Overview of Small Satellite Technology and Systems Design

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Abstract

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

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

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

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

There are many innovations that now making small satellite industries thrive. These include new manufacturing techniques such as additive manufacturing, new cost-effective launch systems, and new user devices on the ground such as flat panel antennas, whose costs are now reducing. This chapter, however, seeks to provide an overview the new technology and systems associated with the design of small satellites themselves.

This overview chapter thus seeks to give some insight into the progress that is being made into the better design and more effective use of small satellite structures, power systems, antenna, sensors, stabilization, and pointing systems as well as the other key components, systems, and subsystems critical to small satellites' successful operation. These innovative designs are important to the success of all types of small satellites that range from CubeSats and smaller on one hand plus the microsats and minisats that are key to deployment of the new large-scale commercial constellations. Innovations that apply to one type of small satellite can and often do apply to other types as well.

Finally this section addresses not only technical advances that relate to small satellites as free flyers in space but two other innovations that may become increasingly important in the future. Thus innovations related to hosted payloads that can fly on other satellites – large or small – represent another type of "small satellite." These are also addressed as well as high-altitude platforms (HAPs) that can serve the same function as a small satellite for an island country or in a constellation can provide services akin to that of a satellite.

Keywords

Attitude Determination and Control Systems (ADCS) · Batteries · Constellation design and deployment · CubeSat · Digital processors · High-altitude platform systems (HAPs) · Hosted payloads · Microsatellites · Minisatellites · Miniaturization · Off-the-shelf components · Phased array antennas · PocketQube · Radio frequency (RF) and optical system design · Reaction wheels · Satellites as software defined digital processors · Satellite payload · Satellite radio design and operation · Sensors · Small satellite deorbit considerations · Small satellite registration and frequency allocations · Small satellite structures · Solar arrays · Spacecraft bus · Spacecraft power · Stabilization · Synthetic aperture radar · Thermal systems · Torque rods · Thrusters and microthrusters

1 Introduction

The first satellites that were launched from Sputnik 1 to Score to Relay, Telstar, Syncom, and Early Bird were all small satellites. The demand for greater ranges of commercial services and more sophisticated experimental missions quickly changed to size, mass, and volume of satellites and so-called small satellites such as the AMSAT "OSCAR" satellites, designed and built by amateur volunteers, was seen as only a sideline. The primary use of commercial satellites for telecommunication, broadcasting, and networking services that were deployed in Clarke or geosynchronous orbit led to deployment of satellites that were many metric tons in size. This was because the large antenna size and high power systems were needed to compensate for the large "path loss" associated with transmitting signals the nearly 36,000 km between GEO satellites and Earth.

The switch from analog to digital processing based telecommunications satellites was perhaps the first key step in the evolution toward the recognition that small satellites might have a more important in the world of space applications in the future.

The faster and more capable digital processors became, the smaller these units became. Integrated circuits, monolithic devices, and application-specific integrated circuits (ASICs) all became key to the processing of signals for telecommunications, remote sensing, meteorological satellites, and Global Navigation Satellite Systems (GNSS). Also the sensors used for imaging or tracking stars also became digitized as well.

The next large step came when satellite service innovators decided to try developing low Earth orbit (LEO) satellites for mobile communications and also proposed LEO satellites broadband services. Satellite systems such as Iridium, Globalstar, Orbcomm, and Teledesic all proposed to use of the LEO orbit. The objective was to gain the advantage of low-latency transmission and significantly less path loss due to the spreading of the signal that originated at GEO orbit. In the case of mobile satellite service, the satellite would be moving relative to the transceiver on the ground, and so tracking of the satellite would be required in any event. The low Earth orbits, the digital processing of satellite signals, and the ability to use application-specific integrated circuits in the user devices combined to allowed the cost of user devices to be greatly reduced.

The mobile satellite systems (i.e., Iridium, Globalstar, and Orbcomm) proved that this type of technology could work in practice. Further these systems demonstrated that small, compact, and relatively inexpensive transceivers could communicate with LEO satellites that move swiftly overhead and across the horizon as quickly as in 7 min or so. The phased array antenna system that was deployed on the Iridium system also demonstrated that electronically steered signals could work effectively to provide a commercial mobile satellite signal. The second-generation Globalstar mobile satellite system joined in using phased array antennas that used electronic steering of signals rather than relying on dish antennas that required physical tracking via a moving satellite antenna system.

The Teledesic system, which sought to provide truly broadband communications, rather than just voice or data services (as in the case of Iridium and Globalstar) or low rate data (as in the case of Orbcomm), represented the greatest technical challenge. In the case of Teledesic, it set the objective of supporting gigabit/second speeds or video transmission services. Although this multi-billion dollar LEO satellite network was never deployed, it provided a clear theoretical basis for how this type of high-throughput satellite system might operate. In many ways Teledesic provides a firm theoretical basis for the type of new satellite services that current broadband mega-LEO constellations are now in the process of introducing during the 2020s.

In the 1980s and 1990s, the combination of technologies that is now undergirding the current small satellite revolution thus all started coming together. These included (i) constellations of satellites in LEO-based networks; (ii) highly efficient digital communications systems that could use digital encoding and forward error correction that now include Trellis, Turbo, and High Efficiency Video Coding (HEVC) and (H.264) encoding systems (How to configure… 2019); and (iii) phased array antennas and flat panel antennas that can be used as satellite antenna systems and simpler systems for user transceivers on the ground.

In close parallel ground-based cellular networks and Wi-Fi and WiMax wireless networks were expanding to provide broader and broader band services. The thirdgeneration cellular system gave way to the fourth-generation cellular network that are today giving way to the 5th Generation networks that are now operating in the millimeter wave bands. Likewise the latest generation of high-throughput satellites (HTS) were also operating at faster and faster speeds and at higher frequency bands such as the so-called Ka bands (30 GHz and 20 GHz) and now the V bands (48 GHz and 38 GHz). Essentially wireless and satellite networks were both seeking to provide broadband data and video streaming services to consumers at speeds and competitive costs similar to that offered via fiber-optic cable systems. Fiber networks offered blazing speeds and low costs. Yet fifth-generation cellular and high-throughput satellite networks were playing rapid catch-up capabilities to offer mobility as well as broadband and ever lower costs as well.

The final act in this small satellite revolution was the "NewSpace" or "Space 2.0" innovations. Here, suddenly, was a spate of important new innovations. These innovations included (i) lower launch costs via reusable launchers and small launchers built out of new materials; (ii) new methods of efficient manufacturing, including additive manufacturing; (iii) miniaturization of electronic components, sensors, digital processors, and many other elements that can be used in small satellite networks; and (iv) innovative ways to use off-the-shelf components other approaches to developing and testing small satellites to be built and efficiently tested through the processes developed at the Surrey Space Centre, the Surrey Space Technology Ltd., and Utah State University Space Labs.

In the sections that follow, a brief overview discussion is provided first of the technical challenges to be met in terms of viable and safe operation, followed by the need for technical innovations related to performance. Many technical, operational, or systems aspects are concerned with the design and deployment of small satellites that are discussed in the remaining articles found in Part 3 of the Handbook (NASA 2019).

2 Technical Challenges to Be Met by Small Satellite Developers and Operators

There are a number of challenges that are key to successful and safe operation of small satellites. These represent capabilities that are not only key to small satellites but for the long-term sustainability of space and operation of all types of satellites as well. The first in importance is the key technical challenge of safe operation for the entire time of small satellite mission from launch to deorbit (Earle et al. 2019).

2.1 The Challenge of Safe Operation

Safe operation is the paramount requirement. This is achieved most effectively through precise observation, maneuverability, and communication. Each of these objectives can be quite technically challenged. Other aspects of small satellites still have significant knowledge gaps – especially when it comes to safe operation. Many of these safety challenges were codified by young space professionals studying under the auspices of the Space Generation Advisory Council and the International Space University (Esionwu 2014).

There are particular deficiencies in controllable and predictable end of life disposal as well as precise managing exceptionally large constellations of small satellites. Most small satellites reside in low Earth orbits. A number of these rely on atmospheric drag to dissipate orbit energy and thus cause reentry within a few years without any specific provision for deorbit on demand. This will not be sufficient if in the future, there are many thousand small satellites occupying LEO. Elements of each independent mega constellation must be replaced either on schedule or because of unexpected failure. Numerous inoperative satellites present in orbit for many years will represent a growing problem over time. Very small satellites, such as CubeSats and even smaller, often cannot accommodate reliable, on demand, reentry systems (Puig-Suari et al. 2008).

Thus there are proposals to limit small satellites launches that lack the ability to deorbit on demand to quite low orbits such as below 300 km, or to be launched not as free flyers but within a joint platform that has a deorbit capability, or to have passive systems to speed deorbit processes (Pelton 2015).

As constellations of satellites that are much more massive than a few kilograms and deployed in larger numbers, the concern certainly grows. Exquisite collaboration and coordination will be required to accommodate such increased traffic in LEO. Those that are planning to deploy so-called Mega-LEO constellations of small satellites understand the demands of managing thousands of small satellites with compacted coordination. Some proponents of small satellite constellations are considering higher altitudes, and indeed 03b has plans for a significant new mPOWER MEO network.

Some analysts believe this might also have difficulties. Even though fewer satellites are necessary, they must have more electrical energy and power systems and must also have larger antennas, and, in general, be larger. The trade-off between more and smaller satellites against fewer, larger, and longer-lived satellites at higher altitude with a larger cross section that might become a target for collision has not been well addressed.

2.2 Communications and Controllability Challenges

Small satellites must be able at least to downlink data. These communication links enable ranging at least and perhaps angular resolution sufficient for reasonable orbit determination. However, observations of this nature for the smallest of the small satellites are gathered over extremely short arcs and are often conducted with small antennas with poor angular resolution. Gathering and processing sufficient information to determine orbits may require several passes, and there are gaps between observations that are long enough for orbits to change materially due to environmental variability during the intervals when the satellite cannot be observed.

When many small satellites are deployed in succession, it is very difficult to discriminate among them. Some unique electromagnetic emission or reflection is required. If there is full two-way linkage, a satellite can be queried explicitly. Otherwise, observable maneuvers must be commanded, and which satellite executes that maneuver is identified. This is a common occurrence with radio-controlled model aircraft and commercial light aircraft lost over expansive wilderness.

Several small satellites have never been found by any of these schemes, particularly those suffering some debilitation on deployment.

This raises other issues. If the satellite trajectory cannot be controlled or even known very well, then how well can observations of other bodies in space or on the Earth accurately be registered in any reference frame?

2.2.1 Maneuverability

All satellites should be able to maneuver for station-keeping and to diminish the probability of collision. The minisats and microsats that are being deployed in large constellations all have significant maneuverability, but CubeSats and below may not have this capability. If time is not a serious constraint and urgency is not involved in avoiding an orbital conjunction, a few low thrust actions may be adequate. Again with sufficient time warning the command to fire a thruster need not be applied very early. Figure 1 demonstrates this for a past real conjunction with impulsive chemical thrusters.

Maneuver timing is typically not the critical path in collision avoidance. Maneuver planning almost always take much longer. Consequently, observations, orbit update, and communicating commands to a satellite are the critical elements. This is much easier for GEO than for LEO. This favors the French Space Agency (CNES) “middle man” process or the European Space Agency (ESA) ESOC process that both confirm US Joint Space Operation Center (JSPOC) warnings and execute avoidance based on trustworthy, well-understood analysis and data. This is hardly possible for the preponderance of small satellites which do not have the same type of analytical process capability.

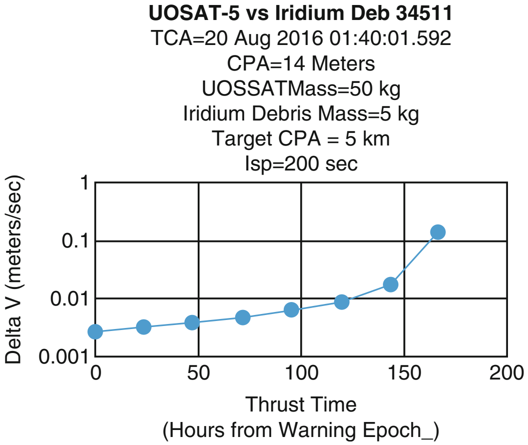

Fig. 1 Thrust levels required depending on advance warning of potential conjunction between smallsat and Delta launch vehicle. (Graphic courtesy of US Air Force)

There are several excellent surveys of small satellite propulsion alternatives. There are chemical, electrochemical, and electric thrusters for small satellites, but few for vehicles as small as CubeSats. Propulsion must not jeopardize large, primary payloads. Both chemical and electric systems add some risk to the launch. Therefore, pressurized cold gas and even water are being considered and indeed have in some cases actually tested. Passive resistance type systems for small satellites to aid deorbit capabilities, such solar sails and aerodynamic devices, have been discussed, but passive systems are not responsive or reliable enough for this type of collision avoidance application.

Avoidance maneuvers cannot be developed more than a few tens of hours in advance because satellite trajectories cannot be estimated with actionable precision more than a few tens of hours in advance, particularly in drag-dominated low Earth orbits.

All of these possibilities are practical for long-term, modest orbit or attitude adjustment, but they seem unsuitable or unreliable for relatively short notice collision avoidance.

Small satellites in conjunction with other small satellites, depending on their size and thruster capability, almost always, have no avoidance alternatives (Tummala and Dutta 2017).

Since desirable missions all favor the same orbit regimes, collisions among small satellites should not be discounted. Conjunction management between small satellites and larger satellites that can maneuver enough to avoid catastrophe becomes the sole responsibility of the larger satellite, which requires more energy to adjust its orbit than the small satellite would.

Having optimized orbit architecture, one must assure that the probability of encountering other satellites during the mission is acceptable. The hypothetical small satellite experiences close approach within 20 km of a Thor Agena D rocket body. The relative geometry between a launcher and a possible small satellite conjunction is very consequential. This is particularly so when the launcher is nearly perpendicular to the satellite's velocity vector. Depending on the duration of the mission, it is important to observe the object closely for most of the mission as well as check regularly for other close approaches. Several satellites approached within 50 km at the time the analysis was conducted.

2.2.2 Observability

If an object in orbit cannot maneuver, knowing where it is becomes critical. The object must be discernible either passively either by its own emissions or reflections of background radiation. Or it might be illuminated actively. The degree to which the object's state of motion can be determined or its future state estimated depends on the distribution of observation opportunities and the density of observations acquired during each observation interval (Finkleman 2013).

Observability should be among principal considerations for the design of a spacecraft of vehicle and also can influence the choice of orbit architecture. As an example, consider a single small satellite for which there are sufficient optical observables. Assume that mission requirements allow any reasonable altitude or inclination. The task is to find an orbit during which there is the greatest cumulative time of observation given a small set of ground-based sensors.

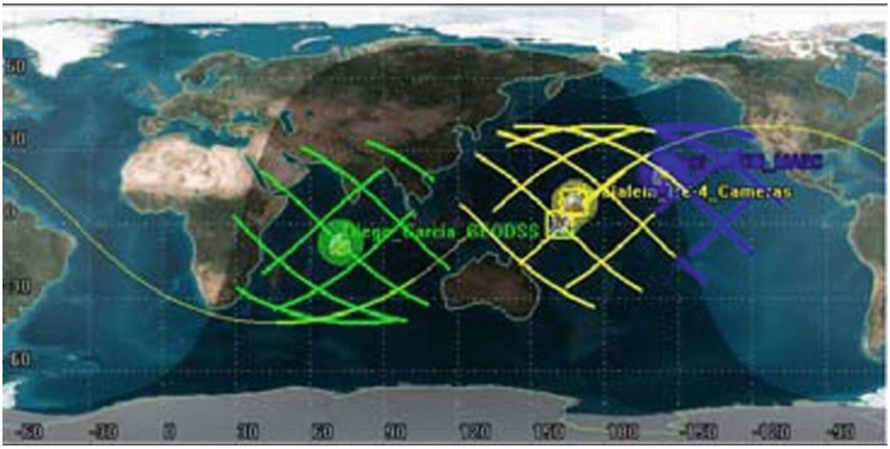

Fig. 2 Small satellite orbit designed for greatest time of observation from designated observation locations. (Courtesy of the US Air Force)

This is shown in Fig. 2 below that depicts a typical situation with tracking instruments around the world that in this case involves tracking facilities in Hawaii (indicated by tracking data in blue), Kwajalein (indicated by tracking data in yellow), and Diego Garcia (indicated by tracking data in green). These three stations are utilized to undertake the assigned tracking.

Safe operation thus often requires some compromise in mission capability. For a single satellite to “see” most of the Earth over time (and thus to be seen), the inclination and apogee should be as high as possible. For example, if one wishes to monitor synoptic energy balance, there would be only rare and brief opportunities for the designated sensors to gather data for orbit estimation. “In this case, the optimal parameters for longest cumulative observation over the course of a day were: inclination 32°, eccentricity 0.1, apogee altitude 8490 km. The observation passes over the course of the day for the satellite chosen for analyses are shown in bold lines in Fig. 2.”

> There is also an opportunity to observe small satellites almost ubiquitously with radio telescopes. Almost all satellites have significant radio frequency signatures from instrumentation and internal electronics, not to mention communication devices. Very precise orbit observations are feasible, and the observations can also reveal anomalies in electrical devices onboard. (Finkleman 2016)

3 Small Satellites and Attitude Determination and Control Systems (ADCS)

Constant improvement is being made in the attitude determination and control systems (ADCS) for small satellites. Many of the first of the cube satellites launched well over 20 years ago were fairly crude devices that often were designed by students for short-term experiments and had little or no capabilities for attitude determination and control systems (ADCS). In more recent years, increasingly sophisticated systems and sensors have been developed both to detect the orientation of small satellites and capabilities to maintain stability and even three-axis stabilization. A systematic study of over 350 nanosatellites in the 1–10 kg range in a survey for the period 2003 through 2016 has produced the following findings.

> The ADCS information of 357 nanosatellites were available for statistical analysis. Of the 357 nanosatellites only 5% had no ADCS, 17% used passive magnetic control, 2% used gravity gradient stabilization, 6% used other passive methods of stabilization (e.g., aerodynamic), 2% were spin stabilized, 11% used active magnetic control, 3% were momentum wheel stabilized, and 54% were reaction wheel 3-axis stabilized. (Xia et al. 2017)

It is not clear if this survey can be taken as truly representative of small satellites. But it can be reasonably assumed that significant progress has been made in this area since the earliest days of small sat experimentation. One can thus reasonably assume that at for at least most microsats and minisats that are being launched in today's large constellations a high percentage of these satellites have reaction wheel three-axis stabilized capabilities and also have thruster jets that can allow these larger small satellites to be deorbited from low Earth orbit (LEO) at end of life.

There is still concern for all small satellites not so equipped. There is especial concern for femto-satellites (e.g., chipsats), pico-satellites (e.g., PocketQubes), nanosats (e.g., CubeSats), and even microsats and minisats that are not equipped with attitude determination and control systems (ADCS) nor thruster jets for deorbit capability. Indeed these systems also generally lack passive systems to that can be deployed to assist with deorbit. This suggests that all such truly small satellites without such capabilities should only be launched at lower altitudes, such as 300 km or below, to insure that they will naturally deorbit due to gravitational effects, especially during solar max period when the Earth's atmosphere expands and creates additional drag conditions.

4 Power, Energy Storage, and Power Conditioning Systems for Small Satellites

The power systems for small satellites much like larger satellite depend on a combination of solar arrays that collect energy from the sun and batteries for periods when satellites are obscured from the sun. The further constraint of small satellites is, of course, the limited volume and mass associated with these type spacecraft. Craft as small as picosats (i.e., PocketQubes) still can display solar cells, but in limited number. For CubeSats batteries similar to those used in cellphones, i.e., lithium batteries, can be recharged and support missions that last months and even years (see Fig. 3). Small satellites with short lifetimes might subsist on energy stored in batteries at launch. Solar cells are the only way to replenish energy on orbit.

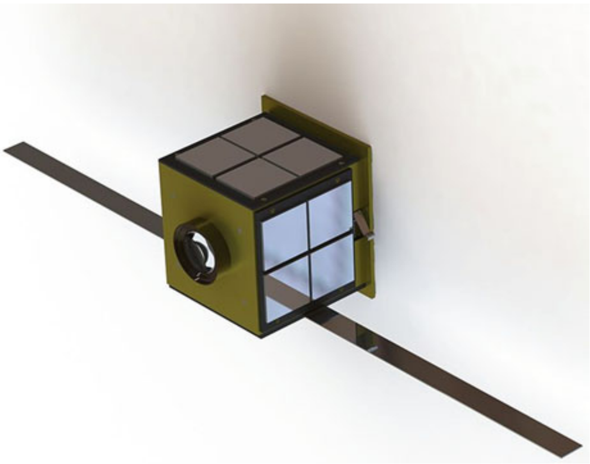

Fig. 3 This PocketQube design only had room for four solar cells since the antenna extension mechanism was deemed more important. (Graphic courtesy open access commons)

Energy often is not extractable with characteristics that onboard electronics require. Relative to large satellites, small satellites lack the design parameter space among orbit, operational access, solar illumination, thermal management, electronics, and other essentials.

The issue of power system design with small satellites often hinges on the cost of the photovoltaic cells that are used. The amorphous silicon PV cells are the lowest in cost. Other more sophisticated cells such as gallium arsenide cells, or violet solar cells with multiple gates, or in future years perhaps quantum dot units can produce more power and can be coated with glass to have longer life. These are trade-off decisions that must be against program cost constraints, desired lifetime, and mass and volume limits. Fortunately small satellite programs can benefit from research that is being undertaken for terrestrial applications or much larger and expensive satellite programs.

5 Small Satellites and Antenna Performance

There is now considerable experience with the Iridium, Iridium Next, and Globalstar OG2 satellites and other smallsat programs that is helpful in the design of high performance phased array antennas. Smallsats, particularly those in the 50–500 kg range are capable of creating a large number of spot beams to achieve a high degree of frequency reuse and to concentrate power quite effectively. The three keys to satellite efficiency and capacity are available spectrum, power concentration, and complexity as achieved through efficient multiplexing, digital encoding, and forward error correction. The latest satellite technology is able to deliver on all three of these dimensions.

Progress in phased array antenna design with electronic beam forming using electrical or optical processing and unique capabilities such as meta-materials or new technology will be key to progress in the small satellite constellations that are now planned for deployment in coming years.

Larger apertures are more effective than smaller ones. Diffraction and the basic laws of physics rule. Small satellites can embody antennas much larger than the satellites themselves. Using shape memory composites, large antennas with complex figures can be rolled and stored in narrow tubes for deployment on orbit. Research organizations have engaged origami artists to develop large objects that can be stored in small spaces.

Phased array antennas are possible for small satellites. However, they suffer sidelobes that monolithic antennas do not experience. They are not as energy efficient, and they are electronically complex. Although the state of the art enables relatively useful small phased arrays, innovative dish antennas can still provide the best technical and cost performance. It is, of course, possible to combine dish reflectors with phased array feed systems. Producing and feeding the electromagnetic energy to be transmitted are also technologically demanding.

Electronically shaped beams and phased array antennas and feed systems have merit when energy must be transmitted or exchanged among many space, airborne, and terrestrial platforms. Higher frequencies experience less diffraction, but they cannot be produced as efficiently as lower frequencies. The highest practical frequencies are optical, light. Optical links between satellites have a long and painful development. Alignment between widely separated, rapidly moving satellites is a challenge. Optical links to the surface of the Earth experience scattering, absorption, and other deleterious phenomena in the atmosphere.

5.1 Small Satellite Radio System Design and Possibility of Optical Links and Processing

The design of radio devices to support various missions related to telecommunications, networking, data relay, tracking, telemetry, command, and other key functions continue to evolve and improve over time. In the earliest days of small sat development, the radio systems were simple and often were operating in the VHF and UHF spectra, but today increasingly sophisticated radio technology is being developed to support broadband throughput needs and radio devices that are operating in the super high frequencies and extremely high frequencies and much more sophisticated and also much higher in cost. There have also been suggestions that optical communications could be used in the case of some small satellite applications such as for intersatellite links. Optical technology such as in the form of optical processing could also be used to replace digital electronic processing as this technology matures.

5.2 Small Satellite Structures

The key to CubeSats is the standardization that allows important components and subsystems to be interoperable and widely available. This standardization of CubeSats into elemental units that can be joined is important. This enables interoperable deployment and launch vehicle fixtures that now range from 1 to 6 units, up to 12 unit, and even up to 27 unit systems (i.e., 30 cm cubes) and also assists with lowering the costs of testing as well as the possibility of accelerating the testing process. This process of standardization of platforms and platform sizes has now even transferred to conventional satellites that are now typically constructed to go on a limited number of platforms. These platforms are often geared to particular sized launch vehicles. There are today suppliers of standardized structures that are not only available online for 1 unit, 2 unit, 3 unit, and 6 unit cube satellites but also are available for PocketQube kits and structures that are exactly one eighth the size of a CubeSat.

This standardization of cost-effective and reliable smallsat structures thus aids at every stage of design, component and subsystem acquisition, construction, testing, and launch service arrangements. The key is not so much in the structures and the materials used in the structures, but the standardization and ease and lower cost of acquisition.

5.3 Deorbit Concepts for Small Satellites

Concerns about the deorbit of small satellites have grown as the number of launches of various sizes of smallsats have risen almost year by year. The prospect for the future of more and more smallsat launches has led to increased concerns about orbital debris and improved ways to remove these satellites at end of life. Along with these concerns has come an increased focus on better space situational awareness, the need for space traffic control, and new ways to address the longer-term sustainability of outer space activities. The 21 new guidelines adopted by the UN General Assembly and the UN Committee on the Peaceful Uses of Outer Space (COPUOS) represent some progress, but there are many other ideas that have been suggested. These ideas include restriction of small satellites without active deorbit capabilities to a particular altitude so that natural deorbit occurs in a reasonably short period of time, consolidation of small satellites into joint missions that would contain an active deorbit capability, requirements for passive systems to aid deorbit, etc. (Guidelines for the Long-Term. . . 2019).

There is quite a bit of technology under development to aid with deorbit of defunct satellites. These developments include lower cost and miniaturized attitude determination and control systems as well as stabilization, pointing, and orientation systems (i.e., devices such as magnetic toque rods and miniature reaction wheels) and low cost and miniaturized thrusters, as well as passive systems to create atmospheric drag. These systems are key to being able to remove small satellites from orbit in a timely way. Yet one of these can cause controlled reentry to a specific location or reveal what might survive reentry. It will take a combination of technology and regulatory reform to address the orbital debris problem effectively.

5.4 Small Satellites and Spectrum Allocations and Registration

There are no allocations of satellite frequencies related to telecommunications, remote sensing, or any other applications that are specifically restricted to small satellite activities. The allocations are based on the application and the three ITU regional districts. There are certainly some applications such as amateur radio frequencies or data relay and messaging where smallsats are used. The issue is the rather that small satellite are sometimes not properly registered with the United Nations or their frequency usage not coordinated through the International Telecommunication Union in the designated way. Efforts are being made to see that these procedures are systematically followed.

The future of commercial space applications seems to be headed toward the deployment of more and more smallsat constellations to provide very large networks in LEO and yet others in MEO. Further these networks appeared poised, based on filings, to move to higher and higher frequencies such as Ka band and V band. It is important that these networks be thoroughly coordinated to avoid interference with protected GEO-based networks as well as to avoid interference with other LEO and MEO systems, high-altitude platform systems, and ground-based systems. As more and more of the networks are deployed, especially those in the so-called Mega-LEO systems with thousands of satellites in these constellations, this challenge appears likely to become more difficult. In this regard new technology to minimize interference and new regulatory processes may both become necessary.

5.5 Small Satellites and Advanced Processing and Networking

There are essentially three ways to make satellite services, particularly telecommunications and networking services, more efficient. These involve more power and more highly focused power into smaller catchment areas, more spectrum, and greater bandwidth, through the use of either higher frequencies or methods to reuse frequencies or more efficient ways to process radio signals with great complexity, improved multiplexing, or encoding to send more bits per Hertz. Small satellites are seeking ways to achieve improved capabilities in all three of these areas. This means use of LEO or MEO constellations so as to concentrate power more efficiency and to avoid the extreme path loss and latency that comes from operating in the GEO orbit. This means finding more ways to reuse spectrum by means of spot beam and thus to allow geographic separation of beams, the use of higher frequencies so as to increase available bandwidth, and use of more efficient phase shift keying and other advanced multiplexing systems coupled with advanced coding and forward error correction.

Digital communications, digital processing, and ever more sophisticated software defined modulation, multiplexing, and processing systems to move satellite communications closer to the absolute efficiencies of the Shannon’s Law limits have allowed satellites to gain greater and greater efficiencies. Essentially coder/decoder (Codec) systems in satellites have allowed satellite efficiencies to increase from a level of one bit per Hz to six or even seven bits per Hz simply through advanced software processing of signals. Small satellites, just like large satellites, are digital processors in the sky whose functionality is defined by its software. The key to more efficient small satellites will be through the development of ever better processing systems.

Such enhancements involve both the satellites and terrestrial systems. But terrestrial systems and networks are driven by other established and significant uses. It is unlikely that established terrestrial networks will agree to widespread and expensive changes just to accommodate small satellites. If the small satellites must seek compatibility with existing terrestrial networks, they might no longer be small and inexpensive. These are just some of the dilemmas that small satellite operators will face in years to come.

5.6 Small Satellites and Flight Software, Software-Driven Designs, and Network Control

The future of small satellites is being driven by a significant number of technologies. It is perhaps true that it is new software and artificial intelligence that may end up as one of the very most important drivers of change and innovation. Flight software, network control for satellite constellations, and even use of software to drive the future design of actual satellites are increasingly a part of the mix that is shaping the smallsat revolution. There are at least two key articles in the technology section of the Handbook on Small Satellites that cover the various ways that software and software innovation are shaping the future. These articles discuss the way that small satellites are designed as well as how modest upgrades in performance or reliability are made to small satellite designs as multiple generations of commercial small satellites are created with an ever increasing rapidity that may even come several times within a single year. There is a future for artificial intelligence and software innovation in almost every aspect of the world of small satellites. These can include flight software and network control of a small satellite constellation and in spacecraft design and innovation – from one generation to another in the fast moving spacecraft engineering and performance.

5.7 Optimizing Payloads for Remote Sensing and Monitoring

Most of the articles in Part 3 of the Handbook of Small Satellites address the technical challenges of small satellite and its component elements in terms of design, manufacturing, reliability, cost efficiency, and network operation. There are several articles that address the design and performance of the communications and networking payload and one that addresses the payload characteristics of small satellites for remote sensing. It was the miniaturization of sensors and particularly sensor processing for remote sensing that led the way forward in the small satellite revolution. The first wave was in miniaturized optical sensors. Over time infrared, near-infrared, hyper-spectral sensors, and synthetic aperture radar sensing systems have all been redesigned and shrunk down so as to be used in small satellites that range from 3U CubeSats to minisats. In light of the power requirements associated with radar sensing, that use active rather than passive sensing processes, synthetic aperture radar smallsats are typically larger than

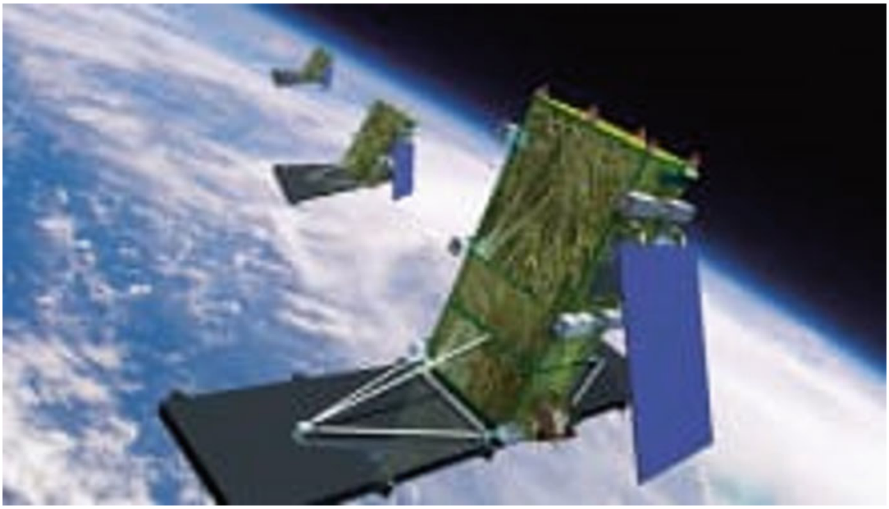

Fig. 4 The new deployed three Canadian RADARSAT constellation that represents the higher end of smallsat design. (Graphic Courtesy of the Canadian Space Agency)

optical remote sensing satellite systems. The Canadian newly launched Canadian RADARSAT Constellation Mission (CRM) deployed in June 12, 2019, represents the largest type of smallsats now used for synthetic aperture radar imaging (Foust 2019) (see Fig. 4).

5.8 Hosted Payloads as a Form of Small Satellite

There are many ideas behind the small satellite revolution. These have included finding ways to use better and more compact designs, creating high efficiency miniaturized components, discovering ways to use off-the-shelf components, developing accelerated and lower cost testing procedures, locating lower cost launch services, as well as developing economies of scale by deploying more small satellites in a constellation. As a part of this process of developing smaller and high efficiency satellites of small scale, it became clear that if one could place a functional payload on a larger satellite where it shared a launch, power, tracking, telemetry and command capabilities, etc. new efficiencies could be gained.

A guest, however, must not inconvenience the host The guest must meet its requirements while joined with the host wherever the host mission requires it to be. These compromises may be possible for some missions, but not for all.

Such a hosted payload might go on a large satellite for the purposes of technology demonstration, but if the host payload were small enough, it might even go on a microsat or a minisat. This, for instance, has been the case with the Aireon ADS-B hosted payload that has been launched onboard of all of the Iridium-NEXT satellites with its 66 satellite constellation (see Fig. 5).

Fig. 5 Aireon hosted payload on Iridium-NEXT satellite. (Graphic courtesy of Iridium)

Thus this handbook has examined this approach to a satellite and provided examples of this approach to small satellite deployment and operation for experiments, technology verification, and even implementation of commercial services.

5.9 High-Altitude Platforms (HAPs) as an Alternative to Small Satellites

Finally the concept of high-altitude platform systems and stratospheric systems is also included in this *Handbook of Small Satellites*. This is because platforms positioned in the stratosphere can be used to create the coverage to provide comprehensive overview or electronic services to an entire island nation or a country with a modest territory. Such high-altitude platforms (HAPs) can provide a range of important governmental services or commercial services. These can, for instance, include high-resolution and hyper-spectral remote sensing, law enforcement, forestry management, agricultural monitoring, fire detection, and particularly communications and broadcasting services (see Fig. 6).

Frequency spectrum has been allocated for UAV- and HAP-type services, and this type of service might be offered by a variety of different technologies that include zeppelins, dirigibles, automated aircraft, and solar-powered platforms. Even the concept of a type of platform that is provided power to operate electric engines and which would be beamed up from the ground have been considered, but not implemented. These transmissions could possibly be microwave, millimeter wave, or even laser-emitted power. Today some companies such as Thales Alenia are offering such systems to deploy high-altitude services by such stratospheric platforms. There have been projects to deploy such systems in countries as large as Japan that would have included the need

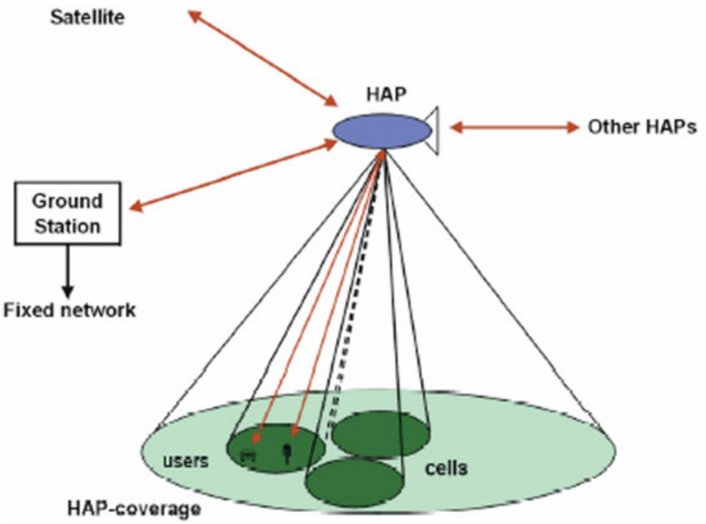

Fig. 6 High-altitude platform (HAP) diagram for telecommunication services. (Graphic from the Global commons)

to deploy as many as 15 such platforms, but his particular program has been discontinued for a number of practical and technical reasons.

6 Conclusion

Small satellites are revolutionary opportunities for organizations and nations. Often the companies building or operating small satellites will have limited financing and other resources. These capabilities should be encouraged and exploited. This article begins with citing the challenges and the risks of unfettered exploitation of this technology. It notes the bounds on the ability of smallsats from minisats and microsats down to nanosats and picosats. It notes the difficulty of small satellites meeting the constraints imposed on larger satellites.

None of these constraints are normative, and very few are broadly legally enforceable. Space mission and commerce stakeholders should consider this small satellite dilemma and arrive at acceptable compromises before compromise ceases to matter if space debris issues mushroom out of control through the lack of regulatory action or at least broad-based agreement on best practices.

Improved technology is essential. The technology that drives innovation in the fields of information, communications, computers, and energy is becoming more powerful each year. The world of small satellites seems to be among the very most dynamic. This is because it is driven by a true sense of innovative thought that is sometimes called “NewSpace” or “Space 2.0.” Many of these innovations grew out of the computer industry and a sense of breakthrough innovation rather than seeking merely a small 5% or 10% gain.

Regardless of the original stimulus, the effort to improve what is possible with small satellites and how they are deployed and used now pervades the industry. Thus there is an effort to increase performance everywhere and in every domain. Thus there is research and innovation related to:

(i) Attitude Determination and Control Systems (ADCS)
(ii) Power systems
(iii) Antenna systems
(iv) Radio and optical communications systems
(v) Use of artificial intelligence and improved software to improve smallsat performance
(vi) Enhancement of their structural design
(vii) Finding better ways to deorbit satellites at end of life
(viii) Improvement of the performance and cost for user terminals on the ground and on the move
(ix) Use of artificial intelligence to design better spacecraft and control constellation networks
(x) Use of advanced processing systems and AI to create better payloads for telecommunications and networking and/or improve sensors for remote sensing
(xi) Creation of even smaller hosted payloads to ride piggyback into space
(xii) Exploration of yet other alternatives to small satellites in the form of high-altitude platforms that can deploy new payloads for communications, broadcasting, law enforcement, agricultural and forestry management, navigation, or other services in perhaps even more cost-effective ways for island countries and other smaller territories

The technology section that follows has sought to be as comprehensive as possible. The articles that follow are filled with innovation and new ideas. It is hoped that this resource will prove useful. Ultimately the goal should not be to make satellites smaller and smaller as an end in itself. The key is to find suitable missions that are suitable for and compatible with small satellite systems and then optimize small satellites that are compatible with those missions. It is accomplishing goals and missions that are the ultimate aim.

7 Cross-References

▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
▶ Hosted Payload Packages as a Form of Small Satellite System

▶ Network Control Systems for Large-Scale Constellations
▶ Power Systems for Small Satellites
▶ RF and Optical Communications for Small Satellites
▶ Small Satellite Antennas
▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
▶ Small Satellite Radio Link Fundamentals
▶ Small Satellites and Structural Design
▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
▶ Stability, Pointing, and Orientation

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