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25 Years of Small Satellites

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ABSTRACT

Twenty-five years ago in 1986, 25 microsatellites were launched into orbit; 24 were military communications satellites lofted by the former Soviet Union as part of a communications constellation. No active nanosatellites or picosatellites were launched that year. Last year (2010), 4 microsatellites, 15 nanosatellites, and 3 picosatellites were launched. Small spacecraft have gotten smaller, and they are being used for more than just communications. Advances in micro/nanoelectronics, microelectromechanical systems, solar cell technologies, global positioning systems, and the Internet have allowed small groups of individuals to design, build, and fly ever-smaller satellites with ever-increasing capabilities. In parallel, small satellite containment and deployment systems like the P-POD for CubeSats have been developed to minimize potential negative impacts on the host launch vehicle and primary payload, thus increasing the number of available launch opportunities. This work discusses small satellite launch trends, technology trends, satellite trends, and small satellite missions.

1.0 SMALL SATELLITES 25 YEARS AGO (1986)

Like most years, 1986 had its ups and downs. Major space-related events included Voyager 2 making its first encounter with Uranus, the painful loss of seven astronauts onboard the U.S. Space Shuttle Challenger, Halley's comet reaching perihelion, and the former Soviet Union launching the Mir space station. For small satellite enthusiasts, 1986 saw the launch of 25 microsatellites (10 to 100-kg mass), no nanosatellites (1 to 10-kg mass), and no picosatellites (0.1 to 1-kg mass). More importantly, these terms didn't even exist; 200-kg and lighter spacecraft were called small satellites or lightsats.

Twenty four of the 25 microsatellites launched in 1986 were 61-kg mass Strela-1M spacecraft built and flown by the former Soviet Union. Strela (Russian for "arrow") spacecraft were designed to provide medium-range, record-and-forward communications using low Earth orbit (LEO).[1] Starting in 1970, operational Strela-1M spacecraft were launched on Kosmos-3M boosters, eight at a time, into ~1500-km altitude orbits at 74^{o} inclination about twice a year. They had an expected operational lifetime of about two years (GEO communications satellites now have 7-to-15 year expected lifetimes) and had to be replaced on that same time scale; 360 Strela-1M spacecraft were launched between 1970 and 1993. About 30 operational satellites, at any given time, gave fairly complete Earth coverage using randomly distributed satellites within individual orbital planes. The Strela-1M satellites were preceded by Strela-1 experimental microsatellites launched during 1964 and 1965, and later replaced by heavier, non-microsatellite class, Strela-2M and Strela-3M communications satellites.

The remaining microsatellite launched in 1986 was the 50-kg mass Fuji-Oscar 12 amateur radio satellite. It was the 12th Orbiting Satellite Carrying Amateur Radio (Oscar) and was put into a 1497 x 1479-km, 50^{o} inclination orbit by a Japanese H-1 launch vehicle.[2] It operated over three years and stopped due to premature battery failure.

2.0 HISTORICAL TRENDS

Figure 1 shows yearly launch rates for microsatellites, nanosatellites, and picosatellites from 1955 through 2010. The upper chart shows microsatellite launches and is color-coded to indicate Strela-1 and -1M launch rates separately from other microsatellites. This chart shows an initial growth spurt lasting about 10 years, followed by a ~10-year decline in non-Strela microsatellite launches. A marked dearth of non-Strela microsatellites occurs from roughly 1977 through 1987; the "Small Satellite Doldrums."

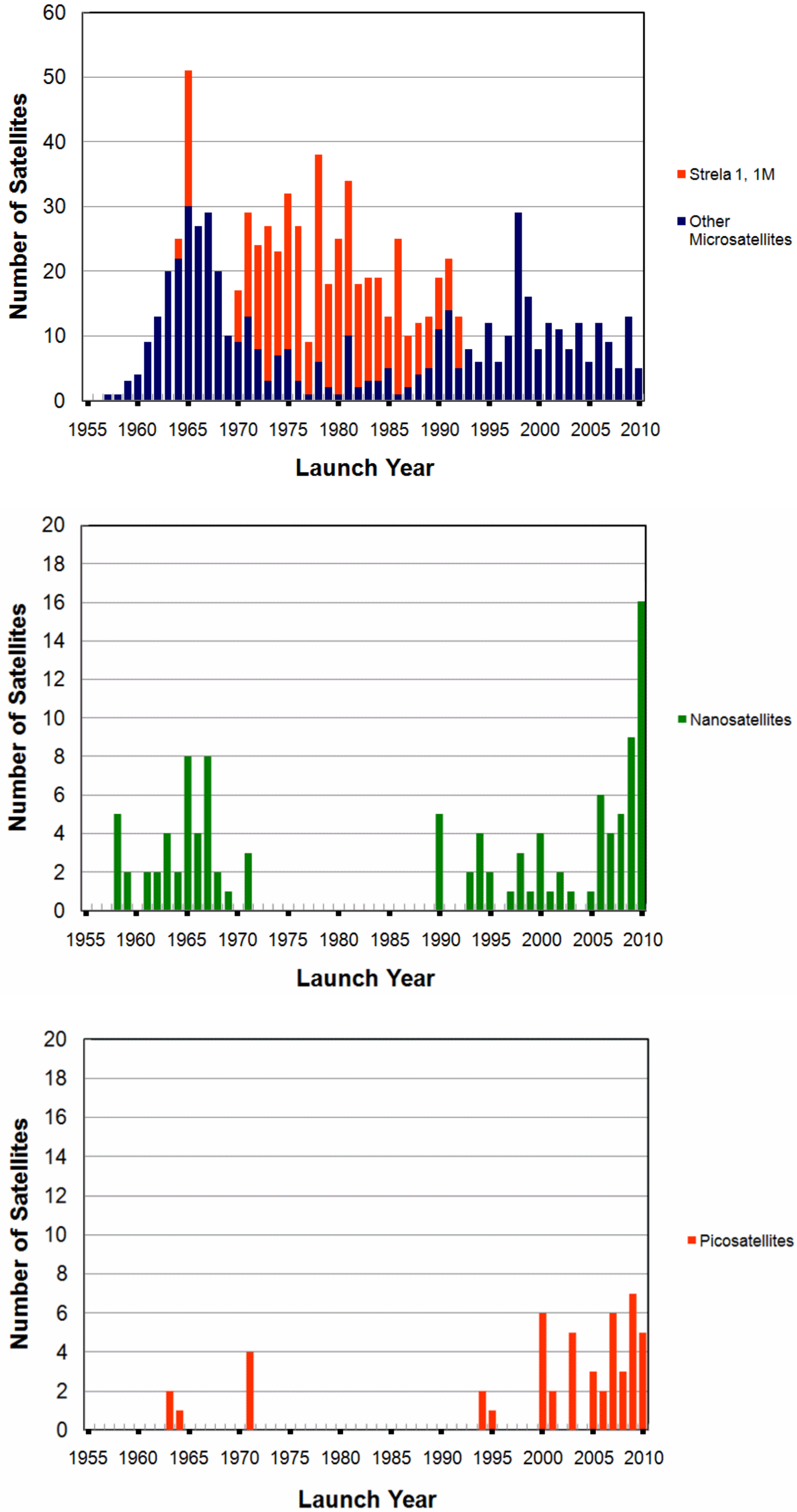

Figure 1. Launch History of Microsatellites, Nanosatellites, and Picosatellites.

The middle chart in Figure 1 shows yearly launch rates for nanosatellites. This chart excludes about 600 Romb subsatellites that were deployed by the former Soviet Union, and later Russia, between 1976 and 1995 from Taifun-2 and Taifun-3 spacecraft.[3] Cosmos 965, for example, was a Taifun-2 satellite with a total mass of 550-kg that deployed 25 Romb radar calibration subsatellites. Although specific data on the deployed Romb subsatellites are hard to obtain, they were most likely nanosatellites based on the initial Taifun-2 spacecraft mass and number of Romb spacecraft deployed. The Romb subsatellites are not included in Fig. 1 because of uncertainty in their mass, the high average launch rate of these spacecraft (about 32 a year over 19 years of launches) that totally eclipsed other nanosatellite launch rates, and their lack of traditional spacecraft subsystems like power conditioning, communications, etc.

The bottom chart in Figure 1 shows yearly launch rates for picosatellites. At the start of 2000, only 10 picosatellites had been launched, and 7 of these were passive, inert satellites for measurement of atmospheric density or radar calibration. These passive picosatellites were launched in 1971, 1994, and 1995. No active picosatellites were launched from 1965 through 1999; over three decades of non-activity.

A large number of small satellites were launched throughout the 1960's to obtain space environment data, flight test various technologies, and provide operational communications. Satellites grew heavier over time as satellite expectation levels, and launch vehicle payload capacity to low Earth orbit, increased. Microsatellites, nanosatellites, and picosatellites were essentially replaced by heaver, much more capable, spacecraft over time. This trend resulted in the "Small Satellite Doldrums." Technology and economics ultimately reversed that trend starting in 1987.

It is interesting that the "Small Satellite Doldrums" did not seem to impact experimental and educational spacecraft launched by the Radio Amateur Satellite Corporation (AMSAT). AMSAT members did not want, or could not afford, communications capabilities provided by large satellites. They made do with small satellites typically in the microsatellite mass range. By 1978, AMSAT had launched 7 educational and amateur radio satellites (OSCAR 1 to OSCAR 7) with masses ranging from 4.5 to 29-kg.[4] By 1987, they launched 5 more satellites with masses ranging from 50 to 91-kg. Two of these spacecraft, OSCAR-9 (also called UoSAT 1) and OSCAR-11 (also known as UoSAT 2), were built by the Centre for Satellite Engineering Research (CSER) at the University of Surrey, in the U.K. They were part of a program to develop low-cost sophisticated satellites to promote space science and engineering in education. These box-shaped spacecraft used several different microprocessors to perform command and control, digital communications, power system control, etc. The term "microsatellite" seemed appropriate for these microelectronics-enabled small spacecraft, and CSER at the University of Surrey can be credited with creating the terms "microsatellite" and "nanosatellite" in 1990.[5]

2.1 Small Satellites Return: 1987 to 1999

"The Small Satellite Doldrums" ended in 1987. Interestingly, two new, pivotal, small satellite conferences were held that year. The first one was sponsored by the American Institute of Aeronautics and Astronautics (AIAA) and the Defense Advanced Research Agency (DARPA). This Meeting on Lightweight Satellite Systems occurred August 4-6 at the Naval Postgraduate School in Monterey, California (USA).[6] DARPA was investing in small satellites called LIGHTSATS, plus associated launchers and ground-based equipment, with a proposed 5-year, billion-dollar effort starting in 1987.[7] This first LIGHTSAT meeting had 47 presentations by military, civil (e.g., NASA), and commercial, experts. Universities were associated with only 3 presentations.

DARPA continued with its LIGHTSAT program and launched two 66-kg mass Multiple Access Communications satellites (MACSATs) in 1990, and seven 22-kg mass "MICROSATS" in 1991.[8,9] The MICROSATS had microprocessor-controlled digital communications payloads. In addition, The U.S. Navy launched the 68-kg mass Small Experimental Communications Satellite (SECS) in April of 1990, and the U.S. Air Force launched the 95-kg Radar Calibration (RADCAL) microsatellite in June, 1993. U.S. military microsatellites were returning to operational use.

The second small satellite conference in 1987 had somewhat larger academic participation. The first annual USU Conference on Small Satellites was held 24 years ago on October 7-9, in Logan, Utah. Technical papers were presented by experts from AMSAT, NASA-Goddard Space Flight Center, the U.S. Army, the Swedish Space Corporation, Globesat, The Johns Hopkins University Applied Physics Laboratory, Boeing, Hercules Aerospace Company, Weber State College, Morton Thiokol, L'Garde, The University of Surrey, Intraspace Corporation, Ball Aerospace, the University of Colorado, the Naval Postgraduate School, Utah State University, the U.S. Air Force, Expanding Horizons Safety Consulting Services, and NASA-Ames Research Center.[10] AMSAT provided several papers,

and would continue to play an important role in small satellite development.

On Jan. 21, 1990, an Ariane-4 put the French SPOT-2 Earth resources satellite into orbit, along with three 9-kg mass AMSAT "MicroSats" (Pacsat, Dove, and Lusat), a 12-kg modified AMSAT MicroSat called Webersat, and two University of Surrey microsatellites (UoSAT-OSCAR 14 and UoSAT-OSCAR 15). This was the first flight of the Ariane Structure for Auxiliary Payload (ASAP) ring that could hold up to six small satellites with a maximum mass of 50-kg each and maximum dimensions of 35 x 35 x 60-cm. The maximum mass that could be put onto the ASAP was 200-kg, and the cost was about $1 million USD.[11] Microsatellites and nanosatellites now had a standard, commercial, low-cost launch service that could put 6 satellites at a time into orbit.

The AMSAT MicroSats (actually nanosatellites by today's standards) were 23-cm cubes covered with solar cells with a maximum output power of 15.7 W. [12] The energy storage system used eight, 6-Ah commercial aviation grade NiCad batteries. AMSAT MicroSats used NEC V-40 microprocessors, had up to 10 Mbytes of solid state memory, and used a 15-cm long local area network to link the 5 electronics trays together. They were basically personal computers with some "unusual" peripherals (radio modems, digital cameras, magnetometers, optical spectrometers, etc.). Several digital satellites with a mass of less than 10-kg were now flight-proven.

The 1990's also saw the establishment of large LEO commercial communications constellations like Iridium and ORBCOMM. The ORBCOMM system was based on microsatellites and required the launch of 34 spacecraft between 1995 and 2000 into different orbital planes. DARPA had Orbital Sciences develop the revolutionary air-launched Pegasus booster to put small satellites into orbit, e.g., the seven 22-kg DARPA "MicroSats" in 1991, and ORBCOMM used this booster to place their spacecraft, six at a time, into orbit. The original ORBCOMM satellites are currently being replaced by heavier (142-kg mass) "OG2" versions.

A major event for small satellite builders around the world occurred in 1991 when the former Soviet Union collapsed. Russia adapted to free market economics, and converted intercontinental ballistic missiles (ICBMs) became available to the world-wide community as low-cost launch vehicles. TUBSAT-N (8.5-kg mass) and TUBSAT-N1 (3-kg mass), launched in July 1998 from a Russian submarine, were early beneficiaries of the post Cold War meltdown.

2.2 Small and Smaller: 2000 to 2010

On January 27, 2000, an Orbital Sciences Minotaur rocket put JAWSAT into orbit. JAWSAT released the 22-kg Optical Calibration Sphere Experiment (OCSE; a 3.5-m diameter balloon), the 52-kg Falconsat-1 from the U.S. Air Force Academy, the 5-kg ASUsat-1, and the 25-kg mass OPAL. OPAL subsequently ejected three picosatellites from Santa Clara University (the 0.2-kg Jak, the 0.5-kg Thelma, and the 0.5-kg Louise), a 0.23-kg amateur radio picosatellite called Stensat, and two 0.3-kg DARPA/The Aerospace Corporation PicoSats.[13] Jak, Stensat, and the two PicoSats were 1" x 3" x 4" (25-mm x 75-mm x 100-mm) in size while Thelma and Louise were 1" x 3" x 8" (25-mm x 75-mm x 200-mm) in size. Two more DARPA/The Aerospace Corporation PicoSats rode into orbit on the second Minotaur launch on July 19, 2000 inside the 120-kg MightySat-II.1 spacecraft built by the Air Force Research Laboratories, and ejected in August 2000.[14] More picosatellites had been orbited in the year 2000 than in any previous year.

An important nanosatellite milestone was achieved in June 2000 when the 6.5-kg mass SNAP-1 was launched along with the 50-kg mass Tsinghua-1 microsatellite that was to serve as a target platform for a satellite inspection mission. SNAP-1 was the first nanosatellite to demonstrate 3-axis attitude control, orbital maneuvering, nearby spacecraft imaging, and on-orbit GPS position and velocity determination.[15]

The success of OPAL eventually led to the establishment of the CubeSat program by Stanford and the California Polytechnic State University – San Luis Obispo that will probably put a hundred nano/picosatellites into orbit over the next decade.[16] All of the picosatellites launched since 2003 (see Fig. 1), except for the DCAM-1 and DCAM-2 subsatellites released by the 315-kg mass Japanese IKAROS interplanetary solar sail in May 2010, have been CubeSats.[17] A CubeSat is basically a 10-cm cubic spacecraft with mass of ~1.0-kg; this was initially set at less than 1.0-kg, but now can range up to 1.33-kg.[18] Establishment of specific CubeSat dimensional, mass, and electrical standards allowed fabrication and flight qualification of a picosatellite containment and ejection system called the P-POD (Poly Picosatellite Orbital Deployer).[19] A P-POD holds 3 CubeSats, a double length CubeSat plus a standard CubeSat, two "one-and-a-half" CubeSats, or a triple length CubeSat. An example of a triple-CubeSat ejected by a P-POD was the NASA Genesat-1 that was launched by a Minotaur launch vehicle in December 2006.[20]

The P-POD minimizes potential interactions with the primary payload(s) on a launch vehicle by physically

enclosing the CubeSats and requiring that they be launched in a dormant "off" state. The Aerospace Corporation developed the A-POD (The Aerospace Corporation Picosatellite Orbital Deployer) 4410 with a 10-cm x 10-cm x 25-cm internal volume, and the A-POD 5510 with a 12.5-cm x 12.5-cm x 25-cm internal volume, that were flight-qualified for use on the U.S. Space Shuttle. Other "POD" variants include the University of Tokyo T-POD (Tokyo Picosatellite Orbital Deployer) that ejects a single CubeSat, the University of Toronto X-POD for a single CubeSat, and X-POD-II for three CubeSats.

Small microsatellites of ~12-kg mass, or "almost nanosatellites", are now beginning to populate LEO. A recent store-and-forward communication system called AprizeSat, formerly called LatinSat, currently has four 11.4-kg mass spacecraft in LEO.[21] These passively-stabilized, inexpensive, 20-cm cubic spacecraft provide store-and-forward communications to small ground terminals. A similar system from Saudi Arabia, called SaudiComSat, now has seven, 12-kg mass, store-and-forward spacecraft on orbit. Five of these satellites were launched on April 17, 2007 on a Russian DNEPR Rocket (a converted ICBM) that placed 16 small satellites into LEO.

Through 1985, a total of 585 microsatellites, 312 of which were Strela-1 or 1-M communications satellites, 43 nanosatellites, and 7 picosatellites were put into orbit. Over the last 25 years, 302 microsatellites, 72 of which were Strela-1 or 1-M communications satellites, 67 nanosatellites, and 42 picosatellites were launched. The last five years have seen continuous yearly launches of picosatellites, and an increasing number of nanosatellites. Last year, more than twice as many nanosatellites were launched as microsatellites. On average, small satellites are getting smaller.

3.0 TECHNOLOGY TRENDS

A number of component technologies have given small satellites significantly enhanced capabilities during the past 25 years, and enabled the evolution of nanosatellies and picosatellites. These technologies include micro/nanoelectronics, microelectromechanical systems, triple-junction solar cells, and lithium-ion batteries. System and system-of-systems level technologies such as modeling software, the Global Positioning System (GPS), and the Internet have further impacted small satellite mission, spacecraft, and ground systems design, fabrication, and use.

3.1 Micro/nanoelectronics

The continuing evolution of micro/nanoelectronics has given us unprecedented computing power in a small package. How much silicon area is required for a ~ 1 MIPS (million instructions per second) microprocessor suitable for basic small satellite command and control functions? This level of computational power was provided by the Intel 80286 microprocessor that first appeared in 1982. Figure 2 shows the past, present, and future size of this processor based on historical and International Technology Roadmap for Semiconductors (ITRS) predictions for future performance.[22] In 1986, this processor required 25 square millimeters of silicon die area. Today, only 0.05 square millimeters are required; a 500 x reduction in area. Some of today's microprocessor dice are so small that you can barely see them with your naked eye.

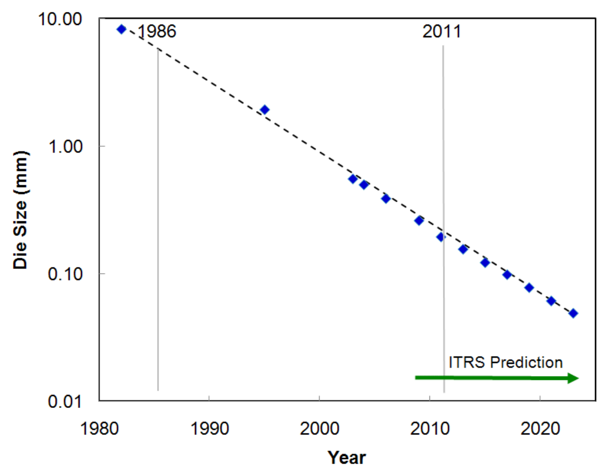

Figure 2. Die Size for an Intel 80286-Class Microprocessor as a Function of Time.

In 1986, most sensors had analog outputs that were read by the flight computer, or by a dedicated analog-to-digital (A/D) converter. Today, these functions are typically accomplished by a tiny microcomputer embedded in the sensor packaging to produce a "smart" sensor. Figure 3 shows a photograph of the MLX90615 infrared thermometer manufactured by Melexis.[23] These are typically used to control automobile heaters and air conditioners, and as medical thermometers to quickly read body temperature. We use these and similar sensors on our small satellites to indicate the presence of the warm Earth within their field-of-view. This particular sensor contains an infrared window, a thermopile detector, and an application-specific integrated circuit (ASIC) in a 5-mm diameter TO-46 transistor can. The ASIC is essentially a microprocessor with a 16-bit analog-to-digital converter. It holds the factory calibration settings, sensor address information for parallel connection of sensors on a 2-wire digital bus, and provides programmable digital signal processing to yield object temperature in degrees Kelvin.

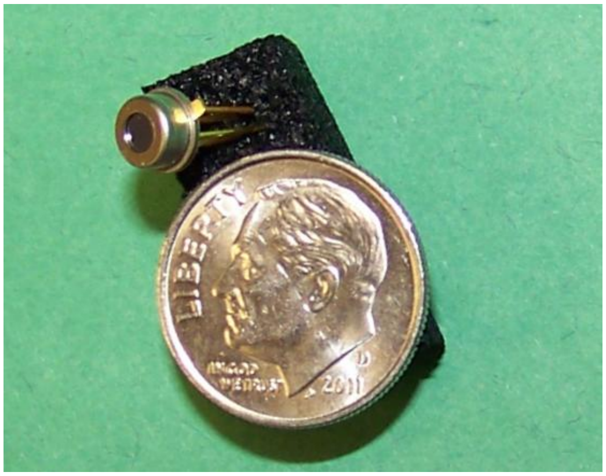

Figure 3. Photograph of a "Smart" Infrared Temperature Sensor Next to a U.S. Dime.

In 1986, small satellites typically had a single flight processor and one or two additional processors for backup and payload operation. Today, we can fit tens, and potentially hundreds of processors in a picosatellite; we used 24 individual processors, excluding an additional 10 embedded in commercial, off-the-shelf (COTS) sensors, in our most recent nanosatellite.

Processor efficiency can become important on a small, power-limited satellite when multiple active processors are used. Low-power microprocessors and microcontrollers are now available with processing performance on the order of 3000 MIPS/W. The Microchip PIC10F222 requires less than 350 μW (175 μA at 2 Volts) when operating at 4 MHz (1 MIPS). While the computational power efficiency is high at 2800 MIPS/W, this microcontroller has only 768 bytes of program memory. It's suitable for simple tasks like timing functions and converting analog sensor outputs into digital outputs. Other examples of ultra low power processors include NEC's VR4131 microprocessor (340 MIPS @ 220 mW; 1545 MIPS/W) and the Atmel AT91R40807 processor used on the CanX-1 (University of Toronto) CubeSat (~1.4 mW/MHz and 36 MIPS @ 40 MHz; 643 MIPS/W).[24,25,26,27]

On-board data storage has also grown by several orders-of-magnitude since 1986. Back then, 1 to 10 megabytes of random access memory storage was typical for small satellites. If power was turned off, the data would be lost. Today, we have non-volatile flash memory that can store 16 gigabytes in a micro-SD package the size of a fingernail. Even picosatellites can store hundreds of gigabytes of data that remain intact after power loss. The problem is what to do with these large amounts of data since it would take over 35 hours to transmit 16 gigabytes of information using a 1-megabit/second downlink. Small satellites still need order-of-magnitude faster downlinks.

A "picture is worth a thousand words," but in the satellite world, a picture can require ten thousand to 10 million words of data storage. Back in 1986, charge coupled device imagers for small satellites typically had less than 500,000 pixels. The technology used to manufacture mass-produced integrated circuits (complementary metal oxide semiconductor or CMOS) was applied over the last 25 years to create inexpensive multi-megapixel cameras that are now used on small satellites. 10-megapixel COTS imagers are readily available, with optional high-definition video capability. Fortunately, the last 25 years has brought image and video compression techniques that enabled a 10x-to-100x reduction in required data storage with little loss in image quality. This has partially compensated for the downlink bottleneck.

3.2 Microelectromechanical Systems

MicroElectroMechanical Systems (MEMS) use modified semiconductor processing techniques to produce micron- to millimeter-scale sensors and actuators. MEMS enabled the inexpensive infrared thermometer shown in Fig. 3, and chip-scale accelerometers and rate gyros for small satellites. Rate gyros are particularly useful for small satellites with limited attitude reference sensors. Optical sensors such as sun sensors and Earth horizon sensors can provide ~1^{o} or better angular accuracy, but at least two different sensors are required to provide complete 3-axis orientation data. Simultaneous data from both sensors typically won't be available over part of the orbit due to eclipse and sensor placement on the satellite. Magnetometers can provide some or all of the missing orientation information, but these are subject to larger angular errors, especially in picosatellites with ferrous components like steel battery cases. A rate gyro with low random angular walk and low in-run rate bias error can be used to provide "gap-filler" satellite orientation between optical attitude fixes.

Typical MEMS rate gyros can provide angular accuracies of up to 5 degrees over 5 minutes, but recent high-performance rate gyros can supply this level of pointing accuracy for 60 minutes or more. One example is the VTI Technologies SCC1300D02 MEMS rate gyro.[28] Table 1 gives specified performance data while Figure 4 shows inertial angle data calculated from a 10-Hz unfiltered rate output from a laboratory test of this device. With proper bias level calibration and filtering, this rate gyro could be used to provide 3^{o} or better pointing accuracy during a 40-minute eclipse.

Table 1. Performance data for the VTI Technologies SCC1300-D02 rate gyro.

Range:	+/- 100°/s
Sensitivity:	0.00512 °/s/LSB
In-Run Bias Stability (3-σ):	<0.000278°/s
Angular Random Walk (3-σ):	0.45°/(hr)$^{1/2}$
Bias Temperature Coefficient:	<+/- 0.004°/s/°C

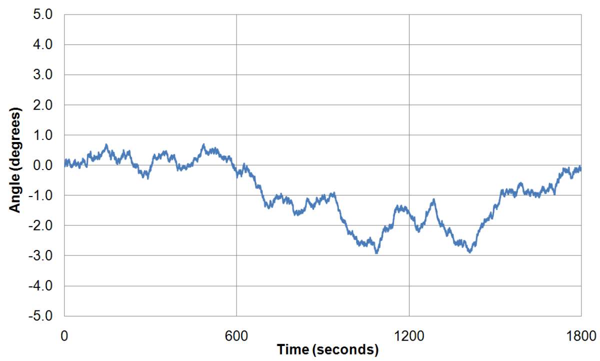

Figure 4. Inertial angular determination data obtained over 30-minutes using a stationary VTI Technologies SCC1300D02 MEMS rate gyro.

3.3 Solar Cells

Solar cells have also come a long way since 1986. Back then, you could choose silicon or gallium-arsenide cells with AM0 (atmospheric mass zero; e.g., in space) BOL (beginning of life) sunlight to DC conversion efficiencies of about 12% to 18%. Today, you can buy triple-junction solar cells with sunlight to DC conversion efficiency in excess of 27%; a 50% to 125% improvement.

Solar cells no longer have to be wired in series to provide usable spacecraft voltages. Silicon cells produce ~0.5-V, gallium arsenide cells produce ~0.9-V, and triple-junction cells produce about 2.4-V. A single triple-junction cell provides enough voltage to directly drive many modern microprocessors and voltage converters. A standard 7-cm x 3.6-cm triple-junction cell produces about 1-Watt with normal solar incidence, and many "1U" CubeSats employ only one or two triple junction cells per 4" square face. Figure 5 shows the vast difference in solar cell configuration between the tetrahedral ERS-12, similar to ERS-11 launched in 1963, and the cubic AeroCube-3, launched in 2009. ERS-12 is 15-cm on a side with 64 silicon cells per side while AeroCube-3 is 10-cm on a side with 1 or 2 triple junction cells per side. The ERS-12 cells are 1-cm by 2-cm in size and produce a maximum power of 1.5-W per side. The AeroCube cells produce a maximum of 1-W or 2-W, depending on which side is normal to the sun, with a far simpler wiring harness.

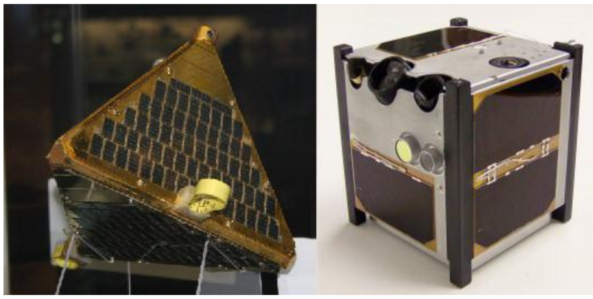

Figure 5. Photographs of ERS-12 (similar to ERS-11) and AeroCube-3 Illustrating the Evolution of Solar Arrays for Very Small Satellites.

3.4 The Global Positioning System

GPS receivers provide time, position, and velocity data to spacecraft. In 1986, only experimental GPS satellites were on orbit and no civilian receivers existed. Today, we have a full operational constellation with civilian access to high-accuracy data. A number of GPS receivers capable of operating at orbital altitudes and velocities are available to the small satellite builder. Examples include the SGR-05U by Surrey Satellite Technology Ltd. and the GPS-12-V1 by SpaceQuest Ltd.[29,30] GPS enables autonomous updating of spacecraft time, and autonomous position determination for cueing sensors, receivers, and/or transmitters.

Advanced GPS receivers also enable determination of line-integrated electron density between the spacecraft and a particular GPS satellite. This is the basis for GPS radio occultation tomography; as a GPS satellite sets behind a LEO satellite, line-integrated electron data are recorded at different times, which results in density data along different paths through the ionosphere. Tomographic reconstruction can provide density vs. altitude data for a vertical slice through the atmosphere. It requires a moderate gain GPS antenna, and 3-axis stabilization to point that antenna in the anti-flight direction.

GPS radio occultation has been demonstrated on the microsatellite "PicoSAT" and was attempted on the CAN-X nanosatellie.[31,32] Space weather forecasts would benefit from multiple micro/nanosatellite platforms providing near real-time data to continually update existing space weather models. This is one potential operational mission for future small satellites.

3.5 The Internet

In 1986, the Internet was used by the government and universities to exchange text files and data. Graphical browsers were not introduced until the mid 1990's. Today, we take the Internet for granted, and it plays a significant role in small satellite design, construction,

and operations. We use the Internet to look up component datasheets, to download design software, to upload mechanical and circuit board designs for fabrication, and to get the latest electronic papers from our colleagues and competitors. It also enables remote operation of ground stations that can be distributed across the planet.

The Mercury system developed by Stanford was designed to operate the OPAL microsatellite over the Internet in the year 2000.[33] Today, we have multiple commercial ground station networks, plus the Global Educational Network for Satellite Operations (GENSO) that communicate over the Internet.[34] GENSO is sponsored by the International Space Education Board that includes participation by the European Space Agency, the Canadian Space Agency, NASA, CNES, and JAXA. A global network of ground stations, easily accessible from the comfort of your home or office, can significantly increase the quantity of data one can download from a satellite per day. The key is to make it accessible to all who need it without generating conflicts.

4.0 SATELLITE TRENDS

The 25 microsatellites launched in 1986 were all communications satellites. GLOMR and the DARPA LIGHTSATs that followed, MACSAT, MICROSAT, and MUBILCOM, were also communications satellites.[35] All these spacecraft used spin (SS) or gravity-gradient (GG) stabilization. The first commercial microsatellite constellation, ORBCOMM, was also composed of communications satellites that used gravity-gradient stabilization.[36] Small spacecraft from that era typically used spin, gravity-gradient, passive magnetic (PM), active magnetic (AM) or no stabilization (NS) at all. These stabilization techniques, except for NS, could provide limited attitude control to a few angular degrees. Gravity-gradient provided nadir-pointing, and permanent magnets provided predictable spacecraft orientation about two axes.

While many small communications satellites could use simple stabilization schemes, three-axis control using reaction wheels (3A), active thrusters (AT), or partial three-axis control using AM, would be required for Earth and space imaging applications. These applications need multiple attitude sensors, on-board attitude control calculators, focal plane imagers, and data storage; technologies that have significantly advanced over the last 25 years. This has lead to imaging microsatellites such as DLR-TUBSAT, MAROC-TUBSAT, LAPAN-TUBSAT, MOST, PROBA-1, and AERCam.[37,38,39,40] An exceptional example of an imaging small satellite is the United Kingdom's TOPSAT.[41] This spacecraft provides 2.8-meter ground resolution and is only slightly heavier than a microsatellite (~115-kg).

Imaging nanosatellites should be possible in the next few years; 10-cm diameter optics can provide 5 m ground resolution from LEO. One recent concept uses modified catadioptric mirror lenses for 35 mm cameras to provide 7.5-m resolution from an altitude of 540-km in a triple-cube nanosatellite.[42]

Another recent trend is the use of nanosatellites for space biology experiments. NASA-Ames Research Center has pioneered the use of triple CubeSats with the design, fabrication, and launch of Genesat-1, Pharmasat, and O/OREOS.[43,44,45] Figure 6 shows a rendering of the Organsim/Organics Exposure to Orbital Stresses (O/OREOS) triple CubeSat.

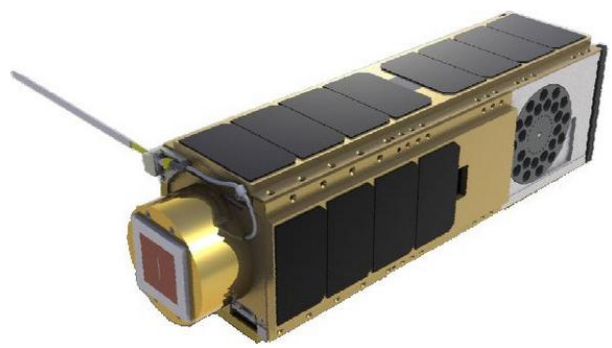

Figure 6. NASA's O/OREOS Nanosatellite. Image Courtesy of NASA.

5.0 SMALL SATELLITE MISSIONS

Table 2 lists examples of past microsatellite, nanosatellite, and picosatellite missions. Missions requiring three-axis stabilization have been limited to microsatellites and a few nanosatellites, but this will change as small (less than 30-cm^3), 3-axis reaction wheel systems become available. Mission additions since 1986 include space biology experiments, general relativity experiments, medium data rate communi-cations, tether experiments, solar sail experiments, seismic monitoring, GPS radio occultation measurements, medium- to high-resolution Earth imaging, stellar magnitude monitoring, asteroid explorers, satellite inspectors, and gravitational field mapping. What will the next 25 years bring?

Table 2. Small Satellite Missions

Mission	Stabilization	Orbit	Examples
Radar calibration	NS	LEO	ODERACS[46]
Atmospheric density measurements	NS	LEO	ODERACS[47]
On-orbit radiation testing of components	NS	LEO, GTO, HEO	ERS-27[48]
Space biology experiments	NS	LEO, GTO, HEO	GeneSat[49]
Laser ranging, general relativity experiments	NS, SS	LEO	LAGEOS[50]
Local space plasma measurements	NS, PM, SS, GG	LEO, GTO, HEO	Munin[51]
Low data rate communications relay	NS, PM, SS, GG	LEO	OrbComm[52]
Low data rate store and forward communications	PM	LEO	UoSAT-2[53]
Medium data rate communications	GG	LEO	MUBLCOM[54]
Tether experiments	GG	LEO	MAST[55]
Seismic monitoring via VLF wave reception	GG	LEO	QuakeSat[56]
Solar studies	SS, AM, 3A	LEO, GTO, HEO	Solrad-3[57]
Solar cell testing	SS, AM, 3A	LEO, GTO, HEO	PSSC Testbed[58]
Ionospheric mapping using GPS radio occultation	AM, 3A	LEO	PICOSAT[59]
Medium to high resolution, targeted Earth imaging	AM, 3A	LEO	TOPSAT[60]
Stellar magnitude monitoring	AM, 3A	LEO, GTO, HEO	MOST[61]
Lunar and asteroid rovers		Interplanetary	MINERVA[62]
Gravitational field mapping	AT	Lunar Orbit	RSTAR[63]
Solar sail/ drag sail development	PM	LEO	NanoSail-D[64]
Satellite Inspector	3A	LEO	SNAP-1[65]

6.0 SUMMARY

Small satellites have become more prevalent since the "Doldrums" of 25 years ago. Due to the development of CubeSats, nanosatellites are now challenging microsatellites in terms of yearly launch rates, and picosatellites are being launched every year. In addition, technology development in micro/nano-electronics, microelectromechanical systems, solar cells, GPS, and the Internet has given small satellites ever-increasing capabilities and new mission opportunities. Today's small satellites are as capable, or more so, than their larger cousins were 25 years ago. This trend should continue over the next 25 years.

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