Chapter 3
The Technology of Small Satellites

The design and manufacture of small satellites can be broken down into two major categories of spacecraft bus and payload. A spacecraft bus is the platform that allows the spacecraft to support a particular function in space, and the payload is the hardware that is specifically designed to carry out the mission (such as telecommunications, navigation, Earth observation, meteorological sensing, surveillance or situational awareness, or some other form of space-related experiment or in-orbit testing of new technology). The bus must be able to provide the power; the thermal environment; pointing and stabilization; and the telemetry, tracking, and command (TT&C) capabilities needed to support the mission. The TT&C systems must have assigned frequencies to support the linking-up of the onboard systems with ground-based tracking and command signals as well as the relay of data to the ground to make sure the satellite is performing correctly.

The "bus" can be quite small, simple, and crude and thus supply very little functionality beyond power and perhaps some radio links to support command and data relay. It can also be relatively sophisticated even on a small satellite. There are buses even for small satellites that provide battery and solar power, heat pipes for thermal control, a tracking, telemetry, command and monitoring system, plus a system for stabilization and pointing of sensors, cameras, or antennas (which constitute the satellite's payload). There are organizations such as Surrey Space Technology, Ltd., Orbital Sciences Corporation, Sierra Nevada Corporation, as well as academic institutions such as Utah State University, the University of Colorado, Boulder, the University of Texas, Austin, etc., that are able to supply spacecraft buses to support a number of small satellite efforts. These start with simple nano-sats or cube-sats and go up to small satellites that can weigh hundreds of kilograms.

The payload of the small satellite, of course, defines its essence and mission. Small satellites typically tend to have a single instrument, sensor, or antenna system as its mission. This is particularly the case for a cube-sat whose typically dimensions are $10 \times 10 \times 10$ cm and which has a mass of about 1 kg (See Fig. 3.1).

The basic cube-sat, which is most commonly designed and built as a student learning experiment, is very simple in concept. There are solar cells on the outside

R.S. Jakhu and J.N. Pelton, *Small Satellites and Their Regulation*, SpringerBriefs in Space Development, DOI 10.1007/978-1-4614-9423-2_3,

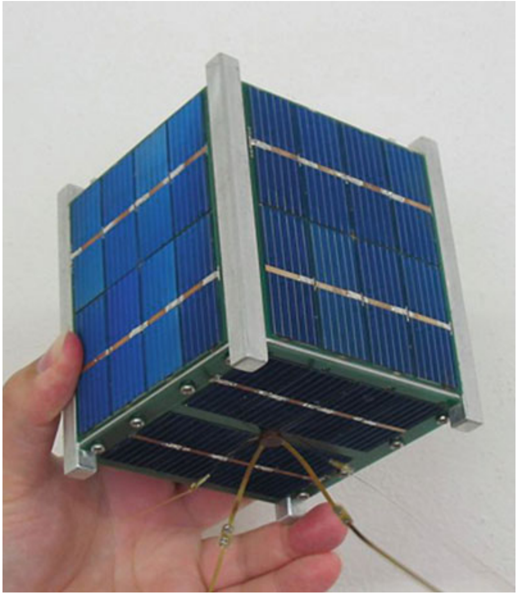

Fig. 3.1 A typical cube-sat (Courtesy of NASA)

and typically lithium ion batteries to supply power, a simple antenna to support tracking and telemetry, and microprocessors and sensors or equipment to support a simple experiment. The basic miniscule cube-sat does not have the size or mass that is required to support any stabilization or pointing system and thus cannot be commanded. There are design efforts to employ on the larger 3U size cube-sat a solar array boom and a low power reaction wheel to provide some degree of stabilization and pointing capability.

Once a cube-sat is released into space, its final orbit is determined by its release. As such, a very low-gain "omni antenna" must be designed to send down telemetry and tracking data regardless of how the cube-sat is oriented in space. The payload might be a camera to snap pictures or a small Geiger counter or infrared sensor or other type of equipment to collect data about radiation, heat patterns, etc. A cube-sat is essentially a teaching device to allow aerospace students to learn some basic engineering concepts and skills and to realize the "thrill" of building a satellite that will fly in space.

The idea of a basic teaching exercise that cube-sats represents is broader than just a typical cube-sat configuration. There are kits that one can order online for "do-it-yourself" basic satellites that include electronics, computer processor(s), and dense data storage, and power systems. Such very basic satellites for student learning may or may not be in a classic cube-sat configuration and may be larger or smaller in size and/or mass. Such a typical kit can be expected to have the following types of components that can be configured into a do-it-yourself cube-sat. In addition, the kit normally includes a number of possible experiments or applications that could be accomplished with such a cube unit that might be on a half, full-scale, 1.5 scale, 2.0 scale, or even 3.0 scale size (See Table 3.1).

Table 3.1 Elements that might be found in a ready-to-build cube-sat kit

Ready-to-build kit for a cube-sat
• Complete, finished, and ready-for-launch cube-sat structure (in 0.5U, 1U, 1.5U, 2U or 3U size) with high strength, low mass, and large internal volume
• A Pluggable Socketed Processor Module for in-lab development and testing, a mother board and for the actual flight model a Pluggable Processor Module (PPM)
• Low-power, high-performance electronics based on your choice of PPM, using
– 16-bit or 32-bit ultra-low power microcontroller
– 8-bit or larger mixed-signal MCU
– 16-bit high-performance microcontroller
– 16-bit digital signal controller
• Multi-tasking software for the processor and a relevant software library
• Plug-in modem/transceiver support and built-in USB 2.0
• USB debug/Flash emulation tool (FET) for programming and debugging
• Power supplies (solar cells & lithium batteries), programming adapters, cables and tools

3.1 Technology Associated with More Sophisticated and Mission-Driven Small Satellites

An insightful publication entitled "The Future of Small Satellites"[1] provides a basis for assessing the ability of small satellites to achieve characteristics that are desirable for safe operation. An important contribution to that volume estimates attainable capabilities based on size.[2] There is a lot more to the small satellite world than just cube-sats and nano sats for students to learn about spacecraft design, to carry out simple experiments, or to test new materials or biological agents in a low-gravity environment. There are many larger and more sophisticated small satellites that can be designed for real space missions. Here, the technology associated with more sophisticated small satellites continues to evolve quickly. The relevant technologies can be usefully examined and discussed under the following categories: power systems; thermal control; ground surveillance and communication characteristics; stabilization and pointing systems; tracking, telemetry and control, maneuverability, etc.

3.1.1 Power Systems for Small Satellites

Power systems for small satellites are, in many ways, parallel to those employed in larger satellites. There are many options in terms of power systems for small satellites. These involve trade-offs between lower cost and lower performance systems

[1] Small Satellites: Past, Present, and Future, Henry Helvajian and Siegfried W. Janson, Eds., ISBN 978-1-884989-22-3, 2009.

[2] Siegfried W. Janson, Satellite Scaling Issues, p. 771, in Small Satellites: Past Present, and Future, Henry Helvajian and Siegfried W. Janson, Eds., Aerospace Corporation Press, 2009.

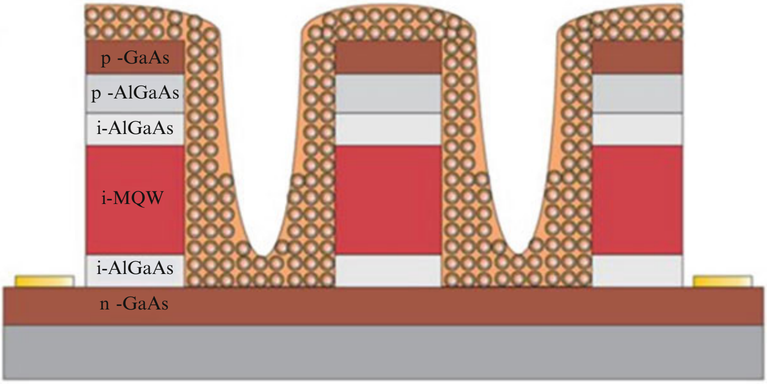

Fig. 3.2 A close-up of the "bumps" in a multi-junction quantum dot solar cell that would produce higher levels of electrical energy and at very high efficiency levels

versus higher cost and higher performance systems. These options include amorphous silicon and structured silicon solar cells and range up to higher cost multi-junction gallium arsenide cells capable of capturing energy in the high-energy ultraviolet range. In the future, there is the prospect of quantum dot technology. These quantum dot solar cells might be able to achieve perhaps 70 % efficiency in converting solar energy into electrical power for spacecraft use. This technology involves creating more effective surface exposure and more photovoltaic junctions to capture more solar energy across the spectrum. Thus the quantum dot solar cells would derive power from the most energetic ultraviolet range of solar radiation down through the visible spectrum. This technology is perhaps some 5–8 years away from commercial manufacture at viable cost levels (See Fig. 3.2).

There are also more efficient solar array and lower mass systems that involve thin film array systems that can be rolled out as opposed to deployed as rigid structures. Of course in the most compact and miniaturized small satellites, the solar cells are confined to the body of the satellite, and no solar arrays are deployed. Such a small satellite is limited in its power generation in that only about 40 % of the body would be able to receive solar radiation since the rest of the spacecraft would in effect be in eclipse. Solar arrays that can be deployed from a three-axis stabilized spacecraft have the advantage of tracking the Sun for maximum illumination. But, of course, such stabilization systems and the need for fuel to power the stabilization and pointing thrusters add weight to the satellite.

Another technology that can be utilized is a solar concentrator that serves to concentrate solar energy so that the solar array "sees" the equivalent of more than one Sun. Relevant research in this area is still seeking reflective materials that are lightweight enough to make such solar concentrators cost efficient. Currently, most small satellites use lower cost silicon solar cells and do not use solar concentrators. There is no systematic approach in this aspect of small satellites. Commercial missions such as mobile satellite constellations will typically use sophisticated solar arrays with high performance gallium arsenide solar cells. The same can be true for

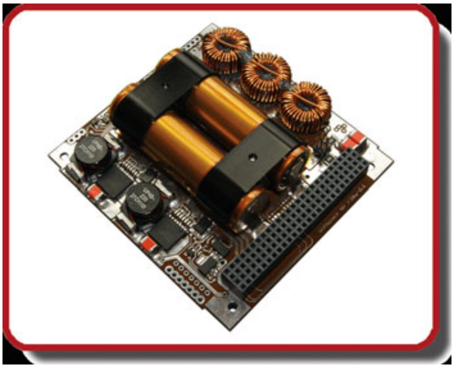

Fig. 3.3 Nano satellite power and energy storage module (Courtesy of ISIS Cube-sat Solutions)

sophisticated small satellite systems designed by a governmental space agency. In contrast small experimental or student satellites will likely use much lower cost amorphous silicon solar cells.

Area per unit volume is greatest for spheres and increases inversely with object size. Therefore, solar-energized small satellites can have higher power to mass ratios than large satellites. However, the power attainable is still rather small. The potential is for no more than 10 W for body mounted cells on a nano sat deployed in a typical low Earth orbit – allowing for eclipse periods. This power output might be doubled if extensible panels are used. However, extensible panels add to mass and increase complexity and failure modes. Current standards and political constraints preclude nuclear energy sources in Earth orbit. This is particularly the case for low Earth orbit since budgets would normally exclude use of radioactive isotopes on small satellites in any event.

There is also the issue of energy storage for the time when the small satellite is in eclipse and no solar illumination is available. Considering allowable charge and discharge rates, nano-sats could sustain 1 W of continuous power for only a few months and as much as 10 W for a few days. In some instances of small satellite design where a particular experiment or test of a new space system or material does not require continuous operation, a lower weight and more compact battery can be employed. Such a battery storage system would thus be designed to provide only sufficient energy storage in order to support TT& C data relays rather than the operation of the payload during the eclipse period. Today, the cost of lithium ion batteries that have relatively dense storage capability has declined on account of their use in support of truly high volume market applications such as laptops, cell phones, etc. The research and development of technology by the most advanced research laboratories for the largest and most sophisticated spacecraft can often be efficiently transferred to smaller-scale projects (See Fig. 3.3 above).

Small satellite programs closely monitor research carried out in support of the most sophisticated programs to see if the outcomes can be usefully applied in smaller projects. If one examines the basic architecture of a large and massive satellite, it becomes readily apparent that the most significant elements of the satellite that are responsible for its large size/mass are usually its power and antenna systems. The first satellites launched into orbit had a power generating capacity of only a few watts. Today, there are massive communications satellites that might be generating 12–18 kW of power, and the solar array systems of the International Space Station can generate hundreds of kilowatts. High-gain antennas that are on the largest contemporary commercial satellites can be up to 22 m in diameter and weigh many hundreds of kilograms. These represent the other major driver of satellite size and mass. Indeed power and power systems are truly the principal drivers that make telecommunications spacecraft larger. Advances in electronics and optical processors, in contrast, keep shrinking the size and mass of modern spacecraft.

3.1.2 Thermal Control

A small satellite has a need for reasonable levels of thermal control so as to not overheat or overcool the electronic systems and the sensors or devices associated with the payload. Since small satellites are reasonably compact, the approach to thermal control is often based on the use of passive systems such as gold foil to reflect solar radiation to avoid overheating and enough absorptive materials to prevent the satellite from becoming too cold. Figure 2.2 above depicts the Fastrac small satellite, and this photo shows the reflective gold foil that serves to create the desired balance of solar heat reflectivity and heat absorption. It is possible that the design of reflective materials on the outside of a small satellite does not provide sufficient thermal conditioning necessary to support sensitive electronics inside the spacecraft. In the case of small satellites ranging up to 1,000 kg in mass, heat pipes to dissipate heat from the interior of the satellite may be required.

One of the effective solutions is what is called a miniaturized loop heat pipe (mini-LHP). Such a mechanism can provide an effective heat transfer function without many of the restrictions of conventional thermal control measures. Traditional techniques such as thermal straps and shunts, conventional heat pipes, mechanically pumped loops, and so on are not usually designed for small satellite use. If such techniques are used in small satellites, they could impose large mass penalties and exceed the weight budget for the mission. Such large-scale systems could also complicate system integration and create difficulties or complications with pre-launch tests – especially at the systems level. Swales Aerospace is one company that has developed a miniature multiple evaporator multiple condenser loop heat pipe that is scalable and is thus particularly optimized for use in a small satellite.[3]

NASA's New Millennium Program Space Technology 8 has developed a miniature loop heat pipe (MLHP). The complete miniaturized system has a mass of just over 300 g, or about a third of a pound. The European Space Agency (ESA), the Japanese Space Agency (JAXA), and other space programs have also devoted resources to developing miniaturized loop heat pipe systems with miniaturized

[3] Ahmed Habtour and Michael Nikitkin, "Miniature Multiple Evaporator Multiple Condenser Loop Heat Pipe"; available online at: http://digitalcommons.usu.edu/smallsat/2005/all2005/131/.

condensers as well.[4] Since the functions performed by such thermal control systems can be critical to the mission in terms of the operation of payload and spacecraft bus electronics, the objective of miniaturization must not overlook the need to achieve a high degree of reliability.

3.1.3 Ground Surveillance and Communication Characteristics

The laws of physics indicate that the aperture size used for imaging or remote sensing clearly limits the amount of electromagnetic energy that can be captured by a satellite. The image resolution obtainable by a small satellite depends on aperture size, and clearly in the case of a small satellite the antenna size cannot be very large. Larger aperture resolution can be simulated with the use of multiple, phase-matched small apertures on multiple small antennas flying in a close and fixed pattern. There are still penalties that occur in such a case. There are losses in terms of spatial frequency content of the scene and the amount of energy that can be captured (i.e., the signal-to-noise gain that is achievable for each aperture). In short there are severe limits on the amount of remote-sensing data and resolution that can be attained by a single nano sat or even a close flying constellation.

Communication antennas have comparable constraints. The tradeoff between antenna gain and effective isotropic radiated power is important. Using the nominal 10-W continuous power level estimate, a nano-sat in low Earth orbit could support a transmission rate of hardly more than one megabit per second or a few kilobits per second from geosynchronous orbit.

3.1.4 Stabilization and Pointing Systems

These two aspects of small satellite operation are not independent, and they impose different technical demands. Large satellites have high inertia, requiring larger torques to initiate motion and to sustain acceleration. Applying torques to the least massive elements of the system thread involved in re-directing bore-sights dynamically can mitigate this. Pointing components can take advantage of stable platforms whose stability is assured by the mass and inertia of the platform. Small satellites do not enjoy that advantage. Pointing and stabilization are very closely coupled. Stabilization is the most important element, since the satellite cannot be allowed to tumble. The low inertia allows high angular acceleration, which must be dampened.[5]

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[4] J. Ku, L. Ottenstein, D. Douglas, "Multi-Evaporator Minature Loop Heat Pipe", NASA Goddard http://www.ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080032843_2008031434.pdf.

[5] Samir Ahmed Rawashdeh, Passive Attitude Stabilization For Small Satellites, unpublished thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering in the College of Engineering at the University of Kentucky, 2009.

Achieving sufficient control over a small satellite is always a challenge. Active techniques, which expend energy either in terms of propulsion or electromagnetically, employ actuators such as momentum storage devices. Such techniques can achieve bore-sight stabilization on the order of very accurate milli-radians.[6] However, active techniques may be a bit too excessive for mission-oriented nano satellites. Passive methods include passive magnetic stabilization, aero-stabilization, and gravity gradient stabilization. Passive techniques can achieve stabilization but with comparatively less precision. Large satellites can, of course, do much better because of their ability to carry much more sophisticated pointing and stabilization systems.

One of the most important differences between a cube-sat or nano satellite and more capable small satellite in terms of mission capability and design is with regard to stabilization and pointing systems. A classic cube-sat, once released, cannot be controlled and remains in its release orbit until gravitational effects cause it to burn up in the atmosphere on its descent. Recently, there have been developmental efforts to create, for a 3U version of a cube-sat, the added capability of a solar array that could act as a gravity gradient boom and also to design a very low power reaction wheel that could achieve some degree of stabilization and pointing capability.[7]

Certainly a small satellite above the class of a cube-sat would typically have some means to orient itself in orbit and would thus be able to exert some degree of control as to its pointing. This capability may extend beyond a gravity gradient boom (or booms) and perhaps will have stored fuel and a thruster system to assist not only with its operation but also with active de-orbit maneuvers at the end of its life.

Perhaps the simplest means of stabilization is known as a gravity-gradient boom system that employs Earth's gravitational effect on deployed booms to generally "point" the satellite toward the ground below. This approach was employed fairly early in the development of satellite technology. The NASA Applications Test Satellite (ATS) series, and in particular, ATS 2, 4, and 5 used this stabilization technique. The medium Earth orbit ATS 2 was launched on April 6, 1967, and remained in orbit for 2 years. ATS 4 and 5 also employed this same technique of extending booms from these spinner spacecraft to achieve stabilization. There are a number of sophisticated small satellite missions that can and do use gravity gradient stabilization where exact pointing is not required. Over a period of 2 years, the Orbview 1 (once known as Matlab 1) and pictured below (See Fig. 3.4) carried out in orbit testing for NASA's lightning detector sensor as a prelude to designing such sensors for the latest NOAA satellites.

The use of gravity gradient stabilization makes a good deal of sense for small satellites since much less hardware and no fuel is required, and they are relatively easier to construct and test. For these reasons, gravity gradient stabilization is less costly – although it also less accurate than active attitude-control systems. Gravity

[6] Siegfried W. Janson, Satellite Scaling Issues, p. 796, in Small Satellites: Past Present, and Future, H Helvajia and S.W. Janson, Eds, Aerospace Corporation Press, 2009.

[7] Erich Bender, "An Analysis of Stabilizing 3U Cube-sats Using Gravity Gradient Techniques and a Low Power Reaction Wheel"; available online at: http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1035&context=aerosp&sei-redir=1&referer=http%3A%2F%2F.

Fig. 3.4 Orbview 1, small satellite with gravity gradient boom extended (Courtesy of NASA)

gradient stabilization as shown in Fig. 3.4 is the only passive attitude-control method used for satellites.

This method of stabilization relies on the highly asymmetrical satellite mass distribution. There is a change in gravitational attraction as the orbit of a satellite increases. The gravitational attraction in geosynchronous orbit, for instance, is 50 times less than it is at Earth's surface. When a satellite is equipped with a long boom, this results in a change in its gravitational attraction, since the principal axes of the satellite are no longer aligned with the orbital reference frame, and this creates a torque. Due to the asymmetric nature of the satellite, the spacecraft will experience a torque tending to align its axis of least inertia with the field direction of Earth's gravity. However, the relative values of the satellite's moment of inertia around the overall center will not only point the spacecraft toward Earth but will set up a slight oscillation. Dampers must therefore be installed on the satellite to reduce this oscillation. As one moves from the smallest to larger satellites in the hundreds of kilograms size range, most missions will transition to the use one of the active stabilization control methods indicated in Fig. 3.5 below.

The actual approach used for active stabilization control hinges on many factors, such as the pointing accuracy required for particular missions, the overall mass budget, the desired mean time to failure for the satellite in terms of its expected lifetime in orbit, as well as other factors. Currently, spin stabilization is not often used because three-axis body stabilization affords greater pointing accuracy and allows solar arrays to be constantly oriented toward the Sun to give 100 % illumination versus the 40 % illumination typically associated with spin-stabilized spacecraft.

Reaction wheels are probably the most common choice for the larger class of small satellites. This is because of proven reliability, reliance on electric power

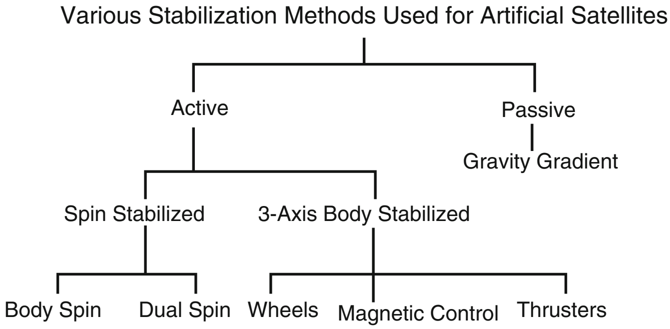

Fig. 3.5 Breakdown of various stabilization techniques for spacecraft

rather than fuel, and scalability of reaction wheels to spacecraft size. Inertia, momentum, or reaction wheels use the same principle of the kid's toy known as a top. The spinning of a wheel or more than one wheel in different planes can serve to keep a satellite oriented in a single direction. Reaction wheels for large spacecraft can spin at very high speeds of up to 5,000 revolutions per minute, but smaller reaction wheels for smaller spacecraft can spin at lower speeds and require much less electrical power to maintain these velocities.

Another issue is how does the satellite know where to point in space if there is no clear up or down? Here again, a number of options are available. One option involves the use of simple Earth, Sun, or star sensors that assist the satellite to point itself correctly. There are also now radio frequency beacons that allow more accurate pointing of satellites with a precision as accurate as 0.05°. In the case of satellites used for astronomy or for telecommunications, where spot beams must be aimed with great precision, such a high level of pointing accuracy is very important. For such missions, three-axis body-stabilized spacecraft are really the only viable option currently available.

3.1.5 Tracking, Telemetry, Command, and Monitoring

Yet another critical element of small satellite design is its tracking, telemetry, and command (TT&C) system. At least two things must be accomplished in order to operate a small satellite and derive useful data from it: (1) It must be possible to obtain accurate ranging data from the satellite in order to know where it is in orbit and to track its orbit with reasonable precision. (2) There must also be a transmission path in a suitable radio frequency band in order to obtain data from the satellite payload in a suitable downlink and, as well, to send commands and signals to the satellite so that it can start experiments, reposition itself, switch on backup units, or otherwise carry out essential functions. These tracking, telemetry, and command functions are carried out in radio frequency bands that are separate and distinct from those used by telecommunications, navigational, or radar remote-sensing satellites. Such missions will have specific radio frequency spectra assigned for their individual functions.

The antennas used to support TT&C functions are small, typically conic-shaped low-gain systems. Low-gain antennas can be used because the data rates involved are not necessarily very high. But, even more importantly, the key is to have antennas that are capable of receiving a signal from virtually any angle in case something should go wrong and the satellite should fall into a tumbling motion or a flat spin. An "omni" antenna may have low gain, but it will pick up a signal from virtually any angle.

3.2 New Technologies to Protect the Payloads on Small Satellites

The challenge of small satellites is to launch a meaningful payload to carry out a useful mission within the small power, mass and size budget that such a platform provides. Fortunately, electronics and processors have continued to shrink in mass and size over time as large-scale integration and application-specific integrated circuits (ASIC) have allowed scientists and engineers to do more with less. Constellations of satellites in low Earth orbit working as an integrated network have also allowed many useful applications for small satellites to evolve as well.

3.2.1 Higher Gain Antennas

One of the bigger challenges has been to incorporate higher gain antennas on small satellites, particularly with the advent of phased-array antennas. A phased-array antenna, phased-array antenna system, or phased-array antenna feed system can be employed in the design of the payload for a small satellite constellation. This technology can be used to electronically form spot beams that create a more efficient telecommunications satellite. One example of this approach is the Iridium satellite system (See Fig. 3.6). The payload design deployed three phased-array antenna panels that allowed a relatively small Iridium satellite to create 48 spot beam patterns on Earth below. The 106 radiating elements allowed 16 beams to be created from each of the three antenna panels for the total of 48 beams. Since the panels were flat and did not have to be deployed in a parabolic shape (as the beams were electronically simulated), the satellite could be much more compact.

On a much smaller scale, Surrey Satellite Technology, Ltd., and the Surrey Space Centre collaborated to launch the STRaND 1 smartphone satellite into space (See Fig. 3.7). This satellite was deployed within a 3U cube-sat platform. The entire "satellite" weighs only 3.5 kg and has been tracked by amateur radio operators from around the world. Miniaturization was used throughout both the bus and the payload.[8]

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[8] "Smartphone satellite "STRaND-1 Operational in Orbit" SSTL News, March 7, 2013; available online at: http://www.sstl.co.uk/News-and-Events?story=2132.

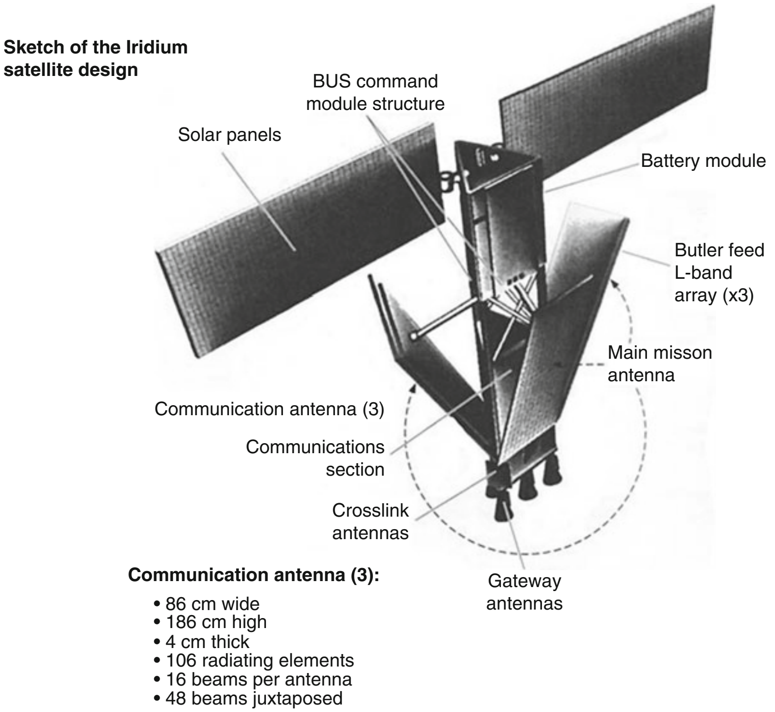

Fig. 3.6 Phased-array antennas on the Iridium satellites

In this case, cheap smartphone electronics is used to control the satellite. STRaND-1, which was built in only six months and as a training project between SSTL and SSC carries an amateur radio AC.25 packet radio downlink that operates at 437.568 MHz. It is able to transmit from its micro antenna at a bit rate of 9.6 kilobits per second using frequency shift keyed modulation and special NRZ1 encoding to maximize throughput. Information on how to receive and decode the downlink telemetry is available on the AMSAT-UK website. Here, the key to accommodating the payload's mission on a 3U cube-sat was micro-electronics and encoding technology rather than innovative antenna design.

Many payloads on small satellites are likely to involve sensors of some type. In this area microelectronics, applications-specific integrated circuits, miniaturized cameras and light and energy sensors, spectrographs, etc., can allow a compact payload to be accommodated on smaller satellite buses than was possible a decade ago. Further, many of these payloads require less power than they did a decade ago. This is generally the case of passive sensing systems for remote sensing and meteorological or Earth observation, but there is a major exception. Active sensing systems, namely radar satellites that must generate power to beam down, still require a major power source. As such, these types of "active sensing" devices require both major power supplies and thus large spacecraft. As noted earlier, improved multi-junction

Fig. 3.7 STRaND 1 Smartphone satellite designed by Surrey Satellite Technology, Ltd

solar cells, quantum dot technology, low-mass solar concentrators as well as improved and more dense battery storage such as lithium ion systems have certainly served to reduce the mass to power generating and storage ratio. Yet, these improvements can only go so far to reduce mass and size requirements. And there are always tradeoffs. A power system might be designed to generate, say, 25 % more power and store it for the same amount of mass and volume, but the cost of doing so in terms of more expensive technology might not result in the realization of significant overall gain even where reduced launch costs are taken into consideration.

3.2.2 Technical Advances to Consolidate "Small Satellite" Missions and Experiments

In general, large launchers are more efficient than smaller rockets. Similarly, larger satellites are more efficient than smaller ones. If there is one telemetry system to support twelve missions, rather than 12 telemetry systems to support 12 different small satellites, the greater efficiency of the former is clear. Consolidation of elements that constitute a satellite "bus" (whether it is solar arrays, batteries, thrusters for stabilization, thermal control systems, sensors for pointing and orientation, or tracking, telemetry, and control) almost always leads to efficiency gains. This also translates into lower labor costs for maintenance of a satellite in orbit. Thus, significant efficiency gains can be achieved by consolidating a number of small payloads that are designed for a particular mission in space. In spite of the consolidation, small independent space missions may still retain their own unique identity. One such approach is provided via NanoRacks, a company that lists the following "space firsts" on its website[9]:

- First company to own and market its own hardware on the space station
- First company to coordinate deployment of a satellite from the ISS
- First company to own and operate the External ISS Platform
- First self-paying high school space project
- First electroplating in space
- First terpenes in microgravity research
- First national space STEM program with no NASA funding (the National Center for Earth and Space Science Education that also works with the Arthur C. Clarke Foundation)
- First Vietnamese satellite in low Earth orbit (FPT University of Hanoi)
- First Israeli program on station (Fisher program)
- First Saudi program on station (KACST)
- First commercial payload on SpaceX (Multiple)
- First company to place customers on all ISS-related launch vehicles – the space shuttle, Soyuz, Progress, ATV, HTV, and SpaceX

Currently the NanoRacks Corporation advertises on its website the following services: (i) internal payloads that allow a series of experiments to fly to the ISS as "nano missions"; (ii) deployment of satellites from the ISS that range from cube satellites to larger small satellites; (iii) access to an external platform on the ISS for experiments and tests in a hostile space environment or for deep space observation; (iv) deployment opportunities from suborbital to deep space.[10]

By acting as a consolidator, NanoRacks allows a large number of tests and experiments in space to occur on a consolidated basis. Although NanoRacks is also involved in the deployment of separate cube and small satellites from the ISS and via other means, the main purpose is to be a consolidator and to minimize the number of separate missions that fly.

NanoRacks is not alone in this effort. Bigelow Aerospace is offering private companies and government agencies the commercial opportunities to fly experimental missions on its private space habitats for periods ranging from a few weeks to many months. There are also plans by JP Aerospace to create a lighter-than-air

[9] The NanoRacks Corporation; available online at: http://nanoracks.com/.

[10] Nano Racks Corporation capabilities; available online at: http://nanoracks.com/products/beyond-iss/.

Dark Sky Station that could fly experiments tens of kilometers above Earth. Other organizations, such as IOS systems, have indicated plans to fly people and experiments up on a commercial basis, and most of those commercial ventures that are planning to offer suborbital flights to passengers could also accommodate experimenters as well. One advantage of all of these various efforts is that the experiments would go up and then come back down without creating new space debris.

There are other options to provide consolidation of space missions and to reduce space debris that take an entirely different tack. One such approach that has become quite popular because it can reduce design, testing, manufacturing, deployment, and operating costs is the concept of "shared" or "hosted payloads." In 2011, a Hosted Payloads Alliance (HPA) was formed to create a mechanism for more effective communications between private enterprise and governments on possible sharing of missions and to explain more broadly the advantages of sharing payloads.

Today, large space service companies such as Intelsat, Inmarsat, SES, and Iridium have staff, and in some cases, entire offices dedicated to developing commercial arrangements with regard to hosted payloads.[11] Initially, the concept involved just one type of experiment, such as CISCO's experimental Internet Router in Space (IRIS) payload on an Intelsat satellite.

More recently, projects are being developed that involve a large number of payloads that can fly on a constellation such as on the next generation of Iridium mobile satellites (i.e., Iridium Next). In fact, one such major hosted payload project is now under contract. Iridium LLC has formed a joint venture with NAV Canada[12] to equip its next generation of mobile satellites with 50-kg packages (drawing some 50 W and up to 200 W of peak power) for an aircraft tracking capability.

Known as Aireon, this joint venture forms part of the replacement constellation for the Iridium global mobile satellite network. The Aireon system will "ride" on this new 66-satellite global airline tracking system. The stated goal is for the Aireon service to use space-qualified Automatic Dependent Surveillance-Broadcast (ADS-B) receivers to provide an unprecedented ability to track aircraft on a totally global basis. The receivers will normally operate at 100 kilobits per second but will be capable of supporting 1 megabit per second speeds if required. This joint venture will, for the first time ever, provide air navigation service providers (ANSPs) the capability to continuously to track aircraft anywhere in the world in near-real time, including over oceanic, polar, and remote regions.[13]

All of these innovative efforts that involve more efficient packaging and seek to put "small satellite" missions onto operations that can fly up and then fly down without creating orbital debris are welcome efforts. The fact that, in most cases, these consolidated space programs lead to cost savings in terms of design, testing, manufacture, launch, and ongoing operations helps to create the right incentives to pursue these consolidated and efficiently packaged space activities.

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[11] Hosted Payload Alliance; available online at: http://www.hostedpayloadsummit.com/.

[12] Nav Canada; available online at: http://www.navcanada.ca/.

[13] Online at: http://www.iridium.com/About/IridiumNEXT/HostedPayloads.aspx.

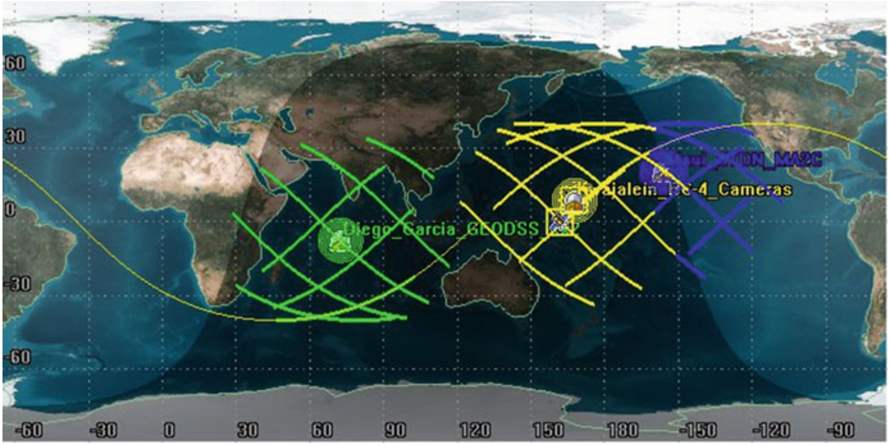

Fig. 3.8 Small satellite orbit designed for greatest observability from designated observation locations

3.2.3 Observability

If an object in orbit cannot be maneuvered, knowing where it is or might be at any point in time is critical. The first consideration is that the object must be discernible either passively by virtue of its own emissions or reflections of background radiation or through active illumination. 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.

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

Safe operation generally requires some compromise in mission capability. For our single satellite to see most of Earth over time, the inclination and apogee should be as high as reasonably possible – taking into account the location of ground observation sites. For example, if one wishes to monitor synoptic energy balance, there would only be brief opportunities for the designated sensors to gather data for orbit estimation. The bold lines in Fig. 3.8 show where the satellites would be visible to the ground observation sites.

3.2.4 Communication and Controllability

A small fraction of satellites intentionally have no communication ability. These are, for example, small satellites whose ballistic coefficients are known precisely and

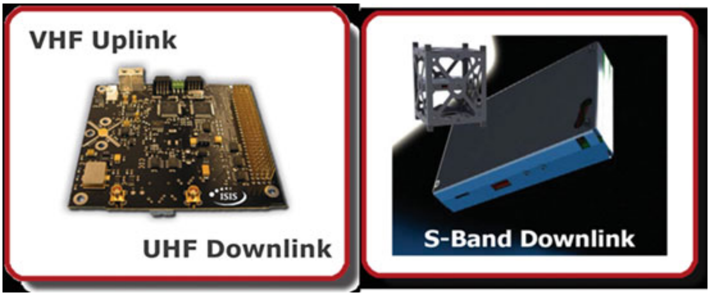

Fig. 3.9 Nano satellite communication module and antenna (Courtesy of ISIS Cube-sat Solutions)

whose surfaces are appropriately faceted and reflective to assure strong returns from passive or active illumination. They are mostly used to calibrate space surveillance sensors or to characterize atmospheric dynamics, since drag may dominate changes in their trajectories, and those changes can be attributed to changes in density.

All other small satellites must be able at the very least to downlink data, if not respond to commands from the ground. These communication links enable ranging at least and perhaps angular resolution sufficient for reasonable orbit determination. However, observations of this nature 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 can be gaps between observations that are long enough for orbits to change materially due to environmental variability as a result of intensive solar radiation or other factors (Fig. 3.9).

3.2.5 Maneuverability

The maneuverability of small satellites depends on the key variables in the rocket equation. The ability to change a satellite's velocity depends on how much propellant is available and how much of the initial mass of the satellite is propellant. Electromagnetic thrusters have specific impulses of thousands of seconds of thrust at very low levels. If 90 % of a nano satellite's mass were propellant, total delta V could be about 1 km/s. This, however, is still a small fraction of low Earth orbit velocity. An inclination change of one degree would require a few hundred meters per second of velocity change. If only 10 % of a nano sat mass were propellant, only a few modest maneuvers would consume the entire capability. Independent of overhead mass and power requirements associated with thruster maneuverability, the bottom line is that one cannot expect much collision avoidance maneuverability from a nano sat, even if it is of an eight unit size.

The limited ability of a small satellite to maneuver is still better than a totally uncontrolled object in orbit. A small satellite may also exploit aerodynamics even in the sparse atmosphere of low Earth orbit. The degree of maneuver depends on the architecture of control surfaces exposed to the environment and the physical characteristics of the environment. A comprehensive review of satellite aerodynamics is available from several sources, including the widely available Wiley *Aerospace Engineering Encyclopedia*.[14] Aerodynamic attitude or orbit control is efficient in that it relies on the upper atmosphere as an energy source, but these techniques are generally unreliable, particularly for collision avoidance purposes. It is impossible to develop avoidance maneuvers in advance with high probability because satellite trajectories cannot be estimated with actionable precision more than a few tens of hours in advance, particularly as a result of the drag-dominated low Earth orbits in which they fly.

According to the reports of the International Network of 50 Double and Triple Cube-sats,[15] aerodynamic forces in the extremely rarefied low Earth orbit regime are very difficult to estimate. Momentum transfer depends on the physical characteristics of satellite surfaces, which change as the satellite is exposed to the environment. There have been notable successes, such as the descent of Curiosity to Mars, and notable failures, such as the Beagle Mars mission.

Propulsive maneuvering capability, when and if available, is thus more suitable. Propulsion requires stored energy and mass. Cube-sat architecture and missions do not allow much mass to be allocated to stored propellants. Chemical propulsion is generally not a viable option for maneuvering. For a variety of reasons related to minimal mass and low-level but quite sustained thrust, electromagnetic propulsion is best. Stored high pressure gas or fluids that can be catalyzed to a high pressured gaseous state with adequate safety and control may also provide suitable propulsion alternatives.

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 on a collision course with other small satellites have no avoidance alternatives. 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.

3.2.6 Assessing Technology Gains Related to Small Satellite Performance

Generally ongoing technology gains continue apace in all aspects of small satellite design and development. Contemporary power systems are able to generate and store more power with less mass and volume. Phased-array antennas and deployable

[14] David Finkleman, "Atmospheric Interactions with Spacecraft", Wiley Encyclopedia of Aerospace Engineering, 2010.

[15] http://ec.europa.eu/enterprise/policies/space/files/qb50_en.pdf.

mesh antennas with phased-array multi-beam feed systems are becoming more economical and capable.

The biggest gains have come from turbo-coding technology, which allows these new and efficient encoding systems to transmit more information per bit transmitted. In general, miniaturized electronics and optics and improved processing and encoding techniques have allowed the biggest gains in small satellite technology. Since satellites today are essentially digital processing units in the sky with specialized software that defines what mission they can carry out, such progress is to be expected. In short, gains in the field of computer technology and computer science programming can generally be transferred to the field of artificial satellites. Thus, parallel gains largely come in the rapidly evolving fields of both computer systems and satellites.

There is yet another area of new technology development that is particularly relevant to the policy and regulatory issues for small satellites that also needs to be given particular attention. This is the area of technology that would allow small satellites to pose less of an issue or concern with regard to the increasingly troublesome issue of orbital debris and de-orbit of small satellites in low Earth orbits that are today becoming more and more congested.

3.3 De-orbit Capabilities for Small Satellites

Active debris removal is imperative since, even if no new space objects are launched, the number of objects already in orbit would create so much more space debris that the use of space might not be sustainable on a business as usual basis. Therefore, various technical means and de-orbiting capabilities have to be developed to support active debris removal.[16]

There are a number of ways to address the orbital debris problem as it relates to small satellites, but in a broader sense, these innovations fall into one of two categories: (i) ways to help de-orbit small satellites more efficiently; and, (ii) ways to repackage small payloads into larger and more efficient systems so that there are fewer of them going into space or, alternatively, they can be de-orbited more effectively as part of larger system.

Incentives to create separate free-flyer small satellite missions remain. This means that the problem of de-orbiting of small satellites at end-of-life remains a very real challenge.

Currently, there is great interest in the development of new technology to assist with de-orbit of these spacecraft. There are several concepts about how this might be done for small satellites and especially for nano satellites with no thrusters or active mechanism to initiate de-orbit. These include inflatable and reflective

[16] "Active Debris Removal – An Essential Mechanism for Ensuring the Safety and Sustainability of Outer Space: A Report of the International Interdisciplinary Congress on Space Debris Remediation and On-Orbit Satellite Servicing," UN Document: A/AC.105/C.1/2012/CRP.16 of 27 January 2012.

balloon-like membranes,[17] inflatable tube structures with thin membranes (known as ITMs),[18] solar sail systems, and tether systems. The idea is that all of these low-mass systems could be either inflated or deployed at the end of life of a small satellite to accelerate its descent from low Earth orbit back to the ground. Many of these de-orbit systems are student projects at research universities. However, NASA's Fastrac Satellite included a 4.0-kg experiment called the NANO-SAIL-D2 that was designed to be deployed from the FASTRAC satellite pictured earlier. When fully deployed, this thin membrane extends up to 100 square feet, or about 9 square meters. Since this solar sail was itself a 3U nano satellite it is clear that such a solar sail to assist with de-orbit could be deployed only for bigger small satellites. This experiment was not a total success in that it was planned to deploy the NANO-SAIL D2 2 weeks after the launch of the FASTRAC satellite on December 3, 2010, but deployment was not achieved as scheduled. Then, for reasons that have not been entirely explained, the NANO-SAIL D2 self-deployed some 6 weeks later on January 17, 2011.[19] In addition, there are planned experiments with tether systems that could aid small satellite de-orbit.

The design of systems that could allow effective and low cost de-orbit of small satellites remains a well-focused area of research. And passive systems to accelerate de-orbit are not only being developed but will likely soon be offered on a commercial basis. Not all de-orbit systems for small and nano-satellites today are entirely based on passive systems. The Surrey Satellite Technology, Ltd., group has developed a micro-thruster system which they are now testing after their successful launch of their latest nanosatellite in February 2013. SSTL and SSC have several upcoming nano- and micro-satellites that will demonstrate the use of deployable sails first to reduce orbital lifetime by increasing drag, and then later to demonstrate the active capture of space debris and de-orbiting by the use of a drag sail.

The STRaND-1 3 U Cube-sat, also shown earlier in Fig. 3.7 above, contains an active micro-thruster system to assist with de-orbit. The active de-orbit system flying on this remarkable nano-satellite is about the size of a loaf of bread and was designed and built by volunteers in a span of only about 3 months. In an apparent reference to the "Star Trek" sci-fi series, this active de-orbit mechanism is called WARP DRIVE. In this instance, however, the name stands for Water Alcohol Resisto-jet Propulsion Deorbit Re-entry Velocity Experiment, and it consists of eight micro-pulse plasma thrusters.[20]

[17] C. Lucking, A Passive High Altitude Deorbiting Strategy Advanced Space Concepts Laboratory, University of Strathclyde; available online at: https://pure.strath.ac.uk/portal/files/5443747/Heiligers_J_Colombo_C_McInnes_CR_Pure_A_passive_high_altitude_deorbiting_strategy_08_Aug_2011.pdf.

[18] Y. Miyazaki et al., "A Deployable Membrane Structure for De-Orbiting a Nano-satellites IAC-07-B4.5.08 (2007); available online at: http://www.iafastro.net/iac/archive/browse/IAC-07/B4/5/7019/.

[19] NASA to Attempt Historic Solar Sail Deployment; available online at: http://science.nasa.gov/science-news/science-at-nasa/2008/26jun_nanosaild/.

[20] WARP DRIVE to be tested on Surrey Space Technology Ltd. STRaND-1 nano-satellite; available online at: http://www.sstl.co.uk/Missions/STRaND-1--Launched-2013/STRaND-1/STRaND-1-FAQs.

Fig. 3.10 Artist representation of "Kickstarter" Plasma Thruster with cube-sat (Courtesy of NASA)

Researchers at the University of Michigan's Aerospace Engineering department are currently working in collaboration with several NASA research centers and private industry as part of what is known as the Kickstarter campaign (Fig. 3.10). This initiative is seeking to develop the Cube-sat Ambipolar Thruster (CAT), a new type of plasma propulsion system. It is hoped that this plasma thruster system would be able to propel cube-sats at low thrust levels in gradually increasing spiral orbits so that they would be able to escape Earth's gravity and go into deep space. Researchers are claiming that they can accomplish this at very low cost.

On one hand, such a system could help remove debris from low Earth orbit. However, long-term spiral orbit deployment from low Earth orbit to deep space could create a risk of collision with orbital debris during the orbit-raising exercise. Thus, a careful risk assessment of this approach is clearly needed.[21]

Clearly, the design and deployment of satellites, including small satellites, involves a great deal of technology and operational expertise. Yet, this is only half of the process. In the next few chapters, key concepts relating to the deployment of satellites in terms of legal, regulatory, licensing, registration, and frequency management issues and processes will be presented. This will be followed by a discussion of the problem of orbital debris, especially in the context of small satellites and then the regulatory processes that have sought to address this issue as well as the responsibility and liability provisions that apply to space objects, especially small satellites.

[21] University of Michigan Kickstarter Campaign to develop Plasma Thruster for Cube-sat Missions; available online at: http://www.kickstarter.com/projects/597141632/cat-a-thruster-for-interplanetary-cube-sats.