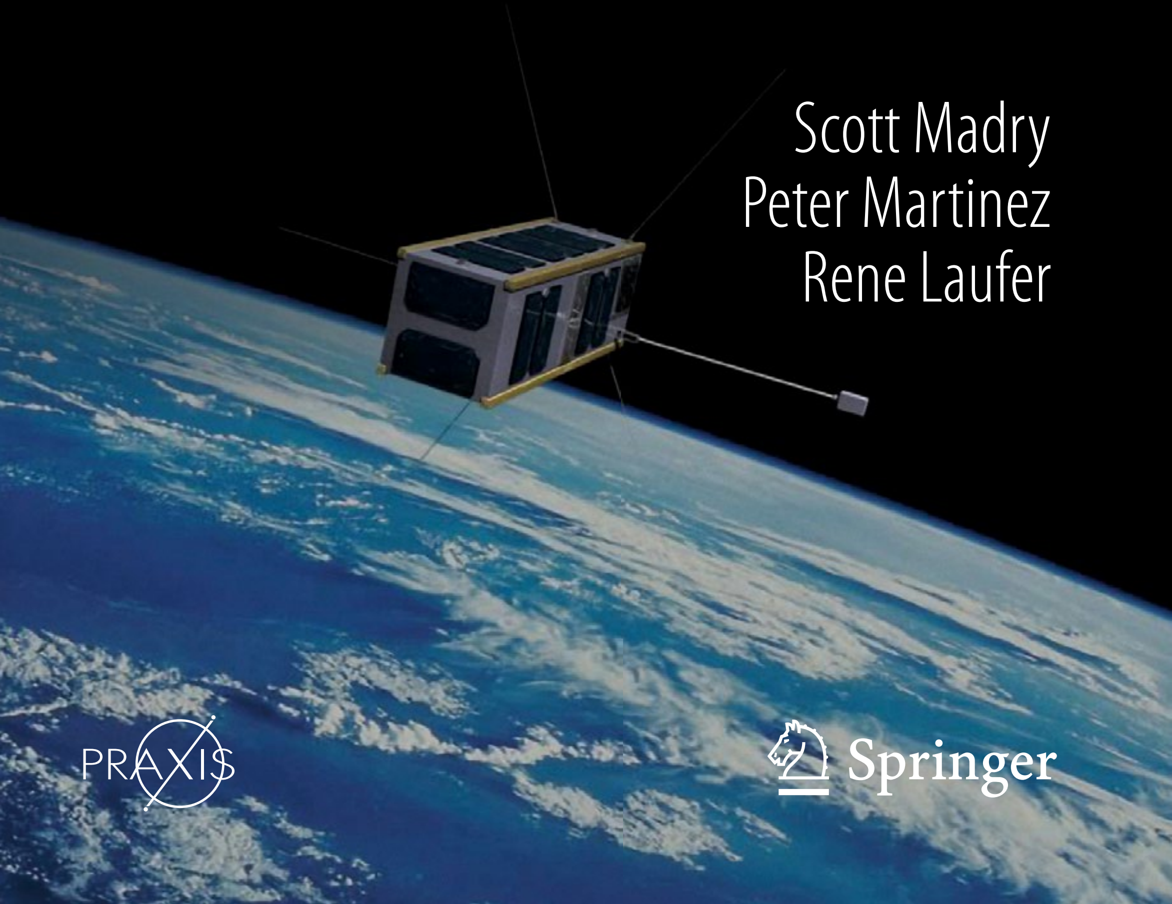
NEW SPACE VENTURES

Innovative Design, Manufacturing and Testing of Small Satellites

Scott Madry
Peter Martinez
Rene Laufer



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Preface

Although space is big (really big), the space community here on Earth is really very small. The authors of this book, who are from South Africa, Germany and the United States, are very pleased to be a part of that small community. It is one of our particular pleasures to have gotten to know and to work with so many colleagues from around the world. It is truly satisfying to have been able to teach so many eager, young minds from every corner of our planet in locations as diverse as Adelaide, Australia; Beijing, China; Cape Town, South Africa; Strasbourg, France; Tel Aviv, Israel; Mexico City, Mexico; Barcelona, Spain; NASA Ames Research Center in Mountain, View California; Montreal, Canada; Graz, Austria; M.I.T. in Cambridge, Massachusetts, USA; and dozens of other locations around the world.

Part of the small nature of the space community is that we see each other regularly. This might be at the annual International Astronautical Congress (IAC), at the U. N. COPUOS meetings, the Manfred Lachs Space Law Conferences in Montreal, meetings of the International Association for the Advancement of Space Safety (IAASS) and at other disciplinary conferences and meetings. In the course of our regular work and travels we learn from each other and the latest trends in space and satellite technology. Meeting and establishing working relations with very interesting and skilled people from around the globe is one of the greatest benefits of working in the space sector. We three authors are no exception to this rule.

This book grew out of such working relationships, between Scott Madry, University of North Carolina; Prof. Peter Martinez of the University of Cape Town in South Africa; Dr. Rene Laufer of the University of Stuttgart in Germany and Baylor University in the United States; and our esteemed editor, Prof. Joseph Pelton of George Washington University in the United States. Drs. Pelton and Laufer and Madry have had the great pleasure of teaching in the very innovative and exciting SpaceLab graduate space program at UCT in Cape Town that was established by Peter Martinez in 2014. This program is focused on the benefits of our access to space for all peoples, with special emphasis on southern Africa.

The domain of space applications, dominated by satellites and their practical applications for telecommunications, remote sensing, and navigation, has broadened and accelerated significantly in recent years, with many diverse nations now engaging in space applications where, just a few decades ago, this was the sole domain of only a few of the major spacefaring powers. This broadening of the practical uses of space for every nation has been energized and accelerated by the miniaturization of space satellites, and the reduction in cost in launching them into orbit. Many nations now develop and operate their own satellite systems, providing important and practical benefits, no matter their level of economic development.

Getting to teach in Cape Town (one of the most dynamic and beautiful cities on the planet) has been a great pleasure. It has provided us with the opportunity to meet and work with the excellent SpaceLab students from around the greater southern Africa region, and to share experiences and ideas with many colleagues from South Africa and beyond. Spending time at another university is always a fascinating experience, filled with reminders of how similar we all are, and how important education is for our common human future. We all have different academic traditions and approaches, but we all share a common goal of excellence in teaching, research, and public service. The global nature of the space community lets us benefit from this on a regular basis.

In the course of teaching there, we conducted a program on small satellites and their growing importance in the space applications domain, particularly for the emerging space nations across the globe. Putting together a new, graduate academic offering is always a challenging and rewarding task. Most of all, it allows the academic to do what we love best – to research an emerging topic, find the threads of meaning, and tease out what is important and what is not. The final and often most important step of all is then to take this distilled knowledge and to put it into an integrated educational package for our students.

We have now collectively offered this smallsat program for two years now at the University of Cape Town. As a consequence of this now relatively mature instructional program, we came to the conclusion that this would be an important contribution for a much broader audience. Accordingly we decided to produce this book on this subject and to make it fully interdisciplinary. Thus we collaborated together during 2017 to produce a book that covers the technology and engineering, the many versatile applications, plus the new economic and business models that smallsats now help define within the so-called “NewSpace” industries. Finally we have addressed the policy and regulatory issues that smallsats gave rise to and especially considered the international regulatory issues that the new large-scale smallsat constellations have generated. We have thus sought to find new and better ways of addressing the problems of registration and notification, intersystem coordination, and especially significant new concerns related to orbital space debris.

This book is based upon our previous work and research. We particularly wanted to present this information to those who want to know more about the great potential that smallsats hold. Thus we hope those that read this book will be inspired and energized to explore even further the potential now offered by the emerging and quickly developing world of small satellites.

This new field of satellite applications is still very much wide open. There are a host of things to do in communications, networking, remote sensing, medicine, education, monitoring for fires, pollution and criminal behavior, agriculture, urban planning, mapmaking, and more. Smallsats open a new world of opportunity. We see, for instance, great potential in smallsats to assist with almost all of the U. N.’s seventeen Sustainable Development Goals for 2030. In some cases this might involve developing countries building, launching and operating smallsat systems themselves. In other cases it might involve obtaining lower cost services obtained from less expensive and responsive smallsat systems operated by others.

This book approaches the subject of smallsats from an interdisciplinary perspective, as we had all practiced, as both students and faculty, at the International Space University over many years. Crossing the traditional disciplinary boundaries is a key aspect of our work, and we have tried to view this exciting and rapidly developing small satellite domain from that more complex perspective. This book presents the emerging world of small satellites from this interwoven view. Thus in its eight chapters it tries to present the interconnected threads that cannot be properly understood from any single academic perspective. In short this is a book for engineers, scientists, space lawyers and regulators, and entrepreneurs who have begun to envision how smallsats could help launch a new service that is needed in the world today.

We have put together a work that we hope will be useful in a variety of contexts, including use in classrooms but also as a practical reference work. It is written in a straightforward narrative style. In short you do not have to be a scientist to read this book. It contains no complex formulas or scientific jargon known only to engineers. We hope it might even be enjoyed by those who opt to read it. You will be the judge of how well we have done.

In sum we do hope that you find something useful here, and that you will keep your eyes and minds on the vast space around us, but also on this very small planet that we all share. It is, like this book, in your hands.

Chapel Hill, NC, USA Scott Madry
Cape Town, South Africa Peter Martinez
Waco, TX, USA Rene Laufer
December, 2017

Acknowledgements

This book grew out of an academic course on small satellites that was presented at the Space Lab at the University of Cape Town. We would like to begin by thanking all of the staff and professionals there that have assisted us over the past two years.

We also want to thank our prolific and ever-patient editor, friend, colleague, and mentor, Prof. Joseph Pelton who was, in fact, the driving force behind this work. His broad knowledge, perspective, and drive have been instrumental in bringing this work to completion. Barbara Wolf, the associate editor for multi-volume reference works and Maury Solomon, senior editor at Springer Press, are always a pleasure to work with. We are very grateful to them for their professionalism and ability. Finally, we thank our many colleagues in the space community that helped us in this endeavor and especially thank our many former and current students at the University of Cape Town and at the International Space University around the world, whose curiosity, imagination, and fascination with all things space have pushed us to produce a work that will be both useful and interesting.

Contents

About the Authors

Scott Madry is the Executive Director of the Global Space Institute as well as research associate professor of archaeology at the University of North Carolina at Chapel Hill, and also serves as the President of Informatics International, Inc. Dr. Madry lectures all over the world on the use of space technology for remote sensing and Earth Observation including its many use for emergency recovery and relief. His books include: Space Systems for Disaster Warning, Response and Recovery; Global Navigation Satellite Systems and Their Applications; and the Handbook for Satellite Applications (1st and 2nd editions).

Peter Martinez is Professor of Space Studies and Head of the SpaceLab at the University of Cape Town, South Africa. From 2010 to 2015 he was the Chairman of the South African Council for Space Affairs. He has been a regular member of the South African delegation to UN COPUOS since 1999 and is the Chair of UN COPUOS' Working Group on the Long-term Sustainability of Outer Space Activities.

Rene Laufer is associate research professor of space sciences at Baylor University, Texas, as well as honorary faculty at the University of Cape Town's Space Lab and co-chairs the International Academy of Astronautics' small satellite committee. He has formerly worked at German Aerospace Center (DLR) and the University of Stuttgart, Germany, in the fields of planetary exploration and small satellites and has taught on various space engineering topics on four continents.

1 Introduction to the World of Small Satellites

Why this book?

Welcome to the strange, rapidly evolving, and highly innovative world of small satellites. Throughout this book we will either spell out this phrase in full or sometimes refer to the objects as "smallsats." Other phrases we will use include "cubesats," "nanosats," "picosats," and even "femtosats." The meaning of these descriptions that refer to different sizes of smallsats will be provided later.

We should start with a brief explanation as to why this book is needed and how it is unique. There are already several books on small satellites that cover various targeted areas such as pertinent regulations and laws as well as business issues and applications. There are yet others that address technological innovations. Then there at least some articles that address policy concerns, such as the spread of orbital debris occasioned by the proliferation of small satellites while other articles have addressed the ability of small satellites to support developing economies in the attainment of the U. N. Sustainability Development Goals for 2030. There are also some materials that provide updates about innovations to support small satellite launches. This book seeks to cover all the bases on an interdisciplinary basis and with a world view. In short this book is meant to explore all the pertinent facts about all aspects of the current and vibrant small satellite revolution that is sweeping the world of space. It seeks to provide a holistic view of small satellites and the opportunities and issues they offer to the world at large at this time.

This book is particularly designed to accomplish a number of important and specific objectives. The aims of this book thus include seeking:

- to explain the wide range of sizes, shapes, mass, applications and capabilities that modern small satellites now represent;
- to outline the evolution over time of small satellites and which entities developed them. This particularly will note the technical innovations

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1_1

and business motivations that have spurred these developments – especially with regard to the swift rise of the "NewSpace" industries that are prompting new satellite and launcher developments;

- to detail how small satellites are making significant impacts on the remote sensing and now even the telecommunications satellite industries;
- to review the development of key new technologies that allow the ever more diverse design of small satellites. These new capabilities include new miniaturized components and the ability to create new components with 3-D printers, satellite designs with less components and ultra-compact sensors, new Earth systems that allow electronic tracking of fast-moving low Earth orbit satellites, and new low cost launchers; and
- to explore to how small satellites pose both new problems and new opportunities. Problems include such aspects as orbital debris, LEO orbit congestion, and potential electromagnetic interference between small satellites in LEO and GEO. On the opportunity side small satellites can allow many more countries to become spacefaring nations and with the right deployment of small satellites they could contribute mightily to the achievement of ambitious 2030 U. N. Sustainability Development Goals.

What Is a "Small Sat"?

It may be surprising to read a book about "smallsats" and to start by learning that there is really no such thing – at least in a precise technical sense. We must start with the difficult assignment of trying to explain exactly what is a "smallsat," and more easily what it isn't. The term "smallsat" actually covers a very wide range of spacecraft that can be as small as a so-called femtosatellite that can have a mass as miniscule as 10 to 100 grams. Yet one can also use the term "smallsat" to refer to a satellite that has a mass of up to 500 kg or more. In between there are "cubesats" that often range between1 unit to 6 units in size. Such cubesats can have a mass as small as about 1 kg or have a mass exceeding 10 kg for a 6-unit cubesat. Further a small satellite might be a one-of-kind student project, or very targeted and a specific scientific mission, or it could be just one out of a thousand small satellites designed for a massive low Earth orbit constellation. These so-called small satellites might be mass produced with components spewed out by 3-D printers, or painstakingly crafted by students working to create their own in-orbit satellite. The difference between the tiniest smallsat and a substantial smallsat can be more than three orders of magnitude. This is akin to saying that a mouse and an elephant are sort of the same thing because they are both mammals.

The one thing we do know is that currently there are plans to launch a lot more "smallsats" than conventional larger spacecraft. This plethora of small satellites being placed into orbit – especially low Earth orbit – is leading to concerns about orbital congestion, orbital debris, and the possibility that the predicted problem known as the Kessler syndrome could now be happening. A short description of this syndrome is the problem of a runaway cascade of ever increasing orbital debris that could deny humans access to space for a very long time. It is ironic that small satellites seem to offer opportunity for human advancement on one hand and yet also significant concern – all at the same time. Some view what is happening in space with runaway growth of small satellites as analogous to human population growth and industrialization here on our planet's surface. Just as human activities are now driving climate change and environmental concerns on Earth, it seems that we are now experiencing environmental concerns with regard to human overuse of outer space – or at least in Earth orbit [1].

Smallsats come in a quite large variety of shapes, sizes and mass and for many different uses. The one key shared characteristic is that they are typically all the result of what might be called the pursuit of value engineering – or more simply, lower cost fabrication and launch. The common trait of a smallsat spacecraft seems to be that their designers are exploring innovative ways to reduce the cost of building, launching, and operating these spacecraft through clever engineering and creating entirely new rules about how to design and build spacecraft. The so-called rise of NewSpace commercial activities is a key of this small satellite revolution. The information contained in Chart 1.1 seeks to sort out some of the confusion and help to clarify what is meant by the clearly ambiguous term "small satellite" or "smallsat." This charts shows that smallsats indeed serve a wide diversity of purposes with different types of craft [2].

Thus there is no precise or definitive explanation as to what is a smallsat or other terms such as nano satellite. Innovative designers have come up with satellite designs that are not much larger than a ping pong ball and weigh about the same. The femtosat, as designed by the Aerospace Corporation, with deployable solar cells and a communications antenna and electronics, actually weighs less than 100 grams. Perhaps nine of them could be fitted into the volume of a Rubik's cube (See Fig. 1.1) [3].

Although an Iridium, a Globalstar or an Orbcom satellite, (see Fig. 1.2) deployed in a low Earth orbit constellation to support mobile communications or business to business (B2B) data relay, is on the order of 10,000 times larger in mass and volume than a femtosat, these are still considered small satellites. These satellites were designed for mass production at lower cost. Thus Iridium, Globalstar and Orbcomm satellites are still legitimately considered small satellites. Indeed these LEO satellites are still far smaller than truly gigantic commercial communications satellites such as those deployed by Intelsat, Inmarsat, ViaSat, Hughes Network Systems, Terrestar, etc., into geosynchronous orbit. These "monster" satellites, with large and sometimes deployable antennas, plus large extendable solar power arrays with up to 18 kilowatts of power, have launch masses in the 7 to 10 m ton range. Small and large are clearly relative terms.

There are other factors that are often common to so-called small sats. There is frequently a close relationship between companies involved in their design and construction and the NewSpace commercial industries that are fueling the revolution that is sweeping through the space industry. For the most part small satellites are typically deployed in low Earth orbit, may incorporate off-the-shelf components, use accelerated or abbreviated testing systems, may involve new design

Chart 1.1 The many applications, sizes, and characteristics of smallsats

Function/Size	Telecommunication Constellation	Messaging/ Data Relay	Amateur Radio	Remote Sensing Constellation	Relay from Ground Systems	Meteorological	Scientific Experiment	Student Experiment
Small mission 100 to 500 kg	Typical (See for example OneWeb)	Typical (See for example Orbcomm)	______	Typical for some commercial constellations	Typical (See for example Orbcomm)	Typical for LEO & larger	Typical	Rare
Microsat 20 to 99 kg	Occasional	Typical	Typical	Occasional	Often	______	Often	Often
1U-6U CubeSat 1 to 25 kg	______	Rare	Occasional	Now much more common i.e. Planet and Terra Bella	Occasional	______	Rare	Typical
Nano, Pico or Femto Sat* (10 grams to 1 kg)	______	______	______	______	______	Occasional	______	Typical

*Definitions can vary, but a nanosat will typically be in the 1 kg to 10 kg range (also this can be a cubesat). A picosat is in the 100-gram to 1-kg range and a femtosat is in the 10-gram to 100-gram range.

Source: Adapted from Table 1.1 in Ram S Jakhu & Joseph N Pelton, *Small Satellites and Their Regulation* (New York: Springer, 2014). (Permission granted by the publisher.)

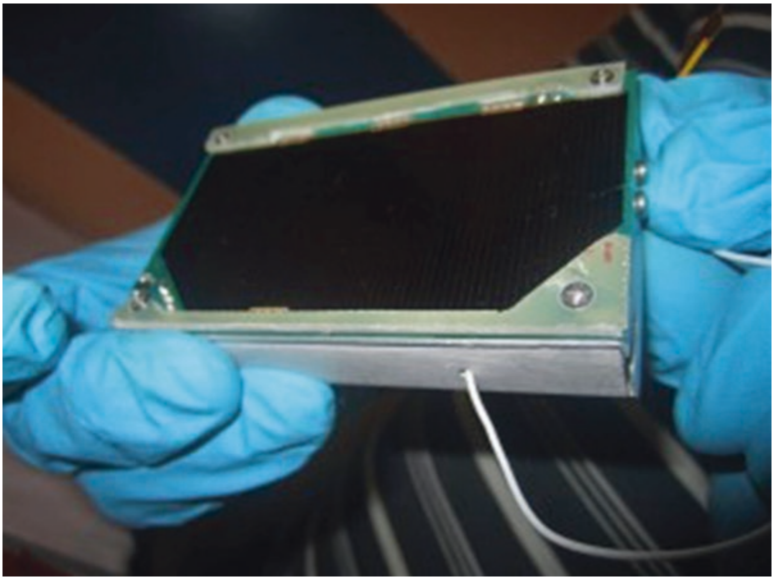

Fig. 1.1 Femtosatellite Pocket-PUCP – Credit Pontificia Universidad Católica del Perú

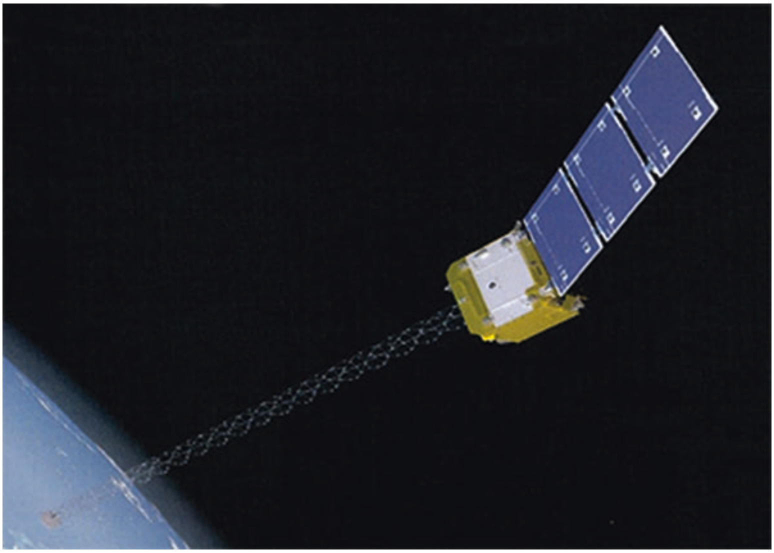

Fig. 1.2 Second generation OrbComm (OG2) satellite at 172 kg is still considered a smallsat. (Graphic courtesy of Orbcomm)

concepts to reduce the number of components in their satellites, and otherwise seek innovative ways to use technology to reduce costs, improve production quality, or enhance realized value or reliability. Small satellite constellations in low Earth orbit are frequently conceived of as a possible means to find either a lower cost alternative to a geosynchronous (GEO) satellite network, or as a way to design a network that involves lower latency, i.e., less transmission delay than a GEO. Frequently the objective can be to accomplish both.

A final unwelcome aspect of the small sat revolution is that there is also often a lack of means for active deorbit at end of life. This problem of de-orbit can contribute to the very serious and growing problem of orbital space debris. The critical issue here seems to be in developing successful means to deorbit smallsats, especially those in large constellations, with a very high degree of reliability, at the end of life [4].

This issue is discussed later in the book, but even a small satellite traveling at a sufficiently high relative speed can crash into another satellite and create thousands of new space debris elements. At one time orbital space debris did not seem like a problem, but now there are perhaps 7,000 kg of space debris heavily concentrated in low Earth orbit and especially polar orbit; this a very serious concern. On February 15, 2017, India launched a vehicle that successfully placed 104 satellites in orbit with one launch. Some satellite operators are now planning smallsat constellations with a thousand or more satellites in a single network. The rise of smallsats thus gives serious new concerns about the creation of potentially deadly torrents of new orbital space debris. This subject is more fully addressed in Chapter 6 of this book [5].

Structure of This Book

Beyond explaining the diversity of types of smallsats as covered in this chapter, this book has a number of additional objectives. The structure of the book is thus as follows:

Chapter 2 provides explanations of the technical aspects involved with the planning, design, manufacture, and deployment of smallsats into orbit. It explains the challenges of creating small satellite networks that are highly cost effective, reasonably reliable, and launched at minimal expense in an efficient manner.

Chapter 3 examines how new small satellite constellations have created new ways to collect and use remote sensing data using totally new approaches that are much more cost effective and have also allowed new applications. Although there remain quite a number of very sophisticated and still quite large and powerful meteorological satellites, surveillance satellites and remote sensing satellites that are carrying out functions that require a diversity of sensing devices, the reduced size of some sensors and the desire to have rapid updates of some data has given rise to small satellite constellations that can produce valuable and timely data for new applications. New companies such as Planet Labs (now officially "Planet") and its recent acquisition of Google Skybox/Terra Bella, have found this "sweet spot" for very small-sized smallsats that operate within global constellations. Not all types of application satellites can yet be shrunk down to become smallsats. Although some radar satellites have become much smaller, many traditional radar satellites still require large aperture size and great power. Also satellites that engage in hyper-spectral sensing, and meteorological satellites that monitor solar storms, lighting strikes, and other phenomena, still remain large and conventional in design.

Chapter 4 examines the more complicated case presented by smallsat constellations when used for satellite communications and why the focus on systems now evolving is on data networking – particularly when transmission delays are key to service offerings.

Chapter 5 explores the many ways that small satellites and innovative spacecraft systems can assist the "Global South." In particular this chapter examines the opportunity of developing countries to use low-cost space systems to address the U. N. Sustainable Development Goals (SDG) for 2025 [6].

Chapter 6 shifts to future prospects and policy and regulatory concerns. It addresses policy concerns at the national, regional, and international level. This includes such items as full compliance with the registration convention for all small satellite launches, the role of small satellites in increasing the build-up of orbital debris, and the current voluntary guidelines to reduce orbital debris. It also addresses the Liability Convention and its impact on those that are now considering the active removal from orbit of orbital debris.

As the Working Group on the Long Term Sustainability of Outer Space Activities considers how to move forward to make space safer the plans for various organizations to launch thousands of small satellites into orbit remains one of the key concerns. As plans are developed for the future launch and deployment of small satellites there are a variety of concepts under discussion, such as deploying small satellites in orbits that easily decay, the use of active or passive deorbit systems to clean up low Earth orbit, and development of new technologies that can somehow help address this issue.

Chapter 7 builds on the previous chapter to explain how in the area of smallsats there might be improved global space governance over time. It discusses the possibility of new space-related standards as well as new rules of the road, proposed codes of conduct, and so-called soft law provisions such as transparency and confidence-building measures (TCBM). This discussion and analysis is provided in the context of issues related to smallsats, but indicates when these problems and issues are interconnected with broader concerns that involve the Outer Space Treaty, the Registration Convention, the Liability Convention, and other subjects related to the longer-term sustainability of outer space activities.

Chapter 8 is the concluding chapter. It seeks to summarize key points covered in the book and provide a top ten listing of things to know about small satellites. It attempts to capture a global perspective from around the world that emphasizes the many positive features of small satellite systems and their potential for cost savings and broader participation in space activities. Smallsats thus now provide support to countries with developing economies, the so-called Global South, to enter into the space age and join the ranks of the spacefaring nations. Finally this chapter also considers future trends and opportunities and explores how small satellites can contribute to a better future.

Appendix 1 provides a glossary of terms and an explanation of key terms related to remote systems, telecommunications, space applications, design and manufacture of small satellites, and policy and regulatory issues and concerns. Appendix 2 provides the Space Debris Mitigation Guidelines of the U. N.

Committee on the Peaceful Uses of Outer Space. Appendix 3 provides the Convention on Registration of Objects Launched into Outer Space. Appendix 4 provides the Convention on International Liability for damage caused by space objects, and Appendix 5 provides the more detailed and technical Space Debris Mitigation Guidelines of the InterAgency space Debris Committee (IADC). These documents in Appendix 2, 3, 4, and 5 are useful background with regard to Chapters 6 and 7 and to the understanding of some of the analysis provided in these chapters.

The Evolutionary Process That Led to the Small Sat Revolution

Sputnik 1, the first artificial satellite, was actually the first microsat, with an 84 kg mass. Oscar 1 was designed and built by volunteers from the Amateur Satellite organization as well as the University of Surrey Space Centre UoSats, were in no way initially seen as being in competition with commercial satellite projects, built by large aerospace corporations and designed by space agency scientists. The key innovation was in thinking about ways to do things more simply, more rapidly, at lower cost, using available components from computers or telecom units. The world of commercial communications satellites, remote sensing, and meteorological satellites continued on the trajectory sometimes called technology inversion. This meant putting more technology, power, and complexity up in space on complicated satellites so that the devices on the ground could be smaller, simpler, and cheaper.

But then the world of NewSpace suddenly intervened as the new millennium began. People such as Elon Musk started SpaceX, and Paul Allen and Burt Rutan developed the SpaceShipOne (see Fig. 1.3) and the WhiteKnight carrier aircraft, which won the XPrize. Peter Diamandis and the Ansari family had created the Ansari XPrize that encouraged totally new commercial space ventures. Suddenly it seemed that everyone was trying to find low-cost ways to fly to space and do so safely. This opened up the world of NewSpace that began throwing out the rules of the past and started seeking new types of solutions not only for low-cost launches but low-cost spacecraft as well [7].

Suddenly the world of space changed. A group of young engineers and students developed a remote sensing concept called Planet Labs (now simply Planet). Their 3-unit cubesats called “Doves” were able to provide reasonably high resolution coverage of the entire world with quick updates that could show changes such as vehicles parked in shopping center lots or increases in flows of water in flooded streams or rivers. Four young graduate students from Stanford developed a low-cost remote sensing satellite network called Skybox using off-the-shelf components that was purchased by Google and is also now a part of Planet. Other innovative systems have been developed as well.

With the success of these small satellite constellations for remote sensing, innovative designers of communications satellite systems, especially for Internet networking, began to see potential for constellations of satellites for communications development – especially in underserved portions of the world. This history and how small satellites could be designed and fabricated in new ways to accomplish new types of services are covered more fully in Chapters 3 and 4.

Fig. 1.3 The SpaceShipOne, winner of the Ansari XPrize competition that fueled a NewSpace commercial revolution. (Image courtesy of Scaled Composites)

As the NewSpace revolution continues to unfold, and new ways of looking at commercial space systems develop, one may see yet other space applications in coming years. In short the dynamic history of small satellites and how they are designed, built, and launched is still unfolding. In the early days of space the creation and building of launch vehicles and of spacecraft was consigned to large space agencies and giant aerospace corporations. Today these rules no longer stand. Just as Silicon Valley transformed the world of computers and networking, the world of small satellites is changing how we think about space.

The Challenges of the Future

The challenges for the future in the world of small satellites are almost equally divided by new opportunities and new ventures by startup commercial ventures on one hand and new problems and issues on the other.

The challenges of the U. N. Sustainability Development Goals are in some ways also challenges to find out how the world of space can help us find better ways to overcome pollution and environmental dangers, better ways to use space systems for health and educational services, better ways to undertake urban planning and new types of economic growth, and even better ways to do everything from farming and fishing to handing out fairer legal decisions and administering policing and justice systems around the world.

As mentioned earlier, though, increasing use of space systems to solve problems here on Earth can give rise to new problems in space such as the buildup of orbital space debris, orbital congestion in LEO, MEO and GEO, and increasing levels of electromagnetic interference between and among space-based networks.

Just as new technologies have led to better spacecraft and new launcher systems, it may be that we need new business, financial, legal, and regulatory systems to make improved use of these new space systems and technologies. The Kessler syndrome stands a serious threat to the future of human access to space. It is not clear to most people that we now depend on space systems for monitoring weather and severe storms and even major cosmic storms from the Sun. We likewise depend on navigation satellites for safely guiding our planes to takeoff, land, and fly across the planet. We use satellites for news, communications, broadcasting, and more. Over 20,000 television channels across the world could go dark if we lost all of our communications satellites. Military defense, police enforcement, fishing, mining, farming, pollution monitoring, and international business communications also depend heavily on our satellites in the skies. If there were a day without satellites we would realize just how dependent modern society has become.

Purpose of This Book

This book seeks to explore all the many opportunities that small satellites can unlock and their potential for space research and applications. It examines the key technologies that are associated with the design, engineering, and launch of small satellites that have rapidly evolved in recent years. It even addresses some of the technical challenges still to be met.

It also explores the ways that small satellites can be used in meaningful ways for remote sensing, Earth observation, and communications. It examines how quickly some of these new systems are being designed and launched as part of the smallsat revolution. It explores the potential of smallsats to meet the needs of developing nations. It considers, in particular, the ways that smallsats could contribute to meeting the U. N. Sustainable Development Goals for 2030.

On the opposite side of the rising potential of smallsats, this book also considers the various policy and regulatory issues that these new types of satellites can also pose. In particular it considers the increasingly severe space debris problem that continues to emerge. Thus there is a consideration of the issues that need to be solved as we open up new frontiers in space and as the potential of smallsats is realized in the decades ahead.

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2

Engineering, Design, and Launch Arrangements of Smallsats

Introduction

For many decades there was a conventional wisdom about how to design, build, test, and launch application satellites – mainly "requirements-driven," based on detailed and often very complex specifications or constraints in documents issued by space agencies or large companies. These "conventionally designed" satellites were intended to sustain commercial or governmental services for telecommunications, broadcasting, remote sensing, meteorological services, navigation and positioning, etc. The basic design of a satellite was based on the premise that any spacecraft needed to be built to sustain operations for many years in the hostile environment of space. Since these satellites were quite expensive due to dedicated launches, care was taken to make sure that all of the components of the satellites were carefully qualified and tested. Such satellites were sent to various types of testing facilities, such as inside thermal vacuum chambers, on shaker tables, and many more for quite extensive testing to ensure that they would operate and function for a long time in space after launch. These satellites had built-in redundancy of key components to allow switching to back-up systems when failures occurred – often with more than one instance.

These conventional satellites contained specially designed payloads often several different at a time and with back-up systems to deliver one or more services such as telecommunications, remote imaging, tracking and position determination, and so on. In addition to the payload a wide range of systems and subsystems ensured that the payload operated reliably in space: structures and mechanisms (e.g., rugged low-mass structural platforms, deployment systems for antennas and solar arrays); power supply systems (e.g., usually batteries and solar cell arrays, electrical wiring and power transfer systems); thermal control systems (e.g., heaters, cooling, or heat dissipating systems); on-board data handling or command and data

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1_2

handling systems (e.g., on-board computers providing also the tracking, telemetry, and command capabilities); communication systems (e.g., antennas, transmitter and receiver); attitude determination and control systems (e.g., for satellite positioning and stabilization using actuators such as reaction wheels, magnetorquers or thrusters and associated fuel supplies, guidance and pointing sensors like star trackers, Sun, Moon and Earth detectors, or precision RF tracking systems for accurate pointing); orbit control or simple propulsion systems (e.g., apogee kick motors); and, if necessary, environment control and life support systems (e.g., for biological research payloads).

The first satellites launched into space had very limited operational capacities and had a mass of around 100 kg or less – making them micro satellites using today's classification. As the sophistication of satellite payloads and their operational capabilities increased along with their mass and size, power requirements, and antenna systems satellites just continued to grow, as did the various launch systems along with them [1].

From the mid-1960s up to today satellites have steadily increased in scope, power demand, complexity, and therefore mass. The largest telecommunications satellites in geosynchronous orbit today can now be well over 5,000 kg in mass and thus can only be launched by large rockets such as the Ariane 5, the Atlas 5, the Delta 4, the H-IIB, the largest Long March rockets (e.g., CZ-3B and now CZ-5 and CZ-7), the GSLV-Mk II, or the upcoming Falcon Heavy.

However, over three decades ago some satellite designers began to question this conventional paradigm about satellites always becoming bigger, more complicated, and designed for a very long operational life. This chapter is about how organizations such as the Surrey Space Centre in Surrey, England, and others around the world began to think about the design, manufacture, launch, and operation of satellites in new and different ways. Thus in the 1980s and the 1990s in particular innovative thinkers and designers began to envision new ways to do innovative things with smaller space missions, dubbed "smallsats."

In the chapter that follows, there are various sections. The first is about the new concept as to how to design and build smallsats. It explains how satellite designers of smallsats conceived of how these compact and less complex satellites could be constructed at much lower cost and perform tasks in new and different ways. This revolution also contributed to the birth of the so-called "NewSpace" commercial ventures. New space entrepreneurs conceived of new ways to utilize smallsats to provide new services in space at much lower cost. The sections that follow this introductory section examine the various components or elements of a satellite and if and how they are different when looked at anew in the context of the smallsat approach.

New Ways to Design and Build Satellites – The Smallsat

The concept of smallsats today has many potential aspects. These can vary based on the type of mission, the number of satellites to be deployed, and who is designing, fabricating, testing, and launching a given satellite. Cubesats (e.g., one unit to six units in size) can be built at quite low cost using kits purchased on-line and commercial off-the-shelf components that have not been spaceflight qualified [2]. This is typical of cubesats developed as university student or even high school student projects, but may also be the case for start-up and NewSpace companies, who wish to deploy systems at the lowest possible costs – basically transferring testing in qualification into the operations phase in space.

In the case of companies that are deploying hundreds or in near-future even thousands of satellites in large-sized constellations the objective might be to achieve economies of scale through mass production, minimizing testing and qualification, or through the use of novel manufacturing techniques such as 3-D printing.

In yet other cases large governmental organizations such as the U. S. Air Force, might contract with a company such as Boeing to conduct a specific space-based experiment, but instead of ordering a large, full-scale experimental satellite they may ask for a miniature satellite that can be quite sophisticated but still built and launched in a relatively short time and at lower overall project cost. The 3-unit cubesat pictured in Fig. 2.1 is 30 cm x 10 cm x 10 cm in size and is known as the SENSE experimental satellite. Two satellites were fabricated within 18 months by the Boeing Corporation for the U. S. Air Force to carry out a high-quality technology demonstration mission for much less money than previous air force experimental satellite missions. This is because a 3-unit cubesat can be developed and built in a short amount of time by a relatively small team and launched for a small fraction of

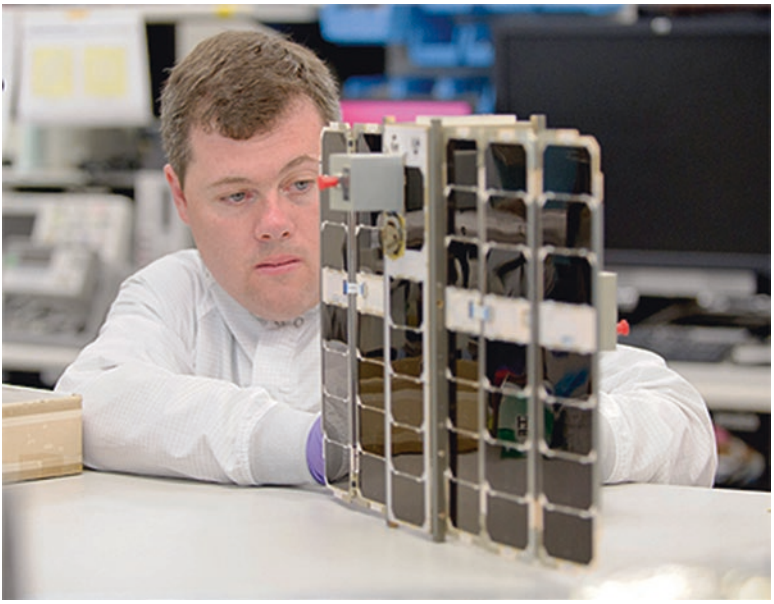

Fig. 2.1 The USAF SENSE 3-unit cubesat manufactured by the Boeing Corporation. (Graphic courtesy of the U. S. Air Force)

the cost associated with a dedicated full-scale satellite launch.

There are thus many cost models that might be applied to a small satellite project today, but in all of these models there are substantial cost savings. To recap, these types of potential savings arise from:

I. The use of low-cost commercial off-the-shelf (COTS) components;
II. The reduction of complexity due to small number of mission objectives (e.g., only one payload) and short mission life time, offering the opportunity of short project schedules and small teams;
III. Mass production of hundreds or thousands of satellites at a time with much of the cost savings coming from economies of scale in design, fabrication, and reduced testing costs;
IV. Lower launch costs due to the lower mass of smallsats and the use of ride-share, so called "piggy-back," launch opportunities.

The assumption that many might make about smallsats is that this term always refers to low-cost, low-reliability satellites that often use unproven components that have not been qualified for space missions. At one stage during the early days of smallsat missions this might have been correct – especially for academic missions – but this is no longer accurate today. High priority missions can in some cases be accomplished with quite compact and even cubesat-sized spacecraft. Not all of the components are lacking space qualification. Some are built for national space agencies with fully space-qualified components, and the market offers today many commercial off-the-shelf components with extensive flight heritage. Also there are now very large constellations being designed and built by highly qualified and experienced satellite manufacturers and again with space-qualified components. In this case the savings are being achieved through manufacturing economies of scale and new testing processes.

Use of Commercial Off-the-Shelf (COTS) Components and Limited Testing

One of the key cost reduction aspects of smallsat systems almost from the outset has been specifically related to the use of commercial off-the-shelf components that results in dramatic reductions in component and systems testing. There can be substantial savings here as well as the opportunity to access the latest generation of technology with regard to digital processors, sensors (e.g., cameras) by just plugging commercial off-the-shelf components into a smallsat. One major risk to the manufacturer of a smallsat, though, is that exposure to space hazards such as radiation, micrometeorites, or rapid thermal shifts could lead to satellite failures. The other threat is that the use of something like commercial off-the shelf wiring, which works in one way on Earth may act in a different way in space or may heat up in a dangerous way. These sorts of risks are key to consider when cubesats are taken to the International Space Station (ISS) and then released into space via the Japanese module's scientific airlock. With the ISS being a human-rated spacecraft, such nano satellites have to be qualified to higher standards than when being carried along using a ride-share opportunity on a common satellite launcher.

The key point is that commercial off-the-shelf materials that are used in smallsats do require some degree of testing to give higher confidence of successful operation and to insure that these components do not create hazards to the launch vehicle or to the ISS. NASA as well as other space agencies, such as ESA and JAXA, have indeed created safety review procedures and organizations (e.g., at the U. S. Kennedy Space Center in Florida or in Bremen, Germany) to help with such safety reviews.

For smallsat companies as well as academic institutions planning satellite constellations, the approach is not to create the safest and most reliable spacecraft but rather to fabricate a very large number to place in orbit with the philosophy that a number will fail, but the sheer numbers of smallsats remaining operational in orbit will provide adequacy of service (e.g., coverage). Carefully considered such testing approaches may lead even to the elimination of certain tests and qualification procedures and instead allow learning from possible failures of spacecraft systems and components in space – and accepting possible losses during early mission operations.

Launch Arrangements

The development of launch vehicles for many years followed the pattern of developing larger and larger lift capabilities with larger spacecraft shrouds to accommodate ever bigger satellites. Today's high throughput satellites, such as the Viasat 1 and 2, the Intelsat Epic satellites, India's I-6K bus, the Hughes Network Systems and Echostar's Jupiter, or Airbus Eurostar-3000 systems, can only be lifted to their required operational orbits by the world's biggest rockets. This situation left smallsats with the prime option of being add-on "piggyback" rides to space.

This trend has continued apace with the latest record-setting launch of 104 cubesats by the XL version of the Indian Space Research Organization's (ISRO) Polar Satellite Launch Vehicle (PSLV) in February 2017. Fig. 2.2 below shows the Indian PSLV launcher that set this latest record for smallsat launches in addition to its other launch missions [3]. Prior to this launch the number of cubesats launched at once had gone up from 10 to more than 20, and up to 37 smallsats at once with a Russian launcher. Today it is clear that, if necessary, hundreds of pico and nano satellites can be released from a single launch. This trend towards increasing numbers of smallsats released per launch gives rise to new concerns about orbital space debris and questions as to whether such launches to LEO should be limited to lower altitudes so that natural orbital degradation can occur within the 25-year limit after end of life – or even shorter.

The advent of the smallsat revolution and burgeoning demand for the launch of more and more cubesats (in the 1- to 6-unit range), as well as for smallsats in the 150- to 500-kg range has led to two changes in the launcher industry – ironically at *both* ends of the launcher capacity scale. Firstly, there have been a number of new development efforts to create lower cost launchers that can loft smallsats to orbit either one at a time or only a few at once. Secondly, there have been technical and institutional

Fig. 2.2 The ISRO PSLV C-37 mission that launched 104 cubesats into LEO in February 2017. (Graphic courtesy of ISRO)

developments to create new special configurations that allow larger launchers to loft a large number of smallsats at the same time. Many launch providers offer secondary or auxiliary structures providing multiple mounting points for micro and even mini satellites as well as pico and nano satellite deployer systems (e.g. Arianespace's ASAP and VESPA platforms or the ESPA ring used on ULA's Delta 4 and Atlas 5 as well as on the SpaceX Falcon 9).

Some of the new initiatives to develop the ability to launch a smallsat to LEO arose as spinoffs from efforts to develop space planes to fly passengers on suborbital flights for space adventures. The SpaceOne small launcher that is scheduled to launch some of the OneWeb satellites is a spinoff of Virgin Galactic's efforts to conduct such suborbital flights. Not all of these efforts reach technological maturity. Most concepts nevertheless stay with the established technology of vertical-take-off rocket systems – mostly expendable or in some cases partially reusable. Swiss Space Systems (S-3), which attempted to do both suborbital spaceflights and small satellite launches, has now gone into bankruptcy – a similar fate met by Texas-based Firefly Space Systems. Other efforts to develop new low-cost rockets are numerous, with more than 30 projects ongoing at the end of 2015. And some of these recently also ended in bankruptcy and certainly more will [4].

In light of the considerable volatility in the launch market it is not useful to list the current range of launch options, which are considerable, with numerous options being available from Europe, the United States, China, India, Russia, and even Israel. Other countries may offer launch capability in the future as well. It is instead best to search various websites that report on launch vehicle development for the latest information.

Small Satellite Payloads – Each Application Can Be Quite Different

Chapters 3 and 4 examine in some depth the evolution of systems and engineering design for remote sensing and telecommunications satellites. The technology associated with the satellite buses for these two types of spacecraft are indeed very similar, but the payload packages are quite different. In the case of remote sensing satellites the continuing reduction in the size of electronics, digital processors, cameras, and sensors along with their increasing performance capabilities made it feasible to create highly capable smallsats for various types of Earth observation missions. The improvement in performance of small digital imaging systems over the past decade was particularly well suited to developing remote sensing smallsats. The high power needs for radar satellites has on the other hand restricted the development of small satellites for remote sensing primarily to optical and infrared sensing. The Surrey Space Centre led the way to create a series of small satellites for remote sensing in the micro and mini satellite class.

Small satellites were also developed for store-and-forward messaging, but not for broadband or voice-related services. The latter tasks are now being approached by various entrepreneurial companies from North America, Europe, and Asia.

In the case of telecommunications satellites, ongoing technical trends have proven to be key. Of particular importance in this regard was the concept of deploying smaller and lower power satellites in constellations in LEO that can have smaller and lower gain phased array antennas. Further, the idea that hundreds or even thousands of such smallsats might be launched has now enlivened the smallsat revolution for the world of telecommunications. Finally, the latest development of new ground antenna systems that use meta-materials, to help generate electronic tracking of fast-moving satellites in LEO constellations, has added further new interest in making such large-scale telecommunications constellations economic in terms of the overall systems costs for the combined space and ground systems.

Federated and fractionated satellites, the latest new concepts in small satellite technology will be of particular interest for the above discussed applications, remote sensing and telecommunications. The sharing of resources between federated spacecraft and therefore utilization of unused resources within constellations will enable a cloud computing-like environment. Fractionated spacecraft with their modular architecture of a large number of free flying payload platforms flying in constellation with a smaller number of communication systems will go even one step further. Both concepts will benefit from small satellite development to further reduce cost and increase utility and even enable new types of missions.

The key point is that each space application or service that might utilize smallsat technology has its own needs in terms of the space segment as well as supporting ground systems. The business and technological case is unique to each application or service and must thus be evaluated on its own merits.

On a final cautionary note, if the smallsat revolution gives rise to an unacceptably large increase in orbital space debris, there could also be longer-term financial, operational, and technical implications for all future space applications. The economics of active debris removal as well as regulatory controls need to be carefully considered and taken into account (especially by national regulators of space activities) as new smallsat constellations are deployed in coming years [5].

Power Systems for Small Satellites

The efficient and low-cost design perspectives that come with the smallsat revolution suggest a careful review of all the various subsystems. There are several key questions that always apply. Can a given subsystem be eliminated altogether? Does it scale down in size in a reasonable way? Is it possible to use reliable commercial off-the-shelf components to build the subsystem, and if so could it lead to safety issues or premature failures? In the case of power, this is a must-have. All of the payloads of a spacecraft, whether for telecommunications, remote sensing, or any other application, require power to operate. There is also a need for power to relay data back to Earth and receive commands from the ground station. It is possible, however, with many smallsat missions to use commercial off-the-self solar cells as well as lithium ion batteries.

The exception would be a small satellite for a large-scale constellation wherein the satellite is much larger (i.e., 150 to 500 kg) and is expected to operate for 5 to 8 years in orbit. In these cases a higher performance photovoltaic array is more appropriate and perhaps even a space-qualified lithium ion battery system might be used as well. In such a case economies might be achieved by bulk purchase of the solar cell arrays and the space-qualified batteries.

Thermal Control Systems for Small Satellites

The thermal control systems for small satellites have many elements in common with their larger cousins. It is important to keep in mind that especially with small satellites that decreasing size increases the density significantly (e.g., 1,000 kg/m^3 and more at a 1-unit cubesat compared to values of only a few 100 kg/m^3 or less with conventional satellites) and therefore poses certain challenges to the thermal design. Approach number one is to use reflective materials such as multilayer insulation foil to avoid overheating and to keep batteries but also low-voltage electronics and payloads within very small temperature ranges. This is to avoid a need for active thermal control devices such as heat pumps to dissipate energy. Avoiding extremely low temperatures is also important, particularly if COTS components are used. Some form of small heater might be needed to prevent components in the smallsat from freezing while the satellite is in Earth's shadow.

The key is to consider the way to keep the smallsat from either freezing or overheating so as to accomplish the mission, but also to do this in the most cost-effective way and with the smallest amount of additional mass. If one uses commercial off-the-shelf electronics components or sensors for the smallsat, it is important to find those components that have been built to operate in the widest possible temperature range and dissipate the least amount of heat. Even then one might consider thermal testing all commercial off-the-shelf components to identify those ones most likely to survive the thermal rigors of spaceflight. In the case of small satellites for constellations of the 150 to 500 kg class the full range of thermal control systems, including heat pipes, heaters, thermal vacuum tests, etc., are available and constitute logical options.

Tracking, Telemetry, Command, and Monitoring Systems for Small Satellites

There is a need for tracking, telemetry, and command (TT&C) for most satellites – namely all those that are intended to maintain specific orbits for a sustainable amount of time and need to be tracked, and also to return data collected by satellites for processing and analysis back on the ground. Even satellites released into random and uncontrolled orbits need the ability to transmit data back to the ground, which is the basic telemetry function. However, the TT&C functions are more difficult to perform when a small satellite does not have attitude control to orient itself to allow antennas with higher gain to be used instead of low-gain omni-antennas that radiate signals in all directions.

The monitoring function that seeks to keep track of the satellite's payload functionality is the most expendable of these activities on smallsats. The monitoring equipment, communications channels, and related transmit antennas can be (and often are) omitted on smallsats.

The TT&C system is an important one to be custom designed to the needs of a particular smallsat mission. Key questions are:

(i) How precisely does the satellite have to be tracked and maintained in its orbit – if at all?
(ii) What data and control commands must be sent to and from the satellite, and which aspects can the satellite handle autonomously? and
(iii) Is this a constellation with multiple satellites that requires special controls or possibly intersatellite links?

A Simplified Approach to Computer Processing and Sensors to Monitor and Control Satellite Functions

Conventional satellites have elaborate systems to support increasing degrees of autonomous control of on-orbit satellites. Sensors can monitor thermal levels, shut offs, or failures of key components such as transponders, cameras, thermal control systems, star trackers, sun sensors, thruster systems, reaction wheels, or stabilization systems. Satellite command and control capabilities, as well as the on-board processor that responds to things like overheating or component failure, are contained in the software associated with the tracking, telemetry, and command system. In the case of very large satellites this could involve millions of lines of code.

For small satellites it is possible to create coding systems to allow even cubesat-sized systems to operate in essentially an automated fashion to support remote sensing, telecommunications, or other functions. This also enables lower cost ground segments. This is often necessary with academic institutions or small start-ups because of their limited budgets. It is also possible to automate such functions as charging and discharging of batteries, switching to various modes of operation when in sunlight or eclipse, since today's computer processors are quite small but still quite high performance. Thus these devices can support software up to millions of lines of code. It is for this reason that a small satellite can be as easily equipped for autonomous operation as a very large satellite. The limitation is the degree to which there can be redundancy of key components that can be included in a small satellite's design. In the case of small satellites, the answer is often to have redundant satellites rather than redundant components on-board a given satellite or to substitute the function of redundant hardware components with software elements.

Structural Platforms, Electrical Wiring, and Other Components for Small Satellites

One of the current advantages available to the designers of small satellites is that there are a wide range of standardized kits that can be ordered online for pico and nano satellites like 1 to 6 unit cubesats. These kits provide at relatively low entry cost a frame, wiring, and other necessary components for a cubesat. Even for larger smallsats in the micro satellite or even 150 to 500 kg range, satellite manufacturers have developed framework structures for different classes, along with deployable solar arrays that are of proven design, resilient operation, and reasonably low cost. Indeed, the manufacturing of some components are now undertaken as 3D printing operations. This increases reliability and cuts costs.

In short, smallsat design and manufacture is easier, faster, more reliable, and lower in cost in today's world. This is true, regardless of whether a given satellite is a one-off student cubesat project or just one in a production run of thousands of larger small satellites for an LEO constellation. The advent of 3D printing, rapid prototyping, software simulation, and other innovations have been transferred from other areas such as automotive and consumer electronics industries to the space industry, and now even major aerospace corporations such as Airbus and Boeing have joined the world of smallsat design and production.

Are Accurate Position Determination and Control Systems Necessary?

One of the reasons that conventional satellites grew in size and sophistication was to support high-powered solar arrays and large high-gain, large-aperture antennas. These large antennas for telecommunications services required exact pointing with high levels of precision of tenth of a degree pointing accuracy down to very high levels of precision of arcminutes or even tens of arcseconds for certain remote sensing or astronomical observations. Today's big satellites for communications have

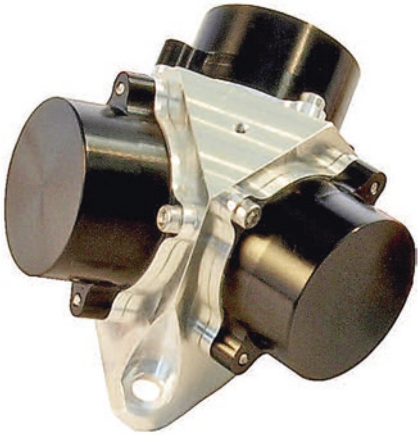

Fig. 2.3 Reaction wheel system for 1-unit cubesat. (Graphic courtesy of Astro-und Feinwerktechnik Adlershof GmbH)

antennas as large as 22 m in diameter. This can be achieved only via reaction wheels that spin at speeds of up to many thousands of rpm as well as position determination systems that combine star trackers and RF precision tracking and exact orientation control systems.

These capabilities are not necessarily needed for nanosats or cubesats with omni-directional antennas. One can use a variety of techniques to orient sensors or antennas toward Earth. One such technique that has been used with success involves magnetorquers orienting themselves along the magnetic field lines of Earth or gravity gradient booms that are extended toward the ground to get the correct orientation.

There are some small satellites that are simply designed for sensing electromagnetic, ionospheric or upper atmospheric phenomena that do not require any particular stabilization. These, however, are the exceptions. Today there are many more micro as well as pico and nanosatellites that now operate with 3-axis positioning stability using reaction wheels and which can also maneuver using extremely low thrust water or alcohol-based thrusters in order to accomplish their mission See Fig. 2.3 that provides an example of a reaction wheel system for a 1-unit cubesat.

Orbit Control and Station-Keeping Systems

One of the key aspects of a small satellite design is whether it will have some sort of thruster to assist with it being deployed in the right orbit and have some degree of station-keeping ability to ensure that it stays in a prescribed orbit. Larger smallsats in the 150- to 500-kg range will almost certainly be scaled-down versions of larger satellites and include thrusters to maintain orbit and to assist with active de-orbit at the end of life. As stated before they will also likely have reaction or inertial wheels in order to maintain three-axis stabilization and accurate pointing to allow precise orientation of antennas, cameras, or payload sensors and to support orbit control and station-keeping.

Stabilization is key to remote sensing satellites that are seeking to point their sensors in a consistent and constant manner back to Earth. Also smallsats are often greatly limited in their ability to utilize communications antennas with any reasonable degree of gain. Thus for smallsats seeking to provide remote sensing, real time or even data relay, machine to machine (M2M) services can provide a stabilization system using X, Y, and Z axes, as depicted in Fig. 2.4.

The requirements for positioning, pointing accuracy, and station-keeping are all determined by the needs of the on-board payload and may depend on the density of satellites in a large-scale constellation. The other key consideration is whether there is a need for active end-of-life disposal measures. For smallsats that are in orbits with an altitude of 300 km or less, gravitational effects and atmospheric effects, especially during solar max, will bring satellites back to Earth in a time period that is less than 25 years after end of life. Operators developing small satellites for large-scale constellations in the 700- to 1,000-km altitude range will definitely need to plan for effective end-of-life disposal if they are not to add to the growing debris population and endanger their own constellations.

Nowadays small satellites are being designed more and more with low cost passive debris removal devices such as inflatable balloons, sails, or webs that serve to create a larger cross section so

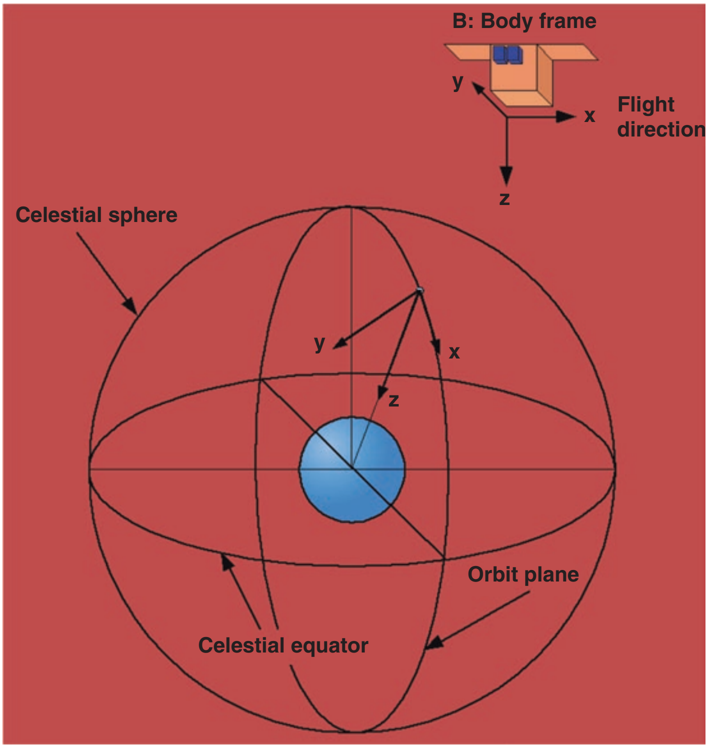

Fig. 2.4 The orbital reference frame used for satellite stabilization and pointing for in-orbit satellites whether large or small

that atmospheric effects will hasten their re-entry. Such systems are recommended in light of the growing amount of debris in low Earth orbit [6].

Intergrating All of the Subsystems Together

Of course a smallsat is an integrated device that must function seamlessly as a whole. The greatest challenge for the design and fabrication of a smallsat is to integrate all of the parts together so they perform flawlessly in space and are able to perform without failure at least for the planned operational lifetime of the satellite. This is truly a case where the whole is greater than the sum of all its parts. Integrating these various parts together, each with their own mean time to failure, so that they fit within the limits specified for mass, volume, thermal extremes, launch vibration effects, and more, is a considerable challenge. Large satellites may allow for 50 kg or more of margin that can be used if a particular component ends up being more massive than allocated. In the case of a cubesat there is very little volume margin allowed, and the mass budget is likewise very strict indeed. The result of all the intense design and engineering can be a very densely compacted system with components being very tightly packed together – causing challenges for thermal control, electromagnetic interferences as well as handling and accessibility during assembly. The STRaND-1 3-unit cubesat shown here illustrates this point quite vividly (see Fig. 2.5 and Chart 2.1).

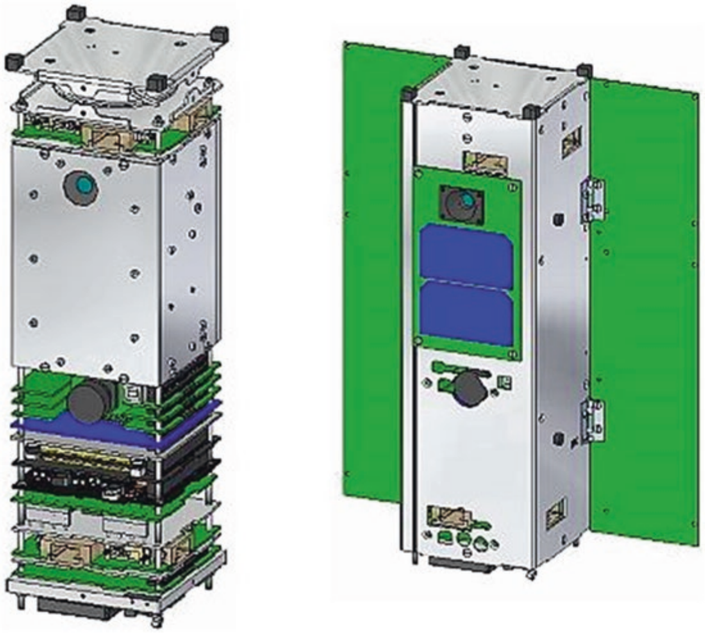

Fig. 2.5 The STRaND-1 3-unit cubesat by Surrey Space Centre, with a mass of 3.5 kg. (Graphic courtesy of the Surrey Space Centre)

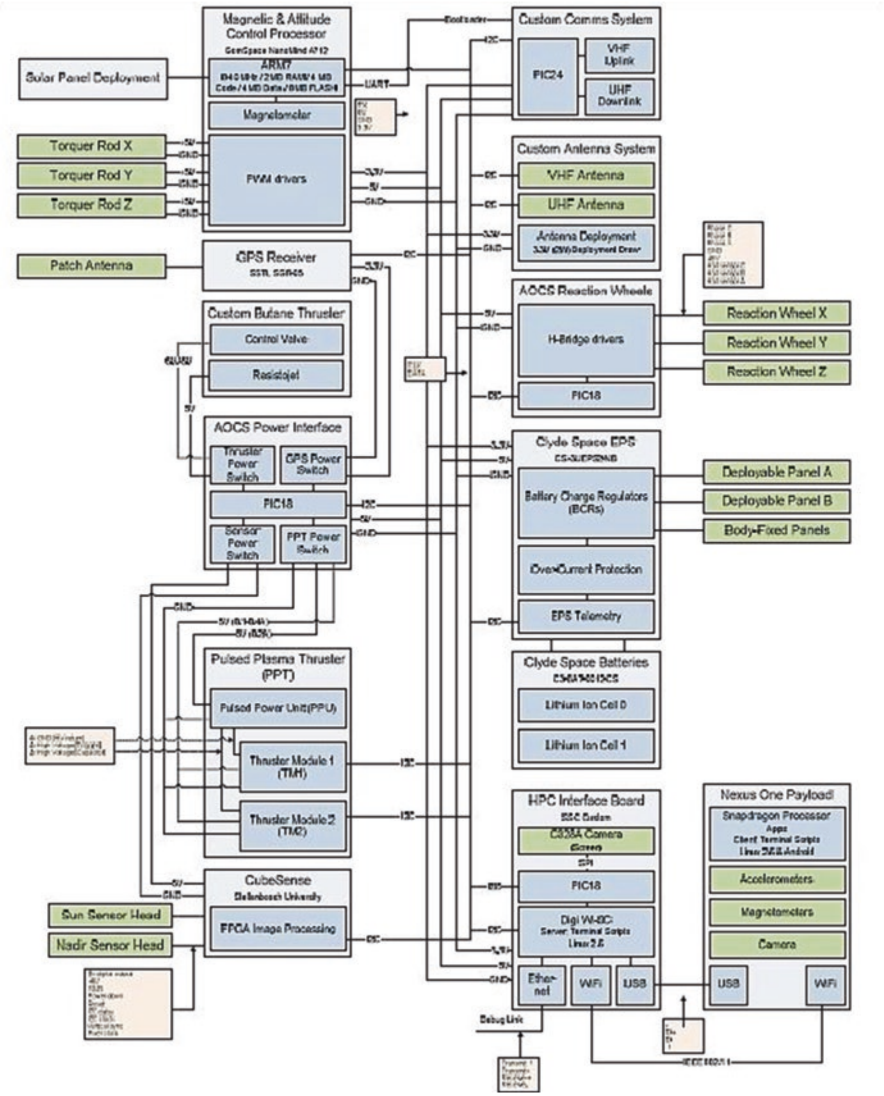

Chart 2.1 A functional diagram of all of the components and subsystems in the STRaND-1 cubesat. This chart is to show the complexity involved. The key components are visible. (Graphic courtesy of the Surrey Space Centre)

The diagram here shows the enormous complexity of all the parts that are packed into this single smallsat and how many components can be included in an extremely compact volume.

It is amazing how the miniaturization of electronic components has allowed all of the parts that make up a complete satellite to be shrunk to the size of a 10 cm x 10 cm x 10 cm cube to achieve a completely self-contained and functioning satellite in outer space. Fig. 2.6 provides a simplified picture of an integrated cubesat and its more vital parts.

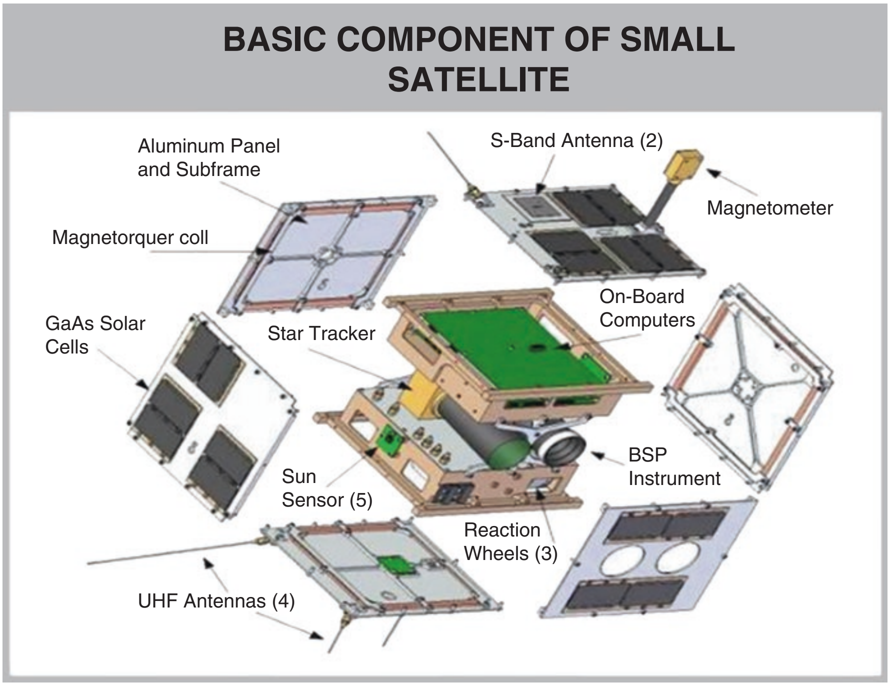

Fig. 2.6 Key component parts of an integrated cubesat shown in exploded form. (Graphic courtesy of UTIAS/SFL)

Fully Integrated Space and Ground Systems

The small satellites that are launched into orbit, at least in one sense of the word, do not operate in a vacuum. There have to be ground systems to track the satellite (if necessary), receive telemetry from the satellite to ensure that it is functioning properly, and even to send commands to the satellite to address problems or to reorient or reposition a satellite. There is much more involved that just building a satellite. Fig. 2.7 shows the full complexity of operations needed to develop and support an operational space system. The various tasks involved (among others) include the following:

- frequencies and ITU procedures for RF coordination
- registration of satellite
- launch arrangements, flight segment, deployment, and telecom
- ground systems for TTC and M
- satellite tasking
- data processing & archiving
- data distribution to end users
- budgeting, scheduling

One key to successful satellite operations is assigning frequencies. There is one set of frequencies assigned for the tracking, telemetry, and command services that control the actual operation of a small satellite typically in the VHF (very high frequency) or UHF (ultra-high frequency) bands. There is also another set of frequencies, one for

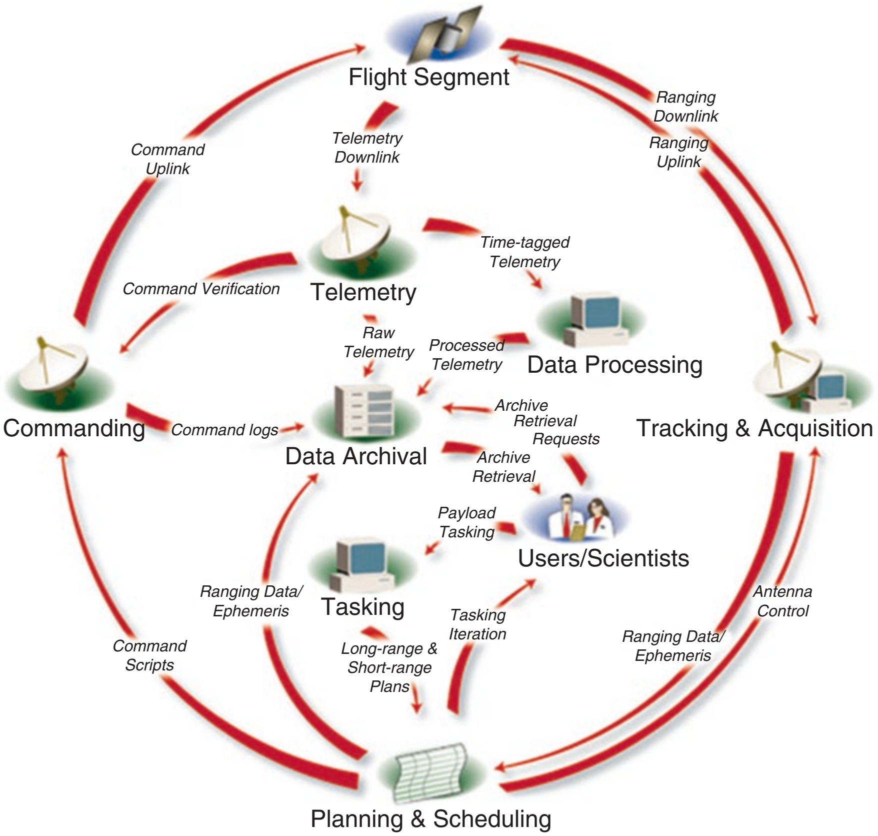

Fig. 2.7 The full complexity of space and ground system for space communications

uplink and another one for downlink, that supports the payload mission itself, which might be telecommunications, relay of remotely sensed data, etc. These are two different frequencies because if the uplink and downlink frequency were the same they would interfere with each other. These frequencies are typically in the S band (i.e., near 2 GHz), but they can be in the UHF band (300 MHz to 3 GHz) or even in X band (8 GHz-12 GHz).

Conclusions

The ingenuity involved in the designing of smallsats is quite impressive. This is because it involves great technical and engineering skill to include all of the many functions needed to complete an entire satellite within a very small volume and also within a very tight mass budget. Further, there is ingenuity in finding ways to use in many cases existing low-cost, commercial off-the-shelf components in the design and fabrication of cubesat systems. Smallsats also open doors to employing new production methods, such as use of 3-D printing to manufacture components of the satellite.

There are also economies-of-scale savings related to the manufacturing and testing of smallsats. This is especially true when hundreds or even thousands of smallsats are produced for large-scale constellations in LEO for telecommunications services. The low latency of service of such smallsat constellations opens new doors to providing low-cost Internet services to developing countries and the Global South, where Internet access is currently much less available than in the economically developed world.

On top of all of these benefits, significantly lower launch costs are also available because smallsats are typically launched into low Earth orbit using rideshare launch opportunities and, of course, their mass and volume are many times less than is the case with conventional satellites.

Although the components that make up a smallsat are very much akin to the parts found in a larger conventional satellite, the engineering and miniaturization of parts creates a very different set of design parameters. Today there are ever more demanding efforts to see how truly small a functioning satellite can be. Thus there are today even femtosats below the size of picosats, and nanosats that are exploring just how small a smallsat might be.

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Smallsats for Remote Sensing – The Swarm Is Here!

3

Introduction

The advent of smallsats for remote sensing services is one of the most interesting and innovative developments in space in recent years. Remote sensing has long been a powerful and useful tool for a wide variety of applications, including land use mapping, agriculture, forestry, meteorology, climate studies, air, water, and ice studies, national security, and much more.

We are currently in the middle of a revolution in how space remote sensing is done. This change is driven by the growing power and availability of smallsats, a new generation of young visionaries, and revolutionary technologies that enable new and useful ways of imaging of our world. There has been for years a predominant paradigm for “progress” in space systems. This has been that progress is achieved through always building bigger and more powerful spacecraft. This concept that we have known since the dawn of the Space Age now seems to be crumbling – at least for many applications.

Space Remote Sensing 1.0

For many years, the world of space remote sensing was dominated by the major spacefaring nations such as the United States, the Soviet Union/Russia, and Europe. This was largely due to the close relationship between civil remote sensing and national security and intelligence needs, coupled with the large size and power needs of early remote sensing systems, limited launch options, and high launch cost, and the complexity of the remote sensing process. The U. S. Landsat satellite series (originally named the Earth Resource Technology Satellite) was first launched on July 23, 1972, and had a spatial resolution of 80 m (Fig. 3.1). This began the era of civil Earth observation (EO) that continues today, with Landsat 8 operating as you read this.

From these early beginnings, satellite remote sensing has developed continuously, with many commercial and governmental satellites now in operation. These are operated by many nations of the world. Traditional EO satellites all

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1_3

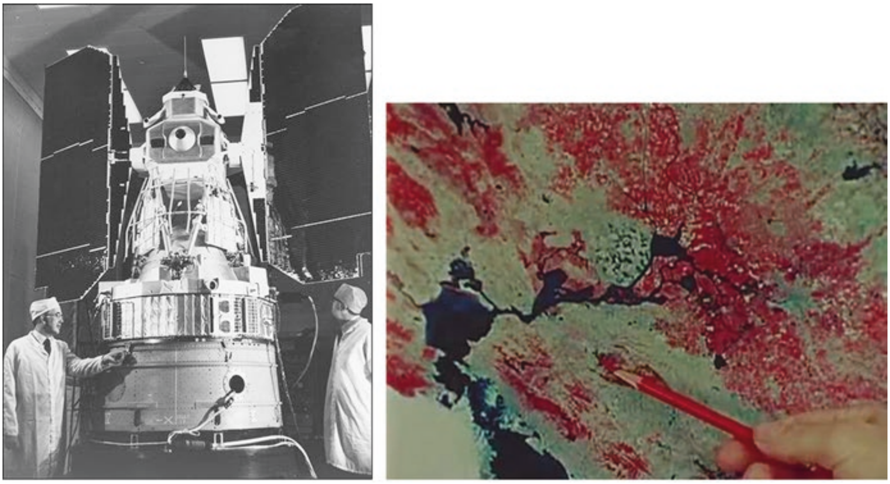

Fig. 3.1 The first Landsat satellite, and an early 80-m pixel false color infrared image of Earth (Graphics courtesy of NASA)

worked within a standard model, with satellites in a polar, Sun-synchronous orbit providing periodic coverage of the planet. These tended to be moderate-sized satellites (~2,000 kg), with three-axis stabilization, occupying orbits in the range of 500 to 1,500 km altitude, and using solar panels and tailored communications systems to send the raw data collected to ground stations, where it was processed by trained specialists using proprietary software for analysis and distribution. From these early beginnings, EO satellites grew larger and more complex, often containing many different instruments for a 'coordinated data capture' approach, but remained within this standard paradigm.

The zenith of this traditional approach to Earth observation may have been the European Space Agency's Envisat, which was launched on March 1, 2002 (Fig. 3.2). This was a massive satellite, with a launch mass of 8,211 kg. It measured 2.5 by 2.5 by 10 m at launch, and an impressive 26 m by 10 m by 5 m in orbit. The satellite required massive solar panels providing 3,560 W of electrical power. It carried ten different instruments and was the largest civilian EO satellite ever launched. It contained both optical and radar sensors, atmospheric sensors, ocean sensors, and more. It was placed into a traditional Sun-synchronous orbit at 790 km, with an orbital period of 101 minutes and a repeat rate (going over the same location on the ground) of every 35 days. Data were transmitted to the ground for analysis by trained specialists. The mission ended in 2012 and returned a decade of impressive data, but at a cost of over €2.3 billion for construction, launch, and operation. Its sensors delivered over one petabyte of data. Today this massive "dead" satellite poses a major risk of in-orbit collision with debris that could lead to the generation of thousands of pieces of new space junk. The proliferation of new large-scale satellite constellations indeed gives rise to mounting concern about increasing amounts of space debris, especially in low Earth orbit.

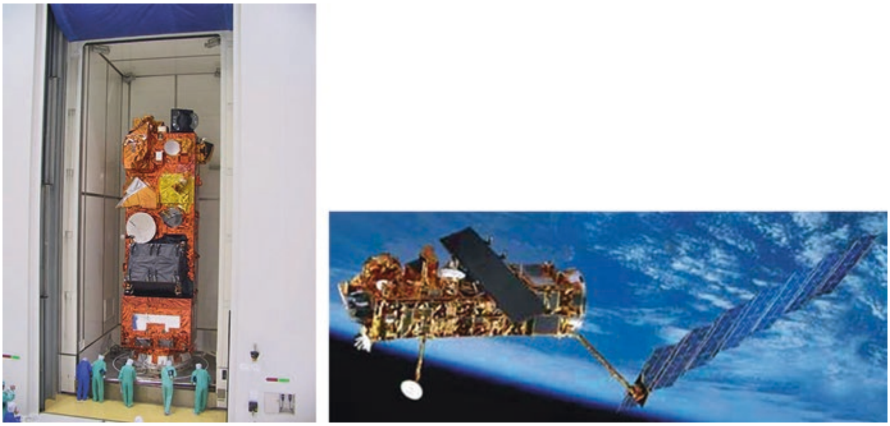

Fig. 3.2 The ESA Envisat in its launch and orbital configuration. (Graphics courtesy of ESA)

We know how to do this traditional remote sensing model very well, and capabilities have steadily improved over time. We have developed ever-higher spatial resolution satellites and launched more numerous and more capable EO systems, but they have generally followed the traditional model described above.

Space Remote Sensing 1.5: The Commercial High Resolution Systems

In 1994, U. S. President Bill Clinton made the decision, driven by the cost of national security satellites and emerging new technologies, to allow the commercial licensing of high spatial resolution satellite imagery (approaching 1-m spatial resolution at the time and which is now more than ten times better). The U. S. Department of Commerce began granting licenses, and several new entrants developed high resolution systems for commercial sale, starting with the EarlyBird satellite by DigitalGlobe in 1997, Ikonos satellite by Space imaging in 1999, Quickbird by DigitalGlobe in 2001, and OrbView-3 by Orbital Imaging in 2003. In 2003 the National Geospatial-Imaging Agency awarded DigitalGlobe a US$500 million contract for imagery. In 2006 OrbImage and Space Imaging merged to create GeoEye, which was then merged into DigitalGlobe in 2013, which was purchased by MDA of Canada in 2017. The current generation of these systems features innovative, high technology satellites with masses in the range of 2,000 to 4,000 kg, in traditional ~600-km polar Sun-synchronous orbits. These systems now provide imagery with spatial resolution as small as 25 cm. Although smaller than earlier EO satellites, these continue to operate in the traditional EO model.

Remote Sensing Today

Today, 34 nations and international organizations (such as ESA) have over 370 EO satellites in orbit [1]. There are as of the start of 2018 over 160 optical satellites, over 30 radar, 7 infrared, over 30 weather and meteorology systems, and more going up all the time. A few of the metsats are in geostationary orbit, but most are polar Sun-synchronous. The United States is the largest EO operator, with over 30% of all such satellites, followed by China with 20%, Japan and Russia (about 5% each). Many other nations operate one or two EO satellites. Civil governmental satellites make up about 45% of these, military systems 30%, and a growing number of commercial and civil users operate 25%. This all adds up to a significant, global commercial business, with estimates of total commercial remote sensing revenue in 2016 of about US$8.9 billion, with projected growth of around 9% per year to over US$19.3 billion by 2025 [2]. This is small compared with satellite telecommunications but is still a significant business as well as a general public good.

A New Paradigm: Remote Sensing 2.0

We are now in the middle of a radical revolution in the EO world. This is made possible by the development of smallsats, the Internet, advances in computing and networking, and a new, entrepreneurial perspective of how space EO can be conducted. This is radically different from the standard EO paradigm.

Surrey Satellite Technology and the Disaster Monitoring Constellation

One of the originators of the use of smallsats for EO was the UK company Surrey Satellite Technology, Ltd. (SSTL) (Fig. 3.3). It was founded in 1985 by Surrey University, and is now owned by Airbus Defense and Space. It was the first to develop modular EO microsatellites, ranging from 36 to 70 kg. These provided 50-m spatial resolution, and higher, with a variety of modular options. Their MicroSat 70 had an adaptable and modular design that could support a variety of payloads up to 25 kg, and modular trays that could be adapted for various sensors and payloads. It was compatible with multiple launchers, and 18 were launched. It was offered by NASA under their Rapid Development Spacecraft program, with launch possible for U. S. government customers only 20 months after signing a contract.

In 2002, SSTL developed the Disaster Monitoring Constellation (DMC) and the DMC International Imaging company. This is a group of small EO satellites, purchased by different countries and operated as a constellation for disaster relief and emergency response. Algeria, China, Great Britain, Nigeria, and Turkey participate under the International Charter for Space and Major Disasters, with launches between 2002 and 2011. Each DMC satellite weighed 90 kg and measured 1-m cubed, and provided 32-m spatial resolution in three spectral bands. It was designed to be compatible with the current Landsat data. The use of eight satellites, all of a common design, provided for fast data collection for events such as the Boxing Day tsunami and Hurricane Katrina, among others, with near daily revisit rates [3].

Surrey has continued its development of ever smaller and more capable satellites, ranging from 15 to 200 kg, and currently offers multiple EO options, including creative arrangements such as shared satellite ownership, international partnerships, and managed data supply

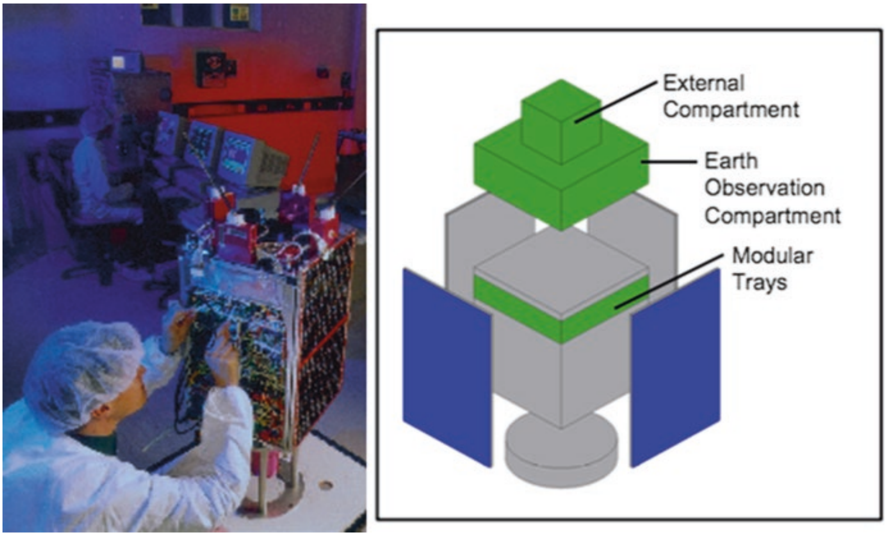

Fig. 3.3 SurrySat MicroSat 70. (Graphics courtesy of NASA)

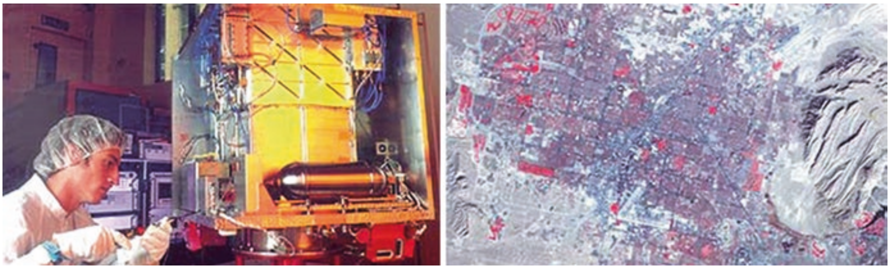

Fig. 3.4 SurreySat DMC and sample image. (Graphics courtesy of NASA)

through their subsidiary DMC International Imaging. Their three-satellite DMC3 constellation has 1-m spatial resolution and daily revisit rates, using a 350-kg bus (Figs. 3.4 and 3.5).

Planet Breaks the Mold

Planet Labs, now named Planet, was founded in 2010 by several young ex NASA Ames Research laboratory staffers, some of whom worked on the innovative NASA Ames PhoneSat project. The PhoneSat project was started in 2009 and was based upon a 1 unit smartphone nanosat (10 cm on a side) weighing 1.35 kg, and which was designed to be the least costly satellite ever launched. It was based entirely on commercial and non-space-rated cell phone systems, with smart phone batteries, cameras, and operating systems. Five phonesats were launched in 2013 and 2014, and all worked well in orbit, including taking pictures of Earth [4] (Fig. 3.6). The cost for each ranged between $3,500 and $7,500 U. S. dollars.

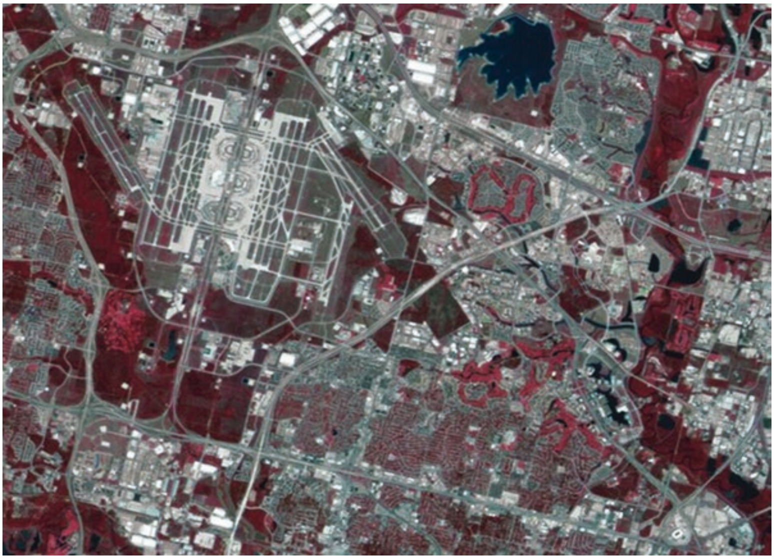

Fig. 3.5 SurreySat image of DFW airport in Texas. (Graphics courtesy of SurreySat U. S.)

Fig. 3.6 The NASA Ames PhoneSat with antenna made from a yellow tape measure (left) and an image taken from space using the smartphone camera (right). (Graphics courtesy of NASA)

Based on their success and the lessons learned from PhoneSat, the staffers decided to apply what they had learned to a commercial EO concept. These young innovators came from a totally new and different perspective. From deep within the Silicon Valley worldview of commercially focused and paradigm-shattering innovation, they wanted to break the mold of how, and why, satellite EO was conducted. Started in a garage in Cupertino, California, their vision was to use a 3-unit cubesat configuration (10 by 10 by 34 cm) to provide daily global imagery with 3- to 5-m resolution; essentially a daily line scanner for Planet Earth, based on commercial technologies.

They would eventually create a swarm of over 130 satellites, where *nothing* would be space-qualified hardware. Instead, their satellites would be powered

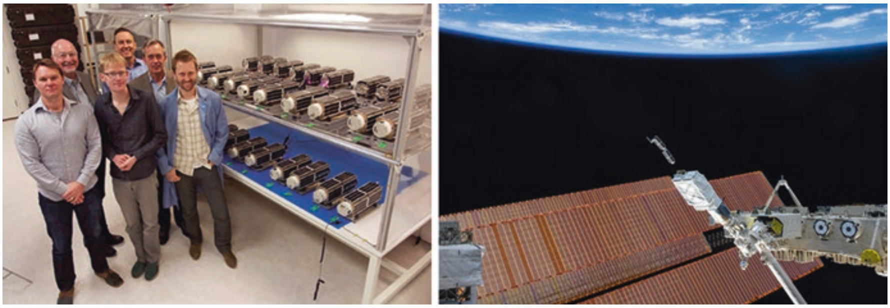

Fig. 3.7 Planet designs and builds its own satellites. (Left) A rack of 'Doves' in Planet's "clean enough" room, and (right) Doves being launched from the International Space Station. (Graphics courtesy of Planet)

by laptop batteries, use cellphone parts, and items from commercial electronics catalogs. They would build all their own hardware in their own 'clean enough' room, with continuous updates and improvements (Fig. 3.7). If satellites failed in orbit they would simply launch new ones. They would launch into any orbit they could access, including low inclination orbits to take advantage of access to the International Space Station, where they could launch up to 28 satellites at a time using Nanoracks modules. In short, they would totally break every tenet of the existing EO paradigm. Cheap, disposable, not space-rated, not built in expensive clean rooms, and not placed into polar orbits. They received an initial US$65 million in private equity, which was later increased to over US$156 million. They are now on their 14th generation of satellites, called 'Doves,' that are launched in 'flocks,' and plan launches of continually updated satellites three or four times per year (Fig. 3.8). They call their approach 'agile aerospace.' The concept is to continually improve and launch new capabilities as they are developed.

The company operates their own mission control center, with custom-developed satellite control software, and a network of 30 ground stations around the world. Data are processed using a scalable Cloud-based environment, and images are web delivered to clients. Planet has developed the Planet Platform, a fully automated processing system that downloads and processes over 5 terabytes of data per day. There is even a program for guest artists in residence to etch artwork on the satellites: "Inspiring and exploring creative possibilities at the intersection of art, aerospace, and our planet." Planet now operates the world's largest constellation of EO satellites (and the largest orbital art project in history), having launched in 2017 some 48 Doves on a Russian Soyuz, and then a record 88 doves on a single Indian PSLV rocket. In 2015, Planet acquired the BlackBridge company, along with its 150-kg RapidEye EO satellites built by Canada's MDA Corp. Then in 2017, it acquired the SkySat satellite constellation of seven satellites from Google (see below). These give Planet daily, global 3- to 5-m imagery, weekly sub meter global coverage, video, night imaging, volumetric analysis, and more, all capable of being integrated with additional geomatics data and web-driven content.

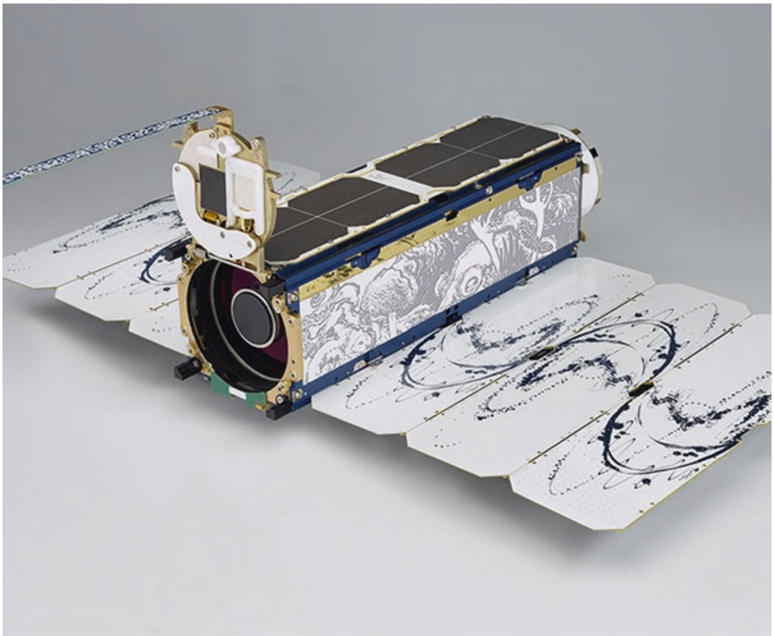

Fig. 3.8 A Planet 3-unit cubesat, complete with artwork. (Graphics courtesy of Planet)

SkyBox/Terra Bella

In 2009 four MBA students at Stanford University in Silicon Valley, California, came up with a novel concept for a new EO business. It was based on a 20x reduction in mass and cost compared with traditional systems, and was based on the use of a 60-cm cubesat bus, non-space-rated auto and cellphone electronics, and open source software. The concept was to provide 1-m resolution imagery and video – a first, primarily for business analytics and commercial applications. They went outside the traditional imaging design and used a two-dimensional video sensor that was originally created for night-vision goggles and uses electronics for video. Their image processing software was, again, from a non-traditional source, coming from the medical imaging field used for MRI and ultrasound imaging. The data are compressed in real time on the satellite before transmission to Earth (Fig. 3.9).

This use of onboard data processing allowed Skybox to build simpler and smaller satellites, using lower bandwidth telemetry to the ground. On the ground, the over 1 terabyte of data received daily are processed using Apache Hadoop Open Source software and a modular 2.4-m ground dish. Google purchased the five-year-old startup company in 2014 for US$500 million. Alphabet (the Google holding company) then sold the company it had renamed Terra Bella and its 1 meter SkySat imagery in April of 2016 to Planet. Google will continue to license imagery from the company under a multi-year deal.

Fig. 3.9 The SkyBox Earth observation satellite under construction. (Graphic courtesy of Planet)

The Current Situation

Other new entrants are hot on the heels of Planet, also taking advantage of the new, lower cost approach to EO. In 2014, BlackSky announced plans for a 60-satellite constellation, and just days later Canadian UrtheCast announced plans to develop a constellation of 16 paired optical and radar satellites called OptiSAR. In light of the high power required for radar sensing, there has been more limited opportunities to use smallsats for this type of EO, as noted in Chapter 2. However, more EO smallsats are certainly in the works.

Free Governmental Moderate Resolution Data

One important aspect of this revolution will be the continued availability of moderate resolution data for free and public use. Partly driven by the government's realization that traditional, moderate spatial resolution data do not have the same commercial value as high resolution images, and are more in the domain of a public good, traditional EO governmental data providers are making commitments to provide these data to the public for no cost. The U. S. Landsat program continues today, with the U. S. current Landsat 8 satellite providing terabytes of free imagery over the Internet, along with all the imagery dating back to 1972 [5].

The European Commission and the European Space Agency have recently committed that all data from their new Copernicus EO program will also be provided free to the public, with open data access to all (Fig. 3.10). The Sentinal 1(radar) and 2 (optical) satellites are now operating, and more will follow. ESA studies have projected over 50,000 new jobs will be created and a €30 billion societal benefit from this

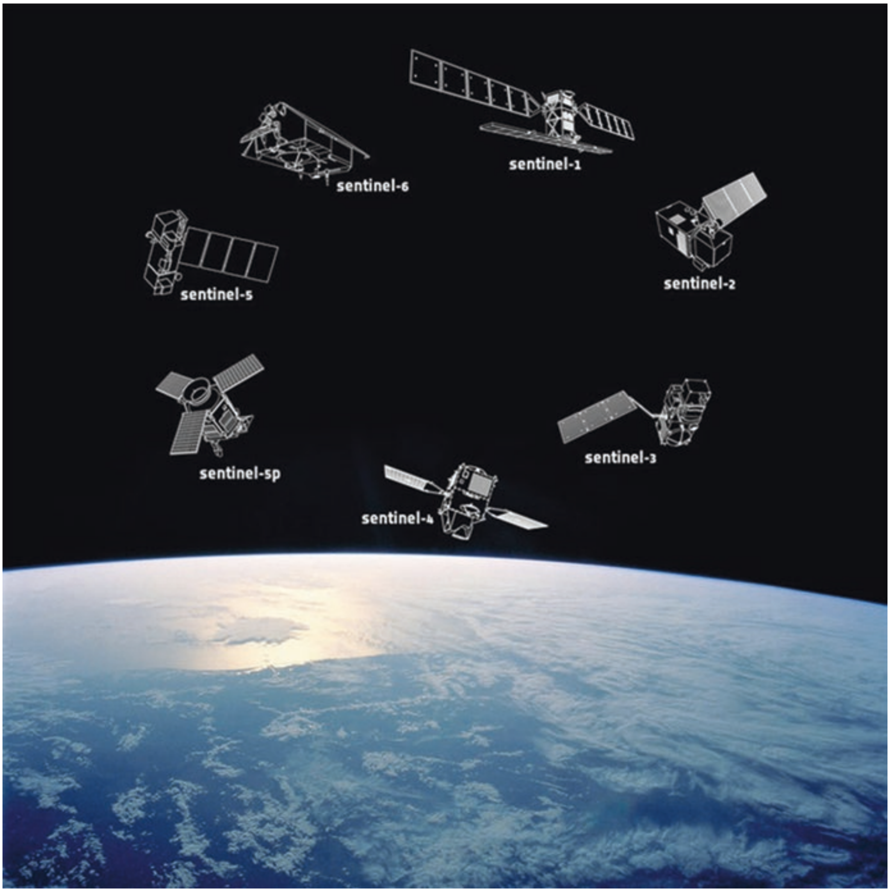

Fig. 3.10 The ESA Sentinel family of satellites. (Graphic courtesy of ESA)

program through 2030. These Sentinels will provide the European component of the Global Earth Observation System of Systems (GEOSS).

This commitment on the part of traditional governmental EO providers is a vital component of ensuring that remote sensing data will be made available to all the people of Earth who can use it. This governmental support ensures that cost of data does not preclude the benefits that these data can provide around the world.

Conclusions

This chapter has documented the rapid and paradigm-shifting development of what might be called Earth observation (EO) 2.0. We have seen, over the course of less than two decades, the change from massive and expensive satellites such as Envisat, costing billions of Euros, to constellations of hundreds of tiny 3-unit cubesats swarming over Earth, collecting daily imagery of our planet – and at a fraction of the cost. We are entering an era of cheaper, faster, and easier access to EO data. We are seeing more spatial, spectral, and temporal data, all being delivered through the Cloud to customers in hours instead of weeks. There is a new focus on non-traditional and commercial markets, with a continuing commitment to provide moderate resolution data for free as a public good. We are seeing a new focus on apps, the Internet, integration with *in-situ* and GIS data. Along with these changes we are also seeing a new focus on the general utility of these data, and less reliance on proprietary data processed by image processing specialists. Traditional issues of dual use will always be with us and will have to be readdressed as new commercial systems become more capable. Finally we will have to grapple with new issues such as space debris and orbital and frequency congestion caused by these (and other) constellations; this will be addressed in later chapters.

We are moving from the traditional paradigm of national, governmental systems, publicly funded and built or operated by major aerospace corporations and national facilities, to one based on new technologies, new approaches, new ideas, new customers, and ever smaller and more numerous satellites. We are seeing major Silicon Valley venture capital groups funding small start-ups with radical ideas and approaches. These are all focused on ever cheaper services, and serving more and new customers and markets. In 2003, global private sector investment in space EO was only US$186 million, while in 2015 there was over US$2.3 billion of private sector investment, the same amount as the cost of the entire ESA Envisat mission over a decade. These newer systems are primarily focused on smallsats, swarms, and ever-larger constellations of ever smaller cubesats providing daily global coverage.

All this is happening at a time when the capabilities of cubesats, the Internet, open source tools, and other innovations have rapidly taken hold. This explosive combination has radically altered forever the traditional EO world. We are now seeing many more players, from many more countries, with many new ideas, and many radically different approaches to how we can do Earth observation. This is all based on the lower cost of smallsats, the reduced cost of launch, and the explosion of web apps, the Internet of Things, and a young generation that have never been without a smartphone. We are quickly moving into an EO paradigm of "more." In this world of more, there are more satellites, and more types of orbits at different altitudes. There are also more ways of sensing. This means more temporal sensing (i.e., more rapid updates), more precise spectral sensing (i.e., more sensing across the spectrum into narrower bands), more radiometric resolution (i.e., into optical, infrared, and even radar bands), and more spatial resolution (i.e., higher resolution with more pixels per sensed areas). Finally, these new sensing capabilities lead to more new applications and more commercial and governmental users. We are quickly moving to a world of multiple daily views of our planet, with global to local coverage that can be integrated with *in-situ* and other data. Other changes that come with EO 2.0 are preprocessing on the satellite and in the Cloud. These capabilities in turn are driving tailored app-based products, all delivered directly to the end user. It is a radical transformation, and no one can really say where it will all lead.

However, the advancing technologies are only a part of this story. A new generation of space entrepreneurs, led by a new generation of commercial space leaders like Musk, Allen, Bezos, and others, are linking their deep financial resources with their passion about space and a driving, free market ethos of innovation and new perspectives about the benefits of space for humanity. This has opened up new and innovative financing and venture capital resources. This NewSpace environment is linked together with a new generation of young minds who do not feel bound by the limitations of large, governmental space projects or past paradigms. This combination, along with the amazing increase in cubesat capabilities for EO missions, are creating a dramatically different new space remote sensing context, one which is rapidly challenging traditional techniques, markets, and ideas about how we can image our Planet Earth and the benefits this can bring, not only to commerce but to humanity. It will be fascinating to see what comes next.

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Innovative New Uses of Smallsats for Networking and Telecom

4

Introduction

The advent of smallsats for remote sensing services as described in the preceding chapter has shaken the world of space applications in a major way – financially, technically, and operationally. Small satellite constellations carrying out remote sensing operations have led to new business models and totally new service requirements. However, applications of small satellites for communications and networking have followed a different course than was the case for remote sensing. This is because sensor technology associated with remote sensing has evolved to become much more miniaturized and thus more easily compatible with small satellites. Commercial communication satellites, especially those in GEO orbit, have evolved in a different direction. Communications satellites have trended toward the use of very large aperture antenna reflectors that in some cases have become as large as 18 to 22 m in diameter. This trend toward large antenna reflectors has led to highly concentrated spot beams that in turn allows the use of smaller and lower cost user antennas on the ground. This also allows intensive frequency reuse by isolating beams from each other to avoid interference between beams using the same portions of the radio frequency spectrum.

In short there are technical factors that favor the use of smaller satellites for remote sensing, especially in low Earth orbit. In contrast there are technical and economic reasons, centered around antenna design and costs and limited spectrum available to satisfy consumer demand for broadband communications that have not provided similar opportunities to use small satellites for telecommunications and broadcasting. However, recently there have been technical, manufacturing, and economic changes that created more opportunities for small satellite constellations in low Earth orbit for communications purposes as well. The reasons behind the changes that now allow more opportunities to use small satellites for communications and IT networking are addressed in this chapter.

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1_4

Historical Background

For many years the world of space and satellite engineering was dominated by the technical, operational, and business concepts that evolved in the 1960s and 1970s and became what might be called a set of conventional wisdoms. These "rules" that largely started with satellite communications were first developed by space agencies, and similar approaches were taken by the first commercial space enterprises to provide telecommunications, networking, and broadcasting, and later remote sensing, weather monitoring, and navigation satellite services. To date all of the satellites for global navigation satellite services and weather monitoring have been designed and built by large prime contractors for national governmental agencies, and thus they are still much more constrained than is the case with commercial satellite services.

These conventional rules about designing, manufacturing, deploying, and operating application satellites were premised on the following basic understandings:

- Launch operations, especially in the early days, were quite expensive, difficult to arrange because only two countries had launch operations, and even then launch vehicle reliability was far from certain.
- Because of the harshness of the space environment and the huge cost of launch, satellites had to be carefully designed, manufactured, and painstakingly tested to ensure they would function in space for a good while and that launch expenses were not wasted.
- Launch activities and ensuing satellite operations required a worldwide network of tracking, telemetry, and command stations that kept tabs on a satellite especially during launch, but also monitored it 24 hours a day during normal on-orbit operations to respond to problems such as component failures, recycling of batteries, switchover to backup systems, to correct antenna pointing and spacecraft orientation, to insure that star trackers and critical equipment such as antennas were functioning correctly and continuously, and also to provide proper power supply during periods of eclipse.

All of these factors, launch arrangements, building and testing high quality satellites, and building and operating a worldwide set of ground facilities that were manned 24 hours a day, led to long lead times, very expensive satellites, expensive ground facilities and high operating costs. This was particularly so for satellite communications because continuous operation availability was essential for telecommunications that sought to maintain at least a 99.98% continuity of service – or less than an hour of outage per year [1].

The first commercial satellite communications services were provided by the Intelsat network that launched Early Bird in 1965, which was designed to compete with the transatlantic cables such as TAT-1, TAT-2, and TAT-3. This satellite was launched by NASA and its design and engineering were carried out by professionals that had worked for governmental space agencies or aerospace or telecommunications companies that had worked for governmental agencies, which had set the highest standards for reliability, redundancy of components, extensive quality testing, and engineering excellence. When commercial satellite communications efforts such as those of Intelsat, and later Inmarsat and Eutelsat, the mindset and "rules" about how to design, build, launch, and operate communications were well established. When these organizations sought to obtain "launch insurance" and "operational insurance" for their satellites, the space insurance providers demanded even stricter standards of engineering excellence, and reliability testing, as well as operational tracking, telemetry, and command processes to ensure reliability.

With the successful deployment of the Early Bird (or Intelsat I satellite) in geosynchronous orbit, the dominant paradigm that developed was to design and build telecommunications satellites to operate in this orbit so that ground station did not have to have elaborate tracking capability and so that only as few as three satellites would be needed to provide complete global coverage. Although the Initial Defense Satellite Communications System was deployed as a low Earth orbit constellation, the success of Early Bird and follow-on Intelsat satellites created a global technical trend toward geosynchronous orbit satellites for telecommunications [2].

The one major exception was the Soviet Union's decision to opt for their Molniya system, which consisted of three 12-hour highly elliptical orbit satellites configured so that they could provide continuous coverage of the Soviet Union 24 hours a day, with each satellite visible at least 8 hours a day in the Soviet Union's northern latitudes. This system, however, required ground systems with tracking ground stations.

As far as satellite communications services are concerned, there was a strong technological path forward that was largely hinged on what is sometimes called "technological inversion." This trend meant making the satellites to be deployed in geosynchronous orbit more powerful, longer lived, and with ever larger antenna beam reflectors that could be kept more stable with their precise 3-axis pointing to exact locations down on Earth.

This satellite architecture trend enabled ground user antennas to become much smaller and lower in cost. This was because the simpler ground systems were not required to track the satellites across the sky, and the link budget to connect with the much more powerful satellites allowed the use of low gain dishes. In short the satellites became more sophisticated and expensive, but this allowed ground terminals to shrink dramatically in size and cost. This is sometimes referred to as "technology inversion." Over the past 50 years technological innovations for large-scale communications satellites have produced amazing advances.

If comparable gains were achieved for automobiles the results might have been delivered in the following manner: (i) a car that could last 12 times longer and still operate essentially at peak performance; (ii) a car that would go 12 times faster; (iii) a car that was 360 times more powerful and could carry 200,000 more passengers; (iv) a car that was 10 million times more fuel efficient; (v) a car that was 2,500 times more convenient and lower cost to use. Of course that car would be quite a bit more expensive to purchase than a conventional car, even allowing for inflation [3].

Table 4.1 Technological progress of communications satellites over a 50-year period. (Source: Presentation of J. Pelton at the International Communications Satellite Systems Conference, Oct. 2016, Columbus, Ohio)

INCREASES IN GEOSYNCHRONOUS SATELLITE COMMUNICATIONS SYSTEMS PERFORMANCE	
Measure of Efficiency Gain	Actual Level of Improvement
Increased lifetime	12 times longer in-orbit lifetimes
Throughput efficiency 0.5 bits/Hz to 6 bits/Hz	12 times more efficient use of spectrum
Available on-board power 50 watts to 18 kilowatts	360 times more on-board power
Antenna gain (from 360° Omni to 1° Spot Beam)	10 million times more beam concentration
Lower sensitivity of ground receivers (40dB down to 6dB)	2500 times less receiving efficiency
Reduction in cost of ground antenna ($10M to $1K)	10,000 times
Increased throughput per satellite 200 kbs to 40 gbs (or more)	200,000 times

Actual relative gains in performance from the Syncom satellite of the 1960s to today's high throughput satellites are reflected in Table 4.1. What Table 4.1 masks is that one geosynchronous communications satellite today can economically provide service to millions of users. This is because more capable and powerful satellites have allowed the cost of once mammoth and costly satellite ground antennas to drop from $10 million (plus a full-time staff of 50 people working 24/7 shifts) down to $2,500 for VSAT terminals and $1,000 or less for satellite phones.

The key to the development of communications satellite services has thus been driven by total systems costs. Thus there was a calculated reasonable "tradeoff" cost of the satellite and its operation vs. the cost of all the user transceivers that would be expected to access the satellite. There was thus a clear objective to achieve balance in terms of overall systems cost optimization.

In terms of these system engineering tradeoffs, this sought-for "balance" has historically been 50% for the space segment and 50% for the ground segment. With this type of trade-off a satellite and its operation that could cost as much as $500 million would be balanced with 500,000 users of the satellite paying $1,000 apiece for a satellite phone. How this process has played out over the past five decades is reflected in the Fig. 4.1, where it can be seen that the satellites have grown in mass, power, and antenna reflector size (i.e., the blue arrows going up), while the ground antennas have continued to shrink in size and cost (i.e., the red arrows going down) as user transceivers have multiplied from dozens to many millions.

Once 3-axis body-stabilized satellites were developed and able to constantly point to Earth with high accuracy through the use of momentum wheels than spun at 4,000 to 5,000 rpm, the high gain antennas on these communications satellites continued to grow in size. The latest technology with in-orbit deployable antennas, as developed by the Harris Corporation and other manufacturers, have now grown to as large as 18 to 22 m in diameter. Fig. 4.2 shows

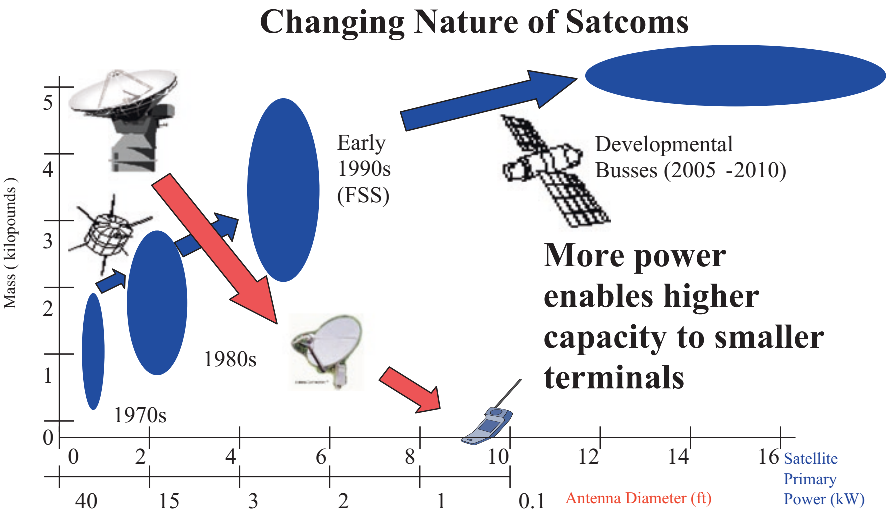

Fig. 4.1 The technology inversion of satellite communications, with satellites going up in size and performance as ground antennas have shrunk in size and cost

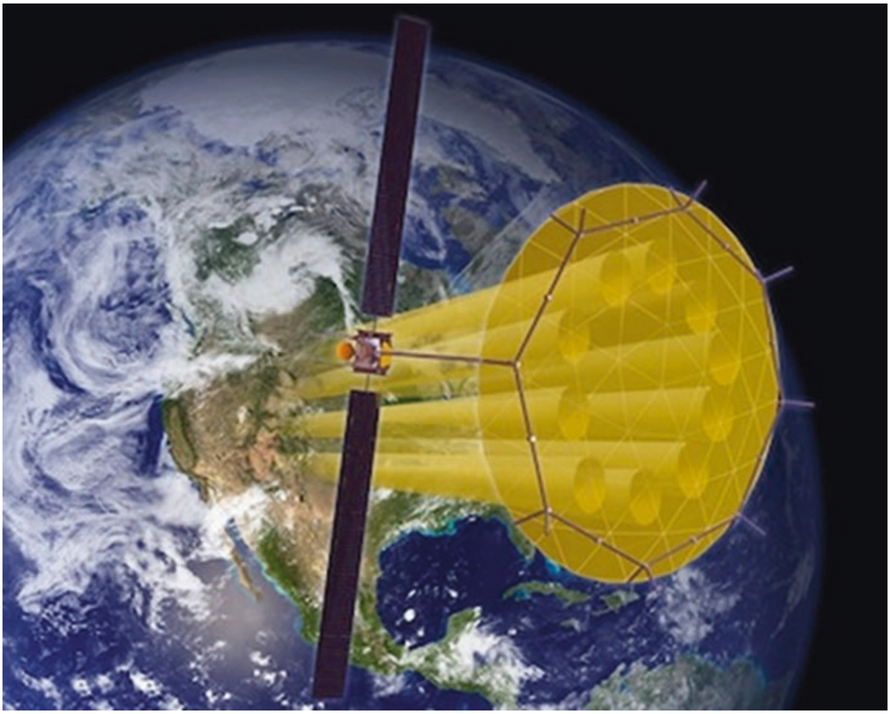

Fig. 4.2 The SkyTerra satellite depicted in operation using a gigantic multi-beam antenna (Graphic courtesy of the Harris Corporation)

the SkyTerra satellite with its large, sophisticated antenna and feed system that can create a very large number of spot beams using just one very large parabolic shaped antenna reflector. This very large and complex satellite with enormous solar arrays and a giant multibeam antenna was the antithesis of a small satellite. Of course the payoff from this very expensive giant 5-ton satellite is the ability to communicate via this spacecraft by a handheld satellite phone of modest cost. But there were some that envisioned that there might be an alternative approach to the development of large-scale and costly satellites to meet other types of communications and networking needs.

The Start of the Small Satellite Movement

The commercial satellite providers and manufacturers that have evolved over the years have had, as explained above, good reasons to make their satellites complex, large, and powerful in order to drive down the cost of user transceivers. Instead of dozens of giant ground antennas that allowed communications by the earliest GEO satellites such as Syncom 2 (1963) and Early Bird (1965), there are today millions of satellite user devices of low cost that are able to link to communications spacecraft because of this technological revolution. Since the satellites have gone from small to very large, while ground user terminals, in a reverse trend, have steadily shrunk to very small size, this process has been called technological inversion. We have in the course of fifty years gone from small and low-powered satellites operating with huge ground antennas to very large satellites that can support communications to and from millions of user transceivers that are constantly going down in size and cost. But the technology keeps changing. One of the key elements of change has come about from new thinking about how to use low Earth orbit satellites for communications and networking and the development of new technology that might make low Earth orbit constellations work effectively to meet new types of networking needs.

The First Small Satellites for Communications

The first step in creating small satellite for communications came through the volunteer efforts of amateur radio operators who also happened to be satellite engineers. These clever engineers collaborated together and went about designing, building, and launching what was called OSCAR-1 (see Fig. 4.3).

This small satellite, the world's first private spacecraft, operated at much lower frequencies and significantly utilized a low Earth orbit rather than a geosynchronous orbit. This was a true small satellite designed to link to amateur radio operators, or "ham operators," around the globe. The satellite's antenna was essentially an omni-directional simple device that could use its very low orbit to connect with the simple short radio message of "Hi" to ham operators across the world with sensitive enough receiving antennas [4].

On December 12, 1961, a Thor-Delta rocket launched a Discover 36 reconnaissance satellite, but also piggybacked aboard was the small Oscar-1 satellite that operated for 22 days before its batteries gave out. OSCAR stood for

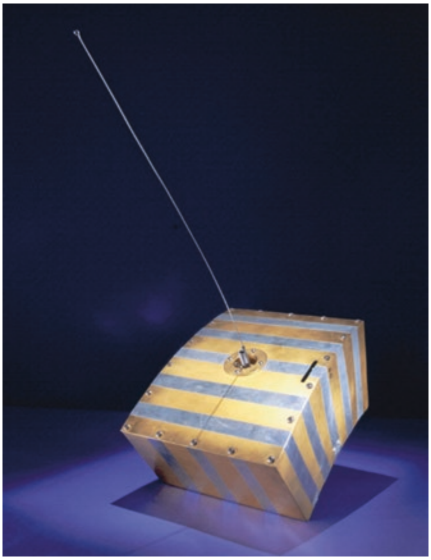

Fig. 4.3 The Amsat engineers designed and built Oscar-1 – the first smallsat for radio communications. (Image courtesy of AMSAT)

Orbiting Satellite Carrying Amateur Radio, and in many ways it represented a key precedent that said individuals, rather than just national space agencies and defense ministries, might dare to create spacecraft to go into the cosmos [5].

Universities and research labs that did not have the resources of space agencies or commercial satellite operators also sought to figure out what could be done with small and low-cost satellites with some efficiency. They explored what might be designed by students and university experimenters, as well as satellite engineers from countries that were just starting up space programs. The Surrey Space Centre at the University of Surrey, the Utah State University, which hosts an annual small satellite conference, and others began to design small satellites for experiments, remote sensing and computer storage and data relay as early as the 1970s.

In addition, national space agencies also began to reach out and seek to collaborate with universities and research centers. NASA was among the first to support various types of what they called "cubesat" programs. Thus a variety of programs began to sprout up around the world and sparked interest in the design of small satellites. Since 1990 NASA has also innovated by beginning to purchase expendable launch vehicle (ELV) services directly from commercial providers to support launch capabilities for small satellite projects. There is almost always some excess volume and auxiliary mass allowance associated with commercial launches, so arranging for a piggyback launch similar to what was arranged for the OSCAR-1 launch clearly was a very logical thing to do. These launch options can be used for small satellites and particularly cubesat projects developed as student experiments for technology demonstations and scientific and applications missions. These commercial launches can accommodate various types of orbital inclinations and altitudes and usually can accommodate several cubesat missions.

Thus for over 20 years small satellite programs have developed contractual arrangements to fly as an auxiliary launch on either space agency or commercial flights. These launch opportunities now exist for launches carried out in the United States, Russia, Europe, India, and China – among other options. New commercial launch operations are expanding these options. Thus the SpaceX Falcon 9, Orbital ATK's Antares, Virgin Galatic Launcher One, Lockheed Martin Athena, and even S-3 in Europe offer exciting new opportunities [6].

These auxiliary launch options have varied from low Earth orbit deployment to even interplanetary missions. In 1998 NASA started its Launch Services Program that assists with small satellite programs by providing advice with regard to independent verification and validation, risk assessment, design and development, and assistance with scheduling of a launch opportunity. Today there are a wide range of possibilities to get small satellite projects launched. These options include working with Nanoracks to fly an experiment on board the ISS. Nanoracks can also assist to get cubeats launched via the Japanese robotic arm from their Kibo experimental module.

The NASA Cube Sat Launch Initiative (CSLI) provides access to space for cubesats developed by NASA centers, accredited educational institutions and non-profit organizations. The object of this program was to provide cubesat developers a low-cost pathway to conduct research in the areas of science, exploration, technology development, education, or operations.

The earliest projects that came out of the Surrey Space Centre program were typically related to remote sensing or store-and-forward data relay. The first of the store-and-forward smallsats developed at Surrey relied on very efficient computer storage that collected data messages as the satellite flew over remote areas and then downloaded the text in digital form as it flew over a few download points located around the world.

One of the first of these small data relay satellites to have an "operational role" was called Livesat. Two of the small University of Surrey satellites (UoSats) designed for store-and-forward data relay were launched under funding provided by the Mitsubishi Corporation. The mission of these two Lifesat small sats was to support remote medical clinics in Africa. Livesat doctors in remote clinics without remote international communications available to them could use these two low Earth orbit satellites to request shipments of drugs, could seek the text from medical journals about the latest research on tropical diseases, and otherwise link to the outside world. In a matter of hours responses to Livesat texts could be received. Although this was far from broadband communications it provided an effective external link for these isolated African doctors.

The Volunteers in Technical Assistance (VITA) also used similarly designed UoSat store-and-forward data relay connections to support their communications needs in other locations around the world, particularly in South America. VITA is a development service organization that seeks to apply new and appropriate technology to aid developing countries. The small remote terminal used by VITA was compact and cost only about $2,000. The communications capabilities provided via the

UoSat network were of enormous help to the VITA-based projects that were carried out in many rural and isolated areas [7].

More recently there was a Surrey Space Centre project that was launched successfully on Feb. 23, 2013, into low Earth orbit. This was a small 3-unit cubesat called STRaND-1. This satellite was controlled by both a classic UoS onboard computer and a Google Nexus “smart phone.” both of which could be accessed from the ground. This small satellite was designed and put together at low cost and in only three months using mostly volunteer effort. It also included a water-alcohol microjet thruster system for maneuverability [8] (see Fig. 4.4).

NASA is also sponsoring a similar “Phone Sat” project that will use a smart phone as an onboard controller. This phonesat system was built in the first instance for a reported cost of only $3,500. The purpose of projects such as STRaND-1 and Phone Sat is the ability to create smart and capable small satellites at very low cost indeed. The key aim is to determine whether small satellites could be viably built using off-the-shelf components without elaborate thermal vacuum testing and reliably operated in space at a small fraction of the costs associated with conventional satellites.

The small satellite movement in many ways started with the efforts at the University of Surrey in the 1970s to explore how to make satellites less costly by using commercial off-the-shelf (COTS) components. Martin Sweeting, a research student at the University of Surrey, started the process by using COTS parts to build UoSat-1 in 1979, which was launched by NASA in 1981. This was followed by UoSat-2, which was launched by NASA in 1984. This put the University of Surrey’s small satellite efforts on the map. These efforts have expanded globally from there. The

Fig. 4.4 A STRaND-1 3-unit cubesat that used a smart phone as a system controller. (Graphic courtesy of Surrey Space Centre)

Surrey Space Centre, under the leadership of Sir Martin Sweeting, has grown to an enterprise with over 200 employees, an annual turnover of over 100 million pounds, and 99% corporate ownership by Airbus DS. Its satellite projects have spread to extensive partnerships around the world with small satellite undertakings in cooperation with the United Kingdom, Algeria, Nigeria, South Korea, Canada, China, Brazil, Germany, France, Finland, the European Space Agency, and more [9].

The University of Surrey has also served as a founding member of what is called the University Global Partnership Network (UGPN). This network seeks to stimulate international collaboration related to small satellite projects. The UGPN thus enables academics and students from some of the world's major universities to work together on issues of global importance such as the current RemoveDEBRIS effort aimed at developing small satellite technology to assist with space debris removal in programs such as "CubeSail" and "RemoveSat."[10].

The Small Satellite Revolution and Communications Services

The revolution in small satellite systems can be said to have started with the Surrey Space Centre's efforts to create small, cost-effective satellites with non-space qualified components that dramatically lowered the cost of their spacecraft. They also found clever ways to package all of the key elements into cubesat-sized units. But this alone was not enough to start a true revolution such as is being experienced today with commercial systems seeking to provide market competitive services – especially for telecommunications and networking offerings. The other key ingredients of this revolution are the following: (i) cost-effective and reliable ways to deploy constellations of spacecraft in low Earth orbit; (ii) new ground antenna technology that allows electronic tracking of low Earth orbit satellites using new meta-material technology; (iii) systems technology that allow low Earth orbit constellations to co-exist with geosynchronous satellite systems without undue harmful interference; and (iv) new manufacturing techniques that allow large-scale production of a number of small satellites at low cost, but with high quality and reliability. Let's explore these innovations one at a time.

Constellations in Low Earth Orbit

There is a significant relative difference in effective communications performance between that of a GEO satellite and that of a low Earth orbit satellite, which is some 40 times closer to Earth (i.e., typically 900 km above Earth's surface as opposed to nearly 36,000 km away from Earth). For a given transmission power the effective strength of the signal is on the order of 1,600 times stronger. This is because the effective "path loss" depends on the distance of the satellite through the inverse square law. Thus a forty-fold difference in distance translates to a factor of 1,600 (i.e., 40^2) difference in the effective received power.

The problem with using low Earth orbit satellites is that they move across the sky quickly. A satellite that is in an orbit perhaps some 900 km high travels across the sky from horizon to horizon in a few minutes. This means that any directional or high-gain antenna has to track the satellite across the sky rapidly and that anyone trying to use that satellite for communications can do so for only about 30 minutes a day as it comes whizzing overhead at high enough angle to be seen several times a day.

The tradeoffs between GEO and LEO satellites were dramatically different. You could use only three GEO satellites to cover the entire world (except for the ice caps) and ground antennas could be high-gain dishes that constantly point to the same location in the sky. You did probably have to make the antennas on the satellite bigger to compensate for the big path loss associated with a GEO satellite, which is almost a tenth of the way to the Moon, but this was acceptable because you had only to build and launch three of these large antenna satellites to complete a global network, or just one of them to cover a large country or region such as Europe. The other option was to build and launch on the order of 50 low Earth orbit satellites to get anywhere close to global coverage, and ground antennas would have to be able to track the fast-moving satellites closely and accurately, or you were forced to use a very low gain “omni” antenna that could capture the satellite signal from any angle. The basic physics thus drove commercial satellite communication companies and defense and governmental satellites to by and large opt for big and powerful GEO satellites or configurations such as the Russian Molniya highly elliptical orbits.

But the experience that was drawn from the Amsat Oscar satellites, the University of Surrey (UoS) satellites, and other experimental projects suggested that there could be low Earth orbit or even medium Earth orbit satellite networks that could work for some applications. The advent of the Internet and the growth of data networking on the ground accelerated this thinking. This is because data networking operates best with minimal transmission delay, or what is called a lack of latency. Since LEO satelites can have on the order of 40 times less latency, this spawned a number of ideas about what might be done with LEO satellites.

Perhaps most ambitious idea to emerge from this new thinking was the project known as Teledesic. This was a so-called “mega-LEO” satellite project to deploy some 840 satellites plus 80 spares to a gigantic network of 920 satellites. The Teledesic satellites would have had antennas that could, in effect, create stable beam patterns that would effectively be “painted” on the ground so that terrestrial antennas would not have to track moving satellites. Instead each satellite as it flew overhead in a fixed grid structure would effectively maintain a beam on the same location with at least a 30 degree masking angle so the ground antennas would, in effect, seem to be seeing a spot beam from a GEO satellite.

The advocates of the program, such as designer James Spencer, suggested that Teledesic satellites could be churned out like television sets or video cassette recorders and launched in bunches and the entire network built and deployed for perhaps $3 billion to $4 billion. The project, which won the early backing of Bill Gates and Craig McCaw, received a great deal of publicity, but it was too “bleeding edge” to succeed in the 1980s.

The Ka-band technology (i.e., 30/20 GHz) was not really developed for satellite transmission or for ground antennas, the cost of designing, building, and deploying the satellites ballooned, and the project was canceled. Other companies, however, filed with the FCC for other Ka-band fixed satellite services, including some that were low Earth orbit constellations, but of the nearly 15 satellite systems that were filed, only the GEO Blue Skies/Ka band satellite was ultimately deployed.

These initiatives, however, laid the groundwork that came in the 1990s. Orbital Sciences (now Orbital ATK) started a store-and-forward data relay project call Orbcom. Motorola backed a satellite project named Iridium to develop a global low Earth orbit network for land, air, and sea mobile voice and data communications to user handheld phones. (The name Iridium comes from the element with atomic number 77. This was because the original design was for 77 small satellites configured in eleven planes, each containing seven satellites. Ultimately it ended with larger satellites in a 66-satellite configuration, but the name remained unchanged.) Globalstar filed and deployed a competitive mobile satellite communications systems that was also in low Earth orbit. This was backed by Space Systems/Loral and involved deploying a network of 48 mobile satellites that covered the world from 55 degrees north to 55 degrees south, since they saw no market in the polar region and also decided to skip intersatellite links. Yet another mobile satellite network known as ICO that was a spin-off of a planned network for land mobile satellite communications by the INMARSAT organization. This proposed medium Earth orbit mobile satellite system was never deployed. These various initiatives, however, shared a common fate in that they all filed for bankruptcy.

This torrent of bankruptcies involving LEO or MEO satellite networks for communications – Teledesic, Orbcom, Iridium, Globalstar, and ICO – had a very negative impact on the commercial communications satellite industry. Many other proposed projects were stillborn as well. The net result was that financial markets and satellite systems operators steered clear of the idea of deploying any new small satellite constellations. But as time passed Orbcom, Iridium, and Globalstar found market traction under restructured ownership and management that has seen them expand their customer base, and these systems have deployed or are deploying a new generation of satellites amid expanding customer demand.

A communications entrepreneur named Greg Wyler who has a vision of providing Internet access to Africa and developing countries in the equatorial region has managed to forge a new coalition of investors. His first project, known as O3b (for the Other Three Billion people), has joined forces with SES of Luxembourg and other investors and deployed a medium Earth orbit satellite, and SES has now exercised its option to buy 100% control. These satellites are really medium-sized satellites, but Wyler saw O3b only as a small step forward to realizing his vision. He has now moved on to launch with gusto his "OneWeb" satellite network. This is a huge low Earth orbit constellation that will begin with deploying some 648 small satellites plus spares in the 800 to 900 km orbital range, beginning with the trial launch of ten production

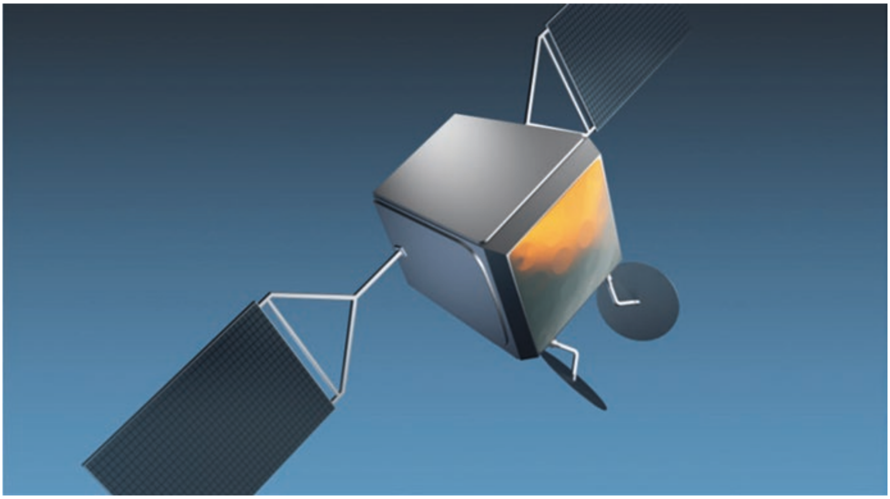

Fig. 4.5 Mock up of OneWeb satellite planned for mass production by Airbus DS. (Graphic courtesy of Airbus DS)

satellites in 2018 and full deployment starting in 2019. Contracts have been let to Airbus to build 900 of these 150-kg small satellites in assembly-line mode [11]. Fig. 4.5 reflects the current design concept for the OneWeb small satellites.

Clearly OneWeb faces a number of challenges. Will all of the satellites be manufactured flawlessly and perform well in orbit? Will all the needed satellites be deployed in a timely manner to form a coherent network that can operate reliably for a number of years? Can these satellites truly avoid harmful interference with GEO satellites that have protected status? Will these small satellites be removed successfully from orbit at end of life to avoid significant orbital debris concerns? Will there be sufficient revenues to pay for all the satellites, the launches, the system operations, and other operating expenses? And finally, will the remaining billions of dollars in capital needed to pay for this fully deployed system actually be raised? [12].

There are also additional hurdles to overcome that include such things as orbital debris and liability concerns, obtaining landing licenses to operate in perhaps as many as 200 countries and territories around the world, and even competition from other large-scale small satellite constellations that are now planned. There are serious questions within the satellite community about the technical and legal implications of operating such massive constellations in orbit, as these are potentially dangerous systems in terms of generating harmful interference with other space systems and in terms of their potential to exacerbate the problems of orbital debris. These questions also include: what if there is an operator accident and two of these satellites collide? or what if an out-of-control defunct satellite crashes into the OneWeb constellation, creating massive new orbital debris problems that lead to huge legal claims?

OneWeb has sought to develop systems to minimize interference with GEO systems, and developed systems to ensure safe end-of-life disposal of its satellites that seem well considered and engineered, but they are as yet unproven. And OneWeb is not the only large-scale constellation of communications satellites now planned. Table 6.1 in Chapter 6 provides a summary of LEO constellations that have been variously proposed or formally filed for in terms of frequency approval and orbital location. If all of the satellites in these proposed systems are built and deployed it would add on the order of 20,000 low Earth orbit satellites to this region of space that already has about 20,000 orbital debris elements being tracked in this region.

There is concern about whether a number of large-scale LEO constellations can all safely co-exist given the fact that the various space agencies now project that there will be an on-orbit collision from current space junk already in orbit, perhaps as often as once every five years [13].

New Ground Antenna Technology

The groundswell of interest in small satellite constellations in low Earth orbit, especially for communications purposes, is based on several factors. One of the most important relates to new ways to keep the cost of satellite ground antennas down to the minimum. The other key issue relates to new approaches to carrying out low-cost manufacturing. This second issue will be discussed immediately below.

There are several approaches to achieving low-cost satellite ground systems (whether on land, at sea, or on aircraft). One approach involves the technology envisioned by the Teledesic system that could “paint” permanently defined spot beam locations on Earth below by using phased array antennas or other smart antenna systems to create continuous coverage of a geographic area by constantly shifting the beam focus from the satellite above to the next one coming into view. This technology can certainly work, but the switching technology is difficult, and the satellite antenna technology is complex and expensive. It would certainly undercut the objective of low-cost manufacture of the satellite.

The other option of having ground-based antennas that would use phased array antennas or phased array “smart feed systems” also undercuts the objective of keeping the user antenna or one-way receiver terminal costs low. The newest approach is to use flat ground antennas made of “smart” metamaterials that are able to electronically track LEO satellites as they travel overhead. This seems to provide a key technical advance that allows these new type antennas to track without physically moving. The Kymeta Company, backed by Bill Gates, is now manufacturing antennas that are compatible with fast-moving LEO small satellites and can be purchased and installed at reasonable cost (see Fig. 4.6).

The user antennas developed for use by Orbcom, Iridium, and Globalstar were able to provide improved access capabilities that were superior to an “omni” antenna by capturing signals from above, but metamaterial antennas are clearly a key advance allows small satellite constellations to be far more technically viable than ever before.

Fig. 4.6 Kymeta "smart" flat antenna that electronically tracks LEO satellites. (Graphic courtesy of Kymeta)

New Manufacturing Techniques

The advances in manufacturing and improved and accelerated testing techniques are clearly the other key step forward. There is no one silver bullet in terms of improved design, manufacturing, and testing technique. The many ways to reduce cost or shrink the size and mass of satellites have come from a wide variety of sources. Some come from technical advances in electronics and coding technology. Some come from smallsat innovators. Others come from new technical innovations from the commercial launch industry, or "non-space" advanced manufacturing areas, such as 3-D printing.

Application Specific Integrated Circuits (ASICs) have created electronic functionality of all sorts of electronics in space and on the ground, and with widespread use these components have also lowered cost. The small satellite design efforts that span many years also come into play. The innovations that started with the AmSat volunteers that created OSCAR and the Surrey Space Centre scientists and engineers that designed the UoSats have demonstrated time and again that commercial off-the-shelf components such as cell phone batteries, or processors, if properly tested and vetted, can replace very expensive space-qualified components.

More recently designers have found ways to eliminate some components from satellites entirely, while 3-D printers can allow effective quality manufacture of complex component parts at significantly reduced costs. Innovations that have come from companies that have found ways to design lower cost small satellites for remote sensing such as Planet Labs (now Planet) and Skybox (which became Terra Bella and then most recently has also merged with Planet). These techniques and processes have been transferred over to those aiming to manufacture small satellites to be used for telecommunications and networking. New lower cost commercial launch vehicles have, of course, served to aid in lowering the overall cost of building and launching all types of spacecraft, big, medium, and small.

It is true that a number of these innovations can also transfer to those that design, build, and operate large commercial satellites. Certainly those that design and build large spacecraft, such as Boeing, MDA, Thales Alenia, and Airbus DS, are today manufacturing small satellites as well.

Those simply seeking to build and launch cubesat projects at universities, research centers, or other smaller companies have benefitted from all of this innovation. It is possible to order a cubesat kit online today that provides the basic structure for 1-unit, 2-unit, 3-unit, up to 6-unit frames as well as many essential components. The prices for key components are typically in the budgetary range of universities.

Many of these providers, however, are restricted from selling components and kits to people or organizations in some countries. The Pumpkin Cubesat Kit website for instance indicates that "United States export laws prohibit Pumpkin (a California corporation) from providing CubeSat Kit components to end-users in the following countries: Cuba, Libya, Iran, Iraq, Sudan, Syria and North Korea. Resellers, freight forwarders, etc., are also prohibited from exporting CubeSat Kit components to these countries." [14].

The image in Fig. 4.7 shows a 3-unit cubesat Motherboard of a picosat satellite that NASA recently deployed from the International Space Station.

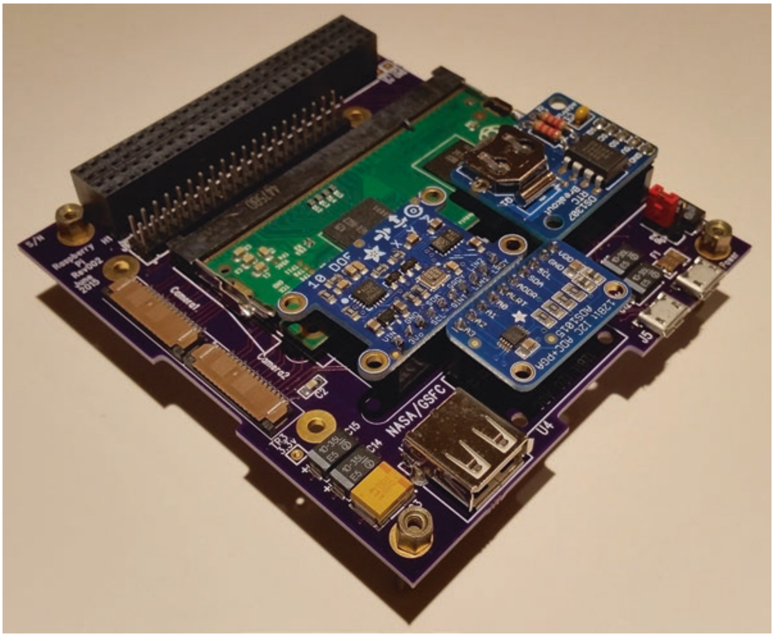

Fig. 4.7 Motherboard for the nanosat 3-unit cubesat that was recently deployed in low Earth orbit. (Graphic courtesy of NASA)

Issues Still Pending with Regard to Small Satellites for Communications Purposes

The above discussions generally covered positive factors that are pushing forward the concepts and technology that are enabling the development of small satellites for communications and networking. And as noted there are many points that are "pro" the development and use of small satellites. It is important to keep these views in some perspective. There are now new so-called "high throughput satellites" that are being deployed by Intelsat, Echostar/Hughes Network Systems, and Viasat, among others, that are quite large but highly efficient GEO satellites – some with transmission speeds in excess of 100 gigabits. There are satellites now in the developmental stages that will exceed terabit-per-second broadband capabilities that will operate using very compact and low-cost user terminals. In terms of transmission cost efficiency, these next generation large-scale conventional GEO satellites can deliver the equivalent of a high-quality voice channel service across oceans or countries at an annual cost of under $5 a year. Thus small satellites for many communications applications are not a truly disruptive economic service that can compete with these super-efficient satellites. Their greatest potential appears to be in providing low-latency, Internet optimized services to underserved developing countries of the Global South.

Even more important to note is that massive deployments of large-scale constellations for low Earth satellites, for whatever reason – remote sensing, communications, surveillance, or scientific data collection – poses some key risks. One of the most important risks relates to orbital space debris. The other major risk is unacceptably high frequency interference or inefficient use of limited spectrum in a very much more extensively data-rich and information-saturated world.

Orbital Space Debris

In the 1970s NASA scientist Donald Kessler issued a warning that the gradual buildup of orbital space debris, especially in low Earth orbit, could ultimately lead to a runaway avalanche of debris that would continually generate new debris through debris-on-debris collisions. At the time this warning was essentially disregarded, since most impact hazards to spacecraft came from the natural phenomenon of micrometeorites. But year after year upper stage launch vehicles, derelict spacecraft, exploded fuel tanks and batteries, the results of explosive bolt releases, and even abandoned tools of astronauts resulted in the growth of what is sometimes referred to as "space junk."

Currently there are over 22,000 debris element more than 10 cm in diameter (i.e., about the size of a baseball) that are being tracked in low Earth orbit. Two recent events have created on the order of 4,500 of these debris elements. One of these was caused by the Chinese intentionally firing a missile in 2007 to destroy one of their defunct weather satellites as an antisatellite test that unfortunately generated some 2,200 long-lived debris elements. Then, in 2009, a defunct Russian Cosmos weather satellite collided with an operational Iridium mobile

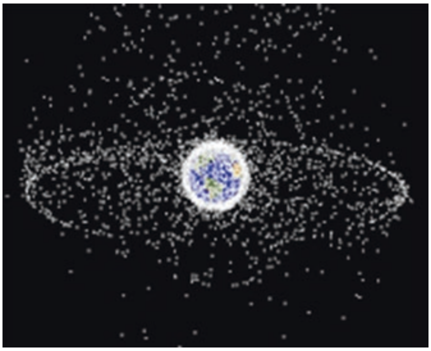

Fig. 4.8 Earth is surrounded by space junk, with the outer circle being GEO debris and the white inner sphere representing LEO debris. (Graphic of courtesy of NASA)

communications satellite and also created about 2,200 new long-lived debris elements. Fig. 4.8 represents a depiction of major orbital debris elements.

One might think at first that debris that is as small as a baseball is surely not such a big worry, but a debris element of this size traveling at nearly 28,000 km/h has the kinetic energy of a bomb. Even debris as small as a paint flake, of which there are over a million, can pierce an astronaut's spacesuit or even crack the window of a crewed spacecraft such as the space shuttle. The current largest worry is of the derelict Envisat, which is the largest object in low Earth orbit, with a 101-minute repeat orbit that is uncontrolled and not capable of being actively de-orbited. If this were to be hit by even a several unit cubesat at extreme relative velocity, it could potentially create a very large new swarm of debris. Currently the European Space Agency is working on its e.Deorbit project that might serve as a proof-of-concept mission that in time might potentially allow the removal of this largest threat to low Earth orbit [15]. NASA, the U. S. Defense Advanced Research Projects Agency (DARPA), the German Space Agency (DLR), and a Swiss research initiative as well as several private research projects are working on parallel active debris removal initiatives as well [16].

The fundamental point here is that the Kessler syndrome, also called the Kessler effect, is a serious threat to all human space activities and that many hundreds of satellites worth many billions of dollars are potentially at risk. Indeed the vital services that these satellites provide for communications, broadcasting, Internet access, remote sensing, weather and climate change monitoring, strategic defense services, and precise timing and navigation are all potentially at risk. The continued deployment of small satellites without stricter controls on their deorbit, proven systems to carry out active deorbit of large derelict objects in low Earth orbit, and other protective actions seems unwise. There are a variety of actions that might be taken to combat orbital debris and thus enable the safer deployment of large-scale small satellite constellations. One concept is to create an orbital debris removal fund that all entities launching satellites would contribute to that would look and feel much like the purchase of satellite launch insurance.

Regardless of the answer and any new regulatory actions concerning orbital debris, those who are planning to deploy large-scale smallsat constellations need to seriously consider the risks that are involved. They should seriously consider what further actions might be taken to minimize the risk of collision between two of the satellites in their own constellation and safe end-of-life de-orbit procedures to follow. Most especially, they need to consider the risks and possible protective actions required to try to avoid a collision of a non-controlled space debris object with a satellite in their constellation – especially if it triggers a further avalanche effect. Protection against these random type events are, of course, the most difficult to prevent.

Minimization of Interference between LEO and GEO Satellites and Frequency Use Efficiency

The other concern is not a physical collision but radio frequency interference. LEO satellites as they cross the area near the equatorial zone risk interference to the many GEO satellites that are protected against interference. There are a variety of means that can be used to avert harmful interference to GEO satellites from LEO satellites, but these have not been fully tested in practice. Some of these techniques to switch off service or to point antennas so as not address the area where GEO satellites operate are quite innovative and some processes have been patented. What is clear is that after a large constellation is deployed, and it is found that the interference minimization process does not fully work, then corrective action is difficult. This is one of several reasons why the decision by OneWeb to deploy ten small satellites for their constellation as an early test phase is a prudent idea.

The problem of interference is, of course, only going to become more difficult in time. There are plans to deploy high-altitude platform systems and Untended Aeronautical Systems to provide various types of communications services at various altitudes up to the stratosphere. In addition, there are ever expanding plans to provide broadband cellular services around the world and possibilities that some of the frequencies allocated to accommodate growth will involve frequencies now used by satellites for communications or closely adjacent frequencies.

Conclusions

This chapter has recapped the history of the technical and operational development of communications satellites and why there has been a continuing effort to develop commercial communications satellite systems that have had higher and higher power and larger and larger high gain antennas to concentrate spot beams and to allow geographic isolation of these spot beams to enable frequency re-use. As these commercial trends continued, other users such as Amsat developed the OSCAR-1 small satellite and the University of Surrey at the Surrey Space Centre developed the small satellites known as UoSats that allowed store-and-forward data relay services.

The first thought of using smaller communications satellites in low Earth orbit came with the idea of providing mobile satellite services at the time that cellular communications started to become popular. The idea that drove for the push for smaller satellites in low Earth orbit was that the user transceivers could be made much smaller and mobile, and also that there would shorter transmission delays compared to the GEO satellites. The initial systems of this type, known as Iridium, Globalstar, ICO, and Orbcom, all had business development and market issues and had to undergo financial restructuring and bankruptcy. Nevertheless the technical viability of these services were ultimately proven. Now, second generation versions of these mobile communications networks are being deployed. Today mobile satellite systems operate both in GEO as well as LEO – each with its technical, operational, service, and market advantages and disadvantages.

Low Earth orbit satellites, because of low latency, or transmission delay, are ideal for data services and especially for Internet-related services. Plans are now underway to construct and deploy a number of large-scale smallsat constellations in low Earth orbit – typically in the 600- to 1,000-km range. Many of these new mega-LEO systems are focused on providing Internet connectivity to the underserved regions of the world, such as in the equatorial regions and the Global South.

Today the expertise gained from the various smallsat predecessor projects is being complemented by totally new innovations to make smallsats for communications and networking services more viable. These current innovations include lower cost satellite manufacture, the expanded use of properly vetted commercial off-the-shelf (COTS) components, new types of satellite design, technology, and coding that allow satellites with fewer components, and lower cost commercial launcher arrangements. All of these factors seem to be combining to allow the launching of new commercial ventures to deploy small satellites in large-scale constellations – both for mobile communications and especially for Internet access in rural and remote areas.

There are, however, areas of concern, and these involve orbital debris-related issues, the potential for expanded radio interference, and a concern as to just how many large-scale LEO constellations can be reasonably deployed without physical and spectrum interference with one another, as well as with GEO satellites above and high-altitude atmospheric platforms below.

Small satellites remain a very broad concept. Femtosats, picosats, nanosats, and cubesats can be quite modest in size and typically have quite limited capabilities in terms of maneuverability. Commercial small satellites for communications have different requirements than those for remote sensing – especially those that can use quite compact optical sensors. Commercial small satellites for communications are much, much more capable and are typically over 100 kg in size and can be almost up to 1.000 kg in size.

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Small Satellites and the U. N. Sustainable Development Goals

5

"There can be no Plan B because there is no planet B."

– Former U. N. Secretary General Ban Ki-Moon. 2016

The Origins of Shared Global Development Goals

The phrase "sustainable development" is now a part of the common lexicon of politicians and civil society. Although one can trace the roots of this concept (at least in the West) to ideas developed in Europe concerning forest management as far back as the 17th century, it is only in the latter half of the 20th century that it became a key theme of the environmental movement, with the realization that economic systems need to fit into a common global ecological system that contains a limited pool of resources. One of the earliest modern expressions of the concept dates to the famous 1972 Club of Rome report entitled *The Limits to Growth* [1]. This study addressed the question of how long it would take to reach the limits of growth on Earth if the growth trends in world population, industrialization, pollution, food production, and resource depletion continued unchanged. For such a scenario the authors predicted a global collapse within a century. However, they also believed that it would be possible to avoid such a catastrophe by marrying economic and environmental concerns:

> *It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential.*

The same year that *The Limits to Growth* study was published, the U. N. Conference on the Human Environment was convened in Stockholm, Sweden, to consider questions concerning the environment and economic and human development. The concept of sustainable development, as it is most widely understood today, derives from the definition contained in the report *Our Common*

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1_5

Future, commonly called the Brundtland Report, which was released by the U. N. World Commission on Environment and Development in 1987 [2].

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:*
>
> - *The concept of 'needs', in particular, the essential needs of the world's poor, to which overriding priority should be given; and*
> - *The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.*
>
> –World Commission on Environment and Development, *Our Common Future* (1987)

This definition of sustainability goes beyond environmental concerns, to a more socially inclusive and intergenerational perspective on environmentally sustainable economic growth. Indeed there are now evolving concepts of law that involve the idea of intergenerational rights.

In 1992 the first U. N. Conference on Environment and Development was held in Rio. The main outcome of this conference was "Agenda 21," a non-binding, voluntary action plan for the United Nations and other multilateral organizations and individual governments around the world that can be executed at local, national, and global levels.

On September 8, 2000, following a three-day Millennium Summit of world leaders at the headquarters of the United Nations, the General Assembly adopted the Millennium Declaration [3]. This declaration contained several political commitments that were subsequently expressed as the Millennium Development Goals, a series of eight goals with twenty-one targets to be achieved by 2015 [4]. Progress towards meeting these goals was uneven, and the international community revisited the global goals in 2015.

On September 25, 2015, the 194 countries of the U. N. General Assembly adopted the 2030 Development Agenda, entitled *Transforming Our World: The 2030 Agenda for Sustainable Development* [5], which has five pillars: people, planet, prosperity, peace, and partnerships. The agenda contains 17 Sustainable Development Goals (SDGs) and 169 targets associated with those goals. The 17 SDGs are designed to "transform our world through ending poverty, protecting the planet and ensuring prosperity for all." The goals, which must be achieved by 2030, include: eradicating poverty and hunger; promoting good health, quality education and gender equality; clean water and affordable energy; decent work and economic growth; sustainable cities and economies; climate action; peace, justice and strong institutions; and strengthening the global partnership for sustainable development. Fig. 5.1 illustrates the SDGs.

The United Nations, Space, and Sustainable Development

From the earliest days of the Space Age, the United Nations has been at the forefront of utilizing space for development.

Fig. 5.1 Sustainable Development Goals (SDGs) adopted by the United Nations in September 2015

The Space Age had its origins in the midst of the Cold War, and there was an appreciation by the international community that the intense rivalries between the superpowers could either be extended to the space domain with grave risks for humanity, or that the exploration and use of outer space could be carried out for the benefit of all humankind.

In 1958, just one year after the launching of the first artificial satellite, the U. N. General Assembly in its resolution 1348 (XIII) established an ad hoc Committee on the Peaceful Uses of Outer Space (COPUOS), comprising 18 member States, to consider questions relating to the peaceful uses of outer space, organizational arrangements to facilitate international cooperation in this field within the framework of the United Nations, and deal with legal problems that might arise in the exploration and use of outer space. In 1959, the General Assembly established COPUOS (whose membership had by then grown to 24 member States) as a permanent body and reaffirmed its mandate in resolution 1472 (XIV). Since then, COPUOS has been the principal international body dealing with matters of international cooperation in the peaceful exploration and use of outer space. Since its establishment in 1959, the membership of COPUOS has grown at a steady pace, and it currently stands at 84 members. This large and growing membership strengthens COPUOS' role as the preeminent multilateral body for discussions on space cooperation, and this is particularly pertinent in the area of sustainable development, which requires concerted global action to meet the SDGs.

Throughout its almost 60-year existence, COPUOS has addressed applications of space relevant to sustainable development and the SDGs. It has done so through the medium of technical presentations by member States as a means of information exchange, through the organization of workshops and conferences, through the organization of training programs and internship programs, and multiple other activities falling under the U. N. Program on Space Applications, which has been operational since 1971. One of the key outputs of this program for developing nations has been a set of educational curriculum resources, developed by the U. N. Office for Outer Space Affairs in cooperation with the U. N.-affiliated Regional Centers for Space Science and Technology Education [6]. These curricula cover: Remote Sensing and Geographical Information Systems; Satellite Communications; Satellite Meteorology and Global Climate; Space and Atmospheric Sciences; Space Law; and GNSS. A curriculum on Basic Space Technology is currently under development.

In recent years, the U. N. Basic Space Technology initiative (UN-BSTI) has been promoting capacity building in the field of small satellites through a series of workshops that have been held in developing countries around the world [7]. The United Nations has also brokered internships and launch opportunities with leading space agencies for developing nations to become space actors through building and operating small satellites. The goal of the U. N.-BSTI is to assist developing countries to establish indigenous capacities in space science and technology. It also promotes international cooperation among various actors in the small satellite community, the use of standards, and adherence to international regulatory frameworks.

The United Nations has also played a leading role in promoting international cooperation in the use of space technology to address humanitarian and environmental concerns. The major space powers and large commercial entities have availed their assets on orbit to support such activities many times in the past. Normally these have involved conventional (i.e., “large”) satellites, but the growing capability of small satellites is now making it possible to augment, in a meaningful way, space systems that support sustainable development. These capabilities have been discussed elsewhere in this book, but some pertinent and specific examples are useful to note here.

When Hurricane Katrina made landfall in New Orleans on August 29, 2005, it wrought devastation on a huge scale. To get an overview of the damage, disaster response coordinators needed satellite imagery, and the first picture received was from the Nigerian satellite NigeriaSat-1 [8], a 100-kg satellite built by Surrey Satellite Technology Ltd. in the UK, and operated as part of the Disaster Monitoring Constellation. This anecdote highlights three points: (i) small satellites are now capable enough to address real developmental issues; (ii) this technology is now in the hands of a growing number of developing nations; and (iii) the private sector is playing a key role in rolling out this technology to new space actors.

Although the cost per kilogram of launching a satellite into space has not changed greatly over the past two decades, the capability per kilogram launched into orbit has grown tremendously. This increase in capability is due to advances in electronics, sensors, IT, and data analytics. As noted earlier it has led to a game-changing revolution in geospatial technology applications, and the next breakthrough area now pending appears to be with small constellations providing networking and digital telecommunications services. Yet other applications will undoubtedly follow. This means that small satellites are now able to support some of the objectives of the SDGs, and developing countries may be able to leverage off of this capability to meet their own national SDG implementation plans. This does not mean that small satellites will be able to do everything in space, but their supplemental role is growing. And ironically, there are environmental and sustainability concerns about the proliferation of small satellites in space in terms of orbital space debris. These caveats must be born in mind as consideration is given to the possible role that small satellites can play in supporting the SDGs.

The U. N. Sustainable Development Goals (SDGs)

Goals 1 and 2: Ending Poverty and Hunger

Approximately 900 million people in developing countries live on $1.90 a day or less. In the two decades following 1990, the number of people living in poverty was reduced by almost half, but food price increases could swiftly reverse these gains. Poverty, food prices, and hunger are inextricably linked. Not every poor person is hungry, but almost all hungry or malnourished people are poor. Hunger is the most severe and critical manifestation of poverty. Millions of people live with hunger and malnourishment because they simply cannot afford to buy enough food, cannot afford nutritious foods, cannot afford farming supplies to grow their own food, or live in areas where severe environmental conditions – often driven by climate change – limit agricultural production.

Globally, 1 in 9 people are undernourished [9], and the vast majority of these people live in developing countries. Poor nutrition causes 45% of deaths in children under five – approximately 3.1 million children die each year. Addressing SDG Goal 2 to end hunger also indirectly addresses Goal 1 (ending poverty), because agriculture is still the single largest employer in the world, providing livelihoods for 40 percent of the world's population. It is the largest source of income and jobs for poor rural households.

The world's agricultural land comprises 49 million km,^{2} about 37.5% of the total land surface of Earth. Satellites can provide timely and reliable information on the development and condition of crops and help to improve crop yields by allowing farmers to make better-informed decisions about when to water, fertilize, and harvest their crops.

Already, small satellites developed by Planet are providing rapidly repeating images of agricultural regions and providing rapid access to these data, see Fig. 5.2 below. So the data to support agriculture is much more readily available. The challenge is now to develop affordable access to the data and applications to provide useful information to farmers on the ground, especially in developing countries.

Goal 3 Good Health and Well-Being

Many of the world's people living in rural areas do not have local access to high-quality health. A visit to a

Fig. 5.2 Two of Planet's 3-unit Dove satellites shortly after deployment from the NanoRacks Cubesat Deployer on the International Space Station on May 17, 2016. (Image courtesy of NASA. Source: https://www.nasa.gov/image-feature/cubesats-deployed-from-the-international-space-station)

specialist requires a lengthy and costly journey to a city that the patient may simply not be financially or physically capable of undertaking.

Small satellite constellations, such as those envisaged by OneWeb, could expand the availability and cost-effective delivery of telemedicine services to remote locations. Such capability could greatly broaden patient access to medical expertise normally only available in tertiary hospitals. Also, by allowing specialists to support rural doctors to treat their patients in situ, small satellite constellations could relieve pressure on the tertiary hospitals in the main cities. In should be noted, however, that new high throughput satellites of larger size might be able to provide similar capabilities.

These expanded satellite capabilities as well as new ground systems – such as those that use metamaterials to create electronic beams that track non-Geo satellites at low cost – could create many new telemedicine services. This might include, for instance, live video teleconsultations, supported in real time with clinical data. Medical information and alerts could also be distributed more rapidly to remote clinics and hospitals. Patient record keeping could also benefit from improved communications provided by small satellite constellations. Such new space capabilities would enable the establishment of national systems of managing patient medical records. These new space-based capabilities might even include inventory control in remote clinics for more rational and efficient delivery of medical supplies, or for monitoring fluctuations in demand for certain medicines in an area. Such capabilities could provide early warning of the spread of certain diseases.

Goal 4: Quality Education

The 2nd Millennium Development Goal was the attainment of universal primary education by 2015. Indeed, significant progress was made to improve education access during the 2000s, specifically at the primary school level, for both boys and girls. However, access to schools does not imply anything about the quality of education, or completion of primary schooling. Many developing countries face challenges with regard to the provision of quality education to learners, especially in rural areas that find it difficult to attract and retain the best educators.

The promise of satellites to support education was already realized many years ago, but the technological support requirements on the ground posed a challenge in terms of implementation. During the 2000s India demonstrated a very successful, large-scale roll-out of tele-education to thousands of schools with its geostationary EduSat program. China, through its national television university that began with demonstration projects in 1987 using Intelsat satellites that were transferred to the Chinasat to service some 90,000 villages, has also been quite successful. Similar success in Indonesia, Thailand, Malaysia, Nigeria, and many other countries have proven that tele-education via satellite networks can be successful.

That experience was successful because of the investment in the educational infrastructure on the ground and the close integration of the space and educational communities. The technological barriers have been considerably lowered in the past ten years, making it now much easier to implement satellite-aided tele-education in the classroom, as well as self-learning supported by Internet access. In short, Internet based tele-education programs via small satellite constellations, which have been optimized for data networking in rural and remote areas, offers many new opportunities.

The envisaged LEO communications satellite constellations could potentially be used to make excellent quality educational materials accessible to every child in a country, no matter where that child lives, or his or her socioeconomic level. Such programs could potentially raise the general educational level of rural communities in the sense that education is not confined to school-age children, but can also take the form of an adult education program that could be delivered through schools, community centers, and libraries (see Fig. 5.3 below).

Addressing the provision of quality education also addresses an important aspect of Goal 1 (ending poverty) because poor education is one of the factors that can lead to being trapped in a cycle of poverty.

Goal 5: Gender Equality

Women and girls represent half of the world's population and therefore also half of its potential. It has been proven, time and again, that empowering women and girls has a multiplier effect that helps drive economic growth and development across the board. Therefore addressing gender inequality is crucial to accelerating sustainable development.

The inspirational power of space to attract young people into science, engineering and technology careers is well known. Girls and young women are just as inspired by space as their male counterparts, but they often lack access to

Fig. 5.3 A ground-station for OneWeb satellites pictured on the roof of a rural school. (Image courtesy of OneWeb)

opportunities or they do not receive encouragement from role models that they can relate to. In some places girls are even actively discouraged from taking mathematical subjects in high school, which excludes them from many career options in science and engineering.

A fact sheet on Women in Science published by the UNESCO Institute of Statistics in 2017 [10] showed that women accounted for less than a third (28.8%) of those employed in scientific research and development careers across the world. This imbalance is greatly exacerbated in developing countries.

Small satellite activities bring the exciting realm of space science and technology within reach of non-governmental organizations that promote greater participation of girls and women in science and technology. One such example is the South African NGO MEDO that specializes in STEM education for school-age girls. This organization has taken advantage of the ready availability of commercial off-the-shelf cubesat components to support a team of young female high-school students to build a cubesat. Students who graduate from the MEDO program are inspired by their encounter with space to consider scientific and technical careers. The following quote by one of their graduates, now studying electrical engineering, is telling: “I feel inspired. I never imagined a girl from a township doing these big and amazing things, learning from world-renowned astronomers.” See Fig. 5.4 below [11].

Goal 6: Clean Water

The aim of Goal 6 is to mitigate urban water challenges, ensure access to basic safe and affordable potable water and

Fig. 5.4 Schoolgirls learning to solder electronic components in one of MEDO's STEM programs. (Image courtesy of MEDO)

sanitation services, and to improve the treatment of waste water. In water-stressed regions, the objectives of Goal 6 can become contentious political issues. Inadequate access to clean water can affect public health, undermine economic performance, and even lead to conflict over access to limited water resources. Small satellites can introduce transparency and public accountability in the area of water resource management. They also provide an affordable means for developing nations to monitor water quality over very wide areas.

There are two ways in which small satellites can support Goal 6. The first is through remote sensing of water bodies, and the second is through relaying in-situ measurements from remote sampling locations.

Remote sensing with satellites enables broad and efficient monitoring of reservoir water levels, providing early warning of shortages and uniform data across different countries that share water sources, and increasing transparency and consistency in water delivery. Earlier in this chapter the point was stressed that the capability per kilogram on orbit has increased dramatically in recent years. The 2-unit cubesat mission called SWEET (Sweet Water Earth Education Technologies) has been proposed by the Technical University of Munich. This small satellite would take advantage of developments in the miniaturization of sensor technology to address the question of whether water quality measurements using a hyperspectral camera might be possible with a cubesat [12]. The objective of SWEET is to monitor 62 freshwater lakes in Africa, which are a source of drinking water to millions of people, with an average revisit time of 3.5 days. The precursor mission, envisaged to be launched from the ISS, could validate the mission concept and technology. An operational system would need a constellation of four satellites placed in a

Sun-synchronous orbit with an initial altitude of around 650 km.

Remote sensing is extremely useful but should be complemented with in situ measurements, especially for determining water quality. Water quality monitoring by water management agencies using conventional ground-based methods is labor intensive and costly, limiting sample collection over temporal and spatial scales. Even for well-resourced agencies, water collection stations may represent only a small percentage of the spatial extent of the water bodies under their management. Samples taken on any given day may not adequately represent the water quality of that location over a week, month, or season. This is where continuous monitoring becomes helpful. One such system, proposed for Tunisia, combines in situ water quality sensors placed in waterways and water bodies with cubesats being used as store-and-forward data relays [13].

Goal 12: Responsible Consumption and Production

Decoupling economic growth from the use of non-renewable natural resources is fundamental to sustainable development. Consumption of non-renewable resources is also directly linked to greater air, soil, and water pollution, which diminishes the capacity of Earth to sustain its growing population. Goal 12 is about ensuring sustainable consumption and production practices.

This goal is linked to a number of other SDGs, and much of what is written about the applications of small satellites to those goals applies here as well. The proliferation of small Earth observation satellites has two effects that pertain to Goal 12, namely making it much harder to conceal irresponsible production and consumption behaviors, and making it much cheaper to monitor large areas to find and document irresponsible consumption and production practices. For example, in arid regions, satellites can be used to expose violations of water quotas by water users.

In April 2016, the U.N. Food and Agriculture Organization (FAO) and Google entered into an agreement to cooperate on using satellite imagery to better manage the world's agricultural resources. In February 2017, Planet acquired Terra Bella from Google. Under the terms of this acquisition agreement, Planet now operates the seven Skysat high-resolution (<1-m) microsatellites, in addition to its own in-house developed fleet of 150-odd medium-resolution (3-5m) Dove satellites. This has created a powerful and unprecedented capability to support the objectives of Goal 12 with small satellites.

Goal 14: Life Below Water

Earth's oceans are under threat from pollution, overfishing, and the effects of global climate change. Billions of people on Earth are dependent on the oceans for their livelihoods and nutrition. Therefore any threat to the Oceans is a direct threat to sustainable development. Sustainable Development Goal 14, *Conserve and sustainably use the oceans, seas and marine resources,* addresses these threats.

Small satellites are playing a significant role in addressing aspects of Goal 14. One key area is that of maritime domain awareness. Many developing countries face the problem of illegal, unreported, and unregulated fishing within their exclusive economic zones by foreign commercial entities that can "out-fish" the locals, because of their superior vessels and technology.

As many of these illegal fishing activities occur far from coastal waters, they are invisible to maritime surveillance capabilities based along coasts. However, few countries have the resources to patrol and investigate suspicious activities over very large expanses of ocean. These gaps in surveillance allow such illegal activities to proceed unchecked, with grave humanitarian and environmental consequences. It is estimated by the FAO that illegal, unreported, and unregulated (IUU) fishing represents a theft of around 26 million tons, or close to $24 billion value of seafood a year. However, IUU fishing has broader social, economic, and security impacts as well. Illegal trawling off the Horn of Africa for decades has been identified as a significant contributing factor to the emergence of piracy in Somalia.

Small satellites are playing a huge role in supporting maritime domain awareness by serving as platforms for Automatic Ship Identification (AIS) systems that allow information to be gathered about vessels and their patterns of activity. Space-based AIS was pioneered in the mid-2000s, initially with microsatellites, such as those built by Orbcom and Aprize Satellite, but with time the technology has been ported to smaller and smaller platforms. The AISSat-1 was a 6-kg satellite developed for the Norwegian Space Center in 2010 as a development project that subsequently entered into operations for the Norwegian coastal management authorities [14]. In 2014 the satellite was supplemented with AISSat-2 and from 2015 by AISSat-3. A more recent entrant in the satellite AIS domain is Spire Global, a private company that was established in 2012 and which to date has launched some 50 of its Lemur series of 3-unit cubesats that now form a constellation providing access to over 1 million AIS messages per day, see Fig. 5.5 below.

Fig. 5.5 A group of Spire's Lemur satellites undergoing testing. (Image courtesy of Spire)

Small satellites are also being used to monitor ocean color, which can reveal the presence of suspended particulate matter, plankton concentrations, and pollution. For example, observations acquired with the Algerian microsatellite AlSat-1 have been used to model suspended particulate matter along the Algerian coast [15].

The SPectral Ocean Color (SPOC) Small Satellite Mission is a 3-unit cubesat under development at the University of Georgia. The primary mission objective of the SPOC satellite is to acquire moderate resolution imagery in several spectral bands ranging from 400 to 900 nm to monitor coastal wetland status, estuarine water quality, and near-coastal ocean productivity. The SPOC satellite was selected by NASA's Undergraduate Student Instrument Project and its Cubesat Launch Initiative to be built in 2016-2018 and launched in the 2018-2020 timeframe [16].

Goal 13: Climate Action

One of the predicted consequences of global climate change is that extreme weather events will become more frequent and more intense. Goal 13 encourages the world to take urgent action to combat climate change and its impacts. As the world faces the possibility of having to deal with more disasters, satellites will increasingly contribute to supporting disaster management.

There are many examples of the use of small satellites to support disaster management. As already stated NigeriaSat-1 was the first satellite to image New Orleans after Hurricane Katrina struck in 2005. That satellite was operated as part of the Disaster Monitoring Constellation for International Imaging (DMCii). The overall constellation comprises a number of remote sensing satellites constructed by the British company Surrey Satellite Technology Ltd. (SSTL) and operated for the Algerian, British, Chinese, Nigerian, Spanish, and Turkish governments by DMC International Imaging (DMCii). The DMC is a private sector member of the International Charter for Space and Major Disasters, under which it contributes imagery free of charge to disaster-affected countries.

Currently in its second generation, the DMC satellites have a 650-km-wide swath with a 22-m GSD. The multiple satellites in the constellation give DMCii the ability to image any point in the world on a daily basis. The DMC illustrates nicely how a constellation of small satellites can collectively provide capabilities that complement those of larger, more expensive satellites. The DMC satellites have also served as a springboard for several countries to start their own national space programs.

Goal 15: Life on Land

Forests cover 30 percent of Earth's surface and are home to more than 80 percent of all terrestrial species of animals, plants, and insects. Around 1.6 billion people depend on forests for their livelihood. This includes some 70 million indigenous people. Deforestation and desertification, caused by human activities and climate change, pose major challenges to sustainable development and affect the lives and livelihoods of millions of people. Thirteen million hectares of forests are being lost every year, while the persistent degradation of dry lands has led to the desertification of 3.6 billion hectares. Deforestation and forest degradation results in the destruction of habitats for many species, soil erosion, decrease in freshwater quality, and higher carbon emissions into the atmosphere.

The objective of Goal 15 is to manage forest in a sustainable manner, combat desertification, halt and reverse land degradation, and halt biodiversity loss. Often the earliest indications of these phenomena manifest in very remote regions of the world. Earth observation satellites enable global monitoring of patterns of deforestation and desertification. It appears that the pace and scale of changes is increasing faster than in the past, so having more monitoring capability that is more widely accessible will place more information in the hands of the public, who can then influence policy makers to address these issues. The advantage of small satellites is that there are now many more "eyes in the sky," making it much harder to conceal illicit activities and easier to expose corrupt government practices that allow rapacious industrial activities to occur in forests that ought to be protected.

Already, the Planet constellation allows daily monitoring of the world's forests that enables early detection of illegal logging and allows regular assessments of the health of forests. In addition, a number of nanosat missions are under development to study forests. CaNOP (Canopy Near-IR Observing Project) is a 3-unit cubesat mission under development at Carthage University in Wisconsin, USA, to provide hyperspectral imaging of forests to study biomass production and carbon uptake in mature and harvested forests. CaNOP was selected in 2016 by NASA to be launched as part of the agency's Educational Launch of Nanosatellites (ELaNa) initiative in 2018. The Kalam mission is a 10-kg nanosat under development by students at the National Institute of Technology Rourkela in India to observe deforestation, biodiversity loss, and land damage caused by open-cast mining operations.

Goal 16: Peace, Justice, and Institutions

Corruption and poor administration have the potential to undermine sustainable development in many ways. The extent to which they actually do so depends on the strength and integrity of national and international institutions. Part of Goal 16 is about building effective, accountable, and inclusive institutions.

Because small satellites can now be accessed (and even owned) by civil society organizations, they can improve transparency and the building of strong democratic institutions by making it much, much harder to conceal human and environmental abuses.

The Eyes on Darfur project was implemented by the NGO Amnesty International in 2007 with the objective of exposing a brutal genocide in Sudan through procuring satellite data from commercial operators. Ironically, the project may actually have led to an escalation of human rights violations, as the Government of Sudan retaliated against the monitored communities in an effort to shut down the project and deter other groups from involvement in the Darfur region [17]. Although the reaction of the government was disappointing, it does show that even brutal aggressors are sensitive to open international exposure of their activities. This is a case where evidence gathered by satellites needs to be used to secure convictions in international courts of justice.

According to the Satellite Industry Association, 51% of the 126 satellites launched in 2016 were non-military Earth-observing satellites [18]. This number (down from the 2015 figure) received a huge boost with the launch of another 88 Dove satellites by Planet in February 2017. As companies such as OneWeb extend more robust broadband connectivity to the entire globe using large networks of small satellites in low Earth orbit, it will also be easier to get news and images out of remote conflict areas, such as, for example, election-related violence.

Conclusion

Despite all the challenges posed by small satellites to the long-term sustainability of the space environment, particularly with regard to the proliferation of orbital space debris, they also hold out great promise to support the attainment of the Sustainable Development Goals by 2030. The key word in both contexts is sustainable, underpinning the fact that, increasingly, human and environmental security on Earth is underpinned by safety and security in outer space.

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Future Prospects and Policy Concerns

6

Introduction

The world of small satellites has now evolved into two different categories or types. One type is that of small satellites that are deployed in quite low Earth orbit so that they naturally decay and return to Earth and thus automatically meet the InterAgency space Debris Committee (IADC) Space Debris Mitigation guidelines that urge removal from orbit within 25 years from their end-of-mission life. These types of small satellites, typically nanosats or picosats, are usually only a few kilograms in mass and are also usually experimental projects.

These experimental cubesat launches are often one-of-a-kind missions for a specific experimental or proof-of-concept purpose. They largely arise from universities, research centers, governmental initiatives, or even secondary school projects. Secondary school projects are often undertaken with technical support provided by groups such as the National Center for Earth and Space Science Education (NCESSE), the Arthur C. Clarke Institute for Space Science Education, or by universities that specialize in small satellite projects such as Utah State University, University of Surrey, etc. Space agencies, such as NASA, ESA, JAXA, the Chinese National Space Agency, ROSCOSMOS, ISRO, the Brazilian Space Agency (AEB), etc., also are now undertaking some of these small satellite experiments. The key is that these undertakings involve only one or a few satellites and they are deployed in low Earth orbits where natural decay in a relatively short period of time can be anticipated. These small satellites pose a minimal orbital debris problem because of their size, orbits, and numbers.

The second category or type of small satellite involves the deployment of larger scale small satellite constellations to carry out commercial or governmental/military missions and are deployed in orbits that are sufficiently high that that they require active propulsion for removal from orbit in order to limit their long-term presence in the LEO region, in accordance with U. N. COPUOS Space Debris Mitigation Guideline 6.

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1_6

Some countries, such as France, have now passed national laws that enforce the removal guidance with penalties for not achieving timely removal from orbit. These types of small satellites, particularly in large-scale satellite constellations, pose the largest regulatory issues. Just in the arena of proposed low Earth orbit small satellite constellations for telecommunications and networking services, the number of small satellites proposed for launch within the next five years is some 15,000 – ten times the number of all operational satellites now in orbit. Further these satellites would be deployed in orbits that typically have orbital altitudes ranging from 500 to 1,200 km. Table 6.1 lists the large-scale small satellite constellations for networking purposes proposed and/or pending as of this writing. Even if only a small number of these projects are realized, this order of magnitude increase in satellites in low Earth orbit would pose a problem in terms of increased levels of anticipated orbital collisions and potentially runaway increases in orbital debris.

The need for better regulatory oversight of small satellites is increasingly being recognized within the U. N. Committee on the Peaceful Uses of Outer Space (COPUOS) and especially within the Working Group on the Long Term Sustainability of Outer Space Activities (LTSOSA). Different strategies, registration processes, and regulatory processes will likely apply to the two types of small satellites. Even so there appears to be a need for improved oversight processes and new approaches to limit either physical collisions in orbit or to limit frequency interference with other satellites – particularly with regard to geosynchronous satellite systems that enjoy a protected status with regard to orbital positions and frequencies, unlike the non-GEO satellites. The increased deployment of small satellites into Earth orbit represents an area of current concern. Thus small satellites and their deployment in Earth orbit represent a concern with regard to the longer-term viability and sustainability of space activities.

Small Satellites Launched for Experimental Purposes into Low Earth Orbits

Some 30 years ago the concept of a cubesat that might be launched for experimental purposes by students and those wishing to undertake simple tests in space was developed with the support of NASA and other space agencies. The prime purpose was to encourage innovative student thinking. The thought was that such student-oriented projects might lead to worthwhile experimental space projects with legitimate outcomes, but that such activities could also stimulate students to appreciate the challenges of designing and building satellites to operate in the harsh environment of outer space and see this as a future career. At the time it was anticipated that only a handful of these satellites would be constructed and launched from universities with space-related programs. The exciting prospect of designing and building actual satellites that could fly in space has been successful to a far greater extent than had been first anticipated. Today hundreds of cubesats (1 unit to 6 units in size) are being built and launched from a wide variety of programs all over the world. Students can buy kits online and build cubesats for a small fraction of the costs that was once needed to create a viable cubesat [1].

There are today even contests supported by various funds to have secondary school students to design and build cube satellites. The popularity of cubesats and the growing number of them being deployed has led to some concern about their proliferation and the associated problem of orbital space debris.

The development of new launch options has been a part of the story with regard to the launch of more and more cube satellites. One of the popular options now available via NanoRacks to launch from the Japanese module from the International Space Station. Further, many national space agencies and commercial launch operators offer low cost launching options to university students and others seeking to launch cubesats into orbit. As noted in the introductory chapter there are now commercial space launchers that can and have now launched over a 100 cubesats from a single launch, and more such launches are now intended [2].

The problem is that most of these cubesats, and even smaller so-called femto satellites (100 g to 1 kg) do not have any control or propulsion system to assist with deorbit. Further only a very few have so-called passive de-orbit systems such as deployed balloons at the end of life that serve to increase the cross-sectional silhouette of the satellite so that solar wind will hasten its deorbit.

There is clear concern about whether the proliferating number of cubesats being launched could increase the orbital debris problem and accelerate the possibility that we reach the point of run-away debris formation known as the so-called Kessler syndrome. Within the U. N. Committee on the Peaceful Uses of Outer Space as well as research centers all over the world this matter is under active consideration as to what might be done to improve the situation and to minimize the problem. Below are some of the many ways that this problem is being addressed in terms of possible solutions.

1. *Registration and Due Diligence.* This initiative involves placing increased emphasis on the fact that launching nations need to register all satellite launches regardless of size [3] and that under the "Liability Convention" [4] such launching nations are "absolutely responsible" for damage caused by satellites for which they responsible as the launching nation. Such a program serves to highlight the need to exercise due diligence as to whether the small satellites that they launch pose a risk to create new orbital debris. (As further background please see Appendix 2 (the approved U.N. orbital debris mitigation procedures, Appendix 3 (the U. N. Registration Convention), and Appendix 4 (The U.N. Liability Convention).
2. *Consolidation:* One idea is that multi-unit platforms with active deorbit capability could be utilized to accommodate a large number of cubesat missions that simply need access to outer space to conduct their experiments. Such a consolidated platform could be designed not only to deorbit carrying as many a sixty or so cubesat modules but also to supply electrical power, telecommunication relays, or other common services to the various small satellites it would carry into space and then deorbit at their end of life. When one considers

the potentially high cost of trying to capture and deorbit, say 64 cubesats, versus the cost of flying a multi-unit platform that consolidates the flight of all these cubesats into a single unit that can be simply deorbited at end-of-life, the economics of this approach seem abundantly clear [5].

Another approach that has been encouraged by U. N. COPUOS is the idea of flying experiments on the International Space Station that could then be deorbited with other materials as part of the International Space Station's normal operations. The advantages of this approach include the fact that astronauts can start, end, or otherwise control experimental activities. Further the ISS can also supply power and telecommunications services. This type of arrangement has been carried out in support of student experiments via the Nanoracks experimental platform that flies on the ISS and has now supported hundreds of student experiments. NanoRacks Platforms is the formal name of this multipurpose research facility onboard the International Space Station (ISS). It is designed to provide not only cubesat form factors onboard the ISS but also serves to provide power and data transfer capabilities to support investigations in microgravity [6].

3. *Passive Deorbit Mechanisms.* A number of universities and research centers are actively exploring the concept of creating low cost and low mass passive systems that could deploy at the end of life for cubesats or other quite small satellites and that could aid deorbit by increasing the cross section that would interact with solar wind to hasten the satellite to naturally deorbit. This deployment of balloons or other such passive systems would be particularly effective during so-called solar max when the solar wind and the atmospheric drag effects are much greater. A good deal of progress has been made in recent years to develop low mass and low cost passive systems to aid orbital decay for cubesats and other types of small satellites when deployed at end of life.
4. *Active Deorbit Mechanisms.* The studies of orbital debris buildup now project the likelihood of major collisions as frequently as once every five years. Priority efforts to remove the largest debris elements, such as the 8-ton Envisat, from low Earth orbit are now underway. The debris elements with the largest cross sections are clearly the prime targets for in-orbit collisions and are thus considered the most important to be removed from orbit. There are dozens of different technical approaches that have been identified as ways to undertake active orbital debris removal. These techniques can be divided into three generically different types of approaches: (i) using ground-based laser or directed energy beam systems to divert in-orbit debris so as to avoid collisions; (ii) sending up systems that can engage in active or passive debris removal techniques to remove one or more debris elements before also deorbiting themselves; and (iii) creation of orbital debris removal systems that use Earth's magnetic field to create a propulsive force so that the removal system can stay in orbit indefinitely, carrying out its debris removal mission. One such concept

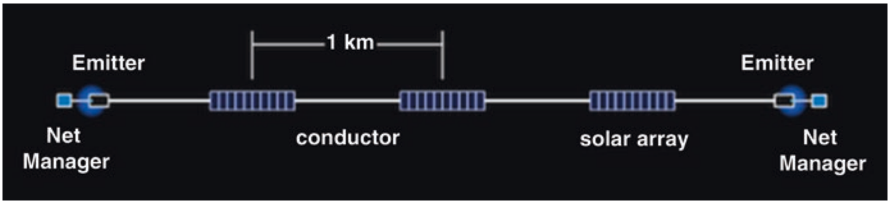

Fig. 6.1 The Electro Dynamic Debris Eliminator system that could stay in Earth orbit indefinitely. (Graphic courtesy of Star Technology and Research.)

Fig. 6.2 MDA on-orbit servicing vehicle approaching to capture a satellite. (Graphic courtesy of MDA)

is the so-called Electro Dynamic Debris Eliminator system shown in Fig. 6.1 [7].

Until such breakthrough technologies are developed and proven to be practical, reliable, and safe to operate, there are a range of more conventional technologies that have been developed by several aerospace companies such as McDonald Dettwiler Associates (MDA), Vivisat, the ConeExpress Life Extension Vehicle, etc., that have developed vehicles for on-orbit servicing. Such vehicles with robotic grappling mechanisms can attach themselves to defunct satellites such as Envirsat or spent upper stage launch vehicles in orbit and then bring them back to Earth to splash down in the ocean in a controlled fashion. Fig. 6.2 provides a depiction of the MDA on-orbit servicing vehicle in a capture mode seeking to mate with an in-orbit satellite.

Perhaps most pertinent to small satellites and space debris removal is the Swiss-based “CleanSpace One’ project, as shown in Fig. 6.3 below. The object of this project is to prove that a cubesat-sized chaser spacecraft with adequate propulsion might be able to capture and deorbit a defunct microsatellite from orbit. The Swiss Space Center and EPPL have thus launched a cubesat into

Fig. 6.3 CleanSpace One depicted as seeking to deorbit the original cubesat. (Graphic courtesy of Swiss Space Center and EPFL)

low Earth orbit and plans to use the CleanSpace One chaser satellite to capture and deorbit the target cubesat [8]. The U. S. Defense Advanced Research Projects Agency (DARPA) and the German space agency DLR have both undertaken similar projects but on a much larger scale.

On the regulatory front, the Liability Convention, which places absolute liability on the launching state for collisions with other objects already in space, constitutes a further complication to the process of active debris removal planning. To date, the Member States of UN COPUOS have made little progress in discussions related to possibly amending the Liability Convention so as to encourage active debris removal, and this is unlikely to change for the foreseeable future. This topic is discussed further in Chapter 7 [9].

Large-Scale Smallsat Constellations and Orbital Debris Concerns

The future deployment of large-scale small satellite constellations is today still a large question mark. The number of proposed such commercial constellations continues to grow, and the number of some of these constellations now envisioned for telecommunications and networking has risen to a level where a single constellation would involve over 7,000 satellites. Further these small satellites would not be cubesats but much larger spacecraft that would typically be 200 to 250 kg in size (see Table 6.1).

At this time only the OneWeb network has been capitalized, and contracts for the construction and deployment of this truly large-scale networks have been

Table 6.1 Proposed and pending large-scale small satellite constellations for networking purposes. (Table composed from various on-line sources) [10]

STATE	CONSTELLATION	NUMBER OF SATELLITES	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
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
US	Boeing	1396-2956	V-band in 1200 km orbit
US	SpaceX	Up to 4000	Ku-Ka band
US	SpaceX	7500 plus	V-band
US	LeoSat	Initially about 80	Ka-band

awarded. On the remote sensing side of these large-scale small satellite constellations, the Planet Labs and Terra Bella satellite networks have been consolidated into the Planet network. It is unclear how many more of these systems might be deployed in the future, but there are several in development and/or initial operation. Fortunately, the 3-unit cubesats in the Planet network, known as Doves, are sufficiently small in size and deployed in sufficiently low Earth orbit that these small satellites seem likely to meet the orbital debris mitigation guidelines of the InterAgency Debris Committee (IADC) that specifies a 25-year time table for the deorbit of defunct spacecraft measured from end of life.

In short the small satellites for telecommunications with particularly large numbers in constellations are the prime issue. Thus it seems that the truly explosive future growth of small satellite constellations will be in the telecommunications and networking applications domains. And even so it appears unlikely that all of the proposed systems as shown in Table 6.1 will be actually constructed and deployed.

It should be noted that because of the need for larger and higher gain antennas and more power, these so-called small satellites are indeed much larger than cube satellites. Thus a typical small satellite in these telecom/networking constellations would be 200 to 250 kg in size, although some might be smaller and others such as LeoSat would be even larger. These constellations are in addition to the networks already deployed for global mobile satellite communications such as the first and second generations of Globalstar and the Iridium and Iridium Next constellation.

The prospect of such a large number of satellites being deployed in the next five years or so can be seen from two entirely different perspectives. On one hand such new large-scale small satellite constellations seem likely to offer new opportunities to the developing world, which now has limited access to broadband networking, especially in rural and remote areas where billions of people have modest access to the Internet. Such cost-effective systems could open up new access for tele-education, telehealth, expanded governmental services, and new commercial, agricultural, and mining services. On the other hand such a big increase in these large-scale satellite networks gives rise to several concerns. One is the possible interference with geosynchronous satellite communications systems that have protected status under International Telecommunication Union (ITU) regulations. The other even greater concern is that of the proliferation of space debris that might expand at an uncontrolled rate and create a cascade of "space junk" that could deny future sustainable access to orbit for all applications. This condition is known as the Kessler syndrome.

A recent study of orbital debris conducted by the University of Southampton, as reported at the ESA 7th Conference on Orbital Debris in April 2017, indicated that successful active removal of satellites from large-scale constellations would make a huge difference. The difference between a 100% success rate in removal of satellites and perhaps a much lower figure such as only 60% would have an enormous impact on the projected number of catastrophic collisions in space. "If only 60 percent of the constellation is successfully deorbited, the number of catastrophic collisions would increase to 300 and the number of fragments larger than 4 inches (10 cm) would skyrocket to 100,000" [11]. This would clearly represent a catastrophic condition that could lead to the end of all types of space applications.

The buildup of space debris has been constantly on the rise since the 1970s. The intentional Chinese destruction of their defunct Chinese weather satellite, the Fengyun-1C, occurred on January 11, 2007, and added over 2,000 trackable new debris fragments, effectively negating the collective debris mitigation efforts of the world space community over the previous two decades. The debris generated by this antisatellite test raised concerns afresh about an arms race in outer space and its attendant dangers for the safety of space operations [12].

Then, in January 2009, the collision of the inactive (and therefore uncontrolled) Russian Cosmos 2251 satellite with the in-service Iridium 33 satellite destroyed both spacecraft and created over 2,000 new debris elements. This catastrophic event gave rise to yet additional concerns that in-orbit collisions of sizable spacecraft was now giving rise to an exponential increase in orbital debris that could make the Kessler Syndrome inevitable [13].

Clearly collisions involving cubesats would produce significantly less debris than the 2007 Chinese antisatellite test and the 2009 Cosmos-Iridium collision, but the constellations that are planned for deployment with satellites in the 200 to 250 kg mass category could result in major escalation in the debris population. If the Southhampton University study is anywhere close to accurate in its projections, the prospects for runaway proliferation of orbital space debris as a result of large constellation deployments seems perilously high [14].

It is prudent on the part of the OneWeb satellite venture that they currently intend to deploy and test ten satellites as a precursor to full deployment of their 648 plus spares satellite constellation in order to carry out pre-operational tests. These in-orbit tests will enable OneWeb to test the ability of their satellites to minimize interference to operational telecommunications satellites in GEO orbit. It will also presumably allow the test of the OneWeb small satellites to deorbit from constellations with minimal risk of engendering a collision with other satellites in the constellation or with orbital debris or other operational satellites [15].

Effective Space Law Regulation of Small Satellites

A recent analysis undertaken by the McGill University Institute of Air and Space Law of major issues included consideration of the future of space commercialization and small satellites over a three-year period from 2014 to 2017 [16]. This study identified the deployment of large-scale small satellite constellations as an area of particular concern. The analysis from the McGill study identified concerns about interference from LEO constellation satellites as they pass over the equatorial region of Earth and potentially interfere with geosynchronous satellites (which have protected status).

The review also considered the ability of these constellations to effectively and continuously control large-scale constellations with potentially thousands of satellites in network operations on a consistent basis without collision. New studies from ESA and the University of Southampton have indicated that there is a significant need to remove satellites from the constellation and de-orbit them effectively without incident to preserve safety and halt orbital debris buildup. This will especially be the case as LEO constellations increase to larger and larger numbers of satellites. The study has suggested that these concerns be given priority consideration at the UNISPACE + 50 event to be held in Vienna, Austria, in 2018 and subsequent efforts to improve global space governance so as to ensure the long-term sustainability of space.

Conclusions

The surprisingly rapid rise of small satellites in their use for experiments, demonstration tests of new technology, and now as vital parts of giant satellite constellations for remote sensing, telecommunications and other applications, has led to new concerns about the safe, reliable, and non-interfering use of such new types of satellite networks.

The new economics and opportunities that arise from small satellite systems have given rise to proposals for unprecedented types of satellite networks and constellations that offer new opportunity, but also serious concerns about potential radio frequency interference and the potential for a rapid buildup of orbital space debris that potentially might deny future access to space by all nations.

Truly small cubesats that are launched into orbit below 300 km in altitude might not pose significant risks. On the other hand vast small satellite constellations with thousands of satellites deployed in low Earth orbit (typically between 500 and 1,200 km) have given rise to serious concerns about orbital debris proliferation. This has led to serious consideration of new types of global space governance that would seek to minimize the risk of runaway debris proliferation.

The OneWeb large-scale constellation, which is the only system now capitalized and under construction, may help to clarify the risks and the safety and control procedures that might be deployed for such networks. All those involved in space enterprises are concerned with the prospects of small satellite constellations that could lead to the onset of the Kessler syndrome. It is to be hoped that new and effective solutions and appropriate safety standards can be established in a timely manner.

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7

Potential Innovations in Space Regulatory Systems and Standards

Introduction

The advent of small satellites has been a source of innovative technology, new entrepreneurial business initiatives, new economic models for space ventures, and many other changes. As noted in Chapter 6 this has not surprisingly given rise to a host of new issues and perceived needs for new standards of operations, codes of behavior, and perhaps new regulatory actions at the national and international level to keep space activities safe, harmonious, and operationally effective. Truly small satellites, of the cubesat and smaller category, have given rise to one set of concerns, while large-scale satellite constellations, sometimes called megaLEO systems, have given rise to other types of concerns.

This chapter addresses possible solutions to the various issues raised in Chapter 6. It thus considers what new standards, codes of conduct, and other soft law instruments, such as transparency and confidence building measures, can provide improved global space governance in these areas of concern. In addition, some possible international regulatory reforms are also proposed.

The U. N. Committee on the Peaceful Uses of Outer Space (COPUOS) at its UNISPACE + 50 event scheduled for Vienna, Austria, in June 2018 had the mission to develop an effective 12-year agenda to support the U. N. General Assembly's 17 Sustainable Development Goals for 2030. One of the pillars of this process is the consideration of how to effectively apply new global space governance to support these goals in terms of possible new rules, regulations, and guidelines. Since the use of smallsats to support the Sustainable Development Goals represents one part of this process, the analysis that follows is hoped to be both timely and useful to this twelve-year process. Further it is hoped that some of the concepts might also prove useful to the discussions within the COPUOS Working Group on the Long Term Sustainability of Outer Space Activities.

Aanalyses of issues and related possible actions that might be considered and implemented at the global, regional,

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1_7

or national level are addressed one by one throughout this chapter. The discussion starts with those issues that relate to the International Telecommunication Union (ITU), which has perhaps the most potential for developing new procedures, processes, or regulations that address small satellite related issues. Next there will be a discussion of matters that fall within the purview of UN COPUOS, and finally there will be consideration of how international, regional, or national actors individually might be able to assist with enhancing collectively the governance and related issues raised by smallsats.

Assessing the ITU's Potential to Assist with Regulatory Reform

The ITU is the world's oldest intergovernmental organization. It began as the International Telegraph Board and was first headquartered in Bern, Switzerland. The initial mission was to coordinate telegraph usage and allow international connection of telegraph systems. In the earliest days of telegraph service, international messages were decoded and walked across international boundaries and then sent along their way again. We have certainly come a long way from this historical situation to today's Internet, which has allowed us to become a globally interconnected world. Today the ITU, which is now headquartered in Geneva, Switzerland, provides standards and assists with the coordination of international communications and networking services of all types. These include texting, facsimile, radio and television broadcasting, telephone, videoconference, high-definition television, digital video/motion picture distribution, unlicensed industrial, scientific, and medical wireless services, and indeed all forms of digital and analog networking, broadcasting, multi-casting, and distribution services. The ITU addresses and agrees on global transmission standards for all types of media and transmission services whether via wire, coaxial cable, optical transmission systems, radio frequency and infrared transmission, or wireless mobile telecommunications systems of all types including cellular telephone, radio communications services (including specialized commercial, medical, and emergency services), satellite services of all types, and even links to UAVs and High-Altitude Platforms. It is, in short, responsible for all types of wire and wireless communications and maintains a master frequency registration file associated with all satellites among other wireless services. Fig. 7.1 shows the ITU headquarters in Switzerland.

The complexity of the frequency allocation plan that is put forth by the members of the ITU is enormous. There are problems with exceptions to this process in that countries can add a footnote to indicate that they are not agreeing to a particular frequency allocation inside their borders. In the case of satellite communications there are many technical coordination issues. For instance, an RF spectrum allocation for one type of service can be closely adjacent to another. The frequency band used for mobile satellite services is adjacent to the frequency spectrum critical to radio astronomy surveys that are particularly sensitive to interference. Further, because of the significant demand for RF spectrum in lower frequencies, the ITU can assign a primary

Fig. 7.1 The International Telecommunication Union (ITU) headquarter facilities in Geneva, Switzerland. (Graphic courtesy of the ITU)

allocation, a secondary allocation, and even a tertiary (or third level of priority) for some types of services. Because of the reserved right of countries to exclude certain frequency allocations within their national borders, and also because the ITU is divided into three different regions (Region One [North and South America and Caribbean countries], Region Two [Europe, Middle East, and Africa], and Region Three [Asia and Australasia]), every country's frequency allocation chart is different. Nevertheless, there is still a good deal of commonality for most allocations.

Each country, however, has its own frequency allocation plan. In the area of satellite services, especially for amateur satellite communications and smallsats, these are generally common. For purposes of illustration, Fig. 7.2 shows the U. S. frequency allocation and illustrates the enormous complexity that is involved. As one moves from the lowest frequencies to the higher frequencies, which provide wider and wider spectrum ranges, the complexity of the allocations still tend to remain but with fewer intricacies. Thus, although the VHF and UHF bands are the most intricate, the microwave and millimeter spectrum ranges still contain complexity as to the types of assigned services.

The ITU Registration and Notification Processes for Satellites

The first step in getting a license to operate a satellite in most countries is to file for the use of the intended frequency with the national radio licensing organization. Each country spells out the type

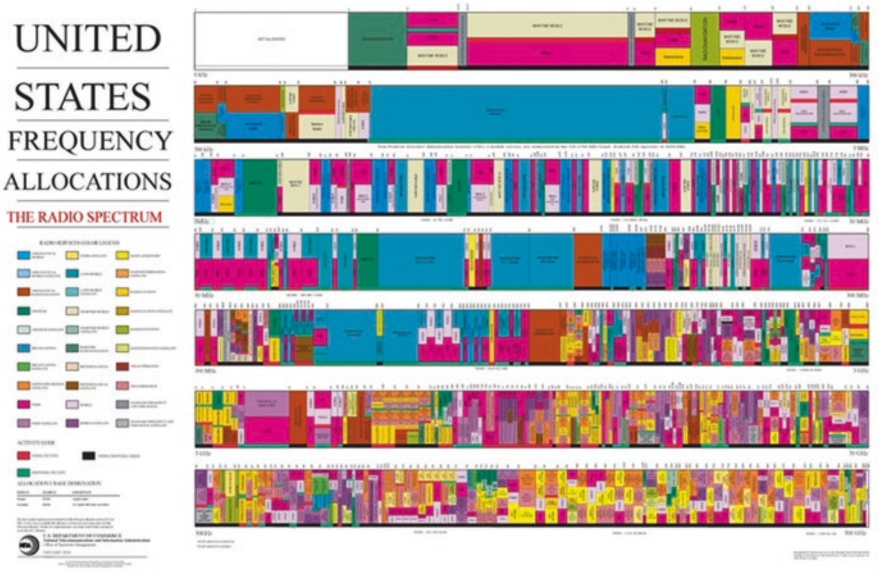

Fig. 7.2 A frequency allocation chart illustrating complexity in frequency allocation processes as typically found in each country – especially for VHF and UHF bands. (This chart is provided for illustrative purposes only. A higher-resolution version may be seen at https://en.wikipedia.org/wiki/Frequency_allocation)

of information that they require in order to provide a license for satellites for which they are considered to be a "launching state" under the Outer Space Treaty and the Registration Convention. In the case of a cubesat experimental project using typical VHF satellite frequencies for data relay and TT&C services this can be a fairly straightforward process. As noted later in this chapter, there have been efforts to streamline the registration, notification, and intersystem coordination processes for experimental cubesat launches.

In the cases where the project is a commercial undertaking intending to deploy one or more satellites to provide fixed satellite services (FSS), broadcast satellite services (BSS), or mobile satellite services (MSS), the national licensing agency will also require much more information. This type of requirement for national licensing information would typically be for the number and size of the satellites and many details of their technical characteristics, plus business plans for the services to be provided, the builder of the satellite and related contractual details, the financial details as to financing, contractors to build and launch the satellite, specific details as to mitigation procedures to lessen the possibility of creating orbital debris, etc. The licensing agency will then determine if this is a legitimate project, and not a so-called "paper filing" and then ultimately determine if the entire system will be licensed. This process in some countries can take some considerable length of time – even years. Once this national licensing decision is made, it is then up to the national administration that is the official member of the ITU to notify the ITU, so that this satellite system can be coordinated with other countries of the world via the official ITU administrative procedures for technical coordination with the satellite systems of other countries.

Some countries have in the past accelerated (and abused) the national review process to file so-called "paper satellites" with certain technical characteristics with the ITU simply to take advantage of the ITU's "first come, first served" principle. Needless to say, such practices undermine the principle of equitable access to spectrum resources. The ITU now has created charges for satellite filing and other milestone procedures to limit such "paper filings."

The filing process is different in the case of GSO (also called GEO) satellite networks. This is because it is necessary to seek specific orbital locations in the GEO belt and to identify slots that might be available that are not occupied by existing satellite networks. In the case of non-GSO satellites that are intended to be deployed in constellations, either in low Earth orbit or medium Earth orbit, the filings with the ITU must spell out the number of operational satellites and spare satellites to deployed, whether or not there are to be inter-satellite links (ISLs) among adjacent satellites, and the specific frequency bands that are to be utilized as well as the specific orbits and orbital patterns to be used by the intended system.

In the case of the first commercial small satellite constellations, known as the Iridium and Globalstar satellite systems for mobile communications, as well as the Orbcom system for mobile satellite data relay, the U. S. Federal Communications Commission (FCC) required information as to the ability of these systems to remove these satellites from orbit at the end of life. Further, the FCC halted the launch of some of the Orbcom launches and requested changes to better ensure that the Orbcom system deployment would not add to orbital debris. This topic of orbital debris mitigation procedures will be discussed later in this chapter.

The Teledesic satellite system, which would have been the first so-called megaLEO system with nearly a thousand satellites, was licensed by the FCC and referred to the ITU for intersystem coordination in official filings by the United States two decades ago, but this system declared bankruptcy and was never launched. Thus this was not a true precedent. The current conditions with regard to the proposals for the deployment of so-called megaLEO small satellite constellations is an unprecedented situation with regard to the actual deployment of a large number of satellites subject to licensing and intersystem coordination processes under the ITU global procedures.

The FCC has, as of the end of 2017, licensed two of the large-scale LEO constellations, namely the OneWeb network (up to 1,000 satellites including spares) and the Telesat (120 satellites plus spares). A number of others are pending, as shown in Table 6.1, which lists the various large-scale networks currently under consideration and their various levels of development. Since these systems are all in a state of flux one should consult the official websites of the ITU or those entities associated with the various systems to seek current information.

This leads to a quite pertinent and difficult issue. Currently there are established procedures for reviewing applications for new satellite systems and licensing their services, but there are no national or global regulatory procedures to decide just how many of these new megaLEO systems can be plausibly deployed, or which frequency plans, RF transmission power levels, or constellation orbital deployment locations are reasonable in terms of approving these systems for launch. As indicated in the Table in 6.1, there could be in the range of 20,000 such satellites launched in the coming decade, in addition to those already deployed in LEO orbits.

No one has established what are acceptable or agreed levels for intersystem coordination in terms of reasonable levels of interference between and among LEO or MEO constellations and particularly levels of interference with regard to "protected" GSO/GEO satellite networks. A further concern is also how many of these new megaLEO constellations can be deployed without posing too great a risk to the future safety of all space operations in the context of orbital crowding and space debris.

The deployment of all of the currently proposed small satellite megaLEO systems could lead to an excessive potential buildup of orbital debris. Increasing the number of objects in low Earth object by tens of thousands of objects without verifiable systems to deorbit these satellites with a high degree of certainty is thought, at least by some, likely to cross the threshold that leads to the so-called Kessler syndrome. This Kessler syndrome means that there could then possibly be a runaway increase in debris elements that in time would become a dangerous and deadly avalanche of "space junk." This specific issue has been addressed earlier and will again be addressed later in this chapter.

It seems urgent to seek reasonable new procedures with regard to the process for licensing, frequency registration, coordination, and deployment of such systems. Such procedures are needed at the national level and also new procedures are needed within the ITU. Some analysts feel that that there should be a moratorium on the deployment of any of these megaLEO systems until a reasonable global decision-making process can be established with regard to how many megaLEO systems can be reasonably deployed and how authorization of systems can be fairly prioritized among various countries. It is becoming urgent for countries with pending proposals for such megaLEO systems, the Inter-Agency space Debris Committee (IADC), the ITU, and the U. N. Office of Outer Space Affairs (OOSA) to create a new coordination and notification process to deal with these new type satellite systems.

This process also needs to address the further issues of excessive interference and excessive orbital debris buildup. The trouble is that this would require an ITU resolution at an upcoming World Radio Conference, or an action by the U. N. Security Council or the General Assembly. None of these actions seems at all likely at this time in that there is no consensus view on any of the key matters. So it is likely that this problem and related concerns will continue to build as more and more megaLEO systems are filed for licensing at the national level and are referred to the ITU for intersystem coordination. When the limits of intersystem coordination appear to be reached, this issue of "too many satellites" in too many non-GSO networks

Fig. 7.3 The OneWeb megaLEO system that will involve nearly 1,000 smallsats orbiting in 800 to 950 km orbits. (Graphic courtesy of OneWeb)

may finally be address seriously [1]. Fig. 7.3 shows the large number of satellites (nearly 1,000) that would exist in the OneWeb constellation alone. The latest systems planned by SpaceX contemplate eight times more satellites than that of the OneWeb system.

Separate from the issue of large-scale commercial satellite constellations, there are also issues related to cubesats and smaller satellites that are being deployed for student experiments and often by developing countries just starting space programs. Here the concern relates to issues such as whether the registration and notification procedures of the ITU might be too stringent and exacting for these non-GSO satellites with short mission lives. This concern led to the adoption of Resolution 757 WRC-12 at the ITU World Radio Conference Twelve, which stated that there were clear distinguishing factors between small satellites (i.e., in this case truly small femto, pico, and nano satellites, or cubesats and below) and the quite different characteristics of larger satellites that were more massive, had longer development and operational lifetimes, and typically used different frequencies and were deployed in different orbits and with fewer orbital controls [2].

This ITU resolution indicated that these differences should be noted in the registration process. The resolution "invited the development of regulatory procedures aimed at facilitating deployment and operation of small satellites and making them successful and timely ….The nature of this category of satellites should be considered, when revising current provisions of the ITU Radio Regulations for the purposes of coordination and notification of satellites" [3].

To date, no such revisions to the ITU Radio Regulations have actually been adopted. At the ITU World Radio Conference (WRC-15), however, the Radio Section of the ITU (ITU-R) was mandated in Resolution 659 to study: "the spectrum requirements for telemetry, tracking and command (TT&C) in the space operation service for the growing number of non-GSO satellites with short duration missions" [4]. The issues related to facilitating the truly small satellites as set forth in Resolution 757-12 have yet to be seriously addressed. In light of the problems and concerns associated with the deployment of the megaLEO systems it seems likely that the streamlining of registration and notification procedures for cubesats will also be delayed [5].

ITU Regulations with Regard to LEO/GEO Interference, Jamming, and Related Concerns

The ITU radio regulations confer on satellites in the geosynchronous/geostationary (GEO/GSO) orbit protection from satellites in non-GSO orbits. This is because these satellites for many years were the almost completely dominant form of space communications and because low Earth orbit (LEO) and medium Earth orbit (MEO) satellites cross the GSO/GEO orbital plane twice with each orbit. This creates the possibility of significant interference to satellites in GSO that are high above the LEO and MEO satellites. Since GSO satellites are typically some 40 times further out from Earth than LEO orbiting satellites there is on the order of 1,600 (40^2) times more path loss than is the case with the satellites orbiting much closer to Earth. This means GSO satellites require more protection against interference from LEO and MEO satellites.

Designers of LEO constellations have had many ideas about how to operate their satellites and meet the protective standards against interference protections and priorities provided to GSO satellites. Some operators have thought of deploying LEO satellites configured with each one having a "chaser" satellite so that the first satellite goes "quiet" as it passes through the GEO plane, and traffic is switched to the chaser satellite and so on around the constellation orbits. Another concept is of an antenna system that swings away from transmitting in the same arc that is used by GSO satellites during the time that they cross the GEO orbital plane. OneWeb and the Telesat constellation have plans to test two trial satellites in orbit before their full constellations are deployed. This form of trial confirmation of non-interference is not currently required under ITU regulations, but it would seem prudent to confirm acceptable levels of non-interference for all current and planned megaLEO systems that operate or will operate in the FSS, MSS, and BSS satellite communications bands.

Currently the ITU procedures with regard to interference are to notify the national administration of the launching nation of an interference problem and request elimination or reduction of the interference to acceptable levels. This process does typically achieve a reasonable level of success in that most interference problems are the result of inadvertent transmissions and are resolved without great difficulty. The ITU has no legal enforcement powers, though, and there are no "ITU police" to hand out fines to offenders. This is a particular problem when the interference is, in fact, intentional jamming.

Some countries engage in intentional jamming as a form of national protection against unwanted transmissions into their country. In these instances there is currently no particular legal or regulatory recourse available. At this time countries are reluctant to give up any more of their sovereignty to international intergovernmental organizations such as the ITU. Yet, given trends of integrative technology, global patterns of economics and trade, and international online employment, the need for regulatory "teeth" for international intergovernmental organizations will perhaps be recognized. The World Trade Organization (WTO) is the only international organization that has the ability to impose fines on nations that engage in trade infractions. Today the ITU has standards and recommended practices that are based on consensus, but it has no specific enforcement power behind these measures. In light of the tremendous importance of the global Internet, corporate intranets, global communications systems and mobile networks, and satellite networks of the world, there should be serious consideration given to strengthening of the ITU Convention to provide greater enforcement powers to this international institution so key to the future sustainability of outer space activities.

ITU Processes for Intersystem Coordination

The ITU has a well-established process for receiving formal notifications of satellite networks filed by member administrations and sharing them with all members of the ITU to determine if there are concerns about interference. The process is for the administrations that have concerns to notify the ITU of perceived possibilities of interference. The administrations that are concerned have the possibility to meet and find ways to minimize interference. If these coordination meetings are successful then the results are formally filed with the ITU. If these discussions are not successful, then ITU officials can meet with the administrations concerned (and with the owners and operators of the satellite systems and their contractors if the administrations are not directly involved with the satellite networks) to resolve the interference issues.

This process has historically led to resolution of the interference problems. There have nevertheless been concerns about the process and particularly with the process that favors those that have deployed satellite networks and have the priority that comes from the "first come, first served" principle. In one instance an orbital location in GSO was optimum for providing service for the Indian Ocean region that provided satellite connectivity between the United Kingdom to the western end of this service region and to Australia at the eastern extreme of this service area. This same GSO orbital location from the perspective of India would also represent the best position to get the optimum power footprint to cover the Indian subcontinent with an Indian satellite and thus minimize the size of ground systems. Since Intelsat had precedence for this location, India had to move their satellite to a less desirable location, and this required them to deploy higher gain ground stations at higher cost.

As a result of this experience, India petitioned the ITU at the next WRC meeting to remove the higher priority accorded to existing satellite network operators. This started a completely new discussion as to how networks are coordinated and priorities are assigned to countries receiving assignments in the orbital arc. Currently there are no procedures with regard to the priorities that might be assigned to satellite constellations in low Earth orbit. The only key regulation that is in effect is that GSO satellites have protected status against non-GSO satellites.

The U. N. COPUOS and the Office for Outer Space Affairs

Liability Convention Concerns

The provisions of the Liability Convention state in Article II that "A launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft in flight" [6]. The convention also specifies in Article I that this liability includes attempted launches and launch failures. This means that a country that launches or procures the launch of even a cubesat would absolutely be liable for any such damages. Under Article III of the convention it specifies that: "In the event of damage being caused elsewhere than on the surface of the Earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, the latter shall be liable only if the damage is due to its fault or the fault of persons for whom it is responsible" [7]. Any country that considers sponsoring the launch of a cubesat must thus consider the potential liability that it is exposed to in doing so.

When the Liability Convention was negotiated and agreed to in the early 1970s only the United States and the U.S.S.R. were launching satellites into orbit. The concept of smallsats, and especially of cubesats and even smaller satellites, was entirely unknown. No one thought that in the future someone might create a very tiny satellite and then launch it along with a larger satellite, and what this would imply from the standpoint of this convention.

Today the situation in space has changed in many ways. Hundreds of cubesats are being launched, and if a launch failure with a rocket carrying a number of cubesats from many different countries end up landing in a major city, causing potentially billions of dollars of damages, it is unclear how damages and apportioned liability would be decided.

As things stand, each country that registers a smallsat with the U. N. Office of Outer Space Affairs office could be held "absolutely" liable for damages, particularly if there were a catastrophic launch failure accident involving people on the ground or in aircraft. In light of the small size of cubesats they fortunately would in virtually all conceivable circumstances burn up before they might hit an aircraft or fall to the ground. (*Note:* See Appendix 4 in this book for the detailed language contained in this convention.)

Registration Convention Improvements

The other most relevant convention involving smallsats is the Registration Convention. As noted earlier at the ITU WRC-12 Resolution 757 was adopted that addressed the issue as to whether the notification language concerning a new satellite network for the purposes of intersystem coordination under the ITU regulations might be changed to streamline the provisions and processes related to smallsats (i.e., cubesats and below). There is a parallel but different provision in the U. N. Registration Convention that requires launching states to provide information with regard to all satellites launched into Earth orbit. This information is, in part to establish potential liability in the case of collisions in space or accidents involving space objects on the ground. It has been suggested that the registration procedures to provide information to the U. N. Office of Outer Space Affairs (OOSA) might be simplified for cubesats and even smaller satellites as well. Again, as in the case of the Liability Convention, the drafters of the Registration Convention did not anticipate that there might be such a development as smallsats that would need to be registered with OOSA in the future.

Currently most smallsats – although not necessarily all – are duly registered. At the start of this process there were only a small number of smallsats. Today over 100 cubesats were deployed in a single launch. And going forward there might be thousands of commercial small satellites that although they might be considered small are indeed of significant size, i.e., in the 150 to 500 kg. If nothing else, this will create a significant new workload for OOSA to register this many satellites.

The main point here is that the Registration Convention does not serve the operational needs of space traffic management, especially for very short-lived cubesat missions, where the orbital lifetime may exceed the time for the registration process to be concluded, as per the convention. And then, there would be the problem of the international U. N. register of space objects being “polluted” with hundreds, if not thousands, of entries for space objects no longer in orbit. Keeping the register up-to-date would be a mammoth task. From an operational perspective, space situational awareness systems are of much more practical use than the space object register. Currently the U. S. Space Command seeks to track all satellites in orbit and orbital debris as well. With the deployment of the S-band radar space fence it will literally be able to track over 100,000 space objects in LEO, MEO, and GEO orbits. The key issue here, of course, is today not the registration of all space objects in Earth orbit to be able to assess liability. Rather the key issue is that of orbital space debris.

Orbital Space Debris

The U. N. Committee on the Peaceful Uses of Outer Space has established a Working Group on the Long Term Sustainability of Outer Space Activities. This working group has been tasked with identifying areas of concern for the long-term sustainability of outer space activities, proposing measures that could enhance sustainability and producing voluntary guidelines to reduce risks to the long-term sustainability of space activities. The working group has addressed thematic areas including sustainable space utilization supporting development on Earth; space debris, space operations and tools to support collaborative space situational awareness; space weather; and regulatory regimes and guidance for actors in the space arena [8].

Despite the UN COPUOS space debris Mitigation Guidelines and the more detailed IADC Mitigation Guidelines (see Appendix 2 and 5 in this book, respectively) the problems of space debris continue to mount. The deployment of conventional and now large-scale LEO constellations to provide remote sensing, fixed and mobile telecommunications, and data-relay services, has tended to raise levels of concern to much higher levels.

In view of the lack of appetite by UN COPUOS to amend the U. N. Outer Space Treaty and its four subsidiary conventions and international agreements, it is unlikely that there will be a new international agreement to address the problem of space debris and its mitigation and containment. The solution may well lie in the establishment of agreed international norms (such as voluntary guidelines) that may be implemented at the national level to impose strict controls related to space debris in various ways. The French government, under the French Space Operations Act, has enacted legislation to impose significant fines on any French space system that does not meet the conditions of the deorbiting of all satellites within 25 years of their operational end of life. The U. S. administrative regulations have similar provisions to enforce due diligence to prevent orbital space debris prior to any launch.

Another approach would be to have an international code of conduct for outer space that would establish clear, albeit not explicitly enforceable, guidelines that would cover space safety concerns including those that relate to improved space situational awareness and mitigation of orbital debris. Some of the concepts that could be considered for a global code of conduct for outer space might include the following:

DEPLOY LEO CUBESATS AND OTHER SMALLSATS AT AN ALTITUDE OF 300 KM OR LOWER: This guideline would urge the deploying of experimental cubesats or smallsats of developing countries in very low, short-lived orbits in order to seek to minimize the problem of orbital debris. The 300-km altitude is suggested to be below the orbit of the ISS, but this is, of course, not a magic number, and it might be moved higher to altitudes such as 350 or 400 km. The key is to set an altitude so that the 25-year guideline would always be met [9].

This policy could be further refined to urge consideration of such projects being sent up and down via the International space station (ISS) or on platforms equipped to accommodate a large number of cubesats. Such a platform that could consolidate smallsat launches could also provide power, TT&C and communications services, as well as most importantly, critical deorbit services. In the case of using a multi-satellite platform with deorbit capabilities, higher altitude orbits with longer lifetimes could be accommodated [10].

Failing that, all such launches would be deployed in space so as to operate at a sufficiently low altitude so that natural gravitational effects and solar wind pressure would hasten their reentry into Earth's atmosphere. What is critical to note is that in the case of a collision at these altitudes, the resulting debris would also decay in a reasonably short period and thus would not pose a risk to other operational satellites or to launch operations.

Regulatory Systems and Funds for Cleaning Up Orbital Debris : Ultimately all of these strategies are still not going to be able to remove all orbital debris from Earth orbit to guarantee true long-term sustainability of the LEO environment. There will need to be some method of active debris removal (ADR). The possibilities in this respect were discussed in Chapter 6 and illustrated in Figs. 6.1, 6.2, and 6.3. The question is under what sort of regulatory framework and under what type of financial or insurance mechanisms might such ADR activities take place?

Scientists and engineers will of course tend to focus on what might be an effective technological approach. It is, however, just as important to develop a suitable economic and regulatory process that is internationally agreed on and viable. There have been a wide range of proposals made in this regard, including the idea of creating a new international approach based on a model such as the original Intelsat organization.

Others have suggested that the funding to support such an active orbital debris removal activity might be structured so that it would work much more like a sort of launch insurance policy. Under this approach all future commercial and governmental launches would be required to pay into this fund. This might be structured so that there could be at least a partial refund after the satellites in question were successfully deorbited or sent beyond Earth orbit cleanly. Such a fund would not restrict active debris removal to a single entity. Instead it would allow for a variety of different technical approaches to be pursued and proven on a competitive basis. It would also allow for commercial entities that removed debris successfully to be compensated by the global debris removal insurance fund. It is also key that this fund could be shut down or phased out if over time debris removal systems became sufficiently successful that this type of operation were thankfully no longer needed [11]. In keeping with the provisions of the Outer Space Treaty, this fund concept could be implemented and managed at a national level. States without the technical capabilities to execute ADR measures could use their national debris removal insurance fund to contract entities in other States with such capabilities to perform the necessary ADR operations on space objects under their jurisdiction and control.

Conclusions

The advent of small satellites, as well as large commercial smallsat constellations, has given rise to a wide range of new concerns and questions as to whether new standards, regulations, or guidelines should be developed and agreed, either globally or at a national level. A number of these issues and possible regulatory solutions or standards have been addressed in this chapter.

Under the ITU regulations and associated processes it might be appropriate to change the notification procedures, to change ITU processes with regard to intersystem interference and jamming, to strengthen ITU regulatory enforcement powers, and to change the processes and requirements with regard to intersystem coordination.

Under the U. N. Committee on the Peaceful Uses of Outer Space and its Subcommittees certain other matters appear necessary to consider. These include: (i) changes to registration processes under the Registration Convention with regard to various types of smallsats and smallsat constellations; (ii) consideration of pragmatic guidelines to establish a common registration practice of States for short-lived smallsats under the Registration Convention, and how the Liability Convention might be interpreted so as to better facilitate active debris removal; (iii) actions that would encourage or enable action at the commercial, the national, and the international level to allow improved space situational awareness; and (iv) new incentives or regulation to prevent the future buildup of orbital debris, initiatives to create new mechanisms such as orbital debris funds, insurance arrangements, or entities to encourage or enable active space debris removal; or (v) better regulations, mechanisms, and technology to help to ensure removal of satellites from orbit at end of life.

At the national level the creation of new mechanisms, regulations, laws, and other measures to aid in the effective registration, intersystem coordination, operation, and removal of small satellites from orbit after their operational end-of-life.

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Conclusions and Top Ten Things to Know About Small Satellites

8

This book has sought to cover all of the key elements associated with the development and future use of small satellites around the world. There are various chapters that have addressed the rapidly evolving technology, the main applications in remote sensing and Earth observation, networking and telecommunications, and the key opportunities that this rapidly developing technology can afford to developing countries and the Global South. There is a detailed analysis of how this technology and small satellite systems might be effectively deployed to achieve the U. N. Sustainable Development Goals by 2030. There is also a detailed analysis of the policy and regulatory issues that small satellites pose to the effective and safe future utilization of space. Further there is a chapter that outlines some possible changes and improvement to standards related to small satellites as well as proposed modifications and improvement to current regulatory provisions concerning space activities in general and smallsats in particular. These suggested enhancements to current global space governance could possibly help to address some of the policy concerns and issues raised.

Certainly one of the continuing and indeed growing concerns is the potential of small satellites to create significant new amounts of orbital space debris. There is particular concern with regard to those commercial initiatives that plan to deploy very large constellations of small satellites into low Earth orbit, especially with regard to those networks with proposed populations of thousands of satellites. The most recent studies suggest that new methods for end-of-life orbital removal are needed to ensure that well above 90% of these defunct satellites can be successfully removed in order to prevent the creation of new space debris. In short, it is essential to have an effective and nearly failsafe means to remove all debris elements of LEO constellation satellites at end of their operational lifetimes. This is essential in order to maintain the effective use of outer space for all nations and future generations. This then becomes bigger than a smallsat matter, but one that concerns all aspects of space applications, sciences and exploration. In a similar

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vein there is also growing concern about radio frequency (RF) interference among and between various space systems and between satellites, high altitude platform systems (HAPS), UAVs, and terrestrial-based mobile communications systems. Here a combination of technical innovation and new regulations may well be necessary.

A Quick Recap

Chapter 1 discussed the quite wide range of spacecraft that are actually covered by the term small satellites, also referred to as smallsats. It noted that everything from a tiny 50-g femtosat to cubesats of 1 unit to 6 units with masses in the range 1 to 8 kg, and even larger small satellites of 150 to 500 kg in mass can be covered by this term. It also noted that smallsats can now be deployed in very large-scale constellations such as OneWeb that potentially might have a thousand or more satellites in a single constellation. Chapter 1 also explained the importance of what might be called "small satellite thinking" or the "NewSpace" philosophy that has led to a host of new space-based entrepreneurial initiatives, which in some ways upended the traditional aerospace industries. Finally Chapter 1 provided a chart that tried to note all the many useful ways that smallsats could be designed and used for new commercial applications, student projects, small scientific projects and experiments, and even military and governmental projects.

Chapter 2 examined and explained a number of the key engineering, design, and manufacturing aspects of smallsats. Many of the technical components related to the designing and manufacturing of a small satellite depend on why it is being built; is it a one-of-a-kind mission or part of a huge constellation comprising over a thousand smallsats? Often smallsats can and do use commercial off-the-shelf components. Smallsat developers also often rely on accelerated or abbreviated testing of the satellites and their components. Such techniques lower costs but can also affect reliability, safety, and on-orbit lifetime. Small satellites, because of their compact size and low mass, also involve very different launch arrangements compared to more traditional satellites. In essence, small satellite design, fabrication, testing, launch, operation, and end-of-life disposal are quite different from past practices and approaches used with regard to conventional satellites. This technical review also acknowledges the various ways that organizations involved in space satellite design and fabrication, such as the Surrey Space Centre, Utah State University, and other NewSpace innovators have helped to spawn a number of new microsatellite projects in terms of new design and manufacturing techniques.

Chapter 3 discussed the amazing applications of smallsats for remote sensing and Earth observation. In light of the miniaturization of sensing instruments and cameras, it was in this realm that smallsats and smallsat constellations first came into the spotlight. It turned out that new initiatives such as Planet Labs and Terra Bella proved that small satellite constellations could compete effectively in the market for commercial space services, as well as create new and innovative applications and new markets. Today these ventures are now merged into a single enterprise known as Planet, but these two revolutionary smallsat ventures were keys to what is now called the smallsat revolution. It was the revolution in remote sensing via smallsats based on quick update of data that helped to redefine the role of small satellites in providing commercial services in other sectors as well. Several other, equally innovative initiatives are underway.

Chapter 4 addressed new ideas that are now emerging as to how to design smallsat constellations to provide new and potentially lower cost ways of networking and telecommunications in the developing world and the Global South. These new-large scale constellations provide an alternative to high-throughput communications satellites that are optimized for developed economy markets. The low Earth orbit small satellite constellations can provide low latency connectivity to the Internet in countries without large terrestrial infrastructure in place. The great number of satellites proposed for deployment in smallsat constellations has also given rise to concerns about orbital debris. These concerns were addressed in Chapter 6.

Chapter 5 addressed how small satellites can be used to assist with achieving the U. N. Sustainable Development Goals and meet the needs of developing countries. In particular it provided numerous examples of smallsats being used to address a range of problems encompassed by the Sustainable Development Goals, inter alia, poverty and hunger, public health, education, environmental issues, climate issues, and peace and security.

Chapter 6 addressed key policy and regulatory concerns. It noted some of the more important future trends with regard to smallsats and also emphasized some of the more important policy, regulatory, and safety concerns in the areas of small satellite development. Some of the most important issues noted included systematic registration of all smallsats as required by the Registration Convention, the rapidly mounting population of orbital debris accumulating especially in low Earth orbit, and the need for appropriate regulations for the removal from orbit of satellites at the end of operational lifetime.

The book ends with a glossary of key terms and acronyms commonly used in the smallsat community.

Top Takeaways from this Book

The smallsat revolution has redefined the world of space for just about everyone. It has dramatically affected the worlds of space applications service providers, satellite manufacturers, launch services providers, and regulators concerned with the safety and regulatory oversight of space services. Here are some top takeaways from this book.

1. **Smallsats represent a very broad range of concepts and capabilities.**

   The term smallsat covers orbitally deployed spacecraft that vary in mass from as small as 50 g (femtosats) up to smallsats that are 250 to 500 kg in mass. Larger forms of smallsats are most typically being designed and deployed in constellations for communications and networking. Some smallsats are unique one-off creations, typically cubesats, and are designed by students and experimenters. Others are designed for mass manufacture for new LEO constellations that involve hundreds if not thousands of satellites deployed in constellations. These can be quite sophisticated satellites containing features such as inter-satellite links (ISLs), and might use the latest manufacturing techniques such as 3-D printing.

In short small satellites cover an enormous range of possibilities in terms of size, mass, sensors, processing capabilities, frequencies, and applications. There can be a difference of five orders of magnitude when it comes to mass and dimensions. You need to know the mission, lifetime, mass, dimensions, orbital characteristics, application, stabilizations and pointing characteristics, constellation deployment (if relevant), and other key parameters such as whether it is unique or part of a series in order to really understand what a particular smallsat actually is.

2. **Smallsats can offer particular and unique benefits and significant new cost reductions, faster times to orbit, and expanded opportunities for participation in the benefits of space.**

Small satellites can provide lower design, testing, manufacturing, and deployment costs. In some cases they can also provide lower operational costs, but in the case of low Earth orbit constellations with very large numbers of satellites the operational costs can go upward. This is because there are complexities of several types that are involved, including management of the constellation so that the satellites do not collide with each other or with other satellites or space debris. Another concern is that low Earth orbit constellations for telecommunications and networking services can interfere with satellites in geosynchronous orbit that occupy the equatorial region and have protected status under the International Telecommunication Union (ITU) regulations. The deployment of small satellites in low Earth orbit constellations can provide quicker updates of data, lower latency with regard to networking and telecommunications applications, and other advantages such as more rapid updates in the case of remote sensing services.

As is the case with most things, there are tradeoffs. Small satellites can be less reliable and pose greater risks of on-orbit collisions, thus increasing serious concerns with regard to the more rapid buildup of orbital space debris that can threaten all types of future space operations and research. Small satellites are therefore not a panacea that can replace all types of medium or larger scale satellites, but they have redefined the economic, technical, operational, and regulatory issues for the entire space industry.

Some have suggested that the advent of smallsats is such a significant market development that it represents a revolutionary market breakthrough. It has even been suggested that the new large-scale LEO constellations for communications and remote sensing will totally reshape the commercial world of satellite applications. The short answer to this is that this remains to be seen.

There is now a new generation of high throughput satellites in geosynchronous orbit, such as Viasat 1 and 2, the Intelsat Epic satellites, and others that are more than ten times more cost effective than earlier generations of communications satellites. These new GEO-based satellites seem quite competitive in the marketplace. Market analysts have even suggested that these GEO networks are competitive with the most cost effective low Earth orbit constellation as now contemplated. Only time will tell which types of satellite systems will be most successful in terms of satellite applications services for the coming decades. The past bankruptcies that have occurred with low Earth orbit systems deployed in the 1990s such as the first generations of Iridium, Globalstar, ICO, and Orbcomm satellites, plus the ill-fated Teledesic mega-LEO system, gives reason to think that smallsat constellations may still have significant market challenges to overcome. On top of market concerns, there are also technical and operational concerns as to whether large-scale LEO constellations will generate significant new problems with regard to the generation of too much orbital space debris, or whether these satellites will generate an excessive amount of intersystem interference with GEO satellites.

3. **Trade-off analysis of the pros and cons of smallsats and their optimum architecture and design are a must.**

   There are no absolutes. Smallsats in some cases are an elegant and effective answer for experimental tests, student experiments, development of constellations to provide rapid remote sensing updates, or low latency Internet services to developing countries in areas with modest infrastructure. In other cases small satellites do not necessarily seem to provide the optimum answer. Only careful tradeoff studies and systems' analyses of all the expenses for the space segment and Earth station equipment will indicate the best technical, operational, and financial solutions. These analyses will need to consider a variety of factors. One of the prime factors relates to the design of the Earth station system that will work most efficiently with low Earth orbit constellations.

   The advantages of GEO satellites that appear to remain in the same spot over Earth and thus not require tracking and can be constantly pointed to the same location in the sky is an important economic advantage. New ground antenna systems that can allow electronic tracking can change the cost equations, but the performance of this new type of ground system still remains to be proven in terms of overall costs, interference, and reliability. Other tradeoff calculations involve the difference in lifetime between satellites in LEO, MEO, and GEO orbits' determination of optimum levels of redundancy; lifetime extension versus simple replenishment of satellites; and other issues such as resilience. Here there are concerns related to ion bombardment of satellites from the Van Allen Belts, although this is a larger concern for MEO satellites than LEO satellites.

   Different small satellite projects and initiatives have different goals and objectives. Thus there are no magic answers as to whether to build a satellite to last a few weeks or a few months, a year, 5 years, 15 years, or longer. Key tradeoffs tend to address issues such as lifetime, redundancy, position-keeping and redundancy, ability to deorbit, frequency spectrum choices, sensor resolution, and off-the-shelf components versus space-qualified elements. There are typically considerable differences in approach used for those attempting specific experiments that can be conducted in short periods of time, versus those attempting to provide commercial services with a high degree of reliability over long periods of time.

Recently a new type of tradeoff dynamic has emerged. This is the question as to whether experiments or services that might be carried by small satellites could also be accomplished at lower cost or greater efficiency via the use of high altitude platform systems (HAPS). These are platforms that can operate at stratospheric altitudes and are sometimes referred to as operating in the "protozone."

4. **Another key element of the smallsat revolution is new, lower cost, and more flexible launch options.**

   Like in the old riddle of which came first, the chicken or the egg, was it the lower cost launch options that led to the development of the enthusiasm for small satellites or did the small satellite phenomena give rise to the availability of lower cost launchers?

5. **Smallsats represent not only new technology and systems in space and on the ground, but they have given rise to new business models and new space entrepreneurial initiatives.**

6. **One of the greatest potential benefits of smallsats is to lower entry barriers to space activities for developing countries and the Global South.**

   Smallsats can help them meet their development goals and assist with the attainment of the U. N. Sustainable Development Goals by 2030.

   Because of lower development costs and wide commercial availability of components and subsystems, and even entire turnkey solutions delivered on orbit, developing countries now have access to a much wider spectrum of cost-effective options to acquire an/or develop their own national space capabilities in support of national and global development goals.

7. **The interest by developing countries in space systems and space applications has also served to increase interest in space by younger people and helped to inspire more interest in science, technology, engineering, and math.**

8. **The lower cost and flexibility presented by smallsats that has opened up new opportunities by developing countries to utilize space, could also open up new possibilities for new space regulations and standards.**

9. **The great interest and enthusiasm for smallsats and an explosion of smallsat launches along with tremendous expansion of global broadband mobile communica-**

tions has created a near crisis in competing radio frequency allocation needs and interference issues.

10. **One of the greatest problems that SmallSats – particularly large-scale constellations – pose is the potential buildup of orbital space debris to unacceptably high levels.**

The UN COPUOS Working Group on the Long-term Sustainability of Outer Space Activities, the various space agencies of the world, the Inter-Agency Space Debris Coordination Committee (IADC), the Space Data Association, the International Association for the Advancement of Space Safety (IAASS) and many other organizations around the world are very concerned about the buildup of space debris and thus are trying to develop better methods to address this issue. These efforts include: (i) getting all launching nations to completely and consistently register all smallsat launches; (ii) to have stricter national due diligence efforts to review stringently all launches before they occur to make sure that the launch will not lead to the proliferation of debris; (iii) to enact national legislative efforts to enforce the IADC's recommended "25-year rule" to ensure that a spacecraft deorbits within 25 years of the end of its operational life; (iv) to see that spacecraft are drained of fuel and batteries are discharged to prevent their blowing up in space; and (v) to devise new methods to make sure that small satellites in large-scale constellations are removed with high efficiency at the end of their operational life, an efficiency that is significantly better than that achieved with earlier LEO constellations such as Iridium, Geostar, Orbcom, and so on.

Final Thought

It used to be said that the sky is the limit, but that is no longer true. Today's space technology is giving us unprecedented capabilities to reach to the stars, or at least to use innovative smallsat technology to learn and do more than ever before.

Appendix 1: Glossary of Terms and Acronyms

Active debris removal (ADR): Any 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.

Agreement Governing the Activities of States on the Moon and Other Celestial Bodies ("The Moon Agreement"): International agreement, popularly known as the Moon Agreement, was signed on December 5, 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. It also introduces the concept of "common heritage of mankind" in reference to celestial bodies and their natural resources. This has proven to be one of the more controversial space agreements with far fewer countries actually ratifying this agreement than the other four space agreements adopted in the 1960s and early in the 1970s.

Airspace: The definition of airspace and outer space as well as the demarcation between the two has not really been decided yet. 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 Van Karman line, the point where it is physically not possible for aircraft to fly, which is 100 km from the surface of Earth. States have "complete and exclusive sovereignty over the airspace above [their] territory" as per Article 1 of the Chicago Convention.

Angara 1.2 Launch Vehicle: This is the two-stage Russian launch vehicle that is designed to launch small satellites into low Earth orbit. In Feb. 2017 it was announced that a contract had been signed for the Angara rocket to launch the South Korea Kompsat 6 into low Earth orbit. Eventually the Angara A5 heavy lift rocket with three stages will replace the Proton rocket.

Asia-Pacific Regional Space Agency Forum (APRSAF): This forum was established in 1993 to include participants from the Asia-Pacific regions for the purposes of coordinating and

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enhancing space activities of the region. Members to APRSAF constitute private companies and organizations, governmental bodies, international organizations as well as independent entities. It supports space-related projects and holds annual meetings and workshops.

Asia-Pacific Space Cooperation Organization (APSCO): A regional organization covering the Asia-Pacific area that seeks cooperation within the region in space technology and applications. Sixteen countries became member to the organization that was established in 1992, and its convention was fully signed and came into full force in 2002.

ASK-1: A proposed satellite network of some 10 small satellites that is envisioned by Norway. It is planned to operate in highly elliptical Earth orbit and to use X-, Ku-, and Ka-bands.

B2B: Business to business communications. This involves satellite store-and-forward data relay but does not include voice communications.

BRICS: An acronym that refers the countries of Brazil, Russia, India, China, and South Africa.

Canpol-2: A proposed Canadian smallsat constellation of 72 small satellites using VHF-, UHF-, X-, and Ka-bands, which would operate in highly elliptical orbits.

Centre National d'Etudes Spatiales (CNES): The French national space agency.

China National Space Agency (CNSA): This is the official space agency for China.

Committee on Space Research (COSPAR): The international scientific committee, also known as COSPAR, was established in 1958 with its main objective to promote international cooperation in scientific research that relates to uses of outer space. Its main goal is to achieve effective circulation of relevant information at the international level. It was established by the International Council for Science and hosts annual conferences, workshops, and assemblies.

"Common heritage of mankind": A phrase that is explicitly stated in Article 11, Paragraph 1, of the Moon Agreement. This was an attempt to formally characterize celestial bodies, and their presumably their natural resources, as being a part of common community of interest for humanity. This phrase was also used in Article 136 of the U. N. Convention on the Law of the Sea of 1982 with regards to the Deed Seabed and utilization of its natural resources. The exact meaning of the phrase is now in some international dispute.

Commercial Spaceflight Federation: An organization of companies seeking to develop new commercial systems and activities related to spaceflight, including operators of spaceports, developers, and operators of spaceplanes and other related activities. It was originally organized as the Private Spaceflight Federation but subsequently changed its name to include all types of commercial spaceflight activities.

Commercial Space Launch Amendments Act of 2004: U. S. legislation that is also known by the acronym CSLAA.

Commercial Space Launch Competitiveness Act of 2015: The most recent act covering U. S. regulation of commercial spacecraft flight and commercial space activities as of the end of 2017. This is the act that in Title IV addresses the regulation of space mining activities.

Comstellation: A proposed large-scale comstellation of 794 small satellites in low Earth orbit using Ka-band frequencies.

Consultative Committee on Space Data Systems (CCSDS): An international committee whose mission is to coordinate the collection and use of space data systems.

Cubesat: This refers to a quite small cube-shaped satellite that is 10 cm x 10 cm x 10 cm and has a mass of around 1 kg. Cubesats start at 1 unit and increase to up to 6-unit sizes.

Customary law: Custom is one of the sources of international law (as per Article 38 of the ICJ statute) and consists in State practice and opinio juris. As customary law it could be defined as the whole range of rules that emerge from the practice that is followed by States and is believed to be binding without entailing the form of conventional law.

Data Relay Store-and-Forward Service: This is a type of service that a limited number of low Earth orbit satellites in orbit can provide by storing uploaded data messages and then downloading them when over the desired location. The University of Surrey Satellites (UoS) were pioneers in perfecting this type of small satellite service. The data relay only service can sometimes be referred to as B2B (or business to business) service.

Defense Advanced Research Projects Agency (DARPA): This defense agency of the United States was originally established as the Advanced Research Projects Agency (ARPA). It has the charter to develop the most advanced, state-of-the-art technology for the United States defense and has played a key role in space technology and systems development, including smallsat technology.

The Disaster Charter: This is the short and more popular name for the "Charter on Cooperation to Achieve the Coordinated Use of Space Facilities in the Event of Natural or Technological Disasters." The Disaster Charter was established in 2000 and was negotiated as the result of discussions and proposals carried out at UNISPACE III. The charter provides remote sensing data in a timely manner and at no cost, and it has been activated nearly 100 times. Entities such as GEO (Group on Earth Observations), (GMES) Global Monitoring for Environment and Security and STDM (U. S. Space Technology Disaster Management) are contributing to the charter.

DLR: An acronym in German is expressed as *Deutsches Zentrum für Luft und Raumfahrt*. This is the German Aerospace Center that is, in effect, the German space agency.

Dual-use satellites/payloads: Satellites and payloads that can be used for both civilian (mainly commercial) and military purposes simultaneously or alternatively. Sometimes this represents a single spacecraft used for both military and civilian communications using the same payload. In other cases there can be a satellite with several payloads, and some payloads are used for civilian purposes while other payloads are used for military purposes.

Due diligence: A legal term used in domestic and in international law. In international legal usage it refers the principle that States should consider the consequences of their activities before undertaking them and abstain from them if it is foreseen that they will cause harm or hinder activities of other states; or alternatively they should take all necessary steps to avoid such consequences.

Same concept characterizes also the manner in which space activities should be undertaken under the terms of the Outer Space Treaty.

Due regard: A concept that refers to the obligation of States to undertake their activities in a manner so as not to cause harm to other States. The difference of the term from due diligence is that the former refers to the stage of operation, whereas the latter to the stage of preparation. In space law, the term is met in Article IX of the Outer Space Treaty.

Electron Launch Vehicle: This is the new launch vehicle developed by Rocket Labs of New Zealand and California, a NewSpace company seeking to develop a low cost launcher for small satellites. It was planned for a launch to the Moon in a bid to win the Lunar XPrize.

EMI: Electromagnetic interference.

Equal non-discriminatory sharing/uses of outer space: This notion was introduced in the of space law with the Outer Space Treaty and later reiterated in the Moon Agreement and requires the equal participation of States to the sharing and uses of outer space “irrespective of their degree of economic and scientific development.”

Equitable sharing/uses of outer space: In contrast to an “equal sharing,” “equitable sharing” of the benefits that emerge from the uses of outer space refers to a “balanced sharing” according to the needs, capabilities, and financial investments of the States and not necessarily equal sharing from the results of space-related activities. The Moon Agreement establishes this notion as it refers to benefits that result from the uses of natural resources of celestial bodies. The exact meaning of this phrase is also a matter of some international dispute.

European Space Agency (ESA): This is the integrated space agency that includes most European nations. It has a different membership from the European Union. This difference in membership and the different financial terms that apply to these international agencies sometimes complicate the administration and financing of space activities in Europe.

European Commission (EC): This is the authority with its various directorates under which the European Union (EU) operates.

European Union: This is the name of the integrated organization that provides elements of regional government for Europe and for which the “Euro” is the common currency.

Extremely Eccentric Earth Orbit (EEO) or Highly Eccentric Orbit (HEO): This is a very highly elliptical orbit. It is also sometimes known as the Molniya orbit since this was the first satellite system to use this orbit for practical purposes to operate a network.

EUTELSAT: European Telecommunications Satellite Organization.

Federal Aviation Administration (FAA): National aviation authority of the United States that is responsible for the “advancement, safety and regulation of civil aviation.” Within its jurisdiction fall also air traffic control activities. The FAA Office of Space Transportation is responsible for licensing and oversight of the safety of commercial space activities.

Fault-based liability: In contrary to the absolute liability as founded in Article II of the Liability Convention, fault-based liability requires the existence of fault by the State in order to attribute liability to it. This kind of liability is provided in Article III of the Liability Convention for damages caused elsewhere than on the surface of Earth.

Federal Communications Commission (FCC): This is the U. S. regulatory commission that is responsible for the assignment and allocation of radio frequencies in the United States, including those used for space communications and those used at very high altitudes (i.e., the protozone).

Femtosat: This is the smallest class of satellite with its size being considered to be in the 10 to 100 g range, or about up to about 120 g or 4 ounces.

FIA: Fédération Internationale de l'Automobile.

Firefly: This was a launcher development company seeking to create a new low cost launch vehicle for small satellites. This venture went bankrupt in October 2016 and immediately furloughed its staff in hopes of refinancing.

FOSA: French Operations Space Act.

GAGAN: GPS Aided Geo Augmented Navigation system.

GEO: Geosynchronous Earth orbit. See also Geostationary Earth orbit (GSO).

Geostar: A low Earth orbit satellite system for personal mobile communications that was deployed shortly after the Iridium system was deployed. This constellation consists of 48 satellites plus spares and provides service between the latitudes of 55 degrees North to 55 degrees South.

Geosynchronous Earth orbit (GSO): This is very similar to geostationary Earth orbit (GEO). GSO is almost a theoretical concept because a perfect GSO satellite would always remain perfectly in the equatorial plane. The pull of the Moon's gravity and anomalies in Earth's shape and density are constantly pulling a GEO satellite either north or south of the equator. After a satellite builds up inclination so that it is 7 degrees above or below the equator it is considered to be outside the protected area accorded to GEO or GSO satellites.

Globalstar: This is a U. S.-based mobile satellite system.

GLONASS: The Russian GNSS satellite system, which is expressed in the original Russian as *GLObal'naya NAvigatsionnaya Sputnikovaya Sistema.*

GNSS: Global Navigation Satellite Systems.

Global Positioning System (GPS): The popularly used name of the U. S. NAVSTAR satellite navigation system operated by the U. S. military to provide precise navigation and timing.

HAPS: High Altitude Platform Systems.

IGC: International Committee on Global Navigation Satellite Systems.

Indian Regional Navigation Satellite System (IRNSS): This is the PNT satellite system operated by India with a combination of MEO and GEO satellites. It is different from most other systems in that it is regional and does not operate on a global basis.

Indian Space Research Organization (ISRO): The Indian space agency.

INMARSAT: International Maritime Satellite Organization.

INTELSAT: International Telecommunications Satellite Organization.

International Association for the Advancement of Space Safety (IAASS): Established in 2004, IAASS is a non-profit organization that has as objective the achievement of broad international cooperation for the advancement in the field of safety of space systems. IAASS was granted the status of observer at the UNCOPUOS.

International Astronautical Congress (IAC): A once-a-year meeting sponsored by the IAF, IAA and IISL (see below).

International Astronautical Federation (IAF): Organizer and sponsor of the IAC meeting (see above).

International Astronautical Union (IAU): a general assembly held once every three years.

International Bank for Reconstruction and Development (IBRD): This is the specialized agency of the United Nations that address world banking and especially financing and development for economically developing countries. See IMF.

International Civil Aviation Organization (ICAO): U. N. specialized agency that was established in 1947 in order "to manage the administration and governance on the Chicago Convention." ICAO adopts SARPs (Standards and Recommended Practices) through the member States to the Chicago Convention with the purpose of achieving safe, secure, and economically and environmentally sustainable aviation. It is comprising the 191 member States of the convention.

International Council of Scientific Unions (ICSU): This is the global council that includes the Committee on Space Research (COSPAR) and the International Astronautical Union (IAU).

International Court of Justice (ICJ): This is the international court that interprets international law and decides cases where treaties, conventions, or other established international space law might be in dispute.

International Global Navigational Satellite Service (GNSS): This is another way of describing positioning, navigation, and timing PNT satellite services.

International Maritime Organization (IMO): This is the specialized agency of the United Nations that addresses all aspects of international maritime services, operations, and safety, including communications. Previously known as the International Maritime Consultative Organization (IMCO).

International Monetary Fund (IMF): This is the specialized agency of the United Nations addressing the financial needs of the least economically developed nations.

International Standards Organization (ISO): This is the international standards agency that sets many international technical standards used by governments and commercial organizations to insure quality and international standardization.

International Telecommunication Union (ITU): This is the U. N. specialized agency for information and communication technologies. It is the oldest U. N. agency as it was established in 1865. It is located in Geneva, Switzerland, and its legal framework consists of the ITU Convention, the ITU Constitution, and the ITU Radio Regulations.

International Traffic in Arms Regulations (ITARs): Regulations that control the traffic (export and import) of articles and services that relate for defense purposes. They constitute, in essence, implementation of the 22 U.S.C. 2778 of the Arms Export Control Act and are issued by the U. S. Department of State. Any small satellite designer that uses components involving U. S. suppliers should be aware of these regulations and the restrictions that apply.

Iridium: This was the world's first low Earth orbit constellation that deployed small satellites to provide mobile satellite communications to subscribers using small handsets for voice and data communications. This initial system experienced bankruptcy and had to be restructured financially. Its Iridium Next system, with its second generation satellites, is currently being deployed. These satellites have piggyback payloads that are meant to support aircraft precise navigation. Iridium is currently deploying its next generation of LEO satellites in a constellation.

ITU Convention: This is the convention of the International Telecommunication Union, which is an internationally agreed to treaty.

ITU RR: International Telecommunication Union Radio Regulations.

Japanese Aerospace Exploration Agency (JAXA): This is the Japanese space agency.

Launcher One: This is the small rocket launcher being developed by Virgin Galactic to offer the ability to launch small satellites into low Earth orbit as soon as 2019. The launch system is under contract to provide some of the launches to support the deployment of the OneWeb satellite constellation. (See SpaceShip2.)

Launching authority: Entity that authorizes the launching of space objects into outer space. This is a concept that is distinct from the "launching state" and often linked to licensing entities. The launching entity is also often the "launching state," as noted in the registration process of the U. N. Office of Outer Space Affairs.

Launching State: State that launches or procures the launching of a space object, or a state from the territory or facilities of which the launch takes place (Article I of the Liability Convention and Registration Convention).

LEOSAT: This is a proposed low earth orbit small satellite constellation that is optimized to serve the needs of large businesses networking needs.

Liability Convention: Convention on International Liability for Damage Caused by Space Objects, March 29, 1972. After ten years of negotiations UN COPUOS Legal Subcommittee adopted the resolution 2777 (XXVI) in 1971, which introduced the Liability Convention. The convention entered into force in 1972 and covers liability issues that emerge from space activities by distinguishing between absolute liability and fault-based liability. It is a victim-oriented treaty as it provides for absolute liability for damages caused on the surface of Earth and fault-based liability for damages occurring in outer space.

Long Term Sustainability of Outer Space Activities (LTSOSA): The UN COPUOS has established a Working Group on the Long Term Sustainability of Outer Space Activities. It has made a number of recommendations related to orbital debris, space traffic management and other issues. The outcomes regarding the recommendations can be seen in UN COPOUS documents and in the *International Study on Global Space Governance* (2017).

Low Earth orbit (LEO): This does not indicate a specific orbit, but typical LEO orbits range from 300 to 1,500 km. Many of these are polar, Sun-synchronous orbits.

Millennium Development Goals and Beyond 2015 (MDG): These U. N. goals as originally adopted by the U. N. General Assembly have now been overtaken by the Sustainable Development Goals for 2030 (see SDG).

MEO: Medium Earth orbit.

Micro Satellite: This type of small satellite is often built by smaller manufacturers for specific purposes – often for military or governmental missions. They are often in the 20- to 99-kg range.

Nanosat: A nanosat is another term referring to small satellites without a precise meaning but often with a mass in the 1 to 10 kg range.

NASA: The National Astronautical and Space Administration. NASA is an independent agency of the executive branch of the U. S. federal government that is responsible for the civilian space program and undertakes aeronautics and aerospace research.

Navstar: This is the U. S. GNSS satellite network for position determination and precise timing that is known more commonly as the Global Positioning Satellite (GPS) System.

NGOs: Non-governmental organizations.

OECD: Organization for Economic Cooperation and Development.

Office of Outer Space Affairs (OOSA): This unit of the United Nations supports the operations and activities of the U. N. Committee on the Peaceful Uses of Outer Space. It implements decisions of the General Assembly and support the meetings of UN COPUOS, its legal and scientific and technical subcommittees, and its various working groups. It was formed in 1962 and is currently located in Vienna.

On-orbit servicing: On-orbit servicing refers to the installation, maintenance and repair activities on an object in orbit (a satellite, space station or space vehicle, for example) in order to extend the life of the object of enhance its capabilities. On-orbiting servicing can consist of manned or unmanned missions.

OneWeb: This is a large-scale low Earth orbit constellation of some 800 satellites plus spares that is under contract for manufacture by Astrium Airbus DS. This is only one of the truly large-scale "megaLEO" constellations that is in production for launch. Its prime market is to provide broadband Internet services to areas that are underserved around the world.

Orbital space debris: Refers to defunct manmade objects in space and objects created by a variety of events including exploding batteries and fuel tanks, collisions between satellites, and debris itself colliding with other debris. Also known as space junk, it can consist of old satellites, spent upper stage rockets, fragments from disintegration, erosion and/or collisions.

The Outer Space Treaty (OST): This is the key space treaty that is formally known 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," signed on January 27, 1967. Thus the Outer Space Treaty was opened for signature in January 1967 and entered into force in October 1967. The OST established the basic framework in international space law through core principles. It has currently been ratified by 104 countries.

Outer space: There is no multilaterally accepted definition of what outer space consists of, mainly due to the lack of agreement as to the delimitation between airspace and outer space. Although many theories present different perceptions (e.g., a spatialist approach, functionalist approach, aerodynamic lift theory, etc.), the most acceptable point where outer space should begin is 100 km above the surface of Earth (von Karman line). As a result outer space can be defined as the area that expands above the airspace starting at approximately 100 km above the surface of Earth. Others have suggested that 160 km, which is the minimum altitude needed to sustain an LEO satellite in orbit might be an appropriate altitude for outer space to begin and the upper limit of the so-called protozone.

Passive device deorbit systems: These are devices that can be activated at the end of a satellite's lifetime to create atmospheric drag to assist with the deorbit of a low Earth orbit satellite.

Peaceful uses: From the outset, space law was centered on the uses of outer space for peaceful purposes. Although there is no specific provision that prohibits the use of space for military purposes it was generally agreed during the negotiations of the Outer Space Treaty that outer space can be used for military purposes as long as not in an aggressive manner. Hence peaceful uses can entail military purposes.

Piggyback launches and payloads: A launch may include one or two or even more primary payloads and then a number of smallsats as "piggyback" launches that utilize additional launch capacity beyond that needed for the prime launch objectives. In addition to these auxiliary launch arrangements a satellite may have a primary mission objective that can also include a number of "piggyback" packages that can be carried on and powered by the prime satellite platform. Piggyback launches and piggyback packages on larger satellites open up a wide range of opportunities for smallsat space missions that are just auxiliaries to larger and much higher funded space missions.

Planet (formerly Planet Labs): This remote sensing small satellite constellation deploys 3-unit cubesats known as "Doves" that provide global coverage of the world with rapid updated coverage due to its large network of LEO satellites. It has recently acquired the Terra Bella cubesat system from Google.

Polar, Sun-synchronous orbits: A specific orbit that is often used by remote sensing satellites. These orbits are nearly polar, but with a small retrogressive inclination. This orbit processes 1/365th per day, so that the orbit maintains the same relative position to the Sun as Earth makes its annual orbit. This provides similar lighting conditions for the satellite sensors throughout the year.

Position, navigation, timing services (PNT): This satellite-based service is also known as precise navigation and timing (PNT) services. This is a generic term for the many such systems now operating such as the U. S. Global Positioning Satellite (GPS) system, the Russian Glonass system, the Chinese Beidou system, the Japanese Quasi Zenith system, the Indian Regional Navigation system, and the planned European Galileo system now being implemented.

Protozone: Due to the unclarified demarcation between airspace and outer space, the area above commercial space and below outer space is sometimes referred to as the protozone. This region can be characterized as the area below outer space or the area where satellites cannot sustain orbital flight (i.e., 160 km) and above commercial airspace (i.e., above 21 km).

"Province of mankind": The concept of province of mankind was attributed to outer space in the outer space treaty and later reiterated in the Moon Agreement. The term was meant to establish outer space as accessible to all states and to build foundations for free use and access of outer space by all countries.

Radio frequency (RF): Radio frequencies are electromagnetic wave frequencies within the range from around 3 kHz to 300 GHz. They include, for example, frequencies used for communications or radar signals. A range of radio frequencies, especially those allocated to a particular purpose, is referred to as a spectrum.

Registration Convention: This is the international convention that is formally known as the Convention on Registration of Objects Launched into Outer Space, signed on November 12, 1974. The Registration Convention was adopted by the U. N. General Assembly in 1975 and entered into force on September 15, 1976. It mainly addresses the issues that can arise with respect to the State Parties' responsibilities concerning their space objects and requires that launching States formally register with the U. N. Office of Outer Space affairs all objects launched into outer space.

Res communis: Res communis is a Latin term that was used in Roman law and refers today to the concepts of public domain and is often linked to the concept of "common heritage of mankind."

RFI: Radiofrequency interference.

Remotely piloted aircraft systems (RPAS): This refers to drone aircraft and is a term used by the International Telecommunication Union in reference to spectrum allocations for communications with such aircraft systems.

Radio Regulations Board (RRB): This is a part of the ITU that is concerned with the Radio Regulations adopted by the ITU plenary sessions of the World Radio Conference.

Rocket Labs: This startup NewSpace company based in New Zealand and California is developing a low cost launcher for small satellites called the Electron. It is planned for a launch to the Moon in a bid for Moon Express to win the Lunar XPrize in 2017. The reported cost of this launch is $5 million USD.

Smallsat: This is a general term referring to satellites that are typically 500 kg or less in mass and which have been designed so as to be lower in cost by such means as the use of off-the-shelf components, miniaturized components, or by means of launch as an auxiliary mission involving the launch of a much larger satellite. Such small satellites can be quite small, as characterized by such terms a femtosat, picosat, nanosat, or cubesat. These small satellites can be simply one of-a-kind projects or they can be one of a very large-scale constellation. Most small satellites are launched into low Earth orbit. But these can also be deployed in different orbits for scientific missions or even into deep space such as to explore for suitable asteroids for the purposes of space mining.

Soft law: Soft law can be contrasted with hard law. Contrarily to the latter, soft law does not have binding force. It can be described as a quasi-legal instrument.

Solar flares/storms: A solar flare/storm consists of a flash of brightness observed near the Sun's surface that ejects radiation from the Sun. There are some occasions when in addition to the flare there is also an ejection of ions into space from the Sun's corona. These events that are particularly destructive are called coronal mass ejections. Solar wind, solar flare, and solar storms are monitored closely by meteorological satellites such as NOAA satellites, which sound storm alerts to all satellites to power down. Small satellites in low Earth orbit are generally more protected than satellites in GEO orbit.

Space Data Association (SDA): This is an organization now incorporated on the Isle of Man that was created by operators of commercial satellite networks so as to exchange information and to obtain warnings of the possible conjunction of satellites. This started with just four satellite operators, but today there are nearly fifty participating satellite operators in various types of orbits.

Spacefaring nation: Spacefaring nations are countries that operate launch vehicles or engage in the operation of spacecraft or space planes. Non spacefaring nations are not capable of undertaking such activities. The number of spacefaring nations continues to grow, and the advent of small satellites will enable more and more countries to fabricate small satellites and arrange for their launch into orbit.

Space object: No specific definition exists in the body of space law for space objects, except for the clarification that "the term 'space object' includes component parts of a space object as well as its launch vehicle and parts thereof in Article I of the Liability Convention. However, it is generally accepted in scholarship that a space object can be any object that is launched from Earth to outer space, including all its components and parts. There is no technical distinction between an operational satellite or a spacecraft, a rocket, or space debris. This lack of distinction between functional space objects and non-functioning derelict space objects can lead to difficulties on several different levels.

Space plane: There is no exact definition of a space plane. The usual understanding of this term is a reusable winged vehicle that by flying in a parabolic, non-orbital flight pattern can achieve flight above a 100-km altitude (i.e., the commonly accepted start of outer space). This is so that passengers can experience about 4 minutes of weightlessness and see Earth as a great big blue marble against the dark sky of outer space. There are some "space planes" such as the XCOR Lynx that will fly to less than the 100-km altitude. There are other space planes such as the S-3 that will be able to fly cargo to outer space. Other single-stage-to-orbit vehicles using scram jet technology, such as Reaction Engines Ltd. of the U.K. with its SABRE engines, are meant for hypersonic transport as well as to fly to orbit. The SpaceShip 2 space plane is thought to be getting close to offering parabolic short-term flights to orbit and back in the relatively near future.

Space situational awareness (SSA): This term refers to all the systems and programs that exist in order to enhance awareness of what are the exact orbits of manmade and natural objects that exist in close proximity to Earth. For instance, the space situational awareness program of the European Space Agency (ESA) aims to support Europe's independent utilization and access to space. It was authorized at the November 2008 Ministerial Council, was formally launched in January 2009, and was extended until 2019. The new S-band radar system that is being implemented by the United States in Micronesia in 2017 will be able to track, in low Earth orbit, about 22,000 objects the size of a baseball to a new capability of about a quarter million objects the size of a marble. These SSA systems were initially created to track missile launches, but now play a key role in tracking orbital debris as it continues to grow.

Statute of ICJ: Statute of the International Court of Justice.

STEAM: This is a proposed gigantic constellation of small communications satellites in low Earth orbit that would be composed of over 4,200 satellites that is to operate in the Ku- and Ka-bands.

STRaND-1: This is a recent 3-unit cubesat designed and built at the Surrey Space Centre that included a smart phone.

Suborbital spaceflight: A suborbital spaceflight is one whose trajectory intersects the atmosphere or surface of the gravitating body from which it was launched. Thus, while the spacecraft reaches space, it does not complete one orbital revolution.

Surrey Space Centre: This is the small satellite design, develop, and fabrication center at the University of Surrey that is now owned by Airbus DS.

Sustainable Development Goals (SDG) of the United Nations for 2030: These are 17 specifically set goals with 169 specific targets for global development that have been endorsed by the U. N. General Assembly that set forth clear objectives for improvement in such areas as agriculture, environment, economic growth and employment, health and education, etc. These goals replace the so-called Millennium Development Goals now that the 21st century has arrived.

Secure World Foundation (SWF): This is a non-governmental organization that addresses issues related to space safety, cosmic hazards, orbital space debris, and other issues involving conflicts in or misuse of space.

TCBM: This is an acronym for transparency and confidence-building measures. It frequently relates to customary or well-publicized defense or military uses of space and practices that if used consistently can allay concerns about actions that might be misconstrued as offensive use of space systems.

Telemetry, tracking, and control (TT&C): These are the three basic elements of operation to maintain a satellites or spacecraft in orbit or on a trajectory. Telemetry involves the relay of data from a spacecraft as it operates in space. Tracking is intended to keep making available exact information, such as the location of a satellite in orbit or on a trajectory. Control (or command) is the sending of instructions to a satellite or spacecraft to perform some function such as to activate a component, operate a switch, fire a jet, or otherwise make the space vehicle operate in a proper manner.

3ECOM: This is a proposed Liechtenstein-based low Earth orbit constellation that would include 264 satellites and would operate in the Ku-band and Ka-bands.

Terra Bella: This is a global constellation of remote sensing cubesats that provides rapid video updates using a network of cubesat-type spacecraft that are deployed in a constellation in low Earth orbit. This system uses commercial off-the-shelf components to reduce cost. It was originally undertaken by a group of graduate students from Stanford University and was originally named Skybox. Subsequently the company was purchased by Google and renamed Terra Bella, and was later sold to Planet Labs in 2016 under a continuing use agreement. The consolidated smallsat constellation is now known as simply Planet. (See Planet.)

Unmanned Aerial Vehicles (UAVs): These are aircrafts that operate without a human pilot aboard. The degree of autonomy can vary, as the flight of UAVs can operate under remote control by a human operator or by onboard computers (fully or intermittently autonomously). They are commonly known as drone or unmanned aircraft systems.

U. N. Committee on the Peaceful Uses of Outer Space (UNCOPUOS): The UNCOPUOS was created by the U. N. General Assembly in 1959 to oversee international cooperation in peaceful uses of outer space, encourage research programs, study legal problems arising from the exploration of outer space, register objects launched into space by launching States, and undertake space-related activities that need to be undertaken by the United Nations.

U. N. Conferences on the Exploration and Peaceful Uses of Outer Space (UNISPACE): The UNISPACE Conferences aim to provide a platform of global dialog on issues related to space exploration and exploitation. They are organized by the United Nations to further the cooperation in the peaceful uses of outer space between States and international organizations. There has now been UNISPACE I, II, and III, and in 2018 there will be UNISPACE + 50. These events have been held in Vienna, Austria, where UNCOPUOS meets and OOSA has its offices.

U. N. Convention on the Law of the Sea of 1982 (UNCLOS): This is the very broadly agreed to convention involving the international oceans and seas. Provisions from the UNCLOS are sometimes considered as legal precedent or useful guidelines with regard to outer space.

UNCOPUOS space debris mitigation guidelines: This is a series of non-binding and voluntary regulations approved by the United Nations after being agreed to by the UNCOPUOS in 2010 after years of discussions on the problem of space debris. Although they urge States to limit debris caused during their space operations and minimize respective risks to the environment of outer space, they entail the form of guidelines/recommendations and thus cannot force States to follow them.

U. N. Coordination of Outer Space Activities (UNCOSA): Program with the responsibility of coordinating space activities at the U. N. level.

U. N. Educational, Scientific and Cultural Organization (UNESCO): This specialized scientific agency of the United Nations, headquartered in Paris, also considers space-related matters. It is currently creating an encyclopedia and has a newly created Space Council.

University of Surrey Satellites (UoSat): This is the name given to space satellites developed and fabricated at the Surrey Space Centre in England.

U. N. Office for Disarmament Affairs (UNODA): The UNODA, originally established in 1982 under a different name, became the UNODA in 2007. Its purpose consists of the promotion of nuclear disarmament and non-proliferation, the strengthening of disarmament regimes regarding weapons of mass destruction including chemical and biological weapons, as well as disarmament efforts with respect to conventional weapons such as landmines and small arms (particularly those used in contemporary conflicts).

U. N. Office for Outer Space Affairs (UNOOSA): UNOOSA is a part of the Secretariat of the United Nation. It reinforces the decisions of general assemblies as well as those of the UNCOPUOS. It was established in 1962 and is currently located in Vienna.

U. N. Platform for Space-based Information for Disaster Management and Emergency Response (UNSPIDER): The UNSPIDER is implemented by the U. N. Office for Outer Space Affairs (UNOOSA) and its main purpose is to provide universal access to all countries as well as relevant organizations to information (space-based) and services with respect to disaster management.

U. S. Commercial Space Launch Competitiveness Act of 2015: This is currently the latest U. S. legislation that covers the commercial development of new spaceflight and space systems for the United States. Title IV of this act covers the issue of possible future extraction of natural resources from space objects.

Van Allen Belts: These are the layers of energetic charged particles surrounding Earth. Such layers (or “belts”) are held in place by the latter’s magnetic field.

Venture Class Launch Services Contracts: This is a flexible contractual procurement process that NASA has developed for streamlined procurement processes with small NewSpace companies developing low cost launch vehicles. This process was used to conclude contracts with Virgin Galactic for a Launcher One launch, with Rocket Labs for an Electron launch, and with Firefly for an Alpha rocket launch. The later has now been canceled with the bankruptcy of Firefly.

Vienna Convention on the Law of Treaties of 1969 (VCLT): The VCLT was adopted on May 22, 1969, opened for signature on May 23, 1969, and entered into force on January 27, 1980. It has been ratified by 114 states as of April 2014 and regulates the international law of treaties among states.

Wide Area Augmentation Service: This is a ground-based system used to augment the accuracy of the U. S. operated NAVSTAR-GPS system. It becomes of greater importance as satellite-based navigation plays an increasing role in Next Gen aviation traffic control.

World Economic Forum (WEF): The mission of the World Economic Forum (a Swiss non-profit foundation for public-private cooperation) is to improve the state of the world by engaging diverse world actors such as business, political, academic, and other leaders of society in order to shape global, regional, and industry agendas.

World Intellectual Property Organization (WIPO): This organization, headquartered in Geneva, Switzerland, is concerned with the protection of intellectual property such as copyright, trademarks, and especially patents.

World Meteorological Organization (WMO): This is the international organization that is a specialized agency of the United Nations. It is concerned with coordinating worldwide efforts related to weather forecasting, monitoring and warning, climate change, and space weather – especially the most dangerous solar storms such as X-class flares and coronal mass ejections that can harm spacecraft and global critical infrastructure.

World Radio-communication Conferences (WRCs): These conferences are periodically convened for the purposes of the review and revision (if necessary) of Radio Regulations. These Radio Regulations are agreed to globally and regulate the use of the radio frequency spectrum and geostationary satellite and non-geostationary satellite orbits. These conferences were once known as the World Administrative Radio Conferences (WARCs).

Appendix 2: The Space Debris Mitigation Guidelines of the U. N. Committee on the Peaceful Uses of Outer Space

Introduction

The U. N. General Assembly in 2008 adopted resolution 62/217, endorsing the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. The voluntary guidelines outline space debris mitigation measures for the planning, design, manufacture, and operational phases of spacecraft and launch vehicles. The guidelines call for limiting the long-term presence of spacecraft in low-Earth orbit (LEO), up to some 1,600 km (1,000 miles) above Earth's surface, after the end of their mission. They also call for the removal of such spacecraft from orbit or for their disposal in other orbits that avoid their long-term presence in the LEO region, where the majority of satellites are placed and where they are in greatest danger of collision.

Mazlan Othman, director of the U. N. Office for Outer Space Affairs (UNOOSA), at the time stated: "The prompt implementation of appropriate space debris mitigation measures is in humanity's common interest, particularly if we are to preserve the outer space environment for future generations," willingness of countries to implement these guidelines holds the key to sustainable use of outer space, but the fact that political consensus was reached is a critical starting point acknowledging that space debris cannot be left to just scientists and astronauts.

The Context

The Space Debris Mitigation Guidelines of the U. N. Committee on the Peaceful Uses of Outer Space (A/62/20) seek to curtail the generation of potentially harmful space debris and prevent further pollution of the space environment. These guidelines are closely aligned with the mitigation guidelines developed by the InterAgency space Debris Committee (IADC), which is composed of a number of national space agencies and then reviewed and adopted by UNCOPUOS. The most significant distinction between the UNCOPUOS Mitigation Guidelines that were agreed to by the U. N. General Assembly and the IADC Mitigation Guidelines is that the U. N.-endorsed guidelines do not include the 25-year guideline for removal of spacecraft from orbit dating from the end of life as contained in 5.3.3 of the IADC guidelines. Further these

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1

guidelines contain far more specific technical information. See Appendix 5 in this book to see the IADC guidelines.

Space debris mitigation measures are divided into two broad categories – those that curtail the generation of potentially harmful space debris in the near term and those that limit their generation over the longer term.

According to NASA, the February 2009 satellite collision was the first time two spacecraft ran into each other. Previously there have been four other minor space collisions involving parts of spent rockets or small satellites.

The Committee on the Peaceful Uses of Outer Space (COPUOS), set up by the General Assembly in 1959, promotes international cooperation in the peaceful uses of outer space and develops legal frameworks to address problems arising from the exploration and use of outer space. Since its inception, COPUOS has concluded five major international treaties and five sets of legal principles governing outer space activities.

Satellites and other spacecraft have become an indispensable part of the world's infrastructure, playing a crucial role in international development, security, and environmental monitoring and protection.

Preface

The Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space are the result of many years of work by the Committee and its Scientific and Technical Subcommittee.

At its thirty-first session, in 1994, the Subcommittee considered for the first time, on a priority basis, matters associated with space debris under a new item of its agenda (A/AC.105/571, paragraphs 63-74). In accordance with the agreement of the committee, the subcommittee considered under that item scientific research relating to space debris, including relevant studies, mathematical modeling, and other analytical work on the characterization of the space debris environment (A/48/20, paragraph 87).

In addressing the problem of space debris in its work, the subcommittee at its thirty-second session, in 1995, agreed to focus on understanding aspects of research related to space debris, including debris measurement techniques; mathematical modeling of the debris environment; characterizing of the space debris environment; and measures to mitigate the risks of space debris, including spacecraft design measures to protect against space debris. Accordingly, the subcommittee adopted a multi-year work plan for specific topics to be covered from 1996 to 1998. The subcommittee agreed that at each session it should review the current operational debris mitigation practices and consider future mitigation methods with regard to cost efficiency (A/AC.105/605, paragraph 83).

At its thirty-third session, in 1996, the subcommittee agreed to prepare a technical report on space debris that would be structured according to the specific topics addressed by the work plan during the period 1996-1998 and that the report would be carried forward and updated each year, leading to an accumulation of advice and guidance, in order to establish a common understanding that could serve as the basis for further deliberations of the committee on that important matter (A/AC.105/637 and Corr. 1, paragraph 96).

At its thirty-sixth session, in 1999, the subcommittee adopted the technical report on space debris (A/AC.105/720) and agreed to have it widely distributed, including by making it available to the Third U. N. Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III), the legal subcommittee at its thirty-ninth session, in 2000, international organizations and other scientific meetings (A/AC.105/736, paragraph 39).

At its thirty-eighth session, in 2001, the subcommittee agreed to establish a work plan for the period from 2002 to 2005 (A/AC.105/761, paragraph 130) with the goal of expediting international adoption of voluntary debris mitigation measures. In addition to the plan to address debris mitigation measures, it was envisaged that member States and international organizations would continue to report on research and other relevant aspects of space debris.

In accordance with that work plan, at the fortieth session of the subcommittee, in 2003, the Inter-Agency Space Debris Coordination Committee (IADC) presented its proposals on debris mitigation, based on consensus among the IADC members. At the same session, the subcommittee began its review of the proposals and discussed means of endorsing their utilization.

At its forty-first session, in 2004, the subcommittee established a working group to consider comments from member States on the above-mentioned proposals of IADC on debris mitigation. The working group recommended that interested member States, observers to the subcommittee and members of IADC become involved in updating the IADC proposals on space debris mitigation for the working group's consideration at the next session of the subcommittee.

During the forty-second session of the subcommittee, in 2005, the working group agreed on a set of considerations for space debris mitigation guidelines and prepared a new work plan for the period from 2005 to 2007,which was subsequently adopted by the subcommittee. The working group also agreed on the text of the revised draft space debris mitigation guidelines(A/AC.105/848,annexII, paragraphs 5-6), submitted the text to the subcommittee for its consideration, and recommended that the revised draft space debris mitigation guidelines be circulated at the national level to secure consent for adoption of the guidelines by the subcommittee at its forty-fourth session, in 2007.

At its forty-fourth session, in 2007, the subcommittee adopted the space debris mitigation guidelines (A/AC.105/890, paragraph 99).

At its fiftieth session, in 2007, the committee endorsed the space debris mitigation guidelines and agreed that its approval of those voluntary guidelines would increase mutual understanding on acceptable activities in space and thus enhance stability in space-related matters and decrease the likelihood of friction and conflict (A/62/20, paragraphs 118-119).

In its resolution 62/217 of December 22, 2007, the General Assembly endorsed the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space and agreed that the voluntary guidelines for the mitigation of space debris reflected the existing practices as developed by a number of national and international organizations, and invited member States to implement those guidelines through relevant national mechanisms. This process thus from start to finish entailed almost a 14-year period.

Text of the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space

1. Background

It has been a common understanding that the current space debris environment poses a risk to spacecraft in Earth orbit. For the purpose of this document, space debris is defined as all manmade objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional. As the population of debris continues to grow, the probability of collisions that could lead to potential damage will consequently increase. In addition, there is also the risk of damage on the ground, if debris survives Earth's atmospheric re-entry. The prompt implementation of appropriate debris mitigation measures is therefore considered a prudent and necessary step towards preserving the outer space environment for future generations.

Historically, the primary sources of space debris in Earth orbits have been (a) accidental and intentional breakups that produced long-lived debris and (b) debris released intentionally during the operation of launch vehicle orbital stages and spacecraft. In the future, fragments generated by collisions are expected to be a significant source of space debris.

Space debris mitigation measures can be divided into two broad categories: those that curtail the generation of potentially harmful space debris in the near term and those that limit their generation over the longer term. The former involves the curtailment of the production of mission-related space debris and the avoidance of breakups. The latter concerns end-of-life procedures that remove decommissioned spacecraft and launch vehicle orbital stages from regions populated by operational spacecraft.

2. Rationale

The implementation of space debris mitigation measures is recommended since some space debris has the potential to damage spacecraft, leading to loss of mission, or loss of life in the case of manned spacecraft. For manned flight orbits, space debris mitigation measures are highly relevant due to crew safety implications.

A set of mitigation guidelines has been developed by the Inter-Agency Space Debris Coordination Committee (IADC), reflecting the fundamental mitigation elements of a series of existing practices, standards, codes, and handbooks developed by a number of national and international organizations.

1

– United Nations publication, Sales No. E.99.I.17.

Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space

2

Space acknowledges the benefit of a set of high-level qualitative guidelines, having wider acceptance among the global space community. The working group on space debris was therefore established (by the Scientific and Technical Subcommittee of the Committee) to develop a set of recommended guidelines based on the technical content and the basic definitions of the IADC space debris mitigation guidelines, and taking into consideration the U. N. treaties and principles concerning outer space.

3. Application

Member States and international organizations should voluntarily take measures, through national mechanisms or through their own applicable mechanisms, to ensure that these guidelines are implemented, to the greatest extent feasible, through space debris mitigation practices and procedures.

These guidelines are applicable to mission planning and the operation of newly designed spacecraft and orbital stages and, if possible, to existing ones. They are not legally binding under international law.

It is also recognized that exceptions to the implementation of individual guidelines or elements thereof may be justified, for example, by the provisions of the U. N. treaties and principles on outer space.

4. Space Debris Mitigation Guidelines

The following guidelines should be considered for the mission planning, design, manufacture, and operational (launch, mission, and disposal) phases of spacecraft and launch vehicle orbital stages:

GUIDELINE 1. *Limit debris released during normal operations.*

Space systems should be designed not to release debris during normal operations. If this is not feasible, the effect of any release of debris on the outer space environment should be minimized.

During the early decades of the space age, launch vehicle and spacecraft designers permitted the intentional release of numerous mission-related objects into Earth orbit, including, among other things, sensor covers, separation mechanisms, and deployment devices. Dedicated design efforts, prompted by the recognition of the threat posed by such objects, have proved effective in reducing this source of space debris.

GUIDELINE 2. *Minimize the potential for breakups during operational phases.*

Spacecraft and launch vehicle orbital stages should be designed to avoid failure modes that may lead to accidental breakups. In cases where a condition leading to such a failure is detected, disposal and passivation measures should be planned and executed to avoid breakups.

Historically, some breakups have been caused by space system malfunctions, such as catastrophic failures of propulsion and power systems. By incorporating potential breakup scenarios in failure mode analysis, the probability of these catastrophic events can be reduced.

GUIDELINE 3: *Limit the probability of accidental collision in orbit.*

In developing the design and mission profile of spacecraft and launch vehicle stages, the probability of accidental collision with known objects during the system's launch phase and orbital lifetime should be estimated and limited. If available orbital data indicate a potential collision, adjustment of the launch time or an on-orbit avoidance maneuver should be considered.

Some accidental collisions have already been identified. Numerous studies indicate that, as the number and mass of space debris increase, the primary source of new space debris is likely to be from collisions. Collision avoidance procedures have already been adopted by some member States and international organizations.

Guideline 4: Avoid intentional destruction and other harmful activities.

Recognizing that an increased risk of collision could pose a threat to space operations, the intentional destruction of any on-orbit spacecraft and launch vehicle orbital stages or other harmful activities that generate long-lived debris should be avoided.

When intentional breakups are necessary, they should be conducted at sufficiently low altitudes to limit the orbital lifetime of resulting fragments.

GUIDELINE 5. *Minimize potential for post-mission breakups resulting from stored energy.*

In order to limit the risk to other spacecraft and launch vehicle orbital stages from accidental breakups, all on-board sources of stored energy should be depleted or made safe when they are no longer required for mission operations or post-mission disposal.

By far the largest percentage of the cataloged space debris population originated from the fragmentation of spacecraft and launch vehicle orbital stages. The majority of those breakups were unintentional, many arising from the abandonment of spacecraft and launch vehicle orbital stages with significant amounts of stored energy. The most effective mitigation measures have been the passivation of spacecraft and launch vehicle orbital stages at the end of their mission. Passivation requires the removal of all forms of stored energy, including residual propellants and compressed fluids and the discharge of electrical storage devices.

GUIDELINE 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.*

Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the LEO region should be removed from orbit in a controlled fashion. If this is not possible, they should be disposed of in orbits that avoid their long-term presence in the LEO region.

When making determinations regarding potential solutions for removing objects from LEO, due consideration should be given to ensuring that debris that survives to reach the surface of Earth does not pose an undue risk to people or property, including through environmental pollution caused by hazardous substances.

GUIDELINE 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.*

Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the GEO region should be left in orbits that avoid their long-term interference with the GEO region.

For space objects in or near the GEO region, the potential for future collisions can be reduced by leaving objects at the end of their mission in an orbit above the GEO region such that they will not interfere with, or return to, the GEO region.

Updates

Research by member States and international organizations in the area of space debris should continue in a spirit of international cooperation to maximize the benefits of space debris mitigation initiatives. This document will be reviewed and may be revised, as warranted, in the light of new findings.

Reference

The reference version of the IADC space debris mitigation guidelines at the time of the publication of this document is contained in the annex to document A/AC.105/C.1/L.260.

For more in-depth descriptions and recommendations pertaining to space debris mitigation measures, member States and international organizations may refer to the latest version of the IADC space debris mitigation guidelines and other supporting documents, which can be found on the IADC website (www.iadc-online).

For Further Information

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Useful Web Links

United Nations Office for Outer Space Affairs

http://www.unoosa.org

Report of the Committee on the Peaceful Uses of Outer Space

http://www.un.org/Docs/journal/asp/ws.asp?m=A/62/20 (SUPP)

"Space Solutions for the World's Problems: How the United Nations family uses space technology to achieve development goals" http://www.uncosa.unvienna.org/pdf/reports/IAM2006E.pdf

Gateway to space-related activities of the U. N. system

http://www.uncosa.unvienna.org/uncosa/en/index.html

U. N. News Centre

www.un.org/news

Inter-Agency Space Debris Coordination Committee

http://www.iadc-online.org/

NASA Orbital Debris Program Office

http://www.orbitaldebris.jsc.nasa.gov/

European Space Agency: Space Debris Office

http://www.esa.int/SPECIALS/Space_Debris/index.html

Appendix 3: UN General Assembly Resolution 3235 (XXIX): Convention on Registration of Objects Launched into Outer Space

The United Nations General Assembly,

Reaffirming the importance of international cooperation in the field of the exploration and peaceful uses of outer space, including the Moon and other celestial bodies, and of promoting the rule of law in this new field of human endeavour,

Desiring, in the light of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, 1 the Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space 2 and the Convention on International Liability for Damage Caused by Space Objects, 3 to make provision for registration by launching States of space objects launched into outer space with a view, inter alia, to providing States with additional means and procedures to assist in the identification of space objects,

Bearing in mind its resolution 3182 (XXVIII) on 18 December 1973, in which it requested the Committee on the Peaceful Uses of Outer Space to consider as a matter of priority the completion of the text of the draft Convention on Registration of Objects Launched into Outer Space,

Having considered the report of the Committee on the Peaceful Uses of Outer Space, 4 Noting with satisfaction that the Committee on the Peaceful Uses of Outer Space and its Legal Subcommittee have completed the text of the draft Convention on Registration of Objects Launched into Outer Space,

1. Commends the Convention on Registration of Objects Launched into Outer Space, the text of which is annexed to the present resolution;
2. Requests the Secretary-General to open the Convention for signature and ratification at the earliest possible date;
3. Expresses its hope for the widest possible adherence to this Convention.

2280th plenary meeting,
12 November 1974.

ANNEX

Convention on Registration of Objects Launched into Outer Space

The States Parties to this Convention,

Recognizing the common interest of all mankind in furthering the exploration

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1

and use of outer space for peaceful purposes,

Recalling that the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies of 27 January 1967 affirms that States shall bear international responsibility for their national activities in outer space and refers to the State on whose registry an object launched into outer space is carried,

Recalling also that the Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space of 22 April 1968 provides that a launching authority shall, upon request, furnish identifying data prior to the return of an object it has launched into outer space found beyond the territorial limits of the launching authority,

Recalling further that the Convention on International Liability for Damage Caused by Space Objects of 29 March 1972 establishes international rules and procedures concerning the liability of launching States for damage caused by their space objects,

Desiring, in the light of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, to make provision for the national registration by launching States of space objects launched into outer space,

Desiring further that a central register of objects launched into outer space be established and maintained, on a mandatory basis, by the Secretary-General of the United Nations,

Desiring also to provide for States Parties additional means and procedures to assist in the identification of space objects,

Believing that a mandatory system of registering objects launched into outer space would, in particular, assist in their identification and would contribute to the application and development of international law governing the exploration and use of outer space,

Have agreed on the following:

Article I

For the purposes of this Convention:

(a) The term “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;
(b) The term “space object” includes component parts of a space object as well as its launch vehicle and parts thereof;
(c) The term “State of registry” means a launching State on whose registry a space object is carried in accordance with Article II.

Article II

1. When a space object is launched into Earth orbit or beyond, the launching State shall register the space object by means of an entry in an appropriate registry which it shall maintain. Each launching State shall inform the Secretary-General of the United Nations of the establishment of such a registry.
2. Where there are two or more launching States in respect of any such space object, they shall jointly determine which one of them shall register the object in accordance with paragraph 1 of this article, bearing in

mind the provisions of Article VIII of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, and without prejudice to appropriate agreements concluded or to be concluded among the launching States on jurisdiction and control over the space object and over any personnel thereof.

3. The contents of each registry and the conditions under which it is maintained shall be determined by the State of registry concerned.

Article III

1. The Secretary-General of the United Nations shall maintain a Register in which the information furnished in accordance with Article IV shall be recorded.
2. There shall be full and open access to the information in this Register.

Article IV

1. Each State of registry shall furnish to the Secretary-General of the United Nations, as soon as practicable, the following information concerning each space object carried on its registry:
   (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.
2. Each State of registry may, from time to time, provide the Secretary-General of the United Nations with additional information concerning a space object carried on its registry.
3. Each State of registry shall notify the Secretary-General of the United Nations, to the greatest extent feasible and as soon as practicable, of space objects concerning which it has previously transmitted information, and which have been but no longer are in Earth orbit.

Article V

Whenever a space object launched into Earth orbit or beyond is marked with the designator or registration number referred to in Article IV, paragraph 1 (b), or both, the State of registry shall notify the Secretary-General of this fact when submitting the information regarding the space object in accordance with Article IV. In such case, the Secretary-General of the United Nations shall record this notification in the Register.

Article VI

Where the application of the provisions of this Convention has not enabled a State Party to identify a space object which has caused damage to it or to any of its natural or juridical persons, or which may be of a hazardous or deleterious nature, other States Parties, including in particular States possessing space monitoring and tracking facilities, shall respond to the greatest extent feasible to a request by that State Party, or transmitted through the Secretary-General on its behalf, for assistance under equitable and reasonable conditions in the identification of the object. A State Party making such a request shall, to the greatest extent feasible, submit information as to the time, nature and circumstances of the events giving rise to the request. Arrangements under which such assistance shall be rendered shall be the subject of agreement between the parties concerned.

Article VII

1. In this Convention, with the exception of Articles VIII to XII inclusive, references to States shall be deemed to apply to any international intergovernmental organization which conducts space activities if the organization declares its acceptance of the rights and obligations provided for in this Convention and if a majority of the States members of the organization are States Parties to this Convention and to the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.
2. States members of any such organization which are States Parties to this Convention shall take all appropriate steps to ensure that the organization makes a declaration in accordance with paragraph 1 of this article.

Article VIII

1. This Convention shall be open for signature by all States at United Nations Headquarters in New York. Any State which does not sign this Convention before its entry into force in accordance with paragraph 3 of this article may accede to it at any time.
2. This Convention shall be subject to ratification by signatory States. Instruments of ratification and instruments of accession shall be deposited with the Secretary-General of the United Nations.
3. This Convention shall enter into force among the States which have deposited instruments of ratification on the deposit of the fifth such instrument with the Secretary-General of the United Nations.
4. For States whose instruments of ratification or accession are deposited subsequent to the entry into force of this Convention, it shall enter into force on the date of the deposit of their instruments of ratification or accession.
5. The Secretary-General shall promptly inform all signatory and acceding States of the date of each signature, the date of deposit of each instrument of ratification of and accession to this Convention, the date of its entry into force and other notices.

Article IX

Any State Party to this Convention may propose amendments to the Convention. Amendments shall enter into force for each State Party to the Convention accepting the amendments upon their acceptance by a majority of the States Parties to the Convention and thereafter for each remaining State Party to the Convention on the date of acceptance by it.

Article X

Ten years after the entry into force of this Convention, the question of the review of the Convention shall be included in the provisional agenda of the United Nations General Assembly in order to consider, in the light of past application of the Convention, whether it requires revision. However, at any time after the Convention has been in force for five years, at the request of one third of the States Parties to the Convention and with the concurrence of the majority of the States Parties, a conference of the States Parties shall be convened to review this Convention. Such review shall take into account in particular any relevant technological developments, including those relating to the identification of space objects.

Article XI

Any State Party to this Convention may give notice of its withdrawal from the Convention one year after its entry into force by written notification to the Secretary-General of the United Nations. Such withdrawal shall take effect one year from the date of receipt of this notification.

Article XII

The original of this Convention, of which the Arabic, Chinese, English, French, Russian and Spanish texts are equally authentic, shall be deposited with the Secretary-General of the United Nations, who shall send certified copies thereof to all signatory and acceding States.

IN WITNESS WHEREOF the undersigned, being duly authorized thereto by their respective Governments, have signed this Convention, opened for signature at New York on the fourteenth day of January, one thousand nine hundred and seventy-five.

Appendix 4: Convention on International Liability for Damage Caused by Space Objects

The States Parties to this Convention,

- Recognizing the common interest of all mankind in furthering the exploration and use of outer space for peaceful purposes,
- Recalling the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies,
- Taking into consideration that, notwithstanding the precautionary measures to be taken by States and international intergovernmental organizations involved in the launching of space objects, damage may on occasion be caused by such objects,
- Recognizing the need to elaborate effective international rules and procedures concerning liability for damage caused by space objects and to ensure, in particular, the prompt payment under the terms of this Convention of a full and equitable measure of compensation to victims of such damage,
- Believing that the establishment of such rules and procedures will contribute to the strengthening of international cooperation in the field of the exploration and use of outer space for peaceful purposes,

Have agreed on the following:

Article I

For the purposes of this Convention:

- (a) The term “damage” means 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;
- (b) The term “launching” includes attempted launching;
- (c) The term “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;
- (d) The term “space object” includes component parts of a space object as well as its launch vehicle and parts thereof.

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1

Article II

A launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft in flight.

Article III

In the event of damage being caused elsewhere than on the surface of the Earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, the latter shall be liable only if the damage is due to its fault or the fault of persons for whom it is responsible.

Article IV

1. In the event of damage being caused elsewhere than on the surface of the Earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, and of damage thereby being caused to a third State or to its natural or juridical persons, the first two States shall be jointly and severally liable to the third State, to the extent indicated by the following:
   - (a) If the damage has been caused to the third State on the surface of the Earth or to aircraft in flight, their liability to the third State shall be absolute;
   - (b) If the damage has been caused to a space object of the third State or to persons or property on board that space object elsewhere than on the surface of the Earth, their liability to the third State shall be based on the fault of either of the first two States or on the fault of persons for whom either is responsible.
2. In all cases of joint and several liability referred to in paragraph 1 of this article, the burden of compensation for the damage shall be apportioned between the first two States in accordance with the extent to which they were at fault; if the extent of the fault of each of these States cannot be established, the burden of compensation shall be apportioned equally between them. Such apportionment shall be without prejudice to the right of the third State to seek the entire compensation due under this Convention from any or all of the launching States which are jointly and severally liable.

Article V

1. Whenever two or more States jointly launch a space object, they shall be jointly and severally liable for any damage caused.
2. A launching State which has paid compensation for damage shall have the right to present a claim for indemnification to other participants in the joint launching. The participants in a joint launching may conclude agreements regarding the apportioning among themselves of the financial obligation in respect of which they are jointly and severally liable. Such agreements shall be without prejudice to the right of a State sustaining damage to seek the entire compensation due under this Convention from any or all of the launching States which are jointly and severally liable.

3. A State from whose territory or facility a space object is launched shall be regarded as a participant in a joint launching.

Article VI

1. Subject to the provisions of paragraph 2 of this article, exoneration from absolute liability shall be granted to the extent that a launching State establishes that the damage has resulted either wholly or partially from gross negligence or from an act or omission done with intent to cause damage on the part of a claimant State or of natural or juridical persons it represents.
2. No exoneration whatever shall be granted in cases where the damage has resulted from activities conducted by a launching State which are not in conformity with international law including, in particular, the Charter of the United Nations and the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.

Article VII

The provisions of this Convention shall not apply to damage caused by a space object of a launching State to:

(a) Nationals of that launching State;
(b) Foreign nationals during such time as they are participating in the operation of that space object from the time of its launching or at any stage thereafter until its descent, or during such time as they are in the immediate vicinity of planned launching or recovery area as the result of an invitation by that launching State.

Article VIII

1. A State which suffers damage, or whose natural or juridical persons suffer damage, may present to a launching State a claim for compensation for such damage.
2. If the State of nationality has not presented a claim, another State may, in respect of damage sustained in its territory by any natural or juridical person, present a claim to a launching State.
3. If neither the State of nationality nor the State in whose territory the damage was sustained has presented a claim or notified its intention of presenting a claim, another State may, in respect of damage sustained by its permanent residents, present a claim to a launching State.

Article IX

A claim for compensation for damage shall be presented to a launching State through diplomatic channels. If a State does not maintain diplomatic relations with the launching State concerned, it may request another State to present its claim to that launching State or otherwise represent its interests under this Convention. It may also present its claim through the Secretary-General of the United Nations, provided the claimant State and the launching State are both Members of the United Nations.

Article X

1. A claim for compensation for damage may be presented to a launching State not later than one year following the date of the occurrence of the damage or the identification of the launching State which is liable.
2. If, however, a State does not know of the occurrence of the damage or has not been able to identify the launching State which is liable, it may present a claim within one year following the date on which it learned of the aforementioned facts; however, this period shall in no event exceed one year following the date on which the State could reasonably be expected to have learned of the facts through the exercise of due diligence.
3. The time limits specified in paragraphs 1 and 2 of this article shall apply even if the full extent of the damage may not be known. In this event, however, the claimant State shall be entitled to revise the claim and submit additional documentation after the expiration of such time limits until one year after the full extent of the damage is known.

Article XI

1. Presentation of a claim to a launching State for compensation for damage under this Convention shall not require the prior exhaustion of any local remedies which may be available to a claimant State or to natural or juridical persons it represents.
2. Nothing in this Convention shall prevent a State, or natural or juridical persons it might represent, from pursuing a claim in the courts or administrative tribunals or agencies of a launching State. A State shall not, however, be entitled to present a claim under this Convention in respect of the same damage for which a claim is being pursued in the courts or administrative tribunals or agencies of a launching State or under another international agreement which is binding on the States concerned.

Article XII

The compensation which the launching State shall be liable to pay for damage under this Convention shall be determined in accordance with international law and the principles of justice and equity, in order to provide such reparation in respect of the damage as will restore the person, natural or juridical, State or international organization on whose behalf the claim is presented to the condition which would have existed if the damage had not occurred.

Article XIII

Unless the claimant State and the State from which compensation is due under this Convention agree on another form of compensation, the compensation shall be paid in the currency of the claimant State or, if that State so requests, in the currency of the State from which compensation is due.

Article XIV

If no settlement of a claim is arrived at through diplomatic negotiations as provided for in article IX, within one year from the date on which the claimant State notifies the launching State that it has submitted the documentation of its claim, the parties concerned shall establish a Claims Commission at the request of either party.

Article XV

1. The Claims Commission shall be composed of three members: one appointed by the claimant State, one appointed by the launching State and the third member, the Chairman, to be chosen by both parties jointly. Each party shall make its appointment within two months of the request for the establishment of the Claims Commission.
2. If no agreement is reached on the choice of the Chairman within four months of the request for the establishment of the Commission, either party may request the Secretary-General of the United Nations to appoint the Chairman within a further period of two months.

Article XVI

1. If one of the parties does not make its appointment within the stipulated period, the Chairman shall, at the request of the other party, constitute a single-member Claims Commission.
2. Any vacancy which may arise in the Commission for whatever reason shall be filled by the same procedure adopted for the original appointment.
3. The Commission shall determine its own procedure.
4. The Commission shall determine the place or places where it shall sit and all other administrative matters.
5. Except in the case of decisions and awards by a single-member Commission, all decisions and awards of the Commission shall be by majority vote.

Article XVII

No increase in the membership of the Claims Commission shall take place by reason of two or more claimant States or launching States being joined in any one proceeding before the Commission. The claimant States so joined shall collectively appoint one member of the Commission in the same manner and subject to the same conditions as would be the case for a single claimant State. When two or more launching States are so joined, they shall collectively appoint one member of the Commission in the same way. If the claimant States or the launching States do not make the appointment within the stipulated period, the Chairman shall constitute a single-member Commission.

Article XVIII

The Claims Commission shall decide the merits of the claim for compensation and determine the amount of compensation payable, if any.

Article XIX

1. The Claims Commission shall act in accordance with the provisions of article XII.
2. The decision of the Commission shall be final and binding if the parties have so agreed; otherwise the Commission shall render a final and recommendatory award, which the parties shall consider in good faith. The Commission shall state the reasons for its decision or award.
3. The Commission shall give its decision or award as promptly as possible and no later than one year from the date of its establishment, unless an extension of this period is found necessary by the Commission.

4. The Commission shall make its decision or award public. It shall deliver a certified copy of its decision or award to each of the parties and to the Secretary-General of the United Nations.

Article XX

The expenses in regard to the Claims Commission shall be borne equally by the parties, unless otherwise decided by the Commission.

Article XXI

If the damage caused by a space object presents a large-scale danger to human life or seriously interferes with the living conditions of the population or the functioning of vital centres, the States Parties, and in particular the launching State, shall examine the possibility of rendering appropriate and rapid assistance to the State which has suffered the damage, when it so requests. However, nothing in this article shall affect the rights or obligations of the States Parties under this Convention.

Article XXII

1. In this Convention, with the exception of articles XXIV to XXVII, references to States shall be deemed to apply to any international intergovernmental organization which conducts space activities if the organization declares its acceptance of the rights and obligations provided for in this Convention and if a majority of the States members of the organization are States Parties to this Convention and to the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.
2. States members of any such organization which are States Parties to this Convention shall take all appropriate steps to ensure that the organization makes a declaration in accordance with the preceding paragraph.
3. If an international intergovernmental organization is liable for damage by virtue of the provisions of this Convention, that organization and those of its members which are States Parties to this Convention shall be jointly and severally liable; provided, however, that:
   (a) Any claim for compensation in respect of such damage shall be first presented to the organization;
   (b) Only where the organization has not paid, within a period of six months, any sum agreed or determined to be due as compensation for such damage, may the claimant State invoke the liability of the members which are States Parties to this Convention for the payment of that sum.
4. Any claim, pursuant to the provisions of this Convention, for compensation in respect of damage caused to an organization which has made a declaration in accordance with paragraph 1 of this article shall be presented by a State member of the organization which is a State Party to this Convention.

Article XXIII

1. The provisions of this Convention shall not affect other international agreements in force insofar as relations

between the States Parties to such agreements are concerned.

2. No provision of this Convention shall prevent States from concluding international agreements reaffirming, supplementing or extending its provisions.

Article XXIV

1. This Convention shall be open to all States for signature. Any State which does not sign this Convention before its entry into force in accordance with paragraph 3 of this article may accede to it at any time.
2. This Convention shall be subject to ratification by signatory States. Instruments of ratification and instruments of accession shall be deposited with the Governments of the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America, which are hereby designated the Depositary Governments.
3. This Convention shall enter into force on the deposit of the fifth instrument of ratification.
4. For States whose instruments of ratification or accession are deposited subsequent to the entry into force of this Convention, it shall enter into force on the date of the deposit of their instruments of ratification or accession.
5. The Depositary Governments shall promptly inform all signatory and acceding States of the date of each signature, the date of deposit of each instrument of ratification of and accession to this Convention, the date of its entry into force and other notices.
6. This Convention shall be registered by the Depositary Governments pursuant to Article 102 of the Charter of the United Nations.

Article XXV

Any State Party to this Convention may propose amendments to this Convention. Amendments shall enter into force for each State Party to the Convention accepting the amendments upon their acceptance by a majority of the States Parties to the Convention and thereafter for each remaining State Party to the Convention on the date of acceptance by it.

Article XXVI

Ten years after the entry into force of this Convention, the question of the review of this Convention shall be included in the provisional agenda of the United Nations General Assembly in order to consider, in the light of past application of the Convention, whether it requires revision. However, at any time after the Convention has been in force for five years, and at the request of one third of the States Parties to the Convention, and with the concurrence of the majority of the States Parties, a conference of the States Parties shall be convened to review this Convention.

Article XXVII

Any State Party to this Convention may give notice of its withdrawal from the Convention one year after its entry into force by written notification to the Depositary Governments. Such withdrawal shall take effect one year from the date of receipt of this notification.

Article XXVIII

This Convention, of which the Chinese, English, French, Russian and Spanish texts are equally authentic, shall be deposited in the archives of the Depositary Governments. Duly certified copies of this Convention shall be transmitted by the Depositary Governments to the Governments of the signatory and acceding States.

IN WITNESS WHEREOF the undersigned, duly authorized thereto, have signed this Convention.

DONE in triplicate, at the cities of London, Moscow and Washington, D.C., this twenty-ninth day of March, one thousand nine hundred and seventy-two.

Appendix 5: IADC Space Debris Mitigation Guidelines

Foreword

The Inter-Agency Space Debris Coordination Committee (IADC) is an international forum of governmental bodies for the coordination of activities related to the issues of man-made and natural debris in space. The primary purpose of the IADC is to exchange information on space debris research activities between member space agencies, to facilitate opportunities for co-operation in space debris research, to review the progress of ongoing co-operative activities and to identify debris mitigation options. Members of the IADC are the Italian Space Agency (ASI), British National Space Centre (BNSC), Centre National d'Etudes Spatiales (CNES), China National Space Administration (CNSA), Deutsches Zentrum fuer Luft-und Raumfahrt e.V. (DLR), European Space Agency (ESA), Indian Space Research Organisation (ISRO), Japan, National Aeronautics and Space Administration (NASA), the National Space Agency of Ukraine (NSAU) and Russian Aviation and Space Agency (Rosaviakosmos).

One of its efforts is to recommend debris mitigation guidelines, with an emphasis on cost effectiveness, that can be considered during planning and design of spacecraft and launch vehicles in order to minimise or eliminate generation of debris during operations. This document provides guidelines for debris reduction, developed via consensus within the IADC. In the process of producing these guidelines, IADC got information from the following documents and study reports.

- Technical Report on Space Debris,
- Text of the report adopted by the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space, 1999
- Interagency report on Orbital Debris 1995,
- The National Science and Technology Council Committee on Transportation Research and Development, November 1995
- U.S. Government Orbital Debris Mitigation Standard Practices, December 2000
- Space Debris Mitigation Standard, NASDA-STD-18, March 28, 1996
- CNES Standards Collection, Method and Procedure Space Debris

S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1

- Safety Requirements, RNC-CNES-Q-40-512, Issue 1- Rev. 0, April 19, 1999
- Policy to Limit Orbital Debris Generation, NASA Program Directive 8710.3, May 29, 1997
- Guidelines and Assessment Procedures for Limiting Orbital Debris, NASA Safety Standard 1740.14, August 1995
- Space Technology Items. General Requirements. Mitigation of Space Debris Population
- Russian Aviation & Space Agency Standard OCT 134-1023-2000
- ESA Space Debris Mitigation Handbook, Release 1.0, April 7 1999
- IAA Position Paper on Orbital Debris – Edition 2001, International Academy of Astronautics, 2001
- European Space Debris Safety and Mitigation Standard, Issue 1, Revision 0, September 27 2000
- IADC Space Debris Mitigation Guidelines

Introduction

It has been a common understanding since the United Nations Committee on the Peaceful Uses of Outer Space(UNCOPUOS) published its Technical Report on Space Debris in 1999, that man-made space debris today poses little risk to ordinary unmanned spacecraft in Earth orbit, but the population of debris is growing, and the probability of collisions that could lead to potential damage will consequently increase. It has, however, now become common practice to consider the collision risk with orbital debris in planning manned missions.

So the implementation of some debris mitigation measures today is a prudent and necessary step towards preserving the space environment for future generations.

Several national and international organisations of the space faring nations have established Space Debris Mitigation Standards or Handbooks to promote efforts to deal with space debris issues. The contents of these Standards and Handbooks may be slightly different from each other but their fundamental principles are the same:

(1) Preventing on-orbit breakups
(2) Removing spacecraft and orbital stages that have reached the end of their mission operations from the useful densely populated orbit regions
(3) Limiting the objects released during normal operations.

The IADC guidelines are based on these common principles and have been agreed to by consensus among the IADC member agencies.

1. Scope

The IADC Space Debris Mitigation Guidelines describe existing practices that have been identified and evaluated for limiting the generation of space debris in the environment. The Guidelines cover the overall environmental impact of the missions with a focus on the following:

(1) Limitation of debris released during normal operations
(2) Minimisation of the potential for on-orbit break-ups
(3) Post-mission disposal
(4) Prevention of on-orbit collisions.

2. Application

The IADC Space Debris Mitigation Guidelines are applicable to mission planning and the design and operation of spacecraft and orbital stages that will be injected into Earth orbit.

Organisations are encouraged to use these Guidelines in identifying the standards that they will apply when establishing the mission requirements for planned spacecraft and orbital stages. Operators of existing spacecraft and orbital stages are encouraged to apply these guidelines to the greatest extent possible

3. Terms and Definitions

The following terms and definitions are added for the convenience of the readers of this document. They should not necessarily be considered to apply more generally.

3.1. Space Debris

Space debris are all manmade objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional.

3.2. Spacecraft, Launch Vehicles, and Orbital Stages

3.2.1. Spacecraft - an orbiting object designed to perform a specific function or mission (e.g., communications, navigation or Earth observation). A spacecraft that can no longer fulfill its intended mission is considered non-functional. (Spacecraft in reserve or standby modes awaiting possible reactivation are considered functional.)

3.2.2. Launch vehicle – any vehicle constructed for ascent to outer space, and for placing one or more objects in outer space, and any sub-orbital rocket.

3.2.3. Launch vehicle orbital stages -any stage of a launch vehicle left in Earth orbit. (IADC Space Debris Mitigation Guidelines)

3.3. Orbits and Protected Regions

3.3.1. Equatorial radius of the Earth - the equatorial radius of the Earth is taken as 6,378 km and this radius is used as the reference for the Earth's surface from which the orbit regions are defined.

3.3.2. Protected regions – any activity that takes place in outer space should be performed while recognising the unique nature of the following regions, A and B, of outer space (see Figure 1), to ensure their future safe and sustainable use. These regions should be protected regions with regard to the generation of space debris. (1) Region A, Low Earth Orbit (or LEO) Region – spherical region that extends from the Earth's surface up to an altitude (Z) of 2,000 km (2) Region B, the Geosynchronous Region a segment of the spherical shell defined by the following: lower altitude = geostationary altitude minus 200 km upper altitude = geostationary altitude plus 200km -15 degrees ≤ latitude ≤ +15 degrees geostationary altitude (Z GEO) = 35,786 km (the altitude of the geostationary Earth orbit) Z GEO – 200km Z = 2000km (LEO) Z GEO + 200km Equator Earth (Note: See this URL to view Figure 1 http://www.iadconline.org/Documents/IADC-200201%2C%20IADC%20Space%20Debris%20Guidelines%2C%20Revision%201.pdf)

3.3.3. Geostationary Earth Orbit (GEO) - Earth orbit having zero inclination and zero eccentricity, whose orbital period is equal to the Earth's sidereal period. The altitude of this unique circular orbit is close to 35,786 km.

3.3.4. Geostationary Transfer Orbit (GTO) - an Earth orbit which is or can be used to transfer spacecraft or orbital stages from lower orbits to the geosynchronous region. Such orbits typically have perigees within LEO region and apogees near or above GEO.

3.4 Mitigation Measures and Related Terms

3.4.1. Passivation - the elimination of all stored energy on a spacecraft or orbital stages to reduce the chance of break-up. Typical passivation measures include venting or burning excess propellant, discharging batteries and relieving pressure vessels.

3.4.2. De-orbit - intentional changing of orbit for re-entry of a spacecraft or orbital stage into the Earth’s atmosphere to eliminate the hazard it poses to other spacecraft and orbital stages, by applying a retarding force, usually via a propulsion system.

3.4.3. Re-orbit - intentional changing of a spacecraft or orbital stage’s orbit.

3.4.4. Break-up - any event that generates fragments which are released into Earth orbit. This includes:

(1) An explosion caused by the chemical or thermal energy from propellants, pyrotechnics and so on
(2) A rupture caused by an increase in internal pressure
(3) A break-up caused by energy from collision with other objects.

However, the following events are excluded from this definition:

- A break-up during the re-entry phase caused by aerodynamic forces.
- The generation of fragments, such as paint flakes, resulting from the ageing and degradation of a spacecraft or orbital stage.

3.5 Operational Phases

3.5.1. Launch phase – begins when the launch vehicle is no longer in physical contact with equipment and ground installations that made its preparation and ignition possible (or when the launch vehicle is dropped from the carrier-aircraft, if any), and continues up to the end of the mission assigned to the launch vehicle.

3.5.2. Mission phase – the phase where the spacecraft or orbital stage fulfills its mission. Begins at the end of the launch phase and ends at the beginning of the disposal phase.

3.5.3. Disposal phase – begins at the end of the mission phase for a spacecraft or orbital stage and ends when the spacecraft or orbital stage has performed the actions to reduce the hazards it poses to other spacecraft and orbital stages.

4. General Guidance

During an organisation’s planning for and operation of a spacecraft and/or orbital stage, it should take systematic actions to reduce adverse effects on the orbital environment by introducing space debris mitigation measures into the spacecraft or orbital stage's lifecycle, from the mission requirement analysis and definition phases. In order to manage the implementation of space debris mitigation measures, it is recommended that a feasible Space Debris Mitigation Plan be established and documented for each program and project. The Mitigation Plan should include the following items:

(1) A management plan addressing space debris mitigation activities.
(2) A plan for the assessment and mitigation of risks related to space debris, including applicable standards.
(3) The measures minimising the hazard related to malfunctions that have a potential for generating space debris.
(4) A plan for disposal of the spacecraft and/or orbital stages at end of mission.
(5) Justification of choice and selection when several possibilities exist.
(6) Compliance matrix addressing the recommendations of these Guidelines.

5. Mitigation Measures

5.1. Limit Debris Released during Normal Operations

In all operational orbit regimes, spacecraft and orbital stages should be designed not to release debris during normal operations. Where this is not feasible any release of debris should be minimised in number, area and orbital lifetime. Any program, project or experiment that will release objects in orbit should not be planned unless an adequate assessment can verify that the effect on the orbital environment, and the hazard to other operating spacecraft and orbital stages, is acceptably low in the long-term. The potential hazard of tethered systems should be analysed by considering both an intact and severed system.

5.2. Minimise the Potential for On-Orbit Break-ups

On-orbit break-ups caused by the following factors should be prevented using the measures described in 5.2.1 – 5.2.3:

(1) The potential for break-ups during mission should be minimized.
(2) All space systems should be designed and operated so as to prevent accidental explosions and ruptures at end-of- mission.
(3) Intentional destructions, which will generate long-lived orbital debris, should not be planned or conducted.

5.2.1. Minimise the potential for post mission break-ups resulting from stored energy

In order to limit the risk to other spacecraft and orbital stages from accidental break-ups after the completion of mission operations, all on-board sources of stored energy of a spacecraft or orbital stage, such as residual propellants, batteries, high-pressure vessels, self-destructive devices, flywheels and momentum wheels, should be depleted or “safed” when they are no longer required for mission operations or post-mission disposal. Depletion should occur as soon as this operation does not pose an unacceptable risk to the payload. Mitigation measures should be carefully designed not to create other risks.

(1) Residual propellants and other fluids, such as pressurant, should be depleted as thoroughly as possible, either by depletion burns or venting, to prevent accidental break-ups by over-pressurisation or chemical reaction.
(2) Batteries should be adequately designed and manufactured, both structurally and electrically, to prevent break-ups. Pressure increase in battery cells and assemblies could be prevented by mechanical measures unless these measures cause an excessive reduction of mission assurance. At the end of operations battery charging lines should be de-activated.
(3) High-pressure vessels should be vented to a level guaranteeing that no break-ups can occur. Leak-before-burst designs are beneficial but are not sufficient to meet all passivation recommendations of propulsion and pressurisation systems. Heat pipes may be left pressurised if the probability of rupture can be demonstrated to be very low.
(4) Self-destruct systems should be designed not to cause unintentional destruction due to inadvertent commands, thermal heating, or radio frequency interference.
(5) Power to flywheels and momentum wheels should be terminated during the disposal phase.
(6) Other forms of stored energy should be assessed and adequate mitigation measures should be applied.

5.2.2. Minimise the potential for break-ups during operational phases

During the design of spacecraft or orbital stages, each program or project should demonstrate, using failure mode and effects analyses or an equivalent analysis, that there is no probable failure mode leading to accidental break-ups. If such failures cannot be excluded, the design or operational procedures should minimise the probability of their occurrence. During the operational phases, a spacecraft or orbital stage should be periodically monitored to detect malfunctions that could lead to a break-up or loss of control function. In the case that a malfunction is detected, adequate recovery measures should be planned and conducted; otherwise disposal and passivation measures for the spacecraft or orbital stage should be planned and conducted.

5.2.3. Avoidance of intentional destruction and other harmful activities

Intentional destruction of a spacecraft or orbital stage, (self-destruction, intentional collision, etc.), and other harmful activities that may significantly increase collision risks to other spacecraft and orbital stages should be avoided. For instance, intentional break-ups should be conducted at sufficiently low altitudes so that orbital fragments are short lived.

5.3. Post Mission Disposal

5.3.1. Geosynchronous Region

Spacecraft that have terminated their mission should be manoeuvred far enough away from GEO so as not to cause interference with spacecraft or orbital stage still in geostationary orbit. The manoeuvre should place the spacecraft in an orbit that remains above the GEO protected region. The IADC and other studies have found that fulfilling the two following conditions at the end of the disposal phase would give an orbit that remains above the GEO protected region:

1. A minimum increase in perigee altitude of:

$$235\text{Km} + \left(1000\,C_R - A/m\right)$$

– where C_R is the solar radiation pressure coefficient
– A/m is the aspect area to dry mass ratio (m^2kg^{-1})
– 235 km is the sum of the upper altitude of the GEO protected region (200 km) and the maximum descent of a re-orbited spacecraft due to luni-solar & geopotential perturbations (35 km).

2. An eccentricity less than or equal to 0.003.

Other options enabling spacecraft to fulfill this guideline to remain above the GEO protected region are described in the “Support to the IADC Space Debris Mitigation Guidelines” document. The propulsion system for a GEO spacecraft should be designed not to be separated from the spacecraft. In the case that there are unavoidable reasons that require separation, the propulsion system should be designed to be left in an orbit that is, and will remain, outside of the protected geosynchronous region. Regardless of whether it is separated or not, a propulsion system should be designed for passivation. Operators should avoid the long term presence of launch vehicle orbital stages in the geosynchronous region.

5.3.2. Objects Passing Through the LEO Region

Whenever possible spacecraft or orbital stages that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be de-orbited (direct re-entry is preferred) or where appropriate manoeuvred into an orbit with a reduced lifetime. Retrieval is also a disposal option. A spacecraft or orbital stage should be left in an orbit in which, using an accepted nominal projection for solar activity, atmospheric drag will limit the orbital lifetime after completion of operations. A study on the effect of post-mission orbital lifetime limitation on collision rate and debris population growth has been performed by the IADC. This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit. If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property. This may be accomplished by limiting the amount of surviving debris or confining the debris to uninhabited regions, such as broad ocean areas. Also, ground environmental pollution, caused by radioactive substances, toxic substances or any other environmental pollutants resulting from on-board articles, should be prevented or minimised in order to be accepted as permissible. In the case of a controlled re-entry of a spacecraft or orbital stage, the operator of the system should inform the relevant air traffic and maritime traffic authorities of the re-entry time and trajectory and the associated ground area.

5.3.3. Other Orbits

Spacecraft or orbital stages that are terminating their operational phases in other orbital regions should be manoeuvred to reduce their orbital lifetime, commensurate with LEO lifetime limitations, or relocated if they cause interference with highly utilised orbit regions.

5.4. Prevention of On-Orbit Collisions

In developing the design and mission profile of a spacecraft or orbital stage, a program or project should estimate and limit the probability of accidental collision with known objects during the spacecraft or orbital stage's orbital lifetime. If reliable orbital data is available, avoidance manoeuvres for spacecraft and co-ordination of launch windows may be considered if the collision risk is not considered negligible. Spacecraft design should limit the consequences of collision with small debris which could cause a loss of control, thus preventing post-mission disposal.

6. Update

These guidelines may be updated as new information becomes available regarding space activities and their influence

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S. Madry et al., *Innovative Design, Manufacturing and Testing of Small Satellites*, Springer Praxis Books, https://doi.org/10.1007/978-3-319-75094-1