading of the Outer Space Treaty, the freedoms of Article I would be foremost in any readers mind when they arrived at their understanding of Article II, and logic seems to dictate that these two articles were meant to be read and applied in an internally consistent and coherent manner. This investigation as to the intent of the drafters and negotiations of Article II's prohibition on national appropriation is relevant to today's constellations of numerous satellites as it forms the normative background for these activities.

2.3 Registration

A requirement placed on States active in space is that they notify the United Nations about these activities, as well as list them on their own national registry. International registration is the expression of a desire for openness and international awareness about what objects are in outer space, where they are, where the launched from, and what they are doing. Conversely, national registries of space objects is linked to States seeking to assert their sovereign jurisdictional powers over objects (and personnel thereof) which are physically outside of their territory.

2.3.1 International Registration

The United Nations Office for Outer Space Affairs (UNOOSA) keeps two international registers for objects launched into outer space. One is older and kept pursuant to UN General Assembly Resolution 1721, from 1961. A separate one was created pursuant to the 1975 Registration Convention. The explanation for the existence of two registers is that the 1961 resolution is not mandatory; it is a recommendation from the UN General Assembly to UN Member States. Conversely, registration pursuant to the 1975 Registration Convention is mandatory for States which are party to that Treaty. In practice, however, the registers are very nearly identical. States which are not party to the Registration Convention – and are therefore not compelled to registry with the UN – still register with the UN pursuant to the Resolution 1721. UNOOSA maintains an online index of space objects listed on its register, as making information of this sort available online furthers the purpose of having an international register – namely, transparency and public awareness about what is actually in outer space (UNOOSA 2019a).

2.3.2 National Registration

Another type of registry exists, and for different purposes and maintained by different actors. States themselves keep national registries of their launched space objects. This is done as a consequence of Article VIII of the Outer Space Treaty, which grants them the right to assert legal jurisdictional authority of those space objects.

> A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body. Ownership of objects launched into outer space, including objects landed or constructed on a celestial body, and of their component parts, is not affected by their presence in outer space or on a celestial body or by their return to the Earth.

This is more important than it may appear. Remember that Article II severely limits State sovereignty in space. How can States have any legal authority over things that they launch to space, if there is no sovereignty there? Article VIII permits this exercise of a State's jurisdictional powers in an extraterritorial manner by creating a link between a national registry and the treaty right. The article creates an internationally recognized mechanism for asserting jurisdiction (a component of sovereignty) into outer space. Consequently, States have a right to assert jurisdiction over their space object. This is important to keep in mind as this right is then balanced with the obligations of international responsibility, duty of obligation and supervision, and duty of compliance, as discussed below.

2.4 National Responsibility for National Activities, Whether Governmental or Nongovernmental (Private)

Crucially relevant to the legal status of satellites constellations and the concerns about appropriation are the unique and onerous obligations placed upon States regarding private activities and enterprises in outer space. In international law, the subject (or actors) which are bound by international law are sovereign States. States are the principal entity of the international political order. More recently, international organizations such as the United Nations, the European Union (EU), the International Committee of the Red Cross and Red Crescent (ICRC), and other organizations are also bound by the international law. In this sense, they are considered the "subjects" that international law regulates. However, the substance of international law can address many various activities. The subject matter or the "objects" of international law can be wide and diverse and include organizations of individuals and institutions, such as corporations, and even individuals. As such, international space law can impose norms for private actors such as corporations.

2.4.1 International Responsibility

Most international law does not make States responsible for the actions of private individuals. This is not the case in space law. Article VI of the Outer Space Treaty places the responsibility and even liability of private actors firmly upon the shoulders of States.

> States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty.

2.4.2 Authorization and Continuing Supervision

The second sentence of Article VI then gives States a positive obligation to undertake authorization and continuing supervision of nongovernmental entities.

> The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty.

Consequently, it is not merely sufficient that governments allow private actors to access and explore space. States have a duty to authorize and supervise them. Looking again at the first sentence of Article VI, above, gives some indication as to what standard this supervision must meet. The first sentence of Article VI ends with "... and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty." Consequently, States must authorize and supervise private entities to make sure that these private entities conform with the Outer Space Treaty.

Additionally, Article III of the Outer Space Treaty creates a link between the treaty and the rest of international law, including the UN Charter. Therefore, and to the extent that other sources of international law create norms applicable for private entities in outer space, all national activities – including private, nongovernmental activities – must conform with said laws. Some of these other sources include the other UN treaties on outer space, such as the 1968 Astronaut Rescue and Return Agreement, the 1972 Liability Convention, and the 1975 Registration Convention. Other specialized treaties on outer space, like the international telecommunications regime of the International Telecommunications Union Convention and Constitution, international enviromental law, international humanitiarian law, and other special regimes also form the rest of the normative order for outer space.

2.5 Potential Liability

Supplemental to international responsibility for acts in space committed by private entities is the potential for liability for damage resulting from their activities. Article VIII of the Outer Space Treaty establishes a liability provision, and the 1972 Liability Convention expands the mechanisms for dealing with liability claims. Liability is a requirement to pay compensation to an injured party for the damage or suffering that has been caused to them. In space law, liability is for physical damage to a space object by another space object. These provisions on liability have not yet been enforced relating to any actual claims of damage in space. However, and just like the obligation to be internationally responsible for private actors mentioned in Article VI, the potential for liability serves as a strong motivator and incentive for States to oversee, monitor, and regulate what private actors are doing in space.

2.6 Due Regard

Article IX of the Outer Space Treaty creates some interesting and unsettled normative principles guiding space activities. And while the treaty uses the word States as the entity that it is addressing, it is important to remember Article VI. As a consequence of Article VI, the behavior of private entities is also bound by the terms of the treaty. The first sentence of Article IX creates obligations placed upon States to show due regard to the corresponding interests of others active in space, and to abide by general principles of cooperation and mutual assistance.

> In the exploration and use of outer space, including the Moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty.

It must be admitted that these obligations are of a general nature. What the principles of cooperation and mutual assistance mean is not explicitly defined in the treaty, and no real examples are given. Similarly, the due regard obligation is not refined further.

Perhaps looking elsewhere into the Outer Space Treaty gives some examples. Elsewhere in the treaty, Article V talks about rendering assistance to astronauts. This assistance be seen as adhering to the principles of cooperation, mutual assistance, and due regard to the activities of others. The notification measures (international and national registration) also show a certain amount of regard for others.

2.6.1 Frequencies and Orbits

To also understand these obligations of cooperation, mutual assistance, and due regard, we can look to the actual history of space activities and see what States have, for themselves, determined to be its requirements. Even since before the Outer Space Treaty came into force, States were abiding by the requirements of coordinating frequencies and orbital positions – as internationally governed by the International Telecommunications Union (ITU), and administered by national frequency administers, such as the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) in the United States of America, or by the Office of Communications (Ofcom) in the United Kingdom. The coordination of frequencies is to prevent harmful interference between users of space systems – as each and every satellite must communicate on frequencies along the electromagnetic spectrum, and these frequencies must be coordinated between users.

Additionally, Earth’s Geosynchronous orbit (GSO) is both of intrinsic value and is of a limited nature, so the coordination of orbital “slots” is necessarily required. That this coordination happens successfully across the world on an international and domestic basis is certainly a great example of cooperation, mutual assistance, and of due regard to the corresponding interests of other States.

2.6.2 Space Debris

We can also look at the growing coordination around space debris. Here, space agencies and the scientific community have pooled their expertise and reflected on the growing issue of space debris, especially in lower orbits and other useful orbits. First with the Inter-Agency Space Debris Coordination Committee (IADC) and later at the multilateral level within COPUOS, the development of space debris mitigation guidelines reflect strongly show a due regard to the interests of others, and a spirit of cooperation in their development and observance.

Much more could be written about how the principles of cooperation, mutual assistance, and due regard has developed along various fields of space activities in the previous decades. In sum, they show that States often observe these general principles, and in a manner dependent on the issue at hand (frequency and GEO orbit coordination, space debris mitigation) and in various other manners, including national implementation of previously agreed standards at the international level.

2.7 Harmful Contamination

The second sentence of Article IX prohibits the harmful contamination of outer space and celestial bodies and requires that States shall adopt appropriate measures to fulfill this requirement.

> States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose.

Again, and like previous principles, harmful contamination is not defined or made clearer with an example. However, and linked with the obligation of due regard, the mitigation of space debris is a concrete example of what contamination of space is considered to be.

3 International Governance for the Geostationary Orbit

Headquartered in Geneva, Switzerland, the International Telecommunications Union (ITU) coordinates the use of usable portions of the electromagnetic spectrum, and the use of orbital allocations (“slots”) at the Earth’s Geostationary Orbit (GEO) at 35,786 km above the Earth’s equator. ITU coordination is designed to foster the rational, equitable, efficient, and economical use of these resources. Both usable portions of the spectrum and orbital locations are regarded as limited resources, and these limited resources require coordination between actors. Consequently, there is weight given to those who first apply for rights according to a “first come, first served” basis. However, there is also respect given to potential future users. This balancing of present users with future users is difficult, but it ensures that no State or other actor can rush to seize orbital or spectrum resources.

For the purposes of ITU orbital allocations, there are only two categories of spacecraft: Geostationary (GSO) and Non-Geostationary (NGSO). Currently, the ITU only coordinates GSO. Because of the limited and unique nature of these positions in GSO, coordination there has long been regarded as a necessity. Current capabilities dictate that there are only about 1800 orbital "slots" at GSO. Consequently, GSO is relatively well ordered, especially when compared to other orbits (as shown in Fig. 1 below). It may develop that other orbits closer to Earth may one day soon require coordination, but this is currently not done.

It should also be noted that the orbital "slot" given to users at GSO is a relatively small, three-dimensional "box" in space in which to operate. These slots are therefore quite different from the multiple orbital planes of numerous satellites to be used by constellations (called orbital "shells"), which essentially envelop the entire Earth inside them. The ordered GSO region is in stark contrast to LEO and Medium Earth Orbit (MEO), where satellites owned by many users and for many different purposes are travelling in periodic transits around the Earth, where congestion and the risk of collision persist and are increasing, and where rules on the use and governance of these regions are lacking much specificity.

National administrators of frequencies, such as the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA), which administer commercial and governmental frequencies, respectively, grant licenses to operators in conformity with their interpretation of their international obligations under space law, including both the Outer Space

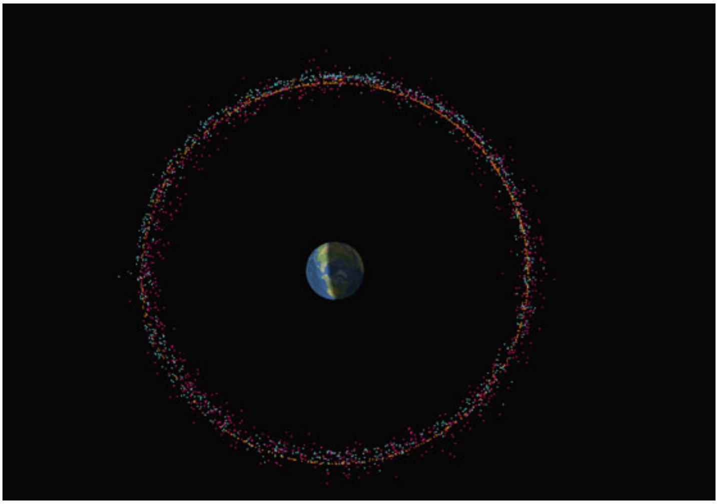


Fig. 1 The relatively well-ordered orbital regime of the Geostationary Orbit (viewed from above), as coordinated by the International Telecommunications Union (ITU). (Image with permission of Moriba Jah, University of Texas at Austin, http://astria.tacc.utexas.edu/AstriaGraph/)

Treaty and the regime of the ITU. To date, the granting of licenses for constellations has progressed without any noticeable qualms about these constellations.

4 MegaLEO Constellations

In light of the foregoing governance regimes, comprised of rights, obligations, and principles, there remains a lack of clear limits to the extent that constellations can be deployed and operated in increasingly valuable and congested orbits. Recent estimates for various commercial constellations in LEO give pause and should provoke caution. The SpaceX Starlink constellation is currently envisaged to consist of nearly 12,000 satellites in LEO by the mid-2020s, although recent filings for frequencies for an astounding potential 30,000 possible additional satellites (Henry 2019) would bring SpaceX's constellation to a truly mind-boggling 42,000 spacecraft in total. OneWeb's constellation is planned for 2000 satellites. Amazon's Kuiper system will constitute 3000 satellites. These three planned systems alone total around 17,000 new spacecraft placed into Earth orbit over the next decade. To put this in perspective, the UNOOSA online index of objects launched into outer space lists slightly less than 5300 objects currently in Earth orbit (as of the time of writing) (UNOOSA 2019a). It is true that these constellations may likely bring many benefits to society. It is also fairly certain that, in regards to outer space activities, the era of constellations will be an entirely new and unprecedented era of space activity.

4.1 SpaceX Starlink

SpaceX is one of the most visible companies with plans to create a large constellation of small satellites for commercial purposes. The SpaceX Starlink constellation is envisioned as a constellation of small satellites (227 kg/500 lbs) to provide low latency Internet services from space. The value proposition for Internet from space is twofold: faster times than terrestrial fiber optic cables is tremendously attractive to some clients, and wider access to Internet for rural and developing States is also an attractive market. Consequently, Internet from space using a constellation of small satellites is seen as a commercially attractive and achievable endeavor.

The Starlink constellation will actually be comprised of many satellites at different altitudes. According to at least one version of their constellation, based on applications to the US Government, Starlink is envisioned as 1584 satellites at 550 km altitude; 1600 satellites at 1110 km, 400 satellites at 1130 km, 375 satellites at 1275 km, and lastly, 450 satellites at 1325 km. That plan would therefore envision a total of 4409 satellites during its first phase and will grow to (as mentioned above) an envisioned 12,0000 satellites by the middle of the 2020s. In July 2019, SpaceX launched the first 60 satellites which will comprise Starlink. The effect on ground based astronomy from the Starlink satellites was almost immediate, and shocking. Within hours, the Starlink deployment was affecting ground based astronomy and the astronomical community was noticing and discussing the situation.

From the Earth and to the naked eye, viewing them in real time, the Starlink satellites appeared to be in a straight line. Figure 2 shows the satellites before they were moved up to a higher orbital altitude and thus became dimmer to the naked eye. This unprecedented sight is noteworthy and unique, like something out of a science fiction movie. Many found it a startling sight.

To ground based astronomers peering much further beyond this stream of satellites, Starlink obscures distant objects behind them. Figure 3 shows the effects of the Starlink satellites over the course of a 25 s exposure looking at the distant galaxy NGC 5353, now obscured in the background. Even nonastronomers should be able to get a feel for the impact that these constellations might have on astronomy, especially taking into account the large numbers of satellites proposed, and of the low altitude of their orbits.

Fig. 2 The SpaceX Starlink satellites seen from the ground 22.5 h after launch. (Image: Marco Langbroek, Leiden, the Netherlands; https://vimeo.com/338361997)

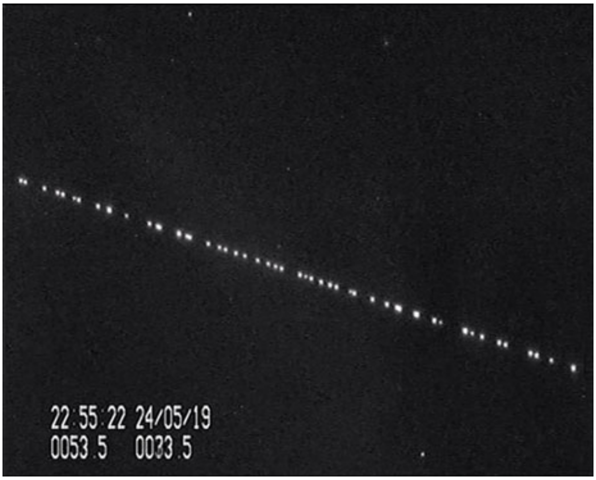
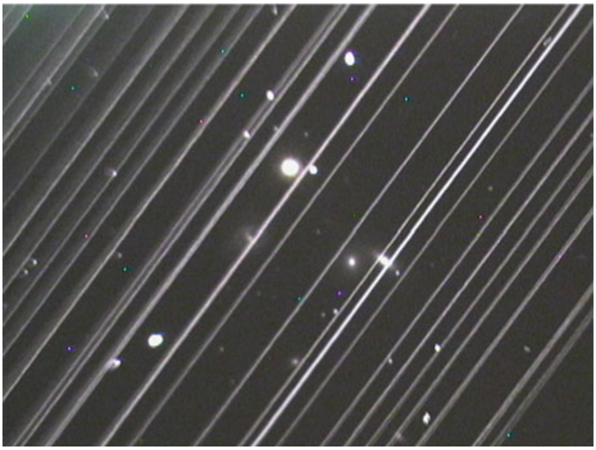


Fig. 3 SpaceX Starlink satellites passing through the ground based observation of the distant galaxy NGC 5353 on May 25, 2019. (Image with permission of Victoria Girgis/Lowell Observatory)



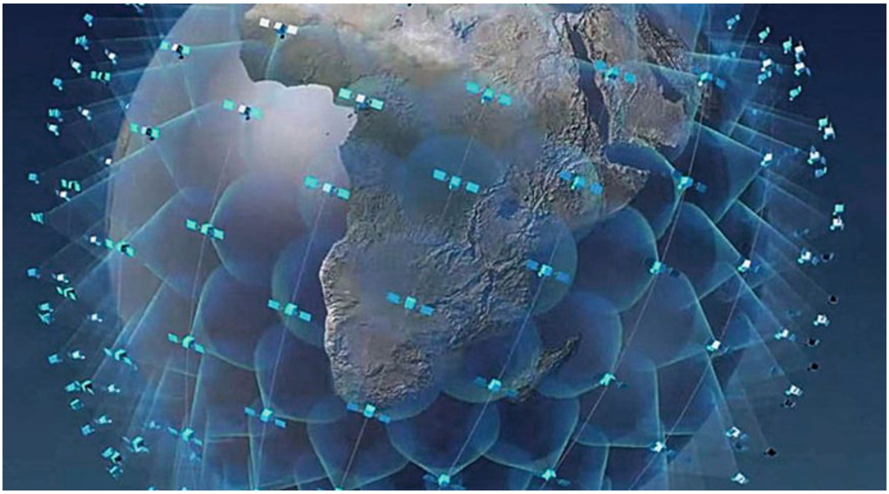


Fig. 4 OneWeb representation of its LEO constellation, upwards of 600 satellites at 1200 km in 24 individual orbital planes. One Web Small Satellite constellation (Graphic courtesy of One Web)

Of this initial deployment of 60 satellites in the Starlink formation, it was later announced that three spacecraft have ceased to operate (Foust 2019). This high failure rate should also be considered in weighing Starlink's observance and adherence of international space law.

4.2 OneWeb

OneWeb has proposed and is planning to deploy another satellite constellations, also for Internet from space, and especially aimed at delivering Internet services to people in underserved communities such as in the Arctic. The proposals for the OneWeb constellation are envisioned as 49 satellites (plus on-orbit spares) in 12 individual orbital planes at 1200 km altitude. At close to 600 satellites, this is also a serious deployment of satellites (Fig. 4).

In 2017, OneWeb announced that they were increasing this proposed 600 satellites with an additional 2000 more, which they have already secured the orbital rights for (Pultarova and Henry 2019). This plan would bring their total to 2620 potential OneWeb satellites.

4.3 Amazon, Teleset, Boeing, and Other Proposed Constellations

The particulars of the plans listed above will undoubtedly be updated and change. Additionally, other constellations are currently proposed by Amazon, LeoSat, SES, Kepler, and Telesat. Others will follow. Leosat has announced a constellation of 84 spacecraft, and Telesat plans for 300 (Pultarova and Henry 2019) (Werner 2019). Kepler Communications has plans for a constellation of up to 140 satellites between 500 and 600 km altitudes, in 7 orbital planes.

5 Are Constellations Appropriation?

The astronomy community has already voiced concerns about the impact that constellations will have on astronomy (AstronomyNow 2019). Constellations also bring potential risks from space debris and radiofrequency interference, both of which will have an effect on space sustainability. Starlink's 1584 satellites in the 550 km region would effectively triple the number of satellites in the 400–600 km region, for example.

Leaving these important concerns aside, constellations should also be considered in the context of their general legal status – and specifically whether large swaths of Low Earth Orbit are being impermissibly claimed and possessed by individual actors (whether the commercial actor itself, or by the authorizing national government).

For example, and as mentioned above, the OneWeb constellation will be in 12 orbital planes at 1200 km. Phase 1 of the SpaceX Starlink constellations will fly 66 satellites in 24 orbital planes, for a total of 1584 satellites in its initial constellation.

Do these megaconstellations constitute an impermissible appropriation (or ownership) of particular regions of outer space? Without offering a definitive conclusion, the following sections first argue why, and then why not, these large constellations in LEO constitute impermissible appropriations of sections of outer space. The reader can consider for themselves which of the following opposing arguments they find more convincing.

5.1 Yes, This Is Impermissible Appropriation

Article II of the Outer Space Treaty, discussed above, is clear on the point that the appropriation of outer space, including the appropriation of either void space or of celestial bodies, is an impermissible and prohibited action under international law. No means or methods of possession of outer space will legitimize the appropriation or ownership of outer space, or subsections thereof.

5.1.1 Excludes Others

The constellations above, because they seem to so overwhelmingly possess particular orbits through the use of multiple satellites to occupy orbital planes, and in a manner that precludes other actors from using those exact planes, constitute an appropriation of those orbits. While the access to outer space is nonrivalrous – in the sense that anyone with the technological capacity to launch space objects can therefore explore space – it is also true that orbits closer to Earth are unique, and when any actor utilizes that orbit to such an extent to these proposed constellations will, it means that other actors simply cannot go there.

To allow SpaceX, for example, to so overwhelmingly occupy a number of altitudes with so many of their spacecraft, essentially means that SpaceX will henceforth be the sole owner and user of that orbit (at least until their satellites are removed). No other actors can realistically expect to operate there until that time. No other operator would dare run the risk of possible collision with so many other spacecraft in that orbit. Consequently, the sole occupant will be SpaceX, and if "possession is 9/10th of the law," then SpaceX appears to be the owner of that orbit.

5.1.2 Done Without Coordination

Additionally, SpaceX and other operators of megaconstellations are doing so without any real international conversation or agreement, which is especially egregious and transgressive of the norms of outer space. Compared to the regime for GSO, as administered by the ITU and national frequency administrators, Low Earth Orbit is essentially ungoverned, and SpaceX and others are attempting to seize this lack of authority to claim entire portions of LEO for itself; and before any international agreement, consensus, or even discussion is had. They are operating on a purely "first come, first served" basis that smacks of unilateralism, if not colonialism.

5.1.3 Governments Are Ultimately Implicated

As we know, under international space law, what a nongovernmental entity does, a State is responsible for. Article VI of the Outer Space Treaty requires that at least one State authorize and supervise its nongovernmental entities and assure their continuing compliance with international law. As such, the prohibition on nonappropriation imposed upon States under Article II of the Outer Space Treaty applies equally to nongovernmental private entities such as SpaceX.

Nevertheless, through the launching and bringing into use of the Starlink constellation, SpaceX will be the sole occupant, and thereby, possessor, both fact and in law, of 550 km, 1100 km, 1130 km, 1275 km, and 1325 km above our planet (or whatever orbits they finally come to occupy). The same is true for the other operators of these large constellations which will be solely occupying entire orbits.

5.1.4 Long-Term Occupation Constitutes Appropriation

These altitudes are additionally significant, as nonfunctional spacecraft in orbits lower than around 500 km will re-enter the Earth's atmosphere in months or a few years, but the altitudes selected for the Starlink constellation, while technologically desirable for their purposes, also mean that any spacecraft which are not de-orbited from these regions may be there for decades, or possibly even hundreds of years. By comparison, the granting of rights for orbital slots at GSO is in 15-year increments, a length of time much less than what the altitudes of the megaconstellations threaten. Such long spans of time at these altitudes by these megaconstellations further bolster the contention that this occupation rises to the level of appropriation of these orbits.

5.1.5 Prevents Others from Using Space

Article I of the Outer Space Treaty establishes that the exploration and use of outer space is "the province of all mankind." It further requires that this exploration and use shall be by all States "without discrimination of any kind, on a basis of equality and in accordance with international law..." However, when one private corporation so overwhelmingly possesses entire portions of outer space, their use is discriminatory to other potential users and interferes with their freedom to access, explore, and use outer space. So long as these actors are so dominantly possessing and occupying those orbits, their actions exclude others from using them. What other operator would dare use orbits where there are already hundreds of satellites operating as part of a constellation? It would be an extremely unwise and risky decision to try to share these orbits with a mega constellation, so they will likely choose other altitudes and orbits. This massive occupation of particular orbits effectively defeats others from enjoying the use of outer space. While a State can issue permits for one of its corporations allowing them to launch and operate satellites to this extent, that does not automatically mean that their activities in outer space, an area beyond national sovereignty, are therefore in perfect accordance with the strictures of international law. Indeed, national permissions offer no such guarantee.

5.1.6 No Due Regard for Others

That these megaconstellations violate the prohibition on appropriation in Article II is additionally supported by Article IX of the Outer Space Treaty. Article IX requires that in the exploration and use of outer space, States "shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space... with due regard to the corresponding interests of other States..." There is hardly any way to view this deployment of megaconstellations as showing any type of due regard to the corresponding interests of others. This lack of regard further supports the notion of their unilateral transgressive violations of the purposes of space law norms.

5.1.7 Harmful Contamination

The impacts of the spacecraft on the pressing issue of space debris need not be gone into detail here. Suffice it to say, megaconstellations threaten mega-debris. The failure rate of these comparatively cheap satellites should give pause, because if 5% of a constellation of 100 satellites fails, this is 5 guaranteed new pieces of debris intentionally introduced to the fragile space domain. Article IX of the Outer Space Treaty warns of harmful contamination of the space environment and requires States to take appropriate measures to prevent this harmful contamination. A responsible government could not, in all seriousness, permit the intentional release of such amounts of space debris, especially in the already fraught orbits that many megaconstellations are headed towards.

While the threat of space debris is not directly relevant to the accusation of appropriation of outer space, it goes towards the argument that these actors are conducting activities in a manner lacking in regard to others, and in fact, amounts to excluding others from using the space domain. By excluding others, this has the effect of taking orbits for themselves, which IS occupation.

5.1.8 If This Isn't Appropriation, Then What Is?

Arguing in the alternative, if these megaconstellations — in their dominant occupation of entire orbits in orbital planes with numerous satellites — could be considered (merely for the sake of argument) to not be appropriation, we must therefore ask: what *would* be appropriation? What use of void space, including orbits of the Earth, would constitute actual appropriation? What further, additional fact of these uses of space, if added to the scenario, would cause that constellation to cross over the line into clearly prohibited appropriation? Perhaps the exact same scenario, but supplemented with an actual, formal claim of sovereignty, issued by a government, is the only element which could be added to megaconstellations which would then cross the threshold into appropriation. However, a formal claim of sovereignty would be merely an act occurring on Earth and would not change any actual facts in the space domain. Consequently, the lack of a formal claim of sovereignty should not be the deciding criteria in arriving at the conclusion that megaconstellations constitute appropriation of orbits.

5.1.9 Conclusion

In conclusion, these megaconstellations effectively occupy entire orbital regions with their vast fleet of spacecraft and in so doing effectively preclude other actors from sharing those domains. They have done so, or are attempting to do so, without any international consensus or discussion, which is most egregious for a domain outside of State sovereignty and which no State can own. Governments will ultimately be responsible for this appropriation, and both are prohibited from appropriating space. In distinction to GSO, their permission to go there means that they could occupy these regions for incredibly long periods — which again shows their appropriation. These constellations significantly prevent others from using those regions, which therefore interferes with others' right to explore and use space. And ultimately, this reckless ambition shows absolutely no due regard (as per Article IX) for the corresponding rights of others. As such, these megaconstellations constitute an impermissible appropriation of particular regions of outer space, regardless of any formal, official claim of such by a responsible, authorizing government.

5.2 No, This Is Not Impermissible Appropriation

An opposite conclusion can also be reasonably arrived at when approached along the following lines. The counter argument would assert that the deployment and operation of these global constellations, such as SpaceX's Starlink, OneWeb, Kepler, etc., are aligned with and in full conformity with the laws applicable to outer space. These constellations are merely the exercise and enjoyment of the freedom of exploration and use of outer space and do not constitute any impermissible appropriation of the orbits that they transit.

5.2.1 Freedom of Access and Use Permits Constellations

Rather than being a violation of other's rights to access and explore outer space, the deployment of these constellations is more correctly viewed as the exercise and enjoyment of the right to access and use outer space. Article I of the Outer Space Treaty establishes a right to access and use space without discrimination.

Not allowing an actor to deploy spacecraft, regardless of their number or destination, would be infringing with the exercise of their freedom. It would be discriminatory. Additionally, actors do not need permission from any other State, or group of States, to access and explore outer space.

5.2.2 Aligned with the Intentions of the Outer Space Treaty

This use of outer space by constellations in LEO, while not explicitly mentioned by the drafters of the Outer Space Treaty or other space law, actually is the fulfillment of their visions for the use of outer space. The preamble to the Outer Space Treaty (which contains the subject matter and purpose of the treaty and can be used for interpreting the operative articles of the treaty) speaks of the aspirations of humanity in exploring and using outer space. It is easy to see constellations that will provide Internet access to the world as fulfilling the visions of the drafters:

> *The States Parties to this Treaty*,
>
> *Inspired* by the great prospects opening up before mankind as a result of man's entry into outer space,
>
> *Recognizing* the common interest of all mankind in the progress of the exploration and use of outer space for peaceful purposes,
>
> *Believing* that the exploration and use of outer space should be carried on for the benefit of all peoples irrespective of the degree of their economic or scientific development,
>
> *Desiring* to contribute to broad international cooperation in the scientific as well as the legal aspects of the exploration and use of outer space for peaceful purposes,
>
> *Believing* that such cooperation will contribute to the development of mutual understanding and to the strengthening of friendly relations between States and peoples,

As such, subsequent article of the Outer Space Treaty should be read in a permissive light, as permitting constellations, rather than a restrictive light which only sees potential negative aspects of constellations.

5.2.3 Due Regard and Harmful Contamination Will be Addressed

Operators in LEO are well aware of the challenges to space sustainability that their constellations will pose and will be taking efforts to mitigate the creation of debris. OneWeb is keenly focused on space sustainability and has even argued that the current norm, whereby spacecraft are not in space for longer than 25 years and are deorbited from lower orbits at the end of their lifetime (aka post mission disposal), is not sufficient to keep outer space clean and that shorter lifespan limits should be imposed on operators, especially operators in LEO, and operators of small satellites.

Additionally, these systems will be able to cooperate with emerging space safety and space traffic management plans and can operate in ways that do not restrict or impinge on other users of the space domain. Because due regard is therefore displayed for the space domain, and to the interests of others, these constellations do not prejudice or infringe upon the freedoms of use and exploration of the space domain and are therefore not occupation, or possession, much less appropriation.

5.2.4 This Does Not Constitute Possession, or Ownership, or Occupation

The use of LEO by satellite constellations is substantially similar to the use of GSO, and therefore permissible. In each region, individual actors are given permission - either from a national administrator or from an international governing body (the ITU) via a national administer–to use precoordinated subsections of space. In a way that is overwhelmingly similar to the use of orbital slots in GSO, the placement of spacecraft into orbits in LEO or higher orbits does not constitute possession, ownership, or occupation of those orbits. This is because States (and their companies) have been occupying orbital slots in GSO for decades, and these uses of GSO have never been accused of "appropriating" GSO. The users have never claimed to be appropriating GSO, and their exercising of rights to use GSO is respected by other actors in the space domain. This is the same situation for other orbits, including LEO and other non-Geostationary orbits.

And while GSO locations are relatively stable (subject to space weather and other perturbations, and require stationkeeping), spacecraft in LEO are actually moving through space and are not stationary, so it is even more difficult to see this use by constellations as occupation, much less appropriation. Moreover, Space Situational Awareness (SSA) and Space Traffic Management (STM) will allow other uses to use these orbits, and nothing about the use of any one user necessarily precludes others. Lastly, there is no intention by operators of constellations to exclusively occupy, must less possess or appropriate, these orbits. Would not the appropriation of outer space be an intentional, volutional act? No such intention can be found in the operators of global constellations.

5.2.5 Conclusion

The development and deployment of constellations is certainly a unique and impressive technological development which will bring unprecedented advancements to both space activity and concerns here on Earth. It offers more benefits than risks. Rather than being multiple users which would threaten orbital safety, a single user at any altitude makes SSA and STM easier, and the actor merely has to govern their own spacecraft, rather than worry about others spacecraft. No such data sharing issues will exist with global constellations.

Consequently, and in conclusion, it is in the wider public interests to permit, and not prevent, actors from planning, developing, deploying, and operating constellations in LEO. This technological advancement, of plentiful, off-the-shelf spacecraft, is the wave of the future for space exploration and utilization. It should not only be permitted, it should be positively authorized, fostered, and nurtured. It is a future we want, where all can benefit from space technologies and capabilities.

6 Conclusion

This chapter has gone over some basic foundational elements in space law, as found in the Outer Space Treaty and subsequent treaties, as well as the ITU regime for frequencies and orbits. Both regimes speak of the freedom of access and use of outer space, as well as the obligations respecting the rights of others to also explore and use outer space. Various articles of the Outer Space Treaty, either creating explicit rights or obligations, or other articles iterating more general concepts (such as due regard, harmful contamination) are applicable to constellations. Some pertinent facts from proposed near-term large constellations of small satellites in LEO were mentioned, and then the legal implications of these constellations were provided.

An argument as to why these constellations constitute impermissible appropriation outer space was made. To be balanced, this argument was followed by a counter-argument as to why these constellations are not an impermissible appropriation. The reader can weigh these arguments and consider which of them, if either, is the more valid and convincing.

It is hoped that this chapter will bring greater context and clarity to those concerned with constellations in LEO and that these novel activities, while certainly attractive for various reasons, have implications under space law and should give cause for concern when considered in the context of space safety and sustainability, as well as implications for international geopolitical reasons. Constellations of small satellites in LEO are certainly the wave of the future and will continue to be developed and deployed. They should be undertaken in a way that adheres to both national and international law, and in a sustainable fashion which protects the long-term sustainability of the space domain, and takes into account not just the interests of the operators, but other users of the space domain, as well as potential future users, and of generations to come who will inherit the space domain as a place for their exploration and use. Respect for the integrity of the space environment remains a lasting value to take into account in all present activities.

7 Cross-References

- ▶ Deorbit Requirements and Adoption of New End-of-Life Standards
- ▶ Legal Issues Related to the Future Advent of Small Satellite Constellations
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Financial Models and Economic Analysis for Small Satellite Systems
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations

- ▶ “Rules of the Road” for Launch and Operation of Small Satellites and Related Issues
- ▶ US Space Policy Directive-3: National Space Traffic Management Policy

References

Convention on International Liability for Damage Caused by Space Objects, Mar 29, 1972, 24 U.S. T. 2389, 961 U.N.T.S. 187 (entered into force Oct 9, 1973)

Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space, G.A. Res. 1962 (XVIII) (Dec 13, 1963) 1963

J. Foust, Can satellite megaconstellations be responsible users of space? SpaceNews (2019), https://spacenews.com/can-satellite-megaconstellations-be-responsible-users-of-space/. Accessed 20 Oct 2019

V. Girgis, Lowell Observatory, https://twitter.com/GirgisVictoria/status/1132535725377744896?s=20

C. Henry, SpaceX SpaceX submits paperwork for 30,000 more Starlink satellites. SpaceNews (2019). https://spacenews.com/spacex-submits-paperwork-for-30000-more-starlink-satellites/. Accessed 20 Oct 2019

International Co-operation in the Peaceful Uses of Outer Space, UNGA Res. 1721 (XVII B), Dec 20, 1961, 1961

NASA Office of Planetary Protection, Overview of Planetary Protection (2019), https://planetaryprotection.nasa.gov/overview. Accessed 20 Oct 2019

T. Pultarova, C. Henry, OneWeb weighing 2000 more satellites. SpaceNews (2019), Feb 27, 2017. https://spacenews.com/oneweb-weighing-2000-more-satellites/. Accessed 20 Oct 2019

Responsible Space (OneWeb), https://www.oneweb.world/responsible-space. Accessed 20 Oct 2019

The Coming Satellite Invasion, AstronomyNow, Oct 2019, pp 28–31

Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, Jan 27, 1967, 610 U.N.T.S. 205., 1967

United Nations Office for Outer Space Affairs, Status of International Agreements Relating to Activities in Outer Space (2019a), http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/status/index.html. Accessed 20 Oct 2019

United Nations Office for Outer Space Affairs, Register of Objects Launched into Outer Space (2019b), http://www.unoosa.org/oosa/en/spaceobjectregister/index.html. Accessed 20 Oct 2019

United Nations Office for Outer Space Affairs, Online Index of Objects Launched into Outer Space (2019c), http://www.unoosa.org/oosa/osoindex/search-ng.jspx?lf_id= . Accessed 20 Oct 2019

United Nations Office for Outer Space Affairs, Online Index of Objects Launched into Outer Space (2019d), http://www.unoosa.org/oosa/osoindex/search-ng.jspx. Filter by “In Orbit: YES”. Accessed 20 Oct 2019

United States Senate, Treaty on Outer Space, Hearings Before the Committee on Foreign Relations, United States Senate, Ninetieth Congress, First Session (1967)

D. Werner, Inflection point within the year for Megaconstellations? SpaceNews (2019), Oct 9, 2019, https://spacenews.com/megaconstellations-satellite-2019/. Accessed 20 Oct 2019

Deorbit Requirements and Adoption of New End-of-Life Standards

Timothy Maclay

Contents

Abstract

Responsible end-of-life disposal measures have been recognized as a critical component of orbital debris mitigation practices from the earliest discussions on space sustainability. NASA's first orbital debris safety standard in 1995 outlined different disposal methods for missions operating in different orbital regimes, limited post-mission orbital lifetime, and called for decommissioned assets to be passivated. It also specified a reliability threshold for post-mission disposal maneuvers and capped the casualty risk resulting from an object's reentry into the atmosphere. Since then, many organizations have issued statements, policies, and standards to promote responsible disposal practices. This chapter reviews some of the more notable publications on the subject, as well as a framework in which all stakeholders can work together to encourage the international community to adopt new standards.

T. Maclay (✉)
OneWeb, McLean, VA, USA
e-mail: TMaclay@oneweb.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_74

Keywords

Orbital debris · Disposal · Deorbit · Orbit lifetime · Passivation · Reliability · Reentry risk · Low-Earth-orbit · Geosynchronous-Earth-orbit · Debris mitigation · Best practices · UN COPUOS · IADC · Responsible practices

1 Introduction

Proper disposal of space hardware has been a central and consistent theme in debris mitigation practices from the earliest discussions on space sustainability. The orbital environment has long been recognized as a natural resource with limits in its capacity to host the hardware that spacefaring nations have been launching in pursuit of the tremendous benefits that satellite applications offer. The natural, dynamic processes that serve to cleanse the Earth's oceanic, atmospheric, and land ecosystems are virtually nonexistent in space. In fact, the only natural cleansing process for the space environment is orbital decay via atmospheric drag, a force that weakens exponentially with altitude and is only truly effective for satellites in the lowest portions of low-Earth-orbit (LEO). Without very intentional management of mission detritus, the sources of orbital debris can outpace this natural sink and threaten the sustainability of activities in this seemingly vast but fragile environment.

Donald J. Kessler and B. G. Cour-Palais forewarned of the possibility of environmental instability when they published a seminal paper in 1978 entitled, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt" (Kessler and Cour-Palais 1978). This early work postulated that an unchecked increase in the population of uncontrolled objects in LEO would eventually lead to cascading collisions and a self-perpetuating growth of orbital debris. However, well ahead of reaching such a point of instability, inadequate disposal practices can lead to increased mission cost, risk, and operational burden for those who follow.

In response, debris mitigation recommendations, standards, and even regulations have been introduced and refined over several decades. At their core, they all share a common objective to encourage space operators to design and operate their missions in ways that do not unnecessarily contribute to the orbital debris environment. Debris mitigation practices typically address four topical areas:

- Intentional debris generation
- Explosion prevention
- Collision avoidance and impact resilience
- Prompt, reliable, and safe disposal

The first of these encourages the use of bolt catchers and other devices to retain debris created by explosive actuators, discourages the release of shrouds or lens caps, and calls for a halt to on-orbit kinetic anti-satellites (ASAT) weapons testing. Explosion prevention focuses largely on preventing the energetic rupture of components (e.g., batteries and pressure vessels) through robust design of hardware, software, and operational procedures. The third category mitigates the risk of colliding with large objects or becoming disabled by a small-particle impact by recommending that satellites are designed to protect critical components and include maneuvering capabilities, and that operators monitor their surroundings for conjunctions with other known objects and take appropriate collision avoidance precautions. And while all of these contribute to an operator's ability to promptly, reliably, and safely dispose of hardware at the end of its mission, there are additional measures focused directly on this last area. This chapter looks in depth at these in particular, reviewing existing guidance and the mechanisms available to industry and policymakers to encourage the adoption of responsible disposal practices by all space operators.

2 Elements of Responsible Disposal

There are a number of elements to consider in planning for the responsible disposal of orbital hardware at the end of its useful mission life (end-of-life, or EOL). One is the method of final disposal. For objects operating in LEO, removal from orbit altogether is recommended. Lowering the orbit's perigee to facilitate atmospheric reentry is the usual means, but retrieval is an acceptable alternative and may become more practical with future developments in on-orbit servicing (OOS) and active debris removal (ADR) capabilities. For objects operating at higher altitudes (e.g., medium-Earth-orbit (MEO) and geosynchronous-Earth-orbit (GEO)), the cost of deorbiting can become unfeasible, and the use of so-called "graveyard orbits" (i.e., placing hardware in stable orbits with little chance of interfering with other operational assets) is a pragmatic and acceptable alternative.

For LEO objects that are deorbited, another consideration is the length of time the object remains in orbit after completing its operational mission. This includes the time it takes to conduct disposal maneuvers, and if the object is left in orbit to reenter the atmosphere randomly, it also includes the remaining orbit lifetime associated with natural decay. The less time decommissioned hardware spends in orbit, the less risk it poses as a collision or explosion hazard.

A third element is having the ability to "passivate" decommissioned hardware. Permanently depleting all internal energy sources after disposal maneuvers are completed diminishes the possibility of subsequent explosion. Otherwise, deterioration from extended thermal cycling, long-term exposure to radiation, and other environmental effects can create situations in which batteries overcharge, fuel tanks over-pressurize, or other explosive conditions develop. Chief among such precautions are disabling charging circuits, depleting battery charge, and venting propulsion systems.

One of the most important elements of disposal is simply to preserve the ability to execute the disposal operation at the end of an object's mission. Failing to do so, and leaving it in orbit potentially long-term, adds to the debris population and places an avoidance burden on other operators using the same altitude. In practice, this is also one of the most difficult provisions to satisfy, for several reasons. First, satellites do not always wear out gracefully; rather, they often fail unpredictably, and suddenly, leaving little or no time to perform disposal maneuvers once a mission-terminating problem is discovered. Additionally, operators naturally strive to keep their assets in service, working around anomalies as they are able, and care must be taken not to pursue mission extension at the expense of disposal reliability. Finally, maneuvering safely requires many of a satellite's subsystems to be functional, so a problem that takes a satellite out of service may very well render it unable to deorbit as well. For example, power, attitude control, communications, and propulsion are all necessary to deorbit a satellite under its own control.

Finally, if an object is to be deorbited, any hazards created as a result of reentry must also be considered. "Designing for demise," for example, assures that debris from an object reentering the Earth's atmosphere burns up completely at altitude such that no fragments reach the ground. However, launch vehicle upper stages, larger satellites, and objects with heat-resilient components often do not disintegrate entirely, and in these cases, the execution of a controlled reentry that targets an ocean or unpopulated landing zone may be warranted.

3 The Origins of Disposal Guidance

NASA first published debris mitigation guidelines in 1995, which took the form of Safety Standard NSS 1740.14 that was issued from NASA's Office of Safety and Mission Assurance (NASA Office of Safety and Mission Assurance, August 1995). With this publication, NASA laid out the following general policy objectives relating to post-mission disposal of space structures and limiting reentry risk:

> NASA programs and projects will assess and limit the probability of accidental explosion during and after completion of mission operations.
>
> NASA programs and projects will plan for the disposal of launch vehicles, upper stages, payloads, and other spacecraft at the end of mission life. Post-mission disposal will be used to remove objects from orbit in a timely manner or to maneuver to a disposal orbit where the structure will not affect future space operations.
>
> NASA programs and projects that use atmospheric reentry as a means to remove space structures from orbit at the end of mission life will limit the amount of debris that can survive uncontrolled reentry. If there is a significant amount of debris surviving uncontrolled reentry, measures will be taken to reduce the risk by establishing procedures or designs to reduce the amount of debris reaching the Earth's surface or to control the location of the ground footprint.

NSS 1740.14 goes on to articulate specific guidelines for each, the essences of which are captured in Table 1 under headings corresponding to the four responsible disposal elements identified above. The standard allowed for three disposal options for missions with perigees at LEO altitudes (<2,000 km): atmospheric reentry, a graveyard orbit between LEO and GEO, or retrieval. It called for missions in higher orbits to use graveyard orbits exclusively, either between LEO and GEO, or above GEO by at least 300 km. It also included an additional restriction for missions in

Table 1 Disposal provisions in NASA's original 1995 Safety Standard NSS 1740.14 and 2012 Technical Standard STD-8719.14A (paraphrased – see original documents for full language)

Disposal element	NSS 1740.14 (1995)	STD-8719.14A (2012)
Disposal method	Missions with perigees <2,000 km: Atmospheric reentry Storage orbit between LEO and GEO or Retrieval Missions with perigees >2,000 km: Storage orbit between LEO and GEO or Storage orbit above GEO by >300 km Additional exclusion of storage orbits that pass within 300 km of 20,200 km altitude	Missions with perigees <2,000 km: Atmospheric reentry Storage orbit between LEO and GEO or Retrieval Missions near GEO: Storage orbit above or below GEO by >200 km Missions between LEO and GEO: Storage orbit with perigee >2,000 km and apogee below GEO by >500 km Exclusion of circular storage orbits near high-value operational assets (e.g., 20,200 km)
Orbital lifetime	Limited to 25 years if disposing via atmospheric reentry Limited to 10 years if disposing via retrieval	Limited to 25 years after mission completion, but no more than 30 years after launch, if disposing via random atmospheric reentry (or as soon as practical for controlled reentry) Limited to 10 years if disposing via retrieval
Energy passivation	Depletion of all on-board sources of stored energy upon completion of mission operations and post-mission disposal maneuvers	Depletion of all on-board energy sources to level that cannot cause breakup once no longer needed for mission operations, post-mission disposal, or control
PMD reliability	Probability of successfully completing disposal of at least 0.99	Probability of successfully completing disposal of at least 0.90
Reentry risk	Controlled reentry or limitation of total debris casualty area for debris surviving an uncontrolled reentry to 8 m^2	Uncontrolled reentry: Limited to 0.0001 (1:10,000) Controlled reentry: Landing zone >350 km from non-US land masses and >50 km from continental US, US territories, or Antarctica Product of reentry burn failure and uncontrolled casualty risk limited to 0.0001 (1:10,000)

near-circular 12-h orbits to use a graveyard orbit at least 300 km above or below 20,200 km altitude to protect the semi-synchronous region.

This first standard also established 25 years as the acceptable orbital lifetime for objects being deorbited via random reentry, although it allowed only 10 years for removal if retrieval is the chosen method. It required all on-board energy sources to be depleted as soon as disposal operations are completed and stipulated a post-mission disposal (PMD) reliability of at least 0.99. Finally, it called for a controlled reentry for objects that were expected to produce a casualty area of more than 8 m^2 under random reentry conditions.

While NASA's 1995 Safety Standard clearly applied only to NASA programs, this early work served as a precedent and basis for debris mitigation policies from other organizations around the world. The National Space Development Agency of Japan (NASDA) adopted similar technical provisions when issuing their own debris mitigation standard in 1996 (National Space Development Agency of Japan, March 1996). The French space agency CNES (Centre National d'Etudes Spatiales) then published theirs in 1999 (Centre National d'Etudes Spatiales (CNES) 1999). Since then a host of additional national policies have emerged since on the subject of orbital debris mitigation practices.

In fact, NASA has even updated its own standard, the latest of which was published in 2012 as NASA Technical Standard 8719.14A, entitled, "Process for Limiting Orbital Debris" (National Aeronautics and Space Administration (NASA), May 2012).

These revised provisions are also summarized in Table 1 for comparison. The most significant changes were the relaxation of PMD reliability from 0.99 to 0.90 and an extension in the timing for passivation in order to retain control of a decommissioned asset.

National space agencies are not alone, however, in publishing guidance for the responsible disposal of space hardware. Industry associations, professional associations, international standards organizations, interagency groups, and even the United Nations have all weighed in on the topic. It is notable that across these various organizations, their treatments are similar in structure and highlight the same priorities, albeit with some variation and evolution in the specific recommendations being put forward. A more thorough historical accounting of debris mitigation publications can be found in "A Handbook for Post-Mission Disposal of Satellites Less Than 100 Kg," published by the International Academy of Astronautics (IAA) (International Academy of Astronautics, May 2019).

4 Current Guidelines and Applicability

While it is not useful to detail a comprehensive anthology of published guidance, it is perhaps worthwhile to review the current state guidance from different types of organizations and how they apply to the space industry.

4.1 UN COPUOS

The most broad, international guidance is arguably provided by the United Nations' long-standing Committee on the Peaceful Uses of Outer Space (UN COPUOS). In 2007, its member states adopted a set of space debris mitigation guidelines (UN COPUOS 2007). These guidelines were put forth by its Scientific and Technical Subcommittee and made a number of qualitative recommendations related to disposal. They called for the removal of LEO objects via controlled reentry when possible, or relocation to orbits that "avoid their long-term presence in the LEO region." GEO missions were simply requested to be left in orbits that avoid long-term interference with the GEO region. A provision was also included to seek to deplete or make safe on-board energy sources when no longer needed but makes no mention of PMD success probability. Finally, the UN guidelines noted that debris surviving reentry should not pose undue risk to people or property, including through environmental pollution. These guidelines were adopted by the full Committee on the Peaceful Uses of Outer Space and then the UN General Assembly.

In addition to these 2007 guidelines, COPUOS also adopted guidelines from the Subcommittee's Working Group on Long-Term Sustainability of Outer Space Activities on two occasions. By 2019, COPUOS membership had grown to 87 member states, and consensus was reached on 21 provisions that included two touching directly on disposal. One calls on states to encourage manufacturers and operators to limit the long-term presence of space objects in protected regions after their missions are completed, and the other calls for the application of techniques to minimize risk associated with fragments surviving reentry (United Nations General Assembly, 17 July 2018).

The COPUOS guidance is necessarily general in nature, given the large number of parties involved in creating it. However, this is also by design as these provisions are not legally binding to the member states, and it was necessary to provide fairly broad latitude for states to tailor their national implementations to suit the particular situations of their domestic programs and industry.

4.2 National Policy

Implementation of debris mitigation practices at the national level typically takes the form of national policies and commercial licensing practices, and it is at least partially motivated and informed by existing UN treaties. In particular, the United Nations adopted the so-called Outer Space Treaty in 1967. Its full name is the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies" (United Nations, "United Nations Treaties and Principles on Outer Space" 2002).

Then in 1972, the UN General Assembly adopted the Liability Convention which is formally known as the "Convention on International Liability for Damage Caused by Space Objects" ("United Nations Treaties and Principles on Outer Space" 2002). These two UN international agreements together place responsibility on the state for "national activities in outer space . . . whether carried out by governmental agencies or by non-governmental entities," require the state to authorize and supervise such activities, and assign to the state the liability for any damage caused to another state party on Earth, in air space, or in outer space (Secure World Foundation 2017 edition).

One example of how debris mitigation practices are implemented in national policy is the US Government Orbital Debris Mitigation Standard Practices (ODMSP). This document was first published in 2001, and an update was released in November 2019 (U.S. Government Orbital Debris Mitigation Standard Practices, November 2019).

The more recent edition closely follows the structure of its predecessor but revises earlier guidance and provides additional technical elaboration. With regard to disposal, the ODMSP reasserts its previous recommendations to passivate immediately upon completion of mission completion, to limit post-mission orbital lifetime for a LEO object to no more than 25 years, and to limit the casualty risk associated with an object reentering the atmosphere to 1 in 10,000. It also calls for PMD reliability to be 0.9, with a goal of 0.99, specifies a deadline of 5 years rather than 10 years if active retrieval is the means of removal, and adds a number of options and a significant amount of detail to the guidance for disposal and storage orbits.

4.3 Commercial Licensing

The authorization and oversight responsibilities a country has for commercial activities in its jurisdiction are carried out by national regulatory agencies. These agencies are often working toward competing objectives; on one hand, they are charged with assuring responsible behavior by their licensees and protecting their respective governments from any liabilities stemming from licensees' actions. On the other, regulations that are too burdensome run the risk of discouraging innovation or motivating industry to do business elsewhere. As a result, regulators often establish rules that emphasize safety while allowing some degree of flexibility in demonstrating how that safety is assured.

Specific regulatory approaches vary from one country to another, but one illustrative example can be offered by considering the approach taken by the Federal Communications Commission (FCC). The FCC licenses commercial communications satellites in the USA and requires its applicants to submit an orbital debris mitigation showing, among other information. Applicants are referred to existing standards, such as the NASA Safety Standard or the ODMSP for guidance, but they are not enforced as requirements. Rather, the FCC makes an overall judgment on the basis of the application of whether the proposed mission is in the public interest. With this approach, industry is given the flexibility to demonstrate the safety of their missions in ways that may not strictly adhere to the referenced standards.

4.4 The Inter-Agency Space Debris Coordination Committee (IADC)

The IADC is an international governmental forum in which 13 member agencies exchange information and coordinate research on space debris, review progress on cooperative activities, and identify debris mitigation options. The IADC published its first space debris mitigation guidelines in 2002 and released a revision in 2007 (Inter-Agency Space Debris Coordination Committee, September 2007). There is now a further statement on large constellations issued in 2017 (Inter-Agency Space Debris Coordination Committee, September 2017).

Some notable differences in the IADC guidance are that storage orbits are not a disposal option for LEO missions at all, and an appropriately high super-synchronous orbit is the only option for disposal of GEO missions. The IADC stresses the importance of PMD reliability but stops short of specifying a threshold either for this or for reentry casualty risk. It does reassert familiar language for a 25-year orbit lifetime limit and depletion or "safing" of on-board energy sources when no longer needed for mission operations or post-mission disposal, although on this last point, their 2017 guidance does encourage operators to shorten orbit lifetime and retain the ability to conduct collision avoidance maneuvers during the disposal phase.

The IADC has no authority to enforce its debris mitigation guidelines. However, because the organization's members are government representatives from many of the world's spacefaring nations, IADC positions are regarded as international consensus and are often cited in national policies and licensing practices, and used as a reference in discussing industry norms.

4.5 International Standards

Another source of guidance comes in the form of internationally recognized standards. The International Organization for Standardization (ISO) has weighed in on the subject of debris mitigation with ISO 24113, "Space Systems – Space Debris Mitigation Requirements." Now in its third edition, ISO's 2019 release updates previous versions published in 2010 and 2011 (International Organization for Standardization 2010, 2011, 2019). This document, as updated, transforms debris mitigation objectives laid out by the UN, the IADC, and others, into specific requirements which can then be enforced by incorporating ISO 24113 into design, manufacturing, and service contracts for satellites and launch vehicles.

ISO 24113 is accompanied by a host of lower-level requirements standards that address implementation for individual topical areas (e.g., fragmentation prevention, disposal methods, reentry safety, etc.). The high-level requirements in ISO 24113 related to disposal reflect common themes with a few minor differences. ISO specifies two protected regions for storage orbits (within 200 km of GEO altitude and LEO, with an upper limit of 2,000 km) but provides no protection of semi-synchronous orbits. It reinforces the 25-year deorbit limit but differentiates starting times for missions with different characteristics. For example, satellites with propulsion systems are given 25 years to deorbit after their operational missions are completed, but for satellites with no collision avoidance maneuvering capability, the clock starts at launch. PMD reliability is required to be at least 0.90, and energy sources capable of causing fragmentation are to be depleted prior to deactivating a spacecraft or losing control of it. Finally, with regard to reentry risk, ISO 24113 simply calls for operators to comply with the requirements imposed on them by their individual licensing conditions and by national and international authorities.

4.6 Industry Associations and Professional Organizations

One striking characteristic of the guidelines set forth by all of the organizations mentioned thus far is how little they differ or have changed over the years. Despite the recent escalation of commercial launch activity and dramatic growth of the debris population (particularly in LEO), debris mitigation standards published in 2019 look remarkably similar to those proposed by NASA in 1995.

For example, the post-mission orbital lifetime threshold of 25 years has for many years withstood the test of time (slight variations of applicability notwithstanding), even though the original architects have noted that "it was an economic compromise" between environmental protection and the cost burden on operators (Kessler 2019). Since then, with technological improvements driving down satellite manufacturing and launch costs, coupled with the proliferation of microsatellites and introduction of large constellations increasing the need for more deliberate management of the orbital environment, this foundational economic balance must assuredly be shifting.

Surprisingly, it is industry rather than governments or regulators that is putting forth today's most progressive proposals in debris mitigation. A number of industry associations and professional organizations have made statements and issued position papers on space sustainability and debris mitigation practices, and one of the most significant of these is a 2019 publication by a new group of industry stakeholders, called the Space Safety Coalition (SSC). The SSC's, "Best Practices for the Sustainability of Space Operations" (Space Safety Coalition, September 2019) puts forward 31 debris mitigation recommendations that were approved by consensus by the coalition's 37 member organizations.

The SSC's best practices call for operators to comply with guidance from the ISO, the IADC, and the UN COPUOS, but then also to adopt a number of provisions that go above and beyond these standards. Building on preexisting guidance, the SSC also makes several suggestions to increase the ability to perform disposal operations. For example, it calls for operators to consider including technologies and features that facilitate capture and deorbit in the event their spacecraft become derelict, and it suggests that passivation measures could be automated to occur if an operator loses contact or control of its asset. The SSC's best practices include a reassessment of PMD reliability prior to extending a mission beyond its design life and stress the importance of PMD by increasing the reliability threshold from 0.90 to 0.95.

With regard to orbital lifetime, the SSC raises the bar for spacecraft with propulsion systems to deorbit within 5 years of mission completion rather than allowing dead spacecraft to linger in LEO for up to 25 years. For those satellites with no active propulsion capabilities, the SSC simply urges operators to strive to deorbit as quickly as possible.

SSC guidance for passivation balances the risk of explosion that arises from retaining on-board energy sources for long durations, with the risk of collision that results from surrendering the ability to conduct collision avoidance maneuvers. The coalition's recommendation is to passivate if post-mission lifetime is expected to be longer than 5 years but to otherwise retain the capability to perform collision avoidance maneuvers during the deorbit phase.

Finally, with regard to reentry risk, the SSC restates existing guidance the reentry casualty risk should be limited to 1:10,000 per object but adds a consideration for operators of multi-satellite systems to evaluate casualty risk on a system-wide, annualized basis. This is particularly important for constellations and other systems that will be replenished on an ongoing basis.

5 Conclusion

Encouraging the widespread adoption of new end-of-life standards will require international coordination among a variety of stakeholders, including governments and regulatory agencies, commercial companies, and nongovernmental organizations. Each plays a distinct role, and the most effective means of shifting behavioral norms in a more responsible direction may be to leverage the influence each has to offer in complementary ways.

A three-tiered approach to accomplishing this was proposed by Maclay and McKnight in a paper they presented at the 2019 International Astronautical Congress (Maclay and McKnight 2019). The concept is illustrated in Table 2. At its foundational layer, a core set of minimum requirements is established within internationally coordinated licensing regimes. These requirements represent the minimum behavioral threshold an operator must meet in order to be granted authorization to launch. It is important for these to be negotiated and normalized internationally to discourage operators from "shopping" for an optimally permissive licensing regime.

A middle tier is where behavioral expectations are set. This is where standards, norms of behavior, and recommendations reside. IADC recommendations, ISO standards, industry association positions, and the like, all contribute to the establishment of what stakeholders expect of each other, which is often well above minimum licensing requirements.

Finally, there needs to be an aspirational tier. This layer articulates the spirit of a particular metric and might even be evaluated on a sliding scale with an unattainable top end. The benefit of this element is to encourage industry's best behaviors by offering some sort of incentive for going above and beyond the behavioral norms. The World Economic Forum is creating the Space Sustainability Rating to do this, with a concept that missions would be evaluated against a number of metrics and awarded an environmental rating commensurate with their achievements towards preestablished, aspirational goals. Other means of encouraging truly

Table 2 Tiered approach to encouraging the adoption of new end-of-life standards

Tier	Bar	Mechanism	Incentive
Aspirational	High	WEF SSR	Rating certification
Expected	Medium	Recommendations Norms Standards	Corporate image Peer pressure Contracts
Required	Low	Licensing	Permission to launch

best behavior include corporate peer pressure, consumer pressure, and even pressure from the investment and insurance communities.

The orbital environment is a shared natural resource and a valuable, fragile environment. Avoiding a tragedy-of-the-commons in space will ultimately require stakeholders to coordinate globally and focus on the creation and adoption of more sustainable disposal standards for space hardware.

6 Cross-References

- ▶ Financial Models and Economic Analysis for Small Satellite Systems
- ▶ Legal Issues Related to the Future Advent of Small Satellite Constellations
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ▶ "Rules of the Road" for Launch and Operation of Small Satellites and Related Issues
- ▶ Small Satellites and Their Challenges to Space Situational Awareness (SSA) and Space Traffic Management (STM)
- ▶ Small Satellites Market Growth Patterns and Related Technologies
- ▶ Space Finance for 'New Space' and Small Satellites
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit

References

Centre National d'Etudes Spatiales, Exigence de Securité – Débris Spatiaux: Méthode et Procedure, CNES MPM-51-00-12, Issue 1, Rev. 0 (1999)

Inter-Agency Space Debris Coordination Committee, IADC space debris mitigation guidelines, IADC-02-01, Revision 1, September 2007

Inter-Agency Space Debris Coordination Committee, IADC statement on large constellations of satellites in low Earth orbit, IADC-15-03, September 2017

International Academy of Astronautics, Study Group 4.23, *A Handbook for Post-Mission Disposal of Satellites Less Than 100 Kg*. Paris, France, (2019)

International Organization for Standardization, Space systems, space debris mitigation requirements, ISO 24113, 3rd edn., July 2019 (2nd edn., May 2011 and 1st edn., July 2010)

D. Kessler, *A Brief History of the NASA Space Debris Programs*. Keynote address, First International Orbital Debris Conference, Sugarland, 9 December 2019

D.J. Kessler, B.G. Cour-Palais, Collision frequency of artificial satellites: the creation of a debris belt. J. Geophys. Res. Space Phys. **83**(A6), 2637–2646 (1978)

T. Maclay, D. McKnight, *Space Environment Management: Framing the Objective and Setting Priorities for Controlling Orbital Debris Risk*, IAC-19-A6.8.3 (International Astronautical Congress, Washington, DC, 2019)

National Aeronautics and Space Administration, Process for limiting orbital debris. NASA Technical Standard NASA-STD-8719.14A (with Change 1), 25 May 2012

National Space Development Agency of Japan, Space debris mitigation standard, NASDA STD-18, March 1996

Office of Safety and Mission Assurance, Guidelines and assessment procedures for limiting orbital debris, NASA Safety Standard NSS 1740.14, August 1995

Secure World Foundation, *Handbook for New Actors in Space*, ISBN: 978-0-692-45413-8, 2017 edition

Space Safety Coalition, Best practices for the sustainability of space operations (16 September 2019), https://spacesafety.org/best-practices/. Last accessed Feb 2020

U.S. Government Orbital Debris Mitigation Standard Practices (November 2019 Update), https://orbitaldebris.jsc.nasa.gov/reference-documents/

United Nations, *United Nations Treaties and Principles on Outer Space*, ST/SPACE/11, New York, 2002

United Nations, Report of the Committee on the Peaceful Uses of Outer Space, General Assembly, official records, sixty-second session, supplement no. 20 (A/62/20), 2007

United Nations General Assembly, Guidelines for the long-term sustainability of outer space activities, COPUOS Scientific and Technical Subcommittee, A/AC.105/C.1/L.366, 17 July 2018

Small Satellites and Their Challenges to Space Situational Awareness (SSA) and Space Traffic Management (STM)

Mark A. Skinner

Contents

Abstract

Small satellites have actually been flown since the beginning of the space age; Sputnik and Vanguard were only tens of centimeters in diameter. For many years however, the trend was to make larger, more powerful, and more complex satellites. Launch vehicles became more capable, able to place in orbit these larger satellites. Recently, thanks to miniaturization of electronics and standardization of sizes, there has been a resurgence in smaller, less expensive (and often less capable) satellites. Rideshare-like services coordinate among small satellites to allow many to share a launch vehicle. Rather than one rocket launching one or a few satellites, many scores are now being launched at once. Space is now more affordable and accessible than it has ever been, but how this new crowded space environment is managed has not kept up with the changes in technology and activity. Efforts to enable space traffic management (STM) are under discussion, and hopefully under way soon, but challenges remain. Such challenges include basic ones to space situational awareness (SSA), such as small satellites being hard to detect, track, identify, and characterize. Existing SSA systems have a hard time keeping up with their smaller sizes and increasing numbers. Often small

---

M. A. Skinner (✉)
The Aerospace Corp, Arlington, VA, USA
e-mail: mark.a.skinner@aero.org

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_75

satellites are not as capable as larger, more expensive system and may lack propulsion, system redundancies, and other safety features, which can be problematic for maintaining a safe near-space environment. As the barriers to entry have lowered, new actors in the space arena have emerged, often without the hard-learned experiences of legacy space actors. Additionally, some “New Space” entrants bring with them a Silicon Valley mindset of “fail fast and break things.” This philosophy is perhaps thought incongruent to the long-term sustainability of outer space. These challenges to the status quo may be resolved through better definition of the governance regime and furtherance of regulations, guidelines, and best practices for STM, by improved technologies (including processing techniques) for SSA, and via education, outreach, and discussion with new entrants in the space regime.

Keywords

Space traffic management · Space situational awareness · CubeSats · Space safety

1 Introduction

Since the start of the space age, various techniques have been devised to detect, identify, and/or obtain trajectory information for satellites. These included using optical telescopes (Institute for Astronomy (IfA) Maui History 2019) and radars (Sridharan and Pensa 1998) to detect and track these early space objects. Compared in size to a modern geosynchronous earth orbit (GEO) communications satellite, satellites from the 1950s and 1960s were quite diminutive and would be considered “SmallSats” today (as may be seen in Figs. 1 and 2).

The first man-made object to orbit the earth, Sputnik 1, was “tracked” by amateur radio operators and was essentially an RF (radio-frequency) beacon that lasted only 22 days; the USSR had no satellite surveillance capability at the time (Universe Today).

For the purposes of discussion, the term “SmallSat” is defined here to be those objects that are currently at the cusp of detection and tracking via standard

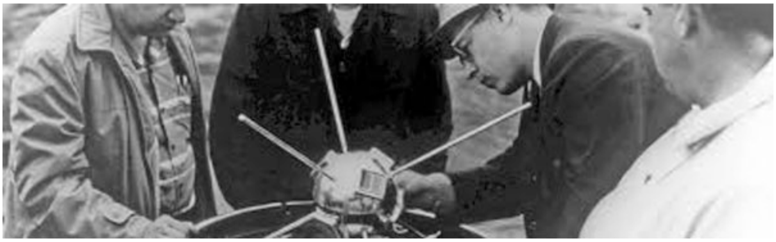


Fig. 1 NASA’s Vanguard satellite was launched on March 17, 1958. Although contact with it was lost in 1964, Vanguard 1 remains the oldest artificial satellite still in earth orbit. (Photo courtesy NASA 2019)

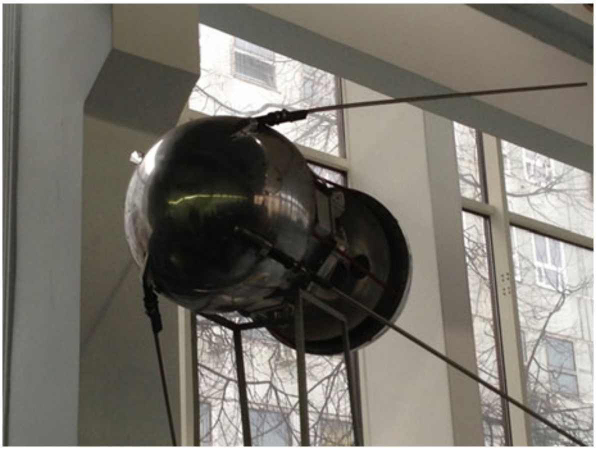


Fig. 2 A model Soviet Sputnik-era satellite. (Photo by the author)

techniques. At present, they are roughly defined as objects ~10 cm in low earth orbit (LEO) and ~1 m at GEO (NASA).

NanoSats (generally defined as between 1 and 10 kg mass (Nano/Microsatellite Market Assessment 2014)) and CubeSats (multiples of 10 cm cubes (Mehrparvar 2014)) are in this size range and are often at the limits of detectability/trackability by space situational awareness (SSA) or space traffic management (STM) systems. Additionally, CubeSats, due to their building-block approach (***n***U form factor), are often indistinguishable from one another, and so this becomes an acute difficulty for SSA/STM systems when several are launched at once (Committee on Achieving Science 2016; Skinner in press), often in an unpowered state. The SSA/STM centers are frequently unable to associate initial orbit trajectory information with an identified CubeSat, which may delay (sometimes up to months) the CubeSat owner/operator (O/O) from making contact with their satellite.

2 Benefits Derived from Small Satellites

Small satellites offer and have realized for society many potential benefits. Their small size and lower cost have allowed for the "democratization" of space, with many states and non-state actors being afforded access to space that previously could not afford the cost of entry. This can be seen both in the number of countries that now have their own satellites for the first time and the increase in the membership of the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) (United Nations Office for Outer Space Affairs). Additionally, the lower cost of small satellites can allow for more proof-of-concept missions and rapid prototyping. This has been demonstrated by, among others, The Aerospace Corporation's series of AeroCube missions (The Aerospace Corporation). Another benefit can accrue to the education of space users; the rapid development cycle (a couple of years rather than ~7–10 years it would take for traditional NASA-style science missions) fits in better with the career “timelines” of undergraduate and graduate students, and the lower costs allow for meaningful participation of even high school and middle school students and hobbyists. The lower costs to acquire and launch small satellites resulted in a rapid increase in the number and variety of new satellite missions.

3 Challenges Posed by Small Satellites

In addition to the benefits afforded by small satellites, they bring with them a host of challenges to the current SSA and STM systems. One of the primary concerns with small satellites is the difficulty of detecting, tracking, and characterizing them. Their small sizes typically offer low returns of signals (radar or optical) for this task. Additionally, consolidation of launches for small satellites, offering a very low cost to orbit, means a massive proliferation of objects in LEO. As Muelhaupt et al. have pointed out (Muelhaupt et al. 2019), a large increase in the number of objects in space, especially LEO, makes the situation very difficult for the current system to react and greatly affects how existing users can conduct their space operations; “business as usual” cannot be maintained.

Small satellites can be hard to identify (due to their oftentimes similar shapes and the low signal-to-noise ratio of radar or optical signals reflected from them), especially during massive launches of CubeSats. Many objects are launched and have still not been positively identified even months after launch (Klotz; Kelso; Skinner in press). Due to their use in rapid prototyping and inexpensive pathfinder missions, and the experimental mindset for these types of missions, small satellites sometimes lack redundancy, and sometimes subsystems such as propulsion, or lack radiation-hardened parts. As one launch consolidator noted, many small satellites are just one SAA passage away from demise (Jeff Roberts, August 2019, Spaceflight Inc., 2019, private communication). This can mean that the small satellite lifetime is much lower than the orbital lifetime, and depending on the orbit of the satellite, it may not be able to be de-orbited within 25 years of the end of the mission. Lack of propulsion hinders collision avoidance with debris objects and also makes the small satellite effective “debris” during encounters with other, larger satellites that do have propulsion.

With the lower costs that small satellites can potentially afford, such as using a CubeSat kit or a shared ride to orbit, and the entrance of many new actors in the space arena (even, e.g., economic journalists (Planet Money)), it may be that the owner/operator of a small satellite is relatively inexperienced, and is perhaps not aware of rules, regulations, guidelines, and best practices, and has not experienced the “hard” lessons of space. What is also seen is the use of small satellites as a test bed for some New Space concepts that often come with an entrepreneurial “move fast and break things” mindset. As Oltrogge et al. (2019) have noted:

> From a financial perspective, this is a classic example of a “Negative Externality,” wherein a spacecraft operator may willingly lose a satellite to a collision or explosion or hardware failure, especially for large constellations with multiple redundancies and quick re-launch/refurbish capabilities. In this situation, the cost to that operator is substantially less than the

> potential cost to society for addressing the subsequent fragmentation event and the debris it generates.

A somewhat overlapping issue to the profusion of small satellites is the proliferation of large constellations of LEO satellites; while only a few of these constellations are planning to deploy small satellites as defined here, there are several constellation deployments planned of 100s and 1000s of new satellites, which may make space operations much more complex. As Muelhaupt et al. (2019) have noted:

> A key element of the problem is that an increase in the LEO population will lead to an increase in close approaches to existing satellites, and the potential for accidental collisions. Conjunction prediction, collision probability (Pc), and maneuver planning for most existing satellite operators is a time- and personnel-intensive operation. Orbit analysts, and propulsion, navigation, and communications systems personnel are involved in evaluating and planning maneuvers over several days and must do so even if the ultimate decision is to "fly through" a close approach. Since most existing systems have small numbers of vehicles and the number of conjunctions any given operator experiences is relatively small, COLA remains a manual process. For systems not designed with automated maneuver planning, a COLA assessment that progresses all the way to a maneuver plan can consume considerable effort, whether or not the maneuver is executed.... Existing operators will not necessarily have large constellations parked nearby, but they will nonetheless be affected by the new activity. The new large constellations' satellites typically will have relatively short lifetimes and will need frequent replenishment. The traffic transiting up and down will be substantial, and failures could leave stranded objects at intermediate altitudes, permanently increasing the collision risk.

Recent events that have affected the community of space users include Swarm and their Space Bees (an unsanctioned launch) (Koren 4/19), SpaceX and the European Space Agency (ESA) close approach (poor cooperation between operators) (Koren 9/19), and SpaceX and the impact of their Starlink satellites' reflections on ground-based astronomers' observations (AAS).

With the growth of commercial and other nongovernmental space missions, another challenge posed is the impact, in some jurisdictions, of the increase in launches on the national airspace. These launches have the potential to disrupt the existing air traffic regime. In the past, when there were many fewer launches, and they were mostly of national significance, the commercial airlines just put up with the disruptions. But with the current trend toward commercial space, airlines are perhaps less willing to suffer delays and loss of revenue to accommodate the new commercial space launches (CRS Reports).

4 Solutions to These Challenges

4.1 The Transition from SSA to STM to SOA

How can the challenges that the proliferation of small satellites means to safe space operations for all space actors be met? There will need to be done more than just improve the knowledge of where things are in space (SSA); better monitoring, management, and regulation of what goes into and what happens in space (STM) will be needed. If this multifaceted approach is taken, it may be possible to transition to Space Operations Assurance (SOA) (Skinner et al. 2019).

What is "space situational awareness"? What is "space traffic management" and "space operations assurance"? How do small satellites challenge them? The topic of "space traffic management" is currently being widely discussed at various international events (Global STM Workshop, STM at IAC 2017, IAASS, SWF 2017). But what is it? Various definitions abound (IAA Cosmic Study, Ailor). The International Academy of Astronautics studies on STM put forward the definition that STM is "the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference (IAA STM)." STM can also be defined in relation to how it relates to space safety and what practical elements make up the activity of STM, with a comparison to the more "intent"-oriented aspects of SSA (Skinner 2018); see Fig. 3 for a graphical depiction of this. STM, unlike SSA, generally includes a "management" or "regulatory" aspect, in addition to monitoring and safety advisory elements. Recent activities within the US government have sought to hand these management aspects to the Federal Aviation Administration Office of Commercial Space Transportation (FAA AST) or the Dept. of Commerce Office of Space Commerce (DOC OSC); Space Policy Directive 3 (SPD-3) explicitly proposes to hand the bulk of the regulatory aspects to the DOC OSC. It was recognized that a regulatory agency would need to take on these responsibilities and

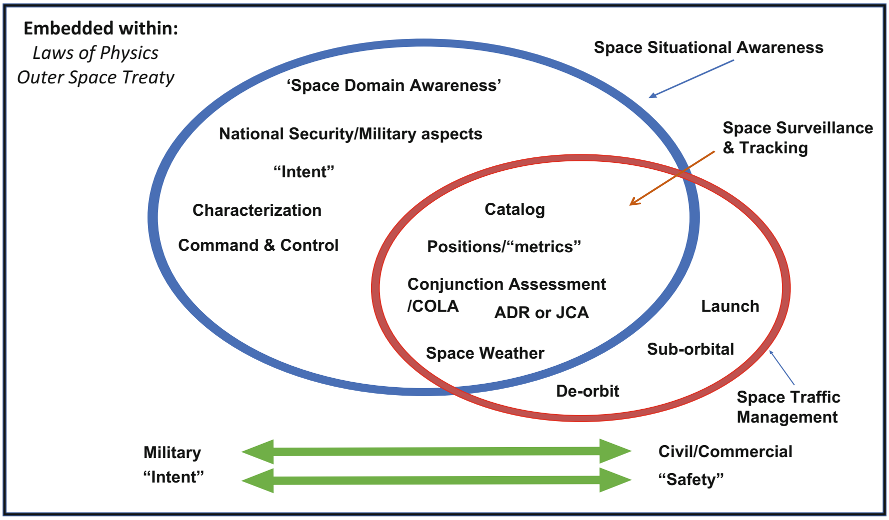


Fig. 3 Comparisons and contrasts of space situational awareness, space surveillance and tracking, and space traffic management from the point of view of a practitioner, based on constituent elements. While launch/sub-orbital/de-orbit activities are of interest to the military, they do not necessarily fall under the rubric of SSA, but the boundaries can be indistinct. ADR is defined as *active debris removal* and JCA as *just-in-time collision avoidance*

that neither of the two chief purveyors of SSA, NASA and the US Air Force, were regulatory agencies.

McKnight (Skinner et al. 2019) defines STM within the broader parameters of Space Operations Assurance (SOA), a framework that has three major categories:

> First, space environmental effects and modeling (SEM) describes why space objects behave the way that they do and informs the next major domain, space situational awareness (SSA). SSA describes what the space objects do in orbit to provide critical background context for space traffic management (STM). STM enables reliable satellite operations for all satellites but with a focus on the potentially large constellations that are slated to be deployed in the near future. Each of these three areas is normally fueled by different people with different skills, yet the final positive outcome depends on all of the players' contributions. The term Space Operations Assurance (SOA) is proposed as the overarching domain (encompassing SEM, SSA, and STM) to fulfill this need. These concepts are displayed in Fig. 4.

But what is advocated for here is that the current regime will not be able to adequately address the challenges posed by a plethora of small satellites; a new civil STM regime as per SPD-3 that can better deal with burgeoning commercial space field (Skinner 2018) will be required. As Muelhaupt et al. have noted (Muelhaupt et al. 2019):

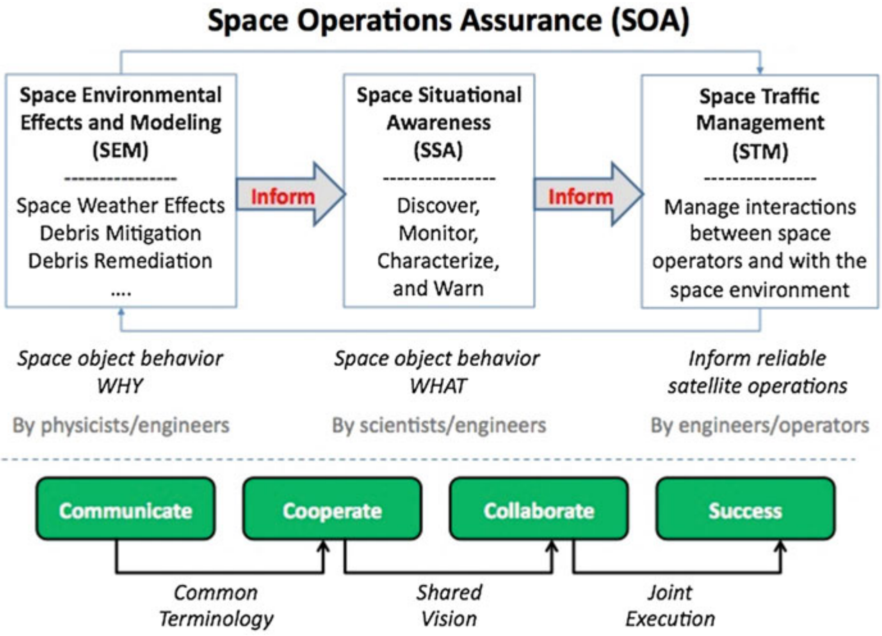


Fig. 4 Space Operations Assurance cycle and the relationship between the constituent members that include SEM, SSA, and STM

> The creation of a new civil space traffic management organization is an opportunity to change "business-as-usual" for space operations. One of the goals listed in SPD-3 is to create an open architecture for sharing SSA data, and foster innovation. A new STM agency can work to establish an effective public-private partnership with industry to address the common needs of the space community.

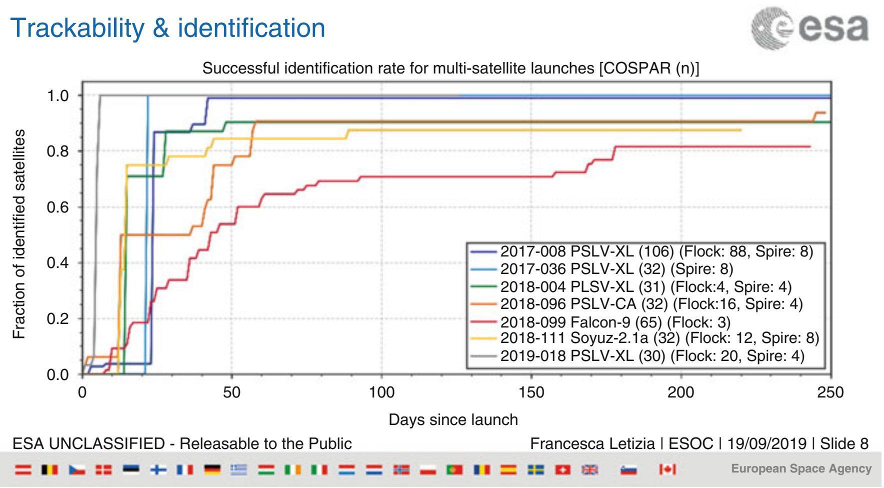
In this new space traffic management regime, how can regulators and future small satellite owner/operators work together to mitigate impacts on existing space operations? There are two key areas of possible cooperation. Primarily, given that small satellites are by definition difficult to track and identify, future STM regulations might stipulate a performance-based approach to making small satellites more visible, by identifying advanced techniques and technologies that owner/operators could choose from during mission design, which, if implemented, would make it easier to determine the location and identification of these small space objects. Such technologies could include optical corner cube reflectors, GPS signal-based positioning devices, radar reflectors, optical beacons, and the like (Skinner 10/19). The second key aspect to the partnership between STM regulators and owner/operators is to coordinate the enhanced sharing of information before, during, and after the active phases of the mission. This may include frequent updates to satellite position, status, maneuver plans, changes in orbit, information on neighboring space objects, etc. In many cases, it may be desirable for the information to be exchanged in an automatic, machine-to-machine fashion, for example, for GPS-based position updates, real-time maneuver information, etc.

As outer space lies above the national airspace (NAS), it is inherently international in nature, with potential interaction between space objects under the supervision and control of various states. Thus, the discussions in the international regime are crucial to mitigating challenges of small satellites. Important high-level multiparty discussions include the work on long-term sustainability at the United Nations Committee on the Peaceful Uses of Outer Space (UN COPOUS) (COPUOS Guidelines); the recently concluded International Telecommunication Union (ITU) World Radio Conference (WRC-19) that included treaty-level discussion on bringing into use of large constellations of satellites, shortened licensing times for short-duration satellites, and amateur frequency band allocations, among other topics (ITU WRC-19); and the Inter-Agency Space Debris Coordination Committee (IADC) technical discussions on space debris guidelines (IADC), as well as work on standards at meetings of the International Organization for Standardization (ISO) (ISO). An important addition to these high-level multilateral fora are the frequent discussions and exchanges of technical information at international conference and workshops, e.g., the International Astronautical Congress, Secure World Foundation-sponsored events, and events sponsored by Lockheed Martin and the Royal Observatory Edinburgh, as well as Embry-Riddle Aeronautical University, University of Texas at Austin, and McGill University, among others.

Technical solutions to small satellite challenges include utilizing novel techniques for tracking and identification of small space objects (Skinner et al. 2019). This can entail implementing techniques or importing information from traditional and non-traditional SSA data providers, to exploit "new" classes of information (space object phenomenologies, observables, "feature-aided tracking" (Chong), etc.) regarding space objects. Necessary standards would need to be created if not currently existing that would allow SSA/STM centers to ingest owner/operator measurements and data in an automatic machine-to-machine fashion; this is especially important for objects that are quasi-continuously thrusting (e.g., employ electric propulsion). This has the important benefit of reducing the burden on radars and optical tracking stations, with potentially improved accuracy, and by automating the process and removing the human in the loop may also improve accuracy and reduce errors.

Another especially important aspect to small satellites is reducing the time it takes to identify newly launched batches of CubeSats (Skinner 2020) (see Fig. 5), as well as development of "space safety" technologies for small satellites, such as appropriate propulsion systems, automatic id/position devices, and de-orbit solutions, including inflatable balloons and drag sails. It would be advantageous to see future small satellites that have built-in high reliability for post-mission disposal, potentially including a "dead man switch" that would allow the vehicle to automatically remove itself from orbit if it loses contact with the ground (Muelhaupt et al. 2019), as well as built-in capability for high-precision orbit knowledge from precision navigation and timing signals, and abilities to automatically share position and maneuver data.

The final aspect to dealing with the challenges to the space environment from small satellites is via education, outreach to new actors in the space arena, and the demonstration of "leadership." What should be encouraged is the development of a consensus on what constitutes "normal" or "safe" behavior in space, via a bottom-up approach, to create norms of behavior, best practices for safety in space, and guidelines to allow new entrants to know what is expected for safe space operations. Also, openness and transparency in space operations should be encouraged, while understanding that business practices and intellectual property concerns may preclude total transparency, a balance can be struck.



Trackability & identification

ESA UNCLASSIFIED - Releasable to the Public

Francesca Letizia | ESOC | 19/09/2019 | Slide 8

European Space Agency

Fig. 5 Rate at which tracked CubeSats have been successfully identified after launch; in many cases not all of the launched objects have been identified, even after months on orbit (Letizia)

Guidelines and best practices, as previously discussed, have been the subject of high-level negotiations, in such fora as the UN COPUS, IADC, etc., but much practical work has also been carried out by industry consortia, e.g., CONFERS (CONFERS), the Global VSAT Forum (GVF), the Space Safety Coalition (SSC), the Space Data Association (SDA), etc. As Muelhaupt et al. noted (Muelhaupt et al. 2019):

> Industry-driven norms and standards of behavior are among the most effective methods for preventing the new activity from contributing to space debris. Innovation by industry can create new solutions and reduce the cost of others. Government should encourage these voluntary, industry-driven approaches where possible.

Others have shown initiative to step forward and show leadership in this realm. For example, the Secure World Foundation, a nonprofit nongovernmental organization (NGO), has published a very practical how-to guide: *Handbook for New Space Actors* (SWF Handbook). Others, such as OneWeb (OneWeb), have announced that they are willing to unilaterally go beyond the current guideline, mandating disposal of LEO satellites 25 years after end of mission, to dispose their satellites promptly after the end of mission. The Space Data Association, a not-for-profit limited corporation, has demonstrated how companies and entities, perhaps in some aspects competitors, can work together to exchange potentially sensitive information to enhance on-orbit safety. It is hoped that the efforts by industry and NGOs will also goad public institutions involved in space to also "lean forward" and provide leadership in this regard.

To incorporate safety into the fabric of space operations, the space community is going to have to make space safety and the sustainable use of outer space part of the ongoing science, technology, engineering, and math (STEM) education efforts. If nontraditional entrants into space are going to be encouraged, for example, a junior high school class, as part of their project to fly a small satellite, they should also learn about responsible space behavior and their responsibilities, legal and otherwise, for being actors in the space area and not contributing to the challenges to maintaining a safe space environment. Regulators could play an important role here, in that granting a license to operate a space object could be contingent on demonstrating knowledge and set of technical proficiencies deemed necessary to safely operate in the space environment, not unlike current automobile drivers' licensing and education requirements. France, in their national space act, has codified the concept of a licensed space actor that confers concrete benefits to those who have demonstrated levels of expertise and proficiency (French Space Act).

5 Conclusion

Small satellites, given their low mass and size, can be inexpensive to acquire and launch into orbit. This has opened up access to space to many new actors in the space arena: high schools and universities, hobbyists, developing countries, research and development teams, and even artists and other nontraditional users. Given their low cost, new ideas and concepts can be investigated with much lower risk and with a much quicker development cycle. This democratization of space will stimulate new space commerce, services, and other societal benefits, as well as greater participation in space activities and knowledge of space technologies and expertise. However, this recent acceleration of small satellite-based space activities is a challenge to the existing space management institutions. Challenges are posed by dint of the satellites' small size, their large numbers, their (sometimes) lack of reliability, and the relative inexperience of some of their owner/operators in working within the existing space community. In this paper a number of potential solutions have been outlined to the challenges posed by increasing numbers of small satellites. These include regulatory changes, as the transition is made from space situational awareness to space traffic management; this transition offers an opportunity to do things in new and perhaps different ways. There are also a number of new (or not so new) technologies and techniques that can be brought to bear to mitigate some of the challenges, especially when it comes to tracking and identification, as well as automating the exchange of information between the owner/operators and the STM/SSA entities. The final approach to overcoming these challenges is via education and outreach to the new actors and getting their participation in the development of regulations, guidelines, best practices, and standards, both domestically and internationally. No one solution will alleviate all of the challenges; but it is felt that these disparate approaches, when applied in concert, stand a good chance of mitigating the various challenges and bringing space users closer to Space Operations Assurance and moving the larger space community in the direction of achieving long-term sustainable use of outer space.

6 Cross-References

- ▶ Deorbit Requirements and Adoption of New End-of-Life Standards
- ▶ Financial Models and Economic Analysis for Small Satellite Systems
- ▶ Legal Issues Related to the Future Advent of Small Satellite Constellations
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ▶ "Rules of the Road" for Launch and Operation of Small Satellites and Related Issues
- ▶ Small Satellites Market Growth Patterns and Related Technologies
- ▶ Space Finance for 'New Space' and Small Satellites
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit

References

Chong, Chee-Yee, and Shozo Mori, Metrics for feature-aided track association, 2006 9th International Conference on Information Fusion. IEEE, 2006

Committee on Achieving Science Goals with CubeSats – Thinking Inside the Box, Space Studies Board, Division on Engineering and Physical Sciences, National Academies of Sciences, Engineering, and Medicine, Achieving Science Goals with CubeSats: Thinking Inside the Box at C-7. (2016). http://www.nap.edu/catalog/23503/achievingscience-with-cubesats-thinking-inside-the-box

CONFERS. https://www.satelliteconfers.org/about-us/. Retrieved 2 Dec 2019

COPUOS Guidelines, A/AC.105/C.1/L.366, Guidelines for the Long-term Sustainability of Outer Space Activities, Working paper by the Chair of the Working Group on the Long-term Sustainability of Outer Space Activities. Committee on the Peaceful Uses of Outer Space, Scientific and Technical Subcommittee Fifty-sixth session, Vienna, 11–22 February 2019

French Space Act, See: Law on Space Operations (Loi relative aux operations spatiales) (hereafter French Law on Space Operations); Loi n° 2008-518 du 3 juin 2008; 34 Journal of Space Law (2008); unofficial translation 34 Journal of Space Law (2008).

Global Space Traffic Management Workshop. https://events.ph.ed.ac.uk/space-traffic2. Accessed 1 Dec 17

GVF Working Group on Sustainable Space Operations. https://gvf.org/working-groups/. Retrieved 2 Dec 2019

https://www.npr.org/sections/money/2017/12/01/567267573/planet-money-goes-to-space. Retrieved Nov 2019

https://aas.org/posts/advocacy/2019/12/aas-works-mitigate-impact-satellite-constellations-ground-based-observing. Retrieved 2 Dec 2019

https://crsreports.congress.gov/product/pdf/IF/IF11351. Retrieved 18 Dec 2019

IAASS Space Safety conference. http://iaassconference2017.space-safety.org/programme-overview/. Accessed 1 Dec 2017

International Academy of Astronautics (IAA) Cosmic Study on Space Traffic Management. Edited by Corinne Contant-Jorgenson, Petr Lála, Kai-Uwe Schrogl. Published by the International Academy of Astronautics (IAA) BP 1268-16. https://iaaweb.org/iaa/Studies/spacetraffic.pdf. Accessed 13 Nov 2017

International Academy of Astronautics (IAA): Space Traffic Management. Edited by Corinne Contant-Jorgenson, Petr Lála, Kai-Uwe Schrogl. Published by IAA, Paris 2006, International Academy of Astronautics (IAA) Cosmic Study on Space Traffic Management. Edited by Corinne Contant-Jorgenson, Petr Lála, Kai-Uwe Schrogl. Published by the International Academy of Astronautics (IAA) BP 126816. https://iaaweb.org/iaa/Studies/spacetraffic.pdf. Accessed 18 Apr 19 at p.10 and also International Academy of Astronautics (IAA): Space Traffic Management. Towards a Roadmap for implementation. Edited by Kai-Uwe Schrogl, Corinne Contant, Jana Robinson, Alexander Soucek. Published by IAA, Paris 2018

Institute for Astronomy (IfA) Maui History. https://www.ifa.hawaii.edu/haleakalanew/history.shtml. Accessed 5 Sept 2019

ITU WRC-19, International Telecommunication Union, Provisional Final Acts WRC-19. https://www.itu.int/pub/R-ACT-WRC.13-2019/en. Accessed 2 Dec 2019

IADC. https://www.iadc-home.org/documents_public. Accessed 2 Dec 2019

ISO, For example, ISO/TC 20/SC 14/WG 4 (Space environment (natural and artificial)) and ISO/TC 20/SC 14/WG 7 (Orbital Debris Working Group). https://www.iso.org/committee/46614.html. Accessed 20 Dec 2019

T.S. Kelso. Challenges Identifying Newly Launched Objects, IAC-17-A6.7.9, International Astronomical Congress 68th meeting, Adelaide, Australia, 25–29 Sep 2017

I. Klotz. SpaceX Rideshare Mission Spawns 12 Orphan CubeSats, Aerospace Daily and Defense Report, 8/12/2019

M. Koren, The Mystery of the ‘SpaceBees’ Just Got Even Weirder, The Atlantic monthly, 5/17/2018. https://www.theatlantic.com/technology/archive/2018/05/rogue-satellites-launch-fcc/555482/. Retrieved 15 Apr 2019

M. Koren. https://www.govexec.com/technology/2019/09/spacex-missed-some-urgent-emails-about-satellite-standoff/159908/. Retrieved 11 Nov 2019

Letizia, Francesca, Results from ESA’s Annual Space Environment Report, July 2019, presented as a key-note address at the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 2019. Used by permission from ESA. https://sdup.esoc.esa.int/discosweb/statistics/. Retrieved 29 Dec 2019

A. Mehrparvar (2014, February 20). “CubeSat Design Specification” (PDF). The CubeSat Program, CalPoly SLO. The CubeSat Program, CalPoly SLO. Retrieved 25 Mar 2017

T.J. Muelhaupt, M.E. Sorge, J. Morin, R.S. Wilson, Space traffic management in the new space era. J. Space Saf Eng **6**(2), 80–88 (2019)

“2014 Nano/Microsatellite Market Assessment” (PDF). Annual market assessment series. Atlanta: SEI. January 2014: 18. Archived (PDF) from the original on 22 February 2014. Retrieved 18 Feb 2014

NASA. Space debris and human spacecraft. Retrieved from website https://www.nasa.gov/mission_pages/station/news/orbital_debris.html. 5 Sept 2019

D.L. Oltrogge, S. Alfano, The technical challenges of better Space Situational Awareness and Space Traffic Management. J Space Saf Eng **6**(2), 72–79 (2019)

OneWeb. https://www.oneweb.world/assets/news/media/Responsible-Space-12pp-Brochure-Web.pdf. Retrieved 15 Dec 2019

Photo courtesy National Aeronautics and Space Administration. Retrieved 5 Sept 2019, from NASA website. https://www.nasa.gov/feature/60years-ago-vanguard-fails-to-reach-orbit

SDA. https://www.space-data.org/sda/features-and-articles/. Retrieved 4 Dec 2019

Secure World Foundation. https://swfound.org/news/all-news/2017/09/swf-leads-discussions-on-commercial-ssa-and-space-traffic-management-at-2017-amos-conference. Accessed 1 Dec 17

M.A. Skinner, Making small satellites visible: Nanosat tracking and identification techniques and technologies, IAC-19-A6.7.5, International Astronomical Congress 70th meeting, 21–25 October 2019, Washington DC, United States

M.A. Skinner, Conceptual Development of a Civil Space Traffic Management System Capability, Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 2018, Ed.: S. Ryan, The Maui Economic Development Board

M.A. Skinner, M.K. Jah, D. McKnight, D. Howard, D. Murakami, K.-U. Schrogl, Results of the international association for the advancement of space safety space traffic management working group. J Space Saf Eng **6**(2), 88–91 (2019)

M.A. Skinner, (in press) CubeSat Confusion: how to avoid ‘dead on arrival’. The Aerospace Corporation, 2020.

Space Traffic Management, W. Ailor, in *Handbook of Space Security Policies, Applications and Programs*, ed. by K.-U. Schrogl, P.L. Hays, J. Robinson, D. Moura, C. Giannopapa, Springer-Verlag, 2015, pp. 231–255

R. Sridharan, A. Pensa, “*US Space Surveillance Network Capabilities*,” from SPIE Conference on Characteristics and Consequences of Space Debris and Near-Earth Objects San Diego, California, SPIE, vol. 3434, 1998, pp. 88–100

SSC. https://spacesafety.org/best-practices/. Retrieved 26 Dec 2019

STM at 2017 IAC, Adelaide Australia. http://www.iafastro.org/events/iac/iac-2017/plenary-programme/space-traffic-management-global-challenge-to-protect-the-strategic-domain-of-space/. Accessed 1 Dec 17

SWF Handbook. https://swfound.org/handbook/. Retrieved 26 Dec 2019

The Aerospace Corporation. https://aerospace.org/aerocubes. Retrieved 18 Dec 2019

United Nations Office for Outer Space Affairs. Members of the Committee on the Peaceful Uses of Outer Space. https://www.unoosa.org/oosa/en/members/index.html. Retrieved 18 Dec 2019

Universe Today. Note that utilizing such an “always-on” radio frequency beacon for a satellite service is today not allowed by international treaty, as being an inefficient use of the radio frequency spectrum. Retrieved from website. https://www.universetoday.com/78110/sputnik-one/. 5 Sept 2019

Long-Term Sustainability of Space and Sustainability Requirements

Darren McKnight

Contents

Abstract

Small satellites must be designed and operated to support the long-term sustainability of safe space operations. This community responsibility is reflected in the debris mitigation guidelines that have evolved over the last 30 years. As with any space system decision, the ability to operate responsibly has many options that can be characterized by a balance of trade-offs. The cost of a system or process may be explicit by needing more power and volume or implicit by merely making the operations more complicated. This chapter provides the high-level trade-offs for means by which small satellites may meet debris mitigation guidelines. The

---

D. McKnight (✉)
Centauri, Chantilly, VA, USA
e-mail: darren.mcknight@centauricorp.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_78

five major issues identified for consideration for a post-mission disposal (PMD) device are effectiveness, SWAP (i.e., size, weight, and power), reliability, orbital risk (i.e., collision risk to other objects), and risk to ground assets. While there are many new approaches to reducing the lifetime of a satellite after its mission is completed, propulsive maneuvers remain the most reliable and effective. Drag enhancement, solar sail, and electrodynamic tether systems are all also reviewed, and engineering issues for their potential use are identified.

Keywords

Debris mitigation · Orbital debris · Space safety · End-of-life technologies · Propulsive deorbit · Electrodynamic tether · Drag augmentation · Solar sail

1 Introduction

The space arena is currently experiencing a period of rapid and dramatic change. In the early decades of the space age, this domain was dominated by a few space powers, and most space actors were governmental entities that carried out national civil and military space programs. Nowadays, there is a much larger number and diversity of space actors. The global commercial space economy has grown from a fledgling enterprise to now exceeding many civil and military space investments. The number of spacefaring countries exceeds 90 depending how you define a spacefaring country: as of this writing (February 2019), over 90 countries have operated a satellite in space, 92 countries are represented in the United Nations Committee on Peaceful Uses of Outer Space (UN COPUOS), more than 50 countries can manufacture satellites, and citizens from over 40 countries have been in space. This increasing growth in the number of space actors has been facilitated by advances in space technology that have also greatly lowered the barriers to entry for new space actors, especially from the private sector. This, in turn, has accelerated the pace of technological development, further lowering entry barriers for emerging space actors.

All of these activities have produced scientific advancements, enhanced nation-state capacity building, and improved the quality of life for many global citizens. However, these positive outcomes have been at the cost of a growing threat from orbital debris in Earth orbit. More than 19,000 objects are cataloged and tracked in Earth orbit; Fig. 1 shows this accumulation by object type. Only about 8% of these are operational satellites; the remaining 92% of the trackable population is debris from over 5,000 space launches and nearly 300 satellite fragmentations over the last 60 years. Despite a concerted international effort, the growth of debris being deposited in Earth orbit has not slowed. International debris mitigation guidelines were agreed upon in the mid-1990s that have been followed to varying levels of compliance over the years; these debris mitigation guidelines will be discussed in a subsequent section.

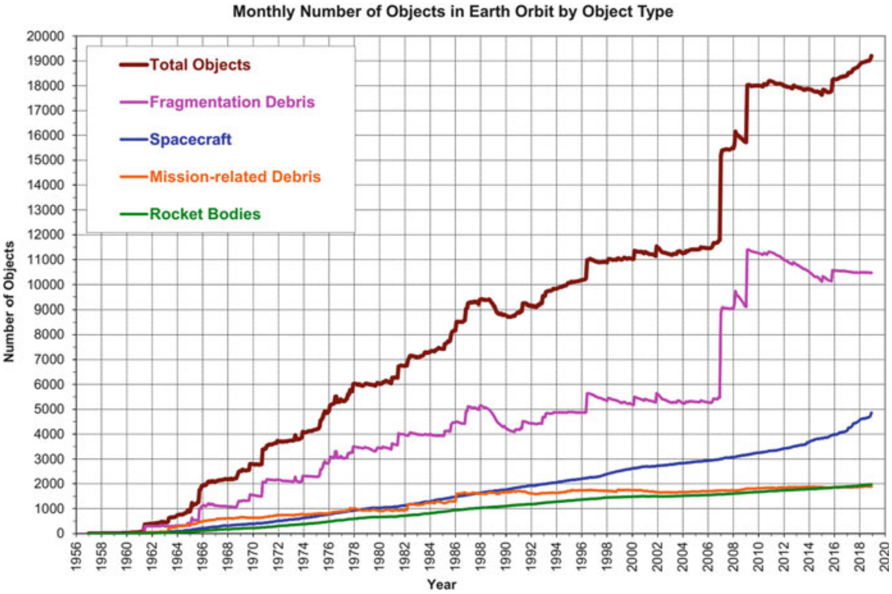


Fig. 1 The cataloged population has grown steadily over time with major fluctuations caused by fragmentation events and orbital reentries which are acccelrated by increased solar activity. (Source: NASA)

Given the risks posed by space debris to the safety and sustainability of space activities, it is the responsibility of every space operator who wants to leverage the space environment to act prudently so that generations to come have the same luxury of high reliability access to space. One way to do this is to develop and implement reliable post-mission disposal (PMD) strategies compliant with debris mitigation guidelines. In a more pragmatic construct, this encourages us all to "leave no footprints" or, possibly, leave where you visit as clean as you found it.

The designers, developers, and operators of microsatellites and smaller satellites (i.e., less than 100 kg) must be astute on ways to implement PMD approaches for these microsatellites, to be compliant with the space debris mitigation guidelines, and enhance the long-term sustainability of the near-Earth space environment. If you are developing or operating a microsatellite, you want to find the best PMD strategy for your mission.

This guidance complements other activities related to smallsats by the International Academy of Astronautics that have highlighted the emerging applications for smallsats empowered by new space technologies. Two recent publications of note are:

- The recently released (2017) International Academy of Astronautics (IAA) study titled "Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery" (http://iaaweb.org/iaa/Scientific%20Activity/cost.pdf).

- The newest version of ISO/TS 20991, *Space Systems – Requirements for Small Spacecraft*, was released in 2018 (http://iaaweb.org/iaa/Scientific%20Activity/Study%20Groups/SG%20Commission%204/sg418/sg418finalreport.pdf).

It must be noted that changes to spacecraft manufacturing, debris mitigation guidelines, the debris environment, etc. may all change the landscape for debris mitigation over time. As a result, it is important to take this handbook as a snapshot in time of useful tools, insights, standards, and procedures; these may change quickly, so the reader is advised to be diligent in keeping abreast of the most up-to-date advancements in these areas.

2 Debris Mitigation Guidelines

In general, all the space debris mitigation guidelines and standards, such as the Inter-Agency Space Debris Coordination Committee (IADC) or International Organization for Standardization (ISO) Standard 24113, apply to any spacecraft, whatever its size. These various sets of guidelines have the following general four elements in common:

1. Passivate energetic sources, such as batteries, and vent excess propellant.
2. Eliminate creation of debris; this includes avoiding explosions and collisions.
3. Ensure that all objects left on-orbit are re-entered within 25 years after the end of their operational life (EOL) or moved to an acceptable graveyard orbit.
4. Suggest to limit the re-entry casualty risk to humans to less than 10^{-4} per re-entry event.

ISO 24113 (2010), first published in 2010 and a third version released in September 2019, is the highest-level standard at the international level dealing with space debris mitigation. It is complemented by second-tier standards, dealing with dedicated topics such as lifetime evaluation of an orbital object, re-entry risk management, collision avoidance, or requirements devoted more precisely to spacecraft or launchers.

These ISO standards are important as they represent requirements, which may turn out to be compulsory for designers and operators, when included in contracts. If such internationally approved requirements are indeed shared by everyone, it would guarantee that every government, academic, and industrial satellite developer or operator plays by the same rules and acts efficiently to control and reduce the threat posed by space debris.

For the common case of a microsatellite presenting no casualty risk, it should re-enter the Earth's atmosphere within 25 years starting from:

(a) The orbit injection period, if the object has no capability to perform collision avoidance maneuvers
(b) The end of operational life (EOL) epoch

This means that if a microsatellite has no propulsion onboard with a thrust level and control sufficient to perform collision avoidance maneuvers, then it should be injected into an orbit compliant with the 25-year rule. This is required even if it is equipped with a post-mission disposal device to reduce the orbital lifetime. Such an altitude, depending on the characteristics of the spacecraft, is in the 600–625 km range.

A satellite which has no onboard propulsion system should not operate in the GEO protected region as it cannot perform collision avoidance maneuvers nor post-mission disposal.

If a microsatellite is equipped with a significant propulsion capability aimed at lowering its final orbit in order to comply with the 25-year rule, then such a maneuver should have a probability of success better than 90%. Otherwise, if there is no propulsion system onboard, the initial injection orbit of the small satellite should naturally comply with the 25-year rule, i.e., be lower than 600–625 km altitude.

In general, all the space debris mitigation rules, such as ISO 24113, apply to any spacecraft, whatever its mass or size. If a microsatellite is equipped with a propulsion system with thrust and reactivity sufficient to enable collision avoidance maneuvers and end-of-life orbit altitude modification, it should (1) comply with the protected region rules in GEO and (2) comply with the 25-year rule in LEO.

The demonstrated probability of success of such end-of-life maneuvers should be higher than 90%. The satellite should also be passivated at EOL. If its structure is such that it may present a casualty risk on ground, then it should be deorbited in a controlled way to guarantee a safe disposal.

If a microsatellite has no capability to perform collision avoidance maneuvers, even if it is equipped with a PMD device, it should not be operated in GEO. In LEO, it should be injected into an orbit naturally compliant with the 25-year rule if it does not have collision avoidance capability even if it is equipped with a PMD device. The satellite should also be passivated at EOL (i.e., safe batteries, capacitors, etc.), and all efforts must be taken to eliminate creation of all debris greater than 1 mm; this includes preventing explosions and avoiding collisions.

3 Determining the Orbital Lifetime of a Microsatellite

Gravity imposes a force on a satellite that causes it to continue to orbit the Earth. If this were the only force acting on a satellite, it would stay in orbit forever. However, the interaction between Earth's atmosphere and the orbiting satellite decreases the satellite of its energy causing it to eventually reach such a low altitude that it can no longer remain in orbit. At this point, it ceases to pose a risk to other orbital assets; however, this re-entering object still has the potential for posing an impact risk to aircraft in flight (Emanuelli and Lips 2015) and to people and property on the Earth. For microsatellites, there is little chance that any material will make it to the ground unless the satellite contains some very unique materials with high melting temperatures (e.g., glass, titanium, etc.) or possibly densely packed components such as batteries and momentum wheels.

The density of the atmosphere decreases exponentially with rising altitude and increases with solar activity and (in a less predictable way) with geomagnetic activity. The solar activity parameter that correlates best with atmospheric density variations is the F10.7 cm solar flux which oscillates on roughly an 11-year cycle. As a result, the effects of drag can vary significantly over time and altitude, making determining an object's orbital lifetime nontrivial. Note: the *operational lifetime* of a satellite is how long it functions properly in space, while *orbital lifetime* is how long it physically remains in orbit.

There are analytic models that can be used to calculate the orbital lifetime from the contraction of the orbit due to atmospheric drag such as Analytical Graphics, Inc. (AGI) Systems Tool Kit (STK). There is also a semi-analytic orbital propagator called STELA (n.d.) (Semi-analytic Tool for End-of-Life Analysis) procured by CNES for lifetime computation in support of the French Space Operation Act. The OSCAR tool inside DRAMA (n.d.) also provides the capability to compute the orbital lifetime using a semi-analytic propagator, with the possibility to analyze post-mission disposal options and their effect. Any of these tools provide an accurate and responsive way to determine the orbital lifetime of a satellite in orbit. This section shows a simplified method to examine orbital lifetimes using a lookup chart taken from a classic book on determining orbital lifetimes to help illustrate the trade-offs between physical parameters relevant for determining the orbital lifetime of a satellite (King-Hele 1987). However, results from STELA are provided for quantitative comparisons, and it is suggested that some sort of high-fidelity orbital lifetime tool such as STELA be used to calculate the orbital lifetime for your respective microsatellite.

3.1 Factors in Determining Orbital Lifetime

The deceleration exerted by atmospheric drag on a satellite is given by:

$$a = \left(\frac{1}{2}\right) C_D \left(\frac{A}{M}\right) \rho\, V^2 \tag{1}$$

where

C_D = coefficient of drag, no units
A = projected satellite area (normal to velocity vector), m^2
M = mass of satellite, kg
$\frac{A}{M}$ = area-to-mass ratio, AMR, m^2/kg
ρ = atmospheric density, kg/m^3
V = velocity through the ambient atmosphere ≈ orbital velocity, m/s

Orbital velocity (approximately 7.6 km/s) varies only slightly in low-LEO, below 1,000 km, where drag affects orbital lifetimes measurably. Conversely, the coefficient of drag varies between 2 and 3 as a function of object shape and altitude (Cook 1965; Herrero 1983). As a result, the four primary variables that determine the orbital lifetime of a satellite are (1) area-to-mass ratio, (2) altitude, (3) coefficient of drag, and (4) solar activity. Each term will be characterized individually before examining how to use them for determining orbital lifetime.

Area-to-mass ratio: The area-to-mass ratio (AMR) can be calculated by dividing the area that the satellite presents in its direction of motion by the mass of the satellite. The larger the AMR, the more atmospheric drag will affect the orbit. So, simply speaking, a satellite with a larger AMR will be removed more quickly from orbit than one with a smaller AMR value at the same altitude and same time. Later in this handbook, how increasing AMR can be used to reduce orbital lifetime is examined.

Interestingly, an AMR value between 0.003 and 0.03 m^2/kg (with the typical value of approximately 0.01 m^2/kg) covers most spacecraft from small 1U cubesats to large commercial communication satellites deployed in GEO. This commonality is due to the physical limitations of how much circuitry can be packed into a payload bus. It is fairly simple to calculate the AMR of a specific satellite, but do not be surprised if it is not in this general range.

If you would like to be conservative, you can use the smallest possible cross-section as the area term. This will produce the largest possible orbital lifetime, so if you can meet the 25-year rule with that minimum value, it provides you some extra confidence that you will be compliant. However, as you will soon find out, there are other factors in the calculation of the orbital lifetime of a satellite that may have even a greater influence on the final value for orbital lifetime.

A 1U cubesat has a minimum cross-sectional area of 0.01 m^2 since one face of the bus is $10\text{ cm} \times 10\text{ cm} = 0.1\text{ m} \times 0.1\text{ m} = 0.01\text{ m}^2$. The actual average cross-sectional area for a tumbling 1U cubesat is 0.015 m^2. The mass of a typical 1U cubesat is about 1 kg so the AMR is easily determined by $0.01\text{ m}^2 \div 1\text{ kg} = 0.01\text{ m}^2/\text{kg}$ (or $0.015\text{ m}^2 \div 1\text{ kg} = 0.015\text{ m}^2/\text{kg}$ for a tumbling 1U cubesat). Some 1U cubesats can be as heavy as 1.5 kg which would produce an AMR of 0.007 m^2/kg or 0.01 m^2/kg, respectively.

A 3U cubesat has a minimum cross-sectional area of 0.01 m^2 and a mean cross-sectional area of 0.03 m^2 (without any deployable appendages). As a result, for the roughly 3–6 kg 3U spacecraft, the AMR ranges from approximately 0.002 to 0.01 m^2/kg. If the 3U cubesat has a fixed orientation so that the area exposed to the atmosphere is constantly 0.03 m^2 (i.e., travels with broadside in the direction of the satellite's motion) and it has a mass of 6 kg, then its AMR is 0.005 m^2/kg.

Altitude: Generally speaking, a satellite's orbit is elliptical – the altitude above the Earth is not constant, and the extremes in altitude of a satellite are provided by two parameters, apogee and perigee. (Alternatively, the two parameters of eccentricity and semimajor axis may be used. Eccentricity, e, is the "ellipticity" of the orbit shape. For example, $e = 0$ is a circular orbit and $0 < e < 1$ for an elliptical orbit. The semimajor axis, a, is roughly the average distance between the center of the Earth and the altitude of the orbiting object. For example, a satellite in an 800-km circular altitude has a semimajor axis of 7,178 km since the radius of the Earth is 6,378 km.) Apogee is the highest altitude that the satellite reaches above Earth's surface during an orbit, while perigee is the lowest altitude. If a satellite is in a circular orbit, apogee and perigee are identical, and the satellite remains at the same altitude throughout its orbit. It should be noted that if a satellite is in an elliptical orbit (i.e., not a circular orbit), drag will first circularize the orbit. That is to say, it will act on the satellite more at the lower altitudes of the orbit; the drag that acts primarily at and around perigee will first largely produce a lowering of the apogee, as shown in Fig. 2.

The reason that altitude is so important is that atmospheric density decreases exponentially with increasing altitude, as shown in Fig. 3.

The atmospheric density may drop by a factor of 100 as altitude increases from 200 km to 400 km. However, going from 600 km to 800 km altitude (i.e., another 200 km increase in altitude), there may only be a factor of 10 reduction in atmospheric density. Above 1,000 km, drag has almost a negligible effect except for objects with very large AMR values; if needed to consider drag at these altitudes, it is advisable to use an analytical model such as STELA.

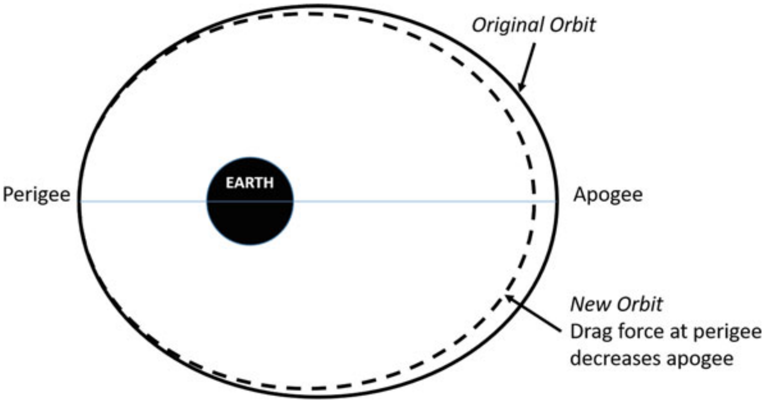


Fig. 2 Atmospheric drag acts first to reduce the apogee of an elliptical orbit

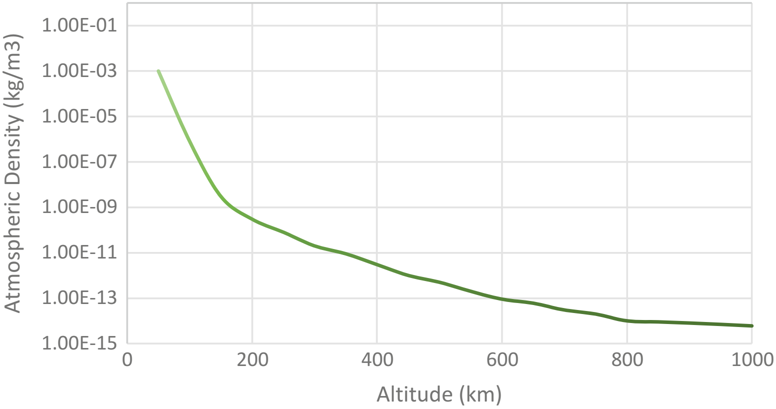


Fig. 3 Atmospheric density in LEO varies exponentially with altitude. (Space Exploration Stack Exchange for US Standard Atmosphere 1976)

Coefficient of Drag (C_D): The coefficient of drag may vary between roughly two and three in LEO depending on the altitude, solar activity, and shape of the object. For objects closer to their EOL (i.e., at 200–400 km), C_D is fairly consistent at 2.0–2.2 (i.e., average of 2.1). However, as altitude rises to near 1400 km, the C_D rises to values approaching approximately 3. Figure 4, provided as part of the STELA application, depicts the average C_D for LEO assuming a general sphere or tumbling plate (STELA Technical Note on Calculating the Coefficient of Drag 2011).

Solar activity: The calculation of a satellite's orbital lifetime is complicated by continual variations in solar activity that lead to changes in atmospheric density in LEO. Radio emissions from the Sun with wavelength of 10.7 cm have been found to correlate most closely with changes in atmospheric density; this is called the F10.7 cm solar flux.

The solar cycle is neither exactly 11 years nor does it follow exactly the same pattern of activity during each cycle. Figure 5 shows the sunspot number (which correlates directly to the F10.7 cm solar flux: F10.7 ≈ 0.9 sunspot number + 59.6) over several centuries highlighting the variability over time. Clearly, there are significant variations over time in both shape and amplitude (i.e., the maximum level and minimum level). Notice how the solar maximum in 2014/2015 (the latest solar maximum on plot) was significantly lower than the previous solar maximum in 2002/2003. Such protracted lower solar activity levels will cause orbital lifetimes to be systematically underestimated.

The uncertainty in solar activity will contribute significantly to possible mismatches between predicted and actual orbital lifetimes. Atmospheric drag effects can

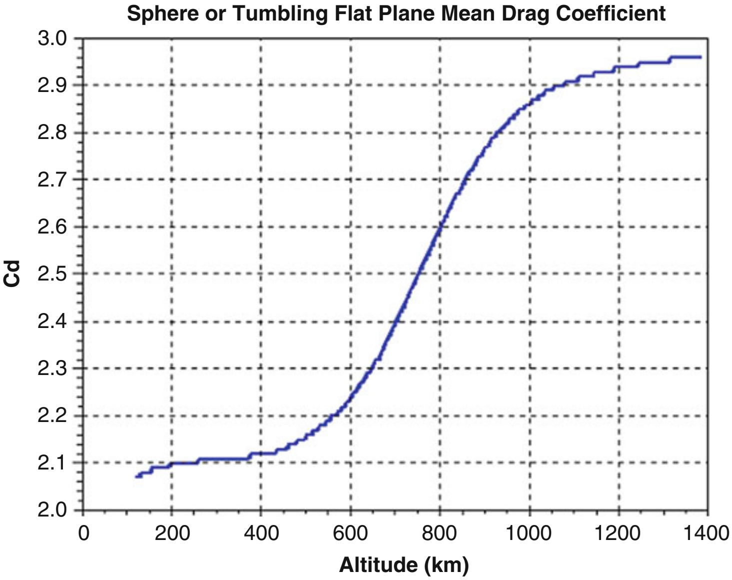


Fig. 4 Coefficient of drag, C_D, varies by altitude in LEO; curve is for a sphere or tumbling flat plate in low solar activity

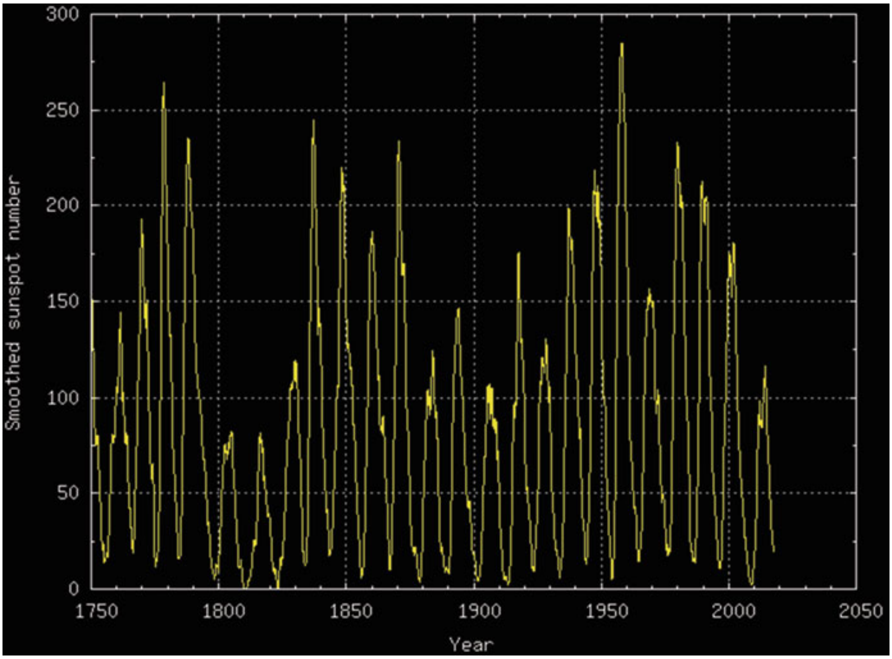


Fig. 5 The solar cycle is not as regular as the name would suggest – it varies in length, shape, and magnitude from cycle to cycle. (Source: Australian Government Space Weather Services)

easily vary by factors of 2–4 between high and low solar activity in comparison with the average values shown in Fig. 5. In other words, during periods of high solar activity, the drag effects (for the same object for same altitude) can be two to four times larger than average; the reverse is true during periods of low solar activity. The OSCAR tool implements different methods providing a forecast of solar and geomagnetic activity as recommended by recent standards. For estimation of orbital lifetime, five different methods may be used to generate future solar and geomagnetic activity data which serves as input for the orbit propagation. The methods are based on recommendations by ISO, ECSS, as well as a method which has been implemented within the French Space Operations Act.

3.2 STELA Orbital Lifetime Calculations

STELA is the Semi-analytic Tool for End-of-life Analysis that has been procured by *CNES* (The French Space Agency) to support the *French Space Operations Act*. Table 1 provides outputs for several microsatellite missions assumed to start in 2018 (for solar activity values) using STELA highlighting the importance of AMR and altitude on orbital lifetime.

The examination of the key parameters that affect orbital lifetime identifies the engineering terms available to manage orbital lifetime: altitude and cross-sectional

Table 1 Using STELA to determine orbital lifetimes for a 1U cubesat with and without a drag-augmentation device hints at the benefit of such a PMD device to limit orbital lifetime

Scenario	Parameters	STELA output
1U in 800 km circular orbit	Assume 1 kg tumbling 1U cubesat (AMR = 0.015 m^2/kg) with an inclination of 90°	92 years
1U in 600 km × 800 km orbit		24 years
1U in 400 km × 1000 km orbit		5 years
1U in 600 km circular orbit		8 years
1U in 800 km circular orbit	Assume 1 m^2 drag-augmentation device and 2 kg microsatellite (AMR = 0.5 m^2/kg) with an inclination of 90°	2 years
1U in 600 km × 800 km orbit		7 months
1U in 400 km × 1000 km orbit		50 days
1U in 600 km circular orbit		70 days

area (which may also vary over time). However, the derived term of coefficient of drag (i.e., based largely on the altitude and shape of a space object) and the dynamic solar environment contribute significantly to the final orbital lifetime and uncertainty in these calculations.

This section has identified STELA as a viable means to determine the orbital lifetime of a space system. Alternatively, ISO 27852 (Space Systems – Estimate of Orbit Lifetime) (https://www.iso.org/standard/68572.html) or other tools like OSCAR or STK can be used to calculate orbital lifetime. However, it is important to remember that the variability of actual solar activity still persists and contributes to the uncertainty in any long-term orbital lifetime calculation, no matter which tool is used. In addition, elliptical orbits with apogees above LEO will definitely require analytic means to estimate orbital lifetimes as solar-lunar perturbations become relevant and significant.

4 Re-entry and Survivability of Microsatellites

There are four primary characteristics that determine whether a given satellite will survive re-entry, as shown in Fig. 6. Microsatellites will pose little air or ground impact risks as long as they comply with the following three characteristics:

- Material: aluminum and circuit boards
- Mass: under 100 kg
- Construction: no hardened or especially densely packed components

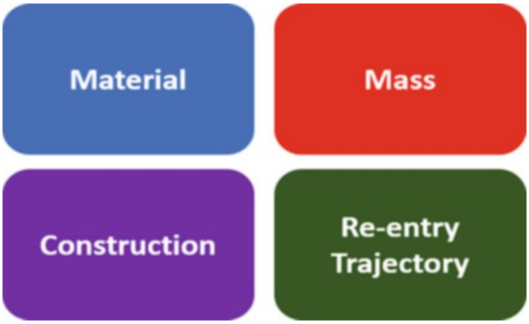


Fig. 6 A microsatellite that has typical mass, construction, and material with a natural re-entry trajectory will pose very little air or ground hazard

The probability of demise of the hardware also depends on the re-entry trajectory.

The use of materials with high melting points (e.g., steel, titanium, glass, beryllium, etc.) and very densely constructed devices should be avoided as much as possible. If the use of such materials and components cannot be avoided, an analysis tool such as ORSAT (n.d.), SCARAB (n.d.), SARA (n.d.), or DEBRISK (https://logiciels.cnes.fr/fr/content/debrisk) should be used to evaluate the probability that objects may survive re-entry to cause damage to property and/or people.

Small satellites are generally fragile objects. Yet, when their orbits decay and the satellite re-enters the atmosphere, there remains a question as to whether parts of the satellite will survive to the ground, and if so, what kind of risk might that hardware pose to population and their property.

Two types of re-entries can occur: controlled and uncontrolled. A controlled re-entry is generally a more complex process and is reserved for missions such as human spacecraft and very large spacecraft with both robust attitude control and propulsion systems. Most re-entry events are uncontrolled re-entries of spacecraft, rocket bodies, and fragmentation debris. Some of these objects can pose a risk of injury to people on the ground or aircraft in flight due to the unpredictability of their trajectories and exactly where and when they will re-enter and, should parts survive re-entry, where they will land. Since a controlled re-entry is much more difficult and expensive to execute than an uncontrolled re-entry, this section will focus on the technical issues surrounding uncontrolled re-entry.

The space object population is made up of operational payloads, defunct payloads, rocket bodies, crewed platforms, mission-related objects, and fragmentation debris. Orbiting objects below 800–1,000 km in altitude have a finite lifetime in orbit due to the interaction with Earth's atmosphere. Atmospheric drag, even with an extremely small atmospheric density, will slowly cause orbiting objects to move to lower orbits. As an object's orbit gets lower and lower, the increasing air density acts upon it until it can no longer maintain its orbit. As the object begins its final re-entry, it starts to heat up.

Fragile parts of the object (such as solar panels) break off due to heating and aerodynamic loading. As the object moves further into the atmosphere, it begins to shed more components and further breaks apart. As this process continues, each piece disintegrates (either partially or completely). Those objects that do not demise will follow their own re-entry trajectory. As the pieces that survive re-entry reach the ground, they create what is known as a footprint.

Since the majority of the Earth's surface is covered by water, a sizable percentage of objects that survive re-entry will land in the water and will consequently likely never be recovered. However, the remaining 30% will land on the ground, where they are often recovered.

4.1 Casualty Risk to the Population

While no one has yet been injured or killed from re-entries, according to the International Academy of Astronautics (IAA) Space Debris Situation Report, the cumulative expected value of the number of people on the ground to have been struck and killed by a falling piece of debris now exceeds one (IAA Space Debris Situation Report on Space Debris 2017). This is reflective of both the large number of massive objects that have re-entered and the growing global population.

Internationally, a 1 in 10,000 probability threshold for an impact casualty risk from an uncontrolled re-entry is a commonly accepted risk level by space agencies and nations around the world (Casualty Risk Tolerance for Re-entering Debris).

4.2 Recommended Design Practices for Minimizing Satellite Survivability upon Re-entry

A microsatellite that is re-entering is unlikely to pose a significant risk to a person on the ground or aircraft in flight. However, to further reduce the risk posed to someone on the ground, a satellite designer can choose materials and design features for the satellite that will increase the likelihood that the satellite and its components will melt during re-entry; this is called design for demise.

The physical characteristics of several common satellite materials are shown in Table 2. The lower the melting temperature and heats of ablation, the more likely it is that the material will burn up during re-entry. Note that the melting point

Table 2 Material properties for several common spacecraft materials shows why beryllium, glass, and titanium are more likely to survive re-entry. (Wertz et al. 2011)

Material	Melting/softening temperature (°K)	Specific heat (J/kg°C)	Heat of ablation (kJ/kg)	Heat of ablation (kJ/m^3)
Graphite/epoxy	700	720	350	550
Aluminum	850	897	900	2,400
Stainless steel	1,700	490	900	7,250
Titanium	1,940	523	1,600	7,050
Zerodur glass	2,000	800	1,400	3,550
Beryllium	1,557	1,020	4,100	7,550

(i.e., temperature at which material becomes a liquid) is related to the material's heat of ablation (i.e., measure of the effective heat capacity of an ablating material, numerically the heating rate input divided by the mass loss rate which results from ablation.). As a result, for objects to survive re-entry, they should have a high melting point, high specific heat, and a high heat of ablation. Conversely, it is best to have lower melting temperatures and lower heats of ablation to ensure disintegration during re-entry.

Materials such as aluminum and graphite/epoxy composites have very low heats of ablation and will readily demise during re-entry. Components made of materials such as titanium, glass, and beryllium have very high heats of ablation and are more likely to survive re-entry. Many variants of glass-ceramics are used in high-temperature applications, such as cooktops, stoves, and fireplaces, so it shouldn't be surprising that they are more likely to survive exposure to high temperatures.

However, there are likely applications where some of these high-temperature materials must be used. Therefore, there are some design practices that can be implemented to reduce the likelihood of them surviving re-entry or reducing the casualty risk on the ground.

First, if the designer can change the aerodynamic characteristics of the object one might encourage disintegration on re-entry. For example, decreasing the blunt edges and making the object less like a ball will decrease the probability of survival.

Second, by bundling objects that would likely survive re-entry, the number of survivable objects may be reduced. For instance, a spacecraft with several batteries that each would likely survive re-entry could be redesigned to put those batteries in a survivable box on the spacecraft. Due to a reduced casualty cross-section, the single survivable box thus poses a lower risk than multiple survivable batteries. This technique may be useful if the material is known to be re-entering over a populated area where fewer lethal pieces making it to the ground would be better. However, generally speaking, it is best to separate objects as soon in the re-entry process as possible to maximize the chances for the material to disintegrate.

Assessing the survivability of a re-entering object is a complex process, but if your spacecraft is a microsatellite or smaller and is constructed of typical spacecraft materials such as aluminum and graphite/epoxy (used for circuit boards), there is a low probability that any material will survive to the ground.

If it is deemed necessary to perform this complex demise modeling, several predictive software models are available. ORSAT (Object Re-entry Survival Analysis Tool) will be used to illustrate the utility of such analytic re-entry breakup and survivability models used in the technical community.

5 Means to Reduce Orbital Lifetime

Strategies for post-mission deorbiting rely on forces which decelerate the satellite, thereby reducing the orbital altitude and resulting in a deorbiting scenario. These strategies fall primarily into four categories:

(a) Propulsion systems
(b) Drag-augmentation devices
(c) Electrodynamic tethers
(d) Solar sails

Post-mission deorbiting of microsatellites may be accomplished either actively or passively. An active approach could be a retrograde thrust to decelerate the satellite and is typically achieved via propulsive devices. The performance of propulsive devices is typically characterized by their capability to change a satellite's velocity (i.e., its ΔV capacity) which, in turn, directly changes the satellite's orbit. Passive deorbiting utilizes the natural orbital environment to generate a retrograde "thrust." For LEO satellites at altitudes below 800–1,000 km, the Earth's atmosphere generates a retrograde force (i.e., atmospheric drag) that causes the satellite's orbit to decay along a spiral trajectory toward the Earth. The rate of the decay is dependent on the satellite's cross-sectional area in the direction of motion. Drag-augmentation devices increase cross-sectional area to passively reduce the post-mission orbital lifetime of satellites in this region. The increase in area is typically achieved by deploying either a drag sail or a gossamer structure (e.g., inflatable balloon or boom). A propulsion system could also enable collision avoidance and controlled re-entry.

Propulsive deorbiting systems rely on a retarding thrust to lower the satellite's altitude. While these systems are straightforward practical solutions, they come at a cost in terms of (i) satellite reliability (i.e., the propulsive system and the attitude determination & control system have to both be functional at the end of the mission) and (ii) require additional launch mass (e.g., a stand-alone propulsion system and/or additional propellant) that usually does not support the mission's operational objectives directly. However, these systems provide a proven way that reduces an object's orbital lifetime in an expeditious fashion and to perform collision avoidance and controlled re-entry, if needed.

5.1 Propulsive Deorbiting

Retrograde propulsive devices for deorbiting typically utilize two strategies: (i) controlled re-entry where the satellite is guided to an impact point over the ocean or an uninhabited area to reduce risk or (ii) uncontrolled re-entry, where the casualty risk to people on the ground has been met, the satellite is maneuvered to a lower perigee or lower circular orbit for an eventual uncontrolled atmospheric re-entry. Typically, high-thrust propulsive systems (e.g., chemical engines) utilize either a one- or two-impulse Hohmann-type transfer to reduce the orbital altitude. (However, the second impulse is generally unnecessary as the atmosphere completes the deorbit maneuver if the perigee is low enough.) Conversely, low-thrust propulsive systems (e.g., electric engines) typically utilize a continuous burn strategy.

The Hohmann-type maneuver uses an impulse at the higher altitude to maneuver the satellite to an elliptic trajectory toward the desired lower altitude and a second impulse to circularize to the lower orbital altitude. The continuous burn trajectories,

Table 3 The comparison of ΔV (m/s) for the two deorbiting strategies highlights the utility of dropping the perigee to 400 km for the higher-altitude LEO orbits

Initial satellite altitude (km)	ΔV (m/s)		Initial satellite altitude (km)	ΔV (m/s)	
	Circularizing strategy	Perigee drop strategy		Circularizing strategy	Perigee drop strategy
650	26.93	68.50	1350	375.86	239.15
700	53.58	81.68	1400	398.93	250.28
750	79.94	94.71	1450	421.78	261.27
800	106.03	107.57	1500	444.40	272.14
850	131.85	120.27	1550	466.80	282.89
900	157.39	132.82	1600	488.98	293.51
950	182.67	145.21	1650	510.95	304.00
1000	207.69	157.46	1700	532.70	314.38
1050	232.46	169.55	1750	554.25	324.64
1100	256.97	181.50	1800	575.59	334.79
1150	281.23	193.31	1850	596.73	344.82
1200	305.25	204.97	1900	617.66	354.73
1250	329.02	216.50	1950	638.41	364.54
1300	352.56	227.89	2000	658.95	374.24

employed by low-thrust propulsive devices, continuously remove energy and achieve lower orbital altitudes through a spiral trajectory.

For microsatellites in Earth orbit that "on paper" do not comply with the 25-year rule, active PMD methods must be considered. A direct and expedient approach is that of a propulsive maneuver to reduce the satellite's altitude such that decay can be achieved within the 25-year threshold or even sooner, if desired.

Two deorbiting strategies are considered: circularizing or perigee drop. The first one is to circularize the orbit to 600 km, and the second is to drop the perigee to 400 km. Results are presented in Table 3 and Fig. 7.

A general trend can be observed in Fig. 7. The circularizing the orbit strategy is more advantageous when the initial satellite altitude is below 800 km. However, from 800 km upward, it is better to execute the perigee drop maneuver.

5.1.1 Challenges of Propulsion System

Propulsion systems are a very well-established technology, and many devices are commercially available for small satellites, even those as small as 1U cubesats. Though there are some challenges in implementing a propulsion system that may affect satellite system design and operations, it is important to point out that a propulsion system cannot be thought of as a "stand-alone" system which will deorbit the satellite. This is because the propulsion system requires a functioning attitude determination and control capability for two reasons. First, the direction in which the thrust is to be oriented needs to be measured onboard and a pointing capability of the spacecraft is needed. Second, direction of the thrust needs to be maintained and controlled during the propulsive maneuver against the (often high) torque generated

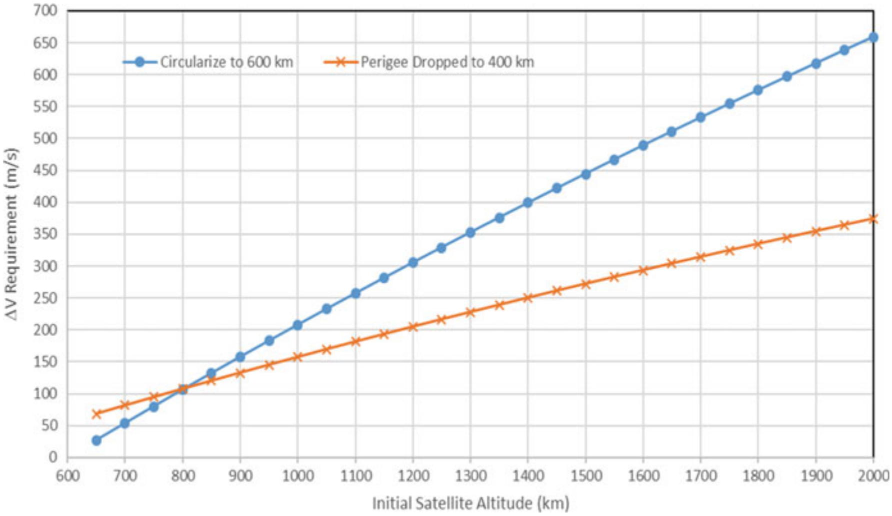


Fig. 7 The orbital altitude where a perigee drop to 400 km is superior to circularizing an orbit to 600 km is about 800 km

by the thrust itself. In addition, the propulsion system typically contributes to the overall spacecraft mass and power budgets plus adding complexity and volume depending on the propulsion system technology and required ΔV.

5.2 Drag Augmentation

Drag augmentation for post-mission disposal (PMD) of LEO satellites is nothing new – the concept has been studied since the late 1980s. An early publication by Petro (1990) discussed the use of deployable balloons as an effective mechanism for deorbiting "objects" below an altitude of 800 km. Since then, there has been a plethora of studies exploring the merits and challenges of drag-augmentation devices for PMD of LEO satellites. A paper by MacDonald provides a summary of some of these activities (Macdonald et al. 2015).

In addition to the studies, flight demonstrations of satellites equipped with devices that can be utilized for drag augmentation during PMD have been attempted. The NanoSail-D mission (ISO 24113 2010) was conceived as solar sail technology demonstrator by NASA to be flown in LEO where it would operate as a drag sail. The satellite was lost during launch in 2008, but its replacement, NanoSail-D2, was successfully flown in 2010; see Fig. 8.

Nanosail-D2 deployed a 9 m^2 sail from a 3U cubesat and managed to deorbit from an initial altitude of 650 km in only 240 days (NASA 2011). A typical cubesat with area-to-mass ratio of 0.01 m^2/kg would have taken around 25 years to deorbit unassisted from this altitude, as per section "Determining the Orbital Lifetime of a Microsatellite".

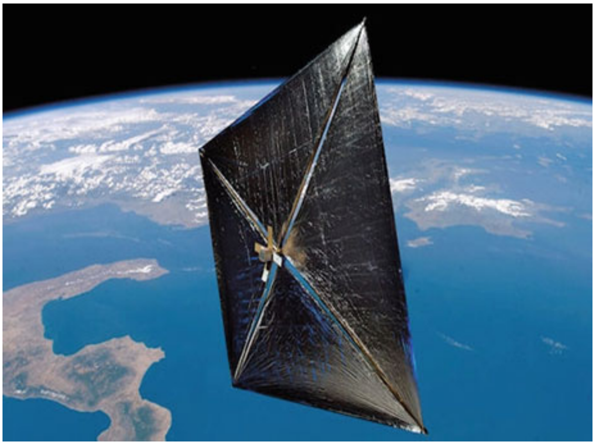


Fig. 8 The NanoSail-D2 was deployed successfully in 2011. (Source: http://www.nasa.gov/mission_pages/smallsats/11-010.html)

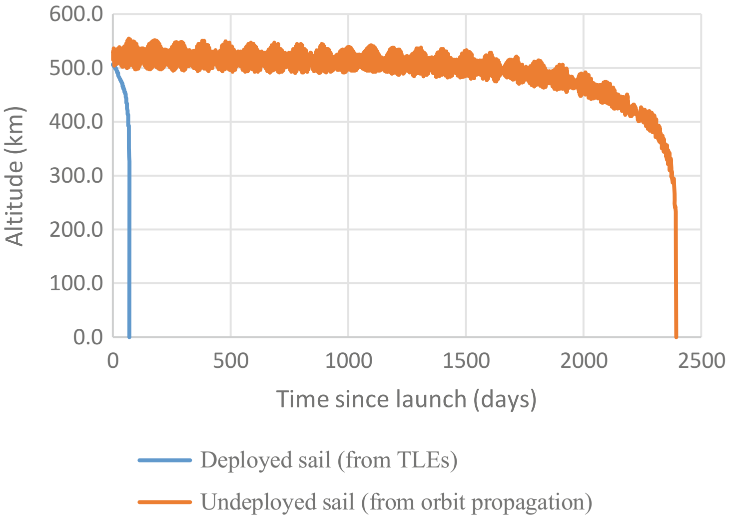


Fig. 9 The deployed sail profile for InflateSail from actual TLEs is depicted versus the simulated undeployed decay profile from orbit propagation

InflateSail was another successful demonstrator of drag-augmented deorbiting; the altitude profile with and without the sail is shown in Fig. 9. The 3U cubesat deployed a 10 m^2 sail that was extended from the cubesat bus using a 1 m inflatable mast (Viquerat et al. 2015). InflateSail was deployed from an initial 518 km × 494 km orbit and stayed in orbit for only 72 days (blue line), but it would have stayed in orbit for over 6 years without the drag sail deployment (Underwood et al. 2017). The analysis of this demonstration implies that a 100 kg spacecraft can comply with the 25-year rule from an altitude of 800 km under average solar activity and active attitude control that points the sail into the RAM direction (Taylor et al. 2018). Note

Fig. 10 Echo II undergoing stress test. (Image credit NASA)

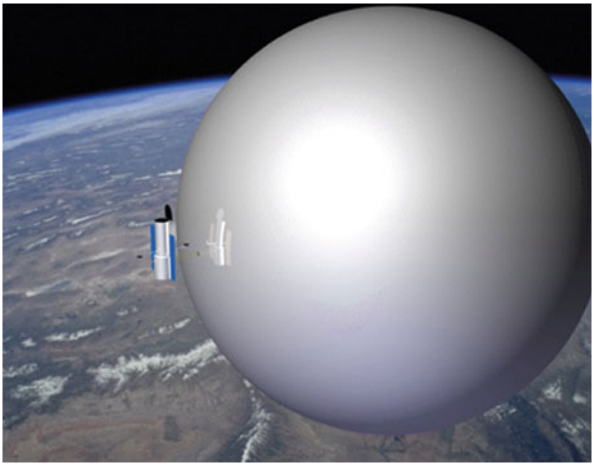


Fig. 11 Global Aerospace GOLD inflatable balloon. (Global Aerospace Corporation)

that by using active attitude control to direct the solar radiation pressure, it is possible to achieve an even shorter deorbit duration from higher initial orbits.

Drag-augmentation devices rely on the force exerted by the atmosphere on the larger exposed area to reduce the orbital lifetime of the satellite. The two most promising drag-augmentation designs are flat drag sails (as shown in Fig. 8) and inflatable gossamer devices (see Figs. 10, 11, and 12). On the one hand, a drag sail typically utilizes structural member(s) to provide support to the sail area, which is usually constructed from lightweight film material. Gossamer drag-augmentation devices are effectively large balloons either inflated or using a deployable shell to significantly increase the satellite's cross-sectional area.

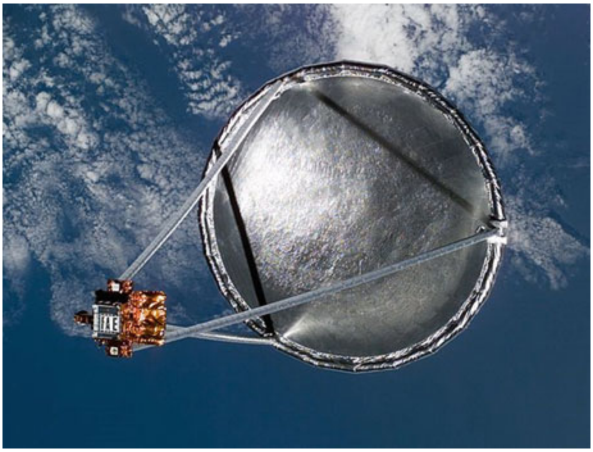


Fig. 12 Inflatable Antenna Experiment. (Image credit NASA)

Examples of successful inflatable space structure missions include the NASA Echo balloons (Fig. 10), Global Aerospace GOLD balloon (Fig. 11), and the Inflatable Antenna Experiment (Fig. 12). Although only the GOLD system was designed to demonstrate drag deorbiting, it was also the only one that did not fly in space.

One reason why an inflatable structure might be preferred is because of the three-dimensional nature of the structure – the orientation of the satellite becomes less important in ensuring a consistently maximum drag force. An inflatable sphere has the same cross-section regardless of orientation, but a flat sail has the potential to create very little drag if the orientation of the satellite is unfavorable. Concerns regarding attitude stability of a drag sail are addressed later.

Since the aerodynamic drag force is directly proportional to the cross-sectional area of the satellite, an increase in cross-sectional area is beneficial in terms of the magnitude of the generated drag force.

A larger drag surface area will lead to a shorter orbital decay duration in LEO, which is desirable from a debris mitigation point of view; however, the larger surface area will also increase the likelihood of a collision. Large structures, such as drag-augmentation devices, will be susceptible to particulate impacts from objects in LEO. While the probability of collision with a "large" object of 10 cm or more (which can lead to a catastrophic collision, catastrophic means that the satellite will be completely fragmented as a result of the encounter with typically 1–3 trackable fragments per kg of mass of the satellite) is manageable, there are many more, smaller particles which have a greater probability of impact that could still disrupt the drag augmentation significantly. The area-time-product (ATP) is often used as a relative measure of how many particulates a satellite may encounter. It is simply the collision cross-sectional area of the satellite multiplied by the time spent in orbit; however, the area to take into account is not always obvious.

Another important design aspect of a drag-augmentation device is that of materials. The intent is to use lightweight materials, otherwise the mass of the deorbiting device will negate the drag-enhancement benefit. The membrane of a drag sail usually consists of a thin polymer film substrate with coating to achieve the desired thermal and optical properties. The most common substrate materials used are Mylar, Kapton, and CP-1. Membranes as thin as 2 μm have been produced, but for such thin membranes, handling and folding become problematic. Atomic oxygen causes erosion of Kapton and aluminum-coated Kapton for exposed materials on space systems operated below 650 km altitude. If the sail has to remain intact for as long as 25 years, it is essential to apply an atomic oxygen-resistant coating.

Successful sail deployments from NanoSail-D2, LightSail-1, InflateSail, and other missions have demonstrated that drag sail deorbiting is indeed feasible for microsatellites. It is important for the technology to become more reliable so that deployment failures do not hamper the success of the deorbiting goals.

Advances in materials and the availability of ultrathin membranes enable gossamer structures that can drastically increase a satellite's AMR with minimal parasitic mass. Such a strategy can be used to comply with debris mitigation requirements. Even a slight increase in AMR will lead to a shorter deorbit duration or increase the altitude from which the satellite can start deorbiting.

Drag augmentation, however, is limited operationally to orbits below 800–1000 km. At higher altitudes the required AMR becomes problematic, such that the deployable structure will be too large and heavy for the satellite. Drag augmentation can also only be applied to situations where an uncontrolled re-entry is acceptable.

Although drag augmentation can be achieved by both deployable sails and inflatable structures, sails remain the more competitive choice for smaller satellites, due to the small mass and volume impact and undesirable complexity of an inflatable system. Drag sails still have challenges. These include guaranteeing reliable deployment, attitude stability, and integration complexity with the host satellite.

5.3 Solar Sail

J. Maxwell and P. Lebedev proved that electromagnetic radiation exerts a force upon any physical body. The value of solar radiation pressure varies with distance to the Sun according to an inverse square law and equals approximately 4.56 $\mu N/m^2$ at the distance of 1 astronomical unit (approximately 150×10^6 km) from the Sun (i.e., at the Earth).

To increase the SRP force acting upon a satellite, one can deploy a large, but lightweight, highly reflective membrane. Such a membrane, along with its mounting system, is called a solar sail. The sail membrane is typically made of some light plastic, such as Mylar or Kapton, and covered with an aluminum layer on one or both sides (McInnes 1999). Though the shape of sail-like deployable space structure is not necessarily flat, this configuration is the most common and the only one discussed.

Solar sails may also be spin-stabilized to exploit the centrifugal force during the deployment process and for keeping the membrane stable. Spin-stabilized sails are considered Class 2 sails. As a result, solar sails of the first class – mostly of square form – are used most often despite their three-axis stabilization constraint and higher operating reliability (than spin-stabilized sails). Since the SRP force is directed close to the normal of the mirrorlike solar sail, three-axis attitude control of the sailcraft is required to provide controllability of the orbital motion.

Several sailcraft have been successfully operated in space, with the first completely successful deployment being the Japanese interplanetary mission IKAROS in 2010 (Shirasawa et al. 2014). Space sailing is an emerging trend in propulsion for small spacecraft as evidenced in its wide application to ongoing missions. However, past successes of solar sails have primarily been on interplanetary missions.

Solar radiation pressure magnitude is obviously almost constant for satellites in LEO, whereas the drag force rapidly decreases with increases in altitude. However, the solar sail goes in and out of the Sun during an orbit and has to be reoriented to maintain a large area pointing toward the Sun. At altitudes above about 700–800 km, the maximum SRP force can surpass the drag force. The absolute values of these two forces for a 3U cubesat with a 5 m × 5 m square sail are shown in Fig. 13.

The behavior of the two main perturbation forces, excluding the J_2 effect (i.e., Earth not being a perfect sphere) which is irrelevant for deorbiting, allows us to come up with an idea of using a sail in the solar mode when the satellite just begins the deorbiting process from a higher LEO orbit (from 800 to 2,000 km) and

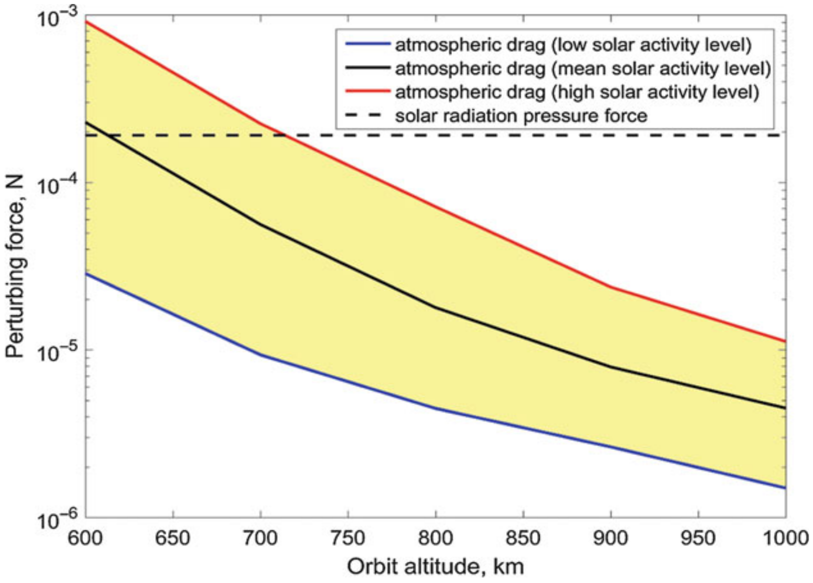


Fig. 13 Perturbing forces of atmospheric drag and solar radiation pressure acting on a 5 kg satellite with a 25 m^2 solar sail are depicted. The qualitative behavior observed is AMR-independent and would be the same for any spacecraft with any sail as long as the sail is kept ram-facing or Sun-facing

switching it to the drag mode when the satellite's orbit drops below approximately 700–800 km. The main challenge here is to properly and efficiently control the solar sail attitude to ensure an SRP-induced secular decrease in the semimajor axis.

It should be noted that there is a trade-off for a mission operator between installing a larger (and, hence, more costly and complex) solar sail and supervising the longer deorbit process: the strategy of exploiting the SRP force is not fully passive although it can be made autonomous or semi-autonomous.

The additional costs for utilizing ground stations and personnel during the deorbiting phase should be taken into account, which often makes targeting the 25-year deorbit period to be nonoptimal. Moreover, the risk of fatal membrane damage and/or failure of some control actuators rapidly rises for a mission lasting longer than 5–10 years.

As a rule of thumb, one can recommend to choose a sail providing the area-to-mass ratio of about 1 m^2/kg. For an altitude above 1,200 km, this value is advised to be upgraded to 2 m^2/kg. As modern solar sails weigh about 50 g/m^2 (including booms and the deployment mechanism), the solar sail system mass ratio can be estimated as being in the region of 5–10% of total spacecraft mass.

5.4 Electrodynamic Tether (EDT)

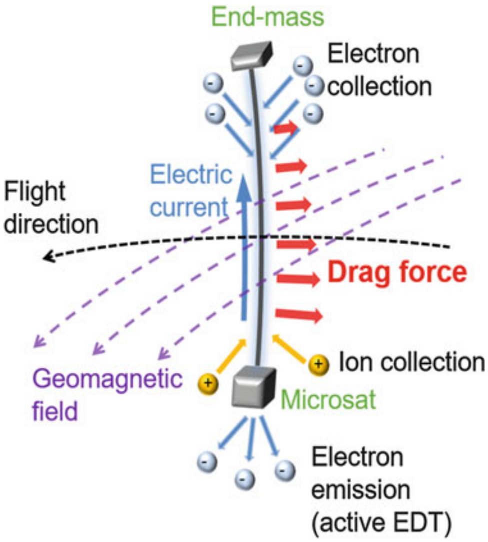
An EDT is a propulsion system which utilizes electromagnetic force as thrust (Cosmo and Lorenzini 1997). In contrast to conventional chemical and electric thrusters, the EDT does not use propellant for thrust generation but creates force by the interaction between an electric current on the spacecraft and the Earth's geomagnetic field. In this section, the principle of EDT, required components, advantages and disadvantages, and performance levels are introduced.

The principle of EDT thrust is shown in Fig. 14. When an end-mass connected with a tether is ejected from a microsatellite, the tether is stabilized in the vertical direction by a gravity-gradient force. An electromotive force is set up within a conductive tether as it moves through Earth's geomagnetic field.

If a pair of plasma contactors at either end of the tether emits and collects electrons, an electric current flows through the tether by closing the circuit via the ambient plasma. The tether then generates a Lorentz force that acts opposite to the direction of flight via interaction between the current and the geomagnetic field. Therefore, an EDT can provide deceleration without the need for propellant or high electrical power. EDT shows promise as a PMD device. An EDT stabilizes with gravity-gradient force, and so it can be installed almost any place on the spacecraft without considering the center of mass.

A bare tether (a conductive wire without insulation) can collect electrons and ions directly from the ambient plasma by the electromotive force (Sanmartin et al. 1993). Electrons are collected at a positive electrical potential part of the tether, and ions are collected at a negative electrical potential part. However, ions are hard to collect as they are heavier than electrons, and so an electron emitter can be installed on the satellite in order to get larger electric current (active EDT). A passive EDT, without

Fig. 14 The principle of operation of an electrodynamic tether (EDT) leverages Earth's magnetic field



an electron emitter, can deorbit a microsatellite as high as 800–1,000 km depending on its orbital inclination and tether configuration such as tether length and width. Alternatively, an active EDT is required for microsatellites at a higher altitude and inclination. The passive EDT is simpler and more cost-effective because no operation is required after the tether is deployed.

The performance of an EDT varies depending on solar activity, tether length, tether diameter, tether material, available electron emitter, and satellite orbit. Figure 15 shows deorbit time with EDT for various spacecraft masses and altitudes using one specific EDT solution: nanoTerminator Tape™ (Hoyt et al. 2009). It enables 3U cubesats to comply with the 25-year rule in orbits up to 1,000 km. However, it should be noted that actual orbital transfer by EDT has not been confirmed, and an on-orbit demonstration is needed.

Solar sails and EDTs have the potential for providing viable PMD options for microsatellites. They characteristically may be effective for a wide variety of relevant missions with conceptually low cost to include price, size, mass, and power required. However, these options have limited operational maturity, but several ongoing and planned on-orbit technology demonstrations may advance the viability of these options in the near future.

More specifically, a passive EDT would be sufficient for a low-inclination orbit, but a 100 kg satellite in sun-synchronous orbit would require a longer (heavier) tether for passive EDT so an active EDT with a small electron emitter may make more sense as it would impose a smaller mass penalty and provide a quicker deorbit time. However, the emitter for the active EDT requires electric power and operation; this is a classic trade-off that depends on what a microsatellite designer and operator have available for their specific mission. These are the exact issues that will be dealt in specific trade-offs for all PMD options.

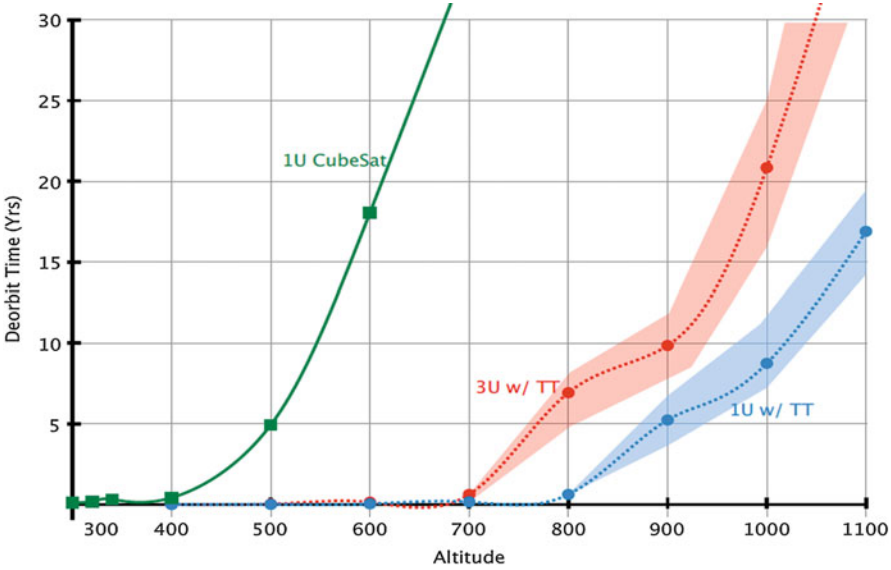


Fig. 15 The deorbit profile for 3U and 1U cubesats using nanoTerminator Tape™ (i.e., TT) follows similar general trends. (Hoyt et al. 2009)

6 Conclusion

The key issues for the selection of the best approach for a given satellite to comply with the debris mitigation guidelines are as follows:

- The potential capability of PMD options assessed have to be considered in tandem with their previous operational usage (i.e., technology readiness level) due to the 90% PMD success rate requirement.
- A propulsive maneuver strategy is the only option that works reliably for all LEO orbits, but it carries with it a large size, weight, and power (SWAP) burden.
- Satellite missions below 800 km have more available PMD options since drag can help removal and the altitude needed to move the system is less (i.e., closer to 615 km altitude).
- Drag-augmentation devices are only viable below 800–1,000 km altitude, and they impose a low to moderate SWAP penalty.
- Between 800 and 1,000 km altitudes, there are several PMD approaches that can assist in the reduction of orbital lifetime with varying SWAP and operational complexity burdens. Note how any option other than propulsion poses significant integrated collision risk when trying to deorbit from above 800 km.
  - Solar sails provide a slow deorbiting capability above 1,000 km and below 800 km behave like a drag sail. Solar sails have proven useful for interplanetary

  applications but require attitude determination and control to function optimally in low Earth orbit (LEO).
  - Electrodynamic tethers (EDTs), while having limited operational experience for deorbiting, hold promise for deorbiting effectiveness up to 1,000 km.
- If a microsatellite is deemed to require a controlled re-entry, then only a propulsion system has proven experience in this application.
- Above 1,000 km altitude, only propulsive systems and solar sails are viable.
- While there have not been any detailed reliability discussions in the trade-off analysis, it may be reasonably assessed that approaches that have been used often and reliably in the past will be more reliable. The "most used" to "least used" for orbit moving are first propulsion, then drag-augmentation, then solar sail, and lastly EDT.

Previous sections provide a clear picture of engineering and performance characteristics for four major families of PMD options for microsatellites. As can be seen from the previous sections, the determination of the best PMD strategies is affected by:

- Mission orbit and requirements
- Satellite capabilities and physical characteristics such as size, weight, and power (SWAP)
- Operational paradigms
- Cost and SWAP requirements
- Technology readiness level
- Operational complexity
- Vulnerability of the PMD options to space environmental effects, to include orbital debris

The interaction of mission parameters and PMD options will vary over time as technology and its implementation advances and regulations evolve.

The most technically developed solutions are those associated with the use of propulsion systems and provide a number of advantages if a propulsion system is already a part of the spacecraft design. Depending on the mission orbit and propulsion system technology, there may be penalties in terms of required fuel. The effectiveness of the other PMD options is more strongly dependent on mission orbits (i.e., altitude and inclination). The availability of commercially produced and space-tested hardware will affect both cost and reliability and will change over time.

A debris impact on a PMD device, however, might degrade its effectiveness or render it useless. Thus, the reliability of a PMD option should be examined carefully.

The pros/cons of PMD options highlight five major issues that must be addressed by any PMD option:

- **EFFECTIVE**: Is it effective? Can the change in altitude be made by the approach selected? The higher the altitude, the more change is needed.
- **SWAP**: What size, weight, and power (SWAP) is required to implement a given PMD approach? Certain approaches have greater engineering requirements that require additional hardware, software, and controls to be deployed. Clearly, the smaller your satellite, the more likely that these requirements will be demanding.
- **RELIABILITY**: How reliable is the PMD option? The reliability required for PMD execution is at least 90%, but evolving discussions are pushing likely reliability levels to 95% and even to 99%. This may limit PMD options for your use even further. This metric is even more challenging when it is likely that many of these PMD devices will be activated after having been on-orbit for many years.
- **ORBITAL RISK**: Does executing a given PMD strategy actually create more risk? This is examined as the area-time-product for collision risk but also includes issues of potential debris generation during a PMD device deployment (e.g., tether release or deployment of a drag-augmentation device).
- **GROUND RISK**: Does the given satellite pose a hazard above the accepted 10^{-4} probability of casualty on the ground? If you have to execute a controlled re-entry due to the potential of some of your hardware posing an impact risk to people on the ground, this will likely limit your PMD option to a propulsive system with assured attitude control until re-entry.

7 Cross-References

- ▶ Deorbit Requirements and Adoption of New End-of-Life Standards
- ▶ Legal Issues Related to the Future Advent of Small Satellite Constellations
- ▶ Financial Models and Economic Analysis for Small Satellite Systems
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ▶ “Rules of the Road” for Launch and Operation of Small Satellites and Related Issues
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit
- ▶ US Space Policy Directive-3: National Space Traffic Management Policy

Acknowledgments With permission, this chapter leverages a recent report A Handbook for Post-Mission Disposal of Satellites Less Than 100 kg, *Published by International Academy of Astronautics, Study Group 4.23, Executed in Coordination with UNISEC-Global*. It was developed to educate smallsat designers, operators, and regulators as to the means and importance of adhering to debris mitigation guidelines. http://www.iaaweb.org/iaa/Scientific%20Activity/sg423finalreport.pdf (last accessed 18 Oct 2019)

References

Casualty Risk Tolerance for Re-entering Debris, http://www.esa.int/Our_Activities/Operations/Space_Debris/Reentry_and_collision_avoidance. Date cited 4 Mar 2018

G.E. Cook, Satellite drag coefficients. Planet. Space Sci. **13**, 929 (1965)

M.L. Cosmo, E. C. Lorenzini, *Tether in Space Handbook*, 3rd edn. (NASA Marshall Space Flight Center, Huntsville, 1997)., https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19980018321.pdf. Last accessed 18 Oct 2019

DRAMA software is freely downloadable from https://sdup.esoc.esa.int. Last accessed 18 Oct 2019, (n.d.)

M. Emanuelli, T. Lips, Risk to Aircraft from Space Vehicles Debris. UN COPUOS Scientific and Technical Subcommittee: 2015 Fifty-Second Session 6 February 2015

F.A. Herrero, *The Drag Coefficient of Cylindrical Spacecraft in Orbit at Altitudes Greater Than 150 km: NASA*. Technical Memorandum 85043 (Goddard Space Flight Center, Greenbelt, 1983)

R. Hoyt, I. Barnes, N. Voronka, J. Slostad, The Terminator Tape™: a cost-effective de-orbit module for end-of-life disposal of LEO satellites, in *AIAA Paper 2009-6733, Space 2009 Conference*, September 2009

http://iaaweb.org/iaa/Scientific%20Activity/cost.pdf. Last accessed 18 Oct 2019

http://iaaweb.org/iaa/Scientific%20Activity/Study%20Groups/SG%20Commission%204/sg418/sg418finalreport.pdf. Last accessed 18 Oct 2019

https://logiciels.cnes.fr/fr/content/debrisk. Last accessed 18 Oct 2019

https://www.iso.org/standard/68572.html. Last accessed 18 Oct 2019

IAA Space Debris Situation Report on Space Debris, 2017

ISO 24113, Space systems, Space debris mitigation requirements, July 2010; 2nd version in 2011

D. King-Hele, *Satellite Orbits in an Atmosphere – Theory and Applications* (Blackie, Glasgow, 1987)

M. Macdonald, C. McInnes, C. Bewick, L. Visagie, V. Lappas, S. Erb, Concept-of-operations disposal analysis of spacecraft by gossamer structure. J. Spacecr. Rocket. **52**(2), 517–525 (2015)

C.R. McInnes, *Solar Sailing: Technology, Dynamics and Mission Applications* (Praxis Publishing, Chichester, 1999)

NASA, NASA's Nanosail-D 'Sails' Home – Mission Complete. NASA, November 29, 2011, http://www.nasa.gov/mission_pages/smallsats/11-148.html. Last accessed 18 Oct 2019

Object Re-entry Survival Analysis Tool, https://orbitaldebris.jsc.nasa.gov/reentry/orsat.html. Last accessed 18 Oct 2019, (n.d.)

A.J. Petro, Techniques for orbital debris control. AIAA PAPER 90-1364 presented at the AIAA, NASA, and DOD, orbital debris conference: technical issues and future directions, Baltimore, 16–19 April 1990

J.R. Sanmartin, M. Martinez-Sanchez, E. Ahedo, Bare wire anodes for electrodynamic tethers. J. Propuls. Power **9**, 353–360 (1993)

Y. Shirasawa, O. Mori, N. Okuizumi, Y. Satou, A. Yamasaki, H. Furuya, T. Nishizawa, H. Sakamoto, G. Ono, Evaluation of sail mechanics of IKAROS on its slow-spin and reverse-spin operation, in *Advances in Solar Sailing*, ed. by M. Macdonald, (Springer, Berlin, 2014), pp. 57–74

Space Exploration Stack Exchange for US Standard Atmosphere, 1976

Spacecraft Atmospheric Re-Entry and Aerothermal Break-Up, https://www.htg-gmbh.com/en/htg-gmbh/software/scarab/. Last accessed 18 Oct 2019, (n.d.)

STELA software is freely downloadable from https://logiciels.cnes.fr/en/content/stela. Last accessed 18 Oct 2019, (n.d.)

STELA Technical Note on Calculating the Coefficient of Drag, March 2011, https://logiciels.cnes.fr/sites/default/files/Stela-User-Manual.pdf. Last accessed 18 Oct 2019

Survival and Risk Analysis (SARA) is part of DRAMA, https://sdup.esoc.esa.int

B. Taylor, C. Underwood, et al., Flight results of the InflateSail spacecraft and future applications of drag sails, in *Smallsat Conference,* Logan, August 2018

C. Underwood, A. Viquerat, M. Schenk, S. Fellowes, B. Taylor, C. Massimiani, R. Duke, B. Stewart, C. Bridges, D. Masutti, A. Denis, The InflateSail cubesat mission: the first European demonstration of drag-sail de-orbiting, in *4th IAA Conference on University Satellite Missions and CubeSat Workshop, IAA-AAS-CU-17-04-05*, Univelt Inc. (2017)

A. Viquerat, M. Schenk, V. Lappas, Functional and qualification testing of the InflateSail technology demonstrator, in *2nd AIAA Spacecraft Structures Conference*, AIAA SciTech Forum (2015). https://doi.org/10.2514/6.2015-1627

J.R. Wertz, D.F. Everett, J.J. Puschell, *Space Mission Engineering: The New SMAD* (Space Technology Library, Microcosm Press, Hawthorme, 2011). Chapter 30.2

“Rules of the Road” for Launch and Operation of Small Satellites and Related Issues

Ram S. Jakhu, Joseph N. Pelton, and Nishith Mishra

Contents

R. S. Jakhu (✉)
Institute of Air and Space Law, McGill University, Montreal, QC, Canada
e-mail: ram.jakhu@mcgill.ca

J. N. Pelton
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

N. Mishra
Faculty of Law, Institute of Air and Space Law, McGill University, Montreal, QC, Canada
e-mail: nishith.mishra@mail.mcgill.ca

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_77

Abstract

This Chapter endeavors to identify the current international and national regulatory and legal framework as well as the guidelines and recommended practices which provide guidance to those space actors that are planning to launch and operate satellites into Earth orbit(s) – especially those anticipating and planning launch of small satellites. Thus, the specific topics addressed in this Chapter include, inter alia, requirements for various types of national licenses, the registration with the United Nation as well as International Telecommunication Union procedures with regard to the use of radio frequencies and intersystem coordination. It also addresses other aspects such as due diligence prior to launch, launch operations and range safety concerns, safety certification of launch facilities, safe operation of small satellites in orbit, orbital debris mitigation efforts to achieve long-term sustainability of such outer space activities, liability for damage caused by space objects, the space situational awareness and space traffic management and space militarization concerns, etc.

Keywords

Absolute liability · Active debris mitigation · CubeSats · De-orbit requirements · Due diligence · Eleven Year Solar Cycle · InterAgency space Debris Coordination Committee (IADC) · Inter-satellite links · International Telecommunication Union (ITU) · ITU Intersystem coordination · Launching state · Launch License · Launch Sites · Liability Convention · Long-term sustainability of outer space activities · MILAMOS · Military Space Activities or Military Uses of Satellites and Space Objects · Moon Agreement or Moon Treaty · Orbital debris · Outer Space Treaty · Proto-space or Proto-zone · Range safety · Range safety officers · Registration Convention · Rendezvous and proximity operations (RPO) · Safety Certification · Satellite Constellations or Networks · Space Situational Awareness (SSA) · Space Traffic Management (STM) · Spectrum Allocation · United Nations Organization (UN) · UN COPUOS Debris Mitigation Guidelines

1 Introduction

The world of spacecraft (satellites or space objects) operations and their regulation is not simple (Jakhu and Pelton 2013). Any person or enterprise which is considering designing, manufacturing, launching a satellite into Earth orbits and operating such space object for specific uses/applications with the use of radio frequency spectrum (predetermined or allocated to the specific nature of services which such person or enterprise seeks to offer) have to be consistent with international treaties, guidelines, and procedures, intersystem frequency coordination, technical standards, and regulatory procedures as well as due diligence procedures and mechanisms established by national governments respectively and in accordance with national laws and regulations. Space operations are, and are becoming more of, a heavily regulated arena, both at international and national levels, primarily because of the increase in number of space actors and activities as well as new problems, such as space debris, radio frequency spectrum, space traffic management, space militarization, etc.

The international space governance efforts in the early days of the space age resulted in negotiation for and adoption of five international conventions related to exploration and use of outer space. These include, inter alia, the Outer Space Treaty (1967), the Liability Convention (1972) (Convention on International Liability for Damage Caused by Space Objects 1972), and the Registration Convention (1974) (Convention on Registration of Objects Launched into Outer Space 1974). These three international conventions, negotiated within the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) and subsequently adopted by the UN General Assembly, are most pertinent in the context of this Chapter regarding launch(es) of spacecraft(s) into Earth orbit(s) or beyond. They deal with regulation and conduct of space activities. During the time these conventions were negotiated and adopted, the United States (USA) and the then Union of Soviet Socialist Republics (USSR) were the only two States that possessed launch capability in the world, and the membership of COPUOS was also limited; and thus, it was easier to reach agreement on key issues related to legal rights and obligations pertaining to the conduct of all space activities, including small satellites.

In over five decades since the conclusion of the Outer Space Treaty in 1967, and four decades since the adoption of the last of the five international conventions (the Moon Agreement that was adopted on 5 December 1979) (Agreement governing the Activities of States on the Moon and Other Celestial Bodies 1979), there has been no adoption of a new significant international convention regulating the conduct of space activities, including launching and operation of small satellites. While there are recommended guidelines, safety standards, and procedures in place which are required to be observed with regard to, for example, mitigation of space debris; none of these guidelines and recommended practices have the status of a binding international treaty, and thus, have no specific sanction(s) to support their enforcement.

Unfortunately, the early international agreements could not anticipate how significantly the world of space would change in the half century that would follow. In this time, conduct and operation of space activities have shifted from being in the exclusive domain of States to a time where these activities are largely being carried out by private companies and enterprises. Moreover, back in the 1960s and 1970s when these early international agreements were negotiated and adopted, there was also no anticipation of the vast number of satellites that are currently being launched into Earth orbits, individually as well as in very large constellations, with some of these constellations now envisioning numbers of small satellites numbering in the thousands. This leads to serious concerns and complexities with regard to orbital space debris, frequency interference, difficulties of orbital and radio frequency management, space situational awareness, on-orbit services, space traffic management, and related liability issues. The addition of high altitude platforms (HAPs) and space plane flights has also raised the issue of where space traffic management processes begin and end as more activities in so-called 'Proto-space' become of regulatory concern.

Primarily due to the lack of progress in the adoption of appropriate international regulations, various governments of space faring nations have started enacting their respective national laws, regulations, and procedures. Thus, they are required to be followed prior to launch, at launch, as well as during a particular satellite/satellite networks' operation. Similarly, there are recommended processes and procedures in place to be followed after the satellite's end of life and other regulatory concerns regarding de-orbiting a launcher's different stages after it has performed its functions of releasing its payload to the stipulated Earth orbit(s). Moreover, with the increasing accumulation of space debris (junk) in Earth orbits, there are emerging concerns about the risks posed by orbital debris. These concerns have only increased in intensity and with time due to deployment of large-scale constellations, bringing to the front, issues regarding space situational awareness and space traffic management. These are often characterized as issues related to the long-term sustainability of outer space activities. Some countries (States) are enacting space-related national legislations which create incentives, as well as penalties, as means to aid in the solution of these emerging problems, and correspondingly, increase safety at all levels for people on the ground, people in aircraft, and people that may travel on new emerging space vehicles and objects. Accordingly, a vast array of international and national legal and regulatory procedures which may be looked into and may be required to be adhered to by space object manufacturers and operators, launch vehicle service providers and operators, etc. are detailed below.

2 National Launch Licensing, Launch Safety, and Due Diligence

States Parties to the Outer Space Treaty are internationally responsible for all their national space activities (Outer Space Treaty, Article VI.). Consequently, the States are obliged to (a) assure that these activities are carried out in conformity with the Outer Space Treaty and (b) to impose the requirement of authorization and continuing supervision on their nongovernmental entities (private companies), if they undertake space activities. In order to fulfill these obligations, space faring nations have adopted their respective national laws and regulations thereby imposing licensing requirements on their private companies and applying technical safety standards.

In all space-faring countries that possess launch capabilities, mainly nongovernmental space launches, launch sites, and facilities are required to be licensed by designated governmental authorities. This launch licensing procedure is separate and distinct from, and in addition to, the national licensing procedure of space objects (as detailed in section "National Payload Licensing"). A part of this process are the preparation of an environmental impact assessment, the possible creation of orbital space debris and fragmentation processes of launcher stages that return to Earth. Finally, there is also a licensing process for launch sites.

The first priority in launch licensing process are safety inspections and safety certifications in order to insure the safety of the people on the ground or in aircraft in flight, who may potentially be injured, or possibly killed, by a launch operation.

A 2-year study conducted by the George Washington University in 2005 highlighted that more number of people have been killed or injured from accidents on the ground by rocket motor explosions or by rockets/spacecraft that have gone off course and crashed into bystanders as compared to the number of astronauts who have been killed while involved in space activities (Pelton et al. 2005: Space Safety Report).

In the United States, NASA and the Air Force certify the launch sites for governmental and military launches respectively (See National Aeronautics and Space Administration 2019). In the case of commercial launch sites, including spaceports used for launch of spaceplanes for space tourism-related launches, it is the US Federal Aviation Administration Office of Commercial Space Transportation (FAA-AST) that, on a 5 year inspection cycle, certifies the safety of these sites (US Department of Transportation 2019). Space launch facilities and sites are certified in accordance with detailed lists of safety standards, criteria, and procedures. Some of the key elements of this inspection process are: (i) the safe storage of combustible fuels and noxious or poisonous materials; (ii) test stands for engine firings; (iii) control facilities that are well removed from launch gantries; (iv) a large well-controlled perimeter that separates the launch facilities from other inhabited areas and preferably has frontage with an ocean area; and (v) a number of other more specific requirements.

The other key element of launch safety is certification of launch operations through issuance of a launch license. This process varies from country to country and has different requirements for systems that intend to launch crew and passengers. In the United States, all commercial launches that involve space planes with crew onboard are being issued experimental licenses only at this time (Coleman et al. 2018). The legislative mandate in terms of responsibilities and organizational arrangements are spelled out in the US Commercial Space Launch Competitiveness Act of 2015 (US Commercial Space Launch Competitiveness Act 2015). Subsequently, the so-called Space Policy Directive 3 issued by the White House on 18 June 2018 has revised some of the responsibilities with regard to commercial space situational awareness and space traffic management from the US FAA-AST to the Office of Space Commerce in the Department of Commerce (United States 2018).

In many other States, there are several common aspects of safety and liability concerns that are now a part of every launch operation review in many countries. The primary concerns are that a launch should not produce any additional orbital debris, that all safety-related matters have been addressed, and that a proper environmental impact review has been carried out. These safety-related requirements prior to a space launch essentially caution States to consider the consequences of their space activities before undertaking them and abstain from them if it is foreseen that they will cause harm or hinder the activities of other States; or alternatively, they should take all necessary steps to avoid such consequences (Madry et al. 2018). Thus, for example, there is a requirement for an environmental impact review to be completed and statement to that effect furnished prior to all launches conducted in the United States (See US Department of Transportation 2015), even for governmental and military launches (National Aeronautics and

Space Administration 2019). An environmental impact assessment (EIA) and review covers a number of different areas. A complete environmental impact assessment in the USA covers such aspects as: (i) negative visual effects; (ii) impact on farms and coastal resources; (iii) air quality (largely in terms of green-house gases); (iv) climate conditions; (v) noise and noise-compatible land use; (vi) biological resources affected; (vii) water resources; and (viii) hazardous materials, solid waste, and pollution prevention (See United States Federal Aviation Administration 2018).

Due to proliferation and rapid increase in numbers of space launches, there are increasing concerns that the environmental impacts associated with rocket (space vehicle) launches have been underestimated in the past. There have been studies conducted of launch vehicle launches which highlight that several relevant factors have not been considered in the environmental impact statements, which statements have now rather become routine and proforma in nature (Grush 2018). These reports, for instance, highlight that routine EIA statements should not only take into account the quantity of green-house gas emissions of a launch but also should consider the key factor of the altitude at which these pollutants are released into Earth's atmosphere; that is, the effect of carbon gases being released at an altitude where the atmosphere is perhaps a hundred times thinner is a key factor to be considered. A report by the Aerospace Corporation suggests that although emissions from liquid fuel burns of kerosene generating black carbon or soot are typically considered in EIA statements, heavier and harmful particulate releases such as chlorine and alumina from solid rocket motors can create particularly negative polluting effects to the Earth's atmosphere and negatively impact Earth's protective ozone layer. The harmful effects of these emissions are not currently being directly addressed although such heavier and larger alumina particles (from solid rocket motors) tend to remain in the northern hemisphere, where most launch sites are located, and in the lower stratosphere (20–30 km above sea level). This study by Aerospace scientists Ross and Vedda recommends that environmental impact studies should consider these factors and address their effects with greater depth; and that more research is required to be carried out in areas of environmental concerns (Ross and Vedda 2018).

3 National Payload Licensing

In addition to the requirement of licenses for launch of vehicles/rockets (addressed above) and for the use of radio frequencies (addressed below), there are several other national legal, regulatory, and procedural requirements that are to be complied with as regards the "payload" of a launch (i.e., satellites or satellite networks or constellations) as well as to its de-orbiting processes. Almost all countries have some form of national laws and regulations pursuant to which they use services provided by satellites. While some countries have made minor amendments to their existing laws to extend their scope to cover space services, others have adopted new and detailed legislations and regulations to regulate the use of satellite(s) for specific applications. For example, in the United States, the operators of satellites (including small satellites) for telecommunications and broadcasting are required to obtain payload licenses from the Federal Communications Commission (FCC) under several very complex laws and regulations (United States, Communications Act 1934). Similarly, Canada regulates small satellites for telecommunications and broadcasting under a group of national laws and regulations (Canada, Telecommunications Act, S.C 1993). In case one wishes to operate a satellite (including a small satellite) for remote sensing (earth observations), there is a need for procuring a specific license for this purpose. Licensing of remote sensing satellites is regulated in the United States under Title 51 of the US Code (United States, U.S.C 2010) and in Canada under the 2005 *Remote Sensing Space Systems Act* (S.C. 2005). It should be noted that payload licenses are generally issued subject to various terms and conditions, some of which often include that the licensee avoids any breach of the State's international obligations, preserves the national security of the State, insures himself against possible liability incurred in respect of damage suffered by a third party, disposes the payload, at the end of its life, according to established policies and procedures, etc.

4 National Radio Frequency Licensing and Support

Once a small satellite project is conceived and designed, at least in a conceptual sense, it is a good idea to give some serious thought to the regulatory matters related to assessment of what spectrum (or radio frequencies) may be required for its operation, including for operational activities of such small satellite(s) such as remote sensing, telecommunications, relay of scientific observation data to ground systems, planned orbital characteristics, and so on.

All satellite operators in all countries are required to get license approvals from their national administrations (relevant governmental agencies) to use spectrum frequency under their respective nationally-sanctioned licensing systems, where specific frequencies are approved for the use of satellites during their lifetimes. Such a national radio frequency licensing requirement is in addition to other licenses (as discussed above) related to launching of payload and launch services as well launch sites and facilities.

The State Parties to the International Telecommunication Union (ITU) Constitution (Article 45(1), ITU Constitution 1992) and Radio Regulations (Article 4(4), ITU Radio Regulations 2016) are under obligation to allow the use of radio frequencies by their operating agencies and entities only in accordance with the Table of Frequency Allocations and other provisions of the Radio Regulations. States are also obliged not to permit the establishment or operation of a radio station by a private person or by any enterprise without a license issued in an appropriate form and in conformity with the provisions of the ITU Radio Regulations (Radio Regulations, Article 18 (1)). Thus States require their private enterprises or entities to seek radio frequency licenses from the designated national governmental bodies and to report their proposed space activities and to make their filings to such national bodies. Thus, in most cases, through national legislations and licensing processes, national administrations have their own internal procedures to consider the merits of filings by a private person or enterprise and the national licensing of the satellite(s) and its launch, before it sends the filings onwards to the ITU in accordance with their international law obligations (discussed below). In the United States, for instance, the Federal Communications Commission (FCC) has been given the role and responsibility for grant of radio frequency (spectrum) licenses for operation of all satellites, including small satellites (Title 47 – Telecommunications 2010). Moreover, it has separate procedures and requirements, for issuance, of licenses satellites in geostationary orbits (U.S. 47 C.F.R § 25.158 2019) and for satellites in other orbits (U.S. 47 C.F.R § 25.157 2019). There are limited requirements in the case of individual CubeSat type launches, but more exacting requirements in the case of commercial filings to deploy new satellite networks (FCC, Guidance on Obtaining Licenses for Small Satellites 15 March 2013). The FCC, since the issuance of the public notice of 15 March 2013, has also provided simplified guidelines for licensing of small satellites which are to be issued under Parts 5 (Experimental Radio Service) or 97 (Amateur Radio Service) of the FCC Rules (FCC Rules and Regulations for Title 47 CFR 2019b).

There are specific and more detailed requirements in the case of filings to deploy satellite-constellations to undertake commercial services (FCC Satellite Licensing Procedures May 2009). In such instances, there is a requirement to define the technical aspects of the proposed system in terms of spectrum usage, mass, power emission levels, orbits, and ground segment specification. In addition, there is a requirement to supply information as to the cost of the spacecraft, the manufacturer of the satellites, the launch services contract, etc. In order to provide the information for the ultimate filing with the ITU that will be made on behalf of the US, there is also the need to spell out all frequencies which are to be used for tracking, telemetry, and command (TT&C) as well as all frequencies assigned to specific services and such aspects as spot beam configurations. This information is needed by other satellite operators around the world to assess whether the proposed new satellite system would result in harmful interference with their own satellites. Thus, an FCC assessment in such cases would consider the technical, operational, financial, and legal viability of the commercial, academic, or scientific activities of the proposed new satellite-constellations or networks.

The US National Telecommunications and Information Administration (NTIA) and Department of Defense (DoD) oversee governmental and military space activities (See NTIA - Driving Space Commerce through Effective Spectrum Policy 2019). The US State Department, as the designated Administration, officially communicates information to the ITU after national licensing processes are completed (US Department of State - International Telecommunication Union 2019). Thus, it becomes important to allow sufficient time prior to the planned launching of satellites for processing of the national license under existing laws and regulations as well as for subsequent filing of required and relevant information with the ITU, which often takes time ranging from months to years.

The US National Aeronautics and Space Administration (NASA) began its CubeSat program in collaboration with colleges and universities some three decades ago and is also another resource that could be consulted with regards to small satellite initiatives. In 2016, NASA created at its NASA Ames Research Center, its Small Spacecraft Systems Virtual Institute (S3VI) (NASA S3VI 2016). Some initiatives of S3VI include the Cube Quest Challenge and the CubeSat Launch Initiative (CLSI). These programs provide opportunities for small satellite payloads built by university students and nonprofit organizations to be launched as auxiliary payloads on upcoming NASA launches. When the program was established, Steve Jurczyk, the then associate administrator for NASA’s Space Technology Mission Directorate (STMD), had said: “NASA sees enormous benefits from investing in research and technology development in small spacecraft systems, such as propulsion, that will be essential in advancing the commercial space sector” (NASA 2016). Thus, in addition to the general objective of providing assistance to small satellite initiatives, NASA also has several programs to assess and test CubeSat designs for safety and reliability of operation. These programs, rather than playing a specific governmental regulatory role, provide useful advice to support many small satellite projects and initiatives. Their objectives and functions include assisting with launch arrangements and a technical review of small-sat/CubeSat missions to make sure that its design is safe. This is particularly important if a CubeSat is intended to be launched via the International Space Station (ISS) through its NanoRacks CubeSat Deplorer or other ISS launch options.

Other countries have their own national regulatory licensing requirements, processes, and mechanisms. Similarly, space agencies of many other States provide useful advice and support to small satellite initiatives. To find out more about such support offerings, it would be useful to refer the websites of the Canadian Space Agency (CSA), the European Space Agency (ESA), the German Space Agency (DLR), the United Kingdom Space Agency, the French Space Agency (Centre national d’études spatiales or CNES), the Italian Space Agency (ASI), the Japanese Space Agency (JAXA), the Russian Space Agency (RosCosmos), the China National Space Administration (CNSA), the Indian Space Research Organization (ISRO), etc.

Further, the various designers and manufacturers of small satellites or companies that provide small satellite launch operations are often well equipped to provide assistance. Many of these companies can provide useful advice and guidance with respect to the necessary filings to be made and detailed information which is required to be prepared for the purpose of obtaining a national license as well as on such information which is required to be furnished to the national administrations for the purpose of subsequent filings by such administrations with the ITU and UN Office of Outer Space Affairs (OOSA).

5 International Radio Frequency Allocation Procedure, Coordination, and Challenges

Once the national radio frequency licensing process is successfully completed, there is an international process of intersystem coordination which is carried out by the ITU in order to coordinate the use of a particular frequency so as to avoid or minimize frequency interference with other existing and planned users and operators that have registered their satellite systems with the ITU.

The ITU’s intersystem radio frequency coordination procedures are required to be complied with if the operator wishes to have international protection against harmful interference, satellite will be operated for international service or if its operation is likely to cause interference with other existing satellite systems or with ground systems, including radio telescopes that are usually sensitive to radio frequency interferences.

National administrations (of countries or States), which are parties to the ITU have certain responsibilities to provide detailed information with regard to frequency usage and orbital characteristics that is required to be filed with the ITU (ITU Regulatory Procedures for Small Satellites 2019a). After such information is formally shared with the members States of the ITU, there may be a possibility that other entities or administrations of other States could indicate that a new satellite or satellite constellation might cause harmful interference and request for ITU’s intersystem coordination processes, mainly bilaterally, to take place in order to avoid or significantly minimize the possible harmful interference (ITU Radio Regulations 2016).

All uses of radio frequencies for satellites need to conform to the requirements of the ITU Radio Regulations. These Radio Regulations are complementary to the ITU Convention and the Constitution (Constitution and Convention of the International Telecommunication Union 1992). Deriving from the principle enshrined in Article 44 of the ITU Constitution of efficient use and equitable access to spectrum/orbit resources, these documents prescribe conditions for use of radio frequencies that are based on the principle that the right to use orbital and spectrum resources for a satellite network or system is acquired through negotiations with the administrations concerned by actual usage of the same portion of the spectrum and orbital resource (ITU Radio Regulatory Framework for Space Services 2019b).

Based on this principle, the ITU spectrum Table of Radio Frequencies included Article 5 of the Radio Regulations is a quite complicated specification and allocation of which radio frequencies are allocated for particular uses. It notes, in some cases, allocations based on a primary, secondary, and even a tertiary basis. There are some uses that can be conducted on a non-inteference basis, and some usage, that operate in a very localized and low power level, can only be used in such a manner. Moreover, this ITU spectrum table of radio frequencies is divided into three zones around the world geographically, where Zone 1 is for Europe, Africa, and the Middle East; Zone 2 covers the Americas and the Caribbean countries; and Zone 3 is for Asia and Australasia.

States/National Administrations agree and adopt this global spectrum allocation table at Plenary Sessions of the World Radiocommunication Conferences of the ITU that meet periodically. Countries, can by adding footnoted exceptions, impose some other restrictions on, or indicate prohibition of, use of a particular frequency allocation within their respective territories. As satellites by their nature are global in their coverage, except for geosynchronous satellites that cover a more limited and specific area, allotment of frequencies and specific assignment of spectrum to global satellite networks is a difficult and very important process to avoid interference with radio frequencies being used by terrestrial systems, aeronautical and high altitude platforms, as well as other satellite systems or their ground stations. Although there are some allocation of spectrum usage in the VHF and UHF bands for academic, scientific, amateur radio, and military usage, the main commercial bands are in the L-band (1–2 GHz; used for mobile communications satellite services), C-band (4–8 GHz), Ku-band (12–18 GHz), Ka-band (26–40) GHz, and most recently, V-band (40–75 GHz) services (ESA 2019).

The procedure of intersystem coordination within the framework of ITU is essentially detailed in Articles 9 and Article 11 of the ITU Radio Regulations. The crux of this procedure is comprised of: (a) Coordination; (b) Notification; and (c) Registration (ITU Radio Regulatory Framework for Space Services 2019). This process is heavily dependent on global cooperation and mutual respect for proper use of spectrum according to coordinated plans. However, as the ITU does not have enforcement measures, policing capability or even the power to impose fines, this is not always completely successful. If the coordinated agreements are not followed, or if jamming occurs, either on an intentional or unintentional basis, this can jeopardize satellite communications or relay of information from remote sensing or other satellite application services.

In the event, there is a reported instance of interference or jamming, the procedure which the ITU officials follow is to bring the issue to the attention of the national administration (State), which is a party to the ITU Convention and from whose territory the interference or jamming occurs or whose national entity or person is determined to be responsible for such activity. The issue of interference is essentially resolved between the allegedly interfering State and the interfered State, with the support of the ITU (Radio Regulations, Article 15, Section VI – Procedure in a case of harmful interference). However, if in such a case, the source of the interference or jamming is the national administration (government) of the allegedly interfering State itself or if such interference or jamming is sanctioned by its national government, there is no obvious further recourse under the current international regime. Moreover, if a State or its national government in question engages in jamming radio or television transmissions in order to protect itself or its sovereignty against acts which it considers as hostile attacks, it can also claim that it is acting in national defense. Fortunately though, most States and commercial entities and organizations typically act in a highly responsible manner, and efforts made worldwide to act in accordance with the ITU spectrum use regulations as well as its own national spectrum controlled by a designated governmental entity which provides oversight of radio frequency and spectrum use within its borders. On a national level, these national administrations or designated governmental entities operate within the purview of applicable national laws and regulations and as such have the power to pursue enforcement measures through fines, or in appropriate circumstances, even criminal prosecution (For United States, see FCC Technical Rule Violation 2019). Similarly, operators of commercial satellite or space systems also have the right to engage in or initiate civil suits and claim compensation for damage.

There is another area of concern with regard to filing of frequency and orbital usage with the ITU; i.e., the problem of "paper satellites", although this has now been largely resolved. This problem arose due to the fact that commercial satellite companies have to first publicly file for national licenses of their new satellite system(s) with the appropriate regulatory body of the concerned State, such as the FCC in the United States. This process can take many months, if not years to complete. This national regulatory review and licensing process precedes the subsequent official filing with the ITU. In addition, due to the ITU's own "first-come, first served" procedure of filing for frequency allocation as well as its international coordination procedures (Radio Regulations, Article 9.), this entire process may sometimes take years to complete for a complex satellite network system. This led to some States' national administrations to file in advance with the ITU for orbital slots and radio frequencies, in order to preserve those slots for its own possible future use or in order to lease or sell them to other users for economic benefits, even without any real intention of using these slots and radio frequencies in the near future (Galeriu 2018). Thus, in order to skirt and exploit the long period of review in the USA, Europe, Japan, or elsewhere, overseas entities operating out of the jurisdiction of such States or national administrations which allowed an immediate filing with the ITU simultaneously with a filing under their national laws to obtain the benefit of the ITU's "first filed, first served" priority (i.e., obtain a priority filing status), indulged in reserving frequencies and spectrum without any intention of actually using it. These artificial filings thus came to be known as "paper satellites." The first of these initiatives was called the "Friendly Skies Company" which was set up in the Kingdom of Tonga, and it filed a series of satellite systems for registration with the ITU, with the hope of "leasing" their early filing precedence status, and thus obtain legal priority over the actual system.

In response to complaints about this practice, the ITU has implemented a series of changes to its rules and procedures. At its World Radiocommunication Conference, 2015, the ITU introduced revised Resolution 49 pertaining to administrative due diligence applicable to some radiocommunication services (ITU Administrative Due Diligence 2015). It now requires verified data and contracts regarding the manufacturer of satellites, information about the entity which is to launch the satellites, etc. Through its Council Decision 482, which has periodically been modified (ITU Cost Recovery for Satellite Network Filings 2019d), it also increased the cost of submitting filings and for its intersystem coordination processes. These steps have largely served to significantly minimize the practice of filing for "paper satellite" systems that were never intended to be built, but rather were simply a ploy to obtain priority filing status, which could then be economically exploited at the expense of those actually seeking to launch a new satellite system (Galeriu 2018).

Additionally, and with specific regard to operation and launch of small satellites, it is also worthwhile to note some important developments and resolutions adopted by the ITU. In recent years, small satellite operators have been using amateur radio frequencies for their noncommercial operations. This has the distinct advantages of lower costs, easier process of coordination, as well as significantly less time period as compared to the full ITU intersystem coordination procedures. However, for commercial uses of small satellites, satellite manufacturers and operators have to still adhere to the intersystem coordination procedures. Recognizing the proliferation of nanosatellites and picosatellites, the ITU had adopted Resolution 757 at its World Radiocommunications Conference in 2012 to "examine the procedures for notifying space networks and consider possible modifications to enable the deployment and operation of nanosatellites and picosatellites, taking into account the short development time, short mission time and unique orbital characteristics" (ITU Resolution 757 2012). Noting that no special coordination procedures are required for small satellites, the ITU, at the 2015 World Radiocommunications Conference adopted another Resolution 659 to "assess the suitability of using existing allocations for the space operations service below 1 GHz to accommodate the telemetry, tracking and command (TT&C) requirements for non-geostationary satellites with short duration missions" (ITU Resolution 659 2015). A short duration mission is stated as any satellite mission with its operating period less than three years. In this regard, studies are ongoing (See International Telecommunication Union 2019), and a decision is to be made at the impending World Radiocommunications Conference 2019 (Oct-Nov 2019). The important take-away of these developments is that a lot of initiatives are being taken by the ITU and its member States to facilitate and simplify procedures relating to small satellites, and specifically with regards to satellites with short duration missions, and it would be worthwhile to keep a track of and stay abreast developments in this field.

6 International Registration with the United Nations

In addition to aforestated filing requirement with the ITU regarding radio spectrum usage and orbital position(s) as well as network coordination, there is also a requirement for a Launching State (i.e., that launched a satellite), to register this space object pursuant to the Registration Convention by providing relevant and applicable information to the UN through the Secretary General (Registration Convention, Article IV 1974). States that are not Parties to the Registration Convention are expected to provide such information in terms of UN General Assembly Resolution 1721 B (XVI) (UNGA Resolution 1721 B (XVI) 1961). Information for the purposes of registration under these instruments are to be provided by a State (its national administration or a designated authority) and not by the commercial entity that has launched a satellite or the launch services contractor/provider. This information is crucial in order to establish which State is the "Launching State" for the launch of such satellite. In turn, obligations are placed upon the State. This registration procedure thus becomes crucial and necessary for several reasons, including to determine which State may be responsible under the Outer Space Treaty and liable for damages under the Liability Convention (Liability Convention, Articles II – V.). Thus, in order to assist States and International Organizations in registering space objects and pursuant to UN General Assembly Resolution 62/101 of 2007, the UN Office for Outer Space Affairs has developed a Model Registration Form (See United Nations Office for Outer Space Affairs 2019).

7 Space Situational Awareness (SSA) and Space Traffic Management (STM)

The issue of space situational awareness and space traffic management has become increasingly important in both a technical competence sense as well as a regulatory sense for several reasons. Prime among these reasons is the rather massive number of new small satellite constellations proposed to be launched at a record rate in the next 5 years. Over 20,000 new satellites are proposed for launch (Madry et al. 2018), which is a number that far exceeds the 2062 operational satellites now in GEO, MEO, and LEO orbits (data by the Union of Concerned Scientists as of 31 March 2019) (Union of Concerned Scientists 2019). On 24 May 2019, a Falcon nine rocket/spacecraft placed 60 small satellites into LEO orbit with a single launch (New York Times 2019). This was only the first step by SpaceX to launch some 4409 Ku-band Starlink satellites into LEO orbit that would be followed by another 7518 satellites operating in the V-Band (Grush 2019b). If these two Starlink networks are fully deployed, it would far exceed all of the satellite launches into Earth orbit prior to 2019. (See Fig. 1).

The increase in space debris the size of a baseball or larger to nearly 18,000 is a clear concern to everyone involved in active space operations. The shooting down of the Chinese weather satellite, Fengyun-1C, created over 2000 major trackable debris elements in 2007 followed by the Russian Cosmos 2251 Satellite and Iridium 33 Satellite collision in 2009 that also created over 2000 more debris present serious

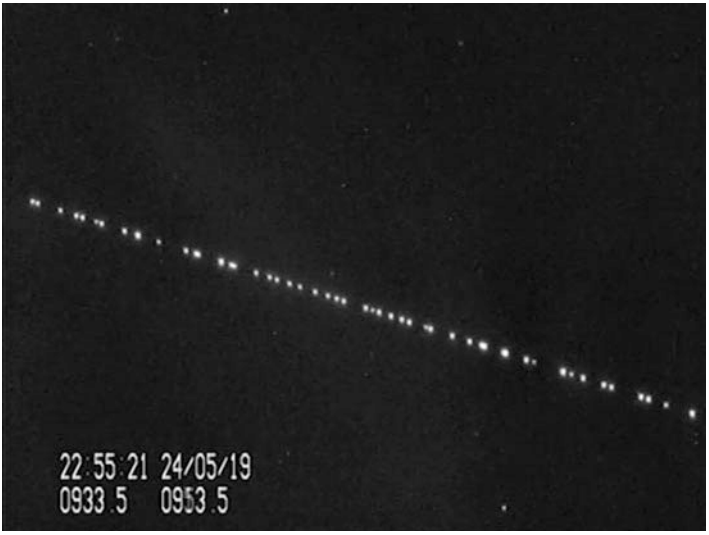


Fig. 1 Night time photo of 60 satellites in the SpaceX Starlink Constellation. (Graphic courtesy of Marco Langbroek)

concerns. Debris created by India's conduct of anti-satellite test on 27 March 2019 is expected to remain in orbit for years and will keep posing threat to active satellites (Henry 2019). The new S-band radar system that will be able to track LEO debris elements down to the size of a ping-pong ball represents an important new capability to improve space situational awareness, but exactly how space awareness will be carried out in the future and what methods will be employed to pursue space traffic management are far from clear. Further, the manner in which these activities will be conducted in terms of separate commercial satellite operations as opposed to military tracking and control has not been clearly established as well. Increasingly, there are a number of commercial companies that have precise space tracking capabilities; and under the US Space Policy Directive 3 issued by the White House on 18 June 2018, it appears that Military SSA capabilities will be separated from the commercial operations (US Space Policy Directive - 3 2018). Commercial companies which provide tracking services to support SSA now include Analytic Graphics Inc. (AGI), EtaMax, Exoanalytics, Globvision, Lockheed Martin, Norstar Space, Polaris Alpha, Schafer, and Spacenav. But it is not clear yet as to how the US Office of Space Commerce, which under US Space Policy Directive 3, has been assigned responsibility for commercial SSA for the USA, will move forward so that this task can best be completed. It is also yet to be determined if this will be carried out by a competitively selected group of commercial operators, and if so, how will this activity be discharged in notifying satellite operators of possible conjunctions that could occur. Till date, there has been a significant problem in this regard. If operators are notified virtually constantly of a possible collision, this overwhelming amount of data or notifications could lead to inaction or indecision by such operators. On the other hand, if there are only very few notifications with a very narrow window set for very close collision possibilities, this could result in too little opportunity for evasive action (Market Watch 2019).

There are several new satellite constellations that are being deployed whose capital valuation might be as high as over $10 billion dollars, and thus these assets are becoming enormously valuable. Further, if an actual collision should occur, the potential of a true run-away avalanche of space debris is extremely high (Pelton 2018) that could have a devastating impact on the global economy. There are now various videos online with titles such as "If there were a day without satellites" (Benedict 2019). These tutorial messages outline and highlight how a loss of satellite networks globally could have an enormous impact on the Internet, global broadcasting, fishing, farming, banking, airline travel, and even global retailing, rescue, and emergency operations as well as national defense and military systems.

It is truly vital that military and commercial systems cope with the increase in space traffic and satellite deployments to make sure that they are safe, and collisions are avoided. The consequences of a major mistake, and a resultant series of major collisions, could have a dramatic impact on the global economy, on human life, and worldwide supply chains of food, water and vital supplies, and national defense systems.

8 International Liability for Damage

As stated above, determination of a “Launching State” status is important for establishing international liability in case of damage caused by a space object, including small satellite. Under the Liability Convention, there is “absolute liability” in case of a space object causing damage on the surface of the Earth or to aircraft in flight (Liability Convention, Article II.). This could, for instance, be due to a launch failure as the Liability Convention specifies that this liability includes liability arising out of attempted launches (Liability Convention, Article I (b).). Thus, this is the reason as to why there is a space range officer in the case of most launches, who can fire a self-destruct button in case an errant rocket is headed for populated areas.

Moreover, damage could also be due to a deorbiting space object that might hit a house, an office building, or an aircraft with passengers. The most prominent example to date is of a spacecraft that crashed in a fairly isolated area in Canada but unfortunately released radiation from its radioactive power source of about 50 kilograms of Uranium-235. The reference here is to the Soviet satellite (COSMOS 954) with a nuclear power source that crashed in northern Canada near the Great Slave Lake on 24 January 1978. The government of the then USSR negotiated a settlement with the Canadian government under the provisions of the Liability Convention as well as general international law. The nuclear power source leaked radiation across a substantial area and the settlement included negotiated compensation for Canada’s clean-up operation (Protocol in respect of the claim for damages caused by the satellite ‘Cosmos 954’ April 1981). (See Fig. 2).

Some countries, that are or become the “Launching States” for small academic or commercial satellites, may not have fully considered the liability implications that they are assuming or have assumed as a small satellite may be seen quite harmless. Some of the “small satellites” now being launched are in the range of 150–500 kg,

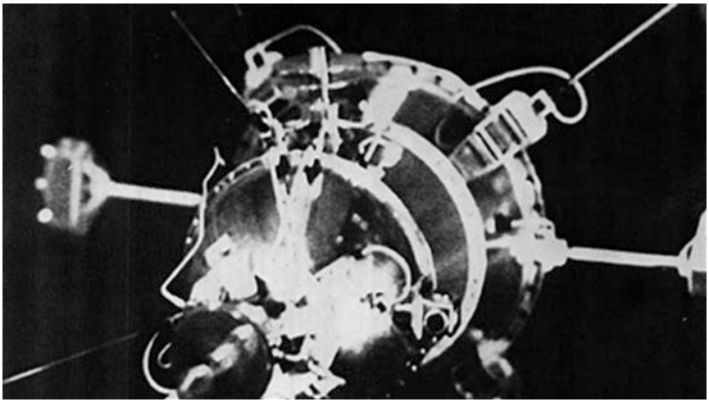


Fig. 2 The Rorsat-Type “Spy” Satellite that Crashed in Canada in 1978. (Graphic courtesy of Canadian Government archives)

and thus sufficiently large to represent a fairly large cross section to become a target for impact by smaller debris elements – especially if hundreds and thousands of them are deployed.

The biggest concern that involves "absolute liability" remains the case of a launch failure where a rocket (space vehicle) and spacecraft might somehow hit an aircraft or a ship with passengers onboard. In this case the liability claim might potentially be quite substantial. It is for this reason that all air flights are currently diverted during a launch from the vicinity of the area from which launches are conducted. Certainly, liability claims are a major concern. Legislation has been passed in many space-faring countries such as the United States, France, Japan, etc. In each instance, there is explicit language in such legislation that spells out the liability that the government is assuming in the case of launches, and in most cases, also places responsibility on a commercial entity or organization to acquire liability insurance for claims that exceed the specified levels; and thus governments provide a level of liability claim protection (51 USC § 50914, 51 USC § 50915; French Space Operation Act 2008, Articles 14 and 15.).

Each country's legislation tends to be different and thus it is important to consult with the relevant governmental officials that provide licensing for commercial launches in order to better understand the level of liability assumed, and the type and levels of liability insurance required. This is, of course, in addition to conventional launch insurance which might be required. The following passage taken from an overview analysis of this subject aptly summarizes the situation as follows:

> The new Japanese law [of November 2016] also provides government support in the provision of financial guarantees required by commercial space launch operators, such as by arranging third-party liability insurance coverage. The required coverage is calculated on the basis of the maximum probable loss estimated in line with the rocket type and the payload content; in the case of damages in excess of this coverage, the law provides that the government is to pay for the residual damages up to a certain limit. This is similar to arrangements that have been adopted in the United States and France, although the French government sets no limit on payments. (Aoki 2017)

To a certain extent, the Government of France has assumed the highest level of liability coverage for Arianespace launches under the French Space Operations Act, 2008, (France, French Space Operation Act 2008) rather than a tiered coverage used by other countries. This does provide an advantage to its launch services provider.

The UN Liability Convention was negotiated and adopted in 1972. As there were only two suppliers of launch services in the world at the time, it was not anticipated then that there could be many scores of suppliers of launch services, and that most of them would be commercial companies. Further, no one anticipated that there could be GNSS systems that provided guidance for aircraft, synchronize the Internet, or that there could possibly be problems such as orbital space debris, or that satellite with a nuclear power supply or noxious gases will be able to bring down destructive spacecraft from the skies. Moreover, the concept of small satellites, such as CubeSats, Nano, and Pico satellites, were also entirely unknown and their proliferation unseen.

Many space lawyers are of the view that the current UN international agreements such as the Outer Space Treaty or the Liability Convention are not adequate to deal with the complexities and challenges of the new space age that we now live in. These instruments that were negotiated 40 to 50 years ago appear to be inadequate to the realities of today's world of space and the many innovations that "NewSpace" industries have brought to the modern world. The provision that creates "absolute liability" under the Liability Convention leaves ambiguous the dangers of damages that might occur in outer space, where liability for damages is only based on fault of an entity (Liability Convention, Article III.); and thus, does not create incentives for active debris removal, or even for its mitigation. It also does not create the appropriate incentives for responsible space activities as regards rendezvous and proximity operations (RPO). It is clearly time to recognize that the long-term sustainability of outer space activities is now closely linked to the modern global economy and extremely vital to human activities on Earth.

Until a new international agreement on liability for damages can be negotiated and adopted, however, there must be ways to incentivize responsible actions to remove space debris from outer space, avoid accidents and collisions in outer space, and create better systems for SSA. One step forward would be to authoritatively define "space objects" in a better and more appropriate manner so as to at least include active spacecraft with human crew and passengers, working and maneuverable spacecraft, partially functional and maneuverable spacecraft. Space debris, on the other hand, should be those space objects that are not functional and not maneuverable.

9 Space Debris: Mitigation and IADC and UN COPUOS Guidelines

It seems unlikely that means will be found in the near future to renegotiate or amend the Outer Space Treaty, or its four supplementary international agreements related to outer space. Thus, in the meantime, the best hope for addressing the issue of space debris problem and to achieve safer means of removing space debris from orbit or to control its deorbiting process in a way so that it constitutes the least risk, lies with two entities. These entities are the UN COPUOS and the Inter-Agency Space Debris Coordination Committee (IADC). The UN COPUOS did finally agree on voluntary guidelines for space debris mitigation in 2007 (United Nations 2007). These voluntary guidelines were, however, essentially based on the work of the IADC that were agreed amongst the participating space agencies, and then with some modifications, were agreed by UN COPUOS and ultimately adopted by the UN General Assembly (UN General Assembly Resolution 62/217 2007).

The UN COPUOS guidelines as adopted are just seven in number and their basic elements are provided in Table 1 below:

The full guidelines can be found in the website of the UN Office of Outer Space Affairs that also maintains the official UN register of launched space objects. One of

Table 1 The basic descriptors of the seven UN COPUOS voluntary guidelines on orbital debris mitigation adopted by the general assembly in December 2007

U.N. COPUOS voluntary guidelines for orbital debris mitigation	
Guideline number	Basic description of guideline
1	Limit debris released during normal operations
2	Minimize the potential for break-ups during operational phases
3	Limit the probability of accidental collisions in orbit
4	Avoid intentional destruction and other harmful activities
5	Minimize potential for post-mission break-ups resulting from stored energy
6	Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-earth orbit (LEO) region after the end of their mission
7	Limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous earth orbit (GEO) region after the end of their mission

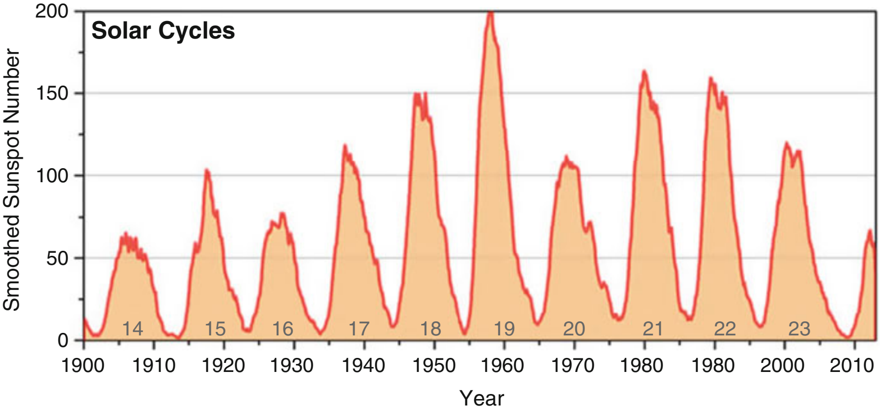


Fig. 3 A depiction of the 11-year Solar Max to Solar Minimum Cycle from 1900. (Graph of solar max cycle by US geospatial services)

the key differences between the COPUOS voluntary guidelines and the IADC developed guidelines is that the COPUOS' recommended practices did not include the concept that space objects should be removed within 25 years of the end of mission. This concept that is present in the IADC guidelines was apparently based on the idea that this would allow the space object to be subject to at least two solar max environments. During solar max conditions which occur in 11-year cycles, there is the maximum atmospheric drag on the spacecraft, thus facilitating satellites or spent rocket stages to naturally deorbit. (See Fig. 3).

Today many large-scale small satellite networks, with lifetimes in the typical range of 6–8 years, might need a resupply of small satellites to their orbits around three times within the above stipulated period of 25 years. Clearly in such an environment, a redeployment schedule for removal of defunct satellites every

25 years would no longer make sense and serve its purpose. If new satellites were deployed say every 8 years, while defunct satellites were removed every 25 years, the buildup over a period of time would be unacceptable. Even the operators of the new large constellations have seen that this guideline would no longer serve their needs as well of those concerned about space debris. It is hoped that the IADC and UN COPUOS will recognize the extent of this problem and develop new guidelines recommending much more rapid removal of spacecraft at end of life or mission. Some analysts have suggested that national regulators should have control of the removal cycle but so far any specific or particular progress on this point of view has not been achieved.

10 Space Safety and Debris Removal or Mitigation

Some have observed that since international progress has been difficult and slow on the topic of space debris mitigation and removal, the key to this problem is action at the national legislative level. Additionally, the UN COPUOS Guidelines on Long-Term Sustainability of Outer Space Activities also stipulate that States should consider a number of elements when developing, revising, or amending, as necessary, national regulatory frameworks for outer space activities including implementing the UN COPUOS Space Debris Mitigation Guidelines through applicable mechanisms (United Nations Guidelines for Long-term Sustainability of Outer Space Activities 2018) as well as States should consider the utilization of recommended practices and voluntary guidelines proposed by the Inter-Agency Space Debris Coordination Committee Guideline A.2 (2) (f)). In addition, it encourages States to develop and use relevant technologies for the measurement, monitoring, and characterization of the orbital and physical properties of space debris (Guideline B.3). It also provides that States should encourage manufacturers and operators of space objects, regardless of their physical and operational characteristics, to design such objects to implement applicable international and national space debris mitigation standards and/or guidelines in order to limit the long-term presence of space objects in protected regions of outer space after the end of their mission (Guideline B.8 (2).) and to investigate and consider new measures to manage the space debris population in the long term (Guideline D.2). Although these guidelines are nonbinding, they represent the common consensus of all States, and thus assume an important role in building and developing national legislation.

In this regard, the Technical Regulations of the French Space Operations Act, 2008, which were adopted in November 2013, have been seen as model legislation from several perspectives. These technical regulations have sought to address a number of space safety and space orbital debris-related issues and created specific guidelines, standards, and have even created a process where penalties could be imposed for noncompliance. This Act, along with the Technical Regulations, specifies a process to make sure that launchers and spacecraft are designed for a safe deorbit process and that the breakup of deorbiting fragments are designed in a manner so as to create the least amount of safety threats and avoid the intentional release of space debris into Earth orbit during normal operations. It also provides for liability coverage of launches and specifies that space objects or orbital stages of a launch vehicle that are not made to deorbit within a 25-year period from end of mission life and are left in LEO orbit would be subject to administrative fines (Lazare 2013). Unfortunately, for reasons set forth above, the 25-year period for deorbiting process is no longer seen as the best or functionally appropriate standard to use.

The United Sates has a number of regulations created by NASA, the FAA-AST, the US Air Force, the National Environmental Protection Agency (NEPA), as well as several laws enacted by the US Congress coupled with the four US Space Policy Directives which seek to define US space practices and standards. However, certain actions and stipulations contained in such legislation and space directives are considered controversial at the international level and are not necessarily appropriate guideline(s) on safety standard for the international community to endorse and follow.

The idea of using national law and regulations for setting standards of safety, de-orbiting guidelines, liability coverage, and perhaps, creating incentives or fines/penalties for not meeting such standards may be a key way forward for sustainable development of space activities in the long term. In light of the fact that international space treaties are quite difficult to negotiate and adopt, national standards and laws are emerging as a way to achieve best practices and perhaps act as a method for space-faring nations to agree on what reasonable practices should be followed.

11 Proto-Space or Proto-Zone

One of the new concerns in terms of space safety and regulatory oversight that has emerged in recent years is with regard to the areas sometimes called subspace, near-space, proto-space, or proto-zone. This is the area above commercial air space (i.e., above 20 km), and below the area where a satellite can orbit on a sustainable basis for the longer term (i.e., 160 km). For many years, this zone was of little practical use, except perhaps the flight of very high-altitude surveillance or spy planes. Increasingly, there has been proposal for stratospheric platforms like high-altitude platform systems (HAPS), hypersonic space planes for space tourism or ultimately point to point transportation, robotic freighters, dark-sky stations, or other applications.

Elsewhere in this Handbook, there is discussion on how an alternative to small satellite systems could be HAPS for some States so as to provide communications, broadcasting, or remote sensing services using such platforms that could, for instance, provide complete coverage for an island State. Such systems could be deployed at lower cost for special applications. Systems such as the Stratobus by Thales Alenia are being offered to provide services that range from detection of forest fires and diseases, rural and remote telecommunications, emergency medical services, as well as many other services (Pelton 2019a).

The problem is that today's radar or software for Global Navigation Satellite Systems (GNSS) services are not optimized to provide services in the 20–160 km range. Further, there are no fixed responsibility for safety and traffic control that have been defined for these areas, especially over international waters and the Polar Regions. Even for proto-space situated above national territories, there are currently no fixed regulatory authorities that relate to and regulate activities such as licensing of HAPS to provide commercial services. Clarification of the regulatory control of the proto-zone and improvement of relevant technical systems for safety and control will become increasingly important in the next decade or so. This will be particularly the case if, in time, there are conflicting uses of the proto-zone for purposes such as hypersonic transport, robotic freighter service, dark sky research facilities, HAPS operation as well as potential activities conducted by military agencies or defense ministries (Pelton 2019b).

There is a fascinating book written by David Loth titled "*How High Is Up*" that considers the legal and military implications of national airspace. This book considers how national airspace of States has ascended upward over time as States were increasingly able to defend and exercise sovereignty over higher and higher altitudes (Loth and Ernst 1964). It has also been suggested earlier that the international law of the seas, with its various protective zones with its littoral area, might serve as a useful model for developing governance for policing and perhaps licensing activities at high altitude or even the stratospheric regions (Pelton 2014). As efforts are being made by States to improve both national military and commercial space situational awareness and space traffic management, it is important that those discussions and agreements cover not only Earth orbit but also the proto-zone region as well.

12 Small Military Satellites, Space Systems, and MILAMOS

There are now a number of small satellite experimental projects for verification of new space technology and systems for military applications. In the last few years, there has also been an attempt to define standards of behavior and military codification of accepted space-related practices. The increased discussion of possible military actions and weapons systems in outer space and the creation of "space forces" have tended to make these attempts at standardization of practices and communications more important and urgent.

The number of dedicated military and dual use satellites being used and operated by armed forces, especially by the armed forces of major space powers, is increasing as they provide inexpensive and efficient services, particularly during geopolitically tense times. Any threat or perceived threat to these satellites could create serious security situations. Even their accidental destruction could be perceived as armed attack, thus creating a possible war situation. International rules are currently not clear on the use of outer space for military purposes. Thus, the Institute of Air and Space Law, McGill University, in collaboration with an international team of legal and technical experts from academic institutions, the industry, armed forces, and government ministries, has undertaken the drafting of the McGill Manual on International Law Applicable to Military Uses of Outer Space (MILAMOS) (More details of MILAMOS 2019). The Manual is intended to objectively articulate and clarify existing international law applicable to military uses of outer space in times of peace, including challenges to peace. The vision of this international effort is to contribute to a future where all space activities are conducted in accordance with the international rules-based global order, without disrupting, and preferably contributing to, the sustainable use of outer space for the benefit of present and future generations of all humanity.

While several aspects of space activities and their legal and regulatory procedures remain the same for civilian as well as military activities, there are also many aspects in which there are significant differences or where special rules and regulations apply to military activities in outer space; and thus, the MILAMOS Project's objective of capturing and clarifying such aspects of law as are specifically applicable to military activities will be beneficial for the international community. To further elaborate a few aspects, for instance, while all telecommunication aspects of civilian satellites are covered under ITU's intersystem coordination mechanism and procedures, however, all Member States of ITU retain their entire freedom with regard to military radio installations and are obligated to observe the ITU regulations only so far as possible (ITU Constitution, Article 48.). Similarly, under national legislation and regulations, in most cases, different and separate regulatory bodies or governmental entities regulate military activities of satellites. Accordingly, in the USA, it is the US Air Force which is responsible for most of military activities in outer space, including those that involve satellites or satellite networks and constellations. It is the US Air Force that certifies launch sites for military launch activities and promulgates regulations and oversees launch activities, as compared to the US Federal Aviation Administration Office of Commercial Space Transportation which provides for certification of launch sites to be used for commercial purposes. Similarly, as noted above in this Chapter, there are distinct and separate standards for Range Safety for military launches in the USA. Moreover, operating a satellite for monitoring or surveillance of military targets has been fully recognized as a legitimate activity. As also discussed, while commercial use of airspace extends to about 10 km, military activities occur up to a much higher altitude; and thus, would have a significantly different effect on legal and regulatory implications for the protozone.

Thus, for satellite (including small satellite) manufacturers and operators, it becomes crucial to refer to national legislation as well as applicable rules of international law if their satellites are intended to be used for military activities or is being manufactured and/or operated at the behest of national administrations solely for military activities.

13 Conclusion

Appropriate laws, regulations, technical standards, and procedures are imperative for smooth and safe operation of small satellites. Since the number of such satellites, the applications they provide, and their operators is rapidly increasing, the necessity for compliance with the existing laws as well as formulation of new "rules of the road" is becoming urgent, not only for the satellite operators but all the concerned governmental authorities, which are internationally responsible for, and could be held liable for damage caused by, small satellites. It is advisable for manufacturers and operators of small satellites to be proactive in supporting their respective governments in the drafting and adoption of new treaties, national laws, regulations, technical standards, and procedures so that such new "rules of the road" are appropriate and effective for the safe design, operation and disposal of small satellites.

14 Cross-References

- ▶ Deorbit Requirements and Adoption of New End-of-Life Standards
- ▶ Long-Term Sustainability of Space and Sustainability Requirements
- ▶ Obtaining Landing Licenses and Permission to Operate LEO Constellations on a Global Basis
- ▶ Requirements for Obtaining Spectrum and of Orbital Approvals for Small Satellite Constellations
- ▶ The Legal Status of MegaLEO Constellations and Concerns About Appropriation of Large Swaths of Earth Orbit
- ▶ US Space Policy Directive-3: National Space Traffic Management Policy

References

Agreement governing the Activities of States on the Moon and Other Celestial Bodies, 05 Dec 1979, 1363 UNTS 3 (entered into force on 11 July 1984) [*Moon Agreement or Moon Treaty*]; accessible at: http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/intromoon-agreement.html. Last Accessed 09 Aug 2019

S. Aoki, New Law Aims to Expand Japan's Space Business, (03 Mar 2017), Nippon.com; accessible at: https://www.nippon.com/en/currents/d00294/new-law-aims-to-expand-japan's-space-business.htm. Last Accessed 10 Aug 2019

Article 4 (4), ITU *Radio Regulations*, 2016 edition; accessible at: https://www.itu.int/pub/R-REG-RR-2016. Last Accessed 10 Aug 2019. [*Radio Regulations*]

Article 45 (1), Constitution of the International Telecommunication Union, 22 Dec 1992, entered into force on 01 July 1994, 1825 UNTS 1 (as amended and adopted: latest by the 2018 Plenipotentiary Conference); accessible at: https://www.itu.int/en/history/Pages/ConstitutionAndConvention.aspx. Last Accessed 10 Aug 2019

R. Benedict, If there were a day without satellites, YouTube; accessible at: https://www.youtube.com/watch?v=5sgM7YC8Zv4&t=102s. Last Accessed 15 Aug 2019

Canada, Telecommunications Act, S.C. 1993, c. 38; accessible at: https://laws-lois.justice.gc.ca/eng/acts/t-3.4/; *Canadian Radio-television and Telecommunications Commission Act*, R.S.C., 1985, c. C-22; accessible at: https://laws.justice.gc.ca/eng/acts/C-22/. Last Accessed 11 Aug 2019; Canada, *Broadcasting Act,* S.C. 1991, c. 11; accessible at: https://laws.justice.gc.ca/eng/acts/B-9.01/. Last Accessed 11 Aug 2019; etc.

K. Coleman, M. Machula, J. Sloan, "FAA Licensing and the NASA Commercial Crew Program" (Oct 2018), Federal Aviation Administration, presentation at 68th International Astronautical Congress (IAC), Bremen; Accessible at: https://www.faa.gov/about/office_org/headquarters_offices/ast/programs/international_affairs/media/Commercial_Crew_Program_and_FAA_Licensing%20_IAC_Bremen_October_2018_508.pdf. Last Accessed 11 Aug 2019

Constitution and Convention of the International Telecommunication Union, 22 Dec 1992, entered into force on 01 July 1994, 1825 UNTS 1 (as amended and adopted: latest by the 2018

Plenipotentiary Conference); accessible at: https://www.itu.int/en/history/Pages/ConstitutionAndConvention.aspx. Last Accessed 10 Aug 2019

Convention on International Liability for Damage Caused by Space Objects, 29 Mar 1972, 961 UNTS 187 (entered into force on 1 Sept 1972) [*Liability Convention*]; accessible at: http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html. Last Accessed 09 Aug 2019

Convention on Registration of Objects Launched into Outer Space, 12 Nov 1974, 1023 UNTS 15 (entered into force on 15 September 1976) [*Registration Convention*]; accessible at: http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introregistration-convention.html. Last Accessed 09 Aug 2019

ESA, *Satellite Frequency Bands*; accessible at https://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Satellite_frequency_bands. Last Accessed 10 Aug 2019

Federal Communications Commission, Guidance On Obtaining Licenses For Small Satellites, 15 Mar 2013, DA-13-445: 28 FCC Rcd 2555 (3); accessible at: https://www.fcc.gov/document/guidance-obtaining-licenses-small-satellites. Last Accessed 11 Aug 2019a

Federal Communications Commission, *Rules and Regulations for Title 47 C.F.R. (United States)*, accessible at: https://www.fcc.gov/wireless/bureau-divisions/technologies-systems-and-innovation-division/rules-regulations-title-47. Last Accessed 11 Aug 2019b

Federal Communications Commission, *Satellite Licensing Procedures*, 27 May 2009, DA-09-1156: 24 FCC Rcd 7156 (9); accessible at: https://www.fcc.gov/document/satellite-licensing-procedures. Last Accessed 11 Aug 2019c

For more detailed information on the ITU coordination procedure, please see International Telecommunication Union, *ITU Radio Regulatory Framework for Space Services*; accessible at: https://www.itu.int/en/ITU-R/space/snl/Documents/ITU-Space_reg.pdf. Last Accessed 09 Aug 2019

For more information, see US Department of State, International Telecommunication Union; accessible at: https://www.state.gov/subjects/international-telecommunication-union/. Last Accessed 11 Aug 2019

For United States, see Federal Communications Commission, Spectrum Enforcement Division, Technical Rule Violation; accessible at: https://www.fcc.gov/reports-research/guides/technical-rule-violations. Last Accessed 11 Aug 2019. For Canada, see Government of Canada, Spectrum Management and Telecommunications, *Compliance and Enforcement*; accessible at: https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/h_sf10951.html. Last Accessed 11 Aug 2019

France, French Space Operation Act 2008, Articles 14, 15; accessible at: http://www.unoosa.org/pdf/pres/lsc2009/pres-04.pdf. Last Accessed 12 Aug 2019

I-D. Galeriu, "Update: 'Paper Satellites' and the Free Use of Outer Space" (Apr 2018), GlobaLex, Global Law and Justice; accessible at: https://www.nyulawglobal.org/globalex/Paper_satellites_free_use_outer_space1.html. Last Accessed 10 Aug 2019a

I-D. Galeriu, "Update: 'Paper Satellites' and the Free Use of Outer Space" (Apr 2018), GlobaLex, Global Law and Justice; accessible at: https://www.nyulawglobal.org/globalex/Paper_satellites_free_use_outer_space1.html. (Last Accessed 10 Aug 2019b)

L. Grush, "Why it's time to study how rocket emissions change the atmosphere" (31 May 2018), The Verge; accessible at: https://www.theverge.com/2018/5/31/17287062/rocket-emissions-black-carbon-alumina-particles-ozone-layer-stratosphere. Last Accessed 10 Aug 2019a

L. Grush, SpaceX is in communication with all but three of 60 Starlink satellites one month after launch (28 June 2019), The Verge; accessible at: https://www.theverge.com/2019/6/28/19154142/spacex-starlink-60-satellites-communication-internet-constellation. Last Accessed 10 Aug 2019b

C. Henry, India ASAT debris spotted above 2,200 kilometers, will remain a year or more in orbit (09 Apr 2019), Space News; accessible at https://spacenews.com/india-asat-debris-spotted-above-2200-kilometers-will-last-a-year-or-more/. Last Accessed 10 Aug 2019

In the United States, see 51 USC § 50914, 51 USC § 50915, *Commercial Space Launch Activities*; accessible at: https://www.govinfo.gov/content/pkg/USCODE-2010-title51/pdf/USCODE-

2010-title51-subtitleV-chap509.pdf. Last Accessed 11 Aug 2019. France, *French Space Operation Act, 2008*, arts. 14, 15; accessible at: http://www.unoosa.org/pdf/pres/lsc2009/pres-04.pdf. Last Accessed 12 Aug 2019

International Telecommunication Union, Space Service Department, *Regulatory Procedures for Small Satellites*; accessible at: https://www.itu.int/en/ITU-R/space/Documents/RegulatoryProceduresSmallSats.pdf. Last Accessed 09 Aug 2019; Also, see ITU Filing Procedures for Small Satellites; accessible at: https://www.itu.int/en/ITU-R/space/Pages/supportSmallSat.aspx. Last Accessed 09 Aug 2019a

International Telecommunication Union, *ITU Radio Regulatory Framework for Space Services*; accessible at: https://www.itu.int/en/ITU-R/space/snl/Documents/ITU-Space_reg.pdf. Last Accessed 09 Aug 2019b

International Telecommunication Union, *Administrative due diligence applicable to some satellite radiocommunication services*, Resolution 49 (REV.WRC-15), World Radiocommunication Conference (Geneva) 2015; accessible at: https://www.itu.int/en/ITU-R/space/WRS16space/RES-49.pdf. Last Accessed 09 Aug 2019c

International Telecommunication Union, Cost recovery for satellite network filings, ITU Council Decision 482 (modified 2019), ITU Document C19/143-e, 20 June 2019; accessible at: https://www.itu.int/ITU-R/go/space-cost-recovery/en. Last Accessed 09 Aug 2019d

International Telecommunication Union, *Regulatory aspects for nanosatellites and picosatellites*, Resolution 757, Radiocommunication Conference (Geneva) 2012; accessible at: https://www.itu.int/dms_pub/itu-r/oth/0c/0a/R0C0A00000A0025PDFE.pdf. Last Accessed 09 Aug 2019e

International Telecommunication Union, *Studies to accommodate requirements in the space operation service for non-geostationary satellites with short duration missions*, Resolution 659, Radiocommunication Conference (Geneva) 2015; accessible at: https://www.itu.int/dms_pub/itu-r/oth/0c/0a/R0C0A00000C0007PDFE.pdf. Last Accessed 12 Aug 2019f

ITU Radio Regulations, 2016 edition; accessible at: https://www.itu.int/pub/R-REG-RR-2016. Last Accessed 10 Aug 2019. [*Radio Regulations*]. Also see, R.S. Jakhu, Regulatory process for communications satellite frequency allocations, in *Handbook of Satellite Applications: Springer Reference* ed. by J. Pelton, S. Madry, S. Camacho Lara (Springer, Berlin/Heidelberg, 2013) pp. 272–292

R.S. Jakhu, J.N. Pelton, *Small Satellites and their Regulations* (Springer, New York, 2013)

B. Lazare, "The French Space Operations Act: Technical Regulations" (02 Dec 2013), 92:2 *Acta Astonautica* 209, 10.1016/j.actaastro.2012.07.031; accessible at: https://www-sciencedirect-com.proxy3.library.mcgill.ca/science/article/pii/S0094576512002949. Last Accessed 10 Aug 2019

D.G. Loth, M. Ernst, *How High Is Up? Modern Law for Modern Man* (Bobbs-Merrill Company, New York, 1964)

S. Madry, P. Martinez, R. Laufer, *Innovative Design, Manufacturing and Testing of Small Satellites* (Springer International Publishing AG, 2018). Series Editor Joseph Pelton) at 115

S. Madry, P. Martinez, R. Laufer, *Innovative Design, Manufacturing and Testing of Small Satellites* (Springer International Publishing AG, 2018: Series Editor Joseph Pelton) at 56; John P. Thomas, "20.000 Satellites For 5G To Be Launched Sending Beams Of Intense Microwave Radiation Over The Entire Earth" (12 Feb 2019), Green World Warriors; accessible at: https://greenworldwarriors.com/2019/02/12/20-000-satellites-for-5g-to-be-launched-sending-beams-of-intense-microwave-radiation-over-the-entire-earth/. Last Accessed 10 Aug 2019; Brian Wang, "Total global satellite plans could have around 20,000 satellites in low and mid earth orbits in the 2020s" (04 Mar 2017), Next Big Future; accessible at: https://www.nextbigfuture.com/2017/03/total-global-satellite-plans-could-have.html. Last Accessed 12 Aug 2019

Market Watch, Space Situational Awareness (SSA) Market to Surpass at a CAGR of 6% by 2024 (10 Feb 2019); accessible at: https://www.marketwatch.com/press-release/space-situational-awareness-ssa-market-to-surpass-at-a-cagr-of-6-by-2024-2019-02-10. Last Accessed 10 Aug 2019

More details of the MILAMOS Project are accessible at: https://www.mcgill.ca/milamos/. Last Accessed 15 Aug 2019

NASA, Small Spacecraft Virtual Institute; accessible at: https://www.nasa.gov/smallsat-institute. Last Accessed 09 Aug 2019a

NASA, SpaceTech, *NASA Establishes the Small Spacecraft Systems Virtual Institute*, 21 Oct 2016; accessible at: https://www.nasa.gov/feature/nasa-establishes-the-small-spacecraft-systems-virtual-institute. Last Accessed 10 Aug 2019b

National Aeronautics and Space Administration, *Procedures for Implementing the National Environmental Policy Act (NEPA)*, U.S. 14 C.F.R § 1216.3; accessible at: https://www.govinfo.gov/app/details/CFR-2016-title14-vol5/CFR-2016-title14-vol5-part1216-subpart1216-3. Last Accessed 11 Aug 2019. Also, see National Aeronautics and Space Administration, *Final Environmental Impact Statement for the Mars 2020 Mission*, Nov 2014; accessible at: https://mars.nasa.gov/mars2020/files/mep/Mars2020_Final_EIS.pdf. Last Accessed 12 Aug 2019

New York Times, SpaceX Launches 60 Starlink Internet Satellites Into Orbit (May 2019); accessible at: https://www.nytimes.com/2019/05/23/science/spacex-launch.html. Last Accessed 10 Aug 2019

J.N. Pelton, "Urgent Security Concerns in the Proto-zone" (May 2014), Manfred Lachs Conference, Institute of Air and Space Law, McGill University, Montreal

J.N. Pelton, Creation of a comprehensive global space risk scale (SRS). J. Saf. Space Eng. **5**(1), 77 (2018)

J.N. Pelton, "New Uses of the Protozone" in *Space 2.0: Revolutionary Advances in the Space Industry* (Springer Nature Switzerland AG, 2019) 78. For more information on Stratobus: Thales, "Stratobus: Why this Stratospheric Airship is already being called a 'Swiss Knife' in the Sky" (22 May 2018); accessible at: https://www.thalesgroup.com/en/worldwide/space/magazine/stratobus-why-stratospheric-airship-already-being-called-swiss-knife-sky. Last Accessed 10 Aug 2019a

J.N. Pelton, A *New Integrated Global Regulatory Regime for Air and Space: The Need for Safety Standards for the "Protozone"* (May 2016), Manfred Lachs Conference, Institute of Air and Space Law, McGill University; Also, see Joseph N. Pelton, "New Uses of the Protozone" in *Space 2.0: Revolutionary Advances in the Space Industry* (Springer Nature, Switzerland, 2019b) pp. 71–85

J.N. Pelton, D. Smith, N. Helm, P. MacDoran, P. Caughran, J. Logsdon, *Space Safety Report: Vulnerabilities and Risk Reduction in U.S. Human Space Flight Programs* (George Washington University, Washington, D.C, 2005)

Protocol in respect of the claim for damages caused by the satellite "Cosmos 954", Canada and the Union of the Soviet Socialist Republics, 2 Apr 1981, 1470 UNTS 270. Also, see Marc Montgomery, "Canada History: 24 Jan 1978 Soviet radiation across the Arctic" (24 Jan 2017), Radio International Canada; accessible at: https://www.rcinet.ca/en/2017/01/24/canada-history-jan-24-1978-soviet-radiation-across-the-arctic./ Last Accessed 10 Aug 2019

Registration Convention, Article IV; Also, see R.S. Jakhu, B. Jasani, J. McDowell, Critical issues related to registration of space objects and transparency of space activities. Acta Astronaut. **143,** 1–15 (1974)

M. Ross, J.A. Vedda, "The Policy and Science of Rocket Emissions" (Apr 2018), Center for Space Policy and Strategy, The Aerospace Corporation; accessible at: http://aerospace.wpengine.netdna-cdn.com/wp-content/uploads/2018/04/RocketEmissions.pdf. Last Accessed 10 Aug 2019

S.C. 2005, c. 45; accessible at: https://laws-lois.justice.gc.ca/eng/acts/r-5.4/index.html. Last Accessed 11 Aug 2019). *Remote Sensing Space Systems Regulations*, SOR/2007–66; accessible at: https://laws-lois.justice.gc.ca/eng/regulations/SOR-2007-66/page-1.html. Last Accessed 11 Aug 2019. Also, see R.S. Jakhu, A.D. Kerkonian, Second independent review of canada's remote sensing space systems act. J Space Law **42**(1) (2018)

See International Telecommunication Union, *Working Party 7B (WP 7B) – Space radiocommunication applications*; accessible at: https://www.itu.int/en/ITU-R/study-groups/rsg7/rwp7b/Pages/default.aspx. Last Accessed 12 Aug 2019

See National Aeronautics and Space Administration, Office of Safety and Mission Assurance, *Range Flight Safety*, updated 10 Apr 2018; accessible at: https://sma.nasa.gov/sma-disciplines/range-flight-safety/2018/04/10/range-flight-safety-program-updates-two-training-courses. Last Accessed 11 Aug 2019. Also, see US Air Force, Air Force Safety Center; accessible at: https://www.safety.af.mil/Divisions/Space-Safety-Division/. Last Accessed 11 Aug 2019

See the latest policy, National Telecommunications and Information Administration, United States Department of Commerce, *Driving Space Commerce Through Effective Spectrum Policy*, 26 Mar 2019; accessible at: https://www.ntia.doc.gov/other-publication/2019/driving-space-commerce-through-effective-spectrum-policy. Last Accessed 10 Aug 2019

See United Nations Office for Outer Space Affairs, *United Nations Register of Objects Launched into Outer Space – Resources and Reference Material for States & Organizations*; accessible at: http://www.unoosa.org/oosa/spaceobjectregister/resources/index.html. Last Accessed 09 Aug 2019

See United States Federal Aviation Administration, Office of Commercial Space Transportation, “Draft Environmental Assessment for Issuing SpaceX a Launch License for an In-flight Dragon Abort Test, Kennedy Space Center, Brevard County, Florida” (Nov 2018); accessible at: https://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/review/launch/media/Draft_EA_for_SpaceX_In-flight_Dragon_Abort_508.pdf. Last Accessed 09 Aug 2019

See US Department of Transportation, Federal Aviation Administration, *Environmental Impacts: Policies and Procedures for considering Environmental Impacts*, FAA Order 1050.1F, 16 July 2015; accessible at: https://www.faa.gov/about/office_org/headquarters_offices/apl/environ_policy_guidance/policy/faa_nepa_order/. Last Accessed 11 Aug 2019

Title 47 – Telecommunications, U.S. 47 C.F.R § 2.106; accessible at: https://www.govinfo.gov/app/details/CFR-2010-title47-vol1/CFR-2010-title47-vol1-sec2-106. Last Accessed 11 Aug 2019

Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 27 Jan 1967, 610 UNTS 205 (entered into force 10 Oct 1967) [*Outer Space Treaty or OST*]; accessible at: http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html. Last Accessed 09 Aug 2019

U.S. 47 C.F.R § 25.157, *Consideration of NGSO-like satellite applications*; accessible at: https://www.govinfo.gov/content/pkg/CFR-2011-title47-vol2/pdf/CFR-2011-title47-vol2-sec25-157.pdf. Last Accessed 11 Aug 2019

U.S. 47 C.F.R § 25.158, *Consideration of GSO-like satellite applications*; accessible at: https://www.govinfo.gov/content/pkg/CFR-2012-title47-vol2/pdf/CFR-2012-title47-vol2-sec25-158.pdf. Last Accessed 11 Aug 2019

Union of Concerned Scientists, *UCS Satellite Database*, 31 March 2019; accessible at: https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database. Last Accessed 11 Aug 2019

United Nations, Report of the Committee on the Peaceful Uses of Outer Space, New York, 2007, Supplement No. 20, A/62/20, paras 118–119; accessible at: http://www.unoosa.org/pdf/gadocs/A_62_20E.pdf. Last Accessed 09 Aug 2019

United Nations Committee on the Peaceful Uses of Outer Space, *Guidelines for the Long-term Sustainability of Outer Space Activities*, 27 June 2018, U.N. Doc. A/AC.105/2018/CRP.20, Guideline A.2 (2)(b); accessible at: http://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf. Last Accessed 09 Aug 2019

United Nations General Assembly Resolution 1721 B (XVI), *International Co-operation in the Peaceful Uses of Outer Space*, Sixteenth Session, 20 Dec 1961; accessible at: http://www.unoosa.org/pdf/gares/ARES_16_1721E.pdf. Last Accessed 09 Aug 2019

United Nations Office for Outer Space Affairs, “Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space”, endorsed by the UN General Assembly in its Resolution 62/217 of 22 Dec 2007; accessible at: http://www.unoosa.org/pdf/publications/st_space_49E.pdf. Last Accessed 09 Aug 2019

United States, Space Policy Directive-3, *National Space Traffic Management Policy*, 18 June 2018; accessible at: https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/. Last Accessed 12 Aug 2019a

United States, Space Policy Directive-3, *National Space Traffic Management Policy*, 18 June 2018; accessible at: https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/. Last Accessed 11 Aug 2019b

United States, Communications Act, 1934 47 U.S.C. 301, *License for radio communication or transmission of energy*, as amended; accessible at: https://www.govinfo.gov/app/details/USCODE-2011-title47/USCODE-2011-title47-chap5-subchapIII-partI-sec301. Last Accessed 11 Aug 2019; *Satellite Communications Regulations,* U.S. 47 C.F.R. § 25.102; accessible at: https://www.govinfo.gov/app/details/CFR-2010-title47-vol2/CFR-2010-title47-vol2-sec25-102. Last Accessed 11 Aug 2019; *Direct Broadcasting Satellite Service Regulations*, U.S. 47 C.F.R. Part – 100; accessible at: https://www.govinfo.gov/app/details/CFR-1997-title47-vol5/CFR-1997-title47-vol5-part100. Last Accessed 11 Aug 2019; etc.

United States, U.S.C. 51, *National and Commercial Space Programs, Subtitle VI – Earth Observations*, 18 Dec 2010, Pub. L. 111–314, § 3, 124 Stat. 3328; accessible at: https://www.govinfo.gov/content/pkg/USCODE-2011-title51/html/USCODE-2011-title51.htm. Last Accessed 11 Aug 2019; Also, see U.S. 15 C.F.R. 960, *Licensing of Private Remote Sensing Systems*; accessible at: https://www.govinfo.gov/app/details/CFR-2014-title15-vol3/CFR-2014-title15-vol3-part960. Last Accessed 11 Aug 2019

US Commercial Space Launch Competitiveness Act, United States Code, Title 49, Subtitle IX, chap.701 – commercial space transportation activities, 25 Nov 2015; accessible at: https://www.congress.gov/bill/114th-congress/house-bill/2262/text. Last Accessed 11 Aug 2019

US Department of Transportation, Federal Aviation Administration, *Office of Commercial Space Transportation Regulations*; accessible at: https://www.faa.gov/about/office_org/headquarters_offices/ast/regulations/. Last Accessed 11 Aug 2019

Part XIII

Small Satellites: Essential Technical, Regulatory, and Management Information

Partial Listing of Small Satellite Constellations and Related System Infrastructure

Joseph N. Pelton and Vatsala Khetewat

Contents

Abstract

This chapter provides a listing of many of small satellite constellations that are being deployed or have been announced for launch by many commercial and governmental entities around the world. There are now so many of these governmental units, organizations, and companies deploying small satellite networks it is quite difficult to monitor the rapid rate of change in the filing of new networks. Further, the network configurations for these constellations are also often in a state of flux. Thus, one might go to the web sites for specific constellations to seek the latest information about these systems. Further, there are various organizations that provide reports on small satellite constellations. Northern Sky Research, Bryce, and Euroconsult are just some of such sources.

This chapter is a technical document with key information regarding the Handbook of Small Satellites.

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

V. Khetewat
International Space University (ISU), Santa Barbara, CA, USA
e-mail: vatsalakhetawat1@gmail.com

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_80

Keywords

Launcher organizations · Small satellite constellations · Sources of further organization

In the early days of space era, there were only sporadic launches of satellites one at a time. Each launch was a widely reported global news event. Today, over a half century later, the world of "NewSpace" that has revolutionized launch vehicle technology and created the smallsat phenomenon, the space industry, has radically changed. Today SpaceX has managed to directly deploy into low Earth orbit, on a single one of its Falcon rockets, 60 satellites for its Starlink constellation in a single launch. And Space X intends to repeat this process until many thousands of its small satellites are deployed to complete its mega-constellation. The Indian Polar Satellite Launch Vehicle launched 104 CubeSat-sized satellites in a single launch with 88 of these satellites being for the Planet's remote sensing constellation. Clearly the world of space has changed.

Small satellites and large-scale constellations numbering in hundreds or even thousands of satellites complicate such issues as space situational awareness, space traffic management, orbit satellite debris, and debris removal. Another thing that it complicates is a clear accounting of what satellites are now up and operational, which satellites are planned for launched, and even keeping track of which spacecraft have deorbited or now represent space debris. This presentation seeks to provide a reasonable accounting of small satellite constellations currently operating in space, hosted payloads that are flying on currently deployed constellations and a reasonable representation of small satellite systems that are planned or have been proposed for deployment in coming months or years.

The preparation of this "accounting" of small satellite constellations has been restricted to civil projects and does not include military- or defense-related projects since information concerning such activities are generally classified. It is hoped that this listing of constellations is reasonably complete and up-to-date even though some projects may have transitioned from planned to operational. Some proposed projects may have been cancelled due to technical, operational, or financial reason. One of the interesting trends is that more and more operators of GEO satellite systems have explored entering the small satellite market through direct investment or in partnerships. To date SES, Intelsat, Sky Perfect, Inmarsat, Iridium, Eutelsat, Telesat, and Yahsat among others have sought partnerships or direct investments in LEO constellations. Also new entrants from the world of cyberspace such as Google, Facebook, and Amazon have invested or are investing into small satellite constellations. Launch vehicle developer SpaceX has made the largest commitment of all with plans to launch a composite total of over 12,500 small satellites with the Skylink and V-band network.

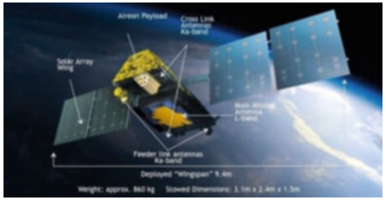
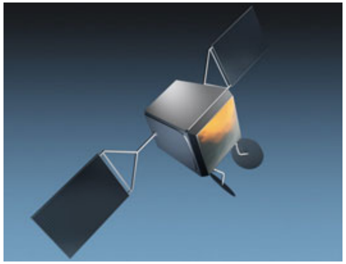
To assist researchers URLs have been provided where possible in order to assist in finding out the latest information concerning particular constellations of interest. It is urged that those seeking the latest status on various constellations go to current websites to learn about the latest updates. It is worth noting that simply because a small satellite constellation is proposed it may not actually be deployed. It must undergo a frequency coordination process under procedures indicated by the International Telecommunication Union (ITU). It must be authorized to operate in particular countries via a landing license in the case of provision of telecommunications services, and it must be licensed by a launching nation that must file the appropriate launch registration with the United Nations consistent with the Registration Convention. Thus many technical, operational, and regulatory actions must be completed before a system is actually launched and deployed in orbit. Every effort has been made to provide the latest and most accurate information, but some data may be incomplete, missing, or misstated. Any errors or omissions are unintentional.

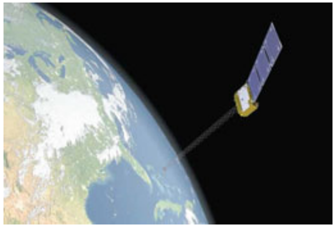
Part 1: Operational Systems (Table 1)

Part 2: Hosted Payload Small Satellite Systems (Table 2)

Part 3: Planned or Proposed Small Satellite Systems (Note all will actually be deployed. Please excuse any omissions that were unintentional not included) (Table 3)

Table 1 World's operational small satellite constellations

Satellite image	Country of origin and type of service	Number of satellites in constellation	Owner and operators website URL
https://spacenews.com/viasat-shrinks-meo-constellation-plans/ **Globalstar 2nd Generation (graphic courtesy of Globalstar)**	**United States** Mobile Communications to handheld transceivers and antennas on the move	24 Satellites in 2nd generation with mass of 700 kg deployed at 1414 km (876 mile) orbital altitude with 55 degree inclination. 80% coverage of the world. 24 ground stations for global interconnection	**Globalstar Inc.** https://www.globalstar.com/en-us/ https://www.orbcomm.com/en/networks/satellite https://www.orbcomm.com/en/networks/satellite
 **Iridium next sat w/ Aerion and exactEarth hosted payloads (graphic courtesy of Iridium)**	**United States** Mobile communications to handheld transceivers. Also provides Aerion aircraft tracking via hosted payload units and exactEarth hosted payloads for automatic identification service (S-AIS)	75 satellites in 2nd generation (66 operational and 9 spares) L-band spectrum in LEO orbit of 781 km with an inclination of 86.4° inclination	**Iridium** https://www.iridium.com https://en.wikipedia.org/wiki/Iridium_satellite_constellation#Second_generation
 **OneWeb satellite manufactured by Airbus (graphic courtesy of OneWeb)**	**European (Britain, Channel Islands)** LEO constellation to provide global networking services. Initial 600 satellites are currently being deployed by Soyuz launch vehicles. Plans seeks to ultimately deploy up to 4000 sats. System operates under the name of WorldVu satellite Ltd. and OneWeb and in filings is also known as L5	Initial operational service now beginning as the first of the large-scale LEO constellations. Investors include Intelsat, Airbus, Arianespace, Virgin Orbit, SoftBank, Qualcomm, Coca Cola, and others. First 600 now being deployed	**WorldVu/OneWeb URLs** https://www.oneweb.world/ https://en.wikipedia.org/wiki/OneWeb_satellite_constellation

 **Second generation of Orbcomm sat (0G2) (graphic courtesy of Orbcomm)**	**United States** Store and data relay to small receivers to provide M2M, AIS, and IoT services globally	Many first generation smallsats plus 12 OG2 satellites operational and others on order for planned launch. 720 km LEO orbits	**Orbcomm** **URL** https://www.orbcomm.com/en/networks/satellite
 Planet's "Dove" 3U CubeSat (graphic courtesy of Planet)	**United States** Medium and high resolution with daily updated global information	Nearly 300 active smallsats of 3 types 1. Skybox's sats 80 cm^3 (high res) (30) 2. Flocks 3 U "Dove" CubeSats (well over 200) (med res) 3. Planet Swift (6) RapidEye sats (medium res) by Surrey Space Tech LLC	**Planet** **URL** https://www.planet.com/
 Spire's Lemur 3U CubeSat (graphic courtesy of Spire)	**United States in cooperation with Europe's Galileo system**	Spire's constellation This is currently a LEO constellation of 80 satellites that are being expanded to collect AIS, meteorological data, and locational data in cooperation with the European Galileo system	**Spire Global's** **URLs** https://www.spire.com https://en.wikipedia.org/wiki/Spire_Global

(continued)

Table 1 (continued)

Satellite image	Country of origin and type of service	Number of satellites in constellation	Owner and operators website URL
 21 AT Three Satellite constellation (graphic courtesy of SSTL)	**China** **Private company known as 21 AT in cooperation with Surrey Space Technology LLC and Urthecast**	3 satellite remote sensing systems in Sun-synchronous polar orbit of 651 km. TIFF format. Provides 1 m and 4 m resolution imaging	Twenty-First Century Aerospace Technology (21 AT) using DHC-3 constellation manufactured by SSTL URL: https://www.prnewswire.com/news-releases/urthecast-and-twenty-first-aerospace-technology-sign-a-strategic-partnership-for-urthedaily-constellation-in-china-662013063.html
 Jilin-1 commercial imaging satellite (image from the Jilin-1 satellite). Image courtesy of NASA spaceflight)	**China** **Jilin's commercial satellite imaging Operated by change Guang Satellite Technology Co. of China established in 2014**	New commercial Chinese commercial imaging company with 1 m resolution imaging (planned to be 60+ satellite constellation)	4 satellite constellations www.charmingglobe.com/EWeb/index.asp
Argos constellation of 7 satellites. This system was first created in 1978. This is a LEO constellation for data relay. It is to be augmented and then replaced by 25 Kineis satellites in 2022. This is an international project led by CLS of France on behalf of NOAA, CNES, EUMETSAT, and ISRO of India. See Kineis in the planned systems below	**CLS of France on behalf of NOAA, CNES, EUMETSAT, and ISRO of India. Founded in 1978**	International data relay system	7 satellite constellation to be replaced by 25 satellite Kineis constellation in 2022 http://www.argos-system.org/great-news-for-argos-users/

O3b constellation in medium Earth orbit (MEO) is not included in this listing because its 24 satellites are considered too large to be considered small satellites

Table 2 Hosted payload small package constellations

Satellite image	Country of origin and type of service	Number of satellites in constellation	Owner and operators website URL
 **Aireon payload on Iridium Next (image courtesy of Iridium)**	Canada (aircraft aviation precision navigation)	66 sats (hosted payloads on Iridium Next)	Aerion hosted payload in partnership with Iridium to provide ADS-B services. **URL** https://www.aireon.com
 **ExactEarth hosted Payload on Paz Radar Sat (image courtesy of Hisdesat) and on Iridium Next**	Canada (automatic identification service)	In flux	Hosted payload on board the Spanish radar satellite PAX owned and operated by Hisdesat S. A. to provide maritime satellite-AIS services. And 58 operating units plus 7 spares on Iridium Next constellation **URL** https://www.exactearth.com/technology/exactview-rt-powered-by-harris

Table 3 Planned and proposed smallsat constellations (This listing represents an effort to list as many of the proposed and planned smallsat constellations as possible. It may not include the latest filings or provide the latest information. See websites for later information. MEO constellation satellites such as now envisioned by SES and VIASAT are too big to be considered small satellites although the VIASAT system MEO sats were included since their size and characteristics may ultimately be such that they might be considered "small satellites" as definitions change.)

Country of origin and constellation name	Type of service provided	Number of satellites	Orbit, network description, and website URL
Argentina **Satellogic's NuSat Aleph-1 constellation**	U/V sensing to 1 m resolution. Remote sensing services commercially offered	300 sats	500 km orbit. Operates in the U-/V-band for global remote sensing. (8 satellites launched prior to 2019, 13 launched in 2019) first phase of 77 sats to be launched in 2020) mass: 37 kg. Chinese launchers **URLs** https://en.wikipedia.org/wiki/%C3%91uSat http://space.skyrocket.de/doc_sdat/nusat-1.htm
Australia **Fleet**	Satellite-based Internet global networking constellation	100 sats Only a few launched by rocket labs	580 km orbit **URL** https://www/fleet.space/about
Australia **Sky and Space Global**	Global IoT connectivity	200 nanosats being built by GOMSpace	To be deployed in 2020–2021 **URL** https://spacenews.com/sky-and-space-global-low-on-cash-seeks-new-investors-for-iot-constellation/
Canada **Canpol 1**	Networking services to support military/defense-related services of Canada	72 sats	LEO constellation plus a number of highly elliptical orbit satellites. LEO 9 sats each in 8 planes. LEO Orbit in VHF-, UHF-, X-, and Ka-bands
Canada **GHGSat's Claire**	Emissions monitoring – measure CO_2 and methane	1 demonstration satellite has been launched and another 19 are planned	Sensors include 2D wide-angle Fabry-Perot imaging spectrometer with 15 kg satellite **URL** https://www.ghgsat.com

Canada Helios Wire Helios constellation	IoT/M2M – uses 30 MHz of S-band spectrum to receive tiny data packages from remote sensors	2 launched and 28 more to come	First payloads hosted on Astro Digital Corvus/Landmapper CubeSats https://helioswire.com
Canada **Kepler**	To provide Internet of Things (IoT) and data services. LEO constellation of 6U CubeSats. Manufactured by ÅACAAC Clyde with TARS platform. 140 6U CubeSats to provide Internet of Things	140 6U cube sats	Service provided in 575 km orbits. **Frequencies:** Ku band (10.7–12.7 GHz transmit 14.0–14.5 GHz **URLs** https://www.keplercommunications.com/ https://spacenews.com/kepler-communications-raises-16-million-for-telecom-constellation/ https://en.wikipedia.org/wiki/Kepler_Communications
Canada **Optistar by Urthecast**	Constellation of 16 satellites. Launch date not known	16 sats	16 satellites in polar orbit, 8 tandem pairs in 2 orbital planes. 1 m resolution in X-band and 5 m resolution in L-band. Provide nearly simultaneous imaging from the paired systems in optical bands and synthetic aperture radar imaging. Also provides geospatial analytics. Satellites to be built by Surrey Space Technology Ltd. **URL** https://www.urthecast.com/optisar/ https://blog.urthecast.com/updates/urthecast-announces-worlds-first-commercial-sar-and-optical-1
Canada **Telesat**	LEO constellation for networking. Proposed to operate at two different orbital altitudes	117 to begin and ultimately 794	72 sats at 1000 km 45 sats at 1248 km To expand to 794 satellites 27.5–30 GHz (uplink) and 17.8–20.2 GHz (downlink) (Ka-band) **URL** https://www.telesat.com/services/leo/why-leo

(continued)

Table 3 (continued)

Country of origin and constellation name	Type of service provided	Number of satellites	Orbit, network description, and website URL
China **Commsat**	LEO constellation for internetworking	800 sats	600 km LEO orbit. This new constellation is intended to provide Internet of Things and data communications services **URL** https://spacewatch.global/2018/12/chinas-new-space-race-iot-startup-commsat-launches-seven-cubesats/
China **Head –“Skywalker” constellation**	LEO constellation for EO and AIS services and data fusion	Head-1 launched and others to follow	AIS/IoT satellite constellation “Skywalker” for Earth observation and automatic identification services. Data fusion of AIS and remote sensing data **URL** http://www.iafastro.org/societes/china-head-aerospace-technology-co/
China **Hongyan**	LEO constellation for internetworking	300 sats	1100 km LEO orbit **URL** https://gbtimes.com/china-to-launch-first-hongyan-leo-communications-constellation-satellite-soon https://gbtimes.com/china-to-build-300-satellite-hongyan-communications-constellation-in-low-earth-orbit/
China **Lucky Stars**	LEO constellation for internetworking	156 sats	1000 km LEO orbit
China **Xiaoxiang-1-02**	Test satellite for a laser communications network	When implemented it would involve 100s of sat	Joint project of Spacety and Laser Fleet. This would be a constellation to provide laser communications-based high-speed Internet access for civil aircraft **URL** https://spacenews.com/more-satellites-in-orbit-following-second-mission-of-2018/
China **Xinghe**	Earth imaging data network	192 sats LEO orbit. Partnership between Spacety and AdaSpaceYalin	**URL** https://spacenews.com/more-satellites-in-orbit-following-second-mission-of-2018/
China **Xinwei**	LEO constellation for internetworking	32 sats 1100 km LEO orbit	**URL** http://www.xinwei.com.ua/en http://en.people.cn/n3/2018/0305/c90000-9433041.html

China **Zhuhai Orbita**	500 km constellation for video and hyperspectral remote sensing	4 OHS hyperspectral and 1 OVS video. Part of larger constellation	**URL** https://spacenews.com/china-launches-five-commercial-remote-sensing-satellites-via-long-march-11/
France **Eutelsat for LEO objects (ELO)**	500–600 km	Network still being defined	**URL** https://news.eutelsat.com/pressreleases/eutelsat-commissions-elo-its-first-low-earth-orbit-satellite-designed-for-the-internet-of-things-2440770 https://spacenews.com/eutelsat-planning-small-leo-internet-of-things-constellation/
France **Kineis (to replace Argos satellite system)**	LEO constellation for IoT and data Internet relay	25 sats 600 km LEO orbit	**URL** https://www.kineis.com/en/
France **MC-Sat constellation by the Thales Group**	LEO constellation for data relay, 5G, and internetworking	800 sats that would potentially grow to 4000	Combination of LEO, MEO, and highly elliptical. Intended to operate in Ku- and Ka-bands
Germany **80 LEO**	LEO constellation for IoT services	80 nano satellites?	**URL** www.80LEO.com/
Germany **SAT4M2M**	Combination of terrestrial and space-based IoT sensor connection network	Design of ground WAN network and satellite still in development	**URL** www.sat4m2m.com/ https://www.newspacepeople.com/company/sat4m2m https://www.microwavejournal.com/articles/29976-sat4m2m-and-fujitsu-to-develop-iot-communications-via-satellites
India **Astrome Tech**	Internet-working	600 sats	1400 km orbit
Korea **Samsung constellation**	Internetworking and support to broadband 5G mobile services	4500 sats	1500 km orbit
Liechtenstein **3Ecom**	Communications and inter-networking	288 sats	24 sats in 12 planes) **URL**

(continued)

Table 3 (continued)

Country of origin and constellation name	Type of service provided	Number of satellites	Orbit, network description, and website URL
Lithuania NanoAvionics' Lituanica Sat-1 and Lituanice Sat-2	Global IoT constellation-as-a-service aimed at IoT/M2M communications providers	2 CubeSats have been launched and another 70 are to come	**URL** https://n-avionics.com
Luxembourg **O3b satellites**	Broadband services	20 satellites to be expanded with nPower system	These satellites at 700 kg minisats are still considered smallsat. The next generation being built by Boeing are larger than most guidelines for smallsats
Netherlands **Lacuna Space**	IoT/M2M constellation	They plan to have a constellation of 32	Selected Open Cosmos to build 3 U demonstrator. First hosted payload on NanoAvionics M6P **URL** http://lacuna.space
Norway **ASK\1**	Support communications services	10 sats	Highly elliptical Earth orbit in X-, Ku-, and Ka-bands
Norway Steam Network	Communication and inter-networking	4425 sats	Ku- and Ka-bands (see SpaceX system) **URL** https://spacenews.com/signs-of-satellite-internet-gold-rush/
Poland **SatRevolution's REC constellation**	Earth observation – imaging the Earth in 50 cm resolution through the use of an innovative deployable telescope	Plan is for a constellation of 1024 satellites	**URL** https://satrevolution.com

Russia **Yaliny**	Internet connectivity and international telephone calls via Internet	135 sats	600 km LEO orbit which is seeking to offer consumers global access to the Internet and international calls via Internet for $10 a month **URL** https://the-dialogue.com/en/en39-pioneers-of-private-astronautics-in-russia-yaliny/
Swiss (Astrocast-Else)/Emirates (Yahsat/Thuraya)	LEO orbit constellation for IoT services	500–600 km 64 satellite constellation	**URL** https://spacenews.com/meet-else-the-thuraya-backed-smallsat-startup-that-wants-to-connect-things-with-cubesats/
Spain **AISTech's Danu and Hydra**	2-way comms, thermal imaging to detect forest fires, aviation tracking (ADS-B)	2 CubeSats launched and 148 are planned	Satellites will be built by GomSpace **URL** https://www.aistechspace.com
United States **Analytical Space**	Experimental CubeSat deployed as precursor to constellation	CubeSat released from iSS as precursor to operational constellation	Data relay constellation intended to use laser communications to support ultimate deployment of high data rate download or remote sensing data www.engine.xyz/founders/analytical-space-inc
United States **Astro Digital Landmapper**	Earth observation	10 satellites have been launched (5 are currently operational) and another 15 to follow	6U CubeSat has 22 m resolution. 16U CubeSat has 2.5 m resolution in RGB, red edge, and NIR using one 70 MP sensor **URL** https://astrodigital.com
United States **Athena**	Networking and broadband services on a global basis	Only one experimental sat as prelude to constellation	LEO constellation filed by PointView technology a subsidiary of Facebook. Frequencies not yet confirmed. Experimental authorization to launch and operate a single low Earth orbit satellite in 2019. The satellite would be in a sun-synchronous orbit between 500 and 550 km. This would presumably be a prelude to a large-scale constellation in Sun-synchronous orbit **URL** https://arstechnica.com/information-technology/2018/07/facebook-follows-spacex-and-oneweb-into-high-speed-satellite-broadband/

(continued)

Table 3 (continued)

Country of origin and constellation name	Type of service provided	Number of satellites	Orbit, network description, and website URL
United States **Audacy**	Data relay network	3 satellite constellation in MEO orbit of 14,000 km	Financing for this system is currently unclear This data relay network of 3 satellites, each orbit Earth every 8 h is designed to provide continuous download capability to a ground-based data relay antenna system. https://audacy.space/constellation
United States **Black Sky**	Remote sensing system and data analytics	60 sats	450 km orbit. This system plans to deploy 21 high-resolution SkySats, 2 medium resolution, 3 low resolution, and one SAR radar satellite (TerraSAR-X) as it initial global system. In late 2018 it launched in global 1 and 2 small satellites to begin its system deployment. It is working in cooperation with AWS **URL** https:www.blacksky.com
United States **Boeing constellation**	Two large-scale LEO constellation to provide global networking services	1396 to 1396–2996 sats	1396 satellites 1025 km orbit 2996 satellites in 1275 km orbit **URL** Currently Boeing has delayed plans for deployment https://spacenews.com/boeing-constellation-stalled-spacex-constellation-progressing/
United States **Capella**	Constellation of X-SAR satellites for radar imaging	36 sats that might expand to 48 sats	500 km orbit. This is a synthetic aperture radar system deploying sub-50 kg microsatellites. This system that will provide radar imaging for the X-band (9.4–9.9 GHz). The satellites will have only a 3-year life time, so it will require frequent replenishment. Full deployment of 36 sat network planned to be achieved around the end of 2021 or early 2022 **URL** https://www.capellaspace.com/ https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/capella-x-sar

United States GeoOptics' CICERO	Weather forecast – using GPS radio occultation for weather data	First operational satellite has been launched in 2017, and there are more planned	LEO constellation; Satellites procured from Tyvak **URL** http://www.geooptics.com
United States HawkEye 360	RF geolocation Radio frequency (RF) mapping with 15 kg nanosats to help monitor transportation across air, land, and sea and assist in emergencies	3 microsatellites launched and another 27 planned. Ultimately a 54 satellite constellation consisting of 18 "trios" of nanosats for triangulation of RF usage to provide global service	LE constellation Built by GomSpace **URL** https://www.he360.com
United States Iceye	Radar-based remote sensing network	18 small satellites of about 100 kg by 2021 or so	Synthetic aperture radar imaging. Seeking to provide coverage several times a day. Negotiating with Audacy to use the MEO data relay satellites for rapid instantaneous download capability. See Audacy **URL** https://www.iceye.com/resources/satellite-missions
United States Iridium/Magnitude Space	Joint Intelsat/ Magnitude Space constellation IoT services	18–24 nanosat constellation	This is to be an L-band system for Internet of Things data relay **URL** https://spacenews.com/iridium-teams-up-with-internet-of-things-startup-magnitude-space/
United States Karousel LLC (backed by Columbia Capital and Telecom Ventures	MEO system for high-throughput satellite service	12 to 24 sats	MEO Orbit 8200 km system that would deploy 5 satellites each in 4 different planes. This is a high-throughput communications and networking system **URL** https://www.defensedaily.com/wp-content/uploads/post_attachment/149310.pdf

(continued)

Table 3 (continued)

Country of origin and constellation name	Type of service provided	Number of satellites	Orbit, network description, and website URL
United States KLEO startup	LEO polar orbiting constellation for IoT-enabled devices	300 sats planned	24 satellites plus spares in 12 polar orbits. Aimed at target market of 80 billion IoT-enabled devices worldwide. To operate in Ka-band. Financing unclear **URL** https://kleo-connect.com/constellation
United Staes Kuiper constellation by Amazon.com	Large-scale LEO constellation	3200 satellites	Details are still pending clarification **URL** https://www.cnbc.com/2019/04/04/amazon-project-kuiper-broadband-internet-small-satellite-network.html
United States LeoSat	Broadband services for corporate enterprise networks	108 sats	1400 km orbit. This is intended to be a highly secured, meshed network of satellite to support business enterprise communications and networking with low latency service. Claims to have signed $2 billion in contracts for service **URL** http://leosat.com
United States O3b mPower satellites	Broadband services	20 satellites to be expanded	Next generation mPower network These satellites at 700 kg each are technically not smallsats, but are still smaller than most commercial GEO satellites **URL** https://03b.com/
United States Orbital Micro Systems	Weather constellation utilizes microwave technology to capture temperature and moisture measurements, refreshed and delivered every 15 min	They plan to have a constellation of 40	LEO; 3U/6U, nanosatellites up to 20 kg in mass, About 24 months lifetime **URL** https://www.orbitalmicro.com

United States Orbital Sidekick (OSK)	A space-based infrastructure of hyperspectral sensors to provide monitoring services and solutions to the energy sector and others	First sensor on ISS. constellation planned for 2020–2021	**URL** https://orbitalsidekick.com
United States PlanetiQ	Weather monitoring using radio occultation measurements	20 satellites microsats	The initial constellation is expected to be 20 satellites. This system will monitor both space weather and atmospheric data using radio occultation data using measures from the GPS, BeiDou, Galileo, and Glonass GNSS systems. It is planning 3 min updates through the use of data relay satellites in GEO orbit **URL** http://planetiq.com/about/aboutplanetiq/
United States SpaceX Starlink	Very large-scale LEO constellation to provide global networking services	4425 sats	Large-scale constellation that is designed to be deployed in mid 2020s at 1150 km altitude **URL** https://en.wikipedia.org/wiki/Starlink_(satellite_constellation)
United States SpaceX V-band constellation	Very large-scale LEO constellation to provide global networking services	7518	335–345 km orbit. This would operate in V-band super high frequencies (SHF) **URL** https://www.theverge.com/2018/11/15/18096943/spacex-fcc-starlink-satellites-approval-constellation-internet-from-space
United States Swarm Technologies	Constellation of CubeSats to provide low-cost texting messages	36	CubeSat constellation with satellite known as “Space Bees” to provide low-cost global texting service. Experimental initial satellites were illegally launched without an FCC license http://fortune.com/2018/12/21/swarm-technologies-fcc-satellite/ **URL** http://fortune.com/2018/12/21/swarm-technologies-fcc-satellite/

(continued)

Table 3 (continued)

Country of origin and constellation name	Type of service provided	Number of satellites	Orbit, network description, and website URL
United States **Theia**	LEO constellation to provide a combination of remote sensing, communication, and networking services as well as data analytics	112 larger satellites and smaller satellites for data relay	800 km LEO orbit. This constellation with radar and infrared optics will also provide networking and data analytic services. Note: this project is not to be confused with the All-Star/Theia project sponsored by Lockheed Martin and Colorado Space Grant Consortium **URL** www.theia.com http://www.khaosodenglish.com/politics/2018/06/05/thailand-to-spend-billions-on-satellites-from-unknown-company
United States **Viasat**	Global MEO system that would compete with SES's 03b MEO constellation	20 satellite MEO constellation to link with Viasat 1 and 2 GEO satellites	This is now a 20 satellite MEO constellation planned for a 8200 km orbit to complement the VIASAT 1 and VIASAT 2 GEO satellite. In some ways it is similar to the SES system of GEO satellites what work in tandem with its MEO network of 03b satellites https://spacenews.com/viasat-shrinks-meo-constellation-plans/. (It is not clear as to the size of these spacecraft and whether they will be considered to be small satellites) **URL** https://viasat.com/
United Kingdom Sky and Space Global's Red Diamond, Green Diamond and Blue Diamond	IoT/communication service (voice, data, and M2M)	3 nanosatellites have been launched, and another 197 are to follow	LEO; Plans to use inter-satellite links. Satellites outsourced from GomSpace; **URL** https://www.skyandspace.global

This chart is copyrighted by Joseph N. Pelton and is licensed to Springer Press for this publication. All rights reserved. Also note that the status of various smallsat constellations can rapidly change and that it is useful to consult relevant websites to seek the latest information on these networks

1 Cross-References

▶ Historical Perspectives on the Evolution of Small Satellites
▶ Introduction to the Small Satellite Revolution and Its Many Implications

References

http://en.people.cn/n3/2018/0305/c90000-9433041.html
http://fortune.com/2018/12/21/swarm-technologies-fcc-satellite/
http://lacuna.space
http://leosat.com
http://planetiq.com/about/aboutplanetiq/
http://space.skyrocket.de/doc_sdat/nusat-1.htm
http://www.argos-system.org/great-news-for-argos-users/
http://www.geooptics.com
http://www.iafastro.org/societes/china-head-aerospace-technology-co/
http://www.khaosodenglish.com/politics/2018/06/05/thailand-to-spend-billions-on-satellites-from-unknown-company
http://www.spacedaily.com/reports/Fleet_Space_
http://www.xinwei.com.ua/en
https://03b.com/
https://arstechnica.com/information-technology/2018/07/facebook-follows-spacex-and-oneweb-into-high-speed-satellite-broadband/
https://astrodigital.com
https://audacy.space/constellation
https://blog.urthecast.com/updates/urthecast-announces-worlds-first-commercial-sar-and-optical-1
https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/capella-x-sar
https://en.wikipedia.org/wiki/%C3%91uSat
https://en.wikipedia.org/wiki/Iridium_satellite_constellation#Second_generation
https://en.wikipedia.org/wiki/Kepler_Communications
https://en.wikipedia.org/wiki/OneWeb_satellite_constellation
https://en.wikipedia.org/wiki/Spire_Global
https://en.wikipedia.org/wiki/Starlink_(satellite_constellation)
https://gbtimes.com/china-to-build-300-satellite-hongyan-communications-constellation-in-low-earth-orbit/
https://gbtimes.com/china-to-launch-first-hongyan-leo-communications-constellation-satellite-soon
https://helioswire.com
https://kleo-connect.com/constellation
https://n-avionics.com
https://news.eutelsat.com/pressreleases/eutelsat-commissions-elo-its-first-low-earth-orbit-satellite-designed-for-the-internet-of-things-2440770
https://orbitalsidekick.com
https://satrevolution.com
https://spacenews.com/australian-startup-fleet-prepares-series-a-to-fund-next-10-satellites/
https://spacenews.com/boeing-constellation-stalled-spacex-constellation-progressing/
https://spacenews.com/china-launches-five-commercial-remote-sensing-satellites-via-long-march-11/
https://spacenews.com/eutelsat-planning-small-leo-internet-of-things-constellation/
https://spacenews.com/fleet-details-100-nanosat- constellation-for-internet-of-things-connectivity/
https://spacenews.com/iridium-teams-up-with-internet-of-things-startup-magnitude-space/
https://spacenews.com/kepler-communications-raises-16-million-for-telecom-constellation/

https://spacenews.com/meet-else-the-thuraya-backed-smallsat-startup-that-wants-to-connect-things-with-cubesats/
https://spacenews.com/more-satellites-in-orbit-following-second-mission-of-2018/
https://spacenews.com/signs-of-satellite-internet-gold-rush/
https://spacenews.com/sky-and-space-global-low-on-cash-seeks-new-investors-for-iot-constellation/
https://spacenews.com/viasat-shrinks-meo-constellation-plans/
https://spacewatch.global/2018/12/chinas-new-space-race-iot-startup-commsat-launches-seven-cubesats/
https://the-dialogue.com/en/en39-pioneers-of-private-astronautics-in-russia-yaliny/
https://viasat.com/
https://www.aistechspace.com
https://www.capellaspace.com/
https://www.cnbc.com/2019/04/04/amazon-project-kuiper-broadband-internet-small-satellite-network.html
https://www.defensedaily.com/wp-content/uploads/post_attachment/149310.pdf
https://www.exactearth.com/technology/exactview-rt-powered-by-harris
https://www.ghgsat.com
https://www.globalstar.com/en-us/
https://www.he360.com
https://www.iceye.com/resources/satellite-missions
https://www.iridium.com
https://www.keplercommunications.com/
https://www.kineis.com/en/
https://www.microwavejournal.com/articles/29976-sat4m2m-and-fujitsu-to-develop-iot-communications-via-satellites
https://www.newspacepeople.com/company/sat4m2m
https://www.oneweb.world/
https://www.orbcomm.com/en/networks/satellite
https://www.orbitalmicro.com
https://www.planet.com/
https://www.prnewswire.com/news-releases/urthecast-and-twenty-first-aerospace-technology-sign-a-strategic-partnership-for-urthedaily-constellation-in-china-662013063.html
https://www.skyandspace.global
https://www.spire.com
https://www.telesat.com/services/leo/why-leo
https://www.theverge.com/2018/11/15/18096943/spacex-fcc-starlink-satellites-approval-constellation-internet-from-space
https://www.urthecast.com/optisar/
https://www.blacksky.com
Technologies_first_satellites_launched_by_Rocket_Lab_999.html
www.80LEO.com/
www.charmingglobe.com/EWeb/index.asp
www.theia.com

Companies Involved in Design, Manufacture, and Testing of Small Satellites

Joseph N. Pelton

Contents

Keywords
Smallsats · Small satellite components · Small satellite integration · Small satellite testing · Smallsat manufacturing

1 Introduction

The small satellite industry has grown at a significant rate over the past decade as it has spread across the world. The most dynamic part of this international growth has been those who design and build cube sat and even smaller-sized satellites. The creation of PocketQube and other new satellite standard for spacecraft even smaller than cube satellites has contributed to this rapid global expansion. The following listing of a number of small satellite companies seeks to provide a representative listing of the companies around the world that have sought a place in the small satellite industry. Inclusion of particular companies in this listing should not be considered an endorsement of individual companies or their particular products or services.

An sincere effort has been undertaken to include as many small satellite companies and component suppliers as possible, but because of the large number

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_81

Table 1 A Representative Listing of Small Satellite Companies Around the World

A global guide to many of the firms involved in designing, manufacturing, operating CubeSat systems, or supplying key components (This list is representative of the global market but should not be considered complete. Sources such as the NANOSAT database should be consulted at https://www.nanosats.eu/#page-top to monitor new suppliers.)

Firms	Location/HQ	Year founded	Main product	Main application	Web site
AAC Microtec	Scotland	Acquired ClydeSpace Ltd in late Dec. 2017	Turnkey production of nanosats	All types of applications for nanosats	http://aacmicrotec.com/
Accion Systems	USA	2014	Thrusters and propulsion for nanosats	Component production for nanosats	https://www.nanosats.eu/org/accion-systems
Adcole Maryland Aerospace	Crofton, Maryland, and Marlborough, Mass, USA	2002 and changed its name in 2017 when Adcole Aerospace merged with Maryland Aerospace	Sun sensors and attitude controls and nanosat components	Component production for nanosats	www.adcole.com/2017/05/adcole-aerospace-division
Aeolus Aero Tech PVt Ltd	Bangalore, India	2010	Smallsat components	Scientific missions	http://www.Aeolusaerotech.com
AIS Tech	Spain	2008	Constellation for remote sensing and remote asset tracking	Earth observation, aviation tracking, and surveillance	http://www.aistechspace.com/
Akash Systems	San Francisco, CA, USA	2016	Nanosats	Nanosat RF transmitters	http://www.akashsystems.com
Alba Orbital	Glasgow, Scotland	2014	Unicorn 1 and 2 nanosats	Pocket nanosats	https://www.albaorbital.com/
Aniara Communications	India	2001	Nexstar 1 & 2	Telecommunications via Nexstar 1 & 2 smallsats	https://www.aniara.co.in/
Avellan Space Technology & Science (AST&Science)	California (USA)	2011	Hyper-integrated satellite	Space exploration	https://www.ast-science.com/

Clyde Space	Scotland	2008	Nano and cube satellite	Research satellites	www.clyde.space/about-us
CubeSatShop	US based	Unknown	Service to connect smallsat designers and builders with suppliers from around the world	Provides connection to 25 nanosat component suppliers with those seeking to build CubeSats/nanosats	https://www.cubesatshop.com/vendor-information/
CubeSpace	Stellenbosch,South Africa	Spin-off of Stellenbosch Univ.	Computer sensors and actuators and attitude determination and control systems for CubeSats	All types of application and research smallsats	https://cubespace.co.za
Dauria Aerospace	Germany, Russia	2011	Small satellite design and manufacture	Earth observation, communications, and navigation satellites	http://eng.dauria.ru/
Deimos Space, SLU, wholly owned subsidiary of Elecnor Deimos	Spain	2001	Small satellites	Earth observation	www.deimos-space.com
Deimos Space, UK, wholly owned subsidiary of Elecnor Deimos	Harwell, Oxford, Didcot, Oxfordshire (UK)	2013	Small satellites and ground segment systems	Earth observation	www.ukspace.org/member/deimos-space-uk-ltd
DHV Technology	Malaga, Spain	2010	Solar panel systems for CubeSats	All types of CubeSat systems	dhvtechnology.com
Enpulsion	Austria and San Jose, California (USA)	Unknown	Nano and micro thruster ion thruster propulsion	All types of small satellites	https://www.enpulsion.com/

(continued)

Table 1 (continued)

A global guide to many of the firms involved in designing, manufacturing, operating CubeSat systems, or supplying key components (This list is representative of the global market but should not be considered complete. Sources such as the NANOSAT database should be consulted at https://www.nanosats.eu/#page-top to monitor new suppliers.)

Firms	Location/HQ	Year founded	Main product	Main application	Web site
			for small satellites and for de-orbiting		
EyasSat	Denver, Colorado, USA	2010	Functionalteaching CubeSat system for engineering in the classroom and laboratory	Training materials for CubeSat design and operation	eyassat.com/products
EagleView	Bellevue, Washington and Rochester, New York (USA)	2013 (in current form since merger with Pictometry International	Data analysis through use of smallsat remote sensing	Geomatics analysis to support geo-intelligence needs of various companies	www.eagleview.com
HCT – Helical Communication Technologies	Rockledge Florida (USA)	2014	Specialized antennas for space and ground systems supporting smallsat projects	Quadrifilar helical antennas supporting all types of smallsat programs	www.helicomtech.com
GeoOptics	Pasadena, California (USA)	2006	24 small satellite constellations	Environmental, weather monitoring	https://www.corporationwiki.com/California/Pasadena/geooptics-inc/67116978.aspx
GomSpace	Denmark	2007	Nano and cube satellite	Research, low-cost science	https:///www.comspace

HEAD Aerospace Group	Beijing, China with offices in Hong Kong, Shanghai, the Netherlands, and France	2007	Attitude and orbit control systems, calibration, electronic components, on-ground testing, technical consulting, market analysis	Components and services for all types of nanosats	https://www.spacebizguide.com/4198-head-aerospace
ISIS – Innovative Solutions In Space	Netherlands	2010	CubeSat bus/platform, deployer and dispensers, launch services	All types of CubeSats	https://www.nanosats.eu/org/isis-innovative-solutions-in-space
Karten Space	Spain	2015	6U CubeSat constellation for remote sensing	Earth observation smallsats (known as KEOSats). Geo-intelligence for business	https://www.nanosats.eu/org/karten-space
Kineis (CLS)	France	2018	Intend to deploy 20 smallsats for remote system by 2021	Earth observation constellation	https://www.nanosats.eu/org/kineis
Kleos Space	Luxembourg	2017	Plans to acquire CubeSats from GomSpace	Geolocation and automatic identification services (AIS) and spectrum monitoring	https://www.nanosats.eu/org/kleos-space
Kubos	Denton, Texas (USA)	2017	Mission design and onboard software	An operating system that can be used on many CubeSat and nanosat missions	https://www.tmro.tv/2017/06/25/kubos-operating-system-cubesats-orbit-10-23/
KU Leuven	Belgium	2010	Attitude control systems, etc.	ADCS for all types of microsats and nanosats	https://www.cubesatshop.com/vendor-information/ku-leuven/

(continued)

Table 1 (continued)

A global guide to many of the firms involved in designing, manufacturing, operating CubeSat systems, or supplying key components (This list is representative of the global market but should not be considered complete. Sources such as the NANOSAT database should be consulted at https://www.nanosats.eu/#page-top to monitor new suppliers.)

Firms	Location/HQ	Year founded	Main product	Main application	Web site
Lens R & D	Noordwijk, Netherlands	2016 (first flight qualified 2018)	Sun sensors	Sun sensors for all types of nanosats	https://lens-rnd.com/
Maryland Aerospace, Inc. (see Adcole Maryland Aerospace)	Crofton, Maryland (USA)	2017	Guidance, navigation, and control systems	All types of smallsats, attitude control systems, KEDS simulation software	https://www.cubesatshop.com/vendor-information/maryland-aerospace-inc/
Microspace	Singapore	2000	Electronics, prototyping, software, etc.	Many components for nanosatellites designed and fabricated	http://www.micro-space.org/engineering.html
Microspace	Italy	This is a part of same company in Singapore	MEMS-based micro-propulsion systems	Microelectromechanical systems	http://www.micro-space.org/engineering.html
NewSpace Systems	Somerset West, South Africa	2012	Components for CubeSats, especially attitude control systems	Key components for all types of CubeSats	https://www.cubesatshop.com/vendor-information/new-space-systems/
Novananoalso provides “nanosat” bus	Lyon, France	2009	Nano satellite	Earth observation	www.novanano.com
NovaWurks	Los Alamitos, California (USA)	2011	Hyper-integrated satellite (HISats), CubeSat platforms	Space exploration, hosted payloads, and small satellite missions	www.novawurks.com

OmniEarth (see EagleView)	Virginia (USA)	2013	18 small satellites (but project now discontinued after acquisition by EagleView	Earth observation analysis	spacenews.com/omniearth-acquired-by-eagleview
Planet Labs (now part of Planet)	Mountain View, California (USA)	2010	Large-scale 3U CubeSat constellation	Earth observation	www.planet.com
PlanetiQ	Maryland (USA)	2012	12–24 small satellite constellation growing to a 300 satellite network	Weather monitoring and weather sensors	planetiq.com
Pumpkin	(USA)	2010	CubeSat kits, components, and software	All types of 1U CubeSat kits	www.cubesatshop.com/product/pumpkin-cubesat-kits
RUAG Aerospace	Switzerland, Austria, Finland, Sweden, USA		Integration, testing, dispensers, etc.		https://www.cubesatshop.com/vendor-information/ruag/
Satrec Initiative	Republic of Korea, Daejeon	1999	Small satellites	Earth observation	www.iafastro.org/societes/satrec-initiative
SCS Space	South Africa		Spacecraft subsystems and ground systems	Imagers for remote sensing	https://www.cubesatshop.com/vendor-information/scs-space/
Skybox Imaging (now part of Planet)	Mountain View, California (USA)	2009	24 satellite constellation	Earth observation	www.planet.com
Solar Mems Technologies SL	Seville, Spain	2009	Microelectromechanical system technology uses in nanosats	Sun sensors for research and solar power satellites	https://www.cubesatshop.com/

(continued)

Table 1 (continued)

A global guide to many of the firms involved in designing, manufacturing, operating CubeSat systems, or supplying key components (This list is representative of the global market but should not be considered complete. Sources such as the NANOSAT database should be consulted at https://www.nanosats.eu/#page-top to monitor new suppliers.)

Firms	Location/HQ	Year founded	Main product	Main application	Web site
					vendor-information/solarmems/
Space Advisory Group	Somerset West, South Africa	2010	Subsidiary of SCS Space	Engineering support, design, and testing for CubeSat projects	https://www.cubesatshop.com/vendor-information/space-advisory-company/
Surrey Space Technology LLC (SSTL) (This is a wholly-owned subsidiary of Space Bus)	University of Surrey (UK)	1985 (perhaps oldest of the small satellite companies and now owned by Airbus	Small satellites of all types	Earth observation, navigation, telecommunications, research, and experimental	www.surrey.ac.uk/surrey-space-centre
Swarm Technologies	California(USA)	2016	4 quarter of a full CubeSats launched without license from FCC. Now have plans for a global constellation	Global low-cost communications	https://www.swarm.space/
Teledyne Paradise Datacom			Supplier of satellite modems, solid-state power amplifiers (SSPA), low-noise amplifiers (LNA), block up converters (BUC), and associated redundancy subsystems	CubeSat and small satellite component suppliers especially for communications and IT systems	https://www.cubesatshop.com/vendor-information/teledyne-paradise-datacom/

Theia Space. This should not be confused with the Theia Constellation (USA)	Spain		ESAT platform for educational purposes	Systems engineering, communications, mission analysis, onboard software, guidance, navigation and control, testactivities, thermal design	https://www.cubesatshop.com/vendor-information/theia-space/
Thoth Technology, Inc.	Based in Africa	Unknown	Environmental payloads, Argus spectrometer, and infrared imagers	Remote sensing by nanosat and high-altitude platforms	https://www.cubesatshop.com/wp-content/uploads/2016/06/thoth.png
TY-Space	China (located at Tsinghua University)	2014 (spin-off of Tsinghua University	Optical sensors, precision star trackers. Used on Vilin-1CubeSats	Scientific and applications nanosats	http://www.ty-space.com/en/
TyvakNano-Satellite System	Irvine, California (USA)	2011	Nano and cube satellites	Scientific missions	www.tyvak.com
VACCO Industries	El Monte, California (USA)		Nano and cube satellites	Micro-propulsion systems for CubeSats	https://www.cubesat-propulsion.com/

of new companies in this field this has proven quite difficult. Any omissions are unintentional. An effort has been made to be as comprehensive as possible, but the large number of companies involved in building small satellites or satellite components is very large and growing daily. Any omission is unintentional.

2 Cross-References

▶ Introduction to the Small Satellite Revolution and Its Many Implications
▶ Historical Perspectives on the Evolution of Small Satellites

References

dhvtechnology.com
eyassat.com/products
http://aacmicrotec.com/
http://eng.dauria.ru/
http://www.Aeolusaerotech.com
http://www.aistechspace.com/
http://www.akashsystems.com
http://www.micro-space.org/engineering.html
http://www.ty-space.com/en/
https://comspace.com
https://cubespace.co.za
https://lens-rnd.com/
https://www.albaorbital.com/
https://www.aniara.co.in/
https://www.ast-science.com/
https://www.corporationwiki.com/California/Pasadena/geooptics-inc/67116978.aspx
https://www.cubesat-propulsion.com/
https://www.cubesatshop.com/vendor-information/
https://www.cubesatshop.com/vendor-information/ku-leuven/
https://www.cubesatshop.com/vendor-information/maryland-aerospace-inc/
https://www.cubesatshop.com/vendor-information/new-space-systems/
https://www.cubesatshop.com/vendor-information/ruag/
https://www.cubesatshop.com/vendor-information/scs-space/
https://www.cubesatshop.com/vendor-information/solarmems/
https://www.cubesatshop.com/vendor-information/space-advisory-company/
https://www.cubesatshop.com/vendor-information/teledyne-paradise-datacom/
https://www.cubesatshop.com/vendor-information/theia-space/
https://www.cubesatshop.com/wp-content/uploads/2016/06/thoth.png
https://www.enpulsion.com/
https://www.nanosats.eu/#page-top
https://www.nanosats.eu/org/accion-systems
https://www.nanosats.eu/org/isis-innovative-solutions-in-space
https://www.nanosats.eu/org/karten-space
https://www.nanosats.eu/org/kineis
https://www.nanosats.eu/org/kleos-space
https://www.spacebizguide.com/4198-head-aerospace
https://www.swarm.space/

https://www.tmro.tv/2017/06/25/kubos-operating-system-cubesats-orbit-10-23/
planetiq.com
spacenews.com/omniearth-acquired-by-eagleview
www.adcole.com/2017/05/adcole-aerospace-division
www.clyde.space/about-us
www.cubesatshop.com/product/pumpkin-cubesat-kits
www.deimos-space.com
www.eagleview.com
www.helicomtech.com
www.iafastro.org/societes/satrec-initiative
www.novanano.com
www.novawurks.com
www.planet.com
www.surrey.ac.uk/surrey-space-centre
www.tyvak.com
www.ukspace.org/member/deimos-space-uk-ltd

Global Launch Vehicle Systems for Potential Small Satellite Deployment

Joseph N. Pelton and Scott Madry

Contents

This chapter key technical and other practical information of launch arrangement and performance for the Handbook of Small Satellites.

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

S. Madry
The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
e-mail: madrys@email.unc.edu

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_82

Abstract

This chapter provides a useful guide to a global listing of various launcher vehicles that have been recently used in small satellite launches, are active in the global launch services market, or are now under immanent development for launch to support commercial space business internationally. Most of these launch vehicles have multiple launch configurations that include strap-on boosters. Further the designs of many launch vehicles have evolved in time and become more capable and with greater lift capability. Thus one must focus on not only the name of a launch system but its actual detailed name and complete model number. In short, the capabilities of launch vehicles change over time. It is best to consult with the latest web site information to obtain the latest information.

Keywords

Angara · Antares · Ariane · Atlas · Blue Origin · Delta · Dream Chaser · Electron · Falcon 9 and other Falcon vehicles · H1 and H2 launch vehicle · International Space Station small satellite dispenser · Launcher One · Launch vehicles · Long March · Minotaur · Nanoracks · New Glenn · Pegasus · Polar Satellite Launch Vehicle · Proton · Rockot · Soyuz · SpaceX · US Launch Alliance · Vega · Vulcan · Zenet

1 Introduction

This chapter provides a useful guide to a global listing of various launcher vehicles that have been recently used in small satellite launches, are active in the global launch services market, or are now under immanent development for launch to support commercial space business internationally. Most of these launch vehicles have multiple launch configurations that include strap-on boosters. Further the designs of many launch vehicles have evolved in time and become more capable and with greater lift capability. The first version of an Atlas, Ariane, Delta, Long March, Soyuz, PSLV, and Minotaur, for instance, and their latest version can be huge – perhaps like the difference between a canary and large-scale Pelican. Thus one must focus on not only the name of a launch system but its actual detailed name and complete model number.

Virtually all of the listed launch vehicles or launch system arrangements (such as an arranged launch through NanoRacks via the International Space Station) can provide a suitable launch configuration or launch dispenser appropriate to be used to support small satellite launches. This listing of launch options thus includes launch from the International Space Station via the Japanese Experiment Module, Reusable Microsat Deployment System, and NanoRacks Kaber system as one of the available launch options for small satellites that are under 82 kg and 1 m^3.

Accordingly, launchers that have not been used for commercial mission and which are not on current offer such as those developed by North and South Korea, Israel, or Iran are not included in the more detailed listing of mature vehicles with a track record of a number of successful launches. Thus the first part of this Appendix does not provide detailed listing for new launch systems such as the Naro-1, Shavit, Kaituozhe-1, Unha, Prime, and Miura 5 or the now bankrupt Firefly. These and other new launch vehicles now under development are, however, included in the second part of this chapter, along with the many new launch vehicle development efforts. These are in some cases also discussed in earlier articles in the Handbook that discuss launcher options for small satellites.

To the extent new launcher systems are developed and are ultimately provided on the global service market, they will be included in future editions of this Handbook.

The costs to launch rocket systems that are cited in this Appendix typically represent figures for 2018 or 2019. Those seeking actual launch arrangements for small satellites should go to the web site URL sources cited in this appendix to seek updated information. It is important to find online the current user's handbook for various launch vehicles that are frequently available online for many launchers and launch service provider and then contact a service representative.

Also those contemplating a launch of a small satellite must also be aware of the need to not only make suitable launch arrangements but arrange for a registration with the United Nations of the all spacecraft that is launched in accord with the provisions of the Registration Convention. These requirements for the launching nation to register all spacecraft launches, including small satellites, are spelled out in Appendix E. Also provided for information purposes are the UN registration forms. Finally it should be noted that satellites that use radio frequencies for command and control of spacecraft and for transmitting telemetry information back to ground receivers or otherwise involve the use of radio frequencies must be licensed by national authorities and the satellites frequencies coordinated by the national relevant administration with the International Telecommunication Union (ITU).

Below is a guide to the launch vehicles and launch opportunities listed in the following Appendix. It provides a listing of the various launch systems, the manufacturer, and country of origin in the order that they appear in this book. Background notes seek to provide the latest status of development and updates on new launchers under development.

Index to Global Launcher Systems Included in This Appendix

Name of launch system	Manufacturer	Country of origin
Angara 1,2, and 5	Khrunichev, KBKhA	Russia
Antares	Northrop Grumman	USA
Antares with Cygnus Capsule	Northrop Grumman	USA
Ariane 5	Arianespace	France-European nations
Ariane with Automated Transfer Vehicle (ATV)	European Space Agency	ESA members
Atlas up to Atlas 5	Lockheed Martin/ULA	USA
Delta up to Delta 4 Heavy	Boeing/ULA	USA
Delta (or Atlas/Falcon/Vulcan) with CST-100 Starliner Capsule	Boeing	USA
Delta-Atlas-Vulcan options	ULA	USA
Dnepr	Yuzhmash et al.	Ukraine/Russia
Dream Chaser	Sierra Nevada	USA
Electron	Rocket Lab	NZ/USA
Falcon 9, Falcon 9 Full Thrust, Falcon Big Rocket	SpaceX	USA
Falcon with Dragon capsule	SpaceX	USA
HII/HIIA	JAXA, Mitsubishi, NG Innovation Systems (subcontractor)	Japan
HIIA (H2 Transfer Vehicle)	JAXA	Japan
ISRO Polar Satellite Launch Vehicle (PSLV)	Indian Space Research Organization (ISRO)	India
ISS Deployment options	NASA	USA
LauncherOne	Virgin Orbit	UK-USA
Long March Series 2ACDEF, 3ABC, 4ABC, 5	Long March	China
Minotaur C, II, XLS (formerly known as Taurus)	Northrop Grumman	USA
New Glenn	Blue Origin	USA
Pegasus	Northrop Grumman Innovation Systems	USA
Proton	Khrunichev	Russia
Rockot	Eurockot	Russia/France
Soyuz	Arianespace	Russia
Vector	Vector Space Systems	USA
VEGA	European Launcher Development (ELD)-Fiat-Veio	Europe
Vulcan	United Launch Alliance (ULA)	USA
Zenit	Being phased out of production	Ukraine

2 Angara 1, 2, and 5 Launch Systems

Angara 5 on launch Pad (Graphic Courtesy of Roscosmos)

Background notes: The Angara rocket family is designed to replace the Proton family. There are several versions currently active that include:
Angara 1, 2 and 5A. Also now proposed are: Angara A3, Angara A5P, Angara A5V Angara A7, Angara A7.2B. The 5A is able to lift able to lift 24.5 tons to LEO (200km). The Angara 7.2 if built would double this payload to 50 tons.

Angara 1, 2 and 5 Launch Vehicle
Manufacturer: Khrunichev, KBKhA
Country of origin: Russia
Height: 42.7 m (140 ft)-64 m (210 ft)
Width: Angara 1.2 2.9 m (9 ft 6 in) Angara A5: 8.86 m (29.1 ft)
Mass: 171,500 kg (378,100 lb)-790,000 kg (1,740,000 lb)
Stages 2 or 3
Capacity
Payload to LEO (Plesetsk) 3,800 kg (8,400 lb)-24,500 kg (54,000 lb)
Payload to GTO (Plesetsk) 5,400 kg (11,900 lb)-7,500 kg (16,500 lb)
Associated rockets
Comparable Naro-1 used a modified URM-1 first stage
Launch history
Status Active
Launch sites Plesetsk Site 35 Vostochny
Total launches 2 (A1.2PP: 1, A5: 1)
Successes 2 (A1.2PP: 1, A5: 1)
First flight A1.2PP: July 9, 2014 A5: Deb 23, 2014
No. boosters 4 Boosters (A5) – URM-1
Engines 1 RD-191
Thrust 1,920 kN (430,000 lbf) (Sea level)
Total thrust 7,680 kN (1,730,000 lbf) (Sea level)
Burn time 214 seconds
Fuel RP-1/LOX
First stage – URM-1 Engines: 1 RD-191 Thrust 1,920 kN
Burn time: Angara 1.2: 214 seconds Angara 5: 325 seconds
Fuel RP-1/LOX
Second stage – URM-2 Engine: 1 RD-0124A Thrust: 294.3 kN
Burn time Angara A5: 424 seconds
Fuel RP-1/LOX
Third stage (A5) – Briz-M (optional)
Engines: 1 S5.98M Thrust: 19.6 kN Burn time: 3,000 sec
Fuel N2O4/UDMH
Third stage (A5) – KVTK (optional, under development)
Engines 1 RD-0146D Thrust 68.6 kN Burn time: 1,350 sec
Fuel LH2/LOX
Sources: http://www.khrunichev.ru/main.php?id=44
https://en.wikipedia.org/wiki/Angara_(rocket_family)

3 Antares 230 Launcher

Antares 230 Launcher at Pad (Graphic courtesy of NASA)

The Antares was developed by Northrop Grumman/Orbital ATK based on the Taurus Rocket. Antares is sometimes referred to as Taurus II. The Ukrainian company Yuzhnoe which designed the Zenit rocket adapted this design for the first stage of the Antares rocket. Thus the first stage is a liquid fueled rocket while the second stage is a solid fuel rocket based on shortened version of the Castor 30 rocket.

The Antares was developed to lift The Cygnus Transfer Vehicle to bring cargo or other materials to the ISS and then become expendable as it re-enters the atmosphere. The Cygnus can bring cubesats or microsats to the ISS for launch. (See next page)

Antares Launch Vehicle by Northrop Grumman

Function: Medium Expendable Launcher
Manufacturer: Northrop Grumman Innovation Systems
Country United States
Launch cost: US$80-85 million

Height 230 series: 42.5 m (139 ft)
Diameter 3.9 m (13 ft)
Status: 100 series cancelled. 230 series active. 300 series in development
Mass 230: 298,000 kg (657,000 lb)
Stages 2 to 3
Capacity
LEO Payload 8,000 kg (18,000 lb[
Associated rockets
Comparable: Delta II and Atlas III
Expendable TV Cygnus (See Next Page)
Status • 200-series: operational
• 230 series: operational
Launch sites Mid Atlantic Rocket Site
Total launches 9 (110: 2, 120: 2, 130: 1 (Failed), 230: 4)
First stage (Antares 200-series)
Empty mass 20,600 kg (45,400 lb)
Gross mass 262,600 kg (578,900 lb
Engines 2 ×RD-181
Thrust 3,844 kN (864,000 lbf)
Burn time 215 seconds
Fuel RP-1/LOX
Second stage CASTOR A/B/XL
Gross mass 30A: 14,035 kg (30,942 lb)
30B: 13,970 kg (30,800 lb)
30XL: 26,300 kg (58,000 lb)
Propellant mass: 30A: 12,815 kg (28,252 lb)
30B: 12,887 kg (28,411 lb)
30XL: 24,200 kg (53,400 lb)
Thrust for 30XL: 474 kN (107,000 lbf)
Fuel: HTPB
Sources: https://en.wikipedia.org/wiki/Antares_(rocket)
http://www.northropgrumman.com/Capabilities/Antares/Pages/default.aspx

4 Antares with Cygnus Capsule

**The Upgraded Cygnus with Increased Cargo Capacity
(Graphic Courtesy of NASA)**

Background Notes: Cygnus has been upgraded to increase the cargo carrying capability on the Antares 230. This improved design increases the payload from 2000 kg to 3200 kg. The Cygnus and Cygnus 230 are also compatible with a launch on an Atlas V 401. This can allow up to 1500 kg more cargo on this launcher vis a vis the original Cygnus.

Cygnus Capsule for Re-Supply of the ISS

Manufacturer	**Northrop Grumman Innovation Systems (formerly Orbital ATK)**
Country of origin:	**United States**
Operator:	**NASA**
Applications:	**ISS resupply**
Specifications	
Spacecraft type :	**Unmanned cargo vehicle**
Design life	**1 week to 2 years**
Dry mass	**3,400 kg (7,500 lb) (Standard)** **3,750 kg (8,270 lb) (Enhanced)**
Payload capacity:	**2,000 kg (4,400 lb) (Standard)** **3,200 kg (7,100 lb) (Enhanced 230)** **3,500 kg (7,700 lb) (Enhanced -Atlas V 401)**
Dimensions	**5.1 m × 3.07 m (16.7 ft × 10.1 ft) (Std)** **6.3 m × 3.07 m (20.7 ft × 10.1 ft) (Enhanced)**
Volume:	**18.9 m^3 (670 cu ft) (Standard)** **27.0 m^3 (950 cu ft) (Enhanced)**
Power	**3.5 kW**
Production	
Status	**In service**
Built	**10**
On order	**11**
Launched	**10**
Operational	**1**
Retired	**8**
Lost	**1**
First launch:	**18 September 2013**

Sources:
http://www.northropgrumman.com/Capabilities/SpacecraftBuses/Pages/default.aspx
and
https://en.wikipedia.org/wiki/Cygnus_(spacecraft)

5 Ariane 5 Launch Vehicle

Ariane 5 on Launch Pad
Guiana Space Centre ELA-3
(Graphic courtesy of Arianespace)

Website URL for Updates
http://www.arianespace.com/

Ariane 6 is under development as a comparable sized vehicle but much more cost effectivie. It will use Vulcan engines or possibly the reusable Prometheus engines are are being designed for much more cost-effective manufacture and might be 10 times less costly. CNES, Airbus-Safran and ESA are developers.

Background Notes:
Ariane 4 (no longer active),
Ariane 6 under development,
Ariane 5 ME no longer under development. Also see Vega.

Ariane 5 Heavy Launch Vehicle

Manufacturer Airbus Defence and Space for ESA
Country of origin: France, ESA member states
Cost per launch: $165–220M
Size
Height 46–52 m (151–171 ft)
Diameter 5.4 m (18 ft)
Mass 777,000 kg (1,713,000 lb)
Stages 2
Capacity Payload to LEO
(260 km (162 mi)
circular, 51.6°) G: 16,000 kg (35,000 lb)
ES: over 20,000 kg (44,000 lb)
Capacity Payload to GTO
G: 6,950 kg (15,320 lb) (Now Canceled)
G+: 6,950 kg (15,320 lb) (Now Canceled)
GS: 6,100 kg (13,400 lb) (Now Canceled)
ECA: 11,115 kg (24,504 lb) (Active)
Small Satellite Launch Capability:
SPELDA Adaptor for Smallsat 'Piggy Back' Launches

Associated Rocket Family: Ariane ECA now active. Development of Ariane ME halted. Ariane 6 to replace Ariance ECA in 2020s and operate at half the cost.

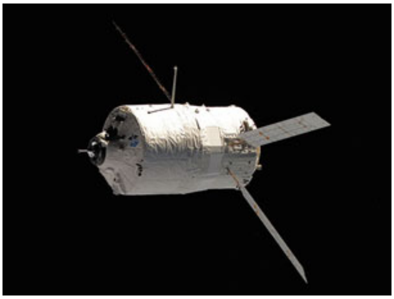
Comparable Launchers
Atlas V 551, Delta IV Heavy, Falcon 9 Full Thrust
JAXA H-IIB, Chinese Long March 5, Proton-M
Launch site: Guiana Space Centre ELA-3
Total launches 103
Successes 98

Fuel AP, Al, HTPB and LH2 / LOX in stage 2

Sources:
http://www.esa.int/Our_Activities/Space_Transportation/Launch_vehicles/Ariane_5_ES

http://www.spacelaunchreport.com/ariane5.html

6 Ariane with Automated Transfer Vehicle



(Graphic courtesy of Arianespace)

Background Notes

The Automated Transfer Vehicle(ATV) is just one of the re-supply options providing key cargo to the ISS. The Cygnus and ATV are now expendable vehicles that on the return burn up in the atmosphere. The SpaceX Dragon capsule and the Boeing CST 100 Starliner are being qualified to carry and return crew from the ISS.

Automated Transfer Vehicle

Role: Supply the International Space Station with propellant, water, air, payload, experiments, and smallsats for deployment.

Crew: None, but human-rated.[1]

Dimensions

Height: 10.3 m (34 ft)

Diameter: 4.5 m (15 ft)[2]

Launch Payload: 7,667 kg (16,903 lb)[3]

Return Payload: None. Disposable.

Mass at launch: 20,750 kg[2]

Pressurized Volume: 48 m3[4]

Electrical Energy Source: 4 solar panel wings of 4 panels each and 40Ah rechargeable batteries

Size: total span 22.3 m

Generated Power: 3,800 W

On-board engines

Main engine: 4 × 490N, Aerojet (GenCorp) Model R-4D-11

Thrusters : 28 × 220N for attitude control & braking, ArianeGroup Lampoldshausen

Performance Endurance: Docked with the ISS **for up to six months**

Apogee: 400 km

Perigee: 300 km

Inclination: 51.6 degrees

Launch Location: CNES's Guiana Space Centre, Kourou in French Guiana

Site: ELA-3

Booster: Ariane 5 ES

Source:

https://web.archive.org/web/20070322203029/http://www.spaceflight.esa.int/users/downloads/factsheets/fs003_12_atv.pdf

https://en.wikipedia.org/wiki/Automated_Transfer_Vehicle

7 Atlas V Launch Series

Atlas V 401 Launch Vehicle

(Gaphic Courtesy of Lockheed Martin)

Background Notes

The Atlas V 400 and 500 series and Atlas Heavy is marketed by the United Launch Alliance. They also market the Delta 4 launchers. The 2 pages below show pertinent information on the size and characteristics of Atlas and Delta Vehicles. The direct marketing of these services by ULA is anticipated to reduce costs. When the Vulcan vehicle is certified, the Delta vehicle is expected to be phased out of service. All of these vehicles can be configured for the launch of cubesats, microsats, and minisats.Although Lockheed Martin is the main contractor for ULA on the Atlas V. There are Russian engines and other sub-contractors that Include Aerojet General, and Northrop Grumman Innovation Systems. SpaceX, in contrast, has moved to vertically integrate the production of its Falcon vehicles and produced a much lower cost launch vehicle. Note: ULA may be sold to Aerojet General.

Atlas V Launch Series of Expendable Rockets

Function: EELV/medium-heavy launch vehicle
Manufacturer: United Launch Alliance-Lockheed Martin et al
Country of origin: United States
Cost per launch: US$110 million in 2016
Height 58.3 m (191 ft)
Diameter: 3.81 m (12.5 ft)
Mass: 334,500 kg (737,400 lb)
Stages: 2
Payload to LEO 8,250–20,520 kg (18,190–45,240 lb)
Payload to GTO4,750–8,900 kg (10,470–19,620 lb)
Comparable: Delta IV Falcon 9 H-IIB Long March 3B Proton-M
Status Active
Launch sites: Cape Canaveral SLC-41 & Vandenberg SLC-3E
Total launches 79
(401: 38, 411: 5, 421: 7, 431: 3)
(501: 6, 521: 2, 531: 3, 541: 6, 551: 9)
Successes 78
(401: 37, 411: 5, 421: 7, 431: 3)
(501: 6, 521: 2, 531: 3, 541: 6, 551: 9)
Partial failures 1 (401 – low orbit, customer declared success)
First flight 21 August 2002
<u>0 to 5 Boosters</u> – AJ-60A engine
Length 17.0 m (669 in)
Diameter 1.6 m (62 in)
Gross mass/Propellant: 46,697kg (102,949lb) 42,630 kg (93,980lb)
Thrust 1,688.4 kN (379,600 lbf)
Burn time 94 seconds
Fuel HTPB

First Stage Length 32.46 m(106.5ft) Diameter 3.81m(12.5ft)
Empty mass 21,054 kg (46,416 lb)
Propellant mass 284,089 kg (626,309 lb)
Engines 1 RD-180 **Fuel**: RP-1/LOX

Second stage – Centaur
Length 12.68 m (41.6 ft) Diameter: 3.05 m (10.0 ft)
Empty mass 2,316 kg (5,106 lb)
Propellant mass: 20,830 kg (45,920 lb)
Engines 1 RL10A or 1 RL10C Fuel: LH2 / LOX
Sources: http://spacelaunchreport.com/atlas5.html
https://en.wikipedia.org/wiki/Atlas_V

8 Boeing: Delta IV Heavy Launch Vehicle

By NASA/Kim Shiflett - http://mediaarchive.ksc.nasa.gov/detail.cfm?mediaid=71145 (image link), Public Domain, https://commons.wikimedia.org/w/index.php?curid=37939869

Delta IV Heavy Launch Vehicle

Function: Orbital heavy-lift launch vehicle

Manufacturer: United Launch Alliance/Boeing

Country of origin: United States

Cost per launch $350 million (2018)

Height 72 m (236 ft)

Diameter 5 m (16 ft)

Width 15 m (49 ft)

Mass 733,000 kg (1,616,000 lb)

Payload to LEO 28,790 kg (63,470 lb)

Payload to GTO 14,220 kg (31,350 lb)

Associated rockets

Family Delta I, II, III and IV now discontinued and Delta IV Heavy to be replaced by the Vulcan.

Comparable Vehicles:

Ariane 5 Falcon Heavy Long March 5 New Glenn Proton-M Vulcan

Status Active but slated to be replaced

Launch sites: SLC-37B, Cape Canaveral
SLC-6, Vandenberg AFB

Total launches 10

Successes 9

Partial failures 1

First flight: 21 December 2004 (USA-181)

Last flight: to be replaced in 2021

Sources:

http://spaceflight101.com/spacerockets/delta-iv-heavy/

https://en.wikipedia.org/wiki/Delta_IV_Heavy

9 Atlas V, Atlas-Centaur, Atlas Vulcan, and Delta IV Heavy Launch Vehicles Marketed by United Launch Services

These launchers are marketed by United Launch Services. Lockheed Martin is the manufacturer of the Atlas V and Atlas-Centaur vehicles, and Boeing is responsible for the Delta 4 and Delta 4 Heavy vehicles. The Delta IV and Delta IV Heavy, because of their high cost, are being phased out of service. The replacement vehicle will be the Vulcan. The Boeing CST Starliner Crew Transfer Vehicle is being designed to be compatible with the Atlas V, the Delta IV, the Vulcan, and the Falcon High Thrust vehicles.

There are multiple ways that these vehicles can be configured to launch small satellites (Fig. 1).

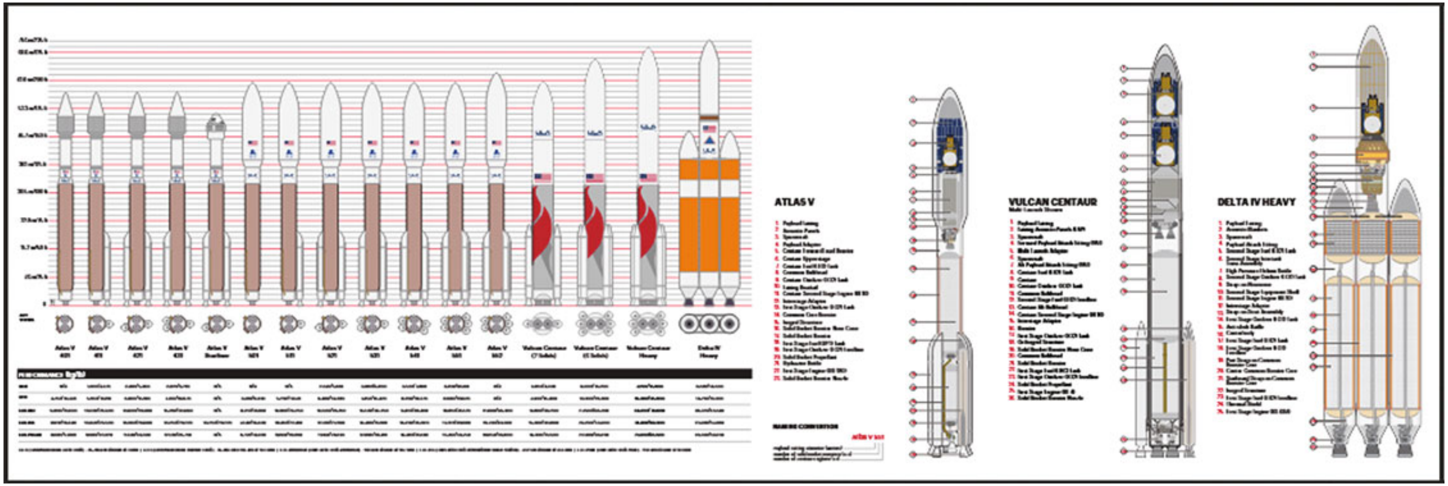


Fig. 1 Graphic showing the range of Atlas V, Atlas Centaur, Atlas Heavy, and Delta launchers in various configurations currently available. (Graphic Provided by United Launch Alliance). (Source: https://www.ulalaunch.com/docs/default-source/rockets/atlas-v-and-delta-iv-technical-summary.pdf)

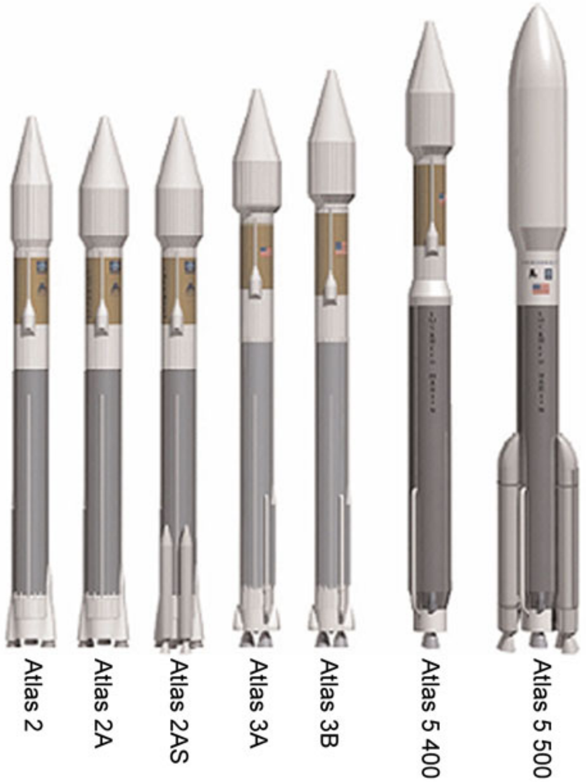


Figure showing the relative size of the Atlas II, Atlas III, and Atlas V 400 and 500 series. (Graphic Courtesy of the Wiki Global Commons)

10 Boeing CST 100 Starliner with Delta 4, Atlas V, Falcon High Thrust, and Vulcan Launchers

(Graphic courtesy of NASA)

This capsule with is a modified version of the Orion capsule that is somewhat smaller in size is also designed to be compatible with Delta 4 (scheduled to be phased out due to high cost), Atlas V, Falcon High Thrust, and new Vulcan Launcher.

Boeing CST 100 Starliner

Manufacturer: Boeing
Country of origin: United States
Operator: Boeing
Applications: Crew Transfer Vehicle
Specifications
Spacecraft type : Crewed Capsule
Design life: 60 hours (free flight)
210 days (docked)
Launch mass 13,000 kg (29,000 lb)
Crew capacity 7
Dimensions
Diameter (CM): 4.56 m (15.0 ft
Length (CM+SM): 5.03 m (16.5 ft)
Volume: 11 m^3 (390 cu ft)
Operational: 2019

Capable of carrying small sats to the ISS for Deployment in Orbit. The Boeing CST-100 Starliner (Crew Space Transportation) crew capsule was developed under NASA's Commercial Crew Development (CCDev) program. Its primary purpose is to transport crew to the International Space Station (ISSand to private space stations such as the proposed Bigelow Aerospace Commercial Space Station. **ompatible with four launch vehicles: Atlas V, Delta IV, Falcon 9, and Vulcan. It can carry supplies to the ISS and small satellites to the ISS for launch.**

Sources:
https://space.skyrocket.de/doc_sdat/cst-100.htm
https://en.wikipedia.org/wiki/Boeing_CST-100_Starliner

11 Dnepr Launch Vehicle

Dnepr Vehicle Launch

(Graphic Courtesy of Global Commons)

Background Notes: This vehicle is now Retired from service.

Dnepr Orbital Carrier Rocket

Manufacturer: Yuzhnoye (design), Yuzhmash (manufacturing), Khartron (control system)

Country of Origin: Soviet Union (original build), **Ukraine (commercial launches after 1999)**

Cost per launch: US$29 million

Height 34.3 meters (113 ft)

Diameter 3 meters (9.8 ft)

Mass 211,000 kilograms (465,000 lb)

Stages 3

Capacity

Payload to LEO:4,500 kilograms (9,900 lb)

Payload to the ISS: 3,200 kilograms (7,100 lb)

Payload to SSO 2,300 kilograms (5,100 lb)

Status Retired

Launch sites: Baikonur, LC-13, Yasny

This launch vehicle was reconfigured from an earlier missile system used for military purposes.

Sources: http://www.russianspaceweb.com/dnepr.html https://en.wikipedia.org/wiki/Dnepr_(rocket)

12 Dream Chaser Space Plane

Artist Image of what the Sierra Nevada Corp Dream Chaser would look like mated to the ISS (Graphic Courtesy of Sierra Nevada Corp.)

Background notes: In January 2016, NASA announced that SN's Dream Chaser had been awarded one of the contracts under the Cargo ReSupply 2 program and committed to six Dream Chasers for this purpose. This is called the Dream Chaser Cargo System.
This latest version of the Dream Chaser Cargo features an expendable cargo portion and also has solar array panels to supply power. It is also capable of returning 1,750 kg (3,860 lb) of cargo to Earth. It could be uprated to return crew from the ISS. The Dreamer Chaser lost out to SpaceX and Boeing for the crewed version

Dreamchaser Space Plane and Cargo Resupply to ISS

Manufacturer Sierra Nevada Corporation

Related spacecraft: Derived from NASA developed HL-20 Personnel Launch System

Hybrid Fueling System: Original version developed using a polymide fuel with nitrous oxide oxidizer as developed by Pioneering space developer Benson of Orbitec . Sierra Nevada Corporation developed its own new polymide fuel after acquiring Orbitec, but has kept nitrous oxide as system oxidizer.

Other Missions:

1. Mission for U.N. Office of Outer Space Affairs for orbital experiments in conjunction with non-space-faring nations.

2. The DC4EU (Dream Chaser for European Utilization), this project is studying using it for sending crews and cargo to the ISS and on missions not involving the ISS, particularly in orbits of substantially greater altitude than the ISS can reach.

3. Stratolaunch and Dream Chaser: This would be a 75% scaled version of the Dream Chaser for commercial missions.

4. Hubble Telescope Service Mission. This is a project under study by NASA but not funded.

Sources:

http://spaceref.com/news/viewpr.html?pid=44072

https://en.wikipedia.org/wiki/Dream_Chaser

13 Electron Launch Vehicle

Electron Launcher at N.Z. Launch Site (Graphic courtesy of Rocket Labs)

Mahia Launch Center New Zealand (Graphic Courtesy of Rocket Labs)

Background Notes: This is one of the most trend setting of the new small launcher ventures. Its many innovations include: the 3D printing of the Rutherford launch engines, it has an unique electric-pump-fed engine (a first), the rockets are fabricated from a light-weight carbon-composite materials. The 3-D printing of the engines saves both time and money. The new plant that Rocket Labs has now opened is producing rocket engines with high efficiency that could support a large number of launches a year if there is sufficient market demand.

Electron Small Launch Vehicle	
Function	Orbital launch vehicle
Manufacturer	Rocket Lab
Country of origin	United States and New Zealand
Cost per launch	About US $6 million
Height	17 m (56 ft)
Diameter	1.2 m (3 ft 11 in)
Mass	12,500 kg (27,600 lb)
Stages	2–3
Capacity	
Payload: 500km Sun-Synchronous orbit: 150–225 kg (330–495 lb)	
Associated rockets	
Comparable: Vector and Launcher One.	
Status	Active
Launch sites: Mahia LC-1 N.N.(active) Mid Atlantic (MARS) planned	
Total launches	4 Successes: 3 Failures : 1 on 1st Test
First flight	25 May 2017
Last flight	16 December 2018
<u>First stage</u>	
Diameter	1.2 m (3 ft 11 in)
Engines	9 × Rutherford
Thrust	Sea level: 162 kN (36,000 lbf)[6]
	Vacuum: 192 kN (43,000 lbf)
Specific impulse	303 seconds (2.97 km/s)
Fuel	RP-1/LOX
<u>Second stage</u>	
Diameter	1.2 m (3 ft 11 in)
Engines	1 × Rutherford
Thrust	Vacuum: 22 kN (4,900 lbf)
Specific impulse	333 seconds (3.27 km/s)
Fuel	RP-1/LOX
<u>Third stage (optional)</u>	
Engines	1 × Curie[8]
Thrust	Vacuum: 0.12 kN (27 lbf)[8]
Fuel	unspecified "green" monopropellant

Sources: https://www.rocketlabusa.com/vehicle/electron/
https://en.wikipedia.org/wiki/Electron_(rocket)

14 Falcon 9 Lifts Off from Kennedy Space Center

Falcon 9 Launch May 2018, Kennedy Space Center-LC-39A with the Bangabandhu-1 satellite (graphic courtesy of SpaceX)

Falcon Rocket Family

From left to right:

Falcon 9 v1.0, v1.1, Full Thrust, Block 5, and Falcon Heavy. The Falcon Heavy is similar to the Atlas V Heavy and Delta 4 Heavy in lift capability. The Falcon family of rockets are all priced significantly below other launchers of similar lift capacity. The ability to recover and reuse the first stage of the Falcon rockets is expected to cost further.

SpaceX's Falcon 9 Block 5 Rocket

Function Orbital launch vehicle

Manufacturer SpaceX

Country of origin United States

Approx. Cost per launch: $50M to $65M (2018)

Height: Full Thrust: 70 m (230 ft)
v1.1: 68.4 m (224 ft)
v1.0: 54.9 m (180 ft)

Diameter: 3.7 m (12 ft)

Mass
Full Thrust FT: 549,054 kg (1,210,457 lb)
v1.1: 505,846 kg (1,115,200 lb)
v1.0: 333,400 kg (735,000 lb)

Stages: 2

Capacity

Payload to LEO (28.5°)
Full Thrust (FT): 22,800 kg (50,300 lb)
v1.1: 13,150 kg (28,990 lb)
v1.0: 10,450 kg (23,040 lb)

Payload to GTO (27°)
Full Thrust (FT): 8,300 kg (18,300 lb)
v1.1: 4,850 kg (10,690 lb)
v1.0: 4,540 kg (10,010 lb)

Launch Sites:
Cape Canaveral SLC-40
Kennedy Space Center LC-39A
Vandenberg SLC-4E
Boca Chica

First Stage Engines
FT: 9 Merlin 1D+
v1.1: 9 Merlin 1D
v1.0: 9 Merlin 1C

Second Stage Engines
FT: 1 Merlin 1D Vacuum+
v1.1: 1 Merlin 1D Vacuum
v1.0: 1 Merlin 1C Vacuum

Sources:
https://web.archive.org/web/20101222155322/
http://www.spacex.com/falcon9.php

15 HIIA Japanese Launch Vehicle

HIIA Launcher at Tanegashima (Graphic courtesy of JAXA)

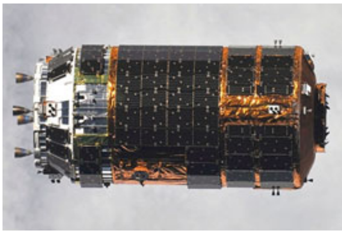
Background Notes

Mitsubishi who handles the commercial launch of the Japanese HII, HIIA, HIIB Launch Vehicles has a launch alliance agreement with Arianespace and Boeing to provide backup arrangements In the event of a need for an earlier launch.

HII , HIIA, HIIB Japanese Medium-lift launch vehicles

Manufacturer: Mitsubishi Heavy Industries (prime)
Northrop Grumman-Orbital ATK (sub)
Country of origin: Japan
Cost per launch: US$90 million
Height 53 m (174 ft)
Diameter: 4 m (13 ft)
Mass 285,000–445,000 kg (628,000–981,000 lb)
Stages: 2 plus 2 to 4 solid rocketer boosters
Payload to LEO 10,000–15,000 kg (22,000–33,000 lb)
Payload to GTO 4,100–6,000 kg (9,000–13,200 lb)
Status Active
Launch sites Tanegashima LA-Y
Success by version: 202 version: 26; **204 version**: 4; **2022 version:** 3
2024 version: 6
Recent Failures of 2024 version: 1
First flight by version: 202: 29 Aug. 2001; **204**: 18 Dec. 2006
2022: 26 Feb. 2005; **2024**: 4 Feb. 2002
Boosters (All variants) – SRB-A
No. boosters 2–4
Thrust of booster: 2,260 kN (510,000 lbf)
Total thrust 4,520–9,040 kN (1,020,000–2,030,000 lbf)
Specific impulse: 280 seconds (2.7 km/s)
Burn time 120 seconds
Fuel: HTPB
Boosters (2022 / 2024) – Castor 4A-XL
No. Solid Boosters 2–4
Thrust 745 kN (167,000 lbf)
Total thrust 1,490–2,980 kN (330,000–670,000 lbf)
Specific impulse: 280 seconds (2.7 km/s)
Burn time: 60 seconds
First stage: Engines : 1 LE-7A **Fuel** LOX / LH2
Thrust 1,098 kN (247,000 lbf)
Burn time: 390 seconds
Second stage: Engines: 1 LE-5B **Fuel** LOX / LH2
Sources:
https://web.archive.org/web/20080228013323/http://www.jaxa.jp/pr/brochure/pdf/01/rocket01.pdf
https://en.wikipedia.org/wiki/H-IIA

16 HII Transfer Vehicle



(Graphics Courtesy of JAXA)

The Japanese Name for the HTV is Kounotori which means White Stork. It is approximately the size of a sight-seeing bus. It has made only minimal trips to the ISS since its development by JAXA.
As of 2015 Japan began a process to Replace the HTV with the HTV-X transfer vehicle. It was designed to carry 6 tons of supplies to the ISS. It is incinerated in the Earth's atmosphere after it leaves the space station.

As part of the agreement to extend the lifetime of the ISS to 2024 there is an agreement to develop the HTV-X as well as a possible return capsule as well.

HII Transfer Vehicle of Japan

Role: Automated cargo spacecraft to resupply the International Space Station. Provides supplies but does not support crew or human passengers.
Crew: None
Dimensions
Height: ~9.8 m (including thrusters)[1]
Diameter: 4.4 m[1]
Spacecraft Mass: 10,500 kg
Total Launch Payload: 6,000 kg/ 6,200 kg
Pressurized Payload: 5,200 kg
Unpressurized Payload: 1,500 kg / 1,900 kg (HTV-6 -
Return Payload: None
Mass at launch: 16.5 ton
Pressurized Volume: 14 m^3

Comparable Transfer Vehicles: European Automated Transfer Vehicle (ATV), Soyuz, Cygnus Capsule**. The Dragon Capsule by Space X and the CST-100 Starliner by Boeing can perform similar functions but these later two capsules/transfer vehicles are designed to support crew as well.**

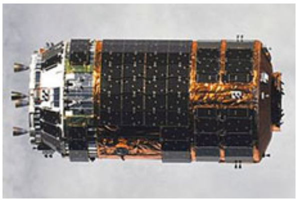
Performance and Endurance: Solo flight about 100 hours, stand-by more than a week, docked with the ISS about 30 days.

Apogee: 460 km
Perigee: 350 km
Inclination: **5**1.6 degrees

Sources:
https://web.archive.org/web/20101116044853/http://www.jaxa.jp/projects/rockets/htv/design_e.html

https://en.wikipedia.org/wiki/H-II_Transfer_Vehicle

17 H2 Transfer Vehicle of Japan



H2 Transfer Vehicle (Graphic Courtesy of NASA)

Background Notes: This H2 transfer Vehicle is being upgraded with HTV-6 To carry an additional 400 kg of unpressurized payload . This like the European ATV does not carry crew. This vehicle can carry microsats and cubesats to the ISS for redeployment via various systems such as Nanoracks and JEM (Kibo) deployment systems. The Japanese name for the H2 Transfer Vehicle is "Kounotori" which means White Crane a name picked by the citizenry of Japan.

H2 Transfer Vehicle of JAXA of Japan

Role: Automated cargo spacecraft to resupply the International Space Station

Crew: None. Expendable vehicle **on return flight from ISS**

Dimensions

Height:	9.8 m (including thrusters)
Diameter:	4.4 m
Spacecraft Mass:	10,500 kg
Total Launch Payload:	6,000 kg / 6,200 kg
Pressurized Payload:	5,200 kg
Unpressurized Payload:	1,500 kg / 1,900 kg (HTV-6)
Return Payload:	None, but can be used to cispose of trash.
Mass at launch:	16.5 ton
Pressurized Volume:	14 m3[

Performance

Endurance: Solo flight about 100 hours, stand-by more than a week, typically docked with the ISS about 30 days

Apogee:	460 km
Perigee:	350 km
Inclination:	51.6 degrees

Sources: https://web.archive.org/web/20101116044853/http://www.jaxa.jp/projects/rockets/htv/design_e.html
https://en.wikipedia.org/wiki/H-II_Transfer_Vehicle

18 Indian Space Research Organization. Polar Satellite Launch Vehicle ISRO/PSLV

The PSLV CA Launcher on Pad (Graphic courtesy of ISRO)

PSLV Medium Lift launch system

Manufacturer: ISRO

Country of origin: India

Cost per launch: $21-31 million

Height 44 m (144 ft)

Diameter 2.8 m (9 ft 2 in)

Mass **PSLV-G**: 295,000 kg (650,000 lb)

PSLV-CA: 230,000 kg (510,000 lb)

PSLV-XL: 320,000 kg (710,000 lb)[2]

Stages 4

Payload to LEO:3,800 kg (8,400 lb)[3]

Payload to SSO: (620 km)1,750 kg (3,860 lb)

Payload to Sub-GTO: 1,425 kg (3,142 lb)

Payload to GTO: 1,200 kg (2,600 lb)[4]

Status: PSLV G, PSLV-C A , PSLV-XL & PSLV-DL all active

Launch sites Sriharikota

Total launches 46

Successes 43

Failures: 2 **Partial failures**: 1

First flight: PSLV-G: 20 Sept. 1993; PSLV-CA: 23 April 2007; PSLV-XL: 22 October 2008; PSLV-DL: 24 January 2019

PSLV-G Key Characteristics: 6 boosters of S9 type

Thrust 510 kN (110,000 lbf)

Burn time 44 seconds

Fuel HTPB

Thrust 703.5 kN (158,200 lbf)

PSLV-XL Key Characteristics: 6 boosters of S12 type

Thrust 703.5 kN (158,200 lbf)

Burn time 70 seconds

Fuel HTPB

PSLV-DL) Key Characteristics: This is a 4 stage rocket with fuels for the 4 stages as follows:

Stage 1] Solid S139 Rocket Engine: **Fuel**: HTPB

Stage 2: Vikas Liquid Engine **Fuel:** N2O4/UDMH

Stage 3: HTPB Solid Rocket engine

Stage 4: 2-PS-4 liquid Engines **Fuel :** MMH/MON

Sources: https://www.isro.gov.in/launchers/pslv
https://en.wikipedia.org/wiki/Polar_Satellite_Launch_Vehicle

19 International Space Station-Japanese Experiment Module SmallSat Deployment and NanoRacks

ISS/JEM Cubesat/Microsat Deployment Systems (Graphic courtesy of JAXA)

Background Notes: There are three ways that space experiments or small satellite deployments can be accom-plished via the International Space Station (ISS) that have be designed and implemented by Nanoracks of Houston, Texas. 1. One system is for on-board experiments that are flown up to the ISS on resupply transport vehicles. These are installed on the Nanoracks experimental system that can be attended to by Astronauts. There are many programs to support student participation in such space experiments such as National Center for Earth and Space Science Education (NCESSE) and the Arthur C. Clarke Institute for Space Education. 2. The second method is to qualify cubesats (up to 6 U cubesats) that are deployed via the Nanoracks External Platform for cubesat release. 3. The third way is the Kaber Reusable Microsat Deployment system developed by Nanoracks that can deploy up to 1 meter micro-sats up 82 Kg in size like "Remove DEBRIS" that was developed the Surrey Space Centre.

JEM (Kibo) Small Sat Deployment Systems
This is the largest module on the International Space Station. Kibo in Japanese means hope.
Pressurized module
Length: 11.19 m (36.7 ft)
Diameter: 4.39 m (14.4 ft)
Mass: 15,900 kg (35,100 lb)

Experiment logistics module
Length: 4.21 m (13.8 ft)
Diameter: 4.39 m (14.4 ft)
Mass: 8,386 kg (18,488 lb)

Exposed Facility: This is also known as "The Terrace" It is equipped with an airlock and 12 experimental stations, 8 of which are replaceable.

Current Experiments in progress:
NREP: Nanoracks External Platform (for Cubesat Deployment)
MAXI: X-ray Astronomy
ICS-EF: Inter-orbital Communications System
CALET: Electron Telescope
CREAM: Cosmic Ray Energetics
ECOSTRESS: Ecosystem Radiometer
GEDI: Global Ecosystem Dynamics

JEM Remote Manipulator System (JEMRMS)
This is robot system intended for operation in space. It is attached to the Pressurized Module (PM). JEMRMS is utilized for experiments being conducted on JEM and to launch microsats (up to 1 meters In size from the Nanoracks Kaber system.

Sources:
https://web.archive.org/web/20090310171550/http://kibo.jaxa.jp/en/about/
https://en.wikipedia.org/wiki/Kibo_(ISS_module)#Exposed_facility

20 Launcher One

'Cosmic Girl' Carrier Vehicle on Test Run

(Graphic courtesy of Virgin Orbit)

Background Notes: The Launcher One and Virgin Orbit enterprise by Sir Richard Branson has evolved over time. The start of this project began with the SpaceShipOne Xprize contest with Burt Rutan, Paul Allen and Richard Branson were involved and the effort to create SpaceShipTwo to fly 'space tourists' or more correctly 'spaceadventurers' on sub-orbital flights. The development's cost and business plan has suggested that additional business was needed to sustain a longer term profitability. The result was to create a "Launcher One" vehicle to lift small satellites to orbit. Originally the. White Knight carrier vehicle was to be used for its air launch, but the larger carrier is now to be used to increase Launcher One's payload. Launcher One has been booked for OneWeb launches and NASA has also contracted for launches.

Launcher One-Air Launched Orbital Rocket

Manufacturer	**Virgin Orbit**
Country of origin:	**United States/ United Kingdom**
Cost per launch	**$10 million - $12 million**
Height	**16 m (52 ft)**
Stages	**2 with optional 3**
Payload to 500 km SSO:	**300 kg (660 lb)**
Payload to 230 km SSO	**500 kg (1,100 lb)**
Associated rockets	
Comparable	**Electron, Vector-H**
Launch history	
Status	**In development**
Launch sites	
	Mojave Air & Space Port, California
	Kennedy Space Center, Florida
	Cornwall Airport Newquay, England
	Ellison Onizuka Kona, Hawaii
First stage	
Diameter	**1.6 m (5 ft 3 in)**
Engines:	**NewtonThree (N3)**
Thrust in Vacuum:	**327 kN (74,000 lbf)**
Burn time:	**180 sec**
Fuel	**Kerosene/LOX**
Second stage:	
Diameter:	**1.3 m (4 ft 3 in)**
Engines	**NewtonFour (N4)**
Thrust	**Vacuum: 22 kN (4,900 lbf)**
Burn time:	**360 sec**
Fuel:	**Kerosene/LOX**

Sources:
http://www.spacelaunchreport.com/launcherone.html
https://en.wikipedia.org/wiki/LauncherOne

21 Long March 5 Launch Vehicle

A Long March 5 Launch Vehicle in Transit to Pad (Graphic Courtesy of CNSA)

A discussion of the Long March launch vehicle family is presented in the following two pages including information on Long March 6,7, 8 and 9.

Long March 5 Heavy orbital launch vehicle

Manufacturer: CALT (Chinese Academy of Launch Technology
Country of origin: China
Height 57 m (187 ft)
Diameter 5 m (16 ft)
Mass 867,000 kg (1,911,000 lb)
Stages 2 plus 4 boosters
Payload to LEO: (200 km × 400 km × 42°) 25,000 kg (55,000 lb)
Payload to GTO: 14,000 kg (31,000 lb)
Payload to TLI 8,200 kg (18,100 lb)
Associated comparable rockets: Ariane 5 Delta IV Heavy, Falcon Heavy New Glenn, Proton-M, Vulcan
Launch Status : Active: 5 launches through 2019 with 1 failure
Launch sites Wenchang LC-1
First flight 3 November 2016
Boosters : 4 of CZ-5-300 type
Length 27.6 m (91 ft)
Diameter 3.35 m (11.0 ft)
Gross mass/Propellant: 155,700kg (343,300 lb) 144,000kg (317,000 lb)
Total thrust **9,600 kN (2,200,000 lbf)**
Burn time 180 seconds **Fuel:** RP-1/LOX
First stage – CZ-5-500
Length 31.7 m (104 ft)
Diameter 5 m (16 ft)
Gross mass/Propellant: 175,600kg (387,100lb) / 158,300 kg (349,000lb)
Engines: 2 × YF-77
Burn time: 480 seconds **Fuel** LH2/LOX
Second stage – CZ-5-HO
Length 10.6 m (35 ft)
Diameter 5 m (16 ft)
Gross mass/Propellant: 22,200kg (48,900lb) /17,100 kg (37,700l
Engines: 2 × YF-75D
Thrust: 176.52 kN (39,680 lbf)88.26
Burn time: 700 seconds **Fuel** LH2/LOX
Third stage – YZ-2(Optional)
Diameter 3.8 m (12 ft)
Engines: 2 x YF-50D
Thrust 6.5 kN (1,500 lbf)
Burn time 1105 seconds **Fuel** N2O4/UDMH
Sources:https://web.archive.org/web/20161224185459/http://spaceflightnow.com/launch-schedule/
https://en.wikipedia.org/wiki/Long_March_5

22 Long March Family for the Long March 2, Long March 3, and Long March 4

The Chinese space program has discontinued its Long March 1, but it now has a full range of launch options that are pictured or described below. The chart immediately shows the Long March 2A, 2C, 2D, 2E, and 2F; Long March 3, 3A, 3B, and 3C; and Long March 4A, 4B, and 4C. The Long March 5, 6, and 7 are the newest Chinese launch vehicles developed since 2015, and the Long March 8 and Long March 9 are currently only in the planning stages.

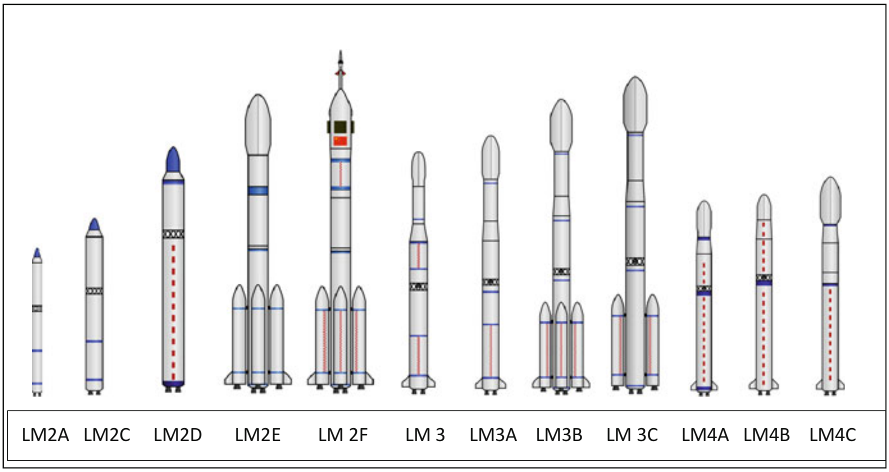


Chart below shows the relative size of various Long March vehicles in series 2, 3, and 4. (Graphic courtesy of the Wikipedia Commons)

23 Long March 6, 7, 8, and 9

There is currently also just a single version of the Long March 5 which is China's heavy-lift vehicle, as described in the page above. In addition there are also the **Long March 6** and *Long March 7*. These are smaller vehicles than the Long March 5 heavy lift.

A detailed description of the characteristics of the Long March 6 which can lift a payload of 1080 kgs to 700 KM sun-synchronous orbit can be found at https://archive.is/20150918112832/http://www.spaceflight101.com/long-march-6.html and at: https://en.wikipedia.org/wiki/Long_March_6.

The details of the characteristics of the Long March 7 launch vehicle which can lift a payload or 13,5000 kg to low Earth orbit (LEO) can be found at http://sinodefence.com/cz-7/ and at https://en.wikipedia.org/wiki/Long_March_7.

Future plans call for a Long March 8 that will be medium-lift vehicle to launch spacecraft to sun-synchronous orbit (SSO) but which will be partially reusable by reclaiming the first stage. The Long March 9 is for launch at the super heavy-lift stage and is comparable to the US Space Launch System (SLS). The comparison of super heavy-lift launch vehicles in the Figure below allows a comparison of the Long March 9 and the Space Launch System rocket.

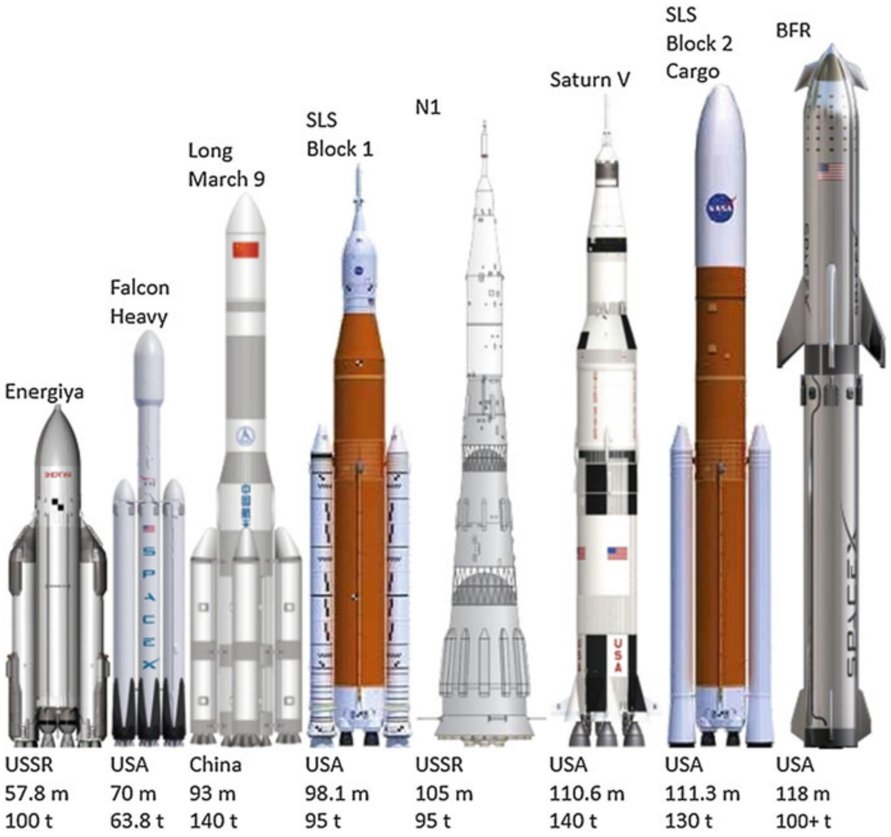


Figure showing the comparative sizes of super heavy-lift rockets from around the world. (Graphic courtesy of the Wikipedia Commons)

24 Minotaur II

MinotaurII Launcher in Flight

(Graphic courtesy global commons)

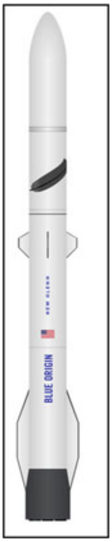
Background Notes*:* This vehicle is Based on a converted solid fueled And decommissioned Minuteman Missile. This was originally developed by Orbital Science-ATK which is now know as Northrop Grumman Innovation Systems. This system has also become the basis for the Antares launcher. This family of launchers ranges from the Minotaur I to V. The Minotaur II And III are suborbital. The Minotaur IV and V, with an Orion, 3rd stage can launch to LEO orbit.

Minotaur I, II, III, IV, and V Launch Systems

Function Suborbital and LEO launch systems
Manufacturer Northrop Grumman Innovation Systems
Country of origin: United States
Height: 19.21 metres (63.0 ft)
Diameter: 1.67 metres (5 ft 6 in)
Mass: 36,200 kilograms (79,800 lb)
Stages: 2 or 3
Capacity
Payload to 8000km S/O400 kilograms (880 lb)
Launch history
Status: Active
Launch sites: Vandenberg LF-06
Total launches: 8
Successes 8
First flight 28 May 2000
First stage : M55E1
Engines: 1 Solid
Thrust: 935 kilonewtons (210,000 lbf)
Fuel: Solid
Second stage – SR19AJ1
Engines: 1 Solid
Thrust: 268 kilo-newtons (60,000 lbf)
Fuel Solid
Third stage (Baseline) – M57A1
Engines 1 Solid
Fuel Solid
Third stage (Minotaur II+) – SR-73-AJ
Engines: 1 Solid
Fuel: Solid
Third stage (Heavy): – Orion 50XL
Engines: 1 Solid
Thrust: 118.2 kilonewtons (26,600 lbf)
Burn time: 74 seconds
Fuel Solid for Minotaur 1 and II Launch Vehicle

Sources:
https://web.archive.org/web/20090508113707/http://www.astronautix.com/lvs/minotaur.htm
https://en.wikipedia.org/wiki/Minotaur_II

25 New Glenn Launcher



(Graphic courtesy of Blue Origin)

Background Notes: The Jeff Bezos owned Blue Origin company is developing the New Glenn heavy lift launcher, new liquid oxygen fueled Be-4 engines for the new Vulcan rocket to be marketed by ULA. It has its own spaceport in West Texas. The first stage of the New Glenn launcher is being designed for the potential of 100 reuses. Blue Origin is developing a smaller launch for sub-orbital flights.

New Glenn Launch Vehicle

Function: Partially reusable heavy orbital launcher
Manufacturer: Blue Origin
Country of origin: United States
Height 2-stage: 95 m (313 ft)
Diameter: 7 m (23 ft)
Capacity
Payload to LEO 45,000 kg (99,000 lb)
Payload to GTO 13,000 kg (29,000 lb)
Comparable associated rockets: Delta IV Heavy ,Falcon Heavy, Long March 5, Saturn C-3 Vulcan
Launch: Status In development
Launch sites: Cape Canaveral LC-36, Vandenberg Air Force Base
First stage
Diameter: 7 m (23 ft)
Engines: 7 × BE-4
Thrust 17.1 MN (3,850,000 lbf)
Fuel Methane / LOX
Second stage
Diameter: 7 m (23 ft)
Engines: 2 × BE-3U
Thrust: 980 kN (220,000 lbf)
Fuel: H2 / LOX

Note: Blue Origin is also developing new rocket engines to be used with the new Vulcan launcher. The first stage engines are reportedly being designed for re-use on up to 100 different launches.

Sources:

https://spacenews.com/bezos-not-concerned-about-competition-possible-ula-sale/
https://arstechnica.com/science/2017/03/blue-origin-releases-details-of-its-monster-orbital-rocket/
https://en.wikipedia.org/wiki/New_Glenn

26 Pegasus

Pegasus in flight after release from Lockheed 1011 Carrier Aircraft (Graphic courtesy NG Innovation)

Background Notes: This is a fairly expensive launch cost for a small payload capacity. This will have to compete with the offerings of Vector, Launcher One by Virgin Orbit, and Rocket Labs. The Pegasus XL played key role in the launch and deployment of the first generation of the Orbcom store-and-forward small satellite constellation.

Pegasus Launch Vehicle

Manufacturer: Northrop Grumman
Function: Launch vehicle
Country of origin: United States
Cost per launch: US$40 million
Height 16.9 meters (55 ft) (Pegasus)
17.6 meters (58 ft) (Pegasus XL)
Diameter: 1.27 meters (4.2 ft)
Mass: 18,500 kilograms (40,800 lb) (Pegasus)
23,130 kilograms (50,990 lb) (Pegasus XL)
Stages: 3. Solid rocket engines developed by Alliant.
Payload to LEO 443 kilograms (977 lb)
Payload dimensions: 1.18 by 2.13 meters (3.9 ft × 7.0 ft)
Derivatives: Taurus and Minotaur-C
Comparable launchers: Launcher One and Vector
Launch history: Early launch failures but after early 40% failures there has been high reliability.
Status: Pegaus XL Still Active
Launch sites: Air launch to orbit via Lockheed 1011 aircraft
Total launches: 43 Successes: 38 Failures: 3 Partial failures: 2
First flight: 5 April 1990 (Pegsat / NavySat)

Note on Pegasus Special Advantage: For many small satellite launchesit is desirable to be the primary payload and thus be placed directly into the desired orbit. This is not possible when launched as a secondary payload and thus being placed in a compromise orbit. The ability to launch from the equator region can avoid the high radiation levels of the South Atlantic Anomaly and place small satellites into equatorial LEO orbits more efficiently.

Sources:
https://web.archive.org/web/20160113130631/
https://www.orbitalatk.com/flight-systems/space-launch-vehicles/pegasus/docs/Pegasus_UsersGuide.pdf
https://en.wikipedia.org/wiki/Pegasus_(rocket)

27 Proton

Proton Launch Vehicle in Flight (Courtesy of Roscosmos)

Background Notes: The Proton is a well proven vehicles with 91 successful flights. Its heavy lift capability and low relative cost makes it competitive. It has been primarily to launch communication satelites to Geosynchronous orbit. The latest version of the Proton M is the Phase IV Proton Briz-M has allowed a payload increase to 6320 kg to a reference GTO orbit with 1500 m/s of residual boost to achieve GSO. This rocket is considered comparable to Atlas 5 Heavy, Delta 4 Heavy, Ariane 5, HIIB, and the Falcon 9 Full Thrust. As of June, 2018 this family of rockets is being discontinued and is to be replaced with the Angara 5.

Proton Heavy-lift launch vehicle

Manufacturer Khrunichev
Country of origin: Russia
Cost per launch: US$65 million
Height 58.2 m (191 ft)[2]
Diameter 7.4 m (24 ft)
Mass 705,000 kg (1,554,000 lb)[2]
Stages 3 or 4
Capacity
Payload to LEO[a] 23,000 kg (51,000 lb)[3]
Payload to GTO 1800 m/s[b] 6,920 kg (15,260 lb)[3]
Payload to GTO 1500 m/s[c] 6,300 kg (13,900 lb)[4]
Payload to GSO[d] 3,250 kg (7,170 lb)[3]
Associated rockets
Family Universal Rocket
Comparable: Ariane , Atlas V 551, Delta IV Heavy, Falcon Full Thrust, H-IIB, Long March 5
Status Active
Launch Sites: Baikonur Site 81/24 & 200/39
Total launches: 102 Successes: 91 Failures: 9 Partials: 2
First flight: 7 April 2001
1st Stage: Length: 21.18 m (69.5 ft) Diameter: 7.4 m (24 ft)
Empty mass: 30,600 kg (67,500 lb)
Propellant mass: 428,300 kg (944,200 lb)
Engines: 6 RD-275M Burn time: 108 sec
Fuel N2O4 / UDMH
Second stage: Length: 17.05 m (55.9 ft)
Diameter: 4.1 m (13 ft)
Empty mass: 11,000 kg (24,000 lb)
Propellant mass: 157,300 kg (346,800 lb)
Engines: 3 RD-0210 1 RD-0211 Burn time: 206 sec
Fuel N2O4 / UDMH
Third stage: Length 4.11 m (13.5 ft)[7]
Diameter 4.1 m (13 ft)[7]
Empty mass: 3,500 kg (7,700 lb)[7]
Propellant mass 46,562 kg (102,652 lb)[7]
Engines 1 RD-0212 Burn time 238 sec
Fuel N2O4 / UDMH
Fourth stage (optional) – Briz-M or Blok DM-2 or Blok DM-03

Sources: http://www.khrunichev.ru/main.php?id=54
https://en.wikipedia.org/wiki/Proton_(rocket_family)

28 Rokot or Rockot Launch Vehicle

Rockot in Launch Flight
(Graphic courtesy of Eurockot)

Backgroun Notes: ROCKOT (meaning 'boom' in Russia) is a three stage liquid propellant launcher largely based on the Russian SS-19 Intercontinental Ballistic Missile which provides Rockot with its first and second stages. The SS-19 has flown over 150 times with only 3 failures. The Breeze-M third stage allows a 2140 kg payload to be launched to LEO orbit. Arianespace is the partner in the Eurockot partnership with the Russian company Khrunichev. The Rockot version with a Ukrainian control system is to stop flying after 2019, due to the Ukrainian ban on technology exports to Russia. A full Russian-made Rockot-2 light carrier rocket may begin flying again in 2021

Rokot Orbital Carrier Rocket
Manufacturer: Eurockot Launch Services,
Country of origin Soviet Union
Cost per launch US$41.8 million[1]
Size
Height 29 metres (95 ft)
Diameter 2.5 metres (8 ft 2 in)
Mass 107,000 kilograms (236,000 lb)
Stages: 3
Payload to LEO 1,950 kilograms (4,300 lb)
Payload to SSO 1,200 kilograms (2,600 lb)
Status Active
Launch sites Baikonur 175/1 & Plesetsk 133/3
Total launches 32
Successes 29
Failures : 2 Partial failures: 1
First flight: 20 Nov. 1990 26 Dec1994 (orbital)
First stage
Diameter: 2.5 m (8.2 ft)
Engines: 3-RD-0233 (15D95)
1 RD-0234(15D96)
Thrust 2,080 kN (470,000 lbf)
Burn time 120 seconds
Fuel N2O4 / UDMH
Second stage
Diameter: 2.5 m (8.2 ft)
Engines 1 RD-0235 (15D113)
1 RD-0236 (15D114)[2][3]
Thrust 255.76 kN (57,500 lbf)
Burn time: 180 seconds
Fuel N2O4 / UDMH
Third stage – Briz-KM
Engines: 1-S5.98M
Thrust: 19.6 kilonewtons (4,400 lbf)
Burn time: 3,000 seconds
Fuel: N2O4 / UDMH

Sources:
https://www.eurockot.com/rockot/launch-vehicle/
https://en.wikipedia.org/wiki/Rokot

29 Soyuz

(Grpahic from Global Commons)

Soyuz 2 is used for commercial launches and is marketed by Arianespace and is launched from the Kourou launch site in Guiana as well as the Angara. See illustration above under Angara to see possible configurations for minisatellites launces on both the Soyuz and Angara. The Soyuz 2 can be booked with the ST fairing and Starsem configuration for $80 milliion per launch.

Soyuz Launchers

Soyuz: A Russian family of expendable launch systems developed by OKB-1 and manufactured by TsSKProgress Rocket Space Centre in Samara, Russia. There have been over 1700 flights of this launcher since its debut in 1966. It has been redesigned and upgraded many times since the 1960s. The Soyuz is the most frequently used launch vehicle in the world. It has an outstanding reliability record, with over 98% reliability in its launches. This exceeds that of the Space Transportation System of the U.S. It is used to launch astronauts to the International Space Station until the U.S. Commercial Crew program is fully qualified as is expected soon.

Country of Origin: Russia/USSR
First flight: November 28, 1966
Stages: 3
Key Vehicles: Soyuz U (retired in 2017), Soyuz FG. Soyuz 2
Type of Fairings for Commercial Flights: A-type or S Type
Type S dimensions: 3.7 m x 7.7m
Type ST with Starsem and Soyuz 2: 4.1 m x 11.7m
Rocket it was Derived from: Vostok
Function: Launch vehicle
Manufacturers: Energia, Progress Rocket Space Centre
Launch sites: Kourou (for Soyuz 2) , Ensemble de Lancement Soyouz, Vostochny Cosmodrome Site 1S
Launcher Stages with dimensions, thrust and specific impulse are provided a sources below:

Sources:
https://en.wikipedia.org/wiki/Soyuz_(rocket_family)
Also see:
http://www.esa.int/Our_Activities/Human_and_Robotic_Exploration/Delta_Mission/Soyuz_launch_vehicle_The_most_reliable_means_of_space_travel

30 Vector Launch Vehicle (due to bankruptcy is not available)

Vector Launch on Pad

(Graphic Courtesy of Vector Space Systems)

https://vector-launch.com/vector-r/

Background Notes:

The Vector-R provides a 60kg payload capability that can be configured for a wide range of CubeSat and Small Satellite mission profiles. The Vector-R fairing is a traditional two-piece design that is of sufficient size to accommodate a wide range of deployment options for multiple smallsats. The R in Vector-R stands for rapid deployment.

Vector Family of Small Launchers

Cost of Launch : **2-3 Million USD**

Height 12 m

Diameter 1.2 m

Mass 5,000 kg

Stages 2/3

Capacity

Payload to LEO: 60 kg

Payload to SSO: 26 kg

Associated rockets

Family: Vector (rocket family)

Derivatives: Vector-H

Comparable: Electron, Falcon 1

<u>Launch history</u>

Status: 2 prototype launches

Launch sites: Pacific Spaceport Complex – Alaska

MARS Pad OB, Spaceport Florida Launch Complex 46

<u>First stage</u>

Diameter: 1.2 m (3 ft 11 in)

Engines: 3 X LP-1

Thrust 18,300 lbf (81,000 N)

Burn time: 143 seconds

Fuel Propylene / LOX

<u>Second stage</u>

Diameter .635 m (2 ft 1.0 in)

Engines 1 X LP-2

Thrust 1,000 lbf (4,400 N)

Burn time 433 seconds

Fuel Propylene / LOX

31 Vega and Vega C Small Launch Vehicle

(Graphic courtesy of ESA)

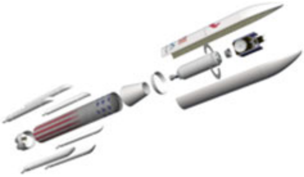
Vega can be configured to launch five 200 Kg minisats to Low Earth Orbit (LEO) and its HEXA 1 &2 adapter can accommodate many 'piggyback' options for nanosat/ picosat launches. Vega C is an upgraded version of Vega with 60% greater payload capability. A Vega Lite launcher is under active study that would be designed to compete with Rocket Labs and Virgin Orbit launchers.

Vega Small Lift Launch Vehicle

Manufacturer: European Launcher Development (ELD)/ Avio
Country of origin: Italy, European Space Agency/ELD
Cost per launch: US$37 million
Height 30 m (98 ft) **Diameter** 3 m (9.8 ft)
Mass 137,000 kg (302,000 lb)
Stages 4
Payload Polar Orbit(700km / inclination 90°) 1,430 kg (3,150 lb)
Payload SSO (400km) 1,450 kg (3,200 lb)
Associated rockets
Delta II 7420, Minotaur IV, Minotaur-C PSLV, Rokot Soyuz-2-1v
Status Active
Launch sites Guiana Space Centre ELV
Total launches 13 **Successes** 13
First flight: 13 Feb. 2012
First stage – P80
Length 11.7 m (38 ft) **Diameter** 3 m (9.8 ft)
Thrust 2,261 kN (508,300 lbf)
Specific impulse 280 s (2.7 km/s)
Burn time 110 s
Fuel HTPB (Solid)
Second stage – Zefiro 23
Length 8.39 m (27.5 ft) **Diameter** 1.9 m (6.2 ft)
Thrust: 871 kN (195,800 lbf)
Specific impulse: 287.5 s (2.819 km/s)
Burn time: 77 s
Fuel HTPB (Solid)
Third stage – Zefiro 9
Length 4.12 m (13.5 ft) **Diameter:** 1.9 m (6.2 ft)
Thrust 260 kN (58,450 lbf)
Specific impulse 296 s (2.90 km/s)
Burn time 120 s
Fuel: HTPB (Solid)
Upper stage – AVUM
Length 1.7 m (5.6 ft) **Diameter**: 1.9 m (6.2 ft)
Engines: 1 RD-843
Thrust 2.42 kN (544.0 lbf)
Specific impulse 315.5 s (3.094 km/s)
Burn time 667 s
Fuel UDMH / N2O4
Sources: https://en.wikipedia.org/wiki/Vega_(rocket) https://web.archive.org/web/20150923180829/http://www.avio.com/files/catalog/pdf/motore_p80_75.pdf

32 The Vulcan Centaur Rocket

By the United Launch Alliance



(graphic courtesy of United Launch Alliance)

Backgroud Notes: The Vulcan is under final development . The ACES is in design development and contains the concept of reusability of the first stage. The Vulcan-ACES Rocket is proposed for the 2020s

A simulated expanded view of the 562-configuration Vulcan Centaur rocket.

Function Partly-reusable launch vehicle
Manufacturer United Launch Alliance
Country of origin United States
Height 58.3 m (191 ft)
Diameter 5.4 m (18 ft)[1]
Mass 546,700 kg (1,205,300 lb)
Stages 2 stages plus 0 to 6 boosters
Capacity
Payload to LEO 34,900 kg (76,900 lb)[2] (Vulcan Heavy Centaur)
Payload to GTO 16,300 kg (35,900 lb)[2](Vulcan Heavy Centaur)
Payload to GEO 7,200 kg (15,900 lb)[2](Vulcan Heavy Centaur)
Launch sites: Cape Canaveral SLC-41
Vandenberg SLC-3E[3]
Projected First flight 2021 (planned)[4]
No. boosters 0–6
Motor GEM 63XL[5]
Thrust 2,201.7 kN (495,000 lbf)
Fuel for Boosters: HTPB 1st Stage: CH4 / LOX
2nd stage: LH2 / LOX (ACES proposed for Mid 2020s
First stage
Diameter
Engines: Two BE-4
Thrust 4,900 kN (1,100,000 lbf)
Fuel CH4 / LOX
Second stage – Centaur (initial flights, late-2010s)
Engines: Two RL10-C
Thrust: 207.6 kN (46,700 lbf)[citation needed]
Specific impulse: 448.5 seconds (4.398 km/s)
Fuel LH2 / LOX
Future Second Stage – ACES (proposed, mid-2020s)
Engine: BE-3 engine
Fuel LH2 / LOX
Source: (Accessed March 2019)
https://www.ulalaunch.com/docs/default-source/rockets/atlas-v-and-delta-iv-technical-summary.pdf
https://en.wikipedia.org/wiki/Vulcan_(rocket)

33 Zenit Launch Vehicle

Zenit Launcher on Pad
(Graphic courtesy of Sea Launch)

Background Notes: The Zenit 3F was Launched by Sea Launch until it ended Service. The Zenit 2 is launched from The Baikonur launch site. The failure **of a Zenit in the launch of an Intelsat** satellite in 2013, and the earlier failure of a Zenit in a launch of multiple Globalstar small satellites and the Closure of the Sea Launch operation that was based in San Diego in the U.S. have a major negative impact on the commercial use of this launcher.

Zenit Launch Vehicle

Function Medium-lift expendable carrier rocket
Manufacturer Yuzhnoye & Yuzhmash
Country of origin: Zenit-2: USSR Zenit-3SL: Ukraine, Russia
Height 57–59.6 m (187–196 ft)
Diameter 3.9 m (13 ft)
Mass 444,900–462,200 kg (980,800–1,019,000 lb)
Stages 2 or 3
Capacity
Payload to LEO Zenit-2: 13,740 kg (30,290 lb)
Payload to SSO Zenit-2: 11,380 kg (25,090 lb)
Payload to GTO Zenit-3SL: 6,000 kg (13,000 lb)
Status Active
Launch sites: Baikonur LC-45 Odyssey (ocean platform)
Total launches: 84
Zenit 2: 36 **Zenit 3SL:** 36 **Zenit 2M:** 2 3SLB: 6 **Zenit 3F:** 4
Successes: 71 **Failures:** 10 **Partial Failures:** 3
First flights: 1985 for Zenit 2 thru 2011 for Zenit 35F.

First stage
Engines: 1 RD-171 Thrusy: 8,180 kilonewtons (1,840,000 lbf)
Burn time 150 seconds **Fuel** RP-1 / LOX

Second stage
Engines 1 RD-120 &1 RD-8
Thrust 912 kilonewtons (205,000 lbf)
Burn time: 315 seconds **Fuel**: RP-1/LOX

Third stage (Zenit-3SL/3SLB) – Block DM-SL
Engines 1 RD-58M
Thrust 84,900 newtons (19,100 lbf) **Burn time** 650 seconds
Fuel RP-1 / LOX

Third stage (Zenit-3F) – Fregat-SB
Engines 1 - S5.92
Thrust 19,600 newtons (4,400 lbf)
Specific impulse : 327 seconds (3.21 km/s)
Burn time: 877 seconds
Fuel: N2O4 / UDMH

New launch systems from around the world seeking to develop new launch vehicle capabilities. (Courtesy of Paper by Carlos Niederstrasser, Northrop Grumman, 32nd Annual AIAA/Utah State University (AIAA/USU Conference on Small Satellites, 2018))

Launch vehicle development company or organization	Name of launch vehicle	Country of origin	Date seeking to offer services	URL for launch vehicle organization
ABL Space Systems	RS1 which is launched from truck-mounted launch systems from an FAA-licensed launch site	USA	Late 2020 or 2021. To launch up to 1200 kg to LEO. Batch and multi-manifest missions	https://www.ablspacesystems.com/
Aphelion Orbitals	Helios and Feynman Launch System. System to place 6 U cubesats in LEO at low cost	USA	2021	https://www.satellitetoday.com/innovation/2017/07/31/startup-aphelion-orbitals-secures-500000-seed-funding/
Bagaveev Corporation	Bagaveev. This is a 3D printed rocket motor. It is designed to place a 12 kg payload into LEO orbit. Pricing of $100 K per kg	USA	2019	https://mach5lowdown.com/2017/03/14/bagaveev-corp/
bspace	Volant: Hosted payloads launched on ARQ system to be launched to the International Space Station in 2020. $80 K for 1 U cubesat	USA	2020	http://www.bspacelaunch.com
Celestia Aerospace	Sagittarius Missile launched from a MiG 29 jet (known as Archer 1) to put 1 U nanosats into orbit at a cost of 200 k euros	Spain	2020–2021	https://medium.com/spacer/celestia-aerospace-a-company-that-is-planning-to-use-a-fighter-plane-
Chinese Aerospace Science and Technology Corporation (CASC)	Kaituozhe-1. No longer active	China	2002 to 2010 developed key concepts for other Chinese launchers	https://en.wikipedia.org/wiki/Kaituozhe_(rocket_family)

(continued)

Cloud IX	Cloud IX vehicle that is balloon launched that is seeking to develop a 22 kg to LEO orbit system at low cost	USA	Not currently known	http://www.cloudix.space/ https://spacenews.com/cloudix-joins-race-to-develop-small-rocket/
CONAE Comisión Nacional de Actividades Espaciales (National Space Agency of Argentina)	Tronador II. Liquid-fueled rocket to lift 250 kg payload to polar orbit. Launches from Puerto Belgrano Naval Base in Argentina	Argentina	2020 or 2021	https://en.wikipedia.org/wiki/Tronador_(rocket)
CubeCab	Cab-3A. Launch vehicle for just one 3 U cubesat. $250 K per launch. Bitcoin Latina has indicated it will launch 300 3 U sats for a LEO network to provide service to Latin America	USA	2020–2022	http://www.cubecab.com http://www.parabolicarc.com/2018/02/11/bitcoinlatina-foundation-cubecab-launch-300-satellite-network-support-bcl-blockchain/
Brazilian Departamento de Ciencia e Tecnologia Aeroespacial	VLM-1 (Microsatellite Launch Vehicle). Planned capability of 150 kg to LEO. CTA is the manufacturer	Brazil in cooperation with Germany (DLR)	2019	https://en.wikipedia.org/wiki/VLM_(rocket)
ESA	Space RIDER (Space Reusable Integrated Demonstrator for Europe Return). Space lifting body (reusable) and compatible with Vega C launcher	Europe Italian Aerospace Research Center (CIRA) and Thales Alenia Space	2022	https://www.esa.int/Our_Activities/Space_Transportation/Space_Rider
Firefly Aerospace	Firefly Alpha	USA	Not active	Now bankrupt and ceased operations
Gilmour Space Technologies	One Vision launcher (tests in 2019). Hybrid rocket engine. Scaled version of Ariel sounding rocket	Australia/ Singapore	Q4 2020	https://www.gspacetech.com/ https://www.gspacetech.com/single-post/2019/02/01/Gilmour-Space-unveils-One-Vision-rocket-ahead-of-suborbital-test-launch

(continued)

Horizon Space Technologies	Black Arrow 2	UK	Status unknown	https://www.seradata.com/horizon-space-technologies-announces-new-black-arrow-2-rocket-at-uk-space-propulsion-workshop/
Interorbital Systems	Neptune N1	USA	N.A.	Status unclear
ispace	Hyperbola 1S (SQX-1Z) (active) Hyperbola 1 and 3 (under development)	China	H-1S active and H-1 and H-3 under development 2021	https://en.wikipedia.org/wiki/I-Space_(Chinese_company)
Israel Aerospace Industries	Shavit (meaning "comet" in Israeli)	Israel	Currently (only used for Israeli launches and launched to the west rather than to the east)	https://en.wikipedia.org/wiki/Israel_Aerospace_Industries
ISRO	PSLV Light (launch of LEO satellites of up to 500Kg and can be assembled in 3 days)	India	2020	https://www.spaceflightinsider.com/organizations/isro/isro-plans-develop-light-lift-rocket-launch-small-satellites-orbit/
LandSpace	Zhuque-1 launcher by private LandSpace company. Capable of 300 kg to LEO orbit or 200 kg to SSO orbit Launch in early 2019 failed to achieve orbit	China	2019	https://en.wikipedia.org/wiki/LandSpace https://spacenews.com/landspace-ready-for-first-chinese-private-orbital-launch-but-looks-to-grander-plans
Launcher, Inc.	Rocket-1. They are currently developing 3D printed rocket engines on a 10-year schedule to have a small satellite launcher by 2025	USA	2025	https://3dprint.com/220518/launcher-a-space-start-up-making-3d-printed-rocket-engines/

(continued)

LEO Aerospace LLC (associated with Purdue University)	Rockoons. High-altitude balloons ascend to 18 km and then sent to orbit by a rocket release. Projected cost of $60,000 per kg	USA	Q4 2018	https://www.purdue.edu/newsroom/releases/2018/Q2/rockoons-may-soon-make-launching-satellites-into-space-more-accessible.html
Link Space Aerospace Technology Group (private Chinese company)	New Line 1 Xin Gan Xian 1. Capable of 200 kg payload to sun-synchronous orbit. Objective is $2.5 million launch cost with reusable first stage	China	2020–2021 (eventually to support point-to-point rocket launches)	https://en.wikipedia.org/wiki/LinkSpace
Naro Space Center in cooperation with GKNPTs Khrunichev	Naro-1 (retired as of 2013)	South Korea in cooperation with Russia	Retired as of 2013	https://en.wikipedia.org/w/index.php?search=&title=Special%3ASearch&fulltext=Search
North Korea National Aerospace Development Administration (NADA)	Kwangmyongsong' and Unha-3 Missile Systems	North Korea	Active systems since 2012	http://www.astronautix.com/u/unha.html
One Space Technology Group (also known as Zero One Space) (private Chinese launch company)	OS-M1 to OS-M4, OS-M4 is capable of lifting 552 kg to LEO and 307 kg to sun-synchronous orbit of up to 800 km. Will seek to develop reusable rockets and even crewed vehicle to LEO orbit	China	2018	https://en.wikipedia.org/wiki/OneSpace On April 3, 2019 the launch of this solid fuel OS-M1 rocket failed to achieve orbit.
Orbex	Prime launch vehicle. Seeks to launch 150 kg to sun-synchronous orbit of 500 km. Seeking to develop a reusable 1st stage rocket. Shares launch site with Rocket Lab's Electron vehicles	UK	2020–2021	https://orbex.space/ https://en.wikipedia.org/wiki/Orbex

(continued)

Orbital Access	Orbital 500R is an air-launched, two-stage to orbit system, designed to deliver payloads of 500kgs to a 600 km sun-synchronous orbit, aircraft deployed with space plane delivery system	UK	2020	https://www.orbital-access.com/
PLD Space	Miura 5 (previously Arion 2). This is a Spanish-developed rocket engine. This is a 3-stage liquid-propelled launch vehicle capable of inserting with a kick state a 300 kg payload into a 400 km LEO orbit	Spain	3Q 2021 (this expected date for Miura 5 with doubled payload up to 300 kg)	https://spacenews.com/pld-space-after-esa-input-doubles-lift-capacity-of-smallsat-launcher/ https://en.wikipedia.org/wiki/PLD_Space
Reaction Engines, Ltd.	Sabre Engine for Skylon single-stage-to-orbit vehicle. This company founded by Alan Bond is the leading developer of SCRAM jet engines	UK	2021	https://www.reactionengines.co.uk/
Relativity	Terran 1 launch vehicle with 3D printed rocket motor. Relativity has partnered with mu space. Terran 1 can be configured to launch 185–1250 kg to LEO. Nominal payload is 700–1200 kg to sun-synchronous orbit. Design reduces launcher to 1000 parts	USA	2022	www.relativity.com
Rocket Crafters Inc. (RCI)	Intrepid-1 RCI is developing hybrid rocket engines (HREs) with an oxidizer and sold fuel for integration with Intrepid-1's 1st and 2nd stages	USA	2019 or 2020	http://rocketcrafters.space/

(continued)

RocketStar	The StarLord is being designed to carry 300 kilograms to LEO and up to 150 kilograms to GEO	USA	2019	http://rocketstar.nyc/satellite-launch-platform.html
Skyrora Space Technologies	Skyrora XL. This is a 3-stage launch vehicle powered by hydrogen peroxide and kerosene. This rocket system is derivative of the Black Arrow and Skylark rockets that preceded Skyrora I and Skyrora XL that is launched from Scotland	UK/Ukraine	2019–2020	https://www.skyrora.com/ https://spacenews.com/uk-ukrainian-launch-vehicle-developer-skyrora-to-establish-smallsat-launch-site/
SpaceOps	RTS-1 Rocky 1. This project is seeking to develop (return to sender) reusable rocket systems	Australia	2019	http://spaceops.com.au/
Spaceflight Industries	This is a service company that locates the best launch services at low cost. They also provide transportation to launch site, integration, and ongoing communications after launch. On Dec. 3, 2018, a Falcon 9 launched 64 small satellites as brokered by Spaceflight	USA	Active	https://www.spaceflightindustries.com https://www.cnbc.com/2019/02/01/morgan-stanley-spaceflight-industries-disrupting-rocket-launch-market.html
Space Launch Services (SpaceLS)	Prometheus-1 is a 3-stage vehicle, employing a regeneratively cooled gas-turbo generator-pumped rocket engine burning kerosene and HTP	UK	Q4 2017	http://www.rocketeers.co.uk/node/4370

(continued)

SpinLaunch	This new “Stealth” launch system has acquired $40 million in venture capital to develop a launch vehicle that is accelerated to hypersonic speeds using ground-based electricity. This claimed to provide orders of magnitude less launching cost to LEO	USA	N.A.	https://www.space.com/40910-stealth-startup-spinlaunch-new-launch-method.html
Stofiel Aerospace	Boreas. This is 3-part small satellite launch system with the world’s first solid fueled rocket designed to thrust, throttle, and vector. With rockets that are 3D printed and scalable to payloads	USA	2019	https://www.stofiel.space/rocket.html
Stratolaunch	The Stratolaunch that was developed by Vulcan Inc. is now ready to launch a series of different launchers. These include (i) the Pegasus by Northrop Grumman Innovation Systems for a 370 kg payload to LEO for single or triple configuration (strato); (ii) the medium launch vehicle for 3400 kg payload; (iii) space plane LEO launcher and for longer-term crewed vehicle	USA	I. Option one: 2019 ii. Option two: 2022 ii. Option three: design study	https://www.stratolaunch.com/2018/08/20/stratolaunch-announces-new-launch-vehicles/
UP Aerospace	Spyder, it has had a total of 12 launches. It has had 7 launches for NASA of small satellites	USA	Currently active out of Spaceport America	https://www.upaerospace.com/

(continued)

VALT Enterprises	VALT (Vertical Air-Breathing Launch Technology). This company that offers suborbital and orbital launches for microsats uses scram jet engines and thus eliminates the e	USA	Not known	http://www.valt-ent.com/
Zero 2 Infinity (strato-balloon)	Bloostar	Spain	2017	

34 Cross-References

- ▶ Historical Perspectives on the Evolution of Small Satellites
- ▶ Introduction to the Small Satellite Revolution and Its Many Implications

References

http://www.khrunichev.ru/main.php?id=44
https://en.wikipedia.org/wiki/Angara_(rocket_family)
https://en.wikipedia.org/wiki/Antares_(rocket)
http://www.northropgrumman.com/Capabilities/Antares/Pages/default.aspx
http://www.northropgrumman.com/Capabilities/SpacecraftBuses/Pages/default.aspx
https://en.wikipedia.org/wiki/Cygnus_(spacecraft)
http://www.esa.int/Our_Activities/Space_Transportation/Launch_vehicles/Ariane_5_ES
http://www.spacelaunchreport.com/ariane5.html
https://web.archive.org/web/20070322203029/http://www.spaceflight.esa.int/users/downloads/factsheets/fs003_12_atv.pdf
https://en.wikipedia.org/wiki/Automated_Transfer_Vehicle
http://spacelaunchreport.com/atlas5.html
https://en.wikipedia.org/wiki/Atlas_V
http://mediaarchive.ksc.nasa.gov/detail.cfm?mediaid=71145 (image link), Public Domain, https://commons.wikimedia.org/w/index.php?curid=37939869
http://spaceflight101.com/spacerockets/delta-iv-heavy/
https://en.wikipedia.org/wiki/Delta_IV_Heavy
https://www.ulalaunch.com/docs/default-source/rockets/atlas-v-and-delta-iv-technical-summary.pdf
https://space.skyrocket.de/doc_sdat/cst-100.htm
https://en.wikipedia.org/wiki/Boeing_CST-100_Starliner
http://www.russianspaceweb.com/dnepr.html
https://en.wikipedia.org/wiki/Dnepr_(rocket)
http://spaceref.com/news/viewpr.html?pid=44072
https://en.wikipedia.org/wiki/Dream_Chaser
https://www.rocketlabusa.com/vehicle/electron/

https://en.wikipedia.org/wiki/Electron_(rocket)
https://web.archive.org/web/20101222155322/
http://www.spacex.com/falcon9.php
https://web.archive.org/web/20080228013323/http://www.jaxa.jp/pr/brochure/pdf/01/rocket01.pdf
https://en.wikipedia.org/wiki/H-IIA
https://web.archive.org/web/20101116044853/
http://www.jaxa.jp/projects/rockets/htv/design_e.html
https://en.wikipedia.org/wiki/H-II_Transfer_Vehicle
https://web.archive.org/web/20101116044853/http://www.jaxa.jp/projects/rockets/htv/design_e.html
https://en.wikipedia.org/wiki/H-II_Transfer_Vehicle
https://www.isro.gov.in/launchers/pslv
https://en.wikipedia.org/wiki/Polar_Satellite_Launch_Vehicle
https://web.archive.org/web/20090310171550/http://kibo.jaxa.jp/en/about/
https://en.wikipedia.org/wiki/Kibo_(ISS_module)#Exposed_facility
http://www.spacelaunchreport.com/launcherone.html
https://en.wikipedia.org/wiki/LauncherOne
https://web.archive.org/web/20161224185459/http://spaceflightnow.com/launch-schedule/
https://en.wikipedia.org/wiki/Long_March_5
https://archive.is/20150918112832/http://www.spaceflight101.com/long-march-6.html https://en.wikipedia.org/wiki/Long_March_6
http://sinodefence.com/cz-7/
https://en.wikipedia.org/wiki/Long_March_7
https://web.archive.org/web/20090508113707/http://www.astronautix.com/lvs/minotaur.htm
https://en.wikipedia.org/wiki/Minotaur_II
https://spacenews.com/bezos-not-concerned-about-competition-possible-ula-sale/
https://arstechnica.com/science/2017/03/blue-origin-releases-details-of-its-monster-orbital-rocket/
https://en.wikipedia.org/wiki/New_Glenn
https://web.archive.org/web/20160113130631/
https://www.orbitalatk.com/flight-systems/space-launch-vehicles/pegasus/docs/Pegasus_UsersGuide.pdf
https://en.wikipedia.org/wiki/Pegasus_(rocket)
http://www.khrunichev.ru/main.php?id=54
https://en.wikipedia.org/wiki/Proton_(rocket_family)
https://www.eurockot.com/rockot/launch-vehicle/
https://en.wikipedia.org/wiki/Rokot
https://en.wikipedia.org/wiki/Soyuz_(rocket_family)
http://www.esa.int/Our_Activities/Human_and_Robotic_Exploration/Delta_Mission/Soyuz_launch_vehicle_The_most_reliable_means_of_space_travel
https://vector-launch.com/vector-r/
https://en.wikipedia.org/wiki/Vega_(rocket)https://web.archive.org/web/20150923180829/http://www.avio.com/files/catalog/pdf/motore_p80_75.pdf
https://www.ulalaunch.com/docs/default-source/rockets/atlas-v-and-delta-iv-technical-summary.pdf
https://en.wikipedia.org/wiki/Vulcan_(rocket)
https://www.ablspacesystems.com/
https://www.satellitetoday.com/innovation/2017/07/31/startup-aphelion-orbitals-secures-500000-seed-funding/
https://mach5lowdown.com/2017/03/14/bagaveev-corp/
http://www.bspacelaunch.com
https://medium.com/spacer/celestia-aerospace-a-company-that-is-planning-to-use-a-fighter-plane-
https://en.wikipedia.org/wiki/Kaituozhe_(rocket_family)
http://www.cloudix.space/
https://spacenews.com/cloudix-joins-race-to-develop-small-rocket/
https://en.wikipedia.org/wiki/Tronador_(rocket)

http://www.cubecab.com
http://www.parabolicarc.com/2018/02/11/bitcoinlatina-foundation-cubecab-launch-300-satellite-network-support-bcl-blockchain/
https://en.wikipedia.org/wiki/VLM_(rocket)
https://www.esa.int/Our_Activities/Space_Transportation/Space_Rider
https://www.gspacetech.com/
https://www.gspacetech.com/single-post/2019/02/01/Gilmour-Space-unveils-One-Vision-rocket-ahead-of-suborbital-test-launch
https://www.seradata.com/horizon-space-technologies-announces-new-black-arrow-2-rocket-at-uk-space-propulsion-workshop/
https://en.wikipedia.org/wiki/I-Space_(Chinese_company)
https://en.wikipedia.org/wiki/Israel_Aerospace_Industries
https://www.spaceflightinsider.com/organizations/isro/isro-plans-develop-light-lift-rocket-launch-small-satellites-orbit/
https://en.wikipedia.org/wiki/LandSpace
https://spacenews.com/landspace-ready-for-first-chinese-private-orbital-launch-but-looks-to-grander-plans
https://3dprint.com/220518/launcher-a-space-start-up-making-3d-printed-rocket-engines/
https://www.purdue.edu/newsroom/releases/2018/Q2/rockoons-may-soon-make-launching-satellites-into-space-more-accessible.html
https://en.wikipedia.org/wiki/LinkSpace
https://en.wikipedia.org/w/index.php?search=&title=Special%3ASearch&fulltext=Search
http://www.astronautix.com/u/unha.html
https://en.wikipedia.org/wiki/OneSpace
https://orbex.space/
https://en.wikipedia.org/wiki/Orbex
https://www.orbital-access.com/
https://spacenews.com/pld-space-after-esa-input-doubles-lift-capacity-of-smallsat-launcher/
https://en.wikipedia.org/wiki/PLD_Space
https://www.reactionengines.co.uk/
www.relativity.com
http://rocketcrafters.space/
http://rocketstar.nyc/satellite-launch-platform.html
https://www.skyrora.com/
https://spacenews.com/uk-ukrainian-launch-vehicle-developer-skyrora-to-establish-smallsat-launch-site/
http://spaceops.com.au/
https://www.spaceflightindustries.com
https://www.cnbc.com/2019/02/01/morgan-stanley-spaceflight-industries-disrupting-rocket-launch-market.html
http://www.rocketeers.co.uk/node/4370
https://www.space.com/40910-stealth-startup-spinlaunch-new-launch-method.html
https://www.stofiel.space/rocket.html
https://www.stratolaunch.com/2018/08/20/stratolaunch-announces-new-launch-vehicles/
https://www.upaerospace.com/
http://www.valt-ent.com/

Forms for Registration of Small Satellites Consistent with the Registration Conventions

Joseph N. Pelton

Contents

Abstract

There is a requirement for all space objects launched into orbit or beyond to be formally registered with the Secretary General of the United Nations by nation states responsible for these launches. This is a requirement of the so-called Registration Convention as well as the subsequent UN General Assembly Resolution 62/101.

This part of the Handbook on small satellites is designed to provide key documentation and forms associated with outer space activities. Thus, the registration form required to be provided to the United Nations is provided below.

Keywords

General assembly · Launching State · Nanosat · Office of outer space affairs · Registration convention · Secretary general · Space object · Small satellite · United Nations

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety,
Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_83

1 Introduction

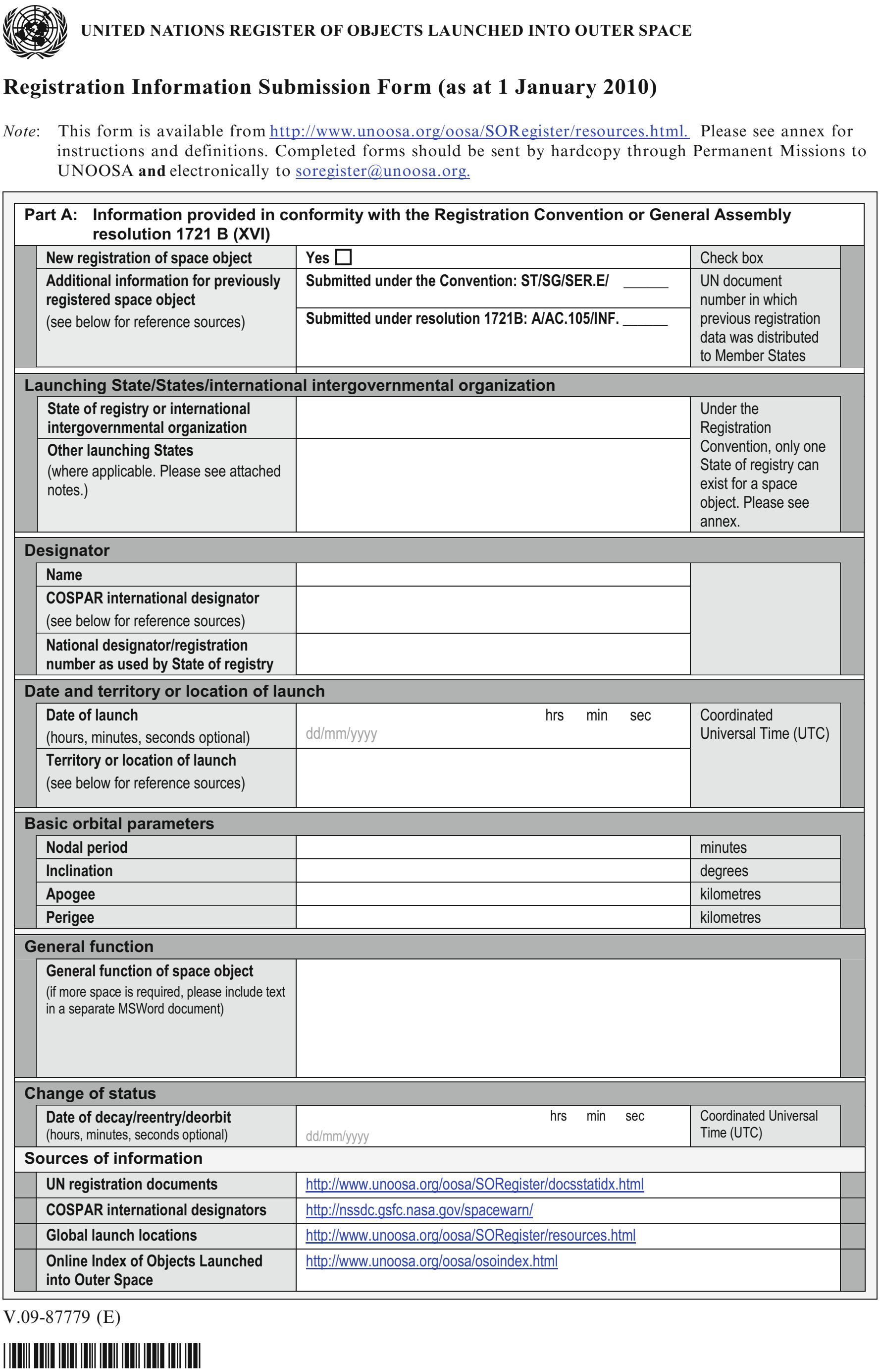
The Registration Convention or General Assembly Resolution 1721 8 (XVI) requires all launching states to register this information with Secretary General who has designated the UN Office of Outer Space Affairs to discharge this duty. The Registry Form that is provided in the next four pages that follow also makes reference to the UN General Assembly Resolution 62/101 that has been added to allow the registration to become more flexible and informative as conditions change over time.

Thus this form, consistent with the changes provided by UNGA Resolution 62/101, allows states to offer updates with regard to a change of function, a transition to a nonfunctional state, a change of orbital parameters or removal from orbit, the intent to engage in activities such as on-orbit servicing or rendezvous and proximity operations, a modification in ownership, the designation of a new spacecraft operator, or other changes to the spacecraft or space object itself. This type of registration currently applies to all space objects launched even for the smallest spacecraft such as femtosats, picosats, or nanosats.

The United Nations Registration form that Launching States are to file with the UN Office of Outer Space Affairs for all objects launched into outer space as provided in this Appendix below can be accessed at the following web site. In the Adobe format, this form can also be filled out online, but this form must be submitted by the launching state. See http://www.unoosa.org/res/oosadoc/data/documents/2008/unoosaregfrm/unoosaregfrm1_0_html/UNOOSA-REG-FRM-01E.pdf.

Important note: Registration of space objects with the Secretary General can only be performed by the government of a state of registry through accredited Permanent Missions to the United Nations or by the headquarters of an international intergovernmental organization that has declared acceptance of rights and obligations under the Registration Convention. Direct submissions by national space agencies, academic institutions, and private entities are not considered to be valid registration submissions.

Editor's note: The information provided here is simply to provide entities seeking to launch small satellites of any type into orbit useful background as to the type of information the official national or international intergovernmental organization would be required to file with the United Nations. Thus the information indicated in the form below is indicative of the information that will be needed to be supplied but that direct filing of this information is not permitted by private organizations for the reasons indicated above. In short this information is simply provided as background. Official filings must come from authorized agencies recognized by the United Nations.



UNITED NATIONS REGISTER OF OBJECTS LAUNCHED INTO OUTER SPACE

Registration Information Submission Form (as at 1 January 2010)

Note: This form is available from http://www.unoosa.org/oosa/SORegister/resources.html. Please see annex for instructions and definitions. Completed forms should be sent by hardcopy through Permanent Missions to UNOOSA **and** electronically to soregister@unoosa.org.

Part A: Information provided in conformity with the Registration Convention or General Assembly resolution 1721 B (XVI)

New registration of space object	**Yes** ☐	Check box
Additional information for previously registered space object (see below for reference sources)	**Submitted under the Convention: ST/SG/SER.E/** ______ **Submitted under resolution 1721B: A/AC.105/INF.** ______	UN document number in which previous registration data was distributed to Member States

Launching State/States/international intergovernmental organization

State of registry or international intergovernmental organization		Under the Registration Convention, only one State of registry can exist for a space object. Please see annex.
Other launching States (where applicable. Please see attached notes.)		

Designator

Name		
COSPAR international designator (see below for reference sources)		
National designator/registration number as used by State of registry		

Date and territory or location of launch

Date of launch (hours, minutes, seconds optional)	dd/mm/yyyy hrs min sec	Coordinated Universal Time (UTC)
Territory or location of launch (see below for reference sources)		

Basic orbital parameters

Nodal period		minutes
Inclination		degrees
Apogee		kilometres
Perigee		kilometres

General function

General function of space object (if more space is required, please include text in a separate MSWord document)	

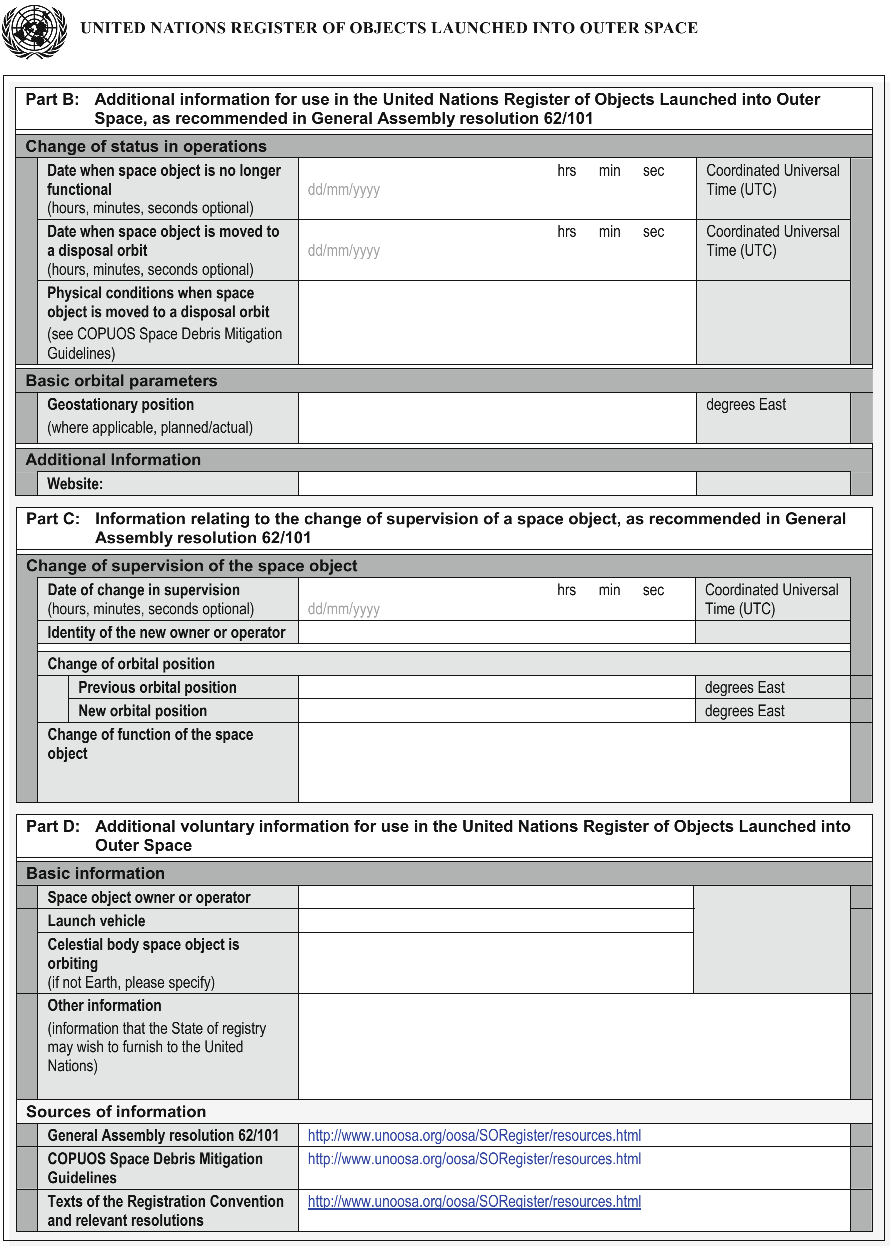
Change of status

Date of decay/reentry/deorbit (hours, minutes, seconds optional)	dd/mm/yyyy hrs min sec	Coordinated Universal Time (UTC)

Sources of information

UN registration documents	http://www.unoosa.org/oosa/SORegister/docsstatidx.html
COSPAR international designators	http://nssdc.gsfc.nasa.gov/spacewarn/
Global launch locations	http://www.unoosa.org/oosa/SORegister/resources.html
Online Index of Objects Launched into Outer Space	http://www.unoosa.org/oosa/osoindex.html

V.09-87779 (E)



UNITED NATIONS REGISTER OF OBJECTS LAUNCHED INTO OUTER SPACE

Part B: Additional information for use in the United Nations Register of Objects Launched into Outer Space, as recommended in General Assembly resolution 62/101

Change of status in operations

Date when space object is no longer functional (hours, minutes, seconds optional)	dd/mm/yyyy hrs min sec	Coordinated Universal Time (UTC)
Date when space object is moved to a disposal orbit (hours, minutes, seconds optional)	dd/mm/yyyy hrs min sec	Coordinated Universal Time (UTC)
Physical conditions when space object is moved to a disposal orbit (see COPUOS Space Debris Mitigation Guidelines)		

Basic orbital parameters

Geostationary position (where applicable, planned/actual)		degrees East

Additional Information

Website:		

Part C: Information relating to the change of supervision of a space object, as recommended in General Assembly resolution 62/101

Change of supervision of the space object

Date of change in supervision (hours, minutes, seconds optional)	dd/mm/yyyy hrs min sec	Coordinated Universal Time (UTC)
Identity of the new owner or operator		
Change of orbital position		
Previous orbital position		degrees East
New orbital position		degrees East
Change of function of the space object		

Part D: Additional voluntary information for use in the United Nations Register of Objects Launched into Outer Space

Basic information

Space object owner or operator	
Launch vehicle	
Celestial body space object is orbiting (if not Earth, please specify)	
Other information (information that the State of registry may wish to furnish to the United Nations)	

Sources of information

General Assembly resolution 62/101	http://www.unoosa.org/oosa/SORegister/resources.html
COPUOS Space Debris Mitigation Guidelines	http://www.unoosa.org/oosa/SORegister/resources.html
Texts of the Registration Convention and relevant resolutions	http://www.unoosa.org/oosa/SORegister/resources.html

UNITED NATIONS REGISTER OF OBJECTS LAUNCHED INTO OUTER SPACE

Annex

Section A. Instructions for completing the form

1. Download the electronic version of the form from http://www.unoosa.org/oosa/SORegister/resources.html.
2. Reference sources and other resources for completion of the form are available from the above web-link.
3. Review definitions in Section B below and complete the form. If there are any queries, please e-mail soregister@unoosa.org.
4. The **completed hardcopy form** should be sent through official government channels to the relevant Permanent Mission to the United Nations (Vienna) to be formally transmitted to the United Nations.
5. The **completed electronic form** should be sent by the appropriate government entity to the United Nations Office for Outer Space Affairs using e-mail soregister@unoosa.org.

Section B. Definition of terms

Part A: Information provided in conformity with the Registration Convention or General Assembly resolution 1721B (XVI)

Launching State/States/international intergovernmental organization

State of registry/international intergovernmental organization:	The State of registry is the launching State which carries the space object on its national registry of objects launched into outer space. The international intergovernmental organization is an organization which has declared its acceptance of the rights and obligations provided for in accordance with Article VII of the Registration Convention. *Note*: In accordance with Article II of the Registration Convention, **only one State of registry can exist for a space object**. When more than one launching State exists, they should jointly determine which State should register the space object.
Other Launching States:	As defined in the Registration Convention, "launching State" means: (i) A State which launches or procures the launching of a space object; (ii) A State from whose territory or facility a space object is launched.

Designator

Name:	The common name/names used to identify the space object.
COSPAR international designator:	Alphanumeric designator established by the Committee on Space Research (COSPAR) for space objects that successfully reach Earth orbit or beyond. The SPACEWARN Bulletin (available at http://nssdc.gsfc.nasa.gov/spacewarn) confirms the designators assigned by the World Warning Agency for Satellites on behalf of COSPAR. The designator can also be obtained from the Online Index of Objects Launched into Outer Space at http://www.unoosa.org/oosa/osoindex.html.
National designator/ registration number:	Designator or registration number assigned to a space object by the State of registry.

Date and territory or location of launch

Date of launch:	The date of launch of the space object using Coordinated Universal Time (UTC) (also referred to as Greenwich Mean Time (GMT)).
Territory or location of launch:	The territory or location of the launch of the space object. For a table of global launch locations, see http://www.unoosa.org/oosa/SORegister/resources.html.

Basic orbital parameters: Basic data on the space object's orbit around the Earth or a celestial body such as the Sun, Moon, etc. If object is orbiting a body other than Earth, please specify. The parameters are:

Nodal period:	Time taken by the space object to complete one revolution around the body it is orbiting.
Inclination:	The angle relative to the equator of the Earth or celestial body the space object is orbiting. Measured counter-clockwise from the equator.
Apogee:	The furthest distance in the space object's orbit from the surface of the body it is orbiting.
Perigee:	The closest distance in the space object's orbit from the surface of the body it is orbiting.

UNITED NATIONS REGISTER OF OBJECTS LAUNCHED INTO OUTER SPACE

General function:	General information on the space object. Can include mission objectives, frequency plans, etc. If required, please attach text in a separate page.
Change of Status:	The date of the space object's decay, reentry, recovery, deorbit or landing.

Part B: Additional information for use in the United Nations Register of Objects Launched into Outer Space, as recommended in General Assembly resolution 62/101

Change of status in operations

Date when space object is no longer functional:	The date using Coordinated Universal Time (UTC) (also referred to as Greenwich Mean Time (GMT)) when the space object ceases to perform operational functions for the State of registry.
Date when space object is moved to a disposal orbit:	The date using Coordinated Universal Time (UTC) when the space object is moved into a disposal orbit. See COPUOS Space Debris Mitigation Guidelines for recommendations on disposal orbits, http://www.unoosa.org/oosa/SORegister/resources.html.
Physical conditions when space object is moved to a disposal orbit:	The physical conditions when the space object is moved into a disposal orbit. Conditions can include the change in orbit (e.g. +300 km above GSO), passivation of the space object and other measures as recommended in the COPUOS Space Debris Mitigation Guidelines.

Basic orbital parameters

Geostationary position:	Applicable only to space objects in the geostationary orbit. Planned and/or actual location of space object in ± degrees East along the equator from the Greenwich meridian (e.g. for 10.5 degrees West, use -10.5 degrees East).

Additional Information

Website:	Address on the World Wide Web for information on the space object/mission/operator.

Part C: Information relating to the change of supervision of a space object, as recommended in General Assembly resolution 62/101

Change of supervision of the space object

Date of change in supervision:	The date using Coordinated Universal Time (UTC) (also referred to as Greenwich Mean Time (GMT)) when the new owner or operator takes supervision of the space object.
Identity of the new owner or operator:	The identity of the new owner or operator of the space object.
Change of orbital position in the geostationary orbit	
Previous orbital position:	The previous operational location of the space object in ± degrees East along the equator from the Greenwich meridian.
New orbital position:	The new operational location of the space object in ± degrees East along the equator from the Greenwich meridian.
Change of function of the space object:	The function of the space object following change in supervision.

Part D: Additional voluntary information for use in the United Nations Register of Objects Launched into Outer Space

Basic information

Space object owner or operator:	The entity that owns or operates the space object.
Launch vehicle:	The launch vehicle used to launch the space object into Earth orbit or beyond.
Celestial body space object is orbiting:	The body that the space object is in orbit around, if not Earth (i.e. the Moon, the Sun, Mars, Jupiter, etc.).
Other information:	Information relating to the space object that the State of registry may wish to furnish to the United Nations.

2 Cross-References

- ▶ Historical Perspectives on the Evolution of Small Satellites
- ▶ Introduction to the Small Satellite Revolution and Its Many Implications

References

http://www.unoosa.org/res/oosadoc/data/documents/2008/unoosaregfrm/unoosaregfrm1_0_html/UNOOSA-REG-FRM-01E.pdf

UN Sustainable Development Goals for 2030

Joseph N. Pelton

Contents

This chapter is a technical document with key information regarding the Handbook of Small Satellites.

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_84

Abstract

On January 2, 2016, the United Nations General Assembly adopted 17 Millennium Development Goals. A short summary of these goals as well as explicit targets to be achieved by 2030 is provided below as provided in United Nations documentation. This document, in addition to providing the official brief explanation of the 17 Goals, also provides the UN-approved specific targets for each goal. Also provided is the United Nation's characterization of the issues to be addressed in terms of related facts and figures associated with each objective as well as supporting rationale for their adoption. For the complete UN text on the 17 SDGs, please go to https://www.un.org/sustainabledevelopment/sustainable-developmentgoals/.

Keywords

UN office of outer dpace affairs · UN sustainable development goals · Development targets · Facts and figures

1 Introduction

On January 2, 2016, the United Nations General Assembly adopted 17 Millennium Development Goals. A short summary of these goals as well as explicit targets to be achieved by 2030 is provided below as provided in United Nations documentation. This document, in addition to providing the official brief explanation of the 17 Goals, also provides the UN-approved specific targets for each goal. Also provided is the United Nation's characterization of the issues to be addressed in terms of related facts and figures associated with each objective as well as supporting rationale for their adoption. For the complete UN text on the 17 SDGs, please go to https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

2 Goal 1: End Poverty

Eradicating poverty in all its forms remains one of the greatest challenges facing humanity. While the number of people living in extreme poverty dropped by more than half between 1990 and 2015 – from 1.9 billion to 836 million – too many are still struggling for the most basic human needs.

Globally, more than 800 million people are still living on less than US $1.25 a day, many lacking access to adequate food, clean drinking water, and sanitation. Rapid economic growth in countries like China and India has lifted millions out of poverty, but progress has been uneven. Women are more likely to live in poverty than men due to unequal access to paid work, education, and property.

Progress has also been limited in other regions, such as South Asia and sub-Saharan Africa, which account for 80% of those living in extreme poverty. New threats brought in by climate change, conflict, and food insecurity mean even more work is needed to bring people out of poverty.

The SDGs are a bold commitment to finish what we started and end poverty in all forms and dimensions by 2030. This involves targeting the most vulnerable, increasing access to basic resources and services, and supporting communities affected by conflict and climate-related disasters.

Goal 1 Targets

- By 2030, reduce at least by half the proportion of men, women, and children of all ages living in poverty in all its dimensions according to national definitions.
- Implement nationally appropriate social protection systems and measures for all, including floors, and by 2030 achieve substantial coverage of the poor and the vulnerable.
- By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership, and control over land and other forms of property, inheritance, natural resources, appropriate new technology, and financial services, including microfinance.
- By 2030, build the resilience of the poor and those in vulnerable situations, and reduce their exposure and vulnerability to climate-related extreme events and other economic, social, and environmental shocks and disasters.
- Ensure significant mobilization of resources from a variety of sources, including through enhanced development cooperation, in order to provide adequate and predictable means for developing countries, in particular least developed countries, to implement. Programs and policies to end poverty in all its dimensions.
- Create sound policy frameworks at the national, regional, and international levels, based on pro-poor and gender-sensitive development strategies, to support accelerated investment in poverty eradication actions.

Facts and Figures

- Eight hundred thirty-six million people still live in extreme poverty.
- About one in five persons in developing regions lives on less than US $1.25 per day.
- The overwhelming majority of people living on less than $1.25 a day belong to two regions: Southern Asia and sub-Saharan Africa.
- High poverty rates are often found in small, fragile, and conflict-affected countries.
- One in four children under age 5 in the world has inadequate height for his or her age.
- Every day in 2014, 42,000 people had to abandon their homes to seek protection due to conflict.

3 Goal 2: Zero Hunger

Rapid economic growth and increased agricultural productivity over the past two decades have seen the number of undernourished people drop by almost half. Many developing countries that used to suffer from famine and hunger can now meet the nutritional needs of the most vulnerable. Central and East Asia, Latin America, and the Caribbean have all made huge progress in eradicating extreme hunger.

These are all huge achievements in line with the targets set out by the first Millennium Development Goals. Unfortunately, extreme hunger and malnutrition remain a huge barrier to development in many countries. Seven hundred ninety-five million people are estimated to be chronically undernourished as of 2014, often as a direct consequence of environmental degradation, drought, and loss of biodiversity. Over 90 million children under the age of 5 are dangerously underweight. And one person in every four still goes hungry in Africa.

The SDGs aim to end all forms of hunger and malnutrition by 2030, making sure all people – especially children – have access to sufficient and nutritious food all year round. This involves promoting sustainable agricultural practices: supporting small-scale farmers and allowing equal access to land, technology, and markets. It also requires international cooperation to ensure investment in infrastructure and technology to improve agricultural productivity. Together with the other goals set out here, we can end hunger by 2030.

There is an imperative today to foster sustainable development. A vision for what this encapsulates is laid out in the new sustainable development agenda that aims to end poverty and promote prosperity and people's well-being while protecting the environment by 2030. As the UN's Development arm, UNDP has a key role to play in supporting countries to make this vision a reality – putting societies on a sustainable development pathway, managing risk and enhancing resilience, and advancing prosperity and well-being.

Goal 2 Targets

- By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious, and sufficient food all year round.
- By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women, and older persons.
- By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists, and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets, and opportunities for value addition and non-farm employment.
- By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production; that help maintain ecosystems; that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters; and that progressively improve land and soil quality.
- By 2020, maintain the genetic diversity of seeds, cultivated plants, and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional, and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed.
- Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development, and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries.
- Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round.
- Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility.

Facts and Figures

- Globally, one in nine people in the world today (795 million) is undernourished.
- The vast majority of the world's hungry people live in developing countries, where 12.9% of the population is undernourished.
- Asia is the continent with the most hungry people – two thirds of the total. The percentage in Southern Asia has fallen in recent years, but in Western Asia it has increased slightly.

- Southern Asia faces the greatest hunger burden, with about 281 million undernourished people. In sub-Saharan Africa, projections for the 2014–2016 period indicate a rate of undernourishment of almost 23%.
- Poor nutrition causes nearly half (45%) of deaths in children under age 5 – 3.1 million children each year.
- One in four of the world's children suffers stunted growth. In developing countries, the proportion can rise to one in three.
- Sixty-six million primary school-age children attend classes hungry across the developing world, with 23 million in Africa alone.
- Agriculture is the single largest employer in the world, providing livelihoods for 40% of today's global population. It is the largest source of income and jobs for poor rural households.

4 Goal 3: Good Health and Well-Being

4.1 Ensure Healthy Lives and Promote Well-Being

Ensuring healthy lives and promoting the well-being for all at all ages are essential to sustainable development. Significant strides have been made in increasing life expectancy and reducing some of the common killers associated with child and maternal mortality. Major progress has been made on increasing access to clean water and sanitation and reducing malaria, tuberculosis, polio, and the spread of HIV/AIDS. However, many more efforts are needed to fully eradicate a wide range of diseases and address many different persistent and emerging health issues.

Goal 3 Targets

- By 2030, reduce the global maternal mortality ratio to less than 70 per 100,000 live births.
- By 2030, end preventable deaths of newborns and children under 5 years of age, with all countries aiming to reduce neonatal mortality to at least as low as 12 per 1000 live births and under age 5 mortality to at least as low as 25 per 1000 live births.
- By 2030, end the epidemics of AIDS, tuberculosis, malaria, and neglected tropical diseases, and combat hepatitis, water-borne diseases, and other communicable diseases.
- By 2030, reduce by one third of premature mortality from noncommunicable diseases through prevention and treatment, and promote mental health and well-being.
- Strengthen the prevention and treatment of substance abuse, including narcotic drug abuse and harmful use of alcohol.
- By 2020, halve the number of global deaths and injuries from road traffic accidents.
- By 2030, ensure universal access to sexual and reproductive health-care services, including for family planning, information and education, and the integration of reproductive health into national strategies and programs.

- Achieve universal health coverage, including financial risk protection, access to quality essential health-care services, and access to safe, effective, quality, and affordable essential medicines and vaccines for all.
- By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.
- Strengthen the implementation of the World Health Organization Framework Convention on Tobacco Control in all countries, as appropriate.
- Support the research and development of vaccines and medicines for the communicable and noncommunicable diseases that primarily affect developing countries; provide access to affordable essential medicines and vaccines, in accordance with the Doha Declaration on the TRIPS Agreement and Public Health, which affirms the right of developing countries to use to the full the provisions in the Agreement on Trade-Related Aspects of Intellectual Property Rights regarding flexibilities to protect public health; and, in particular, provide access to medicines for all.
- Substantially increase health financing and the recruitment, development, training, and retention of the health workforce in developing countries, especially in least developed countries and small island developing states.
- Strengthen the capacity of all countries, in particular developing countries, for early warning, risk reduction, and management of national and global health risks.

Facts and Figures

- Seventeen thousand fewer children die each day than in 1990, but more than six million children still die before their fifth birthday each year.
- Since 2000, measles vaccines have averted nearly 15.6 million deaths.
- Despite determined global progress, an increasing proportion of child deaths are in sub-Saharan Africa and Southern Asia. Four out of every five deaths of children under age 5 occur in these regions.
- Children born into poverty are almost twice as likely to die before the age of 5 as those from wealthier families.
- Children of educated mothers – even mothers with only primary schooling – are more likely to survive than children of mothers with no education.
- Maternal mortality has fallen by almost 50% since 1990.
- In Eastern Asia, Northern Africa, and Southern Asia, maternal mortality has declined by around two thirds.
- But maternal mortality ratio – the proportion of mothers that do not survive childbirth compared to those who do – in developing regions is still 14 times higher than in the developed region.
- More women are receiving antenatal care. In developing regions, antenatal care increased from 65% in 1990 to 83% in 2012.
- Only half of women in developing regions receive the recommended amount of health care they need.
- Fewer teens are having children in most developing regions, but progress has slowed. The large increase in contraceptive use in the 1990s was not matched in the 2000s.

- The need for family planning is slowly being met for more women, but demand is increasing at a rapid pace.
- At the end of 2014, there were 13.6 million people accessing antiretroviral therapy.
- New HIV infections in 2013 were estimated at 2.1 million, which was 38% lower than in 2001.
- At the end of 2013, there were an estimated 35 million people living with HIV.
- At the end of 2013, 240,000 children were newly infected with HIV.
- New HIV infections among children have declined by 58% since 2001.
- Globally, adolescent girls and young women face gender-based inequalities, exclusion, discrimination, and violence, which put them at increased risk of acquiring HIV.
- HIV is the leading cause of death for women of reproductive age worldwide.
- Tuberculosis deaths in people living with HIV have fallen by 36% since 2004.
- There were 250,000 new HIV infections among adolescents in 2013, two thirds of which were among adolescent girls.
- AIDS is now the leading cause of death among adolescents (aged 10–19) in Africa and the second most common cause of death among adolescents globally.
- In many settings, adolescent girls' right to privacy and bodily autonomy is not respected, as many report that their first sexual experience was forced.
- As of 2013, 2.1 million adolescents were living with HIV.
- Over 6.2 million malaria deaths have been averted between 2000 and 2015, primarily of children under 5 years of age in sub-Saharan Africa. The global malaria incidence rate has fallen by an estimated 37% and the mortality rates by 58%.
- Between 2000 and 2013, tuberculosis prevention, diagnosis, and treatment interventions saved an estimated 37 million lives. The tuberculosis mortality rate fell by 45% and the prevalence rate by 41% between 1990 and 2013.

5 Goal 4: Quality Education

5.1 Ensure Inclusive and Quality Education for All and Promote Lifelong Learning

Obtaining a quality education is the foundation to improving people's lives and sustainable development. Major progress has been made toward increasing access to education at all levels and increasing enrollment rates in schools particularly for women and girls. Basic literacy skills have improved tremendously, yet bolder efforts are needed to make even greater strides for achieving universal education goals. For example, the world has achieved equality in primary education between girls and boys, but few countries have achieved that target at all levels of education.

Goal 4 Targets

- By 2030, ensure that all girls and boys complete free, equitable, and quality primary and secondary education leading to relevant and Goal 4 effective learning outcomes.
- By 2030, ensure that all girls and boys have access to quality early childhood development, care, and preprimary education so that they are ready for primary education.
- By 2030, ensure equal access for all women and men to affordable and quality technical, vocational, and tertiary education, including university.
- By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs, and entrepreneurship.
- By 2030, eliminate gender disparities in education, and ensure equal access to all levels of education and vocational training for the vulnerable, including persons with disabilities, indigenous peoples, and children in vulnerable situations.
- By 2030, ensure that all youth and a substantial proportion of adults, both men and women, achieve literacy and numeracy.
- By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship, and appreciation of cultural diversity and of culture's contribution to sustainable development.
- Build and upgrade education facilities that are child, disability, and gender sensitive, and provide safe, nonviolent, inclusive, and effective learning environments for all.
- By 2020, substantially expand globally the number of scholarships available to developing countries, in particular least developed countries, small island developing states, and African countries, for enrollment in higher education, including vocational training and information and communications technology, technical, engineering, and scientific programs, in developed countries and other developing countries.
- By 2030, substantially increase the supply of qualified teachers, including through international cooperation for teacher training in developing countries, especially least developed countries and small island developing states.

Facts and Figures

- Enrollment in primary education in developing countries has reached 91%, but 57 million children remain out of school.
- More than half of children that have not enrolled in school live in sub-Saharan Africa.
- An estimated 50% of out-of-school children of primary school age live in conflict-affected areas.
- One hundred three million youth worldwide lack basic literacy skills, and more than 60% of them are women.

6 Goal 5: Gender Equality

6.1 Achieve Gender Equality and Empower All Women and Girls

While the world has achieved progress toward gender equality and women's empowerment under the Millennium Development Goals (including equal access to primary education between girls and boys), women and girls continue to suffer discrimination and violence in every part of the world.

Gender equality is not only a fundamental human right, but a necessary foundation for a peaceful, prosperous, and sustainable world.

Providing women and girls with equal access to education, health care, decent work, and representation in political and economic decision-making processes will fuel sustainable economies and benefit societies and humanity at large.

Goal 5 Targets

- End all forms of discrimination against all women and girls everywhere.
- Eliminate all forms of violence against all women and girls in the public and private spheres, including trafficking and sexual and other types of exploitation.
- Eliminate all harmful practices, such as child, early, and forced marriage and female genital mutilation.
- Recognize and value unpaid care and domestic work through the provision of public services, infrastructure, and social protection policies and the promotion of shared responsibility within the household and the family as nationally appropriate.
- Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic, and public life.
- Ensure universal access to sexual and reproductive health and reproductive rights as agreed in accordance with the Programme of Action of the International Conference on Population and Development and the Beijing Platform for Action and the outcome documents of their review conferences.
- Undertake reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property, financial services, inheritance, and natural resources, in accordance with national laws.
- Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women.
- Adopt and strengthen sound policies and enforceable legislation for the promotion of gender equality and the empowerment of all women and girls at all levels.

Facts and Figures

- About two thirds of countries in the developing regions have achieved gender parity in primary education.
- In Southern Asia, only 74 girls were enrolled in primary school for every 100 boys in 1990. By 2012, the enrollment ratios were the same for girls as for boys.
- In sub-Saharan Africa, Oceania, and Western Asia, girls still face barriers to entering both primary and secondary schools.

- Women in Northern Africa hold less than one in five paid jobs in the non-agricultural sector. The proportion of women in paid employment outside the agriculture sector has increased from 35% in 1990 to 41% in 2015.
- In 46 countries, women now hold more than 30% of seats in national parliament in at least 1 chamber.

7 Goal 6: Clean Water and Sanitation

7.1 Ensure Access to Water and Sanitation for All

Clean, accessible water for all is an essential part of the world we want to live in. There is sufficient fresh water on the planet to achieve this. But due to bad economics or poor infrastructure, every year millions of people, most of them children, die from diseases associated with inadequate water supply, sanitation, and hygiene.

Water scarcity, poor water quality, and inadequate sanitation negatively impact food security, livelihood choices, and educational opportunities for poor families across the world. Drought afflicts some of the world's poorest countries, worsening hunger and malnutrition.

By 2050, at least one in four people is likely to live in a country affected by chronic or recurring shortages of fresh water.

Goal 6 Targets

- By 2030, achieve universal and equitable access to safe and affordable drinking water for all.
- By 2030, achieve access to adequate and equitable sanitation and hygiene for all, and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.
- By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally.
- By 2030, substantially increase water use efficiency across all sectors, and ensure sustainable withdrawals and supply of fresh water to address water scarcity and substantially reduce the number of people suffering from water scarcity.
- By 2030, implement integrated water resources management at all levels, including through trans-boundary cooperation as appropriate.
- By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes.
- By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling, and reuse technologies.
- Support and strengthen the participation of local communities in improving water and sanitation management.

Facts and Figures

- 2.6 billion people have gained access to improved drinking water sources since 1990, but 663 million people are still without.
- At least 1.8 billion people globally use a source of drinking water that is fecally contaminated.
- Between 1990 and 2015, the proportion of the global population using an improved drinking water source has increased from 76% to 91%.
- But water scarcity affects more than 40% of the global population and is projected to rise. Over 1.7 billion people are currently living in river basins where water use exceeds recharge.
- 2.4 billion people lack access to basic sanitation services, such as toilets or latrines.
- More than 80% of wastewater resulting from human activities is discharged into rivers or sea without any pollution removal.
- Each day, nearly 1000 children die due to preventable water- and sanitation-related diarrheal diseases.
- Hydropower is the most important and widely used renewable source of energy and, as of 2011, represented 16% of total electricity production worldwide.
- Approximately 70% of all water abstracted from rivers, lakes, and aquifers is used for irrigation.
- Floods and other water-related disasters account for 70% of all deaths related to natural disaster.

8 Goal 7: Affordable and Clean Energy

8.1 Ensure Access to Affordable, Reliable, Sustainable, and Modern Energy for All

Energy is central to nearly every major challenge and opportunity the world faces today. Be it for jobs, security, climate change, food production or increasing incomes, access to energy for all is essential.

Sustainable energy is opportunity – it transforms lives, economies, and the planet.

UN Secretary-General Ban Ki-moon is leading a Sustainable Energy for All initiative to ensure universal access to modern energy services, improve efficiency, and increase use of renewable sources.

Goal 7 Targets

- By 2030, ensure universal access to affordable, reliable, and modern energy services.
- By 2030, increase substantially the share of renewable energy in the global energy mix.
- By 2030, double the global rate of improvement in energy efficiency.
- By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency, and

advanced and cleaner fossil fuel technology, and promote investment in energy infrastructure and clean energy technology.

- By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing states, and landlocked developing countries, in accordance with their respective programs of support.

Facts and Figures

- One in five people still lacks access to modern electricity.
- Three billion people rely on wood, coal, charcoal, or animal waste for cooking and heating.
- Energy is the dominant contributor to climate change, accounting for around 60% of total global greenhouse gas emissions.
- Reducing the carbon intensity of energy is a key objective in long-term climate goals.

9 Goal 8: Decent Work and Economic Growth

9.1 Promote Inclusive and Sustainable Economic Growth, Employment, and Decent Work for All

Roughly half the world's population still lives on the equivalent of about US $2 a day. And in too many places, having a job doesn't guarantee the ability to escape from poverty. This slow and uneven progress requires us to rethink and retool our economic and social policies aimed at eradicating poverty.

A continued lack of decent work opportunities, insufficient investments, and underconsumption lead to an erosion of the basic social contract underlying democratic societies: that all must share in progress. The creation of quality jobs will remain a major challenge for almost all economies well beyond 2015.

Sustainable economic growth will require societies to create the conditions that allow people to have quality jobs that stimulate the economy while not harming the environment. Job opportunities and decent working conditions are also required for the whole working age population.

Goal 8 Targets

- Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7% gross domestic product growth per annum in the least developed countries.
- Achieve higher levels of economic productivity through diversification, technological upgrading, and innovation, including through a focus on high value-added and labor-intensive sectors.
- Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity, and innovation, and encourage the formalization and growth of micro-, small-, and medium-sized enterprises, including through access to financial services.

- Improve progressively, through 2030, global resource efficiency in consumption and production and endeavor to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programs on sustainable consumption and production, with developed countries taking the lead.
- By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value.
- By 2020, substantially reduce the proportion of youth not in employment, education, or training.
- Take immediate and effective measures to eradicate forced labor, end modern slavery and human trafficking, and secure the prohibition and elimination of the worst forms of child labor, including recruitment and use of child soldiers, and by 2025 end child labor in all its forms.
- Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment.
- By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products.
- Strengthen the capacity of domestic financial institutions to encourage and expand access to banking, insurance, and financial services for all.
- Increase Aid for Trade support for developing countries, in particular least developed countries, including through the Enhanced Integrated Framework for Trade-Related Technical Assistance to Least Developed Countries.
- By 2020, develop and operationalize a global strategy for youth employment and implement the Global Jobs Pact of the International Labour Organization.

Facts and Figures

- Global unemployment increased from 170 million in 2007 to nearly 202 million in 2012, of which about 75 million are young women and men.
- Nearly 2.2 billion people live below the US $2 poverty line, and poverty eradication is only possible through stable and well-paid jobs.
- Four hundred seventy million jobs are needed globally for new entrants to the labor market between 2016 and 2030.

10 Goal 9: Industry, Innovation, and Infrastructure

10.1 Build Resilient Infrastructure, Promote Sustainable Industrialization, and Foster Innovation

Investments in infrastructure – transport, irrigation, energy, and information and communication technology – are crucial to achieving sustainable development and empowering communities in many countries. It has long been recognized that growth in productivity and incomes and improvements in health and education outcomes require investment in infrastructure.

Inclusive and sustainable industrial development is the primary source of income generation, allows for rapid and sustained increases in living standards for all people, and provides the technological solutions to environmentally sound industrialization.

Technological progress is the foundation of efforts to achieve environmental objectives, such as increased resource and energy efficiency. Without technology and innovation, industrialization will not happen, and without industrialization, development will not happen.

Goal 9 Targets

- Develop quality, reliable, sustainable, and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all.
- Promote inclusive and sustainable industrialization, and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries.
- Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets.
- By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
- Enhance scientific research; upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per one million people and public and private research and development spending.
- Facilitate sustainable and resilient infrastructure development in developing countries through enhanced financial, technological, and technical support to African countries, least developed countries, landlocked developing countries, and small island developing states.
- Support domestic technology development, research, and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities.
- Significantly increase access to information and communications technology, and strive to provide universal and affordable access to the Internet in least developed countries by 2020.

Facts and Figures

- Basic infrastructure like roads, information and communication technologies, sanitation, electrical power, and water remains scarce in many developing countries.
- About 2.6 billion people in the developing world are facing difficulties in accessing electricity full time.

- 2.5 billion people worldwide lack access to basic sanitation, and almost 800 million people lack access to water, many hundreds of millions of them in sub-Saharan Africa and South Asia.
- 1–1.5 billion people do not have access to reliable phone services.
- Quality infrastructure is positively related to the achievement of social, economic, and political goals.
- Inadequate infrastructure leads to a lack of access to markets, jobs, information, and training, creating a major barrier to doing business.
- Undeveloped infrastructures limit access to health care and education.
- For many African countries, particularly the lower-income countries, the existent constraints regarding infrastructure affect firm productivity by around 40%.
- Manufacturing is an important employer, accounting for around 470 million jobs worldwide in 2009 – or around 16% of the world's workforce of 2.9 billion. In 2013, it is estimated that there were more than half a billion jobs in manufacturing.
- Industrialization's job multiplication effect has a positive impact on society. Every 1 job in manufacturing creates 2.2 jobs in other sectors.
- Small- and medium-sized enterprises that engage in industrial processing and manufacturing are the most critical for the early stages of industrialization and are typically the largest job creators. They make up over 90% of business worldwide and account for between 50% and 60% of employment.
- In countries where data are available, the number of people employed in renewable energy sectors is presently around 2.3 million. Given the present gaps in information, this is no doubt a very conservative figure. Because of strong rising interest in energy alternatives, the possible total employment for renewables by 2030 is 20 million jobs.
- Least developed countries have immense potential for industrialization in food and beverages (agro-industry), and textiles and garments, with good prospects for sustained employment generation and higher productivity.
- Middle-income countries can benefit from entering the basic and fabricated metal industries, which offer a range of products facing rapidly growing international demand.
- In developing countries, barely 30% of agricultural production undergoes industrial processing. In high-income countries, 98% is processed. This suggests that there are great opportunities for developing countries in agribusiness.

11 Goal 10: Reduced Inequalities

11.1 Reduce Inequality Within and Among Countries

The international community has made significant strides toward lifting people out of poverty. The most vulnerable nations – the least developed countries, the landlocked developing countries, and the small island developing states – continue to make inroads into poverty reduction. However, inequality still persists and large disparities remain in access to health and education services and other assets.

Additionally, while income inequality between countries may have been reduced, inequality within countries has risen. There is growing consensus that economic growth is not sufficient to reduce poverty if it is not inclusive and if it does not involve the three dimensions of sustainable development – economic, social, and environmental.

To reduce inequality, policies should be universal in principle paying attention to the needs of disadvantaged and marginalized populations.

Goal 10 Targets

- By 2030, progressively achieve and sustain income growth of the bottom 40% of the population at a rate higher than the national average.
- By 2030, empower and promote the social, economic, and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion, or economic or other status.
- Ensure equal opportunity and reduce inequalities of outcome, including by eliminating discriminatory laws, policies, and practices and promoting appropriate legislation, policies, and action in this regard.
- Adopt policies, especially fiscal, wage, and social protection policies, and progressively achieve greater equality.
- Improve the regulation and monitoring of global financial markets and institutions and strengthen the implementation of such regulations.
- Ensure enhanced representation and voice for developing countries in decision-making in global international economic and financial institutions in order to deliver more effective, credible, accountable, and legitimate institutions.
- Facilitate orderly, safe, regular, and responsible migration and mobility of people, including through the implementation of planned and well-managed migration policies.
- Implement the principle of special and differential treatment for developing countries, in particular least developed countries, in accordance with the World Trade Organization agreements.
- Encourage official development assistance and financial flows, including foreign direct investment, to states where the need is greatest, in particular least developed countries, African countries, small island developing states, and landlocked developing countries, in accordance with their national plans and programs.
- By 2030, reduce to less than 3% the transaction costs of migrant remittances, and eliminate remittance corridors with costs higher than 5%.
- More must be done to stop babies from dying the day they are born, United Nations agencies said in a new report issued Thursday, which argued that life-saving know-how and technologies must be made readily available – particularly in Southern Asia and sub-Saharan Africa – where they are most needed.

Facts and Figures

- On average – and taking into account population size – income inequality increased by 11% in developing countries between 1990 and 2010.
- A significant majority of households in developing countries – more than 75% of the population – are living today in societies where income is more unequally distributed than it was in the 1990s.

- Evidence shows that, beyond a certain threshold, inequality harms growth and poverty reduction, the quality of relations in the public and political spheres, and individuals' sense of fulfillment and self-worth.
- There is nothing inevitable about growing income inequality; several countries have managed to contain or reduce income inequality while achieving strong growth performance.
- Income inequality cannot be effectively tackled unless the underlying inequality of opportunities is addressed.
- In a global survey conducted by UN Development Programme, policymakers from around the world acknowledged that inequality in their countries is generally high and potentially a threat to long-term social and economic development.
- Evidence from developing countries shows that children in the poorest 20% of the populations are still up to three times more likely to die before their fifth birthday than children in the richest quintiles.
- Social protection has been significantly extended globally, yet persons with disabilities are up to five times more likely than average to incur catastrophic health expenditures.
- Despite overall declines in maternal mortality in the majority of developing countries, women in rural areas are still up to three times more likely to die while giving birth than women living in urban centers.

12 Goal 11: Sustainable Cities and Communities

12.1 Make Cities Inclusive, Safe, Resilient, and Sustainable

Cities are hubs for ideas, commerce, culture, science, productivity, social development, and much more. At their best, cities have enabled people to advance socially and economically.

However, many challenges exist to maintaining cities in a way that continues to create jobs and prosperity while not straining land and resources. Common urban challenges include congestion, lack of funds to provide basic services, a shortage of adequate housing, and declining infrastructure.

The challenges cities face can be overcome in ways that allow them to continue to thrive and grow while improving resource use and reducing pollution and poverty. The future we want includes cities of opportunities for all, with access to basic services, energy, housing, transportation, and more.

Goal 11 Targets

- By 2030, ensure access for all to adequate, safe, and affordable housing and basic services and upgrade slums.

- By 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities, and older persons.
- By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management in all countries.
- Strengthen efforts to protect and safeguard the world's cultural and natural heritage.
- By 2030, significantly reduce the number of deaths and the number of people affected, and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.
- By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
- By 2030, provide universal access to safe, inclusive and accessible, and green and public spaces, in particular for women and children, older persons, and persons with disabilities.
- Support positive economic, social, and environmental links between urban, peri-urban, and rural areas by strengthening national and regional development planning.
- By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans toward inclusion, resource efficiency, mitigation and adaptation to climate change, and resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels.
- Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials.

Facts and Figures

- Half of humanity – 3.5 billion people – lives in cities today.
- By 2030, almost 60% of the world's population will live in urban areas.
- Ninety-five percent of urban expansion in the next decades will take place in developing world.
- Eight hundred twenty-eight million people live in slums today, and the number keeps rising.
- The world's cities occupy just 3% of the Earth's land but account for 60–80% of energy consumption and 75% of carbon emissions.
- Rapid urbanization is exerting pressure on freshwater supplies, sewage, the living environment, and public health.
- But the high density of cities can bring efficiency gains and technological innovation while reducing resource and energy consumption.

13 Goal 12: Responsible Consumption and Production

13.1 Ensure Sustainable Consumption and Production Patterns

Sustainable consumption and production is about promoting resource and energy efficiency and sustainable infrastructure and providing access to basic services, green and decent jobs, and a better quality of life for all. Its implementation helps to achieve overall development plans; reduce future economic, environmental, and social costs; strengthen economic competitiveness; and reduce poverty.

Sustainable consumption and production aims at "doing more and better with less," increasing net welfare gains from economic activities by reducing resource use, degradation, and pollution along the whole life cycle while increasing quality of life. It involves different stakeholders, including business, consumers, policymakers, researchers, scientists, retailers, media, and development cooperation agencies, among others.

It also requires a systemic approach and cooperation among actors operating in the supply chain, from producer to final consumer. It involves engaging consumers through awareness-raising and education on sustainable consumption and lifestyles, providing consumers with adequate information through standards and labels, and engaging in sustainable public procurement, among others.

Goal 12 Targets

- Implement the 10-year framework of programs on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries.
- By 2030, achieve the sustainable management and efficient use of natural resources.
- By 2030, halve per capita global food waste at the retail and consumer levels, and reduce food losses along production and supply chains, including postharvest losses.
- By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water, and soil in order to minimize their adverse impacts on human health and the environment.
- By 2030, substantially reduce waste generation through prevention, reduction, recycling, and reuse.
- Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle.
- Promote public procurement practices that are sustainable, in accordance with national policies and priorities.
- By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature.

- Support developing countries to strengthen their scientific and technological capacity to move toward more sustainable patterns of consumption and production.
- Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products.
- Rationalize inefficient fossil fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities.

Facts and Figures

- Each year, an estimated one third of all food produced – equivalent to 1.3 billion tonnes worth around $1 trillion – ends up rotting in the bins of consumers and retailers or spoiling due to poor transportation and harvesting practices.
- If people worldwide switched to energy-efficient lightbulbs, the world would save US $120 billion annually.
- Should the global population reach 9.6 billion by 2050, the equivalent of almost three planets could be required to provide the natural resources needed to sustain current lifestyles.
- Less than 3% of the world's water is fresh (drinkable), of which 2.5% is frozen in the Antarctica, Arctic, and glaciers. Humanity must therefore rely on 0.5% for all of man's ecosystem's and freshwater needs.
- Man is polluting water faster than nature can recycle and purify water in rivers and lakes.
- More than 1 billion people still do not have access to fresh water.
- Excessive use of water contributes to the global water stress.
- Water is free from nature, but the infrastructure needed to deliver it is expensive.
- Despite technological advances that have promoted energy efficiency gains, energy use in OECD countries will continue to grow another 35% by 2020. Commercial and residential energy use is the second most rapidly growing area of global energy use after transport.
- In 2002 the motor vehicle stock in OECD countries was 550 million vehicles (75% of which were personal cars). A 32% increase in vehicle ownership is expected by 2020. At the same time, motor vehicle kilometers are projected to increase by 40%, and global air travel is projected to triple in the same period.
- Households consume 29% of global energy and consequently contribute to 21% of resultant CO2 emissions.
- One fifth of the world's final energy consumption in 2013 was from renewables.

- While substantial environmental impacts from food occur in the production phase (agriculture, food processing), households influence these impacts through their dietary choices and habits. This consequently affects the environment through food-related energy consumption and waste generation.
- 1.3 billion tonnes of food is wasted every year, while almost 1 billion people go undernourished and another 1 billion hungry.
- Overconsumption of food is detrimental to our health and the environment.
- Two billion people globally are overweight or obese.
- Land degradation, declining soil fertility, unsustainable water use, overfishing, and marine environment degradation are all lessening the ability of the natural resource base to supply food.
- The food sector accounts for around 30% of the world's total energy consumption and accounts for around 22% of total greenhouse gas emissions.

14 Goal 13: Climate Action

14.1 Take Urgent Action to Combat Climate Change and Its Impacts

Climate change is now affecting every country on every continent. It is disrupting national economies and affecting lives, costing people, communities, and countries dearly today and even more tomorrow.

People are experiencing the significant impacts of climate change, which include changing weather patterns, rising sea level, and more extreme weather events. The greenhouse gas emissions from human activities are driving climate change and continue to rise. They are now at their highest levels in history. Without action, the world's average surface temperature is projected to rise over the twenty-first century and is likely to surpass 3 °C this century – with some areas of the world expected to warm even more. The poorest and most vulnerable people are being affected the most.

Affordable, scalable solutions are now available to enable countries to leapfrog to cleaner, more resilient economies. The pace of change is quickening as more people are turning to renewable energy and a range of other measures that will reduce emissions and increase adaptation efforts.

But climate change is a global challenge that does not respect national borders. Emissions anywhere affect people every.

Goal 13 Targets

- Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.
- Integrate climate change measures into national policies, strategies, and planning.

- Improve education, awareness-raising, and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning.
- Implement the commitment undertaken by developed country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible.
- Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing states, including focusing on women, youth, and local and marginalized communities.
- Acknowledge that the United Nations Framework Convention on Climate Change is the primary international, intergovernmental forum for negotiating the global response to climate change.

Facts and Figures

- From 1880 to 2012, average global temperature increased by 0.85 °C. To put this into perspective, for each 1° of temperature increase, grain yields decline by about 5%. Maize, wheat, and other major crops have experienced significant yield reductions at the global level of 40 Mg per year between 1981 and 2002 due to a warmer climate.
- Oceans have warmed, the amounts of snow and ice have diminished, and sea level has risen. From 1901 to 2010, the global average sea level rose by 19 cm as oceans expanded due to warming and ice melted. The Arctic's sea ice extent has shrunk in every successive decade since 1979, with 1.07 million km^2 of ice loss every decade.
- Given current concentrations and ongoing emissions of greenhouse gases, it is likely that by the end of this century, the increase in global temperature will exceed 1.5 °C compared to 1850–1900 for all but one scenario. The world's oceans will warm and ice melt will continue. Average sea level rise is predicted as 24–30 cm by 2065 and 40–63 cm by 2100. Most aspects of climate change will persist for many centuries even if emissions are stopped.
- Global emissions of carbon dioxide (CO2) have increased by almost 50% since 1990.
- Emissions grew more quickly between 2000 and 2010 than in each of the three previous decades.
- It is still possible, using a wide array of technological measures and changes in behavior, to limit the increase in global mean temperature to 2 °C above pre-industrial levels.
- Major institutional and technological change will give a better than even chance that global warming will not exceed this threshold.

15 Goal 14: Life Below Water

15.1 Conserve and Sustainably Use the Oceans, Seas, and Marine Resources

The world's oceans – their temperature, chemistry, currents, and life – drive global systems that make the Earth habitable for humankind.

Our rainwater, drinking water, weather, climate, coastlines, much of our food, and even the oxygen in the air we breathe are all ultimately provided and regulated by the sea. Throughout history, oceans and seas have been vital conduits for trade and transportation.

Careful management of this essential global resource is a key feature of a sustainable future.

Goal 14 Targets

- By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.
- By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans.
- Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels. By 2020, effectively regulate harvesting and end overfishing, illegal, unreported, and unregulated fishing and destructive fishing practices, and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics.
- By 2020, conserve at least 10% of coastal and marine areas, consistent with national and international law and based on the best available scientific information.
- By 2020, prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing; eliminate subsidies that contribute to illegal, unreported, and unregulated fishing; and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and least developed countries should be an integral part of the World Trade Organization fisheries subsidies negotiation.
- By 2030, increase the economic benefits to small island developing states and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture, and tourism.
- Increase scientific knowledge, develop research capacity, and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to

the development of developing countries, in particular small island developing states and least developed countries.
- Provide access for small-scale artisanal fisheries to marine resources and markets.
- Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in UNCLOS, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of The Future We Want.

Facts and Figures
- Oceans cover three quarters of the Earth's surface, contain 97% of the Earth's water, and represent 99% of the living space on the planet by volume.
- Over three billion people depend on marine and coastal biodiversity for their livelihoods.
- Globally, the market value of marine and coastal resources and industries is estimated at $3 trillion per year or about 5% of global GDP.
- Oceans contain nearly 200,000 identified species, but actual numbers may lie in the millions.
- Oceans absorb about 30% of carbon dioxide produced by humans, buffering the impacts of global warming.
- Oceans serve as the world's largest source of protein, with more than three billion people depending on the oceans as their primary source of protein.
- Marine fisheries directly or indirectly employ over 200 million people.
- Subsidies for fishing are contributing to the rapid depletion of many fish species and are preventing efforts to save and restore global fisheries and related jobs, causing ocean fisheries to generate US$ 50 billion less per year than they could.
- As much as 40% of the world oceans are heavily affected by human activities, including pollution, depleted fisheries, and loss of coastal habitats.

16 Goal 15: Life on Land

16.1 Sustainably Manage Forests, Combat Desertification, Halt and Reverse Land Degradation, and Halt Biodiversity Loss

Forests cover 30% of the Earth's surface, and in addition to providing food security and shelter, forests are key to combating climate change and protecting biodiversity and the homes of the indigenous population. Thirteen million hectares of forests are being lost every year, while the persistent degradation of drylands has led to the desertification of 3.6 billion hectares.

Deforestation and desertification – caused by human activities and climate change – pose major challenges to sustainable development and have affected the lives and livelihoods of millions of people in the fight against poverty. Efforts are being made to manage forests and combat desertification.

Goal 15 Targets

- By 2020, ensure the conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains, and drylands, in line with obligations under international agreements.
- By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests, and substantially increase afforestation and reforestation globally.
- By 2030, combat desertification; restore degraded land and soil, including land affected by desertification, drought, and floods; and strive to achieve a land degradation-neutral world.
- By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development.
- Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity, and, by 2020, protect and prevent the extinction of threatened species.
- Promote fair and equitable sharing of the benefits arising from the utilization of genetic resources, and promote appropriate access to such resources, as internationally agreed.
- Take urgent action to end poaching and trafficking of protected species of flora and fauna, and address both demand and supply of illegal wildlife products.
- By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species.
- By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, and poverty reduction strategies and accounts.
- Mobilize and significantly increase financial resources from all sources to conserve and sustainably use biodiversity and ecosystems.
- Mobilize significant resources from all sources and at all levels to finance sustainable forest management, and provide adequate incentives to developing countries to advance such management, including for conservation and reforestation.
- Enhance global support for efforts to combat poaching and trafficking of protected species, including by increasing the capacity of local communities to pursue sustainable livelihood opportunities.

Facts and Figures

- Around 1.6 billion people depend on forests for their livelihood. This includes some 70 million indigenous people.
- Forests are home to more than 80% of all terrestrial species of animals, plants, and insects.
- 2.6 billion people depend directly on agriculture, but 52% of the land used for agriculture is moderately or severely affected by soil degradation.
- As of 2008, land degradation affected 1.5 billion people globally.
- Arable land loss is estimated at 30–35 times the historical rate.

- Due to drought and desertification, each year 12 million hectares are lost (23 ha per minute), where 20 million tons of grain could have been grown.
- Seventy-four percent of the poor are directly affected by land degradation globally.
- Of the 8300 animal breeds known, 8% are extinct and 22% are at risk of extinction.
- Of the over 80,000 tree species, less than 1% have been studied for potential use.
- Fish provide 20% of animal protein to about 3 billion people. Only ten species provide about 30% of marine capture fisheries, and ten species provide about 50% of aquaculture production.
- Over 80% of the human diet is provided by plants. Only three cereal crops – rice, maize, and wheat – provide 60% of energy intake.
- As many as 80% of people living in rural areas in developing countries rely on traditional plant-based medicines for basic health care.
- Microorganisms and invertebrates are key to ecosystem services, but their contributions are still poorly known and rarely acknowledged.

17 Goal 16: Peace, Justice, and Strong Institutions

17.1 Promote Just, Peaceful, and Inclusive Societies

Goal 16 of the Sustainable Development Goals is dedicated to the promotion of peaceful and inclusive societies for sustainable development, the provision of access to justice for all, and building effective, accountable institutions at all levels.

Goal 16 Targets

- Significantly reduce all forms of violence and related death rates everywhere.
- End abuse, exploitation, trafficking, and all forms of violence against and torture of children.
- Promote the rule of law at the national and international levels and ensure equal access to justice for all.
- By 2030, significantly reduce illicit financial and arms flows, strengthen the recovery and return of stolen assets, and combat all forms of organized crime.
- Substantially reduce corruption and bribery in all their forms.
- Develop effective, accountable, and transparent institutions at all levels.
- Ensure responsive, inclusive, participatory, and representative decision-making at all levels.
- Broaden and strengthen the participation of developing countries in the institutions of global governance.
- By 2030, provide legal identity for all, including birth registration.
- Ensure public access to information and protect fundamental freedoms, in accordance with national legislation and international agreements.
- Strengthen relevant national institutions, including through international cooperation, for building capacity at all levels, in particular in developing countries, to prevent violence and combat terrorism and crime.

- Promote and enforce nondiscriminatory laws and policies for sustainable development.

Facts and Figures

- Among the institutions most affected by corruption are the judiciary and police.
- Corruption, bribery, theft, and tax evasion cost some US $1.26 trillion for developing countries per year; this amount of money could be used to lift those who are living on less than $1.25 a day and above $1.25 for at least 6 years.
- The rate of children leaving primary school in conflict-affected countries reached 50% in 2011, which accounts to 28.5 million children, showing the impact of unstable societies on one of the major goals of the post 2015 agenda: education.
- The rule of law and development has a significant interrelation and is mutually reinforcing, making it essential for sustainable development at the national and international level.

18 Goal 17: Partnerships for the Goals

18.1 Revitalize the Global Partnership for Sustainable Development

A successful sustainable development agenda requires partnerships between governments, the private sector, and civil society. These inclusive partnerships built upon principles and values, a shared vision, and shared goals that place people and the planet at the center are needed at the global, regional, national, and local level.

Urgent action is needed to mobilize, redirect, and unlock the transformative power of trillions of dollars of private resources to deliver on sustainable development objectives. Long-term investments, including foreign direct investment, are needed in critical sectors, especially in developing countries. These include sustainable energy, infrastructure, and transport, as well as information and communications technologies. The public sector will need to set a clear direction. Review and monitoring frameworks, regulations, and incentive structures that enable such investments must be retooled to attract investments and reinforce sustainable development. National oversight mechanisms such as supreme audit institutions and oversight functions by legislatures should be strengthened.

Goals 17 Targets

- Strengthen domestic resource mobilization, including through international support to developing countries, to improve domestic capacity for tax and other revenue collections.
- Developed countries implement fully their official development assistance commitments, including the commitment by many developed countries to achieve the target of 0.7% of ODA/GNI to developing countries and 0.15–0.20% of ODA/GNI to least developed countries. ODA providers are encouraged to consider setting a target to provide at least 0.20% of ODA/GNI to least developed

countries. Mobilize additional financial resources for developing countries from multiple sources.

- Assist developing countries in attaining long-term debt sustainability through coordinated policies aimed at fostering debt financing, debt relief, and debt restructuring, as appropriate, and address the external debt of highly indebted poor countries to reduce debt distress.
- Adopt and implement investment promotion regimes for least developed countries.
- Enhance North-South, South-South, and triangular regional and international cooperation on and access to science, technology, and innovation, and enhance knowledge sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism.
- Promote the development, transfer, dissemination, and diffusion of environmentally sound technologies to developing countries on favorable terms, including on concessional and preferential terms, as mutually agreed.
- Fully operationalize the technology bank and science, technology, and innovation capacity-building mechanism for least developed countries by 2017, and enhance the use of enabling technology, in particular information and communications technology.
- Enhance international support for implementing effective and targeted capacity-building in developing countries to support national plans to implement all the sustainable development goals, including through North-South, South-South, and triangular cooperation.
- Promote a universal, rule-based, open, nondiscriminatory, and equitable multilateral trading system under the World Trade Organization, including through the conclusion of negotiations under its Doha Development Agenda.
- Significantly increase the exports of developing countries, in particular with a view to doubling the least developed countries' share of global exports by 2020.
- Realize timely implementation of duty-free and quota-free market access on a lasting basis for all least developed countries, consistent with the World Trade Organization decisions, including by ensuring that preferential rules of origin applicable to imports from least developed countries are transparent and simple and contribute to facilitating market access.
- Enhance global macroeconomic stability, including through policy coordination and policy coherence.
- Enhance policy coherence for sustainable development.
- Respect each country's policy space and leadership to establish and implement policies for poverty eradication and sustainable development.
- Enhance the global partnership for sustainable development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology, and financial resources, to support the achievement of the sustainable development goals in all countries, in particular developing countries.
- Encourage and promote effective public, public-private, and civil society partnerships, building on the experience and resourcing strategies of partnerships.

- By 2020, enhance capacity-building support to developing countries, including for least developed countries and small island developing states, to increase significantly the availability of high-quality, timely, and reliable data disaggregated by income, gender, age, race, ethnicity, migratory status, disability, geographic location, and other characteristics relevant in national contexts.
- By 2030, build on existing initiatives to develop measurements of progress on sustainable development that complement gross domestic product, and support statistical capacity-building in developing countries.

Facts and Figures

- Official development assistance stood at $135.2 billion in 2014, the highest level ever recorded.
- Seventy-nine percent of imports from developing countries enter developed countries duty-free.
- The debt burden on developing countries remains stable at about 3% of export revenue.
- The number of Internet users in Africa almost doubled in the past 4 years.
- Thirty percent of the world's youth are digital natives, active online for at least 5 years.
- But more four billion people do not use the Internet, and 90% of them are from the developing world.

19 Cross-References

► Introduction to the Small Satellite Revolution and Its Many Implications
► Historical Perspectives on the Evolution of Small Satellites

References

https://www.un.org/sustainabledevelopment/sustainable-development-goals/

Analysis of Orbit Debris

Joseph N. Pelton

Contents

This chapter is a technical document with key information regarding the Handbook of Small Satellites.

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_85

Abstract

There is increasing concern about the proposed deployment of tens of thousands of small satellites in constellations deployed in low-Earth orbit (LEO) without new more strict procedures being agreed for removal of satellites at end of life under more stringent and mandatory processes. This chapter provides the full text of the U.S. Federal Communications Commission's analysis of the proliferation of satellite being deployed in LEO. Recent filings to deploy even larger small satellite constellations and increased congestion in the orbital altitudes between 700 and 1000 km have only served to increase concerns since this FCC analysis was published.

Keywords

Active Debris Removal · Causality Risk Assessment · European Space Agency · Federal Communications Commission (FCC) of the US · Kessler Syndrome · Long term sustainability of access to outer space · Low Earth Orbit (LEO) · Medium Earth Orbit (MEO) · MegaLEO Constellations · NASA · Orbital Debris Removal Techniques · UN Committee on the Peaceful Uses of Outer Space (COPUOS) · UN Guidelines on Orbital Debris Removal · Working Group on the Long Term Sustainability of Outer Space Activities (LTSOSA)

Part 13.6

US Regulatory Approach to Space Debris Mitigation by the Federal Communications Commission

The entire future of small satellite enterprises and projects of all types may very well hinge on the ability to find a systematic solution to orbital debris mitigation and thus avoid possible onset of the Kessler syndrome. This is an ever-increasing concern in that there are currently projections by the European Space Agency and by NASA that there will be a major collision generating a significant degree of new debris elements in the range of every 5 years (ESA) to perhaps every 10 years (NASA). The concern is that despite no new launches, orbital debris will mount over time.

The current situation is that as many as 20,000 new small satellites could be deployed, largely in LEO orbit, by 2025. Unless there is a new program for consistently removing satellites in the crowded region of the LEO orbit, where over 40% of the debris now resides, the situation could spiral out of control.

Thus there is concern that with the relatively immediate future of the next decade or so, there could be the start of a runway avalanche of debris. Such a condition would not only make the deployment and operation of small satellite constellations quite impossible for the future but actually create dire consequences for all types of future satellite launches and operations.

Some countries such as France have enacted the French Space Operations Act (FSOA) that has specified the requirements by French commercial and governmental aerospace operators to follow United Nations recommended guidelines for orbital debris removal and also set standards for maximizing the safety of deorbiting debris from orbit. In the United States, such safety measures have not been enacted into law. Also there are many entities and governmental agencies and departments that are considered with space safety such as the Department of Space, NASA, the US State Department, the Environmental Protection Agency, the Federal Aviation Agency's Office of Commercial Space Transportation, and the Occupational Safety and Health Administration. The US Federal Communications Commission, an independent agency, has developed the most systematic assessment of orbital debris concerns and possible mitigation procedures that might be implemented.

The following FCC paper on migration techniques and processes is a valuable review of the concerns and possible processes that might be implemented to help alleviate this problem. This FCC Fact Sheet is provided as one of the most useful official assessments of this problem and further actions that might be taken. Other countries are developing their own analysis, guidelines, and procedures for those deploying small satellites and due diligence procedures to limit orbital space debris.

It is anticipated that the Inter-Agency Space Debris Coordination Committee (IADC) and the UN COPUOS may seek to address the subject of additional guidelines or actions that might be undertaken to mitigate the creation of additional space debris in the future. Currently the US FCC document "Mitigation of Orbital Debris in the New Space Age" is among the most detailed and comprehensive analysis of this subject. It sets forth the relevant concerns and possible actions that might be undertaken to limit orbital space debris. It is a useful document that is provided for all that are concerned with this important area of concern.

FCC FACT SHEET∗

Mitigation of Orbital Debris in the New Space Age

Notice of Proposed Rulemaking and Order on Reconsideration, IB Docket No. 18-313

Background: Since 2004, when the Commission first adopted rules regarding orbital debris mitigation for Commission-authorized satellites, there have been numerous developments in technologies and business models that could pose new or additional orbital debris risks. These developments include the proliferation of lower-cost small satellites and proposals to deploy large constellations of nongeostationary satellite orbit (NGSO) systems, some involving thousands of satellites. Prompted by our experience and these developments, we now undertake a comprehensive update of our orbital debris mitigation rules for all Commission-authorized satellites, including experimental and amateur satellites.

What the Notice Would Do:

- Propose new and revised application disclosures regarding:
- deployment and use of deployment devices
- risk of collision with large objects
- choice of operational orbital altitude

- potential impact to operations of manned spacecraft
- trackability and maneuvering capabilities of NGSO satellites
- probability of human casualty resulting from uncontrolled atmospheric re-entry of a satellite
- Seek comment on a design reliability standard for large NGSO satellite constellations.
- Make proposals and seek comment related to satellite disposal reliability and methodology, appropriate deployment altitudes in LEO, and on-orbit lifetime.
- Propose new rules for geostationary orbit satellite (GSO) license term extension requests.
- Propose that NGSO satellite operators maintain ephemeris data for each satellite they operate and share that data with the operators of other systems operating in the same region of space.
- Propose new rules and rule updates on additional topics, such as release of persistent liquids, proximity operations, coordination of communications for NGSO orbit-raising maneuvers, and encryption of telemetry, tracking, and command links.
- Propose that Commission satellite licensees indemnify the United States against any costs associated with a claim brought against the United States related to the authorized facilities and seek comment on whether to require that licensees have insurance coverage to provide for payment for any costs associated with such a claim.

What the Order on Reconsideration Would Do:

- Deny a petition for reconsideration of the Commission's 2004 orbital debris mitigation rules filed by the Radio Amateur Satellite Corporation (AMSAT).

Federal Communications Commission FCC-CIRC1811-02
Before the
Federal Communications Commission
Washington, D.C. 20554
In the Matters of
Mitigation of Orbital Debris in the New Space Age
Mitigation of Orbital Debris
IB Docket No. 18-313
IB Docket No. 02-54 (Terminated)
NOTICE OF PROPOSED RULEMAKING AND ORDER ON RECONSIDERATION∗
Adopted: [ ] Released: [ ]
By the Commission:
Comment Date: (45 days after date of publication in the Federal Register)
Reply Comment Date: (75 days after date of publication in the Federal Register)
https://www.fcc.gov/proceedings-actions

1 I. INTRODUCTION

1. In many respects, we are at a turning point in the history of space development. Driven by innovation from both established commercial enterprises and new entrepreneurial endeavors, a new landscape for the private space industry is emerging, sometimes referred to as "New Space." Companies have proposed new satellite constellations, some with satellites numbering in the thousands and would provide broadband and other services worldwide. Relatively inexpensive small satellites, many based on what is known as a "CubeSat" form factor,[1] have demonstrated their utility and capabilities across a wide range of satellite services. The launch industry is more dynamic than ever, with new entrants into the launch vehicle market bringing new capabilities and lowering launch costs. There are risks inherent in any operations in space, however, and while we seek to facilitate the development of this new landscape through our role in satellite authorization, the Commission also has a responsibility to ensure that the operations it authorizes are conducted safely and consistent with the public interest.[2] The current period of innovation in the space industry has resulted and will likely continue to result in a significant increase in the number of satellites and types of operations in orbit, both of which have the potential to increase the amount of orbital debris. Thus, mitigating the growth of orbital debris is more critical than ever to ensure continued, safe operations in space. Orbital debris, also known as "space debris", consists of artificial objects orbiting the Earth that are not functional spacecraft, and can be created under a variety of scenarios involving satellite systems. Orbital debris can affect the cost, reliability, integrity, and capability of new satellite systems and valuable services to the public, and it has the potential to cause physical harm to both people and property.[3] As the Commission has previously found, consideration of orbital debris issues can thus play an important role in preserving access to space for the long term and in ensuring the safety of persons and property in space and on the surface of the Earth.[4]

2. This Notice of Proposed Rulemaking (NPRM or Notice) represents the first comprehensive look at the Commission's orbital debris rules since their adoption in 2004. The proposed changes are designed to improve and clarify these rules based on experience gained in the satellite licensing process and on improvements in mitigation guidelines and practices, and to address the various market developments

---

[1] A "CubeSat" is a standardized small satellite interface consisting of one or more "units." As originally conceived, a CubeSat unit is approximately 10 cm x 10 cm x 10 cm in size. See Streamlining Licensing Procedures for Small Satellites, Notice of Proposed Rulemaking, IB Docket No. 18-86, FCC 18-44 at 4, para. 5 (April 17, 2018) (Small Satellite NPRM).

[2] Mitigation of Orbital Debris, Second Report and Order, 19 FCC Rcd 11567, 11575, para. 14 (2004) (Orbital Debris Order). The Commission has observed that robotic spacecraft are typically controlled through radiocommunications links, and thus there is a direct connection between the satellite's radiocommunications functions and the physical operations of spacecraft. Id.

[3] Id.

[4] Id.

described above. In addition, we deny a petition[5] seeking reconsideration of the Commission's decision in 2004 to apply orbital debris mitigation requirements to amateur service satellites.[6]

2 II. BACKGROUND

3. Pursuant to its authority to determine whether the public interest would be served by the authorization of satellite communications systems, the Commission adopted comprehensive rules on orbital debris in 2004.[7] The core of these rules consists of disclosure requirements that yield information critical to the Commission's overall determination of whether the public interest will be served by approving the proposed operations. Under the Commission's satellite application rules, applicants must include a statement that they have assessed and limited the amount of debris released in a planned manner during normal operations, and have assessed and limited the probability of the satellite becoming a source of debris by collisions with small debris.[8] Applicants must also state that they have assessed and limited the probability of accidental explosions during and after completion of mission operations.[9] The rules also require a statement that the satellite applicant has assessed and limited the probability of the satellite becoming a source of debris by collisions with large debris or other operational satellites.[10] Finally, applicants must include a statement detailing the post-mission disposal plans for the satellite as it enters its end-of-life stage, including the quantity of fuel—if any—that will be reserved for post-mission disposal maneuvers.[11]

4. In addition to general disclosure obligations, the Commission has adopted other rules related to physical spacecraft operations, such as requirements for the maintenance of orbital locations in the geostationary-satellite orbit (GSO),[12] and for GSO inclined-orbit operations.[13] In addition, the Commission has specific post-mission disposal requirements for both GSO and non-geostationary (NGSO) satellites.[14]

---

[5] Radio Amateur Satellite Corporation, Petition for Reconsideration, IB Docket No. 02-54 (filed Oct. 12, 2004) (AMSAT Petition).

[6] See Orbital Debris Order, 19 FCC Rcd at 11608 (paras. 99-100). In the Orbital Debris Order, the Commission amended section 97.207 of its rules, which went into effect on October 19, 2005. See Mitigation of Orbital Debris, 70 Fed. Reg. 59,276 (October 12, 2005); Public Notice, Disclosure of Orbital Debris Mitigation Plans, Including Amendment of Pending Applications, SPB-112, DA 05-2698 (rel. Oct. 13, 2005).

[7] See Orbital Debris Order, 19 FCC Rcd at 11575, para. 14.

[8] 47 CFR § 25.114(d)(14)(i).

[9] 47 CFR § 25.114(d)(14)(ii).

[10] 47 CFR § 25.114(d)(14)(iii).

[11] 47 CFR § 25.114(d)(14)(iv).

[12] 47 CFR § 25.210(j).

[13] 47 CFR § 25.280.

[14] 47 CFR § 25.283.

5. The Commission reviews these disclosures and determines, on a case-by-case basis, whether the public interest will be served by approval of the proposed operations.[15] The rules adopted in 2004 provided some general guidance on the content of disclosures, but the Commission generally declined to adopt a particular methodology for the preparation and evaluation of an applicant's orbital debris mitigation plans.[16] Both applicants and the Commission, however, have relied in a number of cases on standards and related assessment tools, such as the technical standards and related software tools developed by NASA for its space activities,[17] to, respectively, prepare such orbital debris plans and assess their adequacy.[18]

6. Since the Commission's orbital debris rules were adopted in 2004, there have been a number of significant developments with respect to this topic. Internationally, within the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS), the Working Group on the Long-term Sustainability of Outer Space Activities of the Scientific and Technical Subcommittee has developed a set of voluntary guidelines to assist States and international intergovernmental organizations, recognizing that "[t]he proliferation of space debris, the increasing complexity of space operations, the emergence of large constellations, and the increased risks of collision and interference with the operation of space objects may affect the long-term sustainability of space activities."[19] The Inter-Agency Space

---

[15] Orbital Debris Order, 19 FCC Rcd at 11577, para. 19; 47 U.S.C. § 309(a). The Commission's public interest determination regarding an applicant's request for authorization of a satellite communications system is not, of course, based solely on the sufficiency of an applicant's plans for managing orbital debris. It also requires a number of other findings (e.g., that the applicant possesses the basic qualifications to hold the authorization and that the proposed system will conform to the FCC's technical operational rules).

[16] Orbital Debris Order, 19 FCC Rcd at 11577, para. 21

[17] In the Orbital Debris Order, the Commission observed that NASA had adopted publicly-available safety standards that provided a handbook for debris mitigation analysis and activities. Orbital Debris Order, 19 FCC Rcd at 11577, para. 21. See NASA Technical Standard, Process for Limiting Orbital Debris, NASA-STD-8719.14A (with Change 1) (May 25, 2012), http://www.hq.nasa.gov/office/codeq/doctree/871914.pdf (NASA Standard). The NASA Standard is "consistent with the objectives of the U.S. National Space Policy of the United States of America (June 2010), the U.S. Government Orbital Debris Mitigation Standard Practices (February 2001), the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines (October 2002), the Space and Missile Center Orbital Debris Handbook, Technical Report on Space Debris (July 2002), the space debris mitigation guidelines of the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Use of Outer Space, (A/AC.105/720, 1999 and A/AC.105/890, Feb 2007)." Id. at 5.

[18] See, e.g., Part 25 Second Report and Order, 30 FCC Rcd at 14824-25, para. 361 (stating the Commission will rely on the NASA Standard, among other guidance, when assessing satellite end-of-life passivation plans); Orbital Debris Order, 19 FCC Rcd at 11603-04, para. 88 (providing that entities may wish to look at NASA standards as a guide when preparing their human casualty risk assessments); Guidance on Obtaining Licenses for Small Satellites, Public Notice, 28 FCC Rcd 2555, 2558 (IB/OET 2013) ("An orbital debris assessment report prepared consistent with NASA standards is generally sufficient to meet FCC requirements.").

[19] Guidelines for the long-term sustainability of outer space activities, UN Document A/AC.105/L.315 (2018) at 1-2, para. 1.

Debris Coordination Committee (IADC), an inter-governmental committee, updated its Space Debris Mitigation Guidelines in 2007,[20] and more recently, has studied the orbital debris population in the LEO region[21] and has issued a preliminary statement on large constellations of satellites in that region.[22] Domestically, NASA has issued revised versions of its "Procedural Requirements for Limiting Orbital Debris"[23] and its "Technical Standard on the Process for Limiting Orbital Debris",[24] and has updated software available to assess compliance with its guidelines.[25]

7. In addition, the number of debris objects capable of producing catastrophic damage to functional spacecraft has increased. Orbital debris objects greater than one centimeter in diameter can cause catastrophic damage to functional spacecraft.[26] Over 100,000 objects between 1 and 10 cm were estimated to be in orbit in 2004.[27] Approximately 500,000 such objects were estimated to be in orbit as of 2012.[28] Of these, the U.S. Joint Space Operations Center (JSpOC) tracks approximately 23,000 man-made objects achieving orbit.[29] Satellite breakups have been a significant contributor to the increase in the orbital debris population. For example, fragments associated with the intentional fragmentation of the Fengyun 1C spacecraft in 2007 and the accidental collision of the Cosmos 2251 spacecraft with the commercial Iridium 33 spacecraft in 2009 account for over 25% of cataloged on-orbit space objects.[30] The orbital altitudes where these fragments are located is an area of significant density of space objects.[31]

---

[20] IADC Space Debris Mitigation Guidelines, IADC, IADC-02-01, Rev. 1 (2007).

[21] Stability of the Future LEO Environment, IADC, IADC-12-08, Rev. 1 (2013).

[22] IADC Statement on Large Constellations of Satellites in Low Earth Orbit, IADC, IADC-15-03 (2017) (IADC Statement on Large Constellations).

[23] NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environment, NPR 8715.6B (Feb. 16, 2017), https://www.orbitaldebris.jsc.nasa.gov/library/npr_8715_006b_.pdf. (NASA Procedural Requirements); Updates to NASA Procedural Requirements for Limiting Orbital Debris," Nov. 24, 2017, http://sma.nasa.gov/news/articles/newsitem/2017/04/24/updates-to-nasa-procedural-requirements-for-limiting-orbital-debris.

[24] See generally NASA Standard. A further update is forthcoming.

[25] See NASA Orbital Debris Program Office, Debris Assessment Software, https://orbitaldebris.jsc.nasa.gov/mitigation/das.html.

[26] Orbital Debris Order, 19 FCC Rcd at 11570, para. 4.

[27] Id. at 11569, para. 2.

[28] See, e.g., NASA Orbital Debris Program Office, Frequently Asked Questions, http://orbitaldebris.jsc.nasa.gov/faqs.html (Mar. 2012).

[29] See JSpOC CubeSat Recommendations at 1. As of July 2018, the JSpOC is now known as the Combined Space Operations Center, or CSpOC.

[30] P.D. Anz-Meador, "The OD Environment in Numbers," NASA Orbital Debris Quarterly News, Volume 21, Issue 2 at 7 (May 2017), https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv21i2.pdf.

[31] Inter-Agency Space Debris Coordination Committee, IADC Working Group 2, Action Item 27.1, Stability of the Future LEO Environment at 3 (2013).

8. Proposed deployments of large satellite constellations[32] in the intensely used LEO region, along with other satellites deployed in the LEO region, will have the potential to increase the risk of debris-generating events. Work continues in international forums, such as in the IADC, on improved debris limitation practices, including with respect to these "mega constellations."[33] New satellite and deployment technologies currently in use and under development also may increase the number of potential debris-generating events, in the absence of improved debris mitigation practices.

3 III. DISCUSSION

9. We propose a number of changes to our existing disclosure and operational requirements and seek comment on additional potential revisions. In addressing orbital debris mitigation, the Commission has drawn from the technical guidance and assessment tools developed by NASA and the modifications to our rules proposed in this NPRM reflect this approach. In some areas where we have proposed general disclosures in lieu of specific design or operational requirements, we believe such disclosures will provide flexibility for us to address ongoing developments in space station design and other technologies. As a general matter, however, if there are well-defined metrics in any of those areas that could provide a basis for a more specific requirement, we ask that those be identified by commenters.

10. We also note that on June 18, 2018, the President issued Space Policy Directive-3, relating to National Space Traffic Management Policy.[34] Recognizing, among other things, that the volume and location of orbital debris are growing threats to space activities and that it is in the interest of all to minimize new debris and mitigate effects of existing debris,[35] the memorandum directs the Administrator of NASA, in coordination with the Secretaries of State, Defense, Commerce, and Transportation, and the Director of National Intelligence, and in consultation with the Chairman of the Commission, to lead efforts to update the U.S. Orbital Debris Mitigation Standard Practices and establish new guidelines for satellite design and

---

[32] See, e.g., WorldVu Satellites Limited (OneWeb) Petition for Declaratory Ruling, IBFS File No. SAT-LOI-20160428-00041, FCC 17-77, 32 FCC Rcd 5366 (granted June 22, 2017) (planned constellation of 720 satellites at approximate altitude of 1200 kilometers); Space Exploration Holdings, LLC (SpaceX) Application, IBFS File Nos. SAT-LOA-20161115-00118, SAT-LOA-20170726-00110, FCC 18-38 (granted March 28, 2018) (planned constellation of 4,425 satellites at approximate altitudes of 1,110 to 1,325 kilometers).

[33] See, e.g., IADC Statement on Large Constellations; Inter-Agency Space Debris Coordination Committee, An Overview of the IADC Annual Activities, Sept. 7, 2016 http://www.unoosa.org/pdf/SLW2016/Panel4/1._Krag_IADC-16-03_UNCOPUOS_Space_Law_Workshop.pdf.

[34] Space Policy Directive-3, National Space Traffic Management Policy, Presidential Memorandum (June 18, 2018), https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/.

[35] Id. at Sec. 4(b).

operation, as appropriate and consistent with applicable law.[36] It states that the United States should eventually incorporate appropriate standards and best practices into Federal law and regulation through appropriate rulemaking or licensing actions, and that such guidelines should encompass protocols for all stages of satellite operation from design through end-of-life.[37] These efforts are at an early stage and do not provide a basis for specific proposals in this proceeding. However, the Commission's efforts to formulate this NPRM on orbital debris mitigation have been underway for some time, and we believe delaying notice and public comment on proposed improvements to FCC rules would be counterproductive. To the extent that there are updates to the U.S. Orbital Debris Mitigation Standard Practices or other domestic orbital debris guidance documents while this proceeding is open,[38] those developments could be considered in this proceeding.

3.1 A. Control of Debris Released During Normal Operations

11. We start by proposing additional disclosure requirements designed to keep pace with how satellite deployments have evolved over the past decade.

12. In 2004, the Commission observed that satellites used primarily for telecommunications applications do not typically involve the planned release of orbital debris.[39] As part of the orbital debris mitigation disclosure, the Commission nevertheless adopted a requirement that satellite operators represent that they have assessed and limited the amount of debris released in a planned manner during normal operations.[40] It concluded that a statement confirming that no debris would be released by a satellite during normal operations would be sufficient to meet disclosure obligations, and that in any instances where release of operational debris was planned, the Commission would examine such plans on a case-by-case basis and retain the discretion to seek additional information or take action to condition or deny approval, in the event that such a release was found not to serve the public interest.[41] Under this rule, applicants must address any potential operational debris associated with spacecraft operations, except for those directly under the control of the launch vehicle provider.

13. In several recent instances, applicants have sought to deploy satellites using deployment mechanisms that detach from or are ejected from a launch vehicle

---

[36] Id. at Sec. 6(b)(1).

[37] Id. at Sec. 5(b)(1).

[38] See, e.g., Space Policy Directive-3 at Sec. 6(b). The existing U.S. Orbital Debris Mitigation Standard Practices were issued in 2001 and were considered as part of the development of the Commission's orbital debris mitigation rules in the 2000s. See Mitigation of Orbital Debris, Notice of Proposed Rule Making, 17 FCC Rcd 5586, 5590, at para. 10 (2002).

[39] Orbital Debris Order, 19 FCC Rcd at 11578, para. 24.

[40] 47 CFR § 25.114(d)(14)(i).

[41] Orbital Debris Order, 19 FCC Rcd at 11579, para. 24.

upper stage and are designed solely as means of deploying a satellite or satellites, and not intended for other operations. Once these mechanisms have deployed the onboard satellite(s), they become orbital debris. For example, special temporary authority was granted for a spacecraft known as SHERPA, designed to deploy smaller spacecraft from five ports.[42] An experimental authorization was also sought for a satellite that would be one of two satellites deployed from a tubular cylinder deployer, using a spring mechanism.[43] Thus, the deployment of two satellites resulted in three objects, one of which became a debris object very shortly following the beginning of its time in orbit. In other cases, the use of deployment devices, such as separation rings used to facilitate the launch of two geostationary satellites on a single launch vehicle, is an established practice and, while involving the release of operational debris, may in some instances reduce overall debris risk, for example by reducing the number of launches from two to one. As with other manmade objects in space, however, such deployment devices have the potential to collide with other objects and thereby create additional orbital debris. In some instances, the deployment device itself may not require an application for a license from the Commission for radio communications, if it does not have any radio frequency (RF) facilities.

14. In general, generation of operational debris, including from deployment devices, should be minimized. We propose to require disclosure by applicants if such devices are used to deploy their spacecraft, as well as a specific justification for their use. In addition, we propose that the disclosure include information regarding the planned orbital debris mitigation measures specific to the deployment device. Where appropriate, this description of orbital debris mitigation measures may be obtained from the operator of the deployment device.[44] If the deployment device is itself the subject of a separate application for authorization by the Commission (e.g., SHERPA), then the entity seeking a license or a grant of U.S. market access for a satellite may satisfy this disclosure requirement by referencing the deployment device's FCC application or grant. We seek comment on this proposed informational requirement.

3.2 B. Minimizing Debris Generated by Release of Persistent Liquids

15. Most conventional propellant and coolant chemicals evaporate or dissipate if released from a spacecraft. However, certain types of liquids, such as low vapor pressure ionic liquids, will, if released from a satellite, persist in the form of droplets.

---

[42] Spaceflight Inc., IBFS File No. SAT-STA-20150821-00060 (the mission was ultimately cancelled).

[43] See Open Space Networks, ELS File No. 0957-EX-ST-2016, Exh. ODAR at 1-2.

[44] See Appendix A, Proposed Rule Changes, Section 25.114(d)(14)(i).

At orbital velocities, such droplets can cause substantial or catastrophic damage if they collide with other objects.[45] In the last several years, there has been increasing interest in the use by satellites (including small satellites) of alternative propellants and coolants, some of which would become persistent liquids when released by a deployed satellite.

16. Our current rules include a disclosure requirement that satellite operators have assessed and limited the probability of accidental explosions during and after completion of mission operations.[46] This includes a demonstration that debris generation will not result from conversion of energy sources on board into energy that fragments the satellite.[47] But our rules do not require disclosure of liquids that, while not presenting an explosion risk, could nonetheless, if released into space, cause damage to other satellites due to collisions. Accordingly, we propose to include within the rules a requirement to identify any liquids that if released, either intentionally or unintentionally, will persist in a droplet form. We seek comment on this proposal.

3.3 C. Safe Flight Profiles

17. In 2004, the Commission concluded that while the choice of orbit regime (e.g., LEO or GSO) and specific orbital parameters (altitude, inclination, etc.) was generally best left to the operator, in some instances the public interest would be served by a more detailed discussion of how an operator would avoid potential collisions.[48] Our current rules require that an applicant provide a statement regarding the probability of the satellite becoming a source of debris by collisions with large debris or other operational satellites.[49] The existing rule identifies a number of specific disclosures that must be made by applicants in certain circumstances.[50]

18. In an effort to ensure that the physical operations of both existing and planned systems do not contribute to the orbital debris environment, particularly in the heavily-used LEO region, we propose to update our rules. We note that the Commission has fielded an increasing number of applications for NGSO systems for large constellations, as well as for individual small satellites.[51] In an effort to update our rules, as well as implement emerging best practices in an increasingly-crowded

---

[45] A notable example of this type of debris source involves sodium potassium reactor coolant released from Sovietera satellites. "New Debris Seen from Decommissioned Satellite with Nuclear Power Source," NASA Orbital Debris Quarterly News, Volume 13, Issue 1 at 1-2 (January 2009), https://orbitaldebris.jsc.nasa.gov/quarterlynews/pdfs/odqnv13i1.pdf.

[46] 47 CFR § 25.114(d)(14)(ii); see Orbital Debris Order, 19 FCC Rcd at 11580-82, at paras. 29-33.

[47] 47 CFR § 25.114(d)(14)(ii).

[48] Orbital Debris Order, 19 FCC Rcd at 11588, paras. 49-50.

[49] 47 CFR § 25.114(d)(14)(iii).

[50] See id.

[51] See Small Satellite NPRM, FCC 18-44 at 6, para. 9.

space environment, we propose modifications to the current rule, and additional specific disclosures regarding selection of orbit and deployment, trackability, maneuverability, and other related matters.

3.3.1 1. Quantifying Collision Risk

19. Our rules provide for an assessment of the probability of a satellite becoming a source of debris as a result of large object collision, but do not require that the operator quantify this probability.[52] We propose to incorporate into our rules a metric based on the current NASA Standard. Specifically, we propose that applicants for NGSO satellites must demonstrate that the probability that their spacecraft will collide with a large object during the orbital lifetime[53] of the spacecraft will be no greater than 0.001.[54]

We seek comment on whether, if a spacecraft's orbital debris mitigation plan includes maneuvering to avoid collisions, we should, consistent with current licensing practice, consider this risk to be zero or near zero during the period of time in which the spacecraft is maneuverable, absent contrary information. The NASA Standard applies the 0.001 metric on a per-spacecraft basis.[55] We invite comment on whether this metric should also be applied on an aggregate, system-wide basis, i.e., 0.001 for an entire constellation. If such a requirement is adopted on an aggregate basis, would it provide an incentive for evasion of the aggregate limit, for example, through a single controlling party applying for multiple satellite constellations, each of which meets the limit, but which collectively would not? Are existing procedures adequate to identify any such instances of evasion? We also seek comment on whether we should specify a size for what is considered a large object, or whether we should continue our current case-by-case approach, which in practice typically results in consideration of catalogued objects.[56] We note that advancements in capabilities and practices suggest that smaller objects may be catalogued and perhaps routinely tracked in the coming years. The Space Fence ground-based radar, scheduled to begin regular operations in 2019, is designed to

---

[52] 47 CFR § 25.114(d)(14)(iii).

[53] For purposes of this NPRM and our proposed rules, "orbital lifetime" is defined as the length of time an object remains in orbit. Objects in LEO or passing through LEO lose energy as they pass through the Earth's upper atmosphere, eventually getting low enough in altitude that the atmosphere removes them from orbit. NASA Technical Standard, Safety and Mission Assurance Acronyms, Abbreviations, and Definitions, NASA-STD 8709.22 at 94 (with Change 2) (October 31, 2012), http://www.hq.nasa.gov/office/codeq/doctree/NS870922.pdf.

[54] NASA Standard at 32, Requirement 4.5.2. This is consistent with the Commission's recent proposal for satellites licensed pursuant to the proposed streamlined satellite process. Small Satellite NPRM, FCC 18-44 at 18, para. 37. NASA applies this metric to programs and projects involving spacecraft "in or passing through LEO." Id. We propose to apply this to all NGSO satellites.

[55] Id.

[56] Space-Track.org, FAQ, https://www.space-track.org/documentation#/faq (stating 10 cm diameter or "softball size" is the typical minimum size object that current sensors can track and that is maintained by the JSpOC in its catalog).

provide the U.S. Air Force with the ability to detect objects smaller than what can be detected by current systems.[57] Nonetheless, the specific ways in which this new data will be incorporated into the space object catalog, and the extent to which the addition of one sensor can support routine tracking, including tracking sufficient for collision avoidance activities, have not yet been specified.

20. We also propose other revisions to the NGSO-related provisions of the existing rule regarding collision risk.[58] The existing rule states that where a satellite will be launched into a LEO region orbit that is identical, or very similar, to an orbit used by other satellites, the orbital debris mitigation statement must include analysis of potential risk of collision, disclosures regarding whether a satellite operator is relying on coordination with the other system for collision avoidance, and what coordination measures have been or will be taken.[59] First, we propose to revise the wording of the rule to require that, instead of identifying satellites with similar orbits, the orbital debris mitigation statement must identify the planned and/or operational satellites to which the applicant's satellite poses a collision risk, and indicate what steps have been taken or will be taken to coordinate with the other spacecraft or system and facilitate future coordination, or what other measures the operator may use to avoid collision.[60] This revision may provide applicants with more certainty about what must be included in the disclosure and help to identify additional collision risks. We believe that concerns about the risk of collisions involving active spacecraft may be best addressed in the first instance through inter-operator coordination.[61] Second, we propose to extend this rule to all NGSO satellites, rather than only those that will be launched into the LEO region, since overlap in orbits among NGSO spacecraft in other regions could equally result in collision creating orbital debris.[62] We anticipate that in lightly-used orbits, the statement can simply indicate that there are no other planned or operational spacecraft posing a collision risk.

---

[57] See, e.g., Lockheed Martin, Space Fence, https://www.lockheedmartin.com/en-us/products/space-fence.html (last visited Oct. 22, 2018); U.S. Government Accountability Office, Space Situational Awareness, Status of Efforts and Planned Budgets, GAO-16-6R, https://www.gao.gov/products/GAO-16-6R (rel. Oct. 8, 2015).

[58] See 47 CFR § 25.114(d)(14)(iii).

[59] Id.

[60] See Appendix A, Proposed Rule Changes, §25.114(d)(14)(iv).

[61] See, e.g., Telesat Canada, Petition for Declaratory Ruling to Grant Access to the U.S. Market for Telesat's NGSO Constellation, Order and Declaratory Ruling, FCC 17-147, 32 FCC Rcd 9663, 9668, para. 12 (2017). The Commission conditioned grant of market access to Telesat Canada on the provision of additional information about its orbital debris mitigation plan, including: a discussion of any steps that Telesat has taken to coordinate physical operations with authorized and proposed NGSO systems at similar orbital altitudes (both for the main mission and disposal phases); a discussion of the level of data-sharing that would be required with other operators, including analysis of likely requirements for ephemeris refresh rates and time frames for coordination of planned maneuvers (both for the main mission and disposal phases); and whether Telesat has considered alternative orbital altitudes for its operations and whether those altitudes would materially affect Telesat's ability to provide service. Id. at 9669, para. 14.

[62] See Appendix A, Proposed Rule Changes, §25.114(d)(14)(iv).

3.3.2 2. Orbit Selection

21. In addition to quantification of collision risk described above and identification of other relevant planned or operational NGSO satellites, we propose two additional informational requirements with the goals of preventing collisions in crowded orbits, particularly those in the LEO region, and protecting important assets in space.

22. First, for any NGSO satellites planned for deployment above the International Space Station (ISS)[63] and that will transit through the ISS orbit either during or following the satellite operations, we propose that the applicant provide information about any operational constraints caused to the ISS or other inhabitable spacecraft and strategies used to avoid collision with manned spacecraft.[64] For example, will the normal operations of the ISS be significantly disrupted or otherwise constrained by the number of collision avoidance maneuvers that may be necessary as satellites in the constellation transit through the ISS orbit, such as during an uncontrolled de-orbit phase?[65] As noted in the Small Satellite NPRM, deployment of satellites lacking maneuvering capabilities above the ISS, to orbits from which they will eventually transit through the ISS altitude band, increases the likelihood that the ISS will need to conduct avoidance maneuvers, potentially disrupting ISS operations.[66] In that proceeding, the Commission proposed that satellites without propulsion seeking to be processed on a streamlined basis be deployed either from or at altitudes below the ISS.[67] We do not propose similar criteria for satellites authorized outside the streamlined process, but we believe information regarding operational constraints caused to inhabitable spacecraft could help us and any other interested parties to assess the public interest in authorizing any particular satellite or constellation.

---

[63] The ISS operates at an altitude of approximately 400 km.

[64] Between 1999 and July 2015, the International Space Station (ISS) conducted 23 total collision avoidance maneuvers. National Aeronautics and Space Administration, Orbital Debris: Quarterly News, "International Space Station Performs Two Debris Avoidance Maneuvers and a Shelter-in-Place," Vol. 19, Issue 3 at 1 (July 2015), https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv19i3.pdf; see also J.-C. Liou, National Aeronautics and Space Administration, "Orbital Debris Mitigation Policy and Unique Challenges for Cubesats," presentation to the 52nd Session of the Scientific and Technical Subcommittee, Committee on Peaceful Uses of Outer Space, United Nations, February 2015, at 9, available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150020943.pdf.

[65] See NASA NGSO Constellation Comments at 2 (expressing concern about aspect of disposal plan for SpaceX LEO constellation and recommending that SpaceX "seek out creative ways to guarantee they can avoid the ISS and other high value assets" for the entire deorbit phase of their planned spacecraft); Science Applications International Corporation, Orbital Traffic Management Study Final Report, Prepared for NASA Headquarters, at E-1-E-2 (Nov. 21, 2016) (SAIC Orbital Traffic Management Study) ("As debris populations grow in LEO, the odds of [micro-meteoroid or orbital debris] root cause events on ISS will become higher (i.e. worsen)[.]" "Recent analysis by the Aerospace Corporation suggests that the current large planned constellations could increase collision warnings with ISS six-fold, as the decommissioned spacecraft in those constellations decay through the ISS orbit.").

[66] Small Satellite NPRM, FCC 18-44 at 17, para. 34.

[67] Id. at 17, paras. 33-34.

23. Second, we propose that an applicant planning an NGSO constellation that will be deployed in the LEO region above 650 km altitude specify why it has chosen that particular orbit given the number of satellites planned, and describe any other relevant characteristics of the orbit such as the presence of existing debris. Satellites deployed below 650 km will typically re-enter Earth's atmosphere within 25 years,[68] even absent any propulsive or other special de-orbit capabilities. Thus, the collision risks presented by such satellites are generally lower, even if the satellites fail on-orbit and are unable to perform any affirmative de-orbiting maneuvers.[69] Above this approximately 650 km threshold, a satellite that is not affirmatively de-orbited will remain in orbit for significantly longer periods of time. Accordingly, for NGSO deployments above the 650 km altitude, we propose that applicants provide a rationale for choosing a higher orbit, even if the satellites will have propulsive de-orbit capabilities.[70] While we recognize that satellites may be designed to de-orbit within 25 years from altitudes above 650 km, those missions may involve greater risk from an orbital debris perspective due to the possibility of a satellite failure resulting in the satellite remaining in orbit for periods of time in as much as the hundreds or thousands of years.

24. Third, we seek comment on whether we should also require a statement concerning the rationale for selecting an orbit from operators of satellites that will remain in orbit for a long period of time relative to the time needed to perform their mission. For example, a technology demonstration mission in LEO that lasts only a few weeks could result in up to 25 years of collision risk to other operators. One example of an alternative guideline is that operators select orbits such that orbital lifetime exceed mission lifetime by no more than a factor of two. We seek comment on this metric, or alternative metrics that could be incorporated into our rules.

25. Fourth, we note that certain areas of space are more populated with debris, such as that from the Cosmos 2251/Iridium 33 collision. It may be in the public

---

[68] This is consistent with the benchmark contained in the current NASA Standard. NASA Standard at 37, Requirement 4.6.2.

[69] This altitude may vary depending upon the characteristics of the spacecraft and solar activity, but 650 km represents an average approximation. See Inter-Agency Space Debris Coordination Committee, Support to the IADC Space Debris Mitigation Guidelines, IADC-04-06, Rev. 5.5 at 32 (May 2014) ("It is recommended that orbital lifetime be reduced to less than 25 years at the end of mission (approximately 750 km circular orbit for $A/m = 0.05$ m^2/kg, and approximately 600 km circular orbit for A/m=0.005 m2/kg, depending on solar activity to be more exact."); ESA NGSO FSS Comments at 2 (recommending that for large constellations low operational orbits should be considered, noting that average orbital altitudes of less than 650 km for average satellites (< 1 ton) are normally still compatible with a natural decay within 25 years).

[70] As explained in the Orbital Debris Order, the U.S. Government Orbital Debris Standard Practices call for the selection of an orbit from which the spacecraft will remain in orbit no longer than 25 years after mission completion, if the planned disposal method is re-entry into Earth's atmosphere through means of natural atmospheric drag, without the use of propulsion systems. Orbital Debris Order, 19 FCC Rcd at 11592, para. 61; U.S. Government Orbital Debris Standard Practices 4-1, available at https://www.orbitaldebris.jsc.nasa.gov/library/usg_od_standard_practices.pdf (U.S. Government Standard Practices).

interest for new constellations to avoid deployment in such areas to minimize risk, or, stated differently, to design constellations to operate in regions of space where the density of objects is lower, and consequently where the risk of collision with debris objects is lower.[71] We ask whether to require applicants to include an additional disclosure regarding orbit selection based on such risks, or to provide assurances on how the applicant plans to reduce these risks. We also ask whether we should seek additional information or assurances from applicants in more narrow circumstances, for example, where they seek to deploy a large constellation in certain sun-synchronous orbits that have an increased likelihood of congestion.

26. Fifth, in lieu of an informational requirement, should we require all NGSO satellites planning to operate above a particular altitude to include propulsion capabilities reserved for station-keeping and to enable collision avoidance maneuvers, regardless of whether propulsion is necessary to de-orbit within 25 years? If so, above what altitude?

27. Finally, we ask whether we should adopt a maximum limit for variances in orbit for NGSO systems. That is, should we limit the variance in altitude above or below the operational orbit specified in an application for an NGSO system,[72] in order to enable more systems to co-exist in LEO without overlap in orbital altitude, and if so, how should an appropriate limit be set? If such a limit is adopted, should it apply only to near-circular obits, or also to elliptical orbits? We seek comment on these questions, as well as on any additional changes to our rules and policies that may help operators avoid collisions and ultimately reduce the risk of debris generation in heavily-used or otherwise critical orbits.

3.3.3 3. Tracking and Data Sharing

28. The identification of satellites and sharing of tracking data are important to provide timely and accurate assessments of conjunction with other spacecraft.[73] The increase in the number of small satellites, for example, has begun to pose some unique tracking and identification challenges.[74] We believe that improvements in the

---

[71] NASA NGSO Constellation Comments at 2-3 (NASA expressed some concerns regarding proposed orbit of Theia Holdings A, Inc., NGSO satellite constellation, because of the location of other government satellites nearby and the high percentage of Iridium-33/Cosmos-2251 and Fengyun-1C debris in that region).

[72] As an example of the discussion of issues related to variances in orbital altitude for a particular system, SpaceX expressed concern regarding the proposed operational range for OneWeb's planned NGSO system. See Letter from William M. Wiltshire, Counsel to SpaceX, to Marlene H. Dortch, Secretary, FCC, at 2-4, IBFS File Nos. SAT-LOA-20161115-00118 and SAT-LOA-20170301-00027 (filed Dec. 12, 2017).

[73] A conjunction event is one in which space objects, such as an two operational spacecraft or an operational spacecraft and a debris object, are predicted to come within close proximity to each other. A conjunction event may or may not result in a collision.

[74] JSpOC CubeSat Recommendations for Optimal CubeSat Operations, Joint Space Operations Center at 1 (2015), https://file.space-track.org/documents/Recommendations_Optimal_Cubesat_Operations_V2.pdf (JSpOC CubeSat Recommendations); Small Satellite NRPM, FCC 18-44 at 18-19, para. 38.

ability to track and identify satellites in NGSO may help to reduce the risk of collisions. As an initial matter, we propose to require a statement from the applicant regarding the ability to track the proposed satellites using space situational awareness facilities, such as the U.S. Space Surveillance Network.[75] We propose that objects greater than 10 cm by 10 cm by 10 cm be presumed trackable for any altitude up to the geostationary region.[76] For objects with any dimension less than 10 cm, we propose that the applicant provide additional information concerning trackability, which will be reviewed on a case-by-case basis. We also propose that applicants for NGSO systems disclose, as part of their orbital debris mitigation plans, whether satellite tracking will be active and cooperative (that is, with participation of the operator by emitting signals via transponder or sharing data with other operators) or passive (that is, solely by ground based radar or optical tracking of the object).[77] We also ask whether applications should certify that the satellite will include a unique telemetry marker allowing it to be readily distinguished from other satellites or space objects.[78] We further seek comment on whether there are hardware or information sharing requirements that might improve tracking capabilities, and whether such technologies are sufficiently developed that a requirement for their use would be efficient and effective.

29. In addition, we note that the Air Force's 18th Space Control Squadron is currently responsible for maintaining the space catalog and managing United States Strategic Command's space situational awareness sharing program to United States, foreign government, and commercial entities.[79] Among other things, the Air Force's 18th Space Control Squadron currently provides satellite owner/operators with on-orbit conjunction assessments.[80] We seek comment on whether we should adopt an

---

[75] Space situational awareness facilities track satellites and other space objects using radar and other means.

[76] In the Small Satellite NPRM, the Commission proposed that small satellites using the streamlined review process be no smaller than 10 cm x 10 cm x 10 cm, which would help the Commission to process those systems in a streamlined fashion. Small Satellite NPRM, FCC 18-44 at 18-19, para. 38.

[77] See Committee on Achieving Science Goals with CubeSats – Thinking Inside the Box, Space Studies Board, Division on Engineering and Physical Sciences, National Academies of Sciences, Engineering, and Medicine, Achieving Science Goals with CubeSats: Thinking Inside the Box at C-7 (2016), http://www.nap.edu/catalog/23503/achieving-science-with-cubesats-thinking-inside-the-box (discussing tracking technologies).

[78] See Small Satellite NPRM, FCC 18-44, at 19, para. 38. The Commission proposed that small satellites applying under the proposed streamlined process make this certification.

[79] See Peterson Air Force Base, Fact Sheets, 18th Space Control Squadron, https://www.peterson.af.mil/About/Fact-Sheets/Display/Article/1060346/18th-space-control-squadron/.

[80] See SSA Sharing & Orbital Data Requests, Space-Track.org, https://www.space-track.org/documentation#/odr (last visited Oct. 22, 2018) (Space-Track SSA Services Website); See JSpOC CubeSat Recommendations for Optimal CubeSat Operations, Joint Space Operations Center at 2, 3-4.1 (2015), https://file.space-track.org/documents/Recommendations_Optimal_Cubesat_Operations_V2.pdf.

operational rule requiring NGSO satellite operators to provide certain information to the 18th Space Control Squadron or any successor civilian entity, including, for example information regarding initial deployment, ephemeris, and any planned maneuvers. As an example, communication with the Air Force's 18th Space Control Squadron may be particularly important in the case of a multi-satellite deployment, to assist in the identification of the satellite.[81]

30. We also propose that applicants for NGSO systems certify that, upon receipt of a conjunction warning, the operator of the satellite will take all possible steps to assess and, if necessary, to mitigate collision risk, including, but not limited to: contacting the operator of any active spacecraft involved in such warning; sharing ephemeris data and other appropriate operational information directly with any such operator; and modifying spacecraft attitude and/or operations.[82] We seek comment on this approach as one designed to reduce collision risks and enhance certainty among operators, and ask whether any different or additional requirements should be considered regarding the ability to track and identify satellites in NGSO or respond to conjunction warnings.

3.3.4 4. Maneuverability

31. We also propose that applicants for NGSO satellite authorizations demonstrate the extent of any maneuverability. For example, the demonstration could include a description of the number of collision avoidance maneuvers the satellite could be expected to make, and/or any other means the satellite may have to avoid conjunction events. We propose that the description include a discussion of maneuverability both during satellite's operational lifetime and during the remainder of its time in space prior to disposal. We tentatively conclude that such information can assist us in our public interest determination, in particular regarding any burden that other operators would have to bear in order to avoid collisions and false conjunction warnings. We seek comment on this conclusion and note that, as proposed, this is an informational requirement, and would not require that all satellites have propulsion or maneuverability. In addition, we observe that some applications have been granted based on an assessment of information regarding differential drag maneuvers. Recognizing that this is an emerging area from the perspective of collision avoidance, we seek comment concerning effectiveness and suitability of this or other particular maneuvering technologies under real world conditions, and on whether we should implement any specific disclosure requirements with respect to this or other types of emerging maneuvering technology.

---

[81] See JSpOC CubeSat Recommendations at 1 (noting that there were challenges associated with the ORS-3 mission, launching 37 CubeSats, and the DNEPR rocket, launching 31 CubeSats, both in late 2013).

[82] See Appendix A, Proposed Rule Changes, Section 25.114(d)(14)(iv)(A).

3.3.5 5. Multi-Satellite Deployments

32. In recent years, we have observed an increasing number of cases where a single launch vehicle will deploy large numbers of NGSO satellites,[83] often involving some groups of satellites having homogenous designs and others of varying design. A single deployment of a number of satellites from a launch vehicle or free-flying deployment device could result in some heightened risk of collision between objects, or on a longer-term basis due to the similarity of orbits for the released objects. We seek comment on whether we should include in our rules any additional informational requirements regarding such launches.[84] Are there mitigation measures that are commonly employed that mitigate such risks, for example through use of powered flight during the deployment phase and/or through phasing of deployment, that we should consider adopting as requirements under some circumstances?

33. In seeking comment, we recognize that an applicant for a Commission license or authorization may not have access to information regarding other satellites that will be deployed, and ask whether an applicant could obtain general information from the launch provider or aggregator that would assist the Commission in evaluating the risk of collision presented by the deployment itself, even if the launch manifest has not been finalized.

3.3.6 6. Design Reliability

34. In comments filed regarding proposed large constellations of NGSO satellites, NASA suggested that for such constellations, a design and fabrication reliability standard may be appropriate.[85] A design or reliability flaw resulting in malfunction of spacecraft during deployment or mission operations could result in a significant number of non-functional spacecraft in an operational orbit, contributing to the orbital debris population.[86]

35. We seek comment on whether it would be appropriate to impose a design and fabrication reliability requirement, for example, 0.999 per spacecraft, if a NGSO

---

[83] In 2017, for example, a record 104 satellites were launched on a single rocket, the Indian Space Research Organisation's Polar Satellite Launch Vehicle (PSLV). See Department of Space Indian Space Research Organisation, "PSLV-C37 Successfully Launches 104 Satellites in a Single Flight," https://www.isro.gov.in/pslv-c37-successfully-launches-104-satellites-single-flight (last visited Oct. 22, 2018); Santanu Choudhury, "India Breaks Record for Launching Most Satellites from a Single Rocket," Wall Street Journal (Feb. 15, 2017), https://blogs.wsj.com/indiarealtime/2017/02/15/india-breaks-record-for-launching-most-satellites-from-single-rocket/.

[84] See Spaceflight, Inc., IBFS File No. SAT-STA-20150821-0006 (analysis of "within-plane" collision risk for 91 objects planned for deployment in a single launch).

[85] Letter from Anne E. Sweet, NASA Representative on the Commercial Space Transportation Interagency Group, Program Executive, Launch Services Office, Human Exploration and Operations Mission Directorate, NASA to Marlene Dortch, Secretary, FCC, IBFS File Nos. SAT-LOA-20161115-00118, SAT-LOA-20161115-00121 at 1-2 (filed June 26, 2017) (NASA NGSO Constellation Comments).

[86] Id.

satellite constellation involves a large number of satellites or will be initially deployed at higher altitudes in LEO.[87] Deployment of large numbers of satellites increases the spatial density of objects in the region of space where the satellites are deployed, and provides an indicator of potential collision risk. We consider a deployment of 100 satellites over a typical 15-year license term to be a deployment of a large number of satellites, but seek comment on whether a different number may be appropriate. We consider higher altitudes to be those with a perigee above 600-650 km.[88] From these orbits, spacecraft will typically remain in orbit for several decades to centuries, and present a long-term collision risk, unless active measures are taken to shorten orbital lifetimes. We also seek comment and suggestions on other possible metrics, and methods for verifying and assessing compliance with any such metric.

3.4 D. Post-Mission Disposal

36. Post-mission disposal consists of measures taken, often at the end of a spacecraft's useful life, that result in removal of the spacecraft from Earth's orbit, or relocation of the spacecraft to a long term orbit that reduces the risk of collision with operational spacecraft. In 2004, the Commission observed that effective disposal of non-functional spacecraft can both protect operational spacecraft from accidental collisions with orbital debris and reduce the probability of non-functioning objects colliding with one another and creating additional debris.[89] The concerns associated with non-functioning spacecraft are magnified as more satellites are launched, particularly to altitudes where a failed spacecraft may remain in orbit more than 25 years.[90] Under our rules, an applicant's orbital debris mitigation statement must include several elements regarding post-mission disposal, including a description of the planned disposal orbit, for GSO satellites, and a casualty risk assessment for NGSO satellites where planned post-mission disposal involves atmospheric re-entry of the satellite.[91]

---

[87] See id. (suggesting for discussion purposes a design and fabrication reliability on the order of 0.999 or better per spacecraft in a 4,000+ spacecraft constellation); see also Letter from Johann-Dietrich Wörner, Director General, European Space Agency, to Marlene H. Dortch, Secretary, FCC, IB Docket No. 16-408 at 3 (filed Sept. 15, 2017) (ESA NGSO FSS Comments) (noting the exponential relationship between environmental effect and the number of failed spacecraft).

[88] For objects orbiting the Earth, the point in orbit that the object is closest to the Earth is known as the object's "perigee."

[89] Orbital Debris Order, 19 FCC Rcd at 11591, para. 58.

[90] See, e.g., IADC Statement on Large Constellations at 6 (noting that most proposed concepts for large constellations in LEO target at operational altitudes above 1000 km, where the average natural atmospheric drag-induced orbital lifetimes are "quasi eternal"); ESA NGSO FSS Comments at 2 (making the same observation).

[91] 47 CFR § 25.114(d)(14)(iv).

37. Based on our experience since 2004 in evaluating post-mission disposal plans, as well as concerns regarding satellite reliability and large constellations,[92] we propose below specific revisions to our existing disclosure requirements regarding post-mission disposal of NGSO satellites.

3.4.1 1. Probability of Success of Disposal Method

38. Incorporation of Disposal Reliability Metrics. We propose to require that applicants provide information concerning the expected reliability of disposal measures involving atmospheric reentry, and the method by which that expected reliability was derived. We also seek comment on the metric by which such information should be evaluated; for example, should we specify a probability of success of no less than a set figure, such as 0.90?[93] The NASA Standard notes that failure of spacecraft to execute a planned disposal maneuver or operation on a routine basis will result in a more rapid increase in the orbital debris population.[94] Moreover, in the 2004 Orbital Debris Order, the Commission noted that "[r]eliability may be relevant to both the assessment of whether the satellite will meet end-of-life goals, and to the assessment of whether the public interest benefits arising from the satellite's activities will, in fact, be provided."[95] Adding a specific metric for reliability of disposal may help us to better evaluate the applicant's end-of-life disposal plan. We also invite comment as to whether, when assessing the reliability of disposal, we should do so on an aggregate, system-wide basis as well as on a per-satellite basis, and on whether, for large constellation deployments, where due to large numbers of spacecraft aggregate effects could be more damaging to the space environment, a more stringent metric should apply. A recent NASA study of large constellations concluded, for example, that a 0.99 spacecraft post-mission disposal reliability is needed to mitigate the serious long-term debris generation potential from large constellations.[96]

39. Other Requirements for Satellites with Planned Operations in LEO. We propose two additional disclosure requirements related to reliability and seek comment on other possible requirements as well.

---

[92] See, e.g., IADC Statement on Large Constellations at 6 ("It is clear that significant improvements in the reliability of the disposal function at end of life will be needed for the new [large LEO] constellations compared with that currently demonstrated by space systems on orbit.").

[93] See NASA Standard at 41, Requirement 4.6.3.n (specifying that for NASA missions, the probability of success of post-mission disposal operations should be no less than 0.90). This probability metric would apply where post-mission disposal operations will lead to atmospheric reentry or maneuvering the spacecraft into a storage orbit. See id. Consistent with the Commission's discussion in the 2004 Orbital Debris Order, we do not propose to foreclose direct retrieval of the spacecraft from orbit as a means of post-mission disposal. Orbital Debris Order, 19 FCC Rcd at 11591, para. 60.

[94] NASA Standard at 41, Requirement 4.6.3.n.

[95] Orbital Debris Order, 19 FCC Rcd at 11602-03, para. 86.

[96] See J.-C. Liou, et. al., "NASA ODPO's Large Constellation Study" NASA Orbital Debris Quarterly News, Volume 22, Issue 3 at 4-7 (Sept. 2018), https://www.orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv22i3.pdf. The study analyzed three hypothetical constellations operating at 1000 to 1325 km altitudes. Id.

40. First, we propose that the applicant certify that all satellites that will operate at an altitude of 650 km or above will be initially deployed into orbit at an altitude below 650 km and then, once it is determined that the satellite has full functionality, be maneuvered up to their planned operational altitude.[97] This would help to ensure that if satellites are found to be non-functional immediately following deployment, such that they will be unable to perform any maneuvers, they will re-enter the atmosphere within 25 years and not persist in LEO for longer periods of time. As briefly discussed above, [98] ensuring functionality of spacecraft in a large constellation may be particularly important, since an unforeseen flaw could result in the failure of hundreds of satellites of a planned constellation immediately following deployment. We recognize that this requirement may involve additional reserves of fuel, for example, for orbit-raising. In some respects, this is similar to the analysis undertaken in the Commission's 2004 Orbital Debris Order, which resulted in the adoption of a requirement to maneuver GSO spacecraft at end-of-life to a particularly calculated disposal orbit, even though this maneuver required additional fuel.[99] There, the Commission concluded that the additional costs were warranted in order to achieve the public interest in minimizing the hazard posed by orbital debris to the continued safe and reliable use of the GSO region.[100] Similarly, we posit here that the benefits of the continued viability of the LEO region may outweigh the costs of orbit-raising, and seek comment on the costs and benefits associated with this proposal. Relatedly, we seek comment on whether we should require that applicants for large constellations test a certain number of satellites in a lower orbit for a certain number of years before deploying larger numbers, in order to resolve any unforeseen flaws in the design that could result in generation of debris.[101]

41. Second, we propose that applicants seeking to operate NGSO satellite systems provide a statement that spacecraft disposal will be automatically initiated in the event of loss of power or contact with the spacecraft,[102] or describe other means to ensure

---

[97] Appendix A, Proposed Rules. See ESA NGSO FSS Comments at 2 (suggesting that spacecraft be injected into orbits 650 km or lower, and then only move to operational altitude after a successful functional check-out).

[98] See supra Part III.C.6.

[99] See Orbital Debris Order, 19 FCC Rcd at 11593, para. 75.

[100] Id. The GSO region is the region surrounding a circular orbit along the plane of the Earth's equator at an altitude of approximately 35,786 kilometers. Id. at 11568, n. 4. A spacecraft in this orbit can be maintained at a constant longitudinal position relative to the Earth, thus allowing the satellite to be "seen" continuously from, and at a fixed orientation to, any given point on the Earth's surface. Id.

[101] As an example, Telesat Canada, the recipient of a grant of access to the U.S. market for a planned NGSO constellation of 117 satellites, is using prototype satellite(s) for testing and design verification purposes. Telesat Canada, Petition for Declaratory Ruling, IBFS File No. SAT-PDR-20161115-00108, Telesat LOI, Exh. 3 at 5 (granted Nov. 2, 2017). The ESA NGSO FSS comments noted that critical components inducing break-ups are sometimes identified only years after the satellite has been operational, which could result in a large problem with large numbers of satellites, particularly with short production times involved. ESA NGSO FSS Comments at 3.

[102] This type of proposal was suggested by ESA in its comments to the NGSO FSS proceeding, with respect to large constellations. See ESA NGSO FSS comments at 3.

that reliability of disposal will be achieved, such as internal redundancies, ongoing monitoring of the disposal function, or automatic initiation of disposal if communications with the spacecraft become limited.[103] These means would be designed to limit the situations in which the satellite remains on-orbit after a spacecraft failure, or otherwise presents an enhanced hazard for explosions, collisions, or other debris-causing events. Consistent with this rationale, this requirement would help ensure that spacecraft failures do not result in concentration of debris in the LEO region.

42. We recognize that these design features have some associated costs. We seek comment on the costs and benefits associated with this proposed requirement. We also ask whether we should simply require the design to include automatic disposal by a de-orbiting device in the event of loss of power, and on whether any such requirement would provide adequate flexibility for operators to react, for example, if the particular failure mode results in further propulsive maneuvers running a high risk of explosive fragmentation. Are there other technologies that can be used to ensure that satellite disposal is completed, even in the event of a major anomaly, and should we require use of those technologies for satellites that will operate in particular regions?

43. We propose that these two requirements would apply to satellites that will operate above 650 km and below 2,000 km, in other words, in the higher portion of LEO.[104] We also seek comment on whether any requirements should only apply to LEO satellite constellations of a certain size or greater or whether they should apply to all LEO satellites that will operate in the area described.

44. Means of LEO Spacecraft Disposal. Additionally, we seek comment on whether there are other rule changes we should consider related to the disposal of spacecraft from the LEO region. Should we adopt a rule that disposal of spacecraft in the LEO region must be by either atmospheric re-entry or direct retrieval? The U.S. Government Standard Practices, originally developed in the 1990s, recognize disposal to a region above LEO as an option for non-geostationary satellites,[105] but the IADC Guidelines do not recognize this option. The IADC Guidelines instead list the following options for disposal for spacecraft terminating their operational phase in the LEO region: de-orbit, maneuver to an orbit with a reduced lifetime (where the spacecraft will naturally re-enter the atmosphere), or retrieval.[106]

45. We observe that satellites left at higher altitudes will remain in orbit indefinitely, and removal from orbit is generally preferable.[107] With respect to direct retrieval, the Commission concluded in 2004 that direct retrieval was not feasible at that time, but did not preclude direct retrieval as a possible method of post-mission disposal.[108] In assessing whether a post-mission disposal plan is sufficiently reliable, what weight, if

---

[103] Appendix A, Proposed Rules.

[104] Appendix A, Proposed Rules.

[105] U.S. Government Standard Practices at 4-1.

[106] IADC Guidelines at § 5.3.2.

[107] See ESA NGSO FSS Comments at 3 (noting that disposal of satellites in large LEO constellations by orbit raising should be avoided).

[108] Orbital Debris Order, 19 FCC Rcd at 11591, para. 60.

any, and under what circumstances, should we give to proposals to directly retrieve the spacecraft from orbit at its end of life?[109] Should direct retrieval be considered as a valid debris mitigation strategy, for example, only if the retrieval spacecraft are presented for licensing as part of or contemporaneously with the constellation license?

46. Disposal of NGSO Satellites In Orbits Above LEO. We also seek comment on whether to modify the Commission's existing rules regarding end-of-life disposal for satellites to include additional provisions concerning disposal of certain NGSO satellites operating in orbits above LEO. The current rules require disclosure of such plans, and in 2004 we concluded that we would assess disposal plans for satellites that do not pass through the LEO or GEO regions, such as those in highly elliptical orbits or medium Earth orbits, on a case-by-case basis.[110]

47. As a general matter, there appear to be two types of approaches to post-mission disposal above LEO. One approach is to remove a satellite from its operational orbit to another, relatively stable orbit that is sufficiently distinct from those orbits that are currently used or expected to be used for regular operations, so as to eliminate the risk of collisions with such operating satellites.[111] Another approach is to place a satellite into an unstable orbit, i.e., one in which gravitational forces and solar radiation pressure force a growth in the eccentricity of the orbit, ultimately resulting in lowering of the satellite's perigee and re-entry into the atmosphere.[112] While this latter approach may result in disposed satellites traversing other operational orbits and passing through the LEO region, they can ultimately result in removal of the satellite from orbit. Thus, this latter approach may result in less long-term collision risk, although perhaps at the cost of increased short-term risk.

48. We seek comment on whether these practices are sufficiently developed to formalize in our rules. We also seek comment on whether there are any specific guidelines we should include in our rules with respect to these approaches, or with respect to any particular type of orbit.[113]

---

[109] Direct retrieval of satellites implicates the need to assess rendezvous and proximity operations, and any risk of debris generation from those operations.

[110] Orbital Debris Order, 19 FCC Rcd at 11603-04, para 87.

[111] See Satellite CD Radio Inc., IBFS File No. SAT-MOD-20091119-00123, Attachment A at 3-7; O3b Limited, IBFS File No. SES-LIC-20100723-00952, Technical Information to Supplement Schedule S at 37-40; Karousel, LLC, IBFS File No. SAT-LOA-20161115-00113, Letter from Monish Kundra, Karousel LLC, to Jose P. Albuquerque, Chief, Satellite Division, International Bureau, FCC (April 11, 2017) at 7-8. The geostationary disposal requirement in our rules, intended for satellites orbiting at inclinations of approximately 15 degrees or less, can be viewed as an example of this type of disposal.

[112] Space Norway AS, IBFS File No. SAT-PDR-20161115-00111, Technical Information to Supplement Schedule S at 15-18. This approach appears to be more readily available for satellites operating at higher inclinations.

[113] End-of-life Disposal in Inclined Geosynchronous Orbits, Luciano Anselmo & Carmen Pardini, Proceedings of the 9th IAASS Conference, International Association for the Advancement of Space Safety, 2017, pp. 87-94 (outlining modified version of the IADC formula for geostationary satellite disposal, to address satellites in highly-inclined geosynchronous orbits and resulting orbital perturbations).

3.4.2 2. Post-Mission Lifetime

49. As some types of designs lead to satellites that are smaller and less expensive to construct and launch, there has been a corresponding trend toward shorter mission lifetimes for NGSO satellites deployed into the LEO region. For example, the anticipated lifetime of a typical "CubeSat" operating in the Earth exploration-satellite service is only one or two years.[114]

50. Consistent with these shorter mission lifetimes, as well as the number of satellites planned for deployment, we ask whether the 25-year disposal guideline contained in the NASA Standard remains a relevant benchmark.[115] That is, does the guideline that a spacecraft reenter the atmosphere no more than 25 years after the completion of the spacecraft's mission permit spacecraft designs that result in a longer disposal period than may be in the public interest for a particular satellite mission? Should the disposal guideline instead be proportional to mission lifetime, or specific to the orbital altitude where the spacecraft will be deployed?[116] We also note that solar activity can influence the re-entry periods of satellites in LEO,[117] and that future solar activity may vary from predictions[118] In what manner, if any, should we account for variations in solar activity in our rules and in crafting conditions on the grant of specific licenses? Should satellite operators planning disposal through atmospheric re-entry be required to continue obtaining spacecraft tracking information, for example by using radio facilities on the spacecraft, to the greatest extent

---

[114] See, e.g., Planet Labs Inc., Application for Launch and Operating Authority, IBFS File No. SAT-LOA-20130626-00087, Exh. 43 at 2 (describing the nominal lifetime of its Flock 1 satellites as 11 months, with maximum lifetime of 18 months); Planet Labs Inc., Modification Application, IBFS File No. SAT-MOD-20150802-00053, Exh. 43 at 1 (describing expected operational lifetime of a series of additional satellites as approximately two years); Spire Global, Inc., Application for Launch and Operating Authority, IBFS File No. SAT-LOA-20151123-00078, Exh. A at 23 n.73 (describing the operational lifetime of a typical Spire satellite as approximately two years). In the Small Satellite NPRM, the Commission proposed that the total on-orbit lifetime, including both mission and time to de-orbit, be five years or less for small satellites licensed under the proposed streamlined process. Small Satellite NPRM, FCC 18-44 at 15, para. 28. This proposed five-year on-orbit lifetime would apply only to satellites licensed under the streamlined process, see id., and we anticipate that the streamlined process would be used by some, but not all, CubeSats.

[115] NASA Standard at 37, Requirement 4.6.2. The NASA Standard provides the option that, for a spacecraft with a perigee altitude below 2,000 km that will be disposed of through atmospheric re-entry, the operator shall leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch. Id.

[116] See IADC Statement on Large Constellations at 6 (noting that, in reference to the proposed large NGSO constellations, the 25-year lifetime may need to be reduced to limit residence times in orbit).

[117] Relatively weak solar activity can result in a decrease of the atmospheric drag on satellites in LEO, causing longer re-entry periods for retired spacecraft, including beyond a 25-year predicted re-entry period. For a brief summary of satellite drag and its causes, see National Oceanic and Atmospheric Administration, Space Weather Prediction Center, Satellite Drag, http://www.swpc.noaa.gov/impacts/satellite-drag.

[118] See, e.g., Robert Lee Hotz, Strange Doings on the Sun, Wall Street Journal (Nov. 10, 2013), http://www.wsj.com/articles/SB10001424052702304672404579183940409194498.

possible following the conclusion of the primary mission? In addition to these questions, we seek comment generally on how to prevent satellites from becoming sources of orbital debris during the period following their mission lifetime and before disposal through atmospheric re-entry.

3.4.3 3. Casualty Risk Assessment

51. The U.S. Government Orbital Debris Mitigation Standard Practices and the NASA Standard include a policy of limiting to 1 in 10,000 the risk of at least one human casualty, anywhere in the world, from a single, uncontrolled reentering space structure.[119] In order to assist the Commission in evaluating the spacecraft design with respect to human casualty risk, we propose two specific informational requirements for satellites with a planned post-mission disposal of uncontrolled atmospheric re-entry.[120]

52. First, we propose that the human casualty risk assessment include all objects that would have an impacting kinetic energy in excess of 15 joules. This is consistent with the NASA Standard, wherein the potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules.[121]

53. Second, we propose that where the calculated risk of human casualty from surviving debris is determined to be greater than zero, as calculated using either the NASA Debris Assessment Software or a higher fidelity model,[122] the applicant must provide a statement indicating the actual calculated human casualty risk, as well as the input assumptions used in modelling re-entry. We tentatively conclude that these additional specifications will enable the Commission to better evaluate whether the post-mission disposal plan is in the public interest and seek comment on this approach. We further invite comment on whether, when assessing human casualty

---

[119] See Orbital Debris Order, 19 FCC Rcd at 11603, para. 88; NASA Standard at 44, Requirement 4.7.3.

[120] For missions planning controlled reentry, we anticipate evaluating such plans on a case-by-case basis, consistent with the NASA Standard. See NASA Standard at 44, Requirement 4.7.2.

[121] Id. The 15 joule limit has been determined to be the limit above which any strike on a person will require prompt medical attention. NASA Standard, at 45, Requirement 4.7.3.c. The 1:10,000 standard does not account for sheltering, as it is estimated that as much as 80% of the world's population is either unprotected or in lightly-sheltered structures for purposes of protection from a falling object with a kilojoule-level kinetic energy. NASA Standard, at 45, Requirement 4.7.3.d.

[122] The Debris Assessment modeling software is available for use without charge from the NASA Orbital Debris Program office at https://www.orbitaldebris.jsc.nasa.gov/mitigation/das.html. The NASA Standard notes that the re-entry risk assessment portion of Debris Assessment Software contains a simplified model which does not require expert knowledge in satellite reentry analyses and is designed to be somewhat conservative. NASA Standard at 46, Requirement 4.7.4.d. The use of a simplified model may result in a higher calculated casualty risk than models employing higher fidelity calculations and inputs. See, e.g., NASA Orbital Debris Program Office, Orbital Debris Object Reentry Survival Analysis Tool, https://orbitaldebris.jsc.nasa.gov/reentry/orsat.html (last visited Oct. 22, 2018) (explaining that the Object Reentry Survival Analysis Tool (ORSAT) is frequently used for a higher-fidelity survivability analysis after the Debris Assessment Software has determined that a spacecraft is possibly non-compliant with the NASA Safety Standard).

risk, we should do so on an aggregate, system-wide basis as well as on a per-satellite basis, and, if so, what metric should be used to evaluate aggregate risk.

3.4.4 4. Part 25 GSO Satellite License Term Extensions

54. Operators of GSO satellites routinely request that the Commission grant license modifications to extend their authorized satellite operations beyond the initial license terms.[123] When requesting such modifications, licensees typically provide information to the Commission that includes the requested duration of license extension, an estimate of the total remaining satellite lifetime, a statement that the satellite has no single point of failure that would affect its ability to complete end-of- life procedures as planned, a statement concerning the adequacy of remaining fuel reserves to complete deorbit as planned, and a statement on the status of tracking, telemetry, and command links.[124] The Commission reviews these statements and requests additional details when warranted, such as when a satellite has a record of malfunctions, known defects, or experienced other anomalies in its operational history. If satisfied with an applicant's showing, the Commission will grant a modification extending the license term, with the duration of the extension established through a case-by-case analysis.[125]

55. Although there is some evidence that GSO satellites can operate beyond their initial license terms without any significant decrease in their operational capabilities or increase in their risk of on-orbit failure,[126] we are aware of instances in which GSO satellites have experienced sudden failures.[127] Although these cases are exceptional (operators have been able to satisfy their obligation to perform end of-life procedures in almost all cases), the potential consequences of introducing additional debris to the geostationary arc are significant—debris from a collision in

---

[123] The license terms for grants under Part 25 are specified in Section 25.121 of the Commission's rules. 47 CFR § 25.121. With some exceptions, licenses are typically issued for a period of 15 years. See id. We will continue to assess requests for license term extensions for NGSO satellite systems on a case-by-case basis.

[124] See, e.g., Intelsat License LLC, Modification Application, IBFS File No. SAT-MOD-20161004-00097 (granted Dec. 8, 2016) (requesting an extension of the license term of the Galaxy 25 satellite).

[125] See 47 CFR § 25.121(b).

[126] One study on satellite on-orbit mortality provides evidence that satellites that survive their first years of operation tend to exceed their expected design life. Cf. Gregory F. Dubos et al., A Satellite Mortality Study to Support Space Systems Lifetime Prediction, IEEE Aerospace Conference Proceedings (Mar. 2013).

[127] See EchoStar Satellite Operating Corporation, IBFS File No. SAT-STA-20170728-00112 (granted July 27, 2017) (grant of special temporary authority associated with an anomaly that caused EchoStar to temporarily lose control of the EchoStar III satellite); see also SES Americom, Inc., IBFS File No. SAT-STA-20170619-00091 (granted June 19, 2017) (grant of special temporary authority associated with an anomaly that caused SES to temporarily lose control of the AMC-9 satellite). We note that in both instances the operators were ultimately able to regain control of the satellites and deorbit them as planned.

geostationary Earth orbit (GEO) will remain on orbit virtually forever and "[t]he wide-spread distribution of debris across GEO could result in the degradation of the reliability of GEO satellite communications for the foreseeable future."[128]

56. We propose to codify our current practice of requesting certain types of information from GSO licensees requesting license term extensions. The rule would specify that applicants should state the duration of the requested license extension and the estimated total remaining satellite lifetime, certify that the satellite has no single point of failure or other malfunctions, defects, or anomalies during its operations that could affect its ability to conduct end-of life procedures as planned, that remaining fuel reserves are adequate to complete deorbit as planned, and that telemetry, tracking, and command links are fully functional.[129] In the event that the applicant is unable to make any of the certifications, we propose that the applicant provide a narrative description justifying the extension. We seek comment on this approach.

57. We propose to continue to assess the duration of the license term extension on a case-bycase basis, but propose to limit extensions to no more than five years in a single modification application. We tentatively conclude that five years may be an appropriate upper limit for a single modification to help ensure reasonable predictions regarding satellite health while affording operators some flexibility. Additionally, if subsequent extensions are sought, we would have the opportunity to review those extension requests in intervals of five years or less. We seek comment on this tentative conclusion. We also seek comment on whether we should further limit license term extensions or place a cap on the number of times which a GSO satellite license can be extended.

58. We further seek comment on whether there are certain types of satellite buses[130] that may warrant heightened scrutiny for purposes of license extensions. In addition, we seek comment on whether, apart from the review undertaken when a license is extended, there are types or categories of anomalies that should trigger immediate reporting, in order to assess whether reliability of post-mission disposal has been compromised to the point that immediate actions may be required.

3.5 E. Proximity Operations

59. With increasing interest in satellite servicing and other non-traditional missions, there have been an increasing number of commercial missions proposed that involve

---

[128] See, e.g., Orbital Debris Order, 19 FCC Rcd at 11595, para. 66.

[129] Appendix A, Proposed Rules, Section 25.121.

[130] A satellite "bus" is the colloquial term sometimes used to describe a satellite design (structure, power and propulsion systems, etc.) developed by a manufacturer and adapted for specific missions in response to individual customer requirements.

proximity operations and rendezvous of spacecraft.[131] We propose that applicants be required to disclose whether the spacecraft will be performing any space rendezvous or proximity operations. The statement would indicate whether the satellite will be intentionally located or maneuvering near another spacecraft or other large object in space. Such operations present a potential collision risk, and operators will need to address that risk, as well as any risk of explosions or generation of operational debris that might occur through contact between spacecraft, as part of debris mitigation plans. Accordingly, we propose a disclosure requirement regarding these types of operations.

3.6 F. Operational Rules

60. We also propose several updates to satellite operational rules relevant to physical operations.

3.6.1 1. Orbit Raising

61. The Commission's rules provide that, for satellites authorized for normal operations in the geostationary orbit, the Commission authorization also includes authority for telemetry, tracking, and command functions to raise the satellite to its normal orbit following launch.[132] This rule was adopted to make it clear that orbit-raising types of maneuvers in the pre-operational phrase are authorized operations, even though they may vary from the orbital parameters specified in the license.[133] Such authority is currently limited to operations on a non-harmful-interference, unprotected basis.[134] Because orbit-raising maneuvers are performed by satellites intended for non-geostationary orbits as well as for the geostationary orbit, and the number of satellites engaging in orbit-raising maneuvers may increase if other proposals in this Notice are adopted,[135] we take this opportunity to propose and seek comment on expanding the provision to include NGSO system operations.

---

[131] See, e.g., Space Logistics, LLC, Application for Launch and Operating Authority, IBFS File No. SAT-LOA-20170224-00021, Narrative at 1, 6-7 (filed Feb. 24, 2017, granted December 5, 2017).

The Defense Advanced Research Projects Agency (DARPA) has initiated a Consortium for Execution of Rendezvous and Servicing Operations to help develop technical and safety standards for performance of on-orbit activities involving commercial satellites. "CONFERS to establish 'Rules of the Road' for On-Orbit Servicing of Satellites," DARPA, News and Events (Oct. 4, 2017), https://www.darpa.mil/news-events/2017-10-04.

[132] 47 CFR § 25.282; see also Orbital Debris Order, 19 FCC Rcd at 11585, para. 40.

[133] Orbital Debris Order, 19 FCC Rcd at 11585, para. 40.

[134] See 47 CFR § 25.282(b) and (c).

[135] See supra Part III.D.1 (proposing that NGSO space stations planned for operation at certain altitudes be initially deployed in a lower orbit, then subsequently moved to the planned operational altitude).

62. In addition, in a manner similar to the provisions for maneuvering at the end-of-life for a GSO satellite,[136] we propose to require such telemetry, tracking, and command operations to be coordinated between satellite operators as necessary to avoid interference events, rather than require the operations to be performed on a non-interference basis. We tentatively conclude that it is in the public interest that these types of telemetry, tracking and command communications, critical to effective spacecraft maneuvering, be coordinated as necessary to avoid interference, rather than being authorized only on an a non-harmful-interference, unprotected basis. We seek comment on revising our existing rule regarding orbit raising maneuvers to require coordination of such operations to avoid interference events and to extend the application of the rule to NGSO satellites as well as GSO satellites.[137]

3.6.2 2. Maintaining Ephemeris Data

63. The Commission recently adopted a rule requiring that all NGSO FSS licensees or market access recipients ensure that ephemeris data[138] for their constellations are available to all operators of authorized, in-orbit, co-frequency satellite systems.[139] The purpose of the current rule is to ensure compatible operations of NGSO FSS constellations, because knowledge of the physical locations of NGSO FSS satellites is an essential element of spectrum sharing under the Commission's rules.[140] It also may be in the public interest for the physical locations of NGSO satellites to be known for purposes of collision avoidance, regardless of whether that information is necessary for spectrum sharing among systems.

64. We propose that NGSO operators be required to maintain ephemeris data for each satellite they operate and share that data with operators of other systems operating in the same region of space.[141] Specifically, we propose to require that operators share ephemeris data with any other operator identified in its disclosure described above of any operational space stations that may pose a collision risk. We believe this requirement will help to facilitate communications between operators, even before a potential conjunction warning is given. We also propose that the information be shared by means mutually acceptable to the parties involved, to allow for flexibility and efficiency in sharing of information.[142] We seek comment on

---

[136] 47 CFR § 25.283(b) (providing for a space station to operate using its authorized tracking, telemetry, and control frequencies for the purpose of removing the satellite from the geostationary orbit at the end of its useful life, "on the condition that the space station's tracking, telemetry, and control transmissions are planned so as to avoid electrical interference to other space stations, and coordinated with any potentially affected satellite networks.").

[137] See Appendix A, Proposed Rule Changes.

[138] Ephemeris data give the orbital positions of satellites at a given time or times.

[139] 47 CFR § 25.146(e); Update to Parts 2 and 25 Concerning Non-Geostationary, Fixed-Satellite Service Systems and Related Matters, Report and Order and Further Notice of Proposed Rulemaking, 32 FCC Rcd 7809, 7827-28, paras. 56-58 (2017) (NGSO FSS R&O).

[140] NGSO FSS R&O, 32 FCC Rcd at 7827-28, paras. 56-57.

[141] Appendix A, Proposed Rules.

[142] See NGSO FSS R&O, 32 FCC Rcd at 7828, para. 58.

this proposed revision to include these proposed requirements regarding availability of NGSO satellite ephemeris data.[143]

3.6.3 3. Telemetry, Tracking, and Command Encryption

65. There is currently no requirement in the Commission's rules that space station licensees encrypt telemetry, tracking, and command communications.[144] As a practical matter, most satellites do operate with secure encrypted communications links, and all operators have an interest in securing against unauthorized actors interfering with their mission. Certain low-cost satellite missions—some CubeSats or other small satellites, particularly those operated for academic purposes—may not use encryption for telemetry, tracking, and command communication links.[145] The developers in these cases may have concluded that the costs or time associated with implementing encryption of telemetry, tracking, and command communications outweigh the potential risks.[146] Some have observed that a satellite outfitted with onboard propulsion capabilities could pose some risk to the operations of other spacecraft if a malevolent actor were able to take control of and command the satellite and that encryption should therefore be required.[147]

66. We seek comment on whether to include any provisions in our rules concerning encryption for telemetry, tracking, and command communications for satellites with propulsion capabilities, and propose to add a requirement to our operational rules.[148] Should this rule be applicable only to satellites having propulsion systems with certain capabilities, for example, certain ΔV capability? More generally, should we consider such a requirement, regardless of propulsion capabilities, recognizing that other possible harms, such as radio-frequency interference, could result from such scenarios? We anticipate that this rule will have no practical impact for most satellites and systems, which already encrypt communications, and seek comment on whether any burden that would result from adoption of such a rule is justified by the resulting improvements to the security of satellite control operations. Additionally, we seek comment on whether, if such a rule is adopted, there are any criteria that should be identified with respect to the sufficiency of encryption methods.

---

[143] See Appendix A, Proposed Rules. Although not currently included in the Proposed Rule Changes, we also propose to adopt this requirement for satellite operations under Parts 5 and 97.

[144] Section 25.271 of the Commission's rules, relating to control of transmitting stations, for example, specifies some measures for security of earth stations authorized under Part 25, but does not include any provisions regarding

[145] A. Kurzrok, M. Diaz Ramos, and F.S. Mechentel, "Evaluating the Risk Posed by Propulsive Small-satellites with Unencrypted Communications Channels to High-Value Orbital Regimes," 32nd Annual AIAA/USU Conference on Small Satellites, at 1 (2018).

[146] See id. at 4.

[147] See id. at 8; Eleni M. Sims and Barbara M. Braun, "Navigating the Policy Compliance Roadmap for Small Satellites," The Aerospace Corporation, at 9 (2017).

[148] See Appendix A, Proposed Rules. Transmissions by amateur stations can include encrypted telecommand (See 47 CFR § 97.211(b)), and space telemetry transmissions (47 CFR § 97.207(f)).

3.7 G. Liability Issues, Insurance, and Economic Incentives

67. In 2004, the Commission noted that, under international law, the United States government could potentially be presented with a claim for damage resulting from private satellite operations such as disposal or generation of orbital debris.[149] At that time, the Commission considered what role liability and insurance considerations should play in licensing.[150] While the Commission declined to adopt a general insurance requirement, it anticipated that insurance and liability relating to the post-launch period could play a role in determining whether approval of a particular debris mitigation plan serves the public interest.[151]

68. As part of this general update of our rules related to orbital debris mitigation, we now revisit these topics. In so doing, we note that the Commission is a regulatory agency, and unlike agencies with statutory authority to conduct space operations, cannot accept risk on behalf of the United States by encryption of communications. See 47 CFR § 25.271(c) (securing transmitting stations operating by remote control), 25.271(d) (securing transmitting earth station facilities against unauthorized access or use whenever an operator is not present at the transmitter). Our review of an applicant's debris mitigation plan, or grant of a license, does not alter any liability of the applicant or licensee.[152]

69. First, we propose to require Commission space station licensees to, at a minimum, indemnify the United States against any costs associated with a claim brought against the United States related to the authorized facilities. Given the potential risk of a claim being presented to the United States under international law, we tentatively conclude that an indemnification by these U.S.-licensed private operators is appropriate. We propose that the indemnification would take the form of an indemnity agreement, and that we will consult with interagency partners, including the U.S. Department of State, to establish the parameters of such an agreement, including the scope of the indemnification and the means to execute the agreement, including by the appropriate U.S. government official or officials. We seek comment on this proposal, including on the form and content of such an agreement.

70. We further propose that the indemnification agreement would in most cases be completed following grant of a space station license, within thirty days. If no indemnification agreement has been approved within thirty days following grant, the space station license would be terminated. In order to ensure that the agreement is approved well in advance of launch of the space station, we also propose that in no case would the agreement be completed fewer than 90 days prior to the planned date of launch. In rare instances, this may require applicants to begin the agreement process prior to grant. We seek comment on these timing matters, including on whether the timeline should be based on the date on which the satellite is integrated

---

[149] Orbital Debris Order, 19 FCC Rcd at 11612-13, paras. 109-10.

[150] Id.

[151] Id.

[152] Orbital Debris Order, 19 FCC Rcd at 11614, para. 113.

into the launch vehicle in preparation for launch rather than launch date. Finally, we propose to limit the requirement of an executed indemnification agreement to U.S.-licensees only at this time, as U.S. licensees generally have a manifest connection to the United States.[153]

71. We also seek comment on whether we should follow the example of other spacefaring nations and require an insurance policy to be obtained by our licensees to provide for payment for any costs associated with a claim brought against the United States related to the authorized facilities, which may be particularly important in the event of bankruptcy of the licensee. Similar to how the Commission's existing bond requirement ensures that the licensee demonstrate to a surety company that it is willing and able to proceed with the construction of the satellite the licensee has requested authority to construct,[154] this insurance requirement would be a demonstration that the potential risks associated with the satellite activities have been considered. As the Commission noted in the 2004 Orbital Debris Order, insurance can, in some instances, provide an economic incentive for operators to undertake debris mitigation measures.[155] We revisit the Commission's 2004 discussion and conclusions and seek comment on what amount and type of insurance may be appropriate.

72. We also seek comment on whether we should separate this requirement where applicable as between on-orbit liability and spacecraft re-entry liability since on-orbit liability is addressed through a fault regime and re-entry liability is addressed through strict liability regime under the Convention on International Liability for Damage Caused by Space Objects (Liability Convention),[156] and if there are particular indicators that would make insurance necessary in particular cases, or, on the other hand, suggest that categories of operators should be exempt from the requirement to obtain insurance. For example, should small satellites applying under the new streamlined process proposed in the Small Satellite NPRM be exempt from an insurance requirement, since space stations in that category would be relatively

---

[153] See Appendix A, Proposed Rule Changes (proposed Section 25.166). In the United Kingdom, for example, the U.K. Outer Space Act of 1986 requires that a party carrying out certain space activity indemnify the government against claims arising out of that activity. Licensees typically must obtain third-party liability insurance in the amount of 60 million euros. See UK Space Agency, Guidance; License to operate a space object: how to apply; Obligations of licensees, https://www.gov.uk/guidance/apply-for-a-license-under-the-outer-space-act-1986; Outer Space Act, 1986, c. 38, § 5(2)(f) (U.K.), http://www.legislation.gov.uk/ukpga/1986/38. Other nations similarly have requirements with respect to indemnification and insurance. See, e.g., United Nations Office for Outer Space Affairs, Selected Examples of National Laws Governing Space Activities: Sweden, Act on Space Activities (Unofficial Translation) at Section 4, available at http://www.unoosa.org/oosa/en/ourwork/spacelaw/nationalspacelaw/sweden/act_on_space_activities_1982E.html (Sweden's Act on Space Activities indemnification provision).

[154] See, e.g., Amendment of the Commission's Space Station Licensing Rules and Policies, First Order on Reconsideration and Fifth Report and Order, FCC 04-147, at para. 17.

[155] Orbital Debris Order, 19 FCC Rcd at 11614, para. 111.

[156] See Convention on International Liability for Damage Caused by Space Objects of 1972, Articles I and II.

lower risk from an orbital debris perspective? As another example, we ask whether GSO space station licensees should be exempt from an insurance requirement since they may present less risk in the post-mission disposal process since they do not typically re-enter Earth's atmosphere. Relatedly, and/or alternatively, we ask if it would be appropriate to consider differential amounts of insurance that would be required for different types of operations.[157]

73. We further invite comment generally on what economic approaches might be feasible and effective in creating incentives such that appropriate launch vehicle and satellite design choices are made, and appropriate decisions regarding the number of satellites launched are made as well. That is, recognizing debris creation as a negative externality, what approaches might induce private decisions on these design and launch choices to be consistent with the public interest in limiting the growth of orbital debris?

3.8 H. Scope of Rules

3.8.1 1. Amateur and Experimental Operations

74. We are also proposing to amend our rules governing experimental satellite and amateur satellite authorizations to maintain consistency with the proposed revisions to the orbital debris mitigation plan application requirements in our commercial rules.[158] In 2002, the Commission observed that amateur and experimental spacecraft can present the same public interest concerns regarding orbital debris as operations under other rule parts.[159] In the 2004 Orbital Debris Order, the Commission adopted rules requiring that a description of the design and operational strategies used to mitigate orbital debris be provided by an applicant seeking to conduct experimental or amateur satellite operations.[160] These disclosure requirements were consistent with the disclosure requirements adopted for commercial satellite applicants.[161] We

---

[157] We are not considering a limit on the proposed indemnification requirement.

[158] See 47 CFR Part 5, Experimental Radio Service; 47 CFR Part 97, Amateur Radio Service. In this document we use the term "commercial" when referring to operations under Part 25 of the Commission's rules, but we note that there is no requirement in Part 25 that operations authorized under that Part must be for an inherently commercial purpose. 47 CFR Part 25.

[159] Mitigation of Orbital Debris, Notice of Proposed Rulemaking, 17 FCC Rcd 5586, 5612, para. 63 (2002).

[160] Orbital Debris Order, 19 FCC Rcd at 11607-09, paras. 98-101, Appendix B. Specifically, the Commission adopted revisions to Sections 5.63 and 97.207 of the Commission's rules. Id. at Appendix B; 47 CFR § 97.207. The relevant disclosure requirements in Section 5.63 for experimental licensing were subsequently moved to Section 5.64 of the Commission's rules. 47 CFR § 5.64(b); Promoting Expanded Opportunities for Radio Experimentation and Market Trials Under Part 5 of the Commission's Rules and Streamlining Other Related Rules, 2006 Biennial Review of Telecommunications Regulations – Part 2 Administered by the Office of Engineering and Technology (OET), Report and Order, 28 FCC Rcd 758, 823, Appendix B (2013).

[161] Compare 47 CFR §§ 5.63, 97.207 with 47 CFR § 25.114(d)(14).

continue to believe that it is appropriate for amateur licensees[162] and experimental applicants to provide a similar amount of disclosure regarding debris mitigation plans as will be required of commercial satellites under any of the changes to Part 25 discussed above that are adopted by the Commission.[163] We seek comment on this proposal.[164]

75. Since most satellites authorized as amateur operations or licensed as experimental satellites operate at low altitudes, the new proposed informational requirements related to collision avoidance and post-mission disposal for higher LEO altitudes would not apply as a practical matter to amateur or experimental systems, and therefore the burden on applicants for compliance with these new proposed rules would in most instances be non-existent. We tentatively conclude that the proposed requirements that would typically apply, such as quantification of collision risk, would not be unduly burdensome, since these applicants and licensees are already providing orbital debris mitigation information to the Commission, and depending on the types of operations, may currently be asked to provide additional details in order for the Commission to determine that grant of the application or authorization is in the public interest. Including the proposed additional disclosure requirements in the rules applicable to experimental space station applicants and amateur space station licensees would help provide concrete requirements with respect to operations in space. We recognize that there may be differences in the scale and longevity of experimental and amateur satellites versus commercial satellite deployments. In general, however, amateur and experimental operations present the same public interest concerns as operations by commercial operators. For example, some individual amateur or experimental satellites may present the same risks with respect to creation of orbital debris as some individual commercial satellites licensed under Part 25. Thus, we believe that the benefits of the new requirements, such as the disclosure rule relating to the protection of manned spacecraft, in ensuring the continued safe use of the space environment, may outweigh the potential costs to amateur operators or experimental licensees.

76. The proposed rule revisions related to GSO satellite license term extensions[165] and orbit-raising[166] would not, if adopted, apply to amateur or experimental satellites, since those rules are not currently applicable to amateur or experimental services. We also propose to exempt amateur and experimental satellites from the ephemeris data requirement, since authorizations and licenses in those services do

---

[162] In seeking Commission approval of amateur satellite operations, the license grantee of the amateur satellite must submit a pre-launch notification to the Commission, as specified in Section 97.207(g) of our rules. 47 CFR § 97.207(g)(1). This notification must include, among other things, information regarding design and operational strategies for mitigation of orbital debris. Id.

[163] See Guidance on Obtaining Licenses for Small Satellites, Public Notice, 28 FCC Rcd 2555, 2558 (IB/OET 2013) (“An orbital debris assessment report prepared consistent with the NASA standards is generally sufficient to meet FCC requirements.”).

[164] See Appendix A, Proposed Rule Changes, Sections 5.64 and 97.207.

[165] See supra Part III.D.4; Appendix A, Proposed Rule Changes, Section 25.121.

[166] See supra Part III.F.1; Appendix A, Proposed Rule Changes, Section 25.282.

not typically involve many satellites.[167] We seek comment on these proposals. Consistent with the above discussion, and bearing in mind that U.S. treaty obligations do not vary based on the Commission's regulatory classification, we also inquire whether we should require indemnification and/or an insurance policy to be obtained by experimental licensees and authorized amateur operators.

3.8.2 2. Non-U.S.-Licensed Satellites

77. We generally propose that the new and amended rules discussed in this NPRM should be applicable to non-U.S.-licensed satellites seeking access to the U.S. market. In other words, an entity seeking access to the U.S. market must continue to submit the same technical information concerning the satellite involved as is required to be submitted by U.S. satellite license applicants.[168] We seek comment on this proposal. With respect to the proposals regarding indemnification and insurance, we ask whether there are any circumstances where it would be appropriate to apply these potential requirements to applicants requesting operations with non-U.S.-licensed satellites, for example, where the applicant is substantially U.S.-based and the foreign licensing administration has not committed to registering the satellite with the United Nations as that administration's space object.

78. In the Orbital Debris Order, the Commission observed that a categorical exemption for any class of satellites serving the United States would undermine the legitimate public policy objective of mitigating orbital debris.[169] The Commission explained that by requiring technical information concerning orbital debris mitigation from these non-U.S.-licensed space stations, the Commission is ensuring that foreign operators that "seek access to the U.S. market for commercial reasons meet the same public interest requirements as U.S.-licensed operators."[170] In some instances, we note that applicants have sought approval to engage in very limited transmission and reception activities between non-U.S.-licensed space stations and earth stations in the United States, such as communications exclusively for telemetry, tracking, and command. Although applicants seeking approval for communications such as telemetry, tracking, and command only may have a limited commercial connection to the United States, there is nonetheless a commercial reason those applicants are seeking to transmit and/or receive from a U.S. earth station. Therefore, we seek comment on whether these applicants should be subject to the same public interest requirements as a U.S.-licensed satellite operating with a U.S. earth station.

79. We further propose that non-U.S.-licensed satellites may continue to satisfy the disclosure requirement by showing that the satellite system's debris mitigation

---

[167] Therefore, no rule related to ephemeris data is proposed for either part 5 or part 97 of the Commission's rules. See Appendix A, Proposed Rule Changes.

[168] Orbital Debris Order, 19 FCC Rcd at 11605, para. 92; see 47 CFR § 25.137(b) (requiring legal and technical information for the non-U.S.-licensed space station of the kind that § 25.114 would require in a license application for a space station).

[169] Orbital Debris Order, 19 FCC Rcd at 11606, para. 93.

[170] Id.

plans are subject to direct and effective regulatory oversight by the satellite system's national licensing authority.[171] Recognizing that in other countries authority over radiofrequency communications and authority over space operations are often addressed by different entities, in order to satisfy our orbital debris mitigation disclosure requirements, we would expect information showing that the operator has received a license from the entity overseeing space operations, or has initiated that process. This would include information about whether or not that administration is expected to register the space object with the United Nations Register of Objects Launched into Outer Space.[172] We seek comment on whether it is appropriate to continue assessing the direct and effective oversight of a foreign licensing authority on a case-by-case basis. Under this approach, approval of foreign oversight for a system design in one case will not necessarily imply similar approval for a different system design.

I. Regulatory Impact Analysis

80. In this section, we seek comment on whether regulation of U.S. Commission-licensed space stations will help to limit such debris and result in a net benefit, even if it may give rise to some regulatory costs. From an economic perspective, the earth orbital region of space can be viewed as essentially a "commons"— that is, a resource that is "non-excludable" in consumption (use of space is available to all countries), but "rivalrous" (each country's use of space reduces the amount available to others). A significant and fundamental problem with economic commons is the tendency of individuals to exploit the commons in a manner that is unsustainable long term and diminishing the usefulness for others. In the context of the earth orbital environment, operators have an incentive to maximize the use of orbital resources for their own gain, which may result in an unsustainable level of activity for long term use of the same orbits. Space is vast and the distances between objects are generally quite large, and it is generally the case that a large number of operational satellites can share the same or similar orbits with relatively low risk of collision, particularly when they have the ability to maneuver to avoid collisions. However, once a satellite reaches its end-of-life or otherwise ceases to operate, for example, it will become a piece of debris, posing a risk to the safe operations of other existing and future satellites.

81. Debris generation by on-orbit activities is a negative externality, and is one which could lead to the degradation of the commons of the Earth orbital environment. Some unique, relevant aspects of debris include the fact that, particularly at higher orbits, the debris population will not naturally decrease with time even if no additional objects are launched into orbit, and that over time existing pieces of debris

---

[171] 47 CFR § 25.114(d)(14)(v); Orbital Debris Order, 19 FCC Rcd at 11606, para. 95.

[172] The United Nations Register of Objects Launched into Outer Space is maintained by the United Nations Office for Outer Space Affairs. The United Nations Office for Outer Space Affairs reports that 92% of all satellites and other spacecraft launched into Earth's orbit and beyond have been registered. United Nations Office for Outer Space Affairs, Space Object Register, http://www.unoosa.org/oosa/en/spaceobjectregister/index.html.

will tend to collide with other existing pieces of debris producing a "cloud" of debris which increases the likelihood of future collisions. While the debris problem is a significant consideration for the long-term use of orbital resources, such considerations may not play a significant role in economic decision making in the short-term. Individual satellite operators may have an interest in preserving the earth orbital environment for their continued operations, but a desire to avoid the short-term costs associated with deorbiting satellites to mitigate debris risk could override those long-term interests. Given these incentives, in the long term, the debris population is likely to continue to grow and could result in an exponential increase in the debris population such that use of certain valuable orbital configurations may no longer be economically feasible. This tendency of debris to generate yet more debris has come to be known as the "Kessler syndrome," a cascade in which so much debris is created that certain orbits can become unusable for decades or centuries.

82. Private sector revenues from space-based businesses are in the hundreds of billions of dollars per year, and there are hugely important scientific and national defense uses of certain orbits as well. A Kessler syndrome type of scenario could render the use of certain orbits economically infeasible and could have significant and far reaching impacts on the global economy for years to come.[173] Although orbital debris is a global problem, our focus in this proceeding is limited to reassessing the Commission's rules concerning orbital debris that are in place today, which we propose to strengthen in certain respects. The Commission's efforts in this area are only one component in addressing an issue of global concern, but as noted, such efforts are undertaken alongside other domestic and international efforts related to mitigation of orbital debris.[174] We further reiterate the Commission's statement from the 2004 Orbital Debris Order that, "we do not believe that the theoretical possibility that other countries could take ill-considered actions, at variance with international norms, in any way should prevent the Commission from adopting objective and transparent measures concerning orbital debris mitigation that serve the public interest."[175] Moreover, while reduced production of debris by operators with U.S. licenses or market access grants will necessarily benefit the space activities of all nations, we focus here only on benefits to citizens and residents of the U.S.[176]

83. We seek comment on six approaches to reducing debris in orbit, which include the proposals discussed in the individual rule sections above:

84. Fewer Launches. One method of reducing orbital debris would be for the Commission to adopt rules that would have the effect of reducing the overall number of satellites launched. This approach is not proposed above, but would involve, as an example, a limit on the number of individual NGSO satellites that could be

---

[173] See, e.g., Adilov, N., Alexander, P.J., Cunningham, B.M, "An economic analysis of earth orbit pollution," Envr. Resour. Econ. 60, 81-98 (2014).

[174] See supra Section II.

[175] 19 FCC Rcd at 11607, para. 97.

[176] This is in accord with established guidance regarding RIAs. See Circular A-4 (2003), page 15.

authorized in a particular time period, which could have the overall effect of limiting the number of satellites launched. It is not clear, however, that such an action by the Commission would in fact reduce the number of satellites launched, since applicants that would normally be licensed by the Commission could potentially seek authorization from a non-U.S. administration. Moreover, the approach could also limit system capabilities and burden new entrants to the satellite industry, even though prior entrants were not subject to a limit. This approach could also prevent the improvement of services and the introduction of new services, and could, perversely, slow technology development that enables improved debris mitigation. Regulations targeted to address particular activities that create risk from an orbital debris perspective may be more effective than a blanket limitation on U.S. commercial activities in space.

85. Changes in Satellite Design. Another method of reducing orbital debris would be for the Commission to regulate how satellites or satellite system are designed. These regulations would limit the types of design features that increase the orbital debris population or increase the risk that such debris will be created. Some of the proposals above would potentially have the effect of changes in satellite design, for example, if more fuel was necessary onboard to perform orbit raising for satellites being deployed in an NGSO constellation.[177] We recognize that there may be some costs associated with these types of proposals and seek comment on those potential cost in the discussion above. We do not propose to mandate particular designs for satellites and systems, however, such as use of a particular satellite bus design. While costs related to satellite design may be necessary to help achieve the goal of limiting creation of orbital debris, we believe such detailed mandates as specific satellite bus design would be too restrictive to cover the wide range of satellite systems and operations, would be difficult to develop and maintain, and could impose hardware and design costs on Commission-authorized satellites as well as costs related to limitations on innovation, that may be beyond what is necessary to achieve the desired ends.

86. Changes in operations and disposal procedures. This is the approach we propose in the individual rule sections above. We believe this approach gives operators sufficient flexibility in implementing their systems, while achieving results consistent with the public interest in preserving access to space for the long term, as well as the safety of persons and property in space and on the surface of the Earth. There are some costs associated with this approach in preparation of information for Commission review, and in potential modifications related to satellite design, operations, or choice of launch opportunities, in order to comply with the Commission's proposed rules. For example, there may be satellites which, because of planned design, may have structures which survive atmospheric re-entry resulting in certain risks to persons on Earth.[178] An applicant under the Commission's rules, as proposed, would need to assess its satellite plans and make changes as necessary to comply with the rule. As

---

[177] See supra Section III.D.1.

[178] See supra Section III.D.3.

another example, an operator may need to deploy its satellites to a different orbit than originally planned in order to comply with the Commission's rules, as proposed, which could impact its system operations or require choosing a different launch opportunity. In some instances, additional fuel may be necessary to perform maneuvers in order to achieve compliance with the Commission's proposed rules. We consider these costs, of course, in view of the benefits from mitigation of the orbital debris population, as discussed, including the safety and reliability of long-term operations in space, as well as the benefits of safety of manned spaceflight as well as believe that regulation of the operational and disposal procedures, as discussed in this NPRM, will allow satellite operators flexibility in achieving business goals as compared to the other discussed alternatives well as safety of persons and property on the surface of the Earth. We such as limiting numbers of satellites launched, while helping to limit the creation of orbital debris in ways that are more effective than use of economic incentives alone, or active debris cleanup, for example.

87. Use of Economic Incentives. In this NRPM, we ask whether there are other economic incentives available that the Commission could offer that would help achieve the public interest in this area.[179] We seek comment on, for example, the possibility of requiring insurance for on-orbit and re-entry liability.[180] This could encourage satellite applicants to design system operations in ways that would enable them to obtain lower cost insurance products. Economic incentives could serve as a supplement—or an alternative—to adopting the changes in operations and disposal procedures contemplated in this NPRM. Given that debris creation is a negative externality, however, we believe that economic incentives alone may not be sufficient.

88. Active Collision Avoidance. The Commission could also potentially reduce orbital debris by requiring all operators to engage in active collision avoidance, which would involve coordination and maneuvering of spacecraft by operators to limit collisions with other objects in space. The proposals set forth in this NPRM include a certification that the space station operator will take appropriate action(s) following receipt of a space situational awareness conjunction warnings in order to help mitigate risk of collision.[181] We observe that in some instances this may include modifying the spacecraft attitude and/or operations, where possible.[182] Thus, we have proposed a rule that would require an operator to review a conjunction warning and take steps to mitigate collision risk if necessary. This proposed rule would not, however, require execution of collision avoidance maneuvers in response to each and every conjunction warning, since many warnings, upon further review by the operator, are found to not require action. In general, we note that operators with maneuvering capabilities already have an economic incentive to determine whether collision avoidance maneuvers are necessary in response to warnings of potential "conjunctions" from organizations that collect and disseminate such data, and to

---

[179] See supra Section III.G.

[180] Id.

[181] See supra Section III.C.3.

[182] Id.

execute any necessary maneuvers.[183] The Commission's proposal does not require all operators to take actions to avoid collisions, and some satellites may not be equipped to make maneuvers. Moreover, if the Commission were to require an operator to take avoidance action based on each conjunction warning it receives, such action would typically require an expenditure of fuel or other changes to the satellite's operational configuration, which can reduce the expected life of the spacecraft or interrupt the satellite's primary mission. Other satellites would have to add maneuvering capabilities to their designs, even where the risk of the satellite being involved in a collision was relatively low, for example because of deployment to a very low altitude and a resulting short orbital lifetime. As such, there would be an economic burden imposed by a requirement that satellites take active collision avoidance maneuvers in all instances. Spacecraft location data is not so precise that it is easy to make decisions about avoiding collisions, and a collision avoidance maneuver could result in a collision with different objects. Thus, there are costs associated with the planning and execution of maneuvers.

89. Active Debris Cleanup. Another alternative to the rules proposed in this NPRM is for the Commission to consider requiring operators to engage in active debris removal. We ask questions about this disposal method in this NPRM.[184] While the technologies needed to conduct these retrieval operations are continuing to be developed and the cost of launching satellites has fallen significantly, these sorts of operations remain at the more experimental side of satellite operations and still have significant costs. Furthermore, direct retrieval is not without its own risks, and attempts to recover satellites directly may result in the production of more debris than the satellite that was to be retrieved. Even when effective, direct retrieval may make sense only for the largest pieces of debris.

90. We seek comment on this proposed regulatory impact analysis. In connection with this analysis, we also seek comment on the relative costs and benefits of performance-based regulation versus prescriptive regulation in the context of orbital debris mitigation. Although the costs of our proposed approach may in some instances be borne by proponents of amateur satellites as well as experimental licensees, who in some instances may be small businesses, amateur and experimental satellite operations present the same public interest concerns as commercial satellite systems, as discussed above. A Kessler syndrome scenario rendering certain orbits or areas effectively unusable would also impact these types of operations. We believe that from a practical perspective, the additional costs of compliance for amateur and experimental satellites will be limited, and to the extent that there are additional costs, such costs may be reasonable given the potentially significant benefits.

91. In connection with this Notice, we seek comment on the benefits and costs of various combinations of these approaches. In addition, to the extent feasible, we identify alternative options, as described in this Notice.

---

[183] See Id.

[184] See supra Section III.D.1.

4 IV. ORDER ON RECONSIDERATION

92. In this Order on Reconsideration, we reject AMSAT's petition for reconsideration of the Commission's decision to apply orbital debris mitigation requirements to amateur service satellites.[185] AMSAT's Petition relies primarily on arguments that were fully considered in adopting those rules. In addition, to the extent that the Petition advances new arguments that could have been raised earlier in the proceeding, there is no basis to consider such arguments favorably.[186] The reconsideration process is not intended to allow petitioners to alter their position or advance new arguments after the rules are adopted, absent new factual developments.[187] In any event, for the reasons stated below, these arguments lack merit. Accordingly, we dismiss or alternatively deny the Petition pursuant to Section 1.429 of the Commission's rules.[188]

93. Background.—On July 17, 2002, AMSAT filed comments in IB Docket No. 02-54, supporting the Commission's establishment of policies to regulate orbital debris and commenting on the ability of amateur satellites to comply with the proposed orbital debris mitigation requirements.[189] AMSAT also filed a comment regarding the Initial Regulatory Flexibility Analysis in the NPRM.[190] On August 15, 2002, AMSAT filed Reply Comments in that proceeding.[191]

94. In the Orbital Debris Order, the Commission applied debris mitigation rules to amateur satellite licensees, noting that no comments had opposed requiring amateur

---

[185] AMSAT Petition at 1. In the Orbital Debris Order, the Commission amended Section 97.207 of the rules to include debris mitigation requirements for amateur satellite operations. Orbital Debris Order, Appendix B – Rule Revisions, § 97.207.

[186] See 47 CFR § 1.429(b).

[187] See id. Because we are simultaneously initiating a new proceeding concerning these rules, AMSAT may address in that context any factual developments it considers relevant that have occurred since the Orbital Debris Order.

[188] Id.

[189] See Comments of the Radio Amateur Satellite Corporation, IB Docket No. 02-54 (filed July 17, 2002) (AMSAT Comments). In addition, AMSAT filed comments addressing orbital debris mitigation plans in Amendment of Part 97 of the Commission's Rules Governing the Amateur Radio Services et al., Notice of Proposed Rulemaking and Order, 19 FCC Rcd 7293 (2004). See Comments of Radio Amateur Satellite Corporation, WT Docket No. 04-140 (filed June 15, 2004). It also made a further filing in that proceeding, citing to the Orbital Debris Order and noting its intent to file a petition for reconsideration of the Orbital Debris Order. Letter from Perry I. Klein, Vice President, Government Liaison, Radio Amateur Satellite Corporation, to the Commission, WT Docket No. 04-140, at 2 (filed Sept. 16, 2004). In the Commission's Report and Order in the Amendment of Part 97 of the Commission's Rules Governing the Amateur Radio Services et al., it noted that the issue of orbital debris mitigation

[190] Comments of the Radio Amateur Satellite Corporation Regarding Initial Regulatory Flexibility Analysis, IB Docket No. 02-54 (filed July 17, 2002) (AMSAT IRFA Comments). The AMSAT IRFA Comments stated that AMSAT, some universities and colleges building and launching amateur satellites, and individual licensed amateurs should be classified as "small entities" for consideration in the Commission's formulation of new rules. Id. at 1.

[191] Reply Comments of the Radio Amateur Satellite Corporation, IB Docket No. 02-54 (filed Aug. 15, 2002).

service and experimental radio service licensees to disclose their orbital debris mitigation plans.[192] It concluded that the costs involved with modifying amateur service spacecraft to satisfy the orbital debris mitigation requirements were "justified when balanced against the public interest in mitigating orbital debris."[193]

95. In its Petition, filed on October 12, 2004, AMSAT argued that the requirement to provide an orbital debris mitigation plan should not apply to individual amateur satellite operators because that individual may be different than the satellite owner or builder, and the owner or builder should be responsible for matters pertaining to the space vehicle, such as orbital debris mitigation.[194] AMSAT further argued that, to the extent the Commission declines to submit otherwise required filings to the International Telecommunication Union (ITU) due to concerns with debris mitigation plans, such Commission action would be contrary to U.S. obligations under the ITU Radio Regulations.[195] AMSAT also contended that the Commission did not provide any cost-benefit analysis supporting its decision to extend the requirements to amateur satellites, and that the necessary adjustments for amateur satellites to satisfy the rules are cost prohibitive.[196] Finally, it stated that the Commission has not indicated what constitutes an acceptable orbital debris mitigation plan or what action it will take if it finds that a plan is unacceptable, which has resulted in regulatory uncertainty.[197]

96. On November 19, 2004, the Commission issued a Public Notice announcing the filing of AMSAT's Petition.[198] A number of parties filed comments on AMSAT's Petition.[199]

In the Commission's Report and Order in the Amendment of Part 97 of the Commission's Rules Governing the Amateur Radio Services et al., it noted the issue of orbital debris mitigation (Dec. 28, 2004, AMSAT filed a Reply to Oppositions.[200]

97. Discussion. Pursuant to Section 1.429 of the Commission's rules, parties may petition for reconsideration of final orders in a rulemaking proceeding.[201]

---

[192] Orbital Debris Order, 19 FCC Rcd at 11608, para. 100.

[193] Id.

[194] AMSAT Petition at 1-5.

[195] AMSAT Petition at 5.

[196] AMSAT Petition at 4-7. AMSAT stated that it would file comments regarding the Paperwork Reduction Act of 1995. Id. at 4-5; see 44 U.S.C. § 3501 et seq. No such comments were filed. AMSAT later stated that it was unable to file its planned Paperwork Reduction Act comments because not enough data was available. Radio Amateur Satellite Corporation, Reply to Oppositions, IB Docket No. 02-54, at 2 (Dec. 28, 2004) (AMSAT Reply to Oppositions).

[197] AMSAT Petition at 7.

[198] Petitions for Reconsideration and Clarification of Action in Rulemaking Proceeding, Public Notice, Report No. 2682 Correction (rel. Nov. 19, 2004).

[199] See Comments of Clifford Buttschardt, IB Docket No. 02-54 (filed Dec. 16, 2004); Comments of California Polytechnic State University faculty Jordi Puig-Suari, Clifford Buttschardt, and Edward English, IB Docket No. 02-54 (filed Dec. 20, 2004); Comments of Ed Larsen, IB Docket No. 02-54 (filed Dec. 20, 2004), Comments of Emily E. Clarke, Project OSCAR Board Member and Vice President, IB Docket No. 02-54 (filed Dec. 20, 2004).

[200] AMSAT Reply to Oppositions.

[201] 47 CFR § 1.429.

Reconsideration is generally appropriate only where the petitioner shows either a material error or omission in the original order or raises additional facts not known or not existing until after the petitioner's last opportunity to respond. Under Section 1.429(b) of the Commission's rules, petitions for reconsideration that rely on facts or arguments that have not been previously presented to the Commission will be considered only under certain limited circumstances. AMSAT's Petition does not meet the requirements of Section 1.429(b). The Petition relies on facts and arguments that either could have been presented earlier in the proceeding, or were fully considered and rejected.[202]

98. In its Comments in IB Docket No. 02-54, AMSAT agreed with the approach the Commission proposed, stating that the "FCC licensed amateur . . . would become responsible for meeting whatever orbital debris requirements the Commission might decide to include in Part 97 of the Rules."[203] In its Petition, AMSAT provided no explanation for its adoption of the directly contrary position, that an amateur station license grantee under Part 97 of the Commission's rules is not the appropriate party to hold responsible for reporting orbital debris mitigation plans.[204] Section 1.429(b) of the Commission's rules provides for three specific circumstances in which the Commission may, in response to a petition for reconsideration, consider arguments not previously presented. A party's unexplained reversal of a prior position is not one of the permitted circumstances.[205] Nor is there any basis here under Section 1.429 for advancing new arguments with respect to the application of the Commission's rules to amateur station facilities. Accordingly, we dismiss AMSAT's petition.

99. As an alternative and independent ground for rejecting AMSAT's petition, we conclude that AMSAT's arguments are also unconvincing on the merits. As discussed in the Orbital Debris Order,[206] the Communications Act of 1934, as amended (the Act) provides the Commission with broad authority to license radio communications, and encourages "the larger and more effective use of radio in the public interest."[207] In the Orbital Debris Order, the Commission stated that "orbital debris and related mitigation issues are relevant in determining whether the public interest would be served by authorization of any particular satellite system, or by any particular practice or operating procedure of satellite systems."[208]

The Commission's rules[209] pertain only to the apparatus necessary for carrying on radio-communications from space, and not to the vehicle on which the amateur

---

[202] See 47 CFR §§ 1.429(l)(2)-(3).

[203] AMSAT Comments at 4.

[204] AMSAT Petition at 1-5.

[205] See 47 CFR § 1.429(b).

[206] Orbital Debris Order, 19 FCC Rcd at 11575, para. 14.

[207] 47 U.S.C. §§ 301, 307(a).

[208] Orbital Debris Order, 19 FCC Rcd 11575, para. 14.

[209] 47 CFR § 97.3(a)(5), (41); see also ITU Radio Regulations No. 1.61 (2012) (defining "station" as "[o]ne or more transmitters or receivers or a combination of transmitters and receivers, including the accessory equipment, necessary at one location for carrying on a radiocommunication service[.]" (emphasis in original)).

station is carried.[210] However, as established in the Orbital Debris Order, the Commission's public interest considerations in licensing radiocommunications in the amateur-satellite service extend to the physical operations of the satellites and satellite hardware.[211] Indeed, the Act defines "radio communication" as "the transmission by radio of writing, signs, signals, pictures, and sounds of all kinds, including all instrumentalities, facilities, apparatus, and services … incidental to such transmission."[212] The satellite hardware is an integral part of conducting radiocommunications from space. As the Commission explained in the Orbital Debris Order, "[b]ecause robotic spacecraft are typically controlled through radio-communications links, there is a direct connection between the radio-communications functions we are charged with licensing under the Communications Act and the physical operations of spacecraft."[213]

100. AMSAT contends that the individual amateur licensee should not be required to submit information pertaining to what it describes as a space vehicle because, in most circumstances, the amateur will not be responsible for the space vehicle construction, design, or ownership. AMSAT, however, does not explain why the licensee could not obtain this information from the builder or owner.[214] AMSAT claims that amateur licensees are inherently different from commercial operators, and yet, we observe that commercial licensees also do not typically build or design satellites.[215] Nevertheless, commercial licensees have obtained orbital debris mitigation information related to their proposed operations and have supplied such information to the Commission.[216] Neither amateur nor commercial licensees are

---

[210] AMSAT Petition at 1-2.

[211] Orbital Debris Order, 19 FCC Rcd at 11575, para. 14.

[212] 47 U.S.C. § 153(33). As a general matter, those "instrumentalities, facilities, apparatus, and services…incidental to such transmission" could include the physical facilities of a robotic spacecraft, and thus the Commission would have authority to review those physical facilities in connection with authorization of amateur satellite operations. Specific factual scenarios may need to be analyzed in order to determine what is "incidental" to transmissions. In the most common factual scenario, in which the radio transmitter is installed on a robotic spacecraft, and relies on spacecraft power generation facilities, attitude control, or similar equipment needed for successful transmission, the entirety of a satellite on which the transmitting facilities are located can, as a practical matter, be considered a station. Other cases, such as those involving human spaceflight and cargo delivery spacecraft, present a more complex factual scenario, in that a particular transmitting station may be distinct from, but located at least temporarily on another satellite. For example, in recent years numerous small satellites have been deployed from the International Space Station, and many of these have been FCC-licensed. In such cases, Bureau analysis of debris mitigation plans for the small satellite has been limited to the physical apparatus of the deployed satellite, and its operations.

[213] Orbital Debris Order, 19 FCC Rcd at 11575, para. 14.

[214] To the extent AMSAT argues that a grantee of an amateur club station license should not be responsible for orbital debris mitigation information, this rationale also applies. See AMSAT Petition at 2-3.

[215] See, e.g., the Commission's previous Part 25 milestone requirements, which contemplated that a licensee would contract with another party for construction of a satellite system. 47 CFR § 25.164 (2015).

[216] Licensees have often submitted documentation provided by the satellite manufacturer.

required to have the technical competence to single-handedly design an orbital debris mitigation plan. Instead, they must provide information about the plan to the Commission, so the Commission can evaluate whether the proposed operations are in the public interest.[217]

101. AMSAT's newly raised argument that there is an inherent conflict between debris mitigation regulations and coordination and notification procedures in the ITU Radio Regulations is also without merit.[218] Specifically, AMSAT argues that the ITU Radio Regulations themselves may not permit the Commission to delay submitting a notification to the ITU Radiocommunication Bureau because of concerns about orbital debris.[219] We note, however, that there is no duty imposed by the ITU Radio Regulations on any Administration to submit a filing if that Administration is unwilling to authorize such operations. In fact, the ITU Radio Regulations recognize that operations of stations by private persons, such as amateur station operators, are subject to national regulation.[220] Moreover, the Commission's regulations require that, while Commission-licensed amateur operators may operate satellites, the satellite must be on a craft that is "documented or registered" in the United States.[221] We do not consider a craft to be "documented" in the United States if a satisfactory debris mitigation plan has not been prepared, submitted, and favorably reviewed.[222] Further, because Commission authorization is in many instances the sole mechanism by which U.S. amateur satellite operations are authorized and supervised, a contrary interpretation could raise a significant question as to consistency of such operations with U.S. treaty obligations under the Outer Space Treaty.[223]

---

[217] See 47 CFR §§ 97.207(g)(1), 25.114(c)(14), 25.283.

[218] AMSAT Petition at 5.

[219] Id.

[220] See ITU Radio Regulations Article 18.1. ("No transmitting station may be established or operated by a private person or by any enterprise without a license issued in an appropriate form and in conformity with the provisions of these Regulations by or on behalf of the government of the country to which the station in question is subject.").

[221] 47 CFR § 97.5(a)(3).

[222] In an effort to improve the transparency of FCC records in this regard, the Wireless Telecommunication Bureau has begun including approved debris mitigation plans in the ULS file associated with the satellite. In the amateur service, this is the file for the satellite amateur station licensee grantee.

[223] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, Art. 6 ("States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty."). The U.S. State Department generally considers FCC authorization prior to launch to provide a basis for registering a spacecraft under the U.N. Convention on Registration of Objects Launched into Outer Space. U.S. practice is to register such objects following launch, typically some months following launch. Thus, a U.S. amateur satellite must typically be considered "documented" in order for transmissions to be considered authorized in the period before registration is completed.

102. AMSAT's remaining arguments are also without merit. AMSAT argues that the Commission failed to consider the costs of modifying spacecraft to meet the orbital debris mitigation requirements, and therefore has not presented a cost-benefit analysis to support applying those requirements to amateur radio operators.[224] Specifically, AMSAT argues that it is impracticable to add a propulsion system for small LEO spacecraft and that the atmospheric re-entry of these spacecraft within 25 years is not feasible.[225] AMSAT also notes that amateur satellites are typically a secondary payload, and as a result, cannot certify delivery to a particular orbit to ensure proper end-of-life disposal.[226] The Commission has previously addressed the concerns from amateur operators that AMSAT now raises.[227]

In response to comments from AMSAT and others to the NPRM, the Commission declined to exempt amateur service satellites from the rules, on the basis that "amateur satellites pose the same public interest concerns with regard to orbital debris."[228] While recognizing that "post-mission disposal requirements may necessitate modifications in the current design and operation," including the addition of propulsion and or other strategies to cause atmospheric reentry within 25 years, the Commission concluded that "the costs involved with these modifications are justified when balanced against the public interest in mitigating orbital debris."[229] The Commission determined that closer adherence to the disposal methods described in the rules was "warranted in order to limit the growth of orbital debris in LEO[,]"[230] despite the fact that "changes in the design and operation of certain types of LEO spacecraft may be necessary in order to follow these practices and may limit an operator's ability to deploy spacecraft in certain orbital regimes or use certain spacecraft designs."[231] In any event, in the years since the debris mitigation rules were adopted, and notwithstanding any costs imposed by FCC regulations, well over 150 small satellites have been authorized, with at least 20 of those considered amateur satellites. It appears that, to the extent that any costs have been incurred, the main contributor to costs for amateur and similar LEO missions has to do with the availability of launches to appropriate orbits.[232]

103. Finally, we address AMSAT's argument that the Orbital Debris Order does not outline what would constitute an acceptable orbital debris mitigation plan, which according to AMSAT, makes it difficult for the satellite owner/builder to estimate,

---

[224] AMSAT Petition at 5-6.

[225] Id. at 6.

[226] Id. at 7.

[227] Orbital Debris Order, 19 FCC Rcd at 11608, para. 100.

[228] Id.

[229] Id. (emphasis added).

[230] Id. at 11602, para. 85.

[231] Id.

[232] Since most amateur satellites have not been equipped with propulsion or other means of actively de-orbiting, such amateur satellites would need to be launched into appropriate orbits, i.e. those orbits from which the satellites will naturally deorbit within a reasonable period of time.

budget for, and fund the cost of compliance.[233] The various components of an acceptable orbital debris mitigation plan, including post-mission disposal, were addressed extensively in the Orbital Debris Order.[234] We observe that in the years since the Commission issued the Orbital Debris Order, numerous licensees, including amateur satellites operating in LEO, have successfully satisfied our orbital debris mitigation requirements.[235] In addition, the Commission has issued a Public Notice titled Guidance on Obtaining Licenses for Small Satellites, which includes guidance for amateur radio service satellite operators.[236]

104. In summary, the Commission provided ample opportunity for comment on its proposals and then fully considered the public record developed in response to the proposals. The arguments presented by AMSAT should have been presented in AMSAT's Comments to the NPRM, or were already fully considered. In addition, its arguments fail on the merits. Therefore, AMSAT's Petition does not warrant further consideration.

5 V. PROCEDURAL MATTERS

105. Ex Parte Presentations. The proceeding this NPRM initiates shall be treated as a "permit-but-disclose" proceeding in accordance with the Commission's ex parte rules.[237] Persons making ex parte presentations must file a copy of any written presentation or a memorandum summarizing any oral presentation within two business days after the presentation (unless a different deadline applicable to the Sunshine period applies). Persons making oral ex parte presentations are reminded that memoranda summarizing the presentation must (1) list all persons attending or otherwise participating in the meeting at which the ex parte presentation was made, and (2) summarize all data presented and arguments made during the presentation. If the presentation consisted in whole or in part of the presentation of data or arguments already reflected in the presenter's written comments, memoranda or other filings in the proceeding, the presenter may provide citations to such data or arguments in his or her prior comments, memoranda, or other filings (specifying the relevant page and/or paragraph numbers where such data or arguments can be found) in lieu of summarizing them in the memorandum. Documents shown or given to Commission

---

[233] AMSAT Petition at 7.

[234] Orbital Debris Order, 19 FCC Rcd at 11591-92, paras. 58-63.

[235] See, e.g., Application of Planet Labs Inc., IBFS File No. SAT-LOA-20130626-00087 (granted Dec. 3, 2013); Space Imaging, LLC, Declaratory Order and Order and Authorization, 20 FCC Rcd 11964, 11974-75, para. 32 (IB 2005) (finding that the Commission's orbital debris mitigation requirements were satisfied as part of market access determination involving a foreign remote-sensing satellite).

[236] Guidance on Obtaining Licenses for Small Satellites, Public Notice, 28 FCC Rcd 2555 (rel. Mar. 15, 2013).

[237] 47 CFR §§ 1.1200 et seq.

staff during ex parte meetings are deemed to be written ex parte presentations and must be filed consistent with rule 1.1206(b). In proceedings governed by rule 1.49(f) or for which the Commission has made available a method of electronic filing, written ex parte presentations and memoranda summarizing oral ex parte presentations, and all attachments thereto, must be filed through the electronic comment filing system available for that proceeding, and must be filed in their native format (e.g., .doc, .xml, .ppt, searchable .pdf). Participants in this proceeding should familiarize themselves with the Commission's ex parte rules.

106. Comment Filing Requirements. Pursuant to Sections 1.415 and 1.419 of the Commission's rules, 47 CFR §§ 1.415, 1.419, interested parties may file comments and reply comments on or before the dates indicated on the first page of this document. Comments may be filed using the Commission's Electronic Comment Filing System (ECFS). See Electronic Filing of Documents in Rulemaking Proceedings, 63 FR 24121 (1998).

- Electronic Filers. Comments may be filed electronically using the Internet by accessing the ECFS: http://apps.fcc.gov/ecfs.
- Paper Filers. Parties who choose to file by paper must file an original and one copy of each filing. If more than one docket or rulemaking number appears in the caption of this proceeding, filers must submit two additional copies for each additional docket or rulemaking number.

  Filings can be sent by hand or messenger delivery, by commercial overnight courier, or by first-class or overnight U.S. Postal Service mail. All filings must be addressed to the Commission's Secretary, Office of the Secretary, Federal Communications Commission.
  - All hand-delivered or messenger-delivered paper filings for the Commission's Secretary must be delivered to FCC Headquarters at 445 12th Street, SW., Room TWA325, Washington, DC 20554. The filing hours are 8:00 a.m. to 7:00 p.m. All hand deliveries must be held together with rubber bands or fasteners. Any envelopes and boxes must be disposed of before entering the building.
  - Commercial overnight mail (other than U.S. Postal Service Express Mail and Priority Mail) must be sent to 9050 Junction Drive, Annapolis Junction, MD 20701.
  - U.S. Postal Service first-class, Express, and Priority mail must be addressed to 445 12th Street, SW, Washington DC 20554.
- People with Disabilities: To request materials in accessible formats for people with disabilities (braille, large print, electronic files, audio format), send an email to fcc504@fcc.gov or call the Consumer & Governmental Affairs Bureau at 202-418-0530 (voice) or 202-418-0432 (TTY).

107. Initial Regulatory Flexibility Analysis. As required by the Regulatory Flexibility Act of 1980, as amended,[238] the Commission has prepared an Initial

---

[238] 5 U.S.C. § 603.

Regulatory Flexibility Analysis (IRFA) for this Notice, of the possible significant economic impact on small entities of the policies and rules addressed in this document. The IRFA is set forth as Appendix B. Written public comments are requested on this IRFA. Comments must be identified as responses to the IRFA and must be filed by the deadlines for comments on the Notice provided on or before the dates indicated on the first page of this Notice. The Commission's Consumer and Governmental Affairs Bureau, Reference Information Center, will send a copy of the NPRM, including this IRFA, to the Chief Counsel for Advocacy of the Small Business Administration.

108. Paperwork Reduction Act. This document contains proposed new and modified information collection requirements. The Commission, as part of its continuing effort to reduce paperwork burdens, invites the general public and the Office of Management and Budget to comment on the information collection requirements contained in this document, as required by the Paperwork Reduction Act of 1995.[239] In addition, pursuant to the Small Business Paperwork Relief Act of 2002,[240] we seek specifically seek comment on how we might further reduce the information collection burden for small business concerns with fewer than 25 employees.[241]

6 VI. ORDERING CLAUSES

109. Accordingly, IT IS ORDERED, pursuant to Sections 1, 4(i), 301, 303, 307, 308, 309, and 310 of the Communications Act of 1934, as amended, 47 U.S.C. §§ 151, 154(i), 301, 303, 307, 308, 309, 310, that this Notice of Proposed Rulemaking IS ADOPTED.

110. IT IS FURTHER ORDERED that the Commission's Consumer and Governmental Affairs Bureau, Reference Information Center SHALL SEND a copy of this Notice of Proposed Rulemaking, including the initial regulatory flexibility act analysis, to the Chief Counsel for Advocacy of the Small Business Administration, in accordance with Section 603(a) of the Regulatory Flexibility Act, 5 U.S.C. § 601, et seq. (1981).

111. IT IS FURTHER ORDERED that, effective upon release of this Order, the Petition for Reconsideration filed by the Radio Amateur Satellite Corporation on October 12, 2004, IS DISMISSED and, on alternative and independent grounds, DENIED, and IB Docket No. 02-54 IS TERMINATED.

FEDERAL COMMUNICATIONS COMMISSION
Marlene H. Dortch
Secretary

---

[239] Pub. L. 104-13.

[240] Pub. L. 107-198.

[241] 44 U.S.C. § 3506(c)(4).

APPENDIX A

Proposed Rules

The Federal Communications Commission proposes to amend title 47 of the Code of Federal Regulations, parts 5, 25, and 97, as follows:

PART 5 – EXPERIMENTAL RADIO SERVICE

1. The authority citation for Part 5 continues to read as follows:

Authority: Secs. 4, 302, 303, 307, 336 48 Stat. 1066, 1082, as amended; 47 U.S.C. 154, 302, 303, 307, 336. Interpret or apply sec. 301, 48 Stat. 1081, as amended; 47 U.S.C. 301.

2. Amend Section 5.64 by revising paragraph (b)(1), revising and re-designating paragraphs (b)(2), (b)(3) and (b)(4) as (b)(3), (b)(4) and (b)(5), respectively, and adding paragraphs (b)(2), (c), and (d), to read as follows:

§ 5.64 Special provisions for satellite systems.

* * * * *

(b) * * *

(1) A statement that the space station operator has assessed and limited the amount of debris released in a planned manner during normal operations. Where applicable, this statement must include an orbital debris mitigation disclosure for any separate deployment devices not part of the space station launch that may become a source of orbital debris;

(2) A statement that the space station operator has assessed and limited the probability of the space station(s) becoming a source of debris by collisions with small debris or meteoroids that would cause loss of control and prevent post-mission disposal;

(3) A statement that the space station operator has assessed and limited the probability of accidental explosions or release of liquids that could become debris during and after completion of mission operations. This statement must include a demonstration that debris generation will not result from the conversion of energy sources on board the spacecraft into energy that fragments the spacecraft. Energy sources include chemical, pressure, and kinetic energy and debris includes liquids that persist in droplet form. This demonstration should address whether stored energy will be removed at the spacecraft's end of life, by depleting residual fuel and leaving all fuel line valves open, venting any pressurized system, leaving all batteries in a permanent discharge state, and removing any remaining source of stored energy, or through other equivalent procedures specifically disclosed in the application;

(4) A statement that the space station operator has assessed in the aggregate and limited the probability of the space station(s) becoming a source of debris by collisions with large debris or other operational space stations, including the following information:

(i) Where the application is for an NGSO space station or constellation:

(A) The statement must indicate whether the probability in the aggregate of a collision between the space stations(s) and another large object during the total orbital lifetime of the constellation, including any de-orbit phase, is less than 0.001.

(B) The statement must identify any planned and/or operational space stations that may raise a collision risk, and indicate what steps, if any, have been taken to coordinate with the other spacecraft or system, or what other measures the operator plans to use to avoid collision. This includes disclosure of any planned proximity operations. If the planned space station operational orbit is above 650 kilometers, the statement must specify why the planned orbit was chosen, and if the space station will transit through the orbit of the International Space Station (ISS) or orbit of any other manned spacecraft, at any time during the space station's mission or de-orbit phase, and the statement must describe the potential impact to the ISS or other manned spacecraft, if any, including design and operational strategies that will be used to avoid collision with manned spacecraft.

(C) The statement must disclose the accuracy – if any – with which orbital parameters will be maintained, including apogee, perigee, inclination, and the right ascension of the ascending node(s). In the event that a system is not able to maintain orbital tolerances, i.e., it lacks a propulsion system for orbital maintenance, that fact should be included in the debris mitigation disclosure. Such systems must also indicate the anticipated evolution over time of the orbit of the proposed satellite or satellites. All systems should describe the extent of satellite maneuverability, whether or not the space station(s) design includes a propulsion system; and

(D) In addition, the statement must include a description of the means for tracking the spacecraft, including whether tracking will be active or passive. The space station operator must certify that upon receipt of a space situational awareness conjunction warning, the operator will review the warning and take all possible steps to assess and, if necessary, to mitigate collision risk, including, but not limited to: contacting the operator of any active spacecraft involved in such warning; sharing ephemeris data and other appropriate operational information with any such operator; modifying spacecraft attitude and/or operations.

(ii) Where a space station requests the assignment of a geostationary-Earth orbit location, it must assess whether there are any known satellites located at, or reasonably expected to be located at, the requested orbital location, or assigned in the vicinity of that location, such that the station keeping volumes of the respective satellites might overlap or touch. If so, the statement must include a statement as to the identities of those parties and the measures that will be taken to prevent collisions; and

(5) A statement detailing the post-mission disposal plans for the space station at end of life, including the quantity of fuel—if any—that will be reserved for post-mission disposal maneuvers. In addition, the following specific provisions apply:

(i) For geostationary-Earth orbit space stations, the statement must disclose the altitude selected for a post-mission disposal orbit and the calculations that are used in deriving the disposal altitude.

(ii) For spacecraft terminating operations in an orbit in or passing through the low-Earth orbit region below 2,000 km altitude, the statement must indicate whether the spacecraft will be disposed of either through atmospheric re-entry within 25 years following the completion of the spacecraft's mission, or by direct retrieval of the spacecraft.

(iii) Where planned post-mission disposal involves atmospheric re-entry of the space station(s):

(A) The statement must include a demonstration that the probability of success for the disposal method will be no less than 0.90, calculated on an aggregate basis.

(B) For space stations with a planned operational altitude between 650 km and 2,000 km, the statement should include a certification that the satellites will be deployed at an altitude below 650 km, and describe the means that will be used to ensure reliability of disposal, such as through automatic initiation of disposal in the event of loss of power or contact with the space station.

(C) The statement must also include a casualty risk assessment. In general, an assessment should include an estimate as to whether portions of the spacecraft will survive re-entry, including all objects that would impact the surface of the Earth with a kinetic energy in excess of 15 joules, as well as an estimate of the resulting probability of human casualty. Where the risk of human casualty from surviving debris is greater than zero, as calculated using either the NASA Debris Assessment Software or a higher fidelity model, a statement must be provided indicating the actual calculated human casualty risk as well as the input assumptions used in the model.

(c) As a condition of their licenses for experimental satellite facilities, licensees must submit an executed agreement indemnifying the United States against any costs associated with a claim brought against the United States related to the authorized facilities. The agreement, or an updated version thereof, must be submitted no later than 30 days after the grant of the license, an assignment of the license, or a transfer of control of the licensee, or at least 90 days prior to planned launch of the space station, whichever is sooner.

(d) For space stations that include onboard propulsion systems, operators must encrypt telemetry, tracking, and command communications with the space station.

PART 25 – SATELLITE COMMUNICATIONS

3. The authority citation for part 25 continues to read as follows:

Authority: 47 U.S.C. 154, 301, 302, 303, 307, 309, 310, 319, 332, 605, and 721, unless otherwise noted.

4. Amend Section 25.114(d)(14) by revising paragraph (i), revising and redesignating paragraphs (ii), (iii) and (iv) as (iii), (iv) and (v), respectively, redesignating paragraph (v) as (vi), and adding paragraph (ii), to read as follows:

§ 25.114 Applications for space station authorizations.

* * * * *

(d) * * *

(14) * * *

(i) A statement that the space station operator has assessed and limited the amount of debris released in a planned manner during normal operations. Where applicable, this statement must include an orbital debris mitigation disclosure for any separate deployment devices not part of the space station launch that may become a source of orbital debris;

(ii) A statement that the space station operator has assessed in the aggregate and limited the probability of the space station(s) becoming a source of debris by collisions with small debris or meteoroids that would cause loss of control and prevent post-mission disposal;

(iii) A statement that the space station operator has assessed and limited the probability of accidental explosions or release of liquids that could become debris during and after completion of mission operations. This statement must include a demonstration that debris generation will not result from the conversion of energy sources on board the spacecraft into energy that fragments the spacecraft. Energy sources include chemical, pressure, and kinetic energy and debris includes liquids that persist in droplet form. This demonstration should address whether stored energy will be removed at the spacecraft's end of life, by depleting residual fuel and leaving all fuel line valves open, venting any pressurized system, leaving all batteries in a permanent discharge state, and removing any remaining source of stored energy, or through other equivalent procedures specifically disclosed in the application;

(iv) A statement that the space station operator has assessed in the aggregate and limited the probability of the space station(s) becoming a source of debris by collisions with large debris or other operational space stations, including the following information:

(A) Where the application is for an NGSO space station or constellation:

1. The statement must indicate whether the probability in the aggregate of a collision between the space station(s) and another large object during the total orbital lifetime of the constellation, including any de-orbit phases, is less than 0.001;

2. The statement must identify any planned and/or operational space stations that may raise a collision risk, and indicate what steps, if any, have been taken to coordinate with the other spacecraft or system, or what other measures the operator plans to use to avoid collision. This includes disclosure of any planned proximity operations. If the planned space station operational orbit is above 650 kilometers, the statement must specify why the planned orbit was chosen, and if the space station will transit through the orbit of the International Space Station (ISS) or orbit of any other manned spacecraft, at any time during the space station's mission or de-orbit phase, and the statement must describe the potential impact to the ISS or other manned spacecraft, if any, including design and operational strategies that will be used to avoid collision with manned spacecraft;

3. The statement must disclose the accuracy – if any – with which orbital parameters will be maintained, including apogee, perigee, inclination, and the right ascension of the ascending node(s). In the event that a system is not able to maintain orbital tolerances, i.e., it lacks a propulsion system for orbital maintenance, that fact must be included in the debris mitigation disclosure. Such systems must also indicate the anticipated evolution over time of the orbit of the proposed satellite or satellites. All systems must describe the extent of satellite maneuverability, whether or not the space station(s) design includes a propulsion system; and

4. In addition, the statement must include a description of the means for tracking the spacecraft, including whether tracking will be active or passive. The space station operator must certify that upon receipt of a space situational awareness conjunction warning, the operator will review the warning and take all possible steps to assess

and, if necessary, to mitigate collision risk, including, but not limited to: contacting the operator of any active spacecraft involved in such warning; sharing ephemeris data and other appropriate operational information with any such operator; modifying space station attitude and/or operations.

(B) Where a space station requests the assignment of a geostationary-Earth orbit location, it must assess whether there are any known satellites located at, or reasonably expected to be located at, the requested orbital location, or assigned in the vicinity of that location, such that the station keeping volumes of the respective satellites might overlap or touch. If so, the statement must include a statement as to the identities of those parties and the measures that will be taken to prevent collisions; and

(v) A statement detailing the post-mission disposal plans for the space station at end of life, including the quantity of fuel—if any—that will be reserved for post-mission disposal maneuvers. In addition, the following specific provisions apply:

(A) For geostationary-Earth orbit space stations, the statement must disclose the altitude selected for a post-mission disposal orbit and the calculations that are used in deriving the disposal altitude.

(B) For spacecraft terminating operations in an orbit in or passing through the low-Earth orbit region below 2,000 km altitude, the statement must indicate whether the spacecraft will be disposed of either through atmospheric re-entry within 25 years following the completion of the spacecraft's mission, or by direct retrieval of the spacecraft.

(C) Where planned post-mission disposal involves atmospheric re-entry of the space station(s):

1. The statement must include a demonstration that the probability of success for the disposal method will be no less than 0.90, calculated on an aggregate basis.

2. For space stations with a planned operational altitude between 650 km and 2,000 km, the statement should include a certification that the satellites will be deployed at an altitude below 650 km, and describe the means that will be used to ensure reliability of disposal, such as through automatic initiation of disposal in the event of loss of power or contact with the space station.

3. The statement must also include a casualty risk assessment. In general, an assessment should include an estimate as to whether portions of the spacecraft will survive re-entry, including all objects that would impact the surface of the Earth with a kinetic energy in excess of 15 joules, as well as an estimate of the resulting probability of human casualty. Where the risk of human casualty from surviving debris is greater than zero, as calculated using either the NASA Debris Assessment Software or a higher fidelity model, a statement must be provided indicating the actual calculated human casualty risk as well as the input assumptions used in the model.

(D) Applicants for space stations to be used only for commercial remote sensing may, in lieu of submitting detailed post-mission disposal plans to the Commission, certify that they have submitted such plans to the National Oceanic and Atmospheric Administration for review.

(vi) For non-U.S.-licensed space stations, the requirement to describe the design and operational strategies to minimize orbital debris risk can be satisfied by demonstrating that debris mitigation plans for the space station(s) for which U.S. market access is requested are subject to direct and effective regulatory oversight by the national licensing authority.

* * * * *

4. Amend Section 25.121 to add paragraph (f) as follows:

§25.121 License term and renewals.

(f) Geostationary Satellite License Term Extensions. License term extensions for geostationary space stations may be authorized by grant of a modification application in increments of five years or less.

5. Amend Section 25.161 to add paragraph (e) as follows:

§25.161 Automatic termination of station authorization.

(e) The failure to file an executed indemnification agreement in accordance with § 25.166.

6. Add Section 25.166 to read as follows:

§25.166 Indemnification.

As a condition of their licenses, space station licensees must submit an executed agreement indemnifying the United States against any costs associated with a claim brought against the United States related to the authorized facilities. The agreement, or an updated version thereof, must be submitted no later than 30 days after the grant of the license, an assignment of the license, or a transfer of control of the licensee, or at least 90 days prior to planned launch of the space station, whichever is sooner.

7. Revise paragraph (e) to Section 25.271 to read as follows:

§25.271 Control of Transmitting Stations.

* * * * *

(e) An NGSO licensee or market access recipient must ensure that ephemeris data for its space station or constellation is available to all operators of operational satellite systems identified pursuant to § 25.114(d)(14)(iv)(A)(2) that may raise a collision risk.

8. Revise Section 25.282 to read as follows:

§ 25.282 Orbit raising.

A space station may operate in connection with short-term, transitory maneuvers directly related to post-launch, orbit-raising maneuvers, in the telemetry, tracking, and command frequencies authorized for operation at the assigned orbital position. Such orbit-raising operations must be coordinated on an operator-to-operator basis with any potentially affected satellite networks.

9. Add Section 25.290 to read as follows:

§ 25.290 Telemetry, tracking, and command encryption.

For space stations that include onboard propulsion systems, operators must encrypt telemetry, tracking, and command communications with the space station.

PART 97 – AMATEUR RADIO SERVICE

5. The authority citation for part 97 continues to read as follows:

Authority: 48 Stat. 1066, 1082, as amended; 47 U.S.C. 154, 303. Interpret or apply 48 Stat. 1064-1068, 1081-1105, as amended; 47 U.S.C. 151-155, 301-609, unless otherwise noted.

6. Amend Section 97.207 by revising paragraph (g)(1)(i), revising and redesignating paragraphs (g)(1)(ii), (g)(1)(iii), and (g)(1)(iv) as (g)(1)(ii), (g)(1)(iv), and (g)(1)(v), respectively, redesignating paragraph (g)(1)(v) as (g)(1)(vi), adding paragraph (g)(1)(ii), and adding paragraphs (h) and (i), to read as follows:

§ 97.207 Space station. * * * * *

(g) * * *

(1) * * *

(i) A statement that the space station licensee has assessed and limited the amount of debris released in a planned manner during normal operations. Where applicable, this statement must include an orbital debris mitigation disclosure for any separate deployment devices not part of the space station launch that may become a source of orbital debris;

(ii) A statement that the space station licensee has assessed in the aggregate and limited the probability of the space station(s) becoming a source of debris by collisions with small debris or meteoroids that would cause loss of control and prevent post-mission disposal;

(iii) A statement that the space station licensee has assessed and limited the probability of accidental explosions or release of liquids that could become debris during and after completion of mission operations. This statement must include a demonstration that debris generation will not result from the conversion of energy sources on board the spacecraft into energy that fragments the spacecraft. Energy sources include chemical, pressure, and kinetic energy and debris includes liquids that persist in droplet form. This demonstration should address whether stored energy will be removed at the spacecraft's end of life, by depleting residual fuel and leaving all fuel line valves open, venting any pressurized system, leaving all batteries in a permanent discharge state, and removing any remaining source of stored energy, or through other equivalent procedures specifically disclosed in the notification;

(iv) A statement that the space station licensee has assessed in the aggregate and limited the probability of the space station(s) becoming a source of debris by collisions with large debris or other operational space stations, including the following information:

(A) Where the space station is a NGSO space station or constellation:

(1) The statement must indicate whether the probability in the aggregate of a collision between the space station(s) and another large object during the total orbital lifetime of the constellation, including any de-orbit phases, is less than 0.00;1

(2) The statement must identify any planned and/or operational space stations that may raise a collision risk, and indicate what steps, if any, have been taken to coordinate with the other spacecraft or system, or what other measures the operator plans to use to avoid collision. This includes disclosure of any planned proximity operations. If the planned space station operational orbit is above 650 kilometers, the statement must specify why the planned orbit was chosen, and if the space station

will transit through the orbit of the International Space Station (ISS) or orbit of any other manned spacecraft, at any time during the space station's mission or de-orbit phase, and the statement must describe the potential impact to the ISS or other manned spacecraft, if any, including design and operational strategies that will be used to avoid collision with manned spacecraft;

(3) The statement must disclose the accuracy – if any – with which orbital parameters will be maintained, including apogee, perigee, inclination, and the right ascension of the ascending node(s). In the event that a system is not able to maintain orbital tolerances, i.e., it lacks a propulsion system for orbital maintenance, that fact must be included in the debris mitigation disclosure. Such systems must also indicate the anticipated evolution over time of the orbit of the proposed satellite or satellites. All systems must describe the extent of satellite maneuverability, whether or not the space station(s) design includes a propulsion system; and

(4) In addition, the statement must include a description of the means for tracking the spacecraft, including whether tracking will be active or passive. The space station licensee must certify that upon receipt of a space situational awareness conjunction warning, the licensee or operator will review the warning and take all possible steps to assess and, if necessary, to mitigate collision risk, including, but not limited to: contacting the operator of any active spacecraft involved in such warning; sharing ephemeris data and other appropriate operational information with any such operator; modifying space station attitude and/or operations.

(B) Where a space station requests the assignment of a geostationary-Earth orbit location, it must assess whether there are any known satellites located at, or reasonably expected to be located at, the requested orbital location, or assigned in the vicinity of that location, such that the station keeping volumes of the respective satellites might overlap or touch. If so, the statement must include a statement as to the identities of those parties and the measures that will be taken to prevent collisions; and

(v) A statement detailing the post-mission disposal plans for the space station at end of life, including the quantity of fuel—if any—that will be reserved for post-mission disposal maneuvers. In addition, the following specific provisions apply:

(A) For geostationary-Earth orbit space stations, the statement must disclose the altitude selected for a post-mission disposal orbit and the calculations that are used in deriving the disposal altitude.

(B) For spacecraft terminating operations in an orbit in or passing through the low-Earth orbit region below 2,000 km altitude, the statement must indicate whether the spacecraft will be disposed of either through atmospheric re-entry within 25 years following the completion of the spacecraft's mission, or by direct retrieval of the spacecraft.

(C) Where planned post-mission disposal involves atmospheric re-entry of the space station:

(1) The statement must include a demonstration that the probability of success for the disposal method will be no less than 0.90, calculated on an aggregate basis.

(2) For space stations with a planned operational altitude between 650 km and 2,000 km, the statement should include a certification that the satellites will be

deployed at an altitude below 650 km, and describe the means that will be used to ensure reliability of disposal, such as through automatic initiation of disposal in the event of loss of power or contact with the space station.

(3) The statement must also include a casualty risk assessment. In general, an assessment should include an estimate as to whether portions of the spacecraft will survive re-entry, including all objects that would impact the surface of the Earth with a kinetic energy in excess of 15 joules, as well as an estimate of the resulting probability of human casualty. Where the risk of human casualty from surviving debris is greater than zero, as calculated using either the NASA Debris Assessment Software or a higher fidelity model, a statement must be provided indicating the actual calculated human casualty risk as well as the input assumptions used in the model.

(vi) If any material item described in this notification changes before launch, a replacement pre-space notification shall be filed with the International Bureau no later than 90 days before integration of the space station into the launch vehicle.

* * * * *

(h) At least 90 days prior to planned launch of the space station, the license grantee of each space station must submit an executed agreement indemnifying the United States against any costs associated with a claim brought against the United States related to the authorized facilities.

(i) For space stations that include onboard propulsion systems, operators must encrypt telemetry, tracking, and command communications with the space station.

APPENDIX B

Initial Regulatory Flexibility Analysis

As required by the Regulatory Flexibility Act of 1980, as amended (RFA),[242] the Commission has prepared this present Initial Regulatory Flexibility Analysis (IRFA) of the possible significant economic impact on a substantial number of small entities by the policies and rules proposed in this Notice of Proposed Rulemaking (NPRM). Written public comments are requested on this IRFA. Comments must be identified as responses to the IRFA and must be filed by the deadlines specified in the NPRM for comments. The Commission will send a copy of this NPRM, including this IRFA, to the Chief Counsel for Advocacy of the Small Business Administration (SBA).[243] In addition, the NPRM and IRFA (or summaries thereof) will be published in the Federal Register.[244]

---

[242] See 5 U.S.C. § 603. The RFA, see 5 U.S.C. § 601 et seq., has been amended by the Small Business Regulatory Enforcement Fairness Act of 1996, (SBREFA) Pub. L. No. 104-121, Title II, 110 Stat. 847 (1996).

[243] See 5 U.S.C. § 603(a).

[244] Id.

A. Need for, and Objectives of, the Proposed Rules

The Commission originally adopted comprehensive rules relating to the mitigation of orbital debris in 2004. Consideration of orbital debris issues remains an important part of preserving access to space for the long term, as well as the safety of persons and property in space on the surface of the Earth. This NPRM represents the first comprehensive update to our rules on orbital debris mitigation since their adoption. The basis for these revisions and additions to those rules includes the Commission's experience gained in the licensing process, updates in mitigation guidelines and practices, and market developments. Our objective is to ensure that space stations applying for a license or grant of market access, or otherwise authorized by the Commission, including experimental and amateur satellite systems, provide a statement concerning plans for orbital debris mitigation that enables the Commission to fully evaluate whether the proposed operations are in the public interest.

With this in mind, this NPRM seeks comment on a number of proposals revising the Commission's rules and policies for limiting orbital debris. Adoption of the proposed changes would modify 47 CFR parts 5, 25, and 97 to, among other things:

1) Require satellite applicants to demonstrate compliance with certain metrics developed for assessing orbital debris mitigation plans by the National Aeronautics and Space Administration (NASA).

2) Require additional disclosures to the Commission regarding risk of collision, trackability, maneuverability, proximity operations, if any, choice of orbit, and impact on manned spacecraft, if any.

3) Require information regarding the probability of success for the chosen disposal method, where disposal is planned by atmospheric re-entry.

4) Require satellite applicants with planned operations in certain orbits to make certifications related deploying at a lower orbit and then raising the satellite(s) for operations.

5) Require satellite licensees to indemnify the United States government against any costs associated with a claim brought against the United States related to the authorized facilities.

B. Legal Basis

The proposed action is authorized under Sections 1, 4(i), 301, 303, 307, 308, 309, and 310 of the Communications Act of 1934, as amended, 47 U.S.C. §§ 151, 154(i), 301, 303, 307, 308, 309, and 310.

C. Description and Estimate of the Number of Small Entities to Which the Proposed Rules May Apply

The RFA directs agencies to provide a description of, and, where feasible, an estimate of, the number of small entities that may be affected by adoption of proposed rules.[245] The RFA generally defines the term "small entity" as having the same meaning as the terms "small business," "small organization," and "small governmental jurisdiction."[246] In addition, the term "small business" has the same

---

[245] 5 U.S.C. § 604(a)(3).

[246] 5 U.S.C. § 601(6).

meaning as the term “small business concern” under the Small Business Act.[247] A small business concern is one which: (1) is independently owned and operated; (2) is not dominant in its field of operation; and (3) satisfies any additional criteria established by the Small Business Administration (SBA).[248] Below, we describe and estimate the number of small entity licensees that may be affected by adoption of the proposed rules.

Satellite Telecommunications and All Other Telecommunications

The rules proposed in this NPRM would affect some providers of satellite telecommunications services, if adopted. Satellite telecommunications service providers include satellite and earth station operators. Since 2007, the SBA has recognized two census categories for satellite telecommunications firms: “Satellite Telecommunications” and “Other Telecommunications.” Under both categories, a business is considered small if it had $32.5 million or less in annual receipts.[249]

The first category of Satellite Telecommunications “comprises establishments primarily engaged in providing point-to-point telecommunications services to other establishments in the telecommunications and broadcasting industries by forwarding and receiving communications signals via a system of satellites or reselling satellite telecommunications.”[250] For this category, Census Bureau data for 2007 show that there were a total of 512 satellite communications firms that operated for the entire year. Of this total, 482 firms had annual receipts of under $25 million.

The second category of Other Telecommunications is comprised of entities “primarily engaged in providing specialized telecommunications services, such as satellite tracking, communications telemetry, and radar station operation. This industry also includes establishments primarily engaged in providing satellite terminal stations and associated facilities connected with one or more terrestrial systems and capable of transmitting telecommunications to, and receiving telecommunications from, satellite systems. Establishments providing Internet services or voice over Internet protocol (VoIP) services via client-supplied telecommunications connections are also included in this industry.”[251]

The NPRM proposes and seeks comment on a number of rule changes that would affect reporting, recordkeeping, and other compliance requirements for space station operators. Each of these changes is described below.

The NPRM proposes to require several disclosures specifying compliance with several metrics established by NASA, such as probability of collision between the

---

[247] 5 U.S.C. § 601(3) (incorporating by reference the definition of “small business concern” in 15 U. S.C. § 632). Pursuant to the RFA, the statutory definition of a small business applies “unless an agency, after consultation with the Office of Advocacy of the Small Business Administration and after opportunity for public comment, establishes one or more definitions of such term which are appropriate to the activities of the agency and publishes such definition(s) in the Federal Register.” 5 U.S.C. § 601(3).

[248] Small Business Act, 15 U.S.C. § 632 (1996).

[249] See 13 CFR § 121.201, NAICS codes 517410, 517919.

[250] U.S. Census Bureau, 2007 NAICS Definitions, “517410 Satellite Telecommunications.”

[251] U.S. Census Bureau, 2007 NAICS Definitions, “517919 Other Telecommunications.”

spacecraft and large objects. Many of the entities, for example, experimental licensees, that would be affected by these proposed rules already use a format for their orbital debris mitigation plans that is consistent with the NASA Orbital Debris Assessment Report (ODAR). The ODAR format includes several of the proposed NASA metrics that are incorporated into the proposed rules such as calculations related to re-entry casualty risk. Thus, to the extent that these entities already use the ODAR format, there would be no change to their existing recordkeeping and compliance requirements as a result of these proposed changes. For other entities that have not or would not use the ODAR format to report their orbital debris mitigation plans, some of these changes will involve some additional proposed calculations to provide the appropriate certifications, such as certifying that the probability of collision between a space station and another large object is less than 0.001. Given the engineering associated with development of a spacecraft, we expect that these calculations will be a natural outgrowth of work already being performed in designing and planning space station(s) operations. The NPRM also proposes to require that collision risk information be provided in the aggregate, that is, for the space station constellation as a whole. Since most small entities do not launch and operate large satellite constellations, we do not anticipate that this requirement to provide a collision risk assessment in the aggregate will be burdensome. In addition, we note the new requirement for demonstration that the probability of reliability for a particular disposal method is no less than 0.90, calculated on an aggregate basis. We anticipate that most small entities will be planning disposal of their spacecraft by atmospheric re-entry. So long as the spacecraft is deployed into a low altitude orbit, which most small entities' spacecraft are, atmospheric re-entry will be virtually guaranteed within a certain amount of time.

The NPRM also proposes to require that applicants for a space station license or authorization provide disclosures regarding methodologies used for tracking and certifications related to space situational awareness, as well as disclosures regarding choice of orbit and potential impact to manned spacecraft. Information regarding tracking and sharing of data for purposes of space situational awareness should be readily available to applicants and operators. We anticipate that disclosures relating to choice of orbit and potential impacts to manned spacecraft should be an extension of analysis undertaken by a space station operator as part of selection of a launch vehicle and operational orbit.

In addition, the NPRM proposes that operators of spacecraft make ephemeris data available to all operators of operational satellite systems identified as potentially raising a collision risk with its system. We anticipate that small entities will generally be operating only a few spacecraft, and so will only need to address this ephemeris data requirement for a limited number of space stations.

11 See 13 CFR § 121.201, NAICS code 517919.

12 U.S. Census Bureau, 2007 Economic Census, Subject Series: Information, Table 5, "Establishment and Firm Size: Employment Size of Firms for the United States: 2007 NAICS Code 517919" (issued Nov. 2010).

We do not expect that the any of the proposed changes relating to the operation of geostationary-orbit (GSO) space stations would affect small entities, since GSO space stations generally cost hundreds of millions of dollars to construct, launch, and operate. Similarly, we do not expect that the proposed requirements applicable to NGSO space stations operating between 650 km and 2,000 km will apply to small entities, since we expect that most lower-cost space systems are deployed at lower altitudes.

The NPRM also proposes that U.S. space station licensees or grantees submit an executed agreement indemnifying the United States against any costs associated with a clam brought against the United States related to the authorized facilities. This proposal would apply to experimental licensees and authorized amateur space station license grantees, and would likely increase the compliance requirements for some entities. The NPRM also seeks comment on possible insurance requirements for space station licensees/grantees.

Steps Taken to Minimize Significant Economic Impact on Small Entities, and Significant Alternatives Considered

The RFA requires an agency to describe any significant, specifically small business, alternatives that it has considered in reaching its proposed approach, which may include the following four alternatives (among others): "(1) the establishment of differing compliance or reporting requirements or timetables that take into account the resources available to small entities; (2) the clarification, consolidation, or simplification of compliance and reporting requirements under the rules for such small entities; (3) the use of performance rather than design standards; and (4) an exemption from coverage of the rule, or any part thereof, for such small entities."[252]

With respect to the additional orbital debris mitigation plan disclosure requirements described above, we believe that the disclosures will in most instances be consistent with, or a natural outgrowth of, analysis that is already being conducted by space station applicants and/or operators. These additional disclosures should be consistent with the types of operations that are in the space station operator's best interest, such as avoiding collision with other spacecraft. In several instances, certifications are proposed, but in other instances, we believe that a descriptive disclosure is superior to a certification alternative, to provide the applicant with an opportunity to fully explain its plans for Commission evaluation. As an alternative to the disclosures, we could propose not to require any additional information, but as described in the NPRM, the public interest in mitigating orbital debris and ensuring the long-term viability of the space environment may weigh in favor of the additional disclosures. Several of the proposals apply only to space stations with planned deployment altitudes between above 650 km. This 650 km altitude is based upon anticipated on-orbit lifetimes, as described in the NPRM, and we anticipate will not be applicable to most small entities' space stations. That specific altitude was proposed to address orbits where deployments may be of particular concern, without burdening operators planning to deploy in lower orbits. We seek comment in the

---

[252] 13 5 U.S.C. § 603(c)(1)-(4).

NPRM on the costs and benefits of the proposed requirements applying to space stations deployed above 650 km.

The Commission seeks comment on the proposed indemnification requirements related to space station authorization. Given the basis for proposing such a requirement in the NPRM, which relates to the role of the Commission generally, we do not consider categorical exemptions relevant to small entities. As to the insurance proposals, the NPRM asks whether certain entities should be exempted, including entities such as relatively low risk systems, which could ease the potential compliance burden for small entities.

The NPRM seeks comment from all interested parties. Small entities are encouraged to bring to the Commission's attention any specific concerns they may have with the proposals outlined in the NPRM. The Commission expects to consider any economic impact on small entities.

a. Federal Rules that May Duplicate, Overlap, or Conflict with the Proposed Rules

None.

References

https://www.fcc.gov/proceedings-actions

US Space Policy Directive-3: National Space Traffic Management Policy

Joseph N. Pelton

Contents

Abstract

The issues of space situational awareness (SSA) and space traffic management (STM) have come increasingly to the fore as a result of a growing number of proposals to deploy an ever increasing number of satellite constellations that are populated by a huge number of small satellites. There have been new efforts to provide much-improved tracking of these satellites through the deployment of the new S-band radar system by the United States on the Marshall Islands that will be able to track orbital debris and satellites of a size of marble and as many as 400,000 to 500,000 space objects. There are also many new initiatives to provide private tracking capability of space debris through the use of optical telescopes as well as radar systems.

There are also a number of new ideas as to how national regulatory systems might provide expanded space traffic management and space traffic control capabilities. The US Space Policy Directive-3 issued on June 18, 2018, set forth in some detail how the United States might approach both the issues of improved space situational awareness, especially in low Earth orbit (LEO), and

---

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_100

improved approaches to space traffic control. This US Space Policy Directive-3 is perhaps most significant in that it sets for the idea that there should be separate approaches with regard to commercial satellite tracking and traffic control and such activities with regard to national defense activities. The main purpose of this chapter is to provide the full text of US Space Policy Directive-3.

Keywords

Civil space activities · Commercial space activities · Long-term sustainability of space · Mitigation of space debris · National defense · Optical tracking of satellites · Orbital debris · S-band radar · Space data · Space debris · Space object registry · Space situational awareness (SSA) · Space traffic management (STM) · US Department of Commerce (DOC) · US Department of Defense (DOD)

1 Introduction

This technical and regulatory document issued by the US White House on June 18, 2018, is provided as a key resource and useful background information to the discussion of the consideration of the need to improve space situational awareness (SSA) and efforts to increase national systems to undertake enhanced space traffic management (STM) to avoid the increased buildup of orbital space debris and to avoid new collisions of space objects, particularly in low Earth orbit (LEO).

The document provided below which is an official space policy statement issued from the US White House is important in terms of defining a new approach that divides the efforts related to SSA and STM between those activities related to commercial space systems and activities related to national defense. It is also key in that it calls from the development of new science and technology in this field to improve national systems for both SSA and STM capabilities. The full text of the US Space Policy Directive-3 is provided below.

2 US Presidential Memorandum: Space Policy Directive-3, National Space Traffic Management Policy

Issued on: June 18, 2018

MEMORANDUM FOR THE VICE PRESIDENT
THE SECRETARY OF STATE
THE SECRETARY OF DEFENSE
THE SECRETARY OF COMMERCE
THE SECRETARY OF TRANSPORTATION
THE SECRETARY OF HOMELAND SECURITY
THE DIRECTOR OF NATIONAL INTELLIGENCE
THE DIRECTOR OF THE OFFICE OF MANAGEMENT AND BUDGET

THE ASSISTANT TO THE PRESIDENT FOR NATIONAL SECURITY AFFAIRS

THE ADMINISTRATOR OF THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

THE DIRECTOR OF THE OFFICE OF SCIENCE AND TECHNOLOGY POLICY

THE DEPUTY ASSISTANT TO THE PRESIDENT FOR HOMELAND SECURITY AND COUNTERTERRORISM

THE CHAIRMAN OF THE JOINT CHIEFS OF STAFF

SUBJECT: National Space Traffic Management Policy

Section 1. Policy. For decades, the United States has effectively reaped the benefits of operating in space to enhance our national security, civil, and commercial sectors. Our society now depends on space technologies and space-based capabilities for communications, navigation, weather forecasting, and much more. Given the significance of space activities, the United States considers the continued unfettered access to and freedom to operate in space of vital interest to advance the security, economic prosperity, and scientific knowledge of the Nation.

Today, space is becoming increasingly congested and contested, and that trend presents challenges for the safety, stability, and sustainability of U.S. space operations. Already, the Department of Defense (DoD) tracks over 20,000 objects in space, and that number will increase dramatically as new, more capable sensors come online and are able to detect smaller objects. DoD publishes a catalog of space objects and makes notifications of potential conjunctions (that is, two or more objects coming together at the same or nearly the same point in time and space). As the number of space objects increases, however, this limited traffic management activity and architecture will become inadequate. At the same time, the contested nature of space is increasing the demand for DoD focus on protecting and defending U.S. space assets and interests.

The future space operating environment will also be shaped by a significant increase in the volume and diversity of commercial activity in space. Emerging commercial ventures such as satellite servicing, debris removal, in-space manufacturing, and tourism, as well as new technologies enabling small satellites and very large constellations of satellites, are increasingly outpacing efforts to develop and implement government policies and processes to address these new activities.

To maintain U.S. leadership in space, we must develop a new approach to space traffic management (STM) that addresses current and future operational risks. This new approach must set priorities for space situational awareness (SSA) and STM innovation in science and technology (S&T), incorporate national security considerations, encourage growth of the U.S. commercial space sector, establish an updated STM architecture, and promote space safety standards and best practices across the international community.

The United States recognizes that spaceflight safety is a global challenge and will continue to encourage safe and responsible behavior in space while emphasizing the need for international transparency and STM data sharing. Through this national policy for STM and other national space strategies and policies, the United States will enhance safety and ensure continued leadership, preeminence, and freedom of action in space.

Sec. 2. Definitions. For the purposes of this memorandum, the following definitions shall apply:

(a) Space Situational Awareness shall mean the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities.
(b) Space Traffic Management shall mean the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.
(c) Orbital debris, or space debris, shall mean any human-made space object orbiting Earth that no longer serves any useful purpose.

Sec. 3. Principles. The United States recognizes, and encourages other nations to recognize, the following principles:

(a) Safety, stability, and operational sustainability are foundational to space activities, including commercial, civil, and national security activities. It is a shared interest and responsibility of all spacefaring nations to create the conditions for a safe, stable, and operationally sustainable space environment.
(b) Timely and actionable SSA data and STM services are essential to space activities. Consistent with national security constraints, basic U.S. Government-derived SSA data and basic STM services should be available free of direct user fees.
(c) Orbital debris presents a growing threat to space operations. Debris mitigation guidelines, standards, and policies should be revised periodically, enforced domestically, and adopted internationally to mitigate the operational effects of orbital debris.
(d) A STM framework consisting of best practices, technical guidelines, safety standards, behavioral norms, pre-launch risk assessments, and on-orbit collision avoidance services is essential to preserve the space operational environment.

Sec. 4. Goals. Consistent with the principles listed in section 3 of this memorandum, the United States should continue to lead the world in creating the conditions for a safe, stable, and operationally sustainable space environment. Toward this end, executive departments and agencies (agencies) shall pursue the following goals as required in section 6 of this memorandum:

(a) Advance SSA and STM Science and Technology. The United States should continue to engage in and enable S&T research and development to support the practical applications of SSA and STM. These activities include improving fundamental knowledge of the space environment, such as the characterization of small debris, advancing the S&T of critical SSA inputs such as observational data, algorithms, and models necessary to improve SSA capabilities, and developing new hardware and software to support data processing and observations.

(b) Mitigate the effect of orbital debris on space activities. The volume and location of orbital debris are growing threats to space activities. It is in the interest of all to minimize new debris and mitigate effects of existing debris. This fact, along with increasing numbers of active satellites, highlights the need to update existing orbital debris mitigation guidelines and practices to enable more efficient and effective compliance, and establish standards that can be adopted internationally. These trends also highlight the need to establish satellite safety design guidelines and best practices.

(c) Encourage and facilitate U.S. commercial leadership in S&T, SSA, and STM. Fostering continued growth and innovation in the U.S. commercial space sector, which includes S&T, SSA, and STM activities, is in the national interest of the United States. To achieve this goal, the U.S. Government should streamline processes and reduce regulatory burdens that could inhibit commercial sector growth and innovation, enabling the U.S. commercial sector to continue to lead the world in STM-related technologies, goods, data, and services on the international market.

(d) Provide U.S. Government-supported basic SSA data and basic STM services to the public. The United States should continue to make available basic SSA data and basic STM services (including conjunction and reentry notifications) free of direct user fees while supporting new opportunities for U.S. commercial and non-profit SSA data and STM services.

(e) Improve SSA data interoperability and enable greater SSA data sharing. SSA data must be timely and accurate. It is in the national interest of the United States to improve SSA data interoperability and enable greater SSA data sharing among all space operators, consistent with national security constraints. The United States should seek to lead the world in the development of improved SSA data standards and information sharing.

(f) Develop STM standards and best practices. As the leader in space, the United States supports the development of operational standards and best practices to promote safe and responsible behavior in space. A critical first step in carrying out that goal is to develop U.S.-led minimum safety standards and best practices to coordinate space traffic. U.S. regulatory agencies should, as appropriate, adopt these standards and best practices in domestic regulatory frameworks and use them to inform and help shape international consensus practices and standards.

(g) Prevent unintentional radio frequency (RF) interference. Growing orbital congestion is increasing the risk to U.S. space assets from unintentional RF interference. The United States should continue to improve policies, processes, and technologies for spectrum use (including allocations and licensing) to address these challenges and ensure appropriate spectrum use for current and future operations.

(h) Improve the U.S. domestic space object registry. Transparency and data sharing are essential to safe, stable, and sustainable space operations. Consistent with national security constraints, the United States should streamline the interagency process to ensure accurate and timely registration submissions to the United Nations (UN), in accordance with our international obligations under the Convention on Registration of Objects Launched into Outer Space.

(i) Develop policies and regulations for future U.S. orbital operations. Increasing congestion in key orbits and maneuver-based missions such as servicing, survey, and assembly will drive the need for policy development for national security, civil, and commercial sector space activities. Consistent with U.S. law and international obligations, the United States should regularly assess existing guidelines for non-government orbital activities, and maintain a timely and responsive regulatory environment for licensing these activities.

Sec. 5. Guidelines. In pursuit of the principles and goals of this policy, agencies should observe the following guidelines:

(a) Managing the Integrity of the Space Operating Environment.

  (i) Improving SSA coverage and accuracy. Timely, accurate, and actionable data are essential for effective SSA and STM. The United States should seek to minimize deficiencies in SSA capability, particularly coverage in regions with limited sensor availability and sensitivity in detection of small debris, through SSA data sharing, the purchase of SSA data, or the provision of new sensors.

  New U.S. sensors are expected to reveal a substantially greater volume of debris and improve our understanding of space object size distributions in various regions of space. However, very small debris may not be sufficiently tracked to enable or justify actionable collision avoidance decisions. As a result, close conjunctions and even collisions with unknown objects are possible, and satellite operators often lack sufficient insight to assess their level of risk when making maneuvering decisions. The United States should develop better tracking capabilities, and new means to catalog such debris, and establish a quality threshold for actionable collision avoidance warning to minimize false alarms.

  Through both Government and commercial sector S&T investment, the United States should advance concepts and capabilities to improve SSA in support of debris mitigation and collision avoidance decisions.

  (ii) Establishing an Open Architecture SSA Data Repository. Accurate and timely tracking of objects orbiting Earth is essential to preserving the safety of space activities for all. Consistent with section 2274 of title 10, United States Code, a basic level of SSA data in the form of the publicly releasable portion of the DoD catalog is and should continue to be provided free of direct user fees. As additional sources of space tracking data become available, the United States has the opportunity to incorporate civil, commercial, international, and other available data to allow users to enhance and refine this service. To facilitate greater data sharing with satellite operators and enable the commercial development of enhanced space safety services, the United States must develop the standards and protocols for creation of an open architecture data repository. The essential features of this repository would include:

- Data integrity measures to ensure data accuracy and availability;
- Data standards to ensure sufficient quality from diverse sources;
- Measures to safeguard proprietary or sensitive data, including national security information;
- The inclusion of satellite owner-operator ephemerides to inform orbital location and planned maneuvers; and
- Standardized formats to enable development of applications to leverage the data.

To facilitate this enhanced data sharing, and in recognition of the need for DoD to focus on maintaining access to and freedom of action in space, a civil agency should, consistent with applicable law, be responsible for the publicly releasable portion of the DoD catalog and for administering an open architecture data repository. The Department of Commerce should be that civil agency.

(iii) Mitigating Orbital Debris. It is in the interest of all space operators to minimize the creation of new orbital debris. Rapid international expansion of space operations and greater diversity of missions have rendered the current U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) inadequate to control the growth of orbital debris. These standard practices should be updated to address current and future space operating environments.

The United States should develop a new protocol of standard practices to set broader expectations of safe space operations in the twenty-first century. This protocol should begin with updated ODMSP, but also incorporate sections to address operating practices for large constellations, rendezvous and proximity operations, small satellites, and other classes of space operations. These overarching practices will provide an avenue to promote efficient and effective space safety practices with U.S. industry and internationally.

The United States should pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes. This effort should not detract from continuing to advance international protocols for debris mitigation associated with current programs.

(b) Operating in a Congested Space Environment.

(i) Minimum Safety Standards and Best Practices. The creation of minimum standards for safe operation and debris mitigation derived in part from the U.S. Government ODMSP, but incorporating other standards and best practices, will best ensure the safe operation of U.S. space activities. These safety guidelines should consider maneuverability, tracking, reliability, and disposal.

The United States should eventually incorporate appropriate standards and best practices into Federal law and regulation through appropriate rulemaking or licensing actions. These guidelines should encompass protocols for all stages of satellite operation from design through end-of-life.

Satellite and constellation owners should participate in a pre-launch certification process that should, at a minimum, consider the following factors:

- Coordination of orbit utilization to prevent conjunctions;
- Constellation owner-operators' management of self-conjunctions;
- Owner-operator notification of planned maneuvers and sharing of satellite orbital location data;
- On-orbit tracking aids, including beacons or sensing enhancements, if such systems are needed;
- Encryption of satellite command and control links and data protection measures for ground site operations;
- Appropriate minimum reliability based on type of mission and phase of operations;
- Effect on the national security or foreign policy interests of the United States, or international obligations; and
- Self-disposal upon the conclusion of operational lifetime, or owner-operator provision for disposal using active debris removal methods.

(ii) On-Orbit Collision Avoidance Support Service. Timely warning of potential collisions is essential to preserving the safety of space activities for all. Basic collision avoidance information services are and should continue to be provided free of direct user fees. The imminent activation of more sensitive tracking sensors is expected to reveal a significantly greater population of the existing orbital debris background as well as provide an improved ability to track currently catalogued objects. Current and future satellites, including large constellations of satellites, will operate in a debris environment much denser than presently tracked. Preventing on-orbit collisions in this environment requires an information service that shares catalog data, predicts close approaches, and provides actionable warnings to satellite operators. The service should provide data to allow operators to assess proposed maneuvers to reduce risk. To provide on-orbit collision avoidance, the United States should:

- Provide services based on a continuously updated catalog of satellite tracking data;
- Utilize automated processes for collision avoidance;
- Provide actionable and timely conjunction assessments; and
- Provide data to operators to enable assessment of maneuver plans.

To ensure safe coordination of space traffic in this future operating environment, and in recognition of the need for DoD to focus on maintaining access to and freedom of action in space, a civil agency should be the focal point for this collision avoidance support service. The Department of Commerce should be that civil agency.

(c) Strategies for Space Traffic Management in a Global Context.

(i) Protocols to Prevent Orbital Conjunctions. As increased satellite operations make lower Earth orbits more congested, the United States should develop a set of standard techniques for mitigating the collision risk of increasingly congested orbits, particularly for large constellations. Appropriate methods, which may include licensing assigned volumes for constellation operation and establishing processes for satellites passing through the volumes, are needed. The United States should explore strategies that will lead to the establishment of common global best practices, including:

- A common process addressing the volume of space used by a large constellation, particularly in close proximity to an existing constellation;
- A common process by which individual spacecraft may transit volumes used by existing satellites or constellations; and
- A set of best practices for the owner-operators of utilized volumes to minimize the long-term effects of constellation operations on the space environment (including the proper disposal of satellites, reliability standards, and effective collision avoidance).

(ii) Radio Frequency Spectrum and Interference Protection. Space traffic and RF spectrum use have traditionally been independently managed processes. Increased congestion in key orbital regimes creates a need for improved and increasingly dynamic methods to coordinate activities in both the physical and spectral domains, and may introduce new interdependencies. U.S. Government efforts in STM should address the following spectrum management considerations:

- Where appropriate, verify consistency between policy and existing national and international regulations and goals regarding global access to, and operation in, the RF spectrum for space services;
- Investigate the advantages of addressing spectrum in conjunction with the development of STM systems, standards, and best practices;
- Promote flexible spectrum use and investigate emerging technologies for potential use by space systems; and
- Ensure spectrum-dependent STM components, such as inter-satellite safety communications and active debris removal systems, can successfully access the required spectrum necessary to their missions.

(iii) Global Engagement. In its role as a major spacefaring nation, the United States should continue to develop and promote a range of norms of behavior, best practices, and standards for safe operations in space to minimize the space debris environment and promote data sharing and coordination of space activities. It is essential that other spacefaring nations also adopt best practices for the common good of all spacefaring states. The United States should encourage the adoption of new norms of behavior and best practices for space operations by the international community through bilateral and multilateral discussions with other spacefaring nations, and through U.S. participation in various organizations such as the Inter-Agency Space Debris Coordination Committee, International Standards Organization, Consultative Committee for Space Data Systems, and UN Committee on the Peaceful Uses of Outer Space.

Sec. 6. Roles and Responsibilities. In furtherance of the goals described in section 4 and the guidelines described in section 5 of this memorandum, agencies shall carry out the following roles and responsibilities:

(a) Advance SSA and STM S&T. Members of the National Space Council, or their delegees, shall coordinate, prioritize, and advocate for S&T, SSA, and STM, as appropriate, as it relates to their respective missions. They should seek opportunities to engage with the commercial sector and academia in pursuit of this goal.
(b) Mitigate the Effect of Orbital Debris on Space Activities.
    (i) The Administrator of the National Aeronautics and Space Administration (NASA Administrator), in coordination with the Secretaries of State, Defense, Commerce, and Transportation, and the Director of National Intelligence, and in consultation with the Chairman of the Federal Communications Commission (FCC), shall lead efforts to update the U.S. Orbital Debris Mitigation Standard Practices and establish new guidelines for satellite design and operation, as appropriate and consistent with applicable law.
    (ii) The Secretaries of Commerce and Transportation, in consultation with the Chairman of the FCC, will assess the suitability of incorporating these updated standards and best practices into their respective licensing processes, as appropriate and consistent with applicable law.
(c) Encourage and Facilitate U.S. Commercial Leadership in S&T, SSA, and STM. The Secretary of Commerce, in coordination with the Secretaries of Defense and Transportation, and the NASA Administrator, shall lead efforts to encourage and facilitate continued U.S. commercial leadership in SSA, STM, and related S&T.
(d) Provide U.S. Government-Derived Basic SSA Data and Basic STM Services to the Public.
    (i) The Secretaries of Defense and Commerce, in coordination with the Secretaries of State and Transportation, the NASA Administrator, and the Director of National Intelligence, should cooperatively develop a plan for providing basic SSA data and basic STM services either directly or through a partnership with industry or academia, consistent with the guidelines of sections 5(a)(ii) and 5(b)(ii) of this memorandum.
    (ii) The Secretary of Defense shall maintain the authoritative catalog of space objects.
    (iii) The Secretaries of Defense and Commerce shall assess whether statutory and regulatory changes are necessary to effect the plan developed under subsection (d)(i) of this section, and shall pursue such changes, along with any other needed changes, as appropriate.
(e) Improve SSA Data Interoperability and Enable Greater SSA Data Sharing.
    (i) The Secretary of Commerce, in coordination with the Secretaries of State, Defense, and Transportation, the NASA Administrator, and the Director of National Intelligence, shall develop standards and protocols for creation of an open architecture data repository to improve SSA data interoperability and enable greater SSA data sharing.

   (ii) The Secretary of Commerce shall develop options, either in-house or through partnerships with industry or academia, assessing both the technical and economic feasibility of establishing such a repository.
   (iii) The Secretary of Defense shall ensure that release of data regarding national security activities to any person or entity with access to the repository is consistent with national security interests.

(f) Develop Space Traffic Standards and Best Practices. The Secretaries of Defense, Commerce, and Transportation, in coordination with the Secretary of State, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall develop space traffic standards and best practices, including technical guidelines, minimum safety standards, behavioral norms, and orbital conjunction prevention protocols related to pre-launch risk assessment and on-orbit collision avoidance support services.

(g) Prevent Unintentional Radio Frequency Interference. The Secretaries of Commerce and Transportation, in coordination with the Secretaries of State and Defense, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall coordinate to mitigate the risk of harmful interference and promptly address any harmful interference that may occur.

(h) Improve the U.S. Domestic Space Object Registry. The Secretary of State, in coordination with the Secretaries of Defense, Commerce, and Transportation, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall lead U.S. Government efforts on international engagement related to international transparency and space object registry on SSA and STM issues.

(i) Develop Policies and Regulations for Future U.S. Orbital Operations. The Secretaries of Defense, Commerce, and Transportation, in coordination with the Secretary of State, the NASA Administrator, and the Director of National Intelligence, shall regularly evaluate emerging trends in space missions to recommend revisions, as appropriate and necessary, to existing SSA and STM policies and regulations.

Sec. 7. General Provisions.

(a) Nothing in this memorandum shall be construed to impair or otherwise affect:
   (i) the authority granted by law to an executive department or agency, or the head thereof; or
   (ii) the functions of the Director of the Office of Management and Budget relating to budgetary, administrative, or legislative proposals.

(b) This memorandum shall be implemented consistent with applicable law and subject to the availability of appropriations.

(c) This memorandum is not intended to, and does not, create any right or benefit, substantive or procedural, enforceable at law or in equity by any party against the United States, its departments, agencies, or entities, its officers, employees, or agents, or any other person.

(d) The Secretary of Commerce is authorized and directed to publish this memorandum in the Federal Register.

3 Conclusion

Pursuant to this policy directive, efforts have now been undertaken within the US government to respond to the directives provided in the above document. The Office of Space Commerce in the US Department of Commerce has been creating staff competency to address the requirements established in Space Policy Directive-3. These activities have been particularly focused on US commercial space activities and sought to create new SSA and STM capabilities consistent with that directive. The US Department of Defense continues their efforts to be able to track space objects in a comprehensive way to provide for the national defense of the United States.

4 Cross-References

- ▶ Analysis of Orbit Debris
- ▶ Companies Involved in Design, Manufacture, and Testing of Small Satellites
- ▶ Forms for Registration of Small Satellites Consistent with the Registration Conventions
- ▶ Global Launch Vehicle Systems for Potential Small Satellite Deployment
- ▶ Partial Listing of Small Satellite Constellations and Related System Infrastructure
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ UN Sustainable Development Goals for 2030

References

U.S. Space Policy Directive-3, https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/. Issued 18 June 2018

US Government and NASA Documents Related to Orbital Space Debris Mitigation

Joseph N. Pelton

Contents

Abstract

The US Governmental Agencies most concerned with orbital space debris and its mitigation are NASA, the Federal Communications Agency, the Department of Defense, the Department of Commerce and its Office of Commercial Space, the Department of Transportation and its Office of Commercial Space Transportation in the Federal Aviation Agency (FAA-AST), and the National Space Council. The National Space Council has just approved for distribution in November 2019 the latest version of the US Government Orbital Debris Mitigation Standard Practices (ODMSP). This is provided below and also can be found on line (NASA, Orbital debris mitigation standard practices. https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf. November 2019).

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_108

The summary of this report from Space News highlighted its five key elements as follows: “The new document retains four objectives from the original version regarding control of debris in normal operations, minimizing debris from accidental explosions, use of safe flight profiles and operational configurations, and post-mission disposal of space structures. The new version adds a fifth objective to cover additional issues, such as operation of cubesats and large constellations as well as satellite servicing.” (Jeff Frost, U.S. government updates orbital debris mitigation guidelines. Space News, Dec 9, 2019. https://spacenews.com/u-s-government-updates-orbital-debris-mitigation-guidelines/)

Also provided is the reference documents compiled the NASA that prepared the ODMSP update in coordination with all relevant agencies concerned with orbital space debris issues. It is hoped that these procedures will be considered the U.N. Committee on the Peaceful Uses of Outer Space and the UN Office of Outer Space Affairs updates to the U.N. COPUOS prepared guidelines as official agreed in 2007 and ratified by the U.N. General Assembly.

Keywords

Accidental explosions · Department of Defense · FAA Office of Commercial Space Transportation FAA-AST · FCC · International practices · NASA · Operational orbital regimes · Orbital debris · Orbital debris mitigation · Postmission disposal of space structures · Safe Flight profile · Standard practices · U.N. Committee on the Peaceful Uses of Outer Space · U.N. General Assembly · Upper stages of rockets

1 US Government Orbital Debris Mitigation Standard Practices (ODMSP), November 2019 Update

1.1 Preamble

The United States Government (USG) Orbital Debris Mitigation Standard Practices (ODMSP) were established in 2001 to address the increase in orbital debris in the near-Earth space environment. The goal of the ODMSP was to limit the generation of new, long-lived debris by the control of debris released during normal operations, minimizing debris generated by accidental explosions, the selection of safe flight profile and operational configuration to minimize accidental collisions, and post-mission disposal of space structures. While the original ODMSP adequately protected the space environment at the time, the USG recognizes that it is in the interest of all nations to minimize new debris and mitigate effects of existing debris. This fact, along with increasing numbers of space missions, highlights the need to update the ODMSP and to establish standards that can inform development of international practices.

This 2019 update includes improvements to the original objectives as well as clarification and additional standard practices for certain classes of space operations. The improvements consist of a quantitative limit on debris released during normal operations, a probability limit on accidental explosions, probability limits on accidental collisions with large and small debris, and a reliability threshold for successful postmission disposal. The new standard practices established in the update include the preferred disposal options for immediate removal of structures from the near-Earth space environment, a low-risk geosynchronous Earth orbit (GEO) transfer disposal option, a long-term reentry option, and improved move-away-and-stay-away storage options in medium Earth orbit (MEO) and above GEO. The update also incorporates new sections to clarify and address operating practices for large constellations, rendezvous and proximity operations, small satellites, satellite servicing, and other classes of space operations.

The updated standard practices are significant, meaningful, and achievable. The 2019 ODMSP, by establishing guidelines for USG activities, provides a reference to promote efficient and effective space safety practices for other domestic and international operators. The USG intends to update and refine the ODMSP as necessary in the future to address advances in both technology and policy. The USG will follow the ODMSP, consistent with mission requirements and cost effectiveness, in the procurement and operation of spacecraft, launch services, and the conduct of tests and experiments in space. When practical, operators should consider the benefits of going beyond the standard practices and take additional steps to limit the generation of orbital debris. Together with continued development of standards and best practices for space traffic management, the updated ODMSP will contribute to safe space operations and the long-term sustainability of space activities.

2 Objective 1. Control of Debris Released During Normal Operations

Programs and projects will assess and limit the amount of debris released in a planned manner during normal operations. Objects with planned functions after release should follow standard practices set forth in Objectives 2 through 5.

1-1. In all operational orbit regimes: Spacecraft and upper stages should be designed to eliminate or minimize debris released during normal operations. Each instance of planned release of debris larger than 5 mm in any dimension that remains on orbit for more than 25 years should be evaluated and justified. For all planned released debris larger than 5 mm in any dimension, the total debris object-time product in low Earth orbit (LEO) should be less than 100 object-years per upper stage or per spacecraft. The total object-time product in LEO is the sum, over all planned released objects, of the orbit dwell time in LEO.

3 Objective 2. Minimizing Debris Generated by Accidental Explosions

Programs and projects will assess and limit the probability of accidental explosion during and after completion of mission operations.

2-1. Limiting the risk to other space systems from accidental explosions and associated orbital debris during mission operations: In developing the design of a spacecraft or upper stage, each program should demonstrate, via commonly accepted engineering and probability assessment methods, that the integrated probability of debris-generating explosions for all credible failure modes of each spacecraft and upper stage (excluding small particle impacts) is less than 0.001 (1 in 1000) during deployment and mission operations.

2-2. Limiting the risk to other space systems from accidental explosions and associated orbital debris after completion of mission operations: All on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when they are no longer required for mission operations or postmission disposal. Depletion should occur as soon as such an operation does not pose an unacceptable risk to the payload. Propellant depletion burns and compressed gas releases should be designed to minimize the probability of subsequent accidental collision and to minimize the impact of a subsequent accidental explosion.

4 Objective 3. Selection of Safe Flight Profile and Operational Configuration

Programs and projects will assess and limit the probability of operating space systems becoming a source of debris by collisions with human-made objects or meteoroids.

3-1. Collision with large objects during orbital lifetime: In developing the design and mission profile for a spacecraft or upper stage, a program will estimate and limit the probability of collision with objects 10 cm and larger during orbital lifetime to less than 0.001 (1 in 1000). For the purpose of this assessment, 100 years is used as the maximum orbital lifetime. 3-2. Collision with small debris during mission operations: Spacecraft design will consider and limit the probability to less than 0.01 (1 in 100) that collisions with micrometeoroids and orbital debris smaller than 1 cm will cause damage that prevents planned postmission disposal.

5 Objective 4. Postmission Disposal of Space Structures

Programs and projects will plan for disposal procedures for a structure (i.e., launch vehicle components, upper stages, spacecraft, and other payloads) at the end of mission life to minimize impact on future space operations.

4-1. Disposal for final mission orbits: A spacecraft or upper stage may be disposed of by one of the following methods:

(a) Direct reentry or heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit at the end of mission into (1) a reentry trajectory or (2) a heliocentric, Earth-escape orbit. These are the preferred disposal options. For direct reentry, the risk of human casualty from surviving components with impact kinetic energies greater than 15 joules should be less than 0.0001(1 in 10,000). Design-for-demise and other measures, including reusability and targeted reentry away from landmasses, to further reduce reentry human casualty risk should be considered.

(b) Atmospheric reentry: Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to as short as practicable but no more than 25 years after completion of mission. If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit. The risk of human casualty from surviving components with impact kinetic energies greater than 15 joules should be less than 0.0001(1 in 10,000).

(c) Storage between LEO and GEO: I. Maneuver to an eccentric disposal orbit (e.g., GEO transfer) where (1) perigee altitude remains above the LEO zone for at least 100 years, (2) apogee altitude remains below the GEO zone for at least 100 years, and (3) the time spent by the structure between 20,182 +/− 300 km is limited to 25 years or less over 200 years; or, II. Maneuver to a near-circular disposal orbit to (1) avoid crossing 20,182 +/− 300 km, the GEO zone, and the LEO zone for at least 100 years, and (2) limit the risk to other

US Government Orbital Debris Mitigation Standard Practices, November 2019 Update 6operational constellations, for example, by avoiding crossing the altitudes occupied by known missions of 10 or more spacecraft using near-circular orbits, for 100 years. d. Storage above GEO: Maneuver to an orbit with perigee altitude sufficiently above 35,986 km (upper boundary of the GEO zone) to ensure the structure remains outside the GEO zone for at least 100 years. e. Long-term reentry for structures in MEO, Tundra orbits, highly inclined GEO, and other orbits: Maneuver to a disposal orbit where orbital resonances will increase the eccentricity for long-term reentry of the structure. In developing this disposal plan, the program should (1) limit the postmission orbital lifetime to as short as practicable but no more than 200 years, (2) limit the time spent by the structure in the LEO zone, the GEO zone, and between 20,182 +/− 300 km to 25 years or less per zone; and (3) limit the probability of collisions with debris 10 cm and larger to less than 0.001 (1 in 1,000) during orbital lifetime. To limit human casualty risk from the reentry of the structure, surviving components with impact kinetic energies greater than 15 joules should have less than 7 m^2 total debris casualty area or less than 0.0001 (1 in 10,000) human casualty risk. f. Direct retrieval: Retrieve the structure and remove it from orbit preferably at completion of mission, but no more than 5 years after completion of mission. 4-2. Reliability of disposal: The probability of successful postmission disposal should be no less than 0.9 with a goal of 0.99 or better. The geosynchronous Earth orbit (GEO) zone is defined as the region between the altitudes of 35,586 and 35,986 km. The low Earth orbit (LEO) zone is defined as the region below 2000 km altitude. The medium Earth orbit (MEO) is the region between LEO and GEO. Because of fuel gauging uncertainties near the end of mission, a program should use a maneuver strategy that reduces the risk of leaving the structure near an operational orbit regime.

6 Objective 5. Clarification and Additional Standard Practices for Certain Classes of Space Operations

These classes of space operations and structures should follow Objectives 1 through 4 plus additional standard practices for orbital debris mitigation set forth in this section.

5-1. Large Constellations: A constellation consisting of 100 or more operational spacecraft cumulative is considered a large constellation. a. Each spacecraft in a large constellation should have a probability of successful postmission disposal at a level greater than 0.9 with a goal of 0.99 or better. In determining the successful postmission disposal threshold, factors such as mass, collision probability, orbital location, and other relevant parameters should be considered. b. For large constellations, Objective 4-1.a. is the preferred post-mission disposal option for the spacecraft. In developing the mission profile, the program should limit the cumulative reentry human casualty risk from the constellation. 5-2. Small satellites, including CubeSats, should follow the standard practices set forth in Objectives 1 through 4. For spacecraft smaller than 10 cm × 10 cm × 10 cm when fully deployed: a. Any spacecraft in LEO should be limited to an orbital lifetime as short as practicable but no more than 25 years after completion of mission. b. The total spacecraft object-time product in LEO should be less than 100 object-years per mission. 5-3. Rendezvous, proximity operations, and satellite servicing: In developing the mission profile for a structure, the program should limit the risk of debris generation as an outcome of the operations. The program should (1) limit the probability of accidental collision and (2) limit the probability of accidental explosion resulting from the operations. Any planned debris generated as a result of the operations should follow the standard practices for mission-related debris set forth in Objective 1.

US Government Orbital Debris Mitigation Standard Practices, November 2019 Update 85-4. Safety of Active debris removal operations: In developing the mission profile for an active debris removal operation on a debris structure, the program should limit the risk of debris generation as an outcome of the operation. The program should (1) avoid fragmentation of the debris structure, (2) limit the probability of accidental collision, and (3) limit the probability of accidental explosion resulting from the operations. Any planned debris generated as a result of the operations should follow the standard practices for mission-related debris set forth in Objective 1. The operations should be designed for the debris structure to follow applicable postmission disposal practices set forth in Objective 4. 5-5. Tether systems will be uniquely analyzed for both intact and severed conditions (a) for collision risk with large objects during orbital lifetime and collision risk with small debris during mission operations and (b) when performing trade-offs between alternative disposal strategies.

6.1 Orbital Debris Program Office Reference Documents – NASA

orbitaldebris.jsc.nasa.gov/reference-documents.htm

1. **Technical Report on Space Debris (Adobe PDF 579 kb)**
   This is a report published by the Scientific and Technical Subcommittee (STSC) of the United Nations on space debris in 1999. This report summarizes the reviews within the STSC between 1996 and 1998 on orbital debris measurements, modeling, risk assessments, and mitigation measures.
2. **US Government Orbital Debris Mitigation Standard Practices (Adobe PDF 117 kb)**
   The United States Government has formally stated in this document its objectives and practices of limiting the amount of space debris. The four objectives are (1) control of debris released during normal operations, (2) minimizing debris generated by accidental explosions, (3) selection of safe flight profile and operational configuration, and (4) postmission disposal of space structures.
3. **History of On-Orbit Satellite Fragmentations (Adobe PDF 2,251 kb)**
   The 14th edition of this document was published in 2008. This document summarizes all known satellite and upper stage fragmentations prior to 1 August 2007. Available information includes breakup date, breakup altitude, number of debris generated, and references to each event. Gabbard diagrams for many breakup clouds are also included in the document.
4. **Orbital Debris: A Technical Assessment (Adobe PDF 9,371 kb))**
   This is a document published by US National Research Council in 1995. It examines the methods used to characterize the orbital debris environment and assesses the hazards a debris population poses to spacecraft. Recommendations to improve debris research and the protection of spacecraft and specific recommendations on methods to reduce future debris creation are also included in the document.
5. **Interagency Report on Orbital Debris (Adobe PDF 7,456 kb)**
   This document was published by the National Science and Technology Council Committee on Transportation Research and Development in 1995. It contains an up-to-date portrait of the orbital debris measurement, modeling, and mitigation efforts and a set of recommendations outlining specific steps necessary to minimize the potential hazards posed by orbital debris.
6. **IADC Space Debris Mitigation Guidelines (Adobe PDF 99 kb)**
   This document describes the guidelines adopted by the 11 members of the Inter-Agency Space Debris Coordination Committee (IADC) in 2002 and slightly revised in 2007. The guidelines were developed via consensus within the IADC, with an emphasis on cost effectiveness that can be considered during planning

and design of spacecraft and launch vehicles in order to minimize or eliminate generation of debris during operations.

7. **UN Space Debris Mitigation Guidelines (Adobe PDF 1,382.4 kb)**
   This document describes the guidelines adopted by the Scientific and Technical Subcommittee (STSC) of the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) in February 2007. The guidelines were developed via consensus within the STSC, and the full COPUOS endorsed the guidelines in June 2007, followed by General Assembly endorsement later in 2007. These guidelines are consistent with the US Government Orbital Debris Mitigation Standard Practices and the IADC Space Debris Mitigation Guidelines.
8. **NASA Procedural Requirements for Limiting Orbital Debris – NPR 8715_006B (Adobe PDF 102 kb)**
   NPR8715.6B became effective on 16 Feb 2017. It reflects NASA's policy to limit future orbital debris generation. The applicability, authority, and references of the requirements and the responsibility within NASA organizations are all clearly stated in the document.
9. **NASA Standard 8719.14 (Adobe PDF 445 kb)**
   NASA has adopted a policy to control the generation of orbital debris in NASA Procedural Requirements 8715.6A and has implemented this policy in NASA Standard 8719.14. All NASA flight projects are now required to provide debris assessments and end-of-mission planning as a normal part of the project development.
10. **Handbook for Limiting Orbital Debris – NASA-HDBK 8719.14**
    This NASA-HDBK serves as a companion to NASA Procedural Requirements (NPR) 8715.6A, NASA Procedural Requirements for Limiting Orbital Debris and NASA-STD 8719.14, Process for Limiting Orbital Debris and contains the background and reference materials to aid in understanding the foundation and science for predicting and limiting orbital debris.

7 Conclusion

The current plans for deployment of a significant number of small satellite constellations populated by a large number of satellites numbering in the thousands have greatly raised concerns about orbital space debris and the need for new procedures to be adopted that require more stringent guidelines for the mitigation of the formation of new space debris. The analysis that has been undertaken by the Aerospace Corporation has suggested that all of the large constellations that are being deployed or that have been proposed could result in unintended collisions both during deployment and during removal at end of life (Muelhaupt et al. 2019).

The USA has undertaken several efforts to devise stricter controls to monitor all launches so as to prevent the formation of new debris and ensure safe removal of space structures at end of life. It has sought to share this information with the international community to seek tighter procedures that are enforced around the world.

8 Cross-References

- ▶ Analysis of Orbit Debris
- ▶ Companies Involved in Design, Manufacture, and Testing of Small Satellites
- ▶ Forms for Registration of Small Satellites Consistent with the Registration Conventions
- ▶ Global Launch Vehicle Systems for Potential Small Satellite Deployment
- ▶ Partial Listing of Small Satellite Constellations and Related System Infrastructure
- ▶ UN Sustainable Development Goals for 2030
- ▶ US Space Policy Directive-3: National Space Traffic Management Policy

References

T.J. Muelhaupt, M.E. Sorge, J. Morin, R.J. Wilson, Space traffic management in the new space era. J. Space Saf. Eng. **6**(2), 80 (2019)

Part XIV

Conclusions

Conclusion: The Many Technical, Market, Economic, and Practical Aspects of the World of Small Satellites

Joseph N. Pelton

Contents

Abstract

The most significant change in the world of space applications in the past decade is what might be called the small satellite revolution. This small satellite revolution is closely aligned with what is also now known as "Space 2.0" or "NewSpace." Probing discussions of this small satellite revolution and efforts to identify the prime factors that gave rise to this profound change in the space industry produce a number of diverse but convincing answers to what has produced this small satellite revolution. The drivers of this change, largely within the past decade, include (i) new types of flat panel user antennas that can

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_99

electronically track low Earth orbit satellites in mega-constellations; (ii) new more efficient ways to design and manufacture small satellites at much lower cost and sometimes with the use of off-the-shelf technology; (iii) new lower-cost launchers that can deploy small satellites at much lower cost; (iv) advances in microelectronics, smaller but higher performance sensors, improved component design and manufacture, etc.; (v) a rapid evolution of space services markets through the creation of new types of commercial satellite applications as well as expanded attempts to provide expanded space services to unserved markets in developing economies – especially in the case of broadband Internet streaming and remote sensing; (vi) entrepreneurial business innovation in the space field, often driven by out-of-the-box thinking from the world of computer services and social media; and (vii) new ways of financing small satellite startup ventures based on mechanism such as "Kickstarter," crowdsourcing, rounds of venture capital funding, and crossover investment in satellite applications from new industries such as from the world of computer and information services, investment banking, and other revenue sources.

This *Handbook of Small Satellite* has sought to examine in some depth all of the sources of change that has produced the small satellite revolution. It has examined the technical, operational, financial, business, economic, regulatory, launcher, and institutional aspects of this important new world of space applications. Innovation is everywhere. There are actually contributions not only on the technical and operational side but from every other side of the business as well. Thus change has come from the small satellite business (i.e., new entries and startups that operate on completely different business models and timetables). There are key changes, from the world of manufacturing and design (i.e., additive manufacturing and use of off-the-shelf components). The small satellite business models have helped reinvent the world of space business and finance that is quite different from the approach taken by giant aerospace companies born of the so-called world of the military-industrial complex. Thus new business practices from the world of small satellites reflect many new patterns of thinking (i.e., new sources of financing and "clean enough rooms"). This new type of entrepreneurial thinking has led to many new ideas such as about sparing philosophies and rapid prototyping and new generations of satellite design in months rather than years. Small satellites have, in short, shaken up thinking throughout the space industry, and change has percolated almost everywhere one might imagine – and then some.

This final chapter seeks to sum up the many areas of change and innovation that have been born of the new world of small satellites. Thus this concluding chapter is divided into discussing important new aspects of the world of small satellites that have permeated the entire space industry. These various sections that are drawn from the component parts of the book include defining the various types of small satellites; satellite technology; design and manufacturing; launch and deployment; operations and sparing philosophy; ground systems technology; business, financing, risk-minimization, and insurance; and regulatory, safety, and institutional issues.

This chapter concludes with some notes about the practical aspect that are available to readers of the handbook. This includes some guidance with regard to what detailed information is available concerning actual small satellite systems

that have been deployed and projects to test new technology or to address space debris concerns. This includes some background with regard to information provided in Section 13 related to small satellite businesses, launch vehicle providers, small satellite networks deployed or planned to be deployed, registration processes related to small satellite systems, the UN sustainability guidelines, and how small satellite systems might relate to the meeting of these goals.

Finally, this conclusion underscores how dynamic both the small satellite market and the launch vehicle systems newly designed to support the launch of small satellites is at this early stage of development. Bankruptcies, mergers, and other realignments are already happening. The COVID-19 will serve to accelerate downturns for small satellite ventures and new launch vehicle developments alike. OneWeb declared bankruptcy as of May2020, but bailout financing from the UK Government and financing from Indian mobile communications carrier Bharti Global has managed to rescue this system. ‘New Space’ ventures Speedcast Ltd. and Leosat plus launcher companies Vector and Firefly have all now gone bankrupt, and many other companies have indicated a pause or withdrawal from possible small satellite enterprises. And most of these negative impacts preceded the economic downturns that will be a consequence of the Covid-19 virus that most economists foresee as likely to generate a global economic recession. Some economists forecast that the downturn on space-related ventures might be as much as a 30% reduction in new investment. Not until 2022 will the impact be clearly quantifiable.

Keywords

Additive manufacture · Broadband networking · Chip satellites · Crowdsourcing · Cube satellites · Deorbit guidelines · Design and manufacture · Electronic tracking of satellites · Entrepreneurial businesses · Femto satellites · Flat panel antennas · Inter-Agency Space Debris Coordination Committee (IADC) · International Telecommunication Union (ITU) · Launch vehicles · Low Earth orbit (LEO) · Liability · Mega-constellations · Microsatellites · Minisatellites · Nanosatellites · Phased array antennas · Pico satellites · Off-the-shelf components · Rapid prototyping · Regulatory provisions · Small satellites · Space applications · Space markets · Sparing philosophy · UN Committee on the Peaceful Uses of Outer Space (UN COPUOS) · Venture capital

1 Introduction

The very first satellites that were launched into orbit such as Sputnik 1, Explorer 1, Score, etc. were, in fact, small satellites. The rapid growth of demand for expanded satellite services for telecommunications, remote sensing, meteorology, and especially the concept of human space travel and the development of larger launch vehicles quickly led to more and more massive satellites to be launched. The pattern of larger and more capable satellites launched by larger and more powerful satellites continued for at least four decades. The advantages of communications satellites operating from Clarke orbit so that ground stations did not have to track the geostationary spacecraft that seemed to hover overhead tended to sustain that pattern of more powerful satellites with larger, high gain antennas for many years.

A combination of factors that evolved in recent years has tended to favor a new focus on smaller satellites for testing new technologies and for experimentation (by students and scientists). There has now been a rapid growth in small satellites for many different reasons. This has led in particular to the building of lower-cost small satellites to be deployed low Earth orbit for a variety of new commercial applications. Microelectronics, smaller but higher quality sensors, lower-cost components, new manufacturing techniques and processes, lower-cost launch vehicles, and new phased array, and flat panel antennas that can be used for satellites and also for ground user systems, all support the feasibility of small satellites for commercial networks such as broadband networking via so-called mega-constellations. Now many thousands of small satellites are proposed for launch in these small satellite constellations for broadband networking, remote sensing, and other entirely new services such as RF geolocation, data relay, automatic identification systems, and more.

Currently, there are less than 2000 operational satellites in Earth orbit. If all of the proposed networks of small satellites were to be launched in coming years, the number of operational satellites would increase by a factor of over ten times. On the one hand, these seem to offer new opportunity for a variety of new lower-cost satellite services to be offered on a global basis and reduce the cost of services for communications, networking, remote sensing, and more. On the other hand, there are serious concerns about the rapid expansion of small satellite constellations in Earth orbit of potential space debris and an increased rate of orbital collisions that could greatly accelerate the creation of new debris and threaten the opportunity of access to space in future years.

The prospect of new lower-cost space services, on the one hand, that is offset by serious concerns that large-scale mega-constellations leading to additional space collisions and rapid debris buildup is creating concern about what these new deployment of small satellites portend for the future.

This *Handbook of Small Satellites* has sought to provide a comprehensive set of information about all aspects of these new small satellite systems and their threats and opportunities to future space services. It also notes that volatility in the markets will continue for the decade ahead. Technological, market, and regulatory changes plus competitive suits will create churn, consolidation, and bankruptcy.

The COVID-19 pandemic that occurred in 2020 has caused health and economic consequences of staggering worldwide consequences that will accelerate the instability in the small satellite markets. This horrific pandemic will impact the small satellite and launch industry in the months ahead. Despite these economic failures, the innovative new small satellite technologies, the new more efficient launch systems, the new ground systems, and the many other innovations discussed in this handbook remain valid and very useful sources of new enterprise in this field. In the late 1990s, the original small satellite constellations saw major economic collapses. The economic failures constituted by Iridium, Globalstar, ICO, and Orbcomm made a huge impact on satellite development and the ready access to capital financing for some time. Yet recovery was achieved in the years that followed. The same seems likely to occur in this instance as well. Despite these setbacks, the information in this handbook remains useful and quite relevant.

It is, nevertheless, best to consult current websites to chart the latest status of the companies seeking to compete in these markets.

2 Defining the Various Types of Small Satellites

One of the least clear terms in the field of space systems is that of a small satellite. There are truly small satellites in range of nanosats and below. These diminutive satellites are often used for the proof of concept or testing of new satellite technologies and systems or student or scientific experimentation. These quite small satellites include femtosats in the range of 10–100 g, picosatellites from 100 g to 1 kg, and nanosat that range in mass from 1 to 10 kg. Nanosats more or less include 1–6 unit cubesats. Other terms that are in common use are "chipsats" that are usually femtosats and "pocket satellites" that are one-eighth the size of a cubesat and are typically picosats. Increasingly, we are also seeing the deployment of commercial constellations that operate with satellites that are often 3 unit cubesatellites such as those deployed by Planet or Spire. In this handbook, there have been a number of articles that address the design, operation, and usages related to cubesats/nanosats and below and many other articles that address the larger microsats (10–100 kg) and minisats. Minisats are sometimes referred to as 100–500 kg and sometimes referred to as 100–1000 kg. Most of the large-scale or mega-constellations for broadband networking, mobile communications, or radar sensing are in these larger classes of "smallsats." The satellites for optical remote sensing, data relay, machine-to-machine (M2M), Internet of Things (IoT), or automatic identification systems (AIS) can range from cubesats/nanosats to microsats. These are, however, only general approximations.

The point is that "smallsat" is truly a very broad term of art. One must know a number of details before one can understand what is actually being referred to as a "smallsat." Key characteristics include such aspects as mass, physical dimensions in stowed and deployed conditions, power, operational radio frequency spectrum utilized, function or service provided, orbital characteristics, and stabilization, orientation, and thruster capabilities. In the increasingly complicated world of small satellites, there are other aspects to consider.

Some "smallsats" are not free flyers. They can actually be "hosted payloads" that can be launched on board a larger to medium-sized satellite. Alternatively, a very small payload such as the Aireon constellation, for ASD-B aviation navigation services, can be deployed on board another small satellite constellation. In this

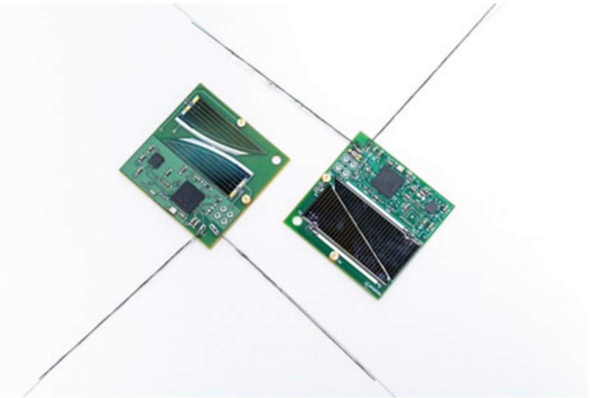


Fig. 1 Both sides of chipsat or femtosat that range in size of 10–100 g. (Graphic courtesy of the global Internet commons)

particular case, this small payload was hosted on the 66 satellites of the Iridium NEXT mobile satellite network.

Yet another alternative in terms of small satellite-type capability is not launching of a small satellite at all. Thus, one might deploy high-altitude platforms (HAPS) or stratospheric systems that operate in proto-space or subspace. Such platforms can provide telecommunications, remote sensing, or other services from high-altitude location in order to provide services that are quite similar in concept to a satellite operating at low altitudes. Thus relevant information and some analysis have also been presented in this handbook on both hosted payload systems and high-altitude platforms.

The first chapters in this handbook have sought to provide useful definitions and typical types of functions for various kinds of small satellites that range from femtosats to minisats. This is a gigantic range to contemplate. Femtosats, as represented by a chipsat, begin on the lowest mass of 10 g (Fig. 1). The highest end of the "smallsat" range is the minisat. These satellites can be as massive as 500 kg to even 1000 kg (Fig. 2).

This great dynamic range in size represents five orders of magnitude of scale. This is a differential divide represented by the relationship between 1 and 100,000. This is more or less equivalent to the size difference between a mouse and a hippopotamus.

3 Small Satellite Technology and Systems

The amazing development of small satellite technology and systems has enabled smaller and smaller satellites to be developed to carry out an ever-expanding range of services in the fields of telecommunications, networking, remote sensing, data relay and machine-to-machine (M2M) communications, RF geolocation, and scientific experimentation. Some of the innovations are a direct application of new commercial devices and components developed in microelectronics; phased array antenna design; optical processors; new types of optical, near infrared, and infrared sensors; and other new

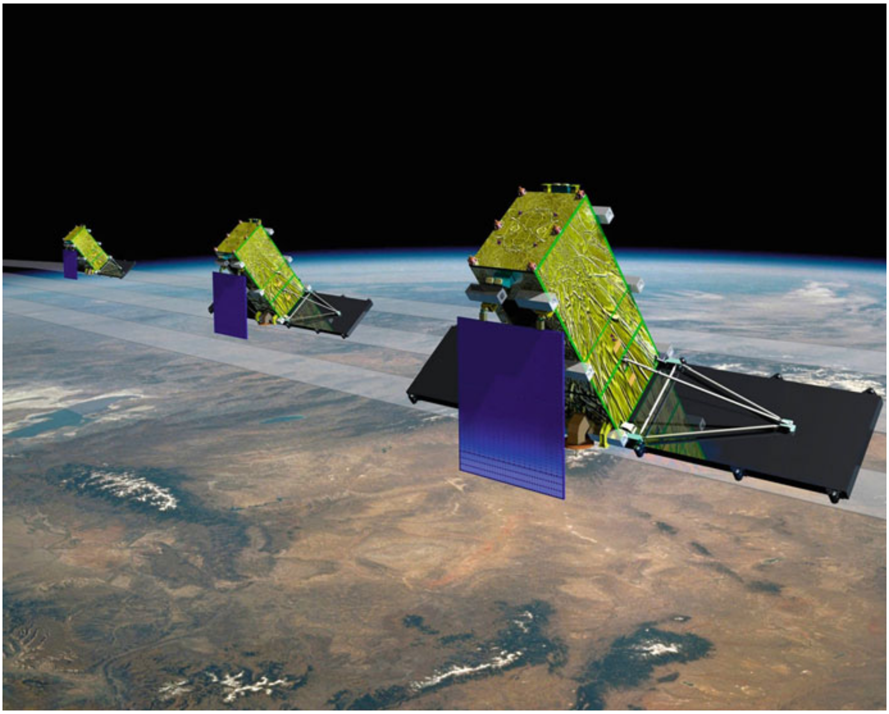


Fig. 2 New Trio of Canadian Radarsats – each minisat with a mass of about 550 kg. (Graphic courtesy of the Canadian Space Agency)

electronic and optoelectronic inventions. Other systems and subsystems are specifically developed by small satellite designers, integrators, and manufacturers seeking to provide more cost-efficient and compact components for small satellite systems. Advances have come from every possible angle and perspective.

There are improvements everywhere. There are enhanced miniaturization and lower-cost components and sensors. Devices with higher spatial, temporal, or radiometric resolution enhanced digital processing or encoding techniques or simply better or higher throughput production systems for these devices. There are improved miniaturized radio devices and sensors; improved navigation, stabilization, orientation, and pointing systems; better digital communications processing and encoding units; shrunk application-specific integrated circuits; better stabilization systems and torque rods; and improved and lower-cost batteries, social cells, and, coming soon, quantum dot solar power systems.

Part 3 of this handbook details the many technical innovations that are being developed in every aspect and subsystem associated with small satellites. These many innovations are linked to the development of smaller, more efficient, higher throughput, higher resolution, and in some cases lower-cost smallsat components. Innovations at every level of design and subsystem technical improvement are needed to create lower-cost and higher performance small satellite units.

Application-specific integrated circuits (ASICs), digital processors (electronic and optical), advanced encoding systems and software (e.g., turbo coding), advanced sensor design, improved smallsat components of all types, and small satellite kits have facilitated the ability of more and more students, experimenters, and even small satellite operators to build small satellite systems more quickly, at lower cost, with greater reliability and with fewer delays. In order to explore specific technical innovations related to the various subsystems involved with the engineering and optimization of small satellites, refer to the chapters in Part 3 of this handbook.

Although improvements in the technical design of many components included in small satellites has led to significant advances, it should also be remembered that satellites, both big and small, are essentially software-defined digital processors in the sky. This means that many of the advances in performance, cost-efficiency, and capability derive from improved software and processing and coding efficiencies. In short, advances are combination of both better hardware and software upgrades as well.

4 Design, Manufacturing, Testing, and Resiliency of Small Satellites

A great deal of the progress that has been made in developing higher performance, higher efficiency, and more cost-effective small satellites has been due to technical improvement of the components involved in small satellites, or enhanced software that allows these satellites to achieve faster throughput, spectrum efficiency, or improved preprocessing of remote sensing data. There are other types of improvements related to manufacturing, testing, design processes, and approaches to resiliency that are also key to improvements in small satellite systems. These innovations are more closely related to process and management concepts that technology per se.

Companies such as Planet, Spire, and other constellations that are deploying three-unit cubesat-type satellites employing a different type of approach to manufacturing and testing that employed by commercial operators who typically order a limited number of large GEO type satellites costing many millions of dollars and which take a number of years to design, manufacture, test, and arrange for launch. These small satellite companies take more of an incremental approach.

It is based on constant improvement in the design and manufacturing of its satellites. There is greater reliance on in-orbit testing of a design that is improved almost satellite to satellite and reliability and performance enhanced based on orbital experience. A network that is based on hundreds of satellites with a mean time to failure of perhaps 3–4 years involves a much different approach to design, manufacturing, reliability, and quality testing and resiliency of a so-called mega-constellation. This type of approach allows the possibility to additive manufacture of component parts that can be enhanced with each production run of small satellites.

Particularly in the area of remote sensing, one batch of small satellites might have a slightly better optical sensor, and another might have an improved battery or better efficiency type of solar cell. With a large number of small satellites constantly in

Fig. 3 The Planet LLC Dove 3 U Cube Satellite has now had 18 generations of design innovation and in-orbit testing. (Graphic courtesy of Planet LLC)

production, efforts can be made to improve the reliability of a satellite design based on monitoring the cause of any in-orbit failures. If each small satellite launched into orbit has a net cost of $100,000 rather than $250,000,000, then the approach to quality testing, design innovation, manufacturing, sparing philosophy, and resiliency changes dramatically.

Those commercial systems that are deploying hundreds if not thousands of telecommunications or networking minisats for large-scale constellations (i.e., smallsats in the 100–500 kg class) might require more homogenous designs and more quality testing in their approach to satellite production than that used by Planet or Spire. Nevertheless, their design, manufacture, and testing operations will tend to be more like the production of a television set or aircraft, than a handcrafted electronic product that goes through years of quality testing as was the case with large GEO satellites. In essence, part of the small satellite revolution has come from entrepreneurial insight and even rebelliousness that has concluded the ways of the past are no longer the best way forward. Small satellites such as the Planet Dove, produced in large numbers for LEO constellations, can lead to faster rates of innovation, more in-orbit testing, new modes of production, and even competitive designs (Fig. 3).

5 Launch and Deployment

Another part of the “Space 2.0” or the “NewSpace” revolution is not only small satellites but new low-cost commercial launch systems. There are scores of new launch service companies that are offering new types of launchers designed to offer launch services geared to accommodate small satellite missions. Rocket Labs, Vector, and Virgin Orbit’s LauncherOne are some of these new rocket systems.

As Virgin Orbit has noted in its promotional materials: “Small satellites are ushering in a new era of space capabilities – connecting us across vast distances, stimulating the global economy, and expanding the limits of human knowledge. This rapidly growing industry requires a launch service that is as agile and affordable as the satellites themselves. But until now, there hasn't been one." The implication is that the LauncherOne rocket system is the solution (Virgin Orbit 2019). The issue of launch arrangements for small satellites is not only that of the convenient availability of launch dates, but it is also cost-effectiveness and reliability of the launcher services. There are indications that larger launch systems might be able to respond effectively to all three aspects of convenience of scheduling, cost competitiveness, and reliability of service.

Conventional launch service providers as characterized by Soyuz/Progress, Ariane, United Launch Services, etc. are seeking to upgrade the launch operations to make them more cost-effective and flexible as to schedule, but the advent of new commercial launch services that employ reusable rockets seems to be particularly well positioned to cater to small satellite launch requirements.

Some analysts have suggested that the biggest innovation in terms of new cost-effective launch arrangements is, in fact, coming from reusable launcher systems that are being developed by SpaceX (i.e., Falcon 9R) and Blue Origin (i.e., New Glenn). These launch systems that are designed to recover launcher stages and then reuse perhaps 25 times or more offer the promise of major cost economies for a wide range of launcher missions. Not only are they offering what seem to be very reliable and cost-effective services, but there are new launch schedules now being offered that will launch once a month and reserve a portion of the launch to accommodate small satellite requirements (see F9R launch vehicle in test flight).

And there are now competitive responses from Ariane with its proposed Themis launcher that is now planned to be available by 2023 which is 2 years earlier than the original planned date of 2025 (ArianeGroup 2019). Further Airbus has announced plans for its new Adeline winged booster stage which is under design development (Airbus Enters 2019) (Fig. 4).

What is clear is the cost to launch a cubesat into orbit will continue to come down and that the flexibility to launch based on the schedule of the smallsat clients will also likely continue to improve. What is unclear is what will be the ability of reusable vehicles to truly achieve 25 reflights with the same launcher stages and the reliability of these reusable systems. Also unclear is whether the truly small launcher systems such as Vector, LauncherOne, and Rocket Labs will be able to remain competitive against the larger reusable systems now active or planned by SpaceX, Blue Origin, Ariane, Airbus, and perhaps others.

6 Operations and Sparing Philosophy and Space Safety Consideration

There are now many student and scientific experiments, test flights of new technology and systems, and one off small satellite missions that will continue to fly into space that are one of a kind missions. If there is a launch failure or the smallsat for some reason does not perform, then the experiment or test flight will simply be tried again. These small satellites typically have no redundancy or backup capability.

Fig. 4 Test flight of the Falcon 9 Reusable (F9R) launcher that promises new economies for smallsat launches. (Graphic courtesy of SpaceX)

They often use off-the-shelf components, and there are no planned backup capabilities to keep costs to the minimum. A majority of these systems have an in-orbit lifetime of less than 3 months, and they are often deployed at a low altitude so that they naturally degrade from their orbit and burn up on reentry. The technical and reliability model for these types of experiments and test flight is clear. No sophisticated sparing, operational resilience plan, or active deorbit process is needed. It is possible that there might be some sort of passive device to create atmospheric drag that might be deployed at end of life to facilitate early deorbit.

The small satellites that are deployed as operational constellations, whether commercial, governmental, or defense related, are a different matter. The planning for network reliability, safe deployment, and safe removal from a constellation is a matter of some importance. Indeed since some of these large networks involve capital investments that will exceed in excess of an estimated ten billion dollars (e.g., the SpaceX Starlink and V-band networks) and also involve significant safety risks to long-term sustainability of space, the risk elements are enormous.

There have been new ways to look at the reliability and resilience of satellite constellations. The design and introduction of the mobile satellite networks as represented by the Iridium and Globalstar constellations involved system planning that relied to some extent on deploying orbital spares. These networks had sufficient satellites in orbit that there was thought that holes in the network could be worked around until replacements deployed. This was particularly the case for the Iridium satellite network that had the additional feature of intersatellite links. The use of intersatellite links to work around failed satellites was also envisioned in the case of the proposed MegaLEO constellation known as Teledesic. Furthermore, the second generation of mobile voice communications systems, i.e., Iridium NEXT and Globalstar (OG2), has intersatellite links to minimize ground system investment and the ability to work around in-orbit satellite failure.

The latest planning for operational system reliability for large mega-constellations has focused on using the entire deployed system as the sparing concept as the size of these networks has increased to hundreds or even thousands of satellites. The sparing philosophy for large small satellite constellations seems adequate to provide for reliability of service for these systems.

The problem of safety and avoidance of potential satellite collisions in the case of very large constellations remains. Studies carried out by the Aerospace Corporation for five of the largest low Earth orbit constellations found that there were significant risks of orbital collisions associated with the initial deployment of these systems as well as significant risk of collision as satellites are removed from service at end of life and deorbited.

This statistical analysis considered the potential risk of a collision occurring over a 10-year period first in terms of the deployment and operational period and second during the removal and deorbit phase for constellations where detailed filing information as to number of satellites, orbital configuration, and density of satellites per orbital configuration. The results of those calculations are shown in Table 1.

This analysis, of course, had to make a number of assumptions in this modeling process, and there is no indication of the level of accuracy that is attributed to the calculations. Nevertheless, even if one assumes that the risks of potential collision have been overestimated by a factor of 2, there is substantial reason for concern that during operations and disposal operations, the risks of collisions seem to be substantial. This analysis also shows that there is an overconcentration in the current filings of LEO satellite constellations that are to be deployed between 850 and 1000 km altitudes (Muelhaupt et al. 2019). The above and other assessments of the ever-growing number of large-scale constellations planned for launch in the next decade have given rise to concerns about space debris removal and efforts to minimize orbital collisions.

There have been calls to revise the UN voluntary guidelines for space debris removal. Many of the operators of mega-constellations have voluntarily committed to rapid removal of satellites at the end of life. The problem with rising concerns about the large number of small satellites now planned to be deployed in large constellations is the lack of system limitations. As the threat of possible orbital collisions rises – both during smallsat constellation systems operation and removal – lack of regulatory control comes into clear focus. Currently, there are no effective

Table 1 Possible collision assessment from mega-constellation as conducted by the Aerospace Corporation (Aerospace Corporation)

Future constellation model	Probability of a collision over 10-year period during operations	Probability of a collision over 10-year period during disposal
FCM 1	8	15
FCM 2	0.5	1.25
FCM 3	1.1	0.6
FCM 4	0.33	0.55
FCM 5	1.25	0.80

controls that limit the number of systems proposed or approved at the national licensing procedures or ITU system coordination processes that now limit the number of satellites or constellations. Table 2 provides a tally of satellite constellations that are just related to proposed broadband telecommunications and networking services. If one totals the maximum number of satellites that could eventually be deployed according to potential full deployment, the number of smallsats as listed in Table 2 could conceivably tally over 27,000 satellites (Pelton 2019a).

This lengthy table just provides proposed smallsats for broadband communications and networking services. It thus does not include, for instance, many more satellites that are now already deployed or proposed for remote sensing, for narrow band data relay, for RF geolocation, or for mobile communications satellite services. What makes the numbers of proposed satellites listed in Table 2 seem so totally remarkable is that the total number of operational satellites now in service as of the start of 2020 is less than 2000. The launch and deployment of so many satellites, followed by the successful operation and maintenance of such massively sized constellations, and then clean disposal of so many satellites are perhaps the greatest challenge of the decade for the space applications industry. This operational challenge might be matched by the growing regulatory challenge. This would be to find

Table 2 The growing number of smallsat constellations for broadband telecommunications. (A compilation of the author)

Proposed small satellite constellations for broadband telecommunications			
Country	System name	Number of sats	Radio frequency bands
Canada	CANPOL-2	72	LEO and highly elliptical Earth orbit in VHF-, UHF-, X-, and Ka-bands
Canada	Telesat constellation	117 satellites plus spares	LEO in Ka-band
Canada	COMSTELLATION	Nearly 800 sats	LEO in Ka-band
France	Thales Group's MCSat	Between 800 and 4000	LEO, MEO, and highly elliptical Earth orbit in Ku- and Ka-bands
Liechtenstein	3ECOM-1	264	Ku- and Ka-bands
Norway	ASK-1	10	Highly elliptical Earth orbit in X-, Ku-, and Ka-bands
UK	L5 (OneWeb)	650–750 initially but in time 1200–4000	Ku- and Ka-bands
USA	Boeing	1396–2956	V-band in 1200 km orbit
USA	SpaceX	4500+	Ku-Ka band
USA	SpaceX	7500 plus	V-band
USA	LeoSat	Initially about 80	Ka-band
USA	Athena-Facebook		Ka-band
USA	Karousel MEO	20 MEO satellites	Ka-band
USA	Kuiper-Amazon	3236	Ka-band in three orbital tiers
USA	O3b mPower MEO	24	Ka-band

means to control and limit the proliferation of smallsat constellations and to facilitate active disposal of satellites at the end of life to cope with related liability issues.

7 Ground Systems Technology

One of the great miscalculations of those that do not know the space applications industry well is to overemphasize the importance of satellites and launchers and underrate the importance of the ground segment. The ground segment associated with space applications as an industry is three to four times the size of the launch services industry. The key to the future of small satellite industry, particularly in the context of constellations, is much more crucially tied to break through in ground system design and performance than perhaps any other factor.

The first step toward new user antenna systems and technology came with the small satellite constellations in low Earth orbit (LEO) that required user transceivers that could receive signals from horizon to horizon as the Iridium and Globalstar satellite crossed over the sky in about 7 min or so. These new type satellite receivers were designed to capture signals coming from the sky and relied on the signal processing power and digitally encoded transmission that were provided by means of application-specific integrated circuits (ASICs). These digital transceiver units could not electronically track the satellites, but they still demonstrated that small compact handheld units could nevertheless receive satellite signal for voice communications from LEO orbit.

The next step forward was to develop ground systems that can provide electronic tracking of LEO satellites in a global constellation without the need for active mechanical tracking. This required computer-generated electronic beams that could be generated by new flat panel antenna systems. The trick is to develop this type of electronic tracking transceivers that would be reliable enough to switch from beam to beam at the rate of about once a minute and from satellite to satellite about every 7 min and also be produced at low cost. Today, there are over 20 companies developing flat panel antennas for users for not only mobile satellite communications but now to support even broadband digital networking services.

As identified in the Northern Sky Research report on Flat Panel Antennas, these companies include ALCAN Systems, Anoki Systems, Ball Aerospace, Boeing, C-Com, GetSat, Gilat Satellite Networks, Kymeta, HiSky, Honeywell, Hughes Network Systems, Isotropic Systems, Omni Wave, Phasor Systems, SatixFy, StarWin, ThinKom, Tianyi Satcom Company, Toshiba, and Viasat. Several other companies deploying large-scale constellations such as SpaceX might become self-producers. In addition, there are other companies that may serve as integrators for military communications satellite companies (Northern Sky Research 2019).

This is an area that is rapidly developing in terms of technology and in achievable cost reductions. One of the many innovators in this area is Isotropic Systems that claim that their optical processing technology will allow one of the most cost-effective designs for low-cost user flat panel satellite antennas (Fig. 5).

Fig. 5 Isotropic Systems flat panel satellite antenna. (Graphics courtesy of Isotropic Systems)

8 Business, Markets, Financing, Risk Minimization, and Legal Challenges

Few industries around the world have shown more dramatic changes than that of the small satellite industry. This is not only change in their technologies but also in terms of new business innovation, new business industries, financial change in terms of capital investment, market focus, and even new approaches to risk management and institutional arrangements. Almost anywhere one looks in the small satellite industry, change is afoot.

8.1 Business and Market Shifts

At the level of business innovation, there are scores of new entities identified in Part 13 of this handbook involved in some aspect of the small satellite industry. There are a large number of companies who are involved in designing and building small satellites, in deploying and operating small satellite constellations, in providing launch services for small satellites of all types and sizes, and in manufacturing ground antennas for users and network connectivity. This has created a somewhat chaotic market, and result may see mergers, acquisitions, spinoffs, and even bankruptcies. Companies that were predominant in some space services for remote sensing, telecommunications, broadcast satellite services, or construction of satellites or Earth stations for some decades may see their roles shift, and new innovators take commanding new market leads. The rate of change and the market shifts are still in a state of flux, and predictions of winners and losers are still unclear in this era of rapid market trajectories – some upward and others down.

While this handbook has been in production, the Vector small satellite launcher company, that offered flexible and quick launching opportunities for small satellites, has been forced to declare bankruptcy. LeoSat that was seeking to deploy a high-performance, corporate-based broadband service using a small satellite constellation has also declared bankruptcy. Intelsat and OneWeb were planning to merge under a financing plan offered via the Japanese banking giant SoftBank, and now Intelsat has filed a very substantial suit against both OneWeb and SoftBank. Audacy that is seeking to provide data relay services via a new constellation has recently pursued talks with Iceye about possible strategic partnerships to achieve support for its high capital costs to complete its network.

Companies that are pursuing total new markets and services have a great challenge of deploying new products or services and establishing a successful business and market as essentially totally new startups. Thus totally new offerings such as the HAPS Stratobus by Thales Alenia and the RF Geolocation offerings by Hawkeye360 have to balance startup costs versus establishing totally new streams. The bottom line is that many of these small satellite ventures and new launch vehicle ventures could fail. On top of this, the most profitable revenue stream for satellites historically has been broadband broadcast of video services that are now being challenged by over-the-top Internet streaming. One of the large market questions is whether LEO small satellite constellations can find a successful way to offer both 5G broadband and video streaming services which are the largest potential markets. These are questions that are still unanswered. The bottom line is that small satellite markets are still quite unsettled and market volatility is a part of the small satellite domain. The fact that Silicon Valley giants such as Google, Facebook, and other Internet backers are a part of the story leads to confidence that many of these ventures can succeed, although some may fail.

8.1.1 Finance and Capitalization

One of the most significant changes is that there are new sources of business innovation and new types of businesses providing innovative sources of capital financing that range from crowdsourcing, Kickstarter, and a number of industrial heavyweights. These include the computer services and networking industries, largely coming from Silicon Valley such as Google, Facebook, Amazon, etc. There are yet others that are heavily involved such as SpaceX and new launch services companies, as well as international banks such as SoftBank of Japan, and others such as Liberty Media, venture capital firms, and others from the Space 2.0 or “NewSpace” industries (Pelton 2019b).

8.2 Risk Management and Insurance

The whole new set of economics associated with the design, manufacture, and operation of small satellites coupled with reduced launch costs and entrepreneurial talent and sense of reinvention has not only reduced the barriers to market entry, but it has created a whole new concept about approaches to sparing philosophy, approach to manufacture and deployment, and strategy related to insurance coverage. The traditional approach associated with high-throughput GEO satellites with very strong cost-effective performance has challenged conventional GEO satellite design from one perspective and has moved toward economies of scale achieved with only a few very high-cost satellites. On the other hand, the new small satellite constellations have initiated a new form of economy of scale by the launch of hundreds if not thousands of small satellites. This approach creates a whole different business model. The business concepts can all be different: (i) system design; (ii) the approach to design and procurement of satellites and launch services; (iii) the sparing, the insurance, and risk minimization philosophy; and (iv) design and implementation of the ground system architecture. These issues and more are now all potentially different. New models are being created and new approaches embraced.

8.3 Legal and Regulatory Concerns

The enormous change created by small satellite technology, constellation design, new ground systems, new businesses, and entrepreneurial innovation has created new businesses and new approaches to space application services and innovative new markets. But there are also new and major concerns about the national and international space regulatory environment. There are key concerns about liabilities, space debris, and sustainable space operations within this new environment. The issues and regulatory concerns cut in different directions. On the one hand, there are concerns that the advantages that small satellites can offer to student experimentation, space programs for developing countries, and use of space technology to meet the sustainable development goals of the UN all argue for limits on overregulation of small satellites. On the other hand, the prospect of the number of operational satellites increases by an order of magnitude in the next decade, and the amount of orbital debris in orbit swelling out of control and making the so-called Kessler syndrome a reality could have catastrophic impact.

There is today a lack of new international regulatory authority to cope with the many changes that have occurred since the five international agreements negotiated and agreed within the United Nations Committee on the Peaceful Uses of Outer Space and the General Assembly in the late 1960s and 1970s. The proliferation of small satellites, LEO and MEO constellations, and space debris poses regulatory challenges. The analysis in this handbook suggests that new international agreements to cope with these problems will not likely be achieved in the near term. Thus national procedures to address orbital debris, space debris removal, space situational awareness, and space traffic management will likely need to lead the way forward in the nearer term. These legal and regulatory concerns will play a key role in how the new space industries and the small satellite industries evolve in the coming decade and perhaps the decade to follow.

9 Practical Reference Information

The field of small satellites is evolving rapidly, the dimensions of the smallsat world seem to be expanding every day, and the complexity will only continue to grow. This handbook has sought to cover every aspect of the small satellite revolution in terms of the satellite and ground system technology, the regulatory, business and financial issues, and the practical aspects of various small satellite projects with useful case studies. Part 13 of this handbook provides useful information on small satellite companies, satellite constellations, launch vehicle companies, processes for registration of satellite launches, the UN Sustainable Development Goals, and more.

10 Conclusion

The *Handbook of Small Satellites* is an interdisciplinary, comprehensive, and hopefully useful guide to every aspect of the world of small satellites. If covers the true small satellites used for experimentation and technology demonstration that range from femtosats, picosats, and nanosats on one hand to the other larger and business-oriented systems on the other hand.

It thus covers commercial small satellite constellations that typically range from three-unit cubesatellites up to microsats and minisats. It has sought expertise from around the world from Africa, Asia, Australia, Europe, North America, and South America and scores of space, satellite, and launch vehicle companies around the world. It seeks to cover the technology; the operational, market, and financial challenges; the regulatory shifts; and the fact that the world of small satellites is still volatile and sometimes uncertain. This is always the case with new technology, new markets, and totally new ways of providing services to a global environment that is rapidly shifting. The unusual market dynamics plus the further complication of the Covid-19 Corona virus makes it difficult to forecast how the world of small satellites will evolve in the next few years.

It has been a collaborative process with careful thought given to every aspect of this complicated new world of small satellites. It is hoped that this reference work proves to be of value to those that consult it as a reference source.

11 Cross-References

- ▶ Analysis of Orbit Debris
- ▶ Companies Involved in Design, Manufacture, and Testing of Small Satellites
- ▶ Forms for Registration of Small Satellites Consistent with the Registration Conventions
- ▶ Global Launch Vehicle Systems for Potential Small Satellite Deployment
- ▶ Historical Perspectives on the Evolution of Small Satellites
- ▶ Introduction to the Small Satellite Revolution and Its Many Implications
- ▶ Partial Listing of Small Satellite Constellations and Related System Infrastructure
- ▶ UN Sustainable Development Goals for 2030

References

Airbus Enters Reusable Rocket Race against SpaceX with Adeline. (2019). https://search.yahoo.com/yhs/search?hspart=trp&hsimp=yhs-001&type=Y115_F1_159651_053019&p=air+bus+adeline+launchpad. Accessed 11 Oct 2019

ArianeGroup Reveals New Launcher Heavily Influenced by Falcon 9. (2019). https://www.reddit.com/r/SpaceXLounge/comments/aw48a6/arianegroup_reveals_new_launcher_heavily/. Last accessed 11 Oct 2019

T. Muelhaupt, M. Sorge, J. Morin, R. Wilson, Space traffic management in the new space age. J. Space Saf. Eng. **6**(2), 80–87 (2019)

Northern Sky Research, in *Flat panel satellite antennas*, 4th edn. (Northern Sky Research, Cambridge, MA, 2019). https://www.nsr.com/research/flat-panel-satellite-antennas-4th-edition/

J.N. Pelton, *Lecture materials, small satellite course* (University of Cape Town, Cape Town, 2019a)

J.N. Pelton, *Space 2.0: Revolutionary advances in the space industry* (Springer Nature, Cham, 2019b)

Virgin Orbit. (2019). https://virginorbit.com. Last accessed 10 Oct 2019

Small Satellites: Glossary of Terms and Listing of Acronyms

Joseph N. Pelton

Keywords

Definitions · Miniaturization · Small satellites · Space 2.0 · Space systems innovations · Small satellite applications · New launch systems for small satellites · Standards

The following text provides a listing of many of the acronyms found in the *Handbook of Small Satellites* as well as a brief definition of the many specialized terms found in this reference book. There are also a listing of many of the proper names of constellations, launch services organizations, and small satellite companies discussed in the text. If they are not found below, they can also likely be located in Part 13 of this handbook that provides essential technical, regulatory, and management information relevant to the field of small satellites.

ACM	Attitude Control Module
Active Debris Removal (ADR)	This refers to a space-based activity designed to accomplish the active removal of debris. This could involve using various techniques to deorbit them from Earth orbit. This is in contrast to passive systems that lead to the ultimate uncontrolled deorbit of a space object due to gravitational effects, atmospheric drag, or other natural effects such as space weather

J. N. Pelton (✉)
Executive Board, International Association for the Advancement of Space Safety, Arlington, VA, USA

International Space University (ISU), Strasbourg, France
e-mail: joepelton@verizon.net

J. N. Pelton (ed.), *Handbook of Small Satellites*,
https://doi.org/10.1007/978-3-030-36308-6_86

ADCS Module	Attitude Determination and Control System Module
ADS-B	Automatic Dependent Surveillance-Broadcast (ADS-B) is a new GNSS-based technology that enables aircraft broadcast signals to be broadcast via satellite while in the air. This information can include flight-related information, i.e., identification, position, altitude, velocity, and other relevant information. This can include surveillance information that is provided on a regular basis to air traffic controllers (ATCs) as well as to other aircrafts (see Aireon).
Aerial	An aerial and an antenna can be used interchangeably. However, an aerial usually implies a very simple type antenna such as dipole or Yagi-type antenna.
Aerobraking	Aerobraking in a maneuver carried out in space to change the speed and direction of a spacecraft by utilizing the atmosphere of a planetary body as a slowing force. This is one of the most common techniques for reducing the speed of a spacecraft in the case of reentry for the purpose of re-landing on Earth or to cause a defunct satellite or space debris object to descend to Earth and in most instances eventually to burn up in the Earth's atmosphere.
Aerodynamics	Aerodynamics is the study of atmospheric effects on various bodies do as to make, in the case of aircraft, spacecraft, or launch vehicles, their flight more efficient and lift or descent achieved in a more controlled and effective manner. One of the key concerns in the space field is aerodynamic heating and thermal protection against aerodynamic heating. When a spacecraft or rocket moves through the atmosphere at hypersonic speeds, temperatures in well above 1000 °C can occur.
AGI	Analytic Graphic Inc. This company is one of the leading companies involved in orbital debris tracking and is the leading contractor for the Space Data Association.
A-GPS	This acronym refers to Augmented Global Positioning Satellite (GPS) System Agreement Governing the Activities of States on the Moon

	and Other Celestial Bodies (also known more simply as “The Moon Agreement”): This international agreement was signed on 5 December 1979 and was the fifth and last of the major space agreements adopted by the General Assembly. The Moon Agreement was adopted via resolution 34/68, and this document reiterates many of the provisions of the Outer Space Treaty but is notable in adding the concept of “the common heritage of mankind” with regard to celestial objects including special emphasis of the Moon.
AIAA	The American Institute of Aeronautics and Astronautics, headquartered in Reston, Virginia
Aireon	This is a hosted payload system that is deployed on the Iridium Next satellites that is designed to provide precise location of aircraft in the new precise navigation system that is being increasingly used on a global basis. These packages are on all 66 operational Iridium satellites plus the 9 spares. These platforms provide Automatic Dependent Surveillance Broadcast (ADS-B) services to aircraft and aircraft controllers. This is a new GNSS-based technology that enables aircraft to engage in precision navigation and assist air traffic controllers to prevent accidents.
Airspace	The definitions of airspace and outer space, as well as the demarcation between the two, have never been clearly decided in terms of international space law. Commercial airspace is that which is regulated for aircraft safety, and this extends from the ground up to 20 km. Military airspace extends beyond these altitudes. Some define airspace as extending up to the von Karman line which is the point where it is physically not possible for aircraft to fly. The von Karman lines are generally thought to be 100 km from the surface of the Earth. States have “complete and exclusive sovereignty over the airspace above [their] territory” as per Art. 1 of the Chicago Convention.
AIS and S-AIS: Automatic Identification System and Satellite-Automatic Identification System	AIS is a global standard for ship-to-ship, ship-to-shore, and shore-to-ship communications, while S-AIS is satellite-automatic identification system. This AIS service has been mandated for all

	shipping since the International Maritime Organization's (IMO) adopted in 1974 the International Convention for the Safety of Life at Sea (SOLAS). This service is designed to provide for maritime collision avoidance, search and rescue (SAR) operations. It creates a system for identifying maritime vessels and allows vessel tracking. Satellite AIS (S-AIS) allows for enhanced coverage in remote areas, such as oceanic and Arctic regions, and complements terrestrial AIS coverage. There are now several constellation of nanosatellites capable of picking up S-AIS signals to increase visibility of vessels in remote areas of the world.
Aleph-1 Constellation	This is an Argentina-based system owned by Satellogic NuSat. Eventually the objective is to launch 300 satellites in this constellation. Nearly 30 of these 37 km satellites have been launched by Chinese launchers to date. The objective for this remote sensing network is to provide 1 m resolution.
Antares	This is a launch vehicle developed by Northrop Grumman Innovation (originally Orbital Sciences Corporation) to provide resupply missions to the Space Shuttle.
Angara	This is the new launcher that is being developed by Khrunichev, KBKhA that is to replace the Proton launcher. It is to be offered with a range of launch capabilities that range from the Angara 1 to the Angara 2 and the largest Angara 5 with the heaviest lift capability.
Antares	This is the launcher developed by Northrop Grumman Innovation (Orbital ATK) that is derived from the Taurus launcher and was selected for the NASA commercial resupply of the International Space Station (ISS). The Antares 230 is the vehicle currently operational, and the Antares 300 is currently in development.
Antenna Gain	The shaping of a parabolic dish in a satellite communication to focus a beam more tightly in comparison to an omni-beam or isotropic beam that has transmit equally in all directions is known as gain. This means, in effect, gain in effective power concentration from 'one' as

	represented by a omni-directional antenna. The shaping of an electronic beam is also a function of the transmission frequency and thus the wavelength. The formula for an electronic antenna's gain is given as: $\text{Gain}\,(dB) = 10 \times \log_{10} k\left(\frac{\pi D}{\lambda}\right)^2$ In this formula D = diameter of the antenna, λ= the wavelength, and k = the efficiency of the antenna. The resulting gain in power is expressed in logarithmic decibels based on a log 10 scale. Thus a gain of 3 dB is an increase of two, a 10 dB gain is a 10-fold increase, a 20 dB increase is a 100-fold increase, and a 30 dB increase represents a 1000-fold increase.
Aperture	This is the size of a satellite transmitting or receiving antenna. The larger the antenna aperture size, the greater the gain and thus the effective performance of a radio antenna.
Aphelion Orbitals	Aphelion Orbitals, a US company offers the Helios and Feynman Launch System for small satellite launches. This launch system is able to place 6U CubeSats into LEO at low cost.
Apogee	The highest point or apex in an elliptical orbit. In Earth orbit, for instance, this would be when a satellite is farthest away from the Earth's surface but travelling at the slowest speed. Also see perigee which represents the reverse condition.
Argos	This is a constellation of seven satellites. This international system was first created in 1978. This is a LEO constellation for data relay. It is to be augmented and then replaced by 25 Kineis Satellite in 2022.
Ariane 5 and Ariane 6	The Ariane 5 is currently the largest launcher operated by Arianespace from its French Guiana launch site. The Ariane 6 is currently underdevelopment and is designed to provide more cost-effective launch capabilities when it is tested and operational.
Arianespace	Is the French aerospace company that is responsible for the development, manufacture, and launch of the Ariane 5 and in the future the Ariane 6 launch vehicle. Arianespace also operates the launch site in French Guiana which

	currently supports launches by not only the Ariane 5 but also the Soyuz and Vega launchers that can both be configured for multiple small satellite launches.
ATC	Air traffic control. This is the responsibility of ICAO at the international level and national or regional air traffic regulatory entities such as the FAA in the United States and EASA in Europe. With the advent of space planes and other near Earth activity involving high-altitude platform systems and robotically controlled vehicles at high altitude, there has been increasing concern, interest, and consideration of the issue of space traffic management, and the interface between missions involve air traffic, robotic aircraft operations, near Earth orbit space activities, and space planes and other vehicles that may travel in both air and outer space. Also see ATM.
ATM	Air traffic management. This is the responsibility of ICAO at the international level and national or regional air traffic regulatory entities such as the FAA in the United States and EASA in Europe.
ATO	This is a term developed by NASA in a case where the launcher has enough velocity to achieve orbit but without achieving the desired orbit required for a particular mission. In many cases there would need to be a decision as to whether to abort the mission and to deorbit from this irregular orbit.
Atlas	This is one of long-term use launch vehicles developed in the United States. It can be used for launch of small satellites, using residual or so-called “piggy-back” launch capacity or for launch of many small satellites at one time.
Bagaveev launcher	The Bagaveev Corporation has developed a 3D-printed rocket motor for its launcher. It is designed to place a 12 kg payload into LEO orbit. Its initial pricing is to launch small satellites at a cost of $100K per kg.
BeiDou	One of two Chinese precision navigation and timing satellite systems. This is the first-generation system, and its translation from Chinese is the “Big Dipper.” Compass is the second-

	generation Chinese system, and it will eventually replace the BeiDou system.
Black Arrow 2	This is a project of the Horizon Space Technologies, Ltd. in the United Kingdom to develop a low-cost launcher based on the original efforts to develop the Black Arrow 1 launcher. Current status unknown.
Blue Origin	This is the commercial launch company founded by Jeff Bezos that is developing the New Shepard and New Glenn launcher. Blue Origin is also developing new launch motors for the United Launch Alliance.
Boeing	Boeing is one of several companies that have filed to launch a large-scale constellation to provide global networking services. It is not clear as to how soon Boeing intends to move forward with this project. Boeing also has a part of its company that provides tracking of orbital debris under contract.
bSpace	This is a new enterprise that is developing the Volant launch system that would similarly to NanoRacks offer launch services via release from the International Space Station using an ARQ. The estimated cost is $80K per kg.
Canpol-1	This constellation of 72 satellites is to be deployed to provide networking services to support military-/defense-related services of Canada. This 72 sats LEO Constellation will be augmented by a number of highly elliptical orbit satellites. This constellation will be deployed with LEO nine sats each in eight planes. The satellites will be equipped to operate in the VHF-, UHF-, X-, and Ka-bands.
Capella	US constellation of 36 satellites that might expand to 48 satellites in a 500 km orbit. This is a Synthetic Aperture Radar System deploying sub-50 kg microsatellites. This system will provide radar imaging for the X band (9.4–9.9 GHz). The satellites will have only a 3-year lifetime, so it will require frequent replenishment. Full deployment of 36 sat network planned to be achieved around the end of 2021 or early 2022.

CDMA	Code-Division Multiple Access. This is a digital multiple access system that is commonly used in digital satellite communications. This is also sometimes called spread spectrum. Also see TDMA.
Celestia Aerospace	This small satellite launcher is accomplished via a Sagittarius Missile launched from a MiG 29 jet (known as Archer 1). This launching arrangement is able to put 1U nanosats into orbit at an estimated cost of 200k euros.
ChipSat	A ChipSat is a type of extremely miniaturized small satellite – often a femto satellite of less than 100 g mass based on system-on-a-chip or embedded systems type of architectures and hardware. With the advantage of easily building and deploying, very large numbers of such ChipSats at very low-cost concepts like fractionated spacecraft or massive distributed missions become feasible – with the negative side effect of possible creation of large number of very small space debris.
Comm Module	Communications Module that provides the particular telecommunications services needed to support a small satellite mission's needs.
Commsat	This is a private Chinese LEO constellation for designed to provide global Internetworking services via a network of 800 sats deployed in a 600 km LEO orbit. This new constellation is intended to provide Internet of Things and data communications services. The launch and full deployment dates are not now known.
Constellation	This is a term widely used to describe a network of satellites that is deployed in a particular way that is most typically designed to provide a global coverage of Earth. The number of satellites that are deployed in a constellation to provide worldwide coverage increases at lower altitudes since the viewing coverage of a satellite decreases as it orbits at lower heights. A three satellite constellation in GEO orbit can provide nearly complete coverage except for the polar region. A MEO constellation can provide worldwide coverage with about 12 to 18 satellites. A

	LEO orbital system will typically require about 50 satellites to provide worldwide coverage.
COPUOS	Committee on the Peaceful Uses of Outer Space. This United Nations committee meets in Vienna and has standing Technical and Legal Committees. It now has over 80 member counties. It was this committee that was responsible for the drafting and agreement of the text for the Outer Space Treaty of 1967 and to follow on subsidiary international agreements related to registration of space objects, astronaut safety, liability, and the so-called Moon Agreement. The UN Office of Outer Space Affairs serves as the secretariat for the COPUOS and also carries out other functions related to outer space activities.
CubeCab	The Cab-3A launch vehicle is being designed to place just one 3U CubeSat into LEO orbit and do so at a cost of $250K per launch. Bitcoin Latina has indicated it will launch 300 3U sats for a LEO network to provide service to Latin America.
CubeSat	A standardized type of small satellite that is 10 cm × 10 cm × 10 cm in size and up to 1.33 kg (often just 1 kg) in mass per one unit (or 1U) according to the CubeSat Design Specifications. The concept of a CubeSat was first introduced in 1999 by professors J. Puig-suari and B. Twiggs. This was also accompanied with the concept known as a CubeSat deployer mechanism (P-POD). Common sizes are 1U, 2U (2 units), 3U (3 units), or 6U (6 units) CubeSats. There are today even with larger sizes like 12U or 24U small satellites for various applications. CubeSats are usually compactly stowed in deployers such as a P-POD system. The advantage of CubeSats is standardized dimensions and mechanisms that allow them to be efficiently launched from launch vehicles or via airlock from the International Space Station or even from other small satellites (like microsatellites) as part of distributed missions.
Delta launch vehicle	This is one of the US developed launch vehicles. The largest of these vehicles is the Delta 4. This

	vehicle that is arranged for launch by the United Launch Alliance is being phased out in favor of the new and more cost-efficient Vulcan launch vehicle.
Dream Chaser	This is a reusable launch system developed by Sierra Nevada. One of the future capabilities under study is the Stratolaunch and Dream Chaser: this would be a 75% scaled version of the Dream Chaser for commercial missions.
DSS	Dark Sky Stations. These are high-altitude platforms that can be used for sustained stratospheric research and might also be used as staging platform to fly small satellites into Earth orbit using electronic propulsion engines.
DHM	Data Handling Module
EPS	Electrical Power Supply
exactEarth	This is a Canadian-based company's hosted payload on board the Spanish Radar Satellite PAX. This satellite is owned and operated by Hisdesat S.A. The mission of exactEarth is to provide maritime satellite-automatic identification services (AIS).
ExoAnalytic	This is one of several private start-up companies that is involved in the tracking of orbital debris and provides data to defense agencies under contract.
EyasSAT	A special small satellite teaching system to aid in the identification of components included in the design of a CubeSat.
FAA-AST	This acronym stands for the US Federal Aviation Administration-Assistant Administrator for Commercial Space Transportation. This is the US Agency that provides the licensing for commercial space launches and has developed safety standards for commercial suborbital flights for so-called space tourism. If the ICAO assumes responsibility for so-called space traffic management (STM), then the FAA-AST will likely be involved in some role in this activity as well.
Falcon family of launch vehicles	These are the rocket systems developed by SpaceX. These have included the Falcon 1, Falcon 9 Full Thrust, Falcon Heavy, and the largest of which is to be the Falcon Big Rocket.

Femto satellite (or Femtosat)	A femto satellite is a highly miniaturized small satellite that is up to 100 g (about 3.5 ounces) in mass according to the most common definition. It is often a CHIPSat or similar stand-alone spacecraft. It can also be a part of a distributed mission concept like a fractionated spacecraft.
Firefly Aerospace	This was a start-up to develop a low-cost launch vehicle for small satellites, but it is now bankrupt and no longer active.
5G	This is the fifth generation of cellular service that enables fast broadband applications for Internet-related and data streaming services. These include over-the-top data streaming video to cell phones and laptops, Internet of Things, and interactive data networking associated with driverless vehicles and their sensors. This will over time replace 4G long-term evolution cellular services.
Flat Panel Antenna	This is an antenna that uses electronic beamforming technologies to track satellites or to send signals from satellites down to Earth. These types of antennas thus do not have to physically track by movement of an antenna reflector. These electronic beamforming antennas can be of any shape and can, for instance, conform to the shape of a roof, a car, or aircraft.
Fleet	This is an Australian constellation that eventually intends to deploy up to 100 satellites to carry out global Internet-based networking services. Initial launches have been provided by Rocket Labs. The network is being deployed in LEO at 580 km altitude.
FOSA	French Operations Space Act
GEO	This is a special orbit, whereby a satellite deployed some 35,870 km above Earth appears to rotate exactly with the Earth's daily rotation. In this orbit ground, antennas do not have to track the satellites since GEO satellites seem to hang about the globe at a constant location.
Globalstar	This LEO constellation has 24 small satellites in its second-generation constellation with each satellite having a mass of 700 kg. These satellites are deployed at 1414 km (876 mile) orbital

	altitude with 55° inclination to provide 80% coverage of the world. There are also 24 ground stations that create the latest infrastructure for global interconnection.
GLONASS	This is the Russian global navigational satellite system.
GNSS	This acronym stands for global navigational satellite system. This type of service is also known as precise navigation and timing (PNT).
GPS	Global Positioning Satellite System of the United States. This system is also known as NAVSTAR. This system is useful to Space Situational Awareness and Space Traffic Management.
GSO	Geostationary Orbit. This is the precise orbit that would stay constantly in the Earth's equatorial belt and also travel around the Earth once every day. This is a theoretical orbit in that there is some excursions by GEO satellites North and South of the equatorial belt as they orbit the Earth. A GEO satellite that moves more than 7° above or below the equatorial location (i.e., North or South of the belt) is no longer considered to be in GSO and not protected with its special status with regard to frequency interference from non-geostationary satellites.
GUI	Graphical User Interface
HII and HIIA Launch Vehicle	This is the launch vehicle developed by JAXA in Japan and represents one option for future small satellite launches.
HAPS	High-Altitude Platform Systems (HAPS)
Hosted Payload	This is a package that flies on another satellite. This is often a smaller payload that flies on a global constellation. One example is the Aireon hosted payload that is flying on the Iridium Next **constellation**.
Hyper-Spectral Sensing	This refers to the latest technology that is used to sense across the spectral band and does so by dividing the optical band into smaller and smaller segments. Obtaining the data broken down into narrow frequency bands can allow much more sophisticated analysis of the data. Increasingly sensing is carried out in 20 to even a 100 or more segmented bands. This can thus now be accomplished even on small remote sensing

	satellites due to the miniaturization of optical sensors.
ICAO	International Civil Aviation Organization, the UN Specialized Agency that is responsible for international coordination of aviation safety standards, known as SARPs, and auditing the safety practices and standards of air carriers. It has been discussed as a possible agency to coordinate international practices and processes related to space traffic management, particularly with regard to the operation of low Earth orbit (LEO) of satellites and perhaps space debris removal.
International Telecommunication Union (ITU)	The specialized agency of the United Nations that is responsible for the international setting of standards for telecommunications, broadcasting, and networking services. This includes standards related to satellite and space services and the allotment of spectrum for space services and coordination of the frequencies and orbits of various satellite systems that are planned by various system operators.
Iridium Satellite Constellation	The second generation of the LEO constellation for mobile satellite communications has been deployed. This network with a total of 75 satellites (i.e., 66 satellites plus 9 spares) is now fully deployed at 781 km altitude with an inclination of 86.4°. All these satellites have a hosted payload called Aireon to provide navigation and tracking information for aircraft on a global basis.
iSpace	iSpace is a Chinese launcher company that has developed the Hyperbola 1S (SQX-1Z) launcher which is under test and also developing in the 2021 time frame the H-1 and H-3 launch systems as follow on programs.
Jilin Commercial Satellite Imaging	This is a Chinese private company's four satellite constellations for remote sensing and provides 1 m resolution imaging. It is operated by Chang Guang Satellite Technology Co. of China that was established in 2014.
Kepler	This is a Canadian-based constellation that has been licensed by the FCC and coordinated with the ITU processes to operate a LEO system

	operating in the Ku-band. This 140 satellite system that will deploy 6U CubeSats to complete this constellation intends to provide Internet of Things (IoT) and data services. These 6U CubeSats are being manufactured by ÅAC Clyde with a TARS platform and when fully deployed this constellation will include 140 small satellites.
Kineis Constellation	This is a new constellation for data relay and other services of 25 satellites to be deployed in 2022. It is to replace the Argo constellation of seven satellites.
LauncherOne	This is the Virgin Galactic launcher that is designed for small satellite launches and will be used as one of the vehicles to deploy satellites in the OneWeb constellation.
LED	Light-Emitting Diode
LEO	This acronym stands for low Earth orbit.
Liability Convention	This is formally called the Convention on International Liability for Damage Caused by Space Objects. This convention formally entered into force in September 1972. See http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html
Lockheed Martin	This company designs and builds launchers that include the Atlas series of rockets. Lockheed has another part of its company that provides commercial tracking services for orbital space debris.
Long March Launch Vehicle	This name relates to the family of Chinese launch vehicles that are used by the Chinese government, Chinese space companies, and international aerospace business. These currently include Long March Series 2ACDEF, 3ABC, 4ABC, and 5.
Magnetorquer	A magnetorquer or magnetic torquer (also known as torque rod) is a key component of a small satellite design. This device is used in a satellite system for attitude control, detumbling, and stabilization. It is designed by putting together a series of electromagnetic coils. The magnetorquer thus built creates a magnetic dipole that interfaces with the Earth's magnetic field so that the counter-force helps to maintain

	attitude control and stabilization (see Torque Rod).
MEO	This acronym stands for Medium Earth Orbit. This is typically considered to in the range of about 8000 km to 12000 km altitude and represents a location that is above the Van Allen lower belt and more or less lower that the outer Van Allen belt that carries a relatively high level of radiation.
Microsatellite (or Microsat)	A microsatellite is a small satellite with a mass between 10 kg and 100 kg according to common definition. The first artificial satellite, Sputnik 1 with 84 kg mass, was a microsatellite, and many milestones in spaceflight or first satellites of countries were achieved with microsatellites. Today the 100 kg limit is more and more raised toward 120–150 kg (into the minisatellite range) due to available payload capacities and mounting adapters but still within common microsatellite envelopes of about ¼ m^3. Sometimes a microsat is defined as only being in the 10 kg to 50 kg ranges.
Minisatellite (or Minisat)	A minisat is a small satellite of more than 100 kg mass and up to 1000 kg according to the most common definition. There is usage that defines the mass range of a minisat to be between 50 kg and 500 kg again depending on the source. Most satellites that are to be deployed within large constellations or other distributed missions for satellite telecommunications and networking, but also small- and medium-size science mission satellites and probes are in the minisat range.
Minotaur 1 and II	This is a launcher developed by Orbital ATK (now Northrop Grumman Innovation) that is being phased out of production and replaced by the Antares launcher.
Multispectral Remote Sensing	This was the type of sensing done by remote sensing satellites that took images of the Earth divided into a few spectral ranges but splitting the entire visible spectrum into perhaps five to eight spectral ranges. Today the latest technology slices the spectrum into much narrower spectral images with what is called hyper-spectral imaging. (Also see Hyper-Spectral Sensing).

Nanosatellite (or Nanosat)	A nanosatellite has a mass of between 1 kg and 10 kg according to common definition. With many nanosatellites being built according to the CubeSats specifications, this term is often (but incorrectly) used interchangeably with a multiunit CubeSat. Nevertheless there are also several other non-CubeSat type of standardized platforms for nanosatellite available on the commercial market – many ranging from less than 10 kg to often up to 25 kg or more and therefore entering the range of small micro-satellites. CubeSat-based designs are commonly launched using a deployer mechanism, but a range of new options are now becoming available.
Navstar	This is the actual name of the satellites in the GPS System. NAVSTAR stands for NAVigation Satellite Timing and Ranging satellites.
NDGPS	The Nationwide Differential GPS System.
New Line-1	LinkSpace Aerospace Technology Group which is a private Chinese company (which is Xin Gan Xian-1 in Chinese) is seeking to develop a launcher named New Line-1 that is capable of launching a 200 kg payload to Sun-synchronous orbit. The ambitious target is to make the New Line-1 launch available for a $2.5 million launch cost and also to achieve a reusable first stage.
New Shepard and New Glenn Launch Vehicles	These are new launch systems being developed by Blue Origin. These systems are developing reusable launch systems.
Northrop Grumman	This is a large aerospace company that has acquired the Orbital Science and ATK that is now known as Northrop Grumman Innovation. Thus Northrop is now the supplier of all the Pegasus, Taurus, and Antares.
Office of Outer Space Affairs (OOSA)	This is the Office of the United Nations that has its offices in Vienna, Austria, and carries out a number of functions to support the functions of COPUOS and its subcommittees and working groups but also additional functions such as maintaining the registry of all satellites and missions launched into space on behalf of the UN Secretary General, the SPIDER emergency

	communications relief program, and various workshops, meetings, and centers around the world.
One Vision launcher	This is a project of the Gilmour Space Technologies Company and is based on a scaled-up version of the Ariel sounding rocket and will use a hybrid rocket engine. Tests are planned for a prototype in 2020.
OneWeb	This is a proposed “swarm constellation” or mega LEO network that would provide global Internet access using initially about 600 small satellites (150 kg class) in low Earth orbit including spares. This will be expanded further in time. These satellites turn to the side on their axis as they approach the equatorial orbital arc to avoid interference with satellites in GEO orbit and then return to pointing to Earth as they pass the equatorial zone.
OOSA	Office of Outer Space Affairs of the United Nations that is headquartered in Vienna, Austria
Optistar	Optistar is a constellation of 16 satellites. This Canadian-owned network is being developed by Urthecast, and the launch date has not been firmly established. The constellation design is for 16 satellites in polar orbit, with 8 tandem pairs in 2 orbital planes, and with 1 m resolution in X-band and 5 meter resolution in L-band. The objective is to provide nearly simultaneous imaging from the paired systems in optical bands as well as synthetic aperture radar imaging. Optistar has indicated that it will also provide geospatial analytics. Satellite manufacturing contracts have been announced, and they are to be built by Surrey Space Technology Ltd.
Orbcomm	This is a small sat store and data relay constellation that connects to small receivers to provide machine to machine (M2M), Automatic Identification Services (AIS), as well as Internet of Things (IoT) services globally. The constellation, in its second generation, when full, will consist of 46 satellites in 720 km altitude LEO orbits.
OS-1 to OS-4	These are rocket systems developed by One Space Technology (it is also known as Zero

	One Space). This is a private Chinese commercial company that has developed the OS-M1 to OS-M4 launcher family. The most capable of these launchers is the OS-M4. It is designed to be capable of lifting 552 kg to LEO and 307 kg to Sun-synchronous orbit and at an altitude of up to 800 km. This company is seeking to develop reusable rockets.
OTT	This stands for over-the-top. This relates to data streaming of video services that are provided via broadband Internet services to set top boxes. This is competitive with satellite subscription television and paid cable television subscription services. This type of service will have a major impact on direct broadcast satellite paid subscription services and the type of traffic LEO satellite constellations carry versus traffic carried on GEO high-throughput satellites.
Outer Space Treaty	This is the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies that entered into force in October 1967. There are four subsidiary international agreements that followed on to this cornerstone treaty governing the use of outer space. See: http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html
PANS	Procedures for Air Navigation Services (PANS). This is a term of art used by the International Civil Aviation Organization (ICAO).
Pegasus Launch Vehicle	This is a smaller launch vehicle originally developed by Orbital Sciences (now Northrop Grumman Innovation). This small rocket was flown to a high altitude and then launched from an especially equipped carrier aircraft. This launcher was used for the launch of the first of the Orbcomm constellation satellites. It is being phased out of production because of its relative high cost for small satellite launches.
Pico Satellite (or Picosat)	A very miniaturized small satellite with a mass between 0.1 and 1 kg according to the most common definition. It can often be a 1U CubeSat when applying the CubeSat Design

	Specifications as a standard. This quite small satellite is most typically used for simple experimentation or component testing and verification in the space environment.
Piggyback	This is a term where a smaller payload is included as a supplementary mission on a launcher where additional mass is available for launch.
Planet LLC	This is a start-up company that combines into a constellation of remote sensing satellites, small 3-Unit CubeSats known as Doves, the higher resolution satellites once known as Skybox and Terra Bella, plus other satellites. It has revolutionized the economics of remote sensing operations and created a new business model in terms of what types of information that it sells to a global network of users. Planet LLC, which acquired Terra Bella from Google, has an ongoing relationship with Google to whom it provides information for Google Maps.
PNT	This acronym stands for precise navigation and timing satellite services.
PocketQube Satellite	A PocketQube is a relatively new type of a very miniaturized small satellite – based on a standard proposed by B. Twiggs in 2009. It represents a follow-up concept to the CubeSat standard. It’s size is 5 cm × 5 cm × 5 cm. (Thus is exactly one-eighth the size of a CubeSat) and also represents a mass of up to 250 g. Due to its very small size, it is typically used for space research or commercial-off-the-shelf component validation and verification in the space environment – especially in the area of electronics or software testing.
Proton	This is the Russian launcher that is manufactured by Khrunichev Manufacturing and represents one of the most utilized launchers of the space age. This is being phased out of production and is to be replaced by the new Angara launcher system that is currently underdevelopment.
Protozone/Protospace	This is the area below sustained orbital space and above commercial air space. This is an altitude below 160 km and above 20 km. Activities that might be carried out in this region might include

	high-altitude platform systems (HAPS), Dark Sky Stations, robotic aircraft, the stratosphere arc of a hypersonic transport vehicle, stratospheric ascent dirigibles or balloons, or military craft for surveillance or other missions.
PSLV	Polar Satellite Launch Vehicle is a launcher developed by the Indian Space Research Organization which has an excellent launch record. Currently it has the record for the most CubeSat launches by launching 104 CubeSats in a single launch in December 2017.
Reaction Wheel Module	This is also known as inertial wheel or momentum wheel, and it is used to maintain a satellite in a three-axis stabilized orientation.
Rocket Labs	This is a start-up launcher company designed to launch small satellites. It is a joint New Zealand and US venture with its launch site in New Zealand. Its electron rockets use unique new materials to reduce the mass of its launch vehicles and additive manufacturing to increase the reliability of its rockets and to reduce manufacturing costs.
Rocket-1	This new small satellite launcher known as Rocket-1 is currently underdevelopment by Launcher, Inc. Unlike most start-ups, this US-based company has a decade-long development schedule. The first step, currently in development, is to have a reliable 3D printed rocket engine. This will be followed by additional development steps that are intended to result in a very low cost and reliable smallsat launcher by 2025.
Rockoons	LEO Aerospace LLC which is associated with Purdue University is seeking to develop what they call Rockoons. The first step in their launch system will be a high-altitude balloons that are designed to ascend to 18 km. Then a rocket will be release to launch small payloads into LEO orbit. There pro then sent to orbit by a rocket. There currently estimate cost would $60,000 per kg or the equivalent of one CubeSat unit.
Rockot	This is the rocket launcher that is marketed by Eurockot which is a joint French-Russian company.

RS-1 launcher	The RS-1 launcher is being developed by ABL Space Systems, a US-based company. It is designed to be a low cost and easily mobile system for the launch of small satellites. The RS-1 could be launched from any approved and licensed location, which is designed to be launched from a truck-mounted launch system or essentially from any FAA licensed launch site.
SARPS	Standards and Recommended Practices (SARPS). This is the mechanism used by the International Civil Aviation Organization (ICAO) to coordinate international safety standards for airlines and aircraft flying in international airspace.
Shavit	This is an Israeli launcher that has been developed by the Israel Aerospace Industries. Shavit means Comet in Israeli. This rocket is launched to the east rather than to the west because of strategic constraints local to the Middle East geopolitical environments.
Sierra Nevada	This is an aerospace company that has among other projects developed the Dream Chaser space plane system. It also can design and fabricate small satellites.
Small Satellite (or Smallsat)	A miniature satellite of less than 500–1000 kg mass (depending on the definition used). This term is actually quite broad in its meaning and application. Thus the term smallsat is now divided into several subcategories. Thus, in descending order, there minisats, microsats, nanosats, picosats, and femto satellite. (See above descriptions.) Small satellites are often launched as secondary or piggyback payloads taking advantage of remaining available payload mass of the launch vehicle. Common goals of small satellite missions are reduction of spacecraft cost, project schedule, or enabling distributed mission concepts such as to deploy satellites in a constellation. Other phrasings that represent much less common terms are “compact satellites,” “light satellites,” or “lean satellites.”
SOLAS	International Convention for the Safety of Life at Sea (SOLAS).

Soyuz	This is a Russian launcher that is currently internationally marketed by Arianespace and is launched from the Ariane launch site in French Guyana.
Space Data Association	This is an organization founded by Intelsat, Inmarsat, and SES to share information about possible conjunction of satellites in orbit or other threats of orbital collisions. It has grown to now include many dozens of space system operators who actively share information to avoid collisions. Also arrangements have been made to obtain critical information from defense agencies who are carrying out defense monitoring and space object tracking. There have been new space policies directed by the US government to seek to develop separate but parallel tracking capabilities for defense space situational awareness and commercial space situational awareness capabilities as set forth in the US Space Directive 3.
Space Rider	The European Space Agency (ESA) (Space Rider project stands for Space Reusable Integrated Demonstrator for Europe Return). It is a joint project of the Italian Aerospace Research Center (CIRA) and Thales Alenia. This is a small reusable space lifting body that is compatible with Vega C launcher.
SpaceX	This company is primarily owned by Elon Musk. It has developed the Falcon series of satellites from the Falcon 1 to the Falcon 9, to the Falcon 9 Heavy and the Big Falcon Rocket. These series of rockets, including the latest capabilities to now reuse the early stages of the rockets, have been instrumental in lowering the cost of launches and have contributed to new economics for small satellite launches. It is intended by SpaceX to launch two very large small satellite constellations known as Starlink. One constellation with over 4500 smallsats and another with over 7500 satellites or a total of over 12,000 satellites.
Spectrum	This is the measure of bandwidth that is used for various satellite applications. The radio-wave spectrum allocated for commercial satellite communications, for instance, is typically either

	500 MHz or 1000 MHz across. One practical problem is that the ITU that is responsible for allocation of radio spectrum for practical or scientific use has divided the world into three regions and the allocations can be and indeed are different for different regions of the world.
Spire	The Spire's constellation is currently a LEO constellation of 80 satellites that is being expanded in its service offering so as to collect AIS, meteorological data, and locational data in cooperation with the European Galileo System.
SSA	Space Situational Awareness. This is a term of art that relates to the tracking of all objects in Earth orbit or a suborbital flight. These activities are carried out in order to track operational satellites and all space objects such as space debris and defunct satellites. Also for security and strategic reasons, space situational awareness is performed to detect possible missile launches that could represent an attack by an armed rocket. Initially these operations were carried out by defense agencies, but more recently there have been a number of private companies and agencies that have developed the capability to monitor and track objects in Earth orbit. An organization known as the Space Data Association (SDA) has been formed to share data on space objects in Earth orbit with a view to avoid collisions of satellites or satellites with space objects that could disable or destroy operational satellites.
SSTL	Surrey Space Technology Limited. This is one of the leading leaders in the design, development, and fabrication of small satellites. This entity which spun off from the University of Surrey is now wholly owned by Airbus.
Starlink	This is the name that Elon Musk has given to his two constellations of small satellites operating in the Ku, Ka, and V band that are planned for launch in the next few years. See SpaceX.
STC	Space Traffic Control. (See Space Traffic Management.)
STM	Space Traffic Management. This concept has many different definitions and possible

	interpretations since it is concept about creating a system for implementing space safety and a future means to avoid collisions of space objects. The International Academy of Astronautics in its study of this subject has posed the following possible definition. “Space Traffic Management is a set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space, and return from outer space to Earth free from physical or radio-frequency interference.”
Satellogic NuSat Aleph-1 Constellation	This is an Argentine constellation for remote sensing. It is ultimately planned to have 300 small satellites in this constellation.
TDMA	Time-Division Multiple Access. This multiplexing system along with CDMA is the most common method of digital communications used on modern telecommunications satellite systems as well as ground-based cellular communications systems. CMDA is used on the Globalstar Mobile Satellite System, and TDMA is used on the Iridium Mobile Satellite System. These types of digitally based multiplexing systems are key to use when satellites are creating a large number of spot beams that involve geographic isolation of frequencies so that spectrum can be reused multiple times.
Telesat Constellation	This is a Canadian network of 117 satellites that will eventually seek to deploy 794 small satellites at a variety of altitudes ranging from 1000 to 1248 km that will operate in the Ka-band and provide networking services on a global basis. This is one of several systems where a satellite operator intends to operate both LEO and GEO satellite networks to service a range of telecommunications and networking markets.
Theia	This is a newly organized company that was organized in 2016. It is planning the deployment of satellites in LEO orbit that will work in tandem with a MEO constellation to distribute remote sensing and strategic business information on a global basis.
Torque Rod	A torque rod, also known as a magnetorquer, consists of a series of electromagnetic coils.

	This thus is able to create a magnetic dipole that interfaces with the Earth's magnetic field. This allows a counter-force to be created to help to maintain attitude control and stabilization. It thus allows a small satellite to avoid tumbling.
21 AT	A Chinese private remote sensing company that currently operates a three satellite constellations. System was designed and manufactured by SSTL and Urthecast.
Unha-3 Launcher	This is under development by the North Korean National Aerospace Development Administration (NADA) (Kwangmyongsong). There launcher is known as the Unha-3 Missile Systems. There is limited knowledge of the launcher system.
Urthecast	This is a Vancouver, Canada-based Earth observation and data analytics company.
VLM-1 Launch Vehicle	Brazilian Departamento de Ciencia e Tecnologia Aeroespacial (CTA) is developing the VLM-1 (Vehicle for the Launch of Microsats). The VLM-1 is planned to have the capability to lift a 150 kg small satellite to LEO. CTA is also the manufacturer
Tronador II	Liquid-fueled rocket that is being designed to lift 250 kg payload to polar orbit. It will launch from Puerto Belgrano Naval Base in Argentina.
United Nations and UN Space-Related Specialized Agencies	This is the public international organization formed to address all matters related to international cooperation and peacekeeping. All so-called specialized international organizations related to various functions come under the UN structure. Entities in the UN structure that have a particular relationship to space include the International Telecommunication Organization (ITU), the International Civil Aviation Organization (ICAO), the United Nations Office on Disarmament Affairs (UNODA), and the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS).
United Nations Sustainable Development Goals	These are the 17 Sustainable Development Goals set by the UN General Assembly with quantitative objectives set for 2030. These replaced the Millennium Development Goals set for 2015.

Vector	A US-based low-cost launcher developed to launch small satellites. It currently offers a Vector A and Vector B launcher option.
Vector launcher	The Vector-R provides a 60 kg payload capability that can be configured for a wide range of CubeSat and small satellite mission profiles. The US developed Vector-R fairing is a traditional two-piece design that is of sufficient size to accommodate a wide range of deployment options for multiple smallsats.
VEGA and VEGA C	These are new and more cost-efficient launchers that have been developed by European Launcher Development (ELD)-Fiat-Veio to respond to the need to launch smaller satellites for large-scale constellations. The Vega and Vega C will be launched from the Arianespace launch facility in French Guiana. It can be configured to launch five 200 kg small satellites into orbit.
Venture Class Contract	This is a low level of easy to execute contract that can be used by NASA to encourage new start-up ventures that are seeking to create new launch capabilities or to build low-cost new small satellites.
Vulcan-Centaur Launcher	This is a new launcher system that is being developed and will be marketed by the United Launch Alliance. This will replace the Delta 4 launcher which has become expensive relative to other launchers that have achieved significant new economies in the past decade.
Zenit	This is a Ukrainian/Russian launcher that is being phased out of production.
Zhuque-1	This small satellite launcher is being developed by the Chinese private aerospace company known as Landspace. The Zhuque-1 is being designed to be capable of lifting 300 kg to LEO orbit or 200 kg to Sun-synchronous orbit (SSO). The initial test launch in 2019 failed to achieve orbit.