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

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Abstract

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

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

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

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

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

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

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

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

Keywords

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

1 Introduction

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

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

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

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

2 “Femtosats”: Small Satellites of Up to 100 Grams

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

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

Table 1 The types of small satellites and typical applications

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

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

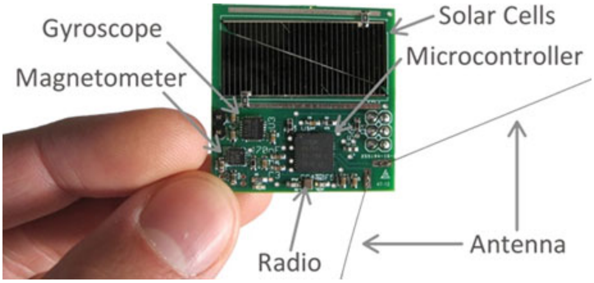


Fig. 1 A “femtosat” or “chipsat”. (Graphic courtesy of Space Stack Exchange)

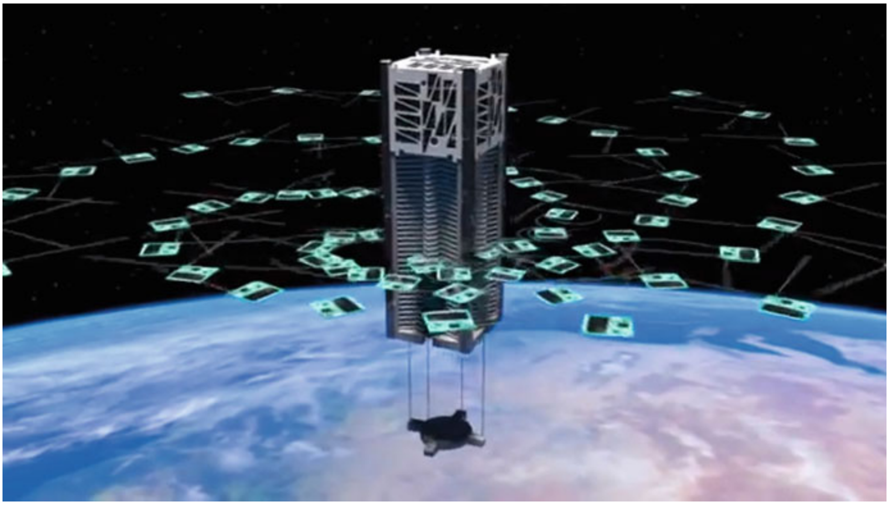


Fig. 2 Kicksat surrounded by a swarm of “femtosats”. (Graphic courtesy of NASA)

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

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

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

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

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

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

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

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

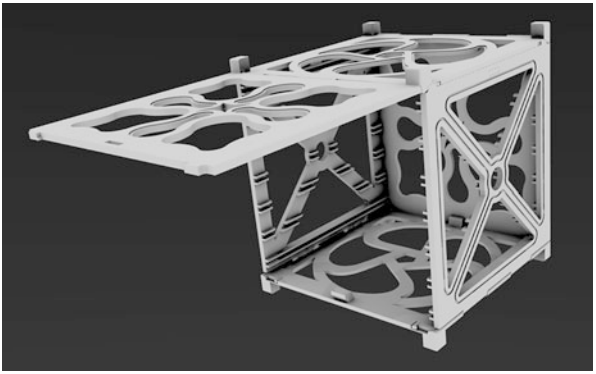


Fig. 3 One of many CubeSat buses that are available for creating a CubeSat today. (Courtesy of Cubesatkit.com)

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

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

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

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

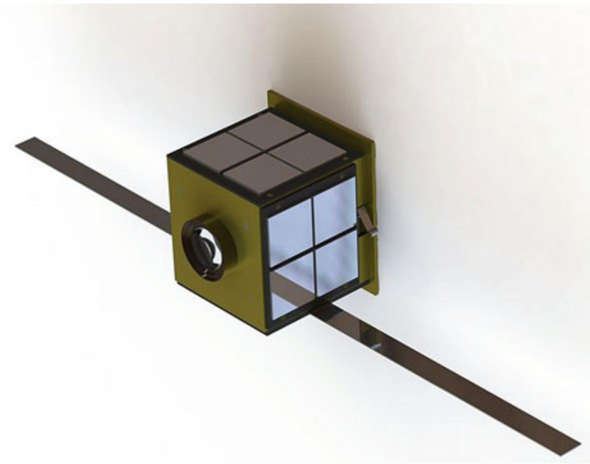


Fig. 4 A pocketqube picosatellite that is one-eighth the size of a CubeSat. (Graphic courtesy open access commons)

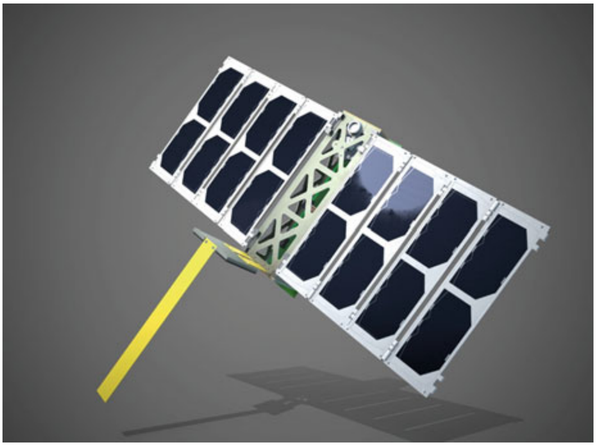


Fig. 5 ESA's Unicorn 2 CubeSat from its Ares development program. (Graphic Courtesy of the European Space Agency)

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

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

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

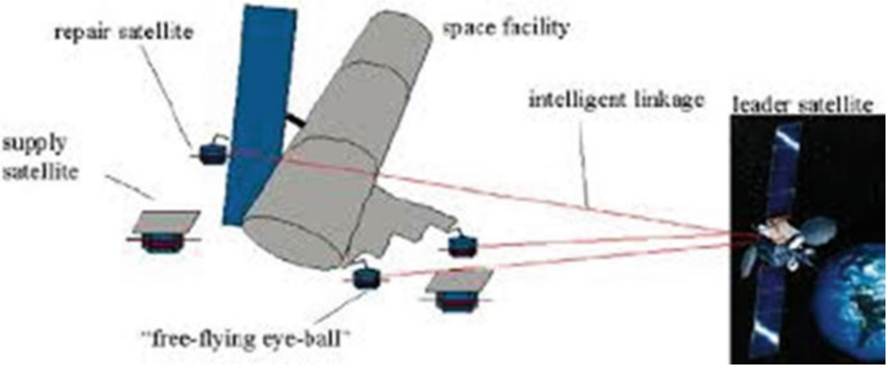


Fig. 6 Pico satellites as “flying eyeballs” in space. (Graphic Courtesy of DARPA)

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

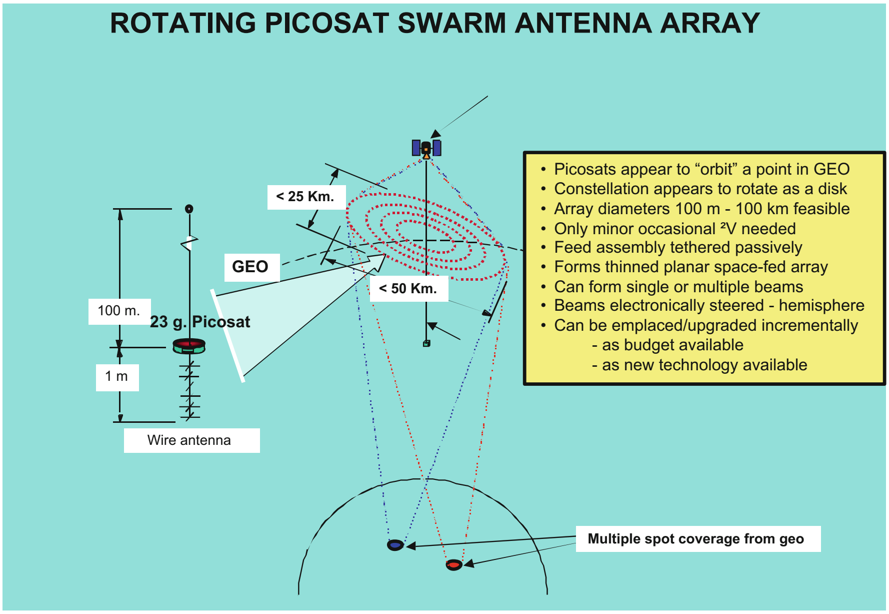
One concept that has been examined is that of an inspector or “free flying eyeball” that could be connected to a spacecraft engaged in Rendezvous and Proximity Operations (RPOs) in space (e.g., for in-orbit servicing). Such small pico satellites could provide useful information to docking with a satellite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

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

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

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

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



- Picosats appear to “orbit” a point in GEO
- Constellation appears to rotate as a disk
- Array diameters 100 m - 100 km feasible
- Only minor occasional ²V needed
- Feed assembly tethered passively
- Forms thinned planar space-fed array
- Can form single or multiple beams
- Beams electronically steered - hemisphere
- Can be emplaced/upgraded incrementally
    - as budget available
    - as new technology available

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

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

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

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

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

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

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

5 The Future of Truly Small-Scale Satellites

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

6 The Technical Issues and Challenges

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

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

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

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

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

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

7 The Legal and Policy Challenges

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

8 Conclusions

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

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

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

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

9 Cross-References

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▶ Overview of CubeSat Technology

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