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Innovative New Uses of Smallsats for Networking and Telecom

Introduction

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

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

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Historical Background

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

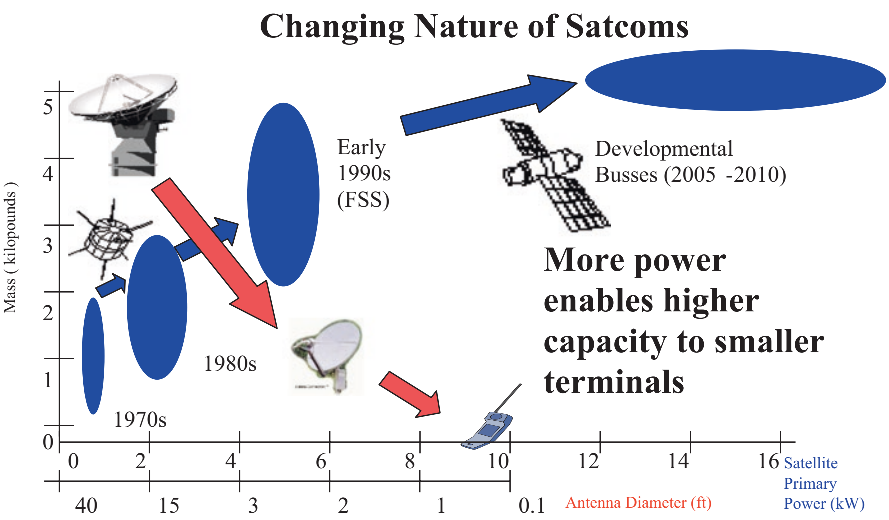

Fig. 4.1 The technology inversion of satellite communications, with satellites going up in size and performance as ground antennas have shrunk in size and cost

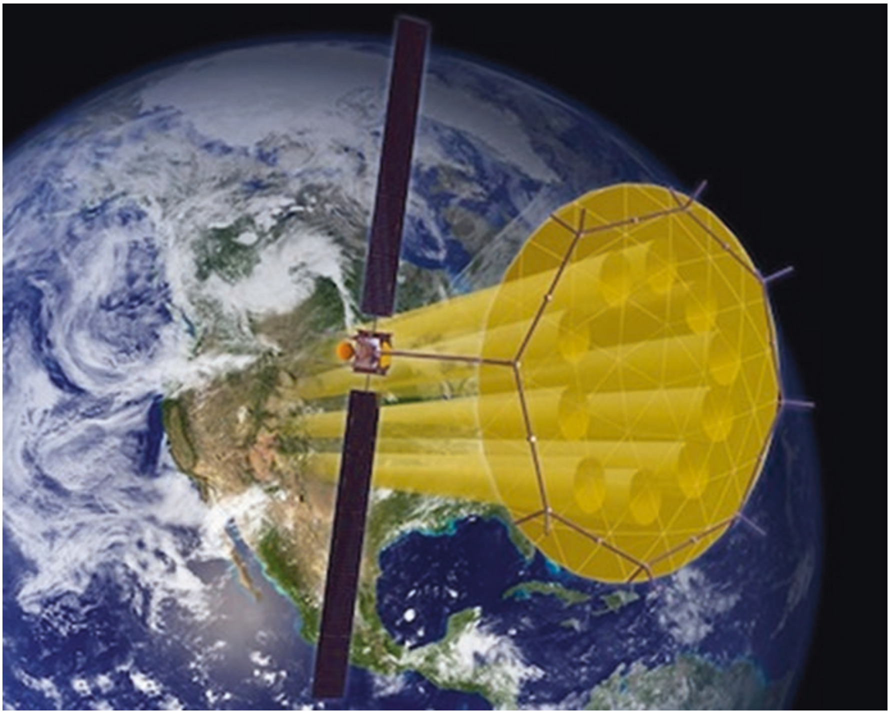

Fig. 4.2 The SkyTerra satellite depicted in operation using a gigantic multi-beam antenna (Graphic courtesy of the Harris Corporation)

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

The Start of the Small Satellite Movement

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

The First Small Satellites for Communications

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

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

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

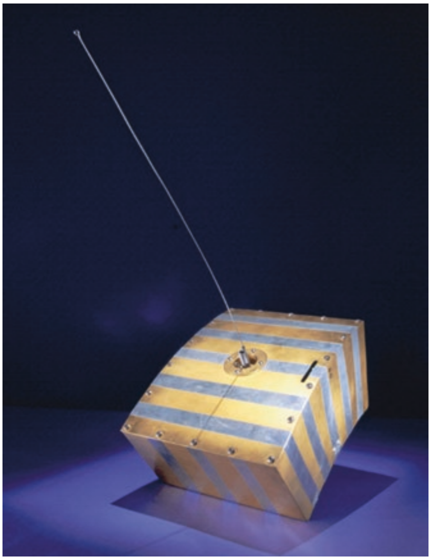

Fig. 4.3 The Amsat engineers designed and built Oscar-1 – the first smallsat for radio communications. (Image courtesy of AMSAT)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The Small Satellite Revolution and Communications Services

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

Constellations in Low Earth Orbit

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

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

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

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

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

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

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

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

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

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

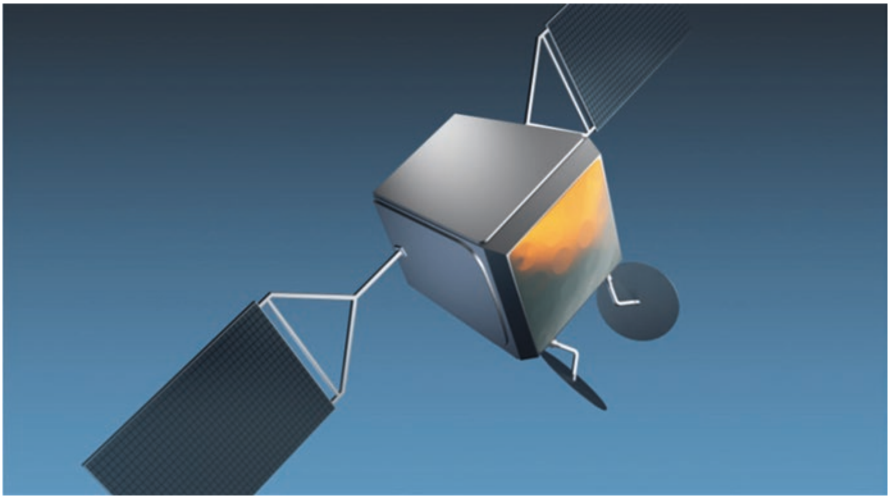

Fig. 4.5 Mock up of OneWeb satellite planned for mass production by Airbus DS. (Graphic courtesy of Airbus DS)

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

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

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

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

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

New Ground Antenna Technology

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

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

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

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

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

New Manufacturing Techniques

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

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

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

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

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

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

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

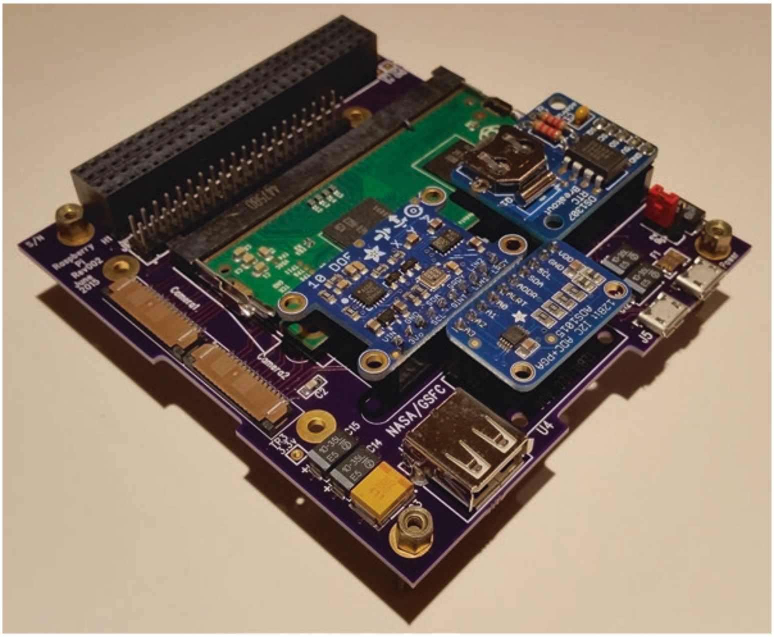

Fig. 4.7 Motherboard for the nanosat 3-unit cubesat that was recently deployed in low Earth orbit. (Graphic courtesy of NASA)

Issues Still Pending with Regard to Small Satellites for Communications Purposes

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

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

Orbital Space Debris

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

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

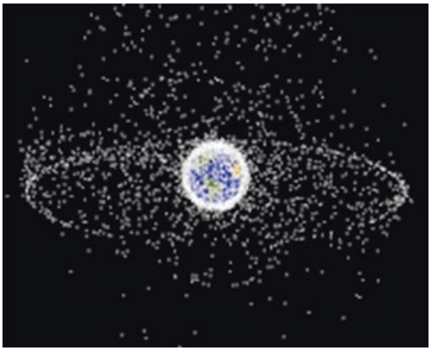

Fig. 4.8 Earth is surrounded by space junk, with the outer circle being GEO debris and the white inner sphere representing LEO debris. (Graphic of courtesy of NASA)

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

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

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

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

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

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

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

Conclusions

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

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

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

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

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

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

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