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.)

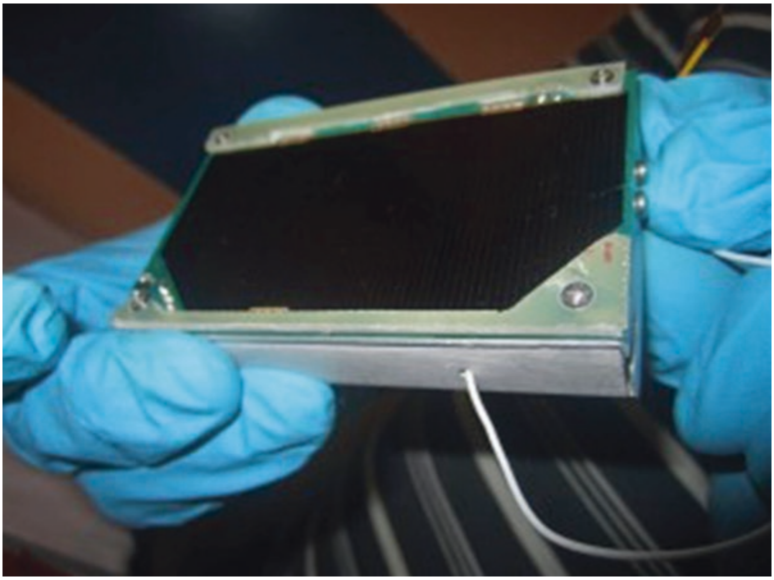

Fig. 1.1 Femtosatellite Pocket-PUCP – Credit Pontificia Universidad Católica del Perú

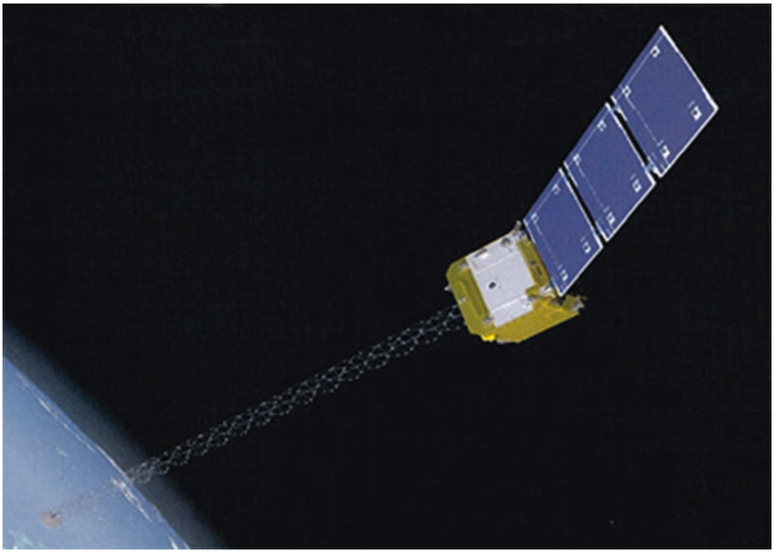

Fig. 1.2 Second generation OrbComm (OG2) satellite at 172 kg is still considered a smallsat. (Graphic courtesy of Orbcomm)

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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