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Review Article

An overview of small satellites in remote sensing*

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Abstract

This article gives a global overview of some aspects of small satellite developments since the launch of Sputnik-1 50 years ago. These developments are offering new opportunities for remote sensing.

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The earliest satellites were small but, as time went on, the satellites that were flown were developed to serve several different projects and they became larger and more expensive and took a long time to design, build and be launched. One of the extreme examples was Envisat. For these large satellites compromises often had to be made

The future is likely to see more small satellites, each of which is dedicated to a particular mission objective and carries a single instrument. Through this approach more and more countries around the world are becoming involved in Earth observation from space, not just in using the data from the major established systems but also in constructing their own systems.

There were some small, low-cost satellites in the early days, but they were overlooked or considered toys by the space community. The first microsatellites were built by enthusiasts of the amateur radio community and launched in the early 1960s. The invention/introduction of the microprocessor in the 1970s represented a quantum jump for the onboard capabilities of a spacecraft. This technology introduction represented a prime catalyst in the development of microsatellites since it enabled small physical structures in support of sophisticated data handling applications. The engineering of microsatellites, which emerged in the early 1980s, took a radical change of approach from the custom design of traditional spacecraft, namely a design-to-capability scheme to achieve cost reductions by focusing on available, and existing technologies using a general purpose bus and 'off-the-shelf' components and instruments.

The new approach of small satellite design was pioneered by Surrey Satellite Technology Ltd (SSTL) of Surrey University, UK. SSTL's lead has now been followed by various companies and space agencies throughout the world. A key feature of this work is the development of microsatellite technology transfer programmes, providing partnerships and on-the-job training of engineers and scientists of foreign national organizations in cooperative programmes – in particular to those who were not in a position to start or afford their own space projects – to participate in the development of their own microsatellites.

In addition to discussing these developments, this article also covers small satellite classification, small satellite initiatives in the USA, small satellite development in the rest of the world, some aspects of the technology and applications of small satellites, and small satellites developed by universities, particularly the CubeSats programme.

Today, small satellites are changing the economics of space. These spacecraft embrace cutting edge Commercial Off-The-Shelf (COTS) technology, permitting novel and less-expensive ways to perform meaningful observation missions, although there are various technical challenges. There are several synthetic aperture radar (SAR) and

1. Introduction

The fact that we have just been celebrating the 50th anniversary of the beginnings of space flight in October 2007 means that it is a fitting occasion to give an overview of small satellite developments in Earth observation/remote sensing and other fields of space flight. In particular, this involves the history of small satellites with reliance on remote sensing.

At the start of the space age, all satellites were small – not by choice, but by necessity. The world's first artificial satellite, Sputnik-1 (which was launched on 4 October 1957), was a 58.0 cm diameter aluminium sphere with a mass of 83 kg and it carried four whip-like antennas that were 2.4–2.9 m long. The first successful US satellite, Vanguard-1 (which was launched on 17 March 1958), was a sphere with a diameter of 16 cm and a mass of 1.6 kg (Meurer 2006).

Practically all the satellites of the first two decades of the space age featured custom designs (in shape, size, stabilization methods, power provision, instrument mounting techniques, onboard data handling, data communications, mass, etc.) to suit the requirements of a particular mission. This meant continued change for the spacecraft builders to incorporate general support functions over and over again, along with very specific mission instruments. The availability of a standard spacecraft bus (for a particular observation capability) was practically unknown until the end of the 1970s.

These custom designs of spacecraft had rather long lead times for requirements and definition prior to any implementation. The general approach of the space industry was to design the technology based on the mission requirements. After defining the requirements and constraints of the mission, each satellite subsystem – power, propulsion, attitude determination and control, thermal control, communications, command and data handling, and the structure – was designed separately and iteratively. Even after a heritage developed, the increasing complexity of ever unique missions made it difficult to carry forward a subsystem design from one satellite to another without significant modifications. All of the scientific spacecraft developed by the US National Aeronautics and Space Administration (NASA) until the late 1980s used this method of design. This methodology of satellite design has unique advantages and accomplishing its mission. On the negative side, such spacecraft are extremely expensive to develop due to the large amounts of manpower needed to design each subsystem separately, often leading to considerable cost overruns (Jilla and Miller 1997).

After a number of early spacecraft or subsystem failures were experienced, the reliability issue became a big hurdle for spacecraft designers due to the requirement of space-qualified components. Electronic devices had to be radiation-hardened to sustain the hostile environment of space. This was another cost driver as well as a performance killer, since the so-called Commercial Off-The-Shelf (COTS) products of newer designs provided much better processing power than the much older space-qualified products. In addition, the critical subsystems of a spacecraft had to be designed in a redundant or dual-redundant configuration (alternate path selection capability) to guarantee operational service in case of a single-point failure.

The MagSat mission (which was launched in October 1979), a dual-spin stabilized satellite, demonstrated for the first time to NASA in particular the usefulness of a general-purpose bus for science applications. The bus could support a variety of bolt-on experiments. The concept has been used extensively ever since. Integration of flight hardware and subsystems has become an important aspect of modular design. The modular design methodology means that the satellite subsystems were developed in the same manner as before. However, the requirements on which the satellite design were based were no longer for a single unique mission, but for an anticipated range of missions. This reduced the costs significantly because each satellite did not need to be designed from scratch.

Spacecraft design (for Earth observation and space science) has experienced interesting trends. Early space age satellites were small due to the limitations of launch capabilities. The current classes of microsatellites (10–100 kg) and minisatellites (100–1000 kg) are a fitting description for these early space age satellites (only with regard to mass). As the space age progressed into the 1970s and 1980s, the capabilities of launch vehicles increased constantly. The Cold War spurred the build up of the space infrastructure. Consequently, satellites became much larger and much more complex. In parallel, electronics became more capable and compact; many subsystems could be combined into a single instrument on a satellite. The new complexity, along with its demands for reliability and quality assurance, had to be managed, generating bureaucracy and large organizations. As a consequence, overall creativity suffered considerably while costs increased rapidly.

At the end of the Cold War (in the early 1990s), there was a reduction in launches with longer in-between periods. Large and complex projects of NASA and ESA encountered planning and re-planning phases alone that came close to a decade or longer. Some examples are:

The planning for the Hubble Space Telescope (HST) started in the early 1970s (and it was launched in 1990). After launch, the spacecraft required a repair mission to start operations (the primary mirror suffered from spherical aberration). This was followed by several servicing missions requiring Space Shuttle flights.

The International Space Station (ISS) programme was started in 1984. The ISS station build-up began in 1998 until 2010; this is to be followed by regular operations.

The Earth Observing System (EOS) programme planning of NASA started in the early 1980s, and was rescoped in 1992. Eventually the spacecraft in this system were finally launched – Terra in 1999, Aqua in 2002 and Aura in 2004.

The planning for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) programme started in 1993 with the intention of combining the US civil and military operational polar-orbiting meteorological satellite programmes of the US National Oceanic and Atmospheric Administration (NOAA) and the Defense Meteorological Satellite Program (DMSP) of the Department of Defense, to reduce duplication of effort and to generate cost savings. A new generation of instruments and spacecraft are under development, creating substantial cost overruns and programme delays. The programme was restructured in 2006/7. The launch of the first NPOESS spacecraft is now expected in 2013.

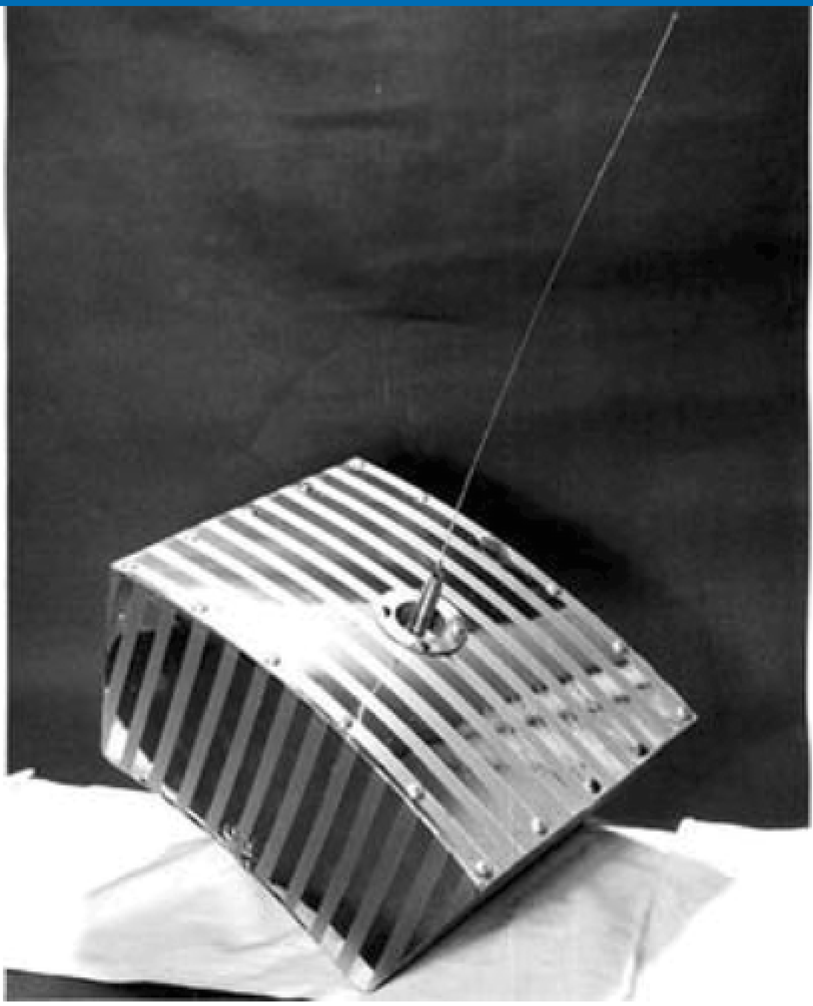
The planning for Envisat of ESA started in the early 1980s and the launch was in 2002 (with over 8000 kg of spacecraft mass, Envisat is the heaviest civil Earth observation mission of all time).

For the experimenter, it meant a reduction in flight opportunities for observations as well as a reduction in technology advances. ‘Gone are the days when novel ideas, new components or a neat scientific idea can be evaluated in orbit quickly and relatively cheaply – and gone are the invaluable opportunities for young engineers and scientists to gain first-hand experience of space before moving to larger projects' (Sweeting 1991).

Already in the early 1960s, the first spacecraft of a family of tiny communication satellites, referred to as OSCAR (Orbiting Satellite Carrying Amateur Radio), was designed and developed by a California-based group of amateur radio enthusiasts. OSCAR-1 (figure 1), the first battery-powered amateur satellite with a mass of 4.5 kg, was launched on 12 December 1961 (piggyback to the Discover-36 spacecraft of the USAF) from Vandenberg Air Force Base (VAFB), California (orbit of 372 km×211 km, inclination of 81.2°, period of 91.8 min). OSCAR-1 orbited for 22 days, and over 570 amateur radio operators in 28 countries reported receiving its simple 'HI-HI' Morse code signals in VHF (A Brief History of Amateur Satellites, URL: http://www.amsat.org/amsat/sats/n7hpr/history.html).

In 1969 the Radio Amateur Satellite Corporation (AMSAT) was founded in Washington DC as an educational organization to give amateur radio satellites an international base. Some OSCAR family advancements include the launch of the very first satellite voice transponder (on OSCAR-3, which was launched on 9 March 1965), and the development of highly advanced digital S&F (store and forward) (on OSCAR-9, alias UoSat-1, which was launched on 6 October 1981) messaging transponder techniques.

Figure 1 Illustration of the OSCAR-1 satellite (image credit: AMSAT).



Display full size

Like many new developments, the small satellites of the early space age were simply overlooked by the established space industry, the space agencies, as well as by the media. There were the many new discoveries of the early missions of the Soviet Union and the USA which caught the attention of the world, as well as the race to the Moon in the 1960s.

The international amateur radio satellite community and associated universities must be regarded as the true pioneers of small satellite technology. They were driven by very real constraints, regarding financial support and technical resources, to evolve a highly pragmatic and cost-effective philosophy for small-scale space engineering as the only practicable means to gain access to space.

2. Small satellite classification

The term ‘microsatellite’ was very probably coined by members of the AMSAT-NA well below 10 kg, were indeed ‘micros’ – at least two orders of magnitude smaller, when compared with the established spacecraft missions of the time. Most experts in the field had a smile when asked about the objectives and the future of such toys in space, which became eventually known as ‘microsatellites’. Could these toys do anything worthwhile? There were many prejudices in the space community when the topic of ‘microsatellites’ was mentioned.

Martin Sweeting of SSTL wrote in his paper of 1991: ‘It may come somewhat as a surprise to learn that some 20 microsatellites have been placed into orbit in the amateur satellite service over the last 25 years! Within Europe, the University of Surrey and its technology transfer company Surrey Satellite Technology Ltd leads research into microsatellite engineering techniques through its UoSat microsatellite programme.’(Sweeting 1991)

In the same paper Sweeting proposed also the first known classification of small satellites, as shown in table 1. Views on what constitutes a small satellite depend on the perspective of the beholder. A small satellite to NASA or to Roskosmos may be considered a monster to a university department. Naturally, there are many different ways to classify artificial satellites – by function, type of orbit, cost, size, performance, and so forth. However, a classification by mass turns out to be quite useful because it has a direct bearing on the launch cost of a spacecraft, representing a considerable hurdle for every mission. Since ‘microsatellite’ was the only term in use in the time frame prior to the 1990s, Sweeting, who had designed several microsatellites at the time, established his satellite classes in the following way: he took the name ‘microsatellite’ for a starter of his class names, and set a mass range to it. Then he selected the other class names by using the magnitude order prefixes of our decimal system to signify the smallness of a satellite in each category by analogy. Hence, the diminutive prefixes (mini-, micro-, nano-, etc. – representing in mathematical terms steps of three orders of magnitude between each other) were chosen for the various small satellite classes – to signify only to a certain extent the corresponding mass classes of small satellites.

Table 1. First satellite classification by Sweeting (1991).

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Subsequently, two more classes (pico- and femto-) were added to Sweeting's original proposal. Also, a correction was made to the minisatellite class, a change from the 100–500 kg to the 100–1000 kg range, to keep to the logic of magnitude orders. The revised version is given in table 2. Within this classification, the term 'small satellite' class is used to cover all spacecraft with a launch mass of less than 1000 kg.

Table 2. Satellite classification by mass criterion.

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Various authors/organizations have advocated these changes in the recent past. An upper limit of 1000 kg for 'minisatellites' was for instance adopted at UNISPACE III (Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space), Vienna, Austria, 19–30 July 1999. At this conference, the cost for developing and manufacturing a typical minisatellite was indicated to be in the order of US$ 5–20 million, while the price tag for microsatellites was estimated as between US$ 2–5 million and for nanosatellites could be below US$ 1 million (all at 1999 price levels) (Sandau 2006a; Sandau et al. 2006).

In particular, the small satellite mission philosophy at UNISPACE III was described to require a design-to-cost approach, within strict cost and schedule constraints, mostly combined with a single mission objective. This focused approach was noted to be supported by the following trends (Barnhart et al. 2006):

- advances in electronic miniaturization and associated performance capability;
- the recent appearance on the market of new small launchers (e.g. through the use of modified military missiles to launch small satellites);
- the possibility of independence in space (small satellites can provide an affordable way for many countries to achieve Earth Observation and/or defence capability, without relying on inputs from the major spacefaring nations); and
- ongoing reduction in mission complexity as well as in those costs associated with management, with meeting safety regulations, etc.

The advantages of small satellite missions were considered to be:

- more frequent mission opportunities and therefore faster return of science and for larger variety of missions and therefore also greater diversification of potential users;

more rapid expansion of the technical and/or scientific knowledge base;

greater involvement of local and small industry.

An early survey on the phenomenon and rationale of small satellites was also conducted by such organizations as the Committee on Small Satellites of IAA (International Academy of Aeronautics) in the late 1980s (IAA Position Paper 1993a,b).

3. UoSat family of small satellites

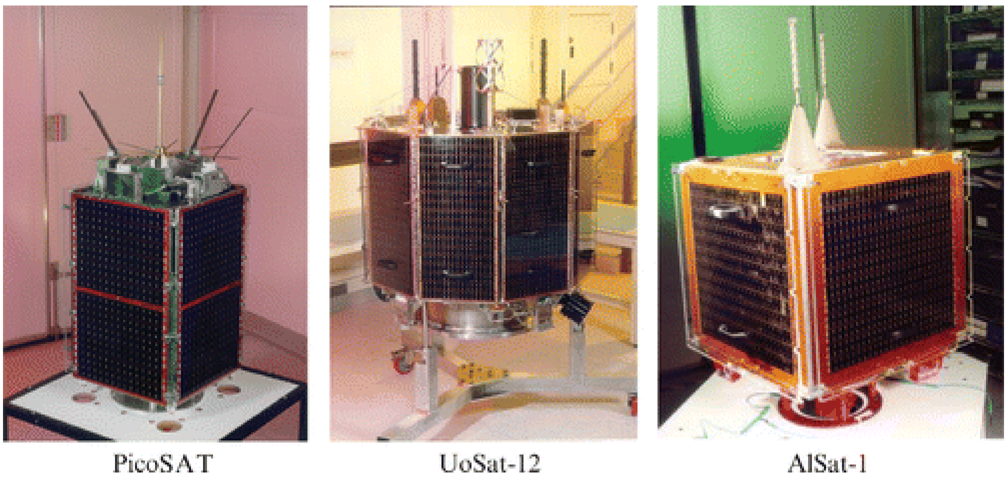
A new approach to small-satellite design was started in the latter part of the 1970s at the University of Surrey in Guildford, Surrey, UK. An early guiding principle was to make space flight affordable to a larger community of interested parties. This required in particular a design-to-capability approach to achieve cost reductions by focusing on available and existing technologies. A small project should only have a small set of goals (requirements) that could be developed by small engineering teams. Each mission under consideration had to adapt to these constraints. Next to low costs, higher risks were taken again with the introduction of more advanced concepts or new technologies into mission designs. More COTS products were used, either to space-qualify these components or subsystems for other missions, or to demonstrate new capabilities on a microsatellite.

The Centre of Satellite Engineering (CSER) at the University of Surrey launched its first microsatellite, UoSat-1 on 6 October 1981 as a secondary payload to NASA's Solar Mesosphere Explorer (SME) mission. This was followed by UoSat-2 with a launch on 1 March 1984 (secondary payload to Landsat-5) (http://www.ee.surrey.ac.uk/SSC/CSER/UOSAT/missions/index.html). Both microsatellites carried experimental communications and technology demonstrations within the amateur satellite service and operated in orbit successfully for more than 8 and 5 years, respectively. As a consequence of these early successes, the University of Surrey created a company, Surrey Satellite Technology Ltd (SSTL) in 1985, dedicated to small satellite research and development looking for new concepts in functionality, services, and in cost reductions.

UoSat-3 (which was launched on 22 January 1990) was the first microsatellite developed and built to an innovative modular bus design by SSTL (figure 2). The introduction of standard hardware and software components provided considerably more flexibility to spacecraft and subsystem manufacturing, integration and testing. In particular, the new approach favoured quick response times of all aspects of satellite manufacturing. This modular design has since been used successfully on all microsatellites of SSTL and is being widely adopted for microsatellite designs worldwide.

The launch industry reacted to the launch requirements of these new small satellites as secondary payloads by providing newly developed launch structures. For example, Ariane Structure for Auxiliary Payloads (ASAP) by ArianeSpace was ready for launch in 1989 offering launch opportunities for multiple small satellites. The ASAP-5 ring structure can accommodate up to eight microsatellites with a volume restriction of 60 cm×60 cm×80 cm. UoSat-3 and UoSat-4 were the first microsatellites, plus four nanosatellites of AMSAT, launched into low Earth orbit with ASAP (22 January 1990), along with the primary payload SPOT-2.

Figure 2 Typical satellites of the SSTL family(image credit: SSTL).



Today, SSTL is regarded as the pioneer of microsatellite design, including a modular and flexible platform (MicroBus), and the development of suitable instruments (see Table 3). Miniaturization techniques of solid-state electronics, sensors, optics, actuators (i.e. miniature mechanisms), etc., are important enabling factors in microsatellite design.

This new approach seems to gain momentum, everywhere. There is also a realization that small-project financing can more easily find support in tight budgets, this applies to government sponsorship of research projects as well as to the commercial sector. Calculated risks are being taken again. Many organizations are re-organizing to improve the conditions for innovation and creativity. The future seems to have room for microsatellites as well as for larger-class satellites, depending on applications and required performance.

Table 3. SSTL-developed small satellites.

4. Small satellite initiatives in the USA

The SMEX (Small Explorer) programme of NASA started in 1988 to provide frequent opportunities for highly focused and relatively inexpensive space science missions on minisatellites (SAMPEX, FAST, TRACE, SWAS, and WIRE). The basic approach was to use a modular design for multiple missions (or a class of missions). Modular designs became possible because the satellite industry had reached a state of maturity and has a large heritage of past satellite designs to learn from and build upon (Reid et al. 1998).

SAMPEX (Solar Anomalous and Magnetospheric Particle Explorer) was designed to monitor the magnetospheric particle populations which occasionally plunge into the middle atmosphere of the Earth. With a spacecraft mass of 161 kg, it was launched on 3 July 1992. It was the first mission in the USA to implement the CCSDS (Consultative Committee for Space Data Systems) communication standards.

FAST (Fast Auroral Snapshot Explorer) was designed to measure and study the rapidly varying electric and magnetic fields and the flow of electrons and ions in the aurora regions of the Earth. With a spacecraft mass of 190 kg, it was launched on 21 August 1996.

TRACE (Transition Region and Coronal Explorer) is a NASA solar minisatellite (250 kg). The spacecraft carries a single instrument, a high-resolution multispectral spectrometer in EUV and UV. TRACE was launched on 2 April 1998 and is operational as of 2007 (design life of 1 year).

SWAS (Submillimeter Wave Astronomy Satellite), an SMEX mission of NASA, was launched on 5 December 1998; this is an astronomy mission with a spacecraft mass of 288 kg. The minisatellite provides a pointing accuracy of 38 arcseconds and jitter<19 arcseconds. The main instrument is a complete radio telescope in space.

WIRE (Wide-Field Infrared Explorer) of NASA was launched on 4 March 1999 (launch mass of 259 kg). WIRE is also an astronomy mission to study the evolution of galaxies. The main instrument, WIRE, consists of a cryogenically cooled, 30 cm imaging telescope. However, WIRE was unable to carry out its primary science mission due to attitude problems.

NASA also started a Small Spacecraft Technology Initiative (SSTI) programme in 1994 with the objective of demonstrating technologies and new approaches for reducing the cost and time of getting civil and commercial space missions from the drawing board to orbit. The programme permitted the spacecraft builder to incorporate commercial standards in the design and qualification process. The first SSTI projects were the spacecraft ‘Lewis’ and ‘Clark’ named after the leaders of the early l9th century US expedition to the Pacific northwest (http://www.sti.nasa.gov/tto/spinoff1996/17.html).

The Lewis minisatellite was designed and built by the team led by TRW, Redondo Beach, California. The spacecraft had a launch mass of 288 kg and was launched on 23 August 1997 carrying a sensor complement of three instruments: HSI (Hyperspectral Imager), LEISA (Linear Etalon Imaging Spectrometer Array), and UCB (Extreme Ultraviolet Cosmic Background Explorer). The spacecraft was lost after 3 days due to an attitude control failure.

The Clark minisatellite was built by a team led by CTA Space Systems of McLean, VA. The spacecraft had a launch mass of 305 kg, representing a demonstration of 36 advanced technologies. However, at the end of February 1998, NASA cancelled the Clark mission due to severe cost overruns and launch delays.

The TOMS-EP (Total Ozone Mapping Spectrometer-Earth Probe) mission of NASA was built by TRW. The spacecraft was launched on 2 July 1996 (spacecraft mass of 294 kg, design life of 2 years) and provided ozone monitoring for more than 10 years. The spacecraft had been operating on the backup transmitter since the primary transmitter failed in April 1998.

OCO (Orbiting Carbon Observatory) is a minisatellite mission of NASA (spacecraft mass of 407 kg using the LeoStar-2 bus of OSC) to provide global measurements of atmospheric carbon dioxide. A launch is projected for late 2008.

The Department of Defense (DoD) and the Defense Advanced Research Projects Agency (DARPA), USA, started a LightSat initiative in the mid-1980s with the goal of reducing the costs and development time of small spacecraft in the 50–1000 kg range. The first microsatellite developed under this programme within less than a year was GLOMR (Global Low-Orbit Message Relay), a digital store-and forward un-stabilized communications satellite (mass of 62 kg) with a launch on Space Shuttle (STS-61-A, 30 October 1985). GLOMR collected sensor data from the ground segment and re-entered the atmosphere after 14 months in orbit.

The MightySat programme of AFRL (Air Force Research Laboratory) started in 1994 with the objective of providing an environment for frequent, inexpensive, on-orbit demonstrations of emerging space system technologies and to accelerate their transition into operational use. MightySat-1 was a spin-stabilized microsatellite of 63 kg launched on 14 December 1998 on the Space Shuttle and ejected. The spacecraft carried several advanced experiments to demonstrate the new technologies. MightySat-1 re-entered the atmosphere on 16 November 1999 due to its relatively low orbital altitude. All objectives were accomplished. MightySat-2 was a technology demonstration mission US Defense Space Test Program (test of high-risk, high-payoff space system technologies), initiated in 1996. The three-axis stabilized small satellite had a mass of 121 kg (payload mass of 37 kg) and was launched on 19 July 2000. The main sensor was the FTHSI (Fourier Transform HyperSpectral Imager). The S-band downlink permitted only a low duty cycle of the instrument. The spacecraft re-entered the atmosphere in November 2002.

Starting in 2003, the DoD has gradually developed a new space operations concept, called Operationally Responsive Space (ORS), which calls for the rapid development and launch of spacecraft to augment or partially replace existing spacecraft. Major partners in the programme are AFRL, NRL and industry. The objective is to develop new small launch vehicles, standardized buses and plug-and-play architectures for small dramatically shorten the development time required for small satellites. The first spacecraft in the programme, TacSat-2 with a mass of 370 kg, was launched on 16 December 2006. Finally, small satellites have found their place as part of a balanced diet of spacecraft types needed to carry out DoD missions.

In July 2007, the Defense Advanced Research Projects Agency (DARPA) issued a broad agency announcement for a programme it calls System F6 (the name F6 is derived from a number of terms used to describe the programme: future, fast, flexible, fractionated, and free-flying). The objective is to create a self-forming network of spacecraft nodes that together act like a single satellite. In its solicitation, DARPA has identified a number of key technologies needed for an F6 system to be successful. These include networking and wireless communications capabilities among the spacecraft nodes, distributed computing, wireless power transfer, cluster flight operations, and the development of a spacecraft black box for each node to diagnose and recover from failures. DARPA is looking for innovative proposals for the performance of research, development, design, and testing to support the agency's System F6 concept (http://www.darpa.mil/TTO/solicit/BAA07-31/F6_BAA_Final_07-16-07.doc).

Table 4 provides an (incomplete) overview of small satellite missions over the last three decades launched in the USA.

Table 4. Small satellites of the USA (chronological order of missions).

A fairly recent development in the USA to increase multiple secondary launch opportunities at affordable costs was provided with the ESPA (EELV Secondary Payload Adapter) fixture of AFRL. The ESPA standard interface consists of a ring that is installed between the rocket's upper stage and the primary payload. Up to six small (⩽180 kg each) secondary payloads may be carried with the ESPA configuration. The first demonstration flight with ESPA capability, namely STP-1 (Space Test Program-1) of DARPA, took place on 9 March 2007 from Cape Canaveral, Florida. The STP-1 rideshare mission consisted of a six-vehicle payload: Orbital Express (OE) consisting of ASTRO and NextSat, MidSTAR-1, STPSat-1, CFESat and FalconSat-3. The six spacecraft were

5. Opening the era of global participation in space missions

The success of the innovative and low-cost microsatellites (SSTL had launched 20 missions over a period of two decades) of the 1980s and 1990s, which were all demonstration missions and were simple in design and functionality, opened completely new perspectives to the space community. Whenever possible and appropriate for the objective, COTS component technology was introduced to keep costs within bounds. Up to the 1980s, missions in Earth observation or in space science of the space agencies had been designed using the most advanced technology available (and standards based on space-qualified components only, delaying the introduction of new technology by several years); multiple instrument payloads were generally flown on large platforms. Only the wealthiest nations could afford such huge investments (Smithies et al. 2002).

These developments must be seen in the light of the global political scene of the time. With the end of the Cold War in the early 1990s, the political world changed dramatically in many respects as well. The improved climate among nations generated in turn more cooperation on many levels, and the field of space flight benefited from this. But the aftermath of the Cold War meant also much tighter budgets on all levels for many national governments. In particular, the research budgets of many nations in East and West experienced great pressures due to the enormous investments needed for the new infrastructures (Germany alone invested hundreds of billions of dollars in the unification process of the country). The entire space sector of Russia and its former satellite states suffered most in the first decade of rearrangement – experiencing a devastating shrinkage in all space programmes. Today, an increasing economic recovery in Russia permits again more investments into its space activities.

The tighter research budgets on all fronts of governments everywhere changed the perspectives of space flight fundamentally. All space agencies, military establishments and institutions experienced a new awareness of continued funding problems; they started to take a look at potential alternatives for a sustained involvement in their future space missions. A promising solution, offering cost savings by an order of magnitude, was seen in the development of small satellites. The microsatellites of SSTL provided even two orders of magnitude in cost savings over their large satellite

6. Microsatellite technology transfer programmes

6.1 SSTL

In 1990, very early in its microsatellite-development history, SSTL started the first microsatellite technology transfer programme, providing partnerships and on-the-job training of engineers and scientists of foreign national organizations in cooperative programmes – in particular to those who were not in a position to start or afford their own space projects – to participate in the development of their own microsatellites. The basic idea was to use the modular UoSat bus (also referred to as MicroBus) for each project and to select or develop payloads that were most suitable to the interest of the customer. On-site training of technical teams of the customer was provided by SSTL to achieve expertise in many aspects of spacecraft and instrument design as well as in spacecraft operations.

A number of rather fruitful SSTL cooperative projects with effective know-how transfer were started in this way:

KitSat-1 (Korea Institute of Technology Satellite) of KAIST (Korean Advanced Institute of Science and Technology), Daejeon, Korea (which was launched on 26 September 1993). As a consequence, KitSat-2 was already built entirely by KAIST engineers in Korea.

PoSat-1 (Portuguese Satellite-1) of the Portuguese consortium LNETI (Laboratorio Nacional de Engenhario e Technologia Industrial). Four engineers were sent to Surrey to participate in on-the-job training and produce the first Portuguese satellite.

FASat-Alfa (Fuerza Aerea Satellite – Alfa) and FaSat-Bravo were produced by a programme between the Chilean Air Fore (FACH = Fuerza Aerea de Chile) and SSTL.

TMSAT (Thai Microsatellite), which was renamed Thai-Paht-1. This was an SSTL project between TSC (Thai Satellite Communication) and MUT (Mahanakorn University of Technology), both of Bangkok, Thailand.

Tsinghua-1, a microsatellite of Tsinghua University, Beijing, was developed and integrated at SSTL.

engineers from ATSB (Astronautic Technology Serdan Berhad) of Kuala Lumpur, Malaysia.

In 1996, SSTL proposed its Disaster Monitoring Constellation (DMC) to the remote sensing community. The idea was to provide a daily global imaging capability at medium resolution (32 m), in three or four spectral bands, for rapid-response disaster monitoring and mitigation. By 1999, five customers or subscribers to the DMC idea had signed agreements with SSTL to share observational data of their spacecraft with every other member in the consortium in case of a disaster event. This innovative proposal provided opportunities, especially to developing countries. The DMC consortium comprises a partnership between organizations in Algeria, China, Nigeria, Turkey and the UK. Again, cooperative projects with effective know-how transfer to the customer were realized by SSTL; the DMC satellites include:

- AlSat-1 of CNTS (Centre National des Techniques Spatiales), Arzew, Algeria.
- NigeriaSat-1, which was built in partnership with NASRDA (National Space Research and Development Agency) and funded by the Government of Nigeria.
- BILSAT-1, which is an Earth observation and technology demonstration mission of BILTEN TUBITAK-ODTU (Science Board of Scientific and Technical Research Council) of Ankara, Turkey.
- UK-DMC, which was funded by BNSC (British National Space Centre).
- Beijing-1, which was built in partnership with MOST (Ministry of Science and Technology) of China.
- NigeriaSat-2, which is under development as of 2007. The NASRDA contract with SSTL specifies the development and building of NigeriaSat-2, including the related ground infrastructure, and a training programme to further develop an indigenous space capability in the Federal Republic of Nigeria.

DMC is in fact the first operational Earth imaging constellation providing pushbroom imagery in a wide swath. All the DMC spacecraft are flown in a single orbital plane providing a cumulative swath. It represents the first application of microsatellites using propulsion for orbit manoeuvres and constellation maintenance.

The impact of SSTL in microsatellite design, the sustained introduction of new technology demonstrations into its missions over more than a quarter century, and in particular its practice of customer-team training have decidedly formed the character indeed outstanding in the global community of small satellite manufactures. The practice of customer-team training has now been adopted by other space companies/institutes as well in the form of cooperative agreements.

6.2 EADS Astrium

EADS Astrium, which was formerly MMS (Matra Marconi Space) of Toulouse, France, started its partnership programme of foreign national organizations in 1992, with NSPO (National Space Organization) of Taiwan as its first customer, offering training courses on various levels of know-how transfer. This was followed by the following cooperative projects (Lambert and Limouzin 2007, Limouzin and Encke 2007) (see table 5):

The FormoSat-2 spacecraft of NSPO (launched on 20 May 2004) was built at EADS Astrium, SAS, France. In this project, the design of the RSI (Remote Sensing Instrument) sensor involved training of the NSPO team by EADS Astrium.

In 2000, the EADS Astrium joint project team in Korea for the development of KOMPSAT-2 involved 10 German and French engineers within the development team of KARI (Korea Aerospace Research Institute), Daejeon. The support covered the design phase to AIT (Assembly, Integration and Test), launch and early orbit operations.

In 1997–1998, EADS Astrium trained 40 Korean engineers from ADD in Earth observation design. The engineers stayed at the Astrium facilities for 2 years in the UK (SAR) and France (EO). The training involved the design of an optical and a SAR payload.

In July 2004, EADS Astrium SAS signed a cooperative agreement for the delivery of the THEOS-1 spacecraft with GISTDA (Geo-Informatics and Space Technology Development Agency) of Bangkok, Thailand. The contract also specifies on-the-job training of Thai engineers as part of the EADS Astrium development team. The joint project team for a full system design, development and production (satellite, ground segment and launch) consists of 20 Thai engineers over 30 months in France and 20 Thai operators trained in Thailand. The launch of THEOS-1 is planned for early 2008 (http://www.aprsaf.org/data/p_saprsaf_data/repo_ap11cd/ss_info/5_SS_THEOS.pdf</url>).

In May 2005, EADS Astrium SAS received a contract award from KARI, Korea, to design and manufacture the first Korean multifunctional geostationary satellite

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and GOCI payloads (prime contractor). The cooperative agreement calls for the training of over 40 Korean engineers by the Astrium design team. The launch of COMS-1 is planned for late 2008.

In 2006, EADS Astrium received a contract from KARI to provide instrument engineering support (training) and instrument manufacture for the KOMPSAT-3 spacecraft, planned to be launched in the timeframe 2009.

AlSat-2 (Algeria Satellite-2) is an optical Earth observation project of CNTS (Algerian National Space Technology Centre). In February 2006 CNTS signed an agreement with EADS Astrium SAS to design and built two satellites. The first of these, AlSat-2A, will be integrated and tested in France at EADS Astrium, whereas the second one, AlSat-2B, will be integrated in Algeria within the small satellite development centre (UDPS) in Oran. The cooperation agreement makes provision for 20 Algerian engineers to work side-by-side with the EADS Astrium development team, with intensive training given in space technology over a period of 2 years.

Table 5. EADS Astrium partnerships with institutions of foreign countries.

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6.3 TUB (Technical University of Berlin)

In 1995 a collaborative agreement was signed between CRTS (Centre Royal Télédétection Spatiale) of Rabat, Morocco, and the Institute of Aeronautics and Astronautics (ILR) at the TUB, Berlin, Germany. The contract called for on-the-job training of Moroccan engineers along with the design and development of Maroc-TUBSAT (launched on 10 December 2001).

In 2003, the TUB signed a memorandum of understanding (MOU) with LAPAN, the Indonesian National Institute of Aeronautics and Space of Jakarta, Indonesia, involving a training programme of LAPAN engineers at TUB and at DLR (Deutsches Zentrum für Luft- und Raumfahrt), along with all the development stages of the spacecraft and its instruments. LAPAN-TUBSAT, a 56 kg microsatellite, was launched successfully on 10 January 2007 on a Polar Satellite Launch Vehicle (PSLV) of the Indian Space Research Organisation (ISRO).

6.4 TRW (Redondo Beach, California, USA)

The FormoSat-1 spacecraft development of NSPO (formerly ROCSat-1), Taiwan (launched on 26 January 1999) was realized as a cooperative development project between TRW of Redondo Beach, California (USA) and NSPO (National Space Organization) of Taiwan offering training capabilities and participation for NSPO engineers in spacecraft design, testing, and spacecraft operation/control. The joint development effort started in June 1994 at the TRW facilities. In May 1997, the spacecraft was returned to NSPO for integration and testing. The launch of FormoSat-1 took place on 26 January 1999 (http://www.nspo.org.tw/2005e/projects/project1/intro.htm).

6.5 SaTReCi (SaTReC Initiative Co. Ltd)

In 2001 ATSB signed a cooperative agreement with SaTReCi of Daejeon, Korea, for the RazakSat project of ATSB, Malaysia. The contract included on-the-job training of ATSB engineers. RazakSat is due for launch in 2008.

DubaiSat-1 is an initiative of EIAST (Emirates Institution for Advanced Science and Technology), a UAE (United Arab Emirates) government entity to build and operate a remote sensing imaging satellite. To this effect a cooperative agreement was signed with SaTReCi of Daejeon, Korea, in April 2006 which includes an on-the-job training programme of a team of UAE engineers in Korea at SaTReCi. The launch of DubaiSat-1 is planned for 2008.

6.6 Yuzhnoye (Ukraine)

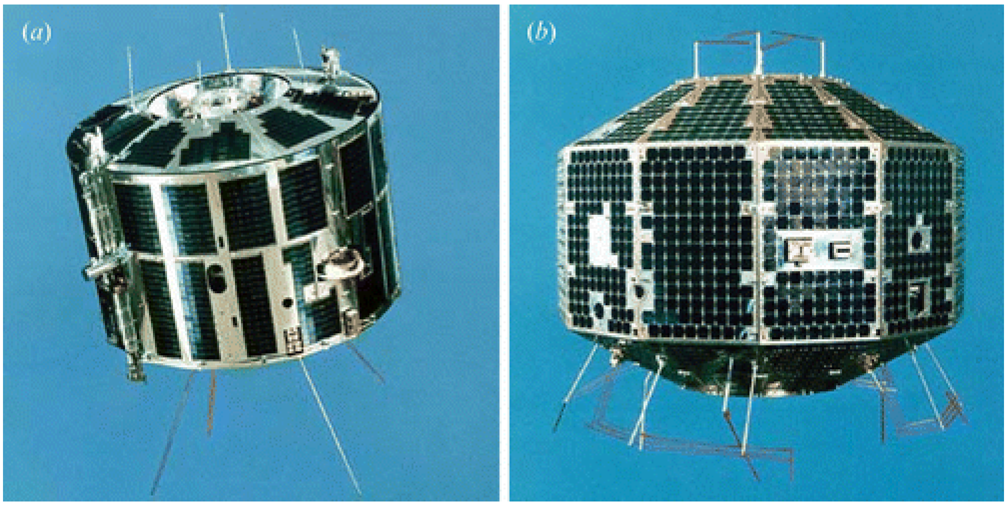
In 2001, the EgyptSat-1 project agreement was signed between NARSS (National Authority for Remote Sensing and Space Science) of Egypt and the State Design Office Yuzhnoye, Dnepropetrosvk, Ukraine. Yuzhnoye designed and developed the spacecraft. The contract included also technical expertise and on-the-job training to Egyptian engineers as well as technology transfer (satellite launched on 17 April 2007).

7. Small satellite development in the rest of the world

The EXOS (Exospheric Observation Satellite) series was developed by ISAS (Institute for Space and Astronomical Science) of the University of Tokyo, Japan. EXOS-A (launched on 4 February 1978, mass 126 kg) and EXOS-B (launched on 16 September 1978, mass

92 kg) are the Japanese contribution of the International Magnetospheric Study (figure 3).

Figure 3 View of the EXOS-A (left) and EXOS-B spacecraft (right) (image credit: ISAS).



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EXOS-B carried out coordinated observations with EXOS-A. Investigations of correlated mechanisms between particles and fields and plasma turbulence were made with in situ measurement techniques using electrostatic particle analysers. The EXOS series spacecraft are in effect good examples in the class of small satellites of their period. Each one of them represented a custom design as well as a corresponding manufacturing process.

Table 6 provides an (incomplete) overview of small satellite missions over the last three decades launched by the rest of the world.

Table 6. Small satellites of the rest of the world (chronological order of missions).

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Major development of small satellite programmes are provided by the following institutions/companies (apart from SSTL).

The Institute of Aeronautics and Astronautics (ILR) at the Technical University of Berlin (TUB), Germany, started with its TUBSAT programme in 1985 (see table 7). A major the field of attitude determination and space-related applications. The DLR-TUBSAT and subsequent missions introduced hibernation mode operations.

Table 7. Overview of the TUBSAT programme.

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The spacecraft in the small satellite programme of the SSC (Swedish Space Corporation), Solna, Sweden are listed in table 8.

Table 8. Smallsat missions developed at SSC, Sweden.

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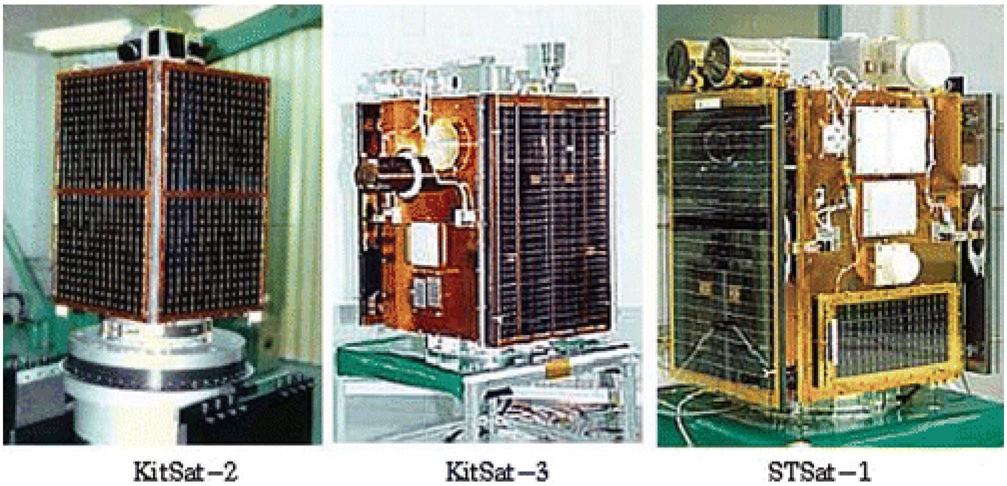
KAIST and SaTReC (Satellite Technology Research Center), and later also SaTReCi (SaTReC Initiative) of Daejeon, Korea, started with the development of their own small satellite programmes in 1992 (after gaining their experience in a technology transfer programme at SSTL, Surrey, UK – followed by the launch of KitSat-1 in 1991) (figure 4).

Figure 4 Examples of small Korean satellites(image credit: SaTReC).



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KitSat-2, developed by KAIST and SaTReC in Korea, was launched on Ariane-4 (along with PoSAT-1 and HealthSAT-2) on 26 September 1993 as an auxiliary payload on the

KitSat-3 (110 kg, launched on 26 May 1999) was developed by KAIST and SaTReC; it carried MEIS (Multispectral Earth Imaging System) developed by SaTReC in cooperation with Stellenbosch University, South Africa. Mission operations were terminated in December 2003 after 4.5 years of mission service (the battery had reached a very low level). In addition, there were four other instruments onboard.

STSat-1 (106 kg, launched on 27 September 2003) is a technology demonstration mission developed by KAIST and SaTReC (based on the KitSat series). The regular observation mission lasted until October 2005, when some abnormal attitude behaviour of the spacecraft was detected.

STSat-2 (~100 kg, launch due in 2008) is being developed by SaTReC. It carries a payload of DREAM (Dual-channel Radiometers for Earth and Atmosphere Monitoring), LRA (Laser Retroreflector Array), DHST (Dual Head Star Tracker), PPT (Pulsed Plasma Thruster) and FDSS (Fine Digital Sun Sensor) and is a technology demonstration experiment.

CNES (Centre National d'Etudes Spatiales, France) started with the development of a small satellite series family called Myriade in 1999 (see table 9). Satellite AIT (Assembly, Integration and Test) is performed by CNES or French industry. There is a partnership between CNES, Thales Alenia Space (TAS, formerly Alcatel Alenia Space), and EADS Astrium SAS. The partnership agreement permits TAS and EADS to use the Myriade bus design and products for their own applications/missions (figure 5).

Table 9. Some smallsats of the Myriade family of CNES.

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Figure 5 Myriade series spacecraft(image credit: CNES, Astrium).

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8. Technology and applications of small satellites

8.1 Nanosatellites and picosatellites

The early microsatellites of the 1980s were simple spacecraft, serving in such niches as S & F (Store and Forward) communications. These spacecraft were for instance built without a propulsion system, due to the cost and complexity of such a system. Attitude control was typically performed using magnetic torquers and gravity stabilization; at a later time, reaction or momentum wheels were introduced. Also, propulsion for attitude control using tiny thrusters could be implemented using cold pressurized gas. However, for orbit changes, such a cold gas system remained simply inadequate. Small satellite projects also have small budgets. Thus, by their very nature, they depend on launch opportunities as secondary payloads which are offered in association with larger satellites. As a consequence, a microsatellite project is, in general, constrained to take the same orbit as the main satellite payload.

The first spaceborne microprocessor (Intel 8080) in Earth observation was flown on the Seasat mission of NASA in 1978. This technology introduction represented a prime catalyst in the development of microsatellites since it enabled the use of small physical

SSTL (as well as of other developers) featured a microprocessor as onboard computer. The UoSat-1 primary onboard computer was based on the RCA CDP 1802 microprocessor (launched in 1981).

Starting in the late 1990s, an evolving micro-technology has permitted the design of single-board spacecraft, referred to as nanosatellites (1 kg<mass⩽10 kg) and picosatellites (mass⩽1 kg) (see table 2). In such single-board designs, there is no physical separation between platform and payload. Naturally, the capabilities and performance of these tiny pioneering satellites are still very limited and inferior to those of their bigger brothers, the microsatellites and minisatellites. This is because they have less pointing accuracy, less power, less communication capability, etc. than the larger microsatellites and minisatellites (Fleeter 1998). However, the main advantages of nanosatellites and picosatellites are their very low cost and the speed of designing/building a satellite practically from off-the-shelf components; these are indeed strong arguments, even for a limited set of objectives that can be achieved. In particular, applications such as technology demonstrations are favoured within the class of nanosatellites and picosatellites (an example is the introduction of such concepts as spacecraft constellations (networks or clusters) for distributed Earth observations or for communication purposes in low Earth orbits). The early nanosatellites and picosatellites are listed in table 10.

Table 10. Chronology of early nanosatellite and picosatellite launches.

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In most nanosatellite designs up to the end of the 20th century, the primary attitude sensor has been a magnetometer which measured the amplitude and direction of the magnetic field vector relative to the spacecraft coordinate system. This measurement was then compared with that of a model of the geomagnetic field for the specific orbital location and the attitude between the spacecraft axes and the inertial reference frame is evaluated (Michalareas et al. 2002).

8.2 ADCS (Attitude Determination and Control Subsystems)

Early microsatellite attitude control subsystems were rather limited in their control gravity-gradient controlled. Only a few experimental systems would use something more advanced. Pointing accuracies in the order of 1° were state of the art.

Generally, attitude was sensed with magnetometers which measured the amplitude and direction of the magnetic field vector relative to the spacecraft coordinate system. This measurement was then compared with that of a model of the geomagnetic field for the specific orbital location and the attitude between the spacecraft axes and the inertial reference frame was evaluated. There were also coarse Sun sensors. The prime actuators used were magnetic coils and gravity gradient booms.

In the mid and late 1990s momentum-bias and experimental three-axis systems were deployed as sufficiently small wheels became available on the market, and it was not until after 2005 that agile three-axis controlled small satellites were becoming commonplace. In particular, the pointing accuracy performance in small satellites has improved considerably – becoming ever more suitable for imaging missions as well as other applications.

Tables 11 and 12 provide an overview of Attitude Determination and Control Subsystems (ADCS) technology introduction into small satellites (Michalareas et al. 2002, Borrien et al. 2006, Davies et al. 2007).

Table 11. Introduction of ADCS technology into small satellites.

Download CSV Display Table

Table 12. Common actuation techniques for attitude control.

Download CSV Display Table

The CAN (Controller Area Network) bus technology, providing a distributed data handling architecture, was first introduced by SSTL on the FaSat-Alfa microsatellite (launched 31 August 1995). In the meantime, this bus standard has been implemented in many small satellite missions.

In the late 1990s the miniaturization technology was considered viable for integration example, STRV-1a (launched on 17 June 1994), a DERA microsatellite (spacecraft mass 52 kg), made flight tests of the xenon gas flow control system, developed for the UK-10 IPS (Ion Propulsion System), with associated solenoid valves, orifices, and valve-actuating electronics. Deep Space 1 (launched on 24 October 1998), a NASA/JPL minisatellite with a mass of 490 kg, carried IPS (Ion Propulsion System) to demonstrate deep space propulsion. UoSAT-12, a minisatellite of SSTL (launched on 12 April 1999, spacecraft mass 325 kg), carries an electric propulsion system, a 100 W resistojet, which uses nitrous oxide as its working fluid. The introduction of various technologies on small satellites is listed in table 13.

Table 13. Introduction of some early onboard technologies/capabilities in spaceflight.

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9. Small satellites developed by universities

9.1 Universities worldwide

During the 1990s, satellite and payload development projects became the programme of choice for challenging (multi-year) training courses in quite a few engineering departments at universities throughout the world. The intent was (and is) always to enrich the student training programme, to stimulate interest in a problem-solving multi-disciplinary technical environment, to be imaginative and resourceful, and to take some risks – with ample and essential help from mentors and partners (industry, institutional, or otherwise). Cooperation on many levels and active participation/publication within the international space science community are important ingredients in the overall objectives of research and development. In some instances, project-sharing among engineering departments of several universities is being practised in order to handle the demanding and complex project goals in a certain time frame. In general, plenty of enthusiasm and much volunteer work by all parties involved are needed to bring such low-cost programme activities to maturity – an invaluable amount of professionalism is gained by all students in such programmes.

The advantages universities bring to spacecraft development can be summed in one word: failure. Student projects have the luxury of failure, something that workers in the professional space industry must avoid. In fact, failing and learning from failure are some of the most important parts of a student's education. Students in a university setting are encouraged to seek out innovative (and therefore often risky) approaches to solving problems. By taking risks and comparing their results with standard methods, the students gain insight into the underlying phenomena and have a better appreciation of accepted practice (Swartwout, M.A. 1997. The Role of Universities in Small Satellite Research, URL: http://ssdl.stanford.edu/ssdl/images/stories/papers/1997/ssdl9705.pdf).

One of the most difficult problems when building small satellite is to get a launch opportunity as a secondary payload with some primary payload. Many things have to be considered for such a piggyback flight, including the orbit, the price tag, and in particular the long waiting periods.

Table 14 provides an (incomplete) overview of small satellite missions over the last 2.5 decades launched by various universities; some of these have been mentioned earlier in this article.

Table 14. Overview of small satellites developed by universities (in chronological order).

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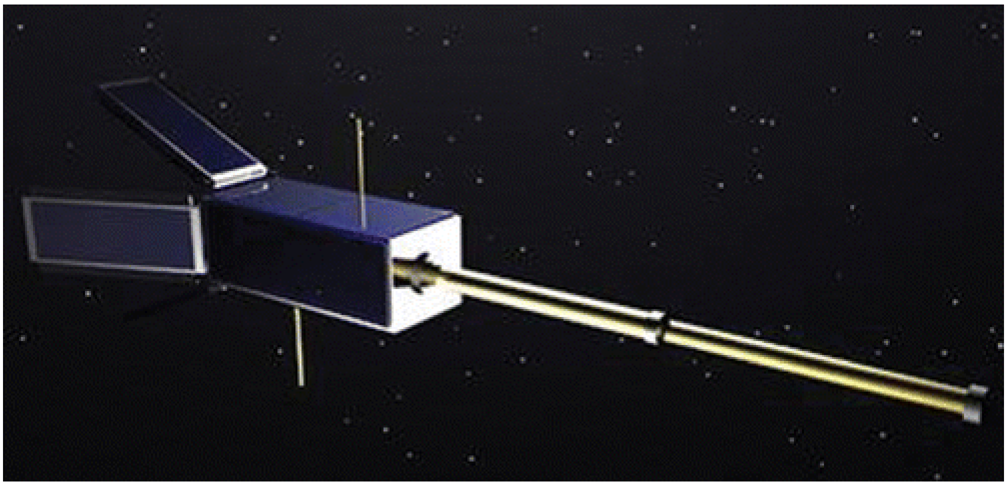
In general, universities take on challenging projects in the field of spaceflight and remote sensing. Some examples (QuakeSat-1, GeneSat-1, CanX-2, DST and PRISM) are given below.

QuakeSat-1 is a research nanosatellite of the QuakeFinder Team of Palo Alto, California, and SSDL (Space Systems Development Laboratory) at Stanford University, Stanford, California. The objective is to detect earthquake signatures in the ELF/VLF (Extremely Low Frequency/Very Low Frequency) spectrum when flying over earthquake regions. The strategy used to detect the small magnetic field measurements (0.5–1000 Hz) relies on the use of a very sensitive AC magnetometer. A launch of the triple-cube QuakeSat (mass 4.5 kg, stowed size of 11 cm×11 cm×35 cm) took place on 3 June

2003 on a Rockot vehicle from Plesetsk, Russia. The spacecraft and its instruments are operational as of 2007 (figure 6).

Figure 6 Artist's view of the deployed triple-cube QuakeSat configuration (image credit: SSDL).



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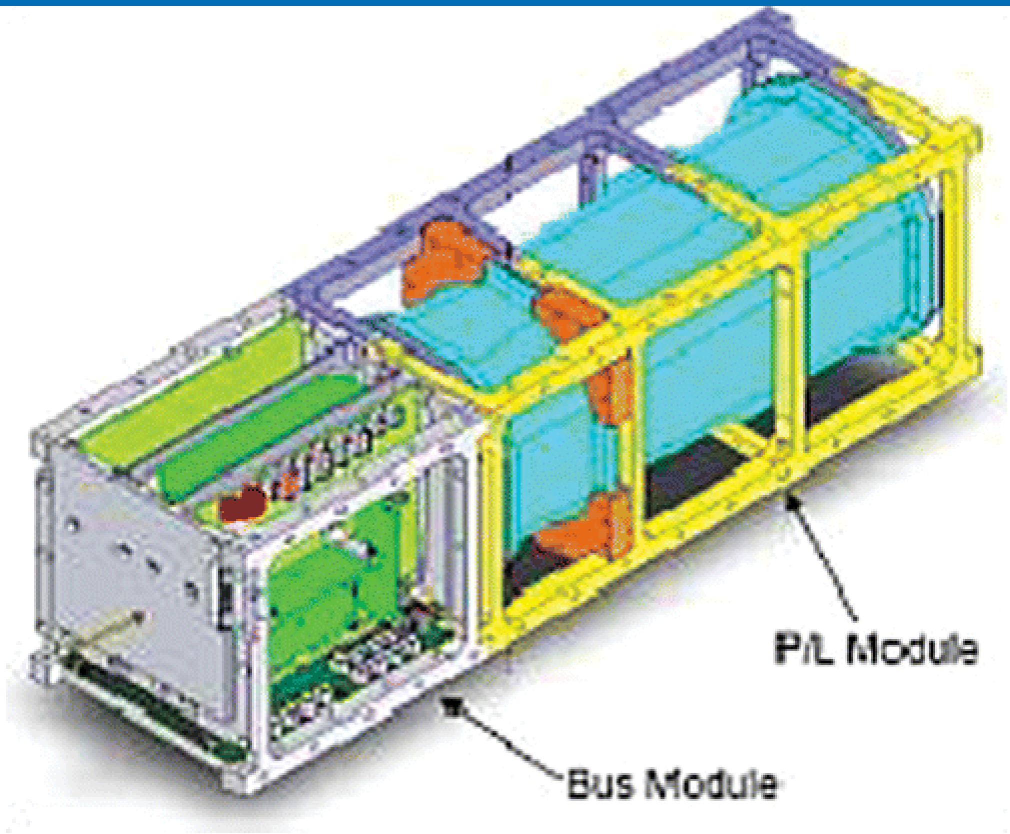
GeneSat-1 is a triple-cube technology demonstration nanosatellite mission (figure 7). It is a cooperative effort between NASA and various universities (Stanford, Santa Clara University) partnered at the Center for Robotic Exploration and Space Technologies (CREST) located at NASA/ARC (NASA/Ames Research Center), Moffett Field, California. The overall objective is to study the effects of the microgravity environment on biological cultures (bacteria, genetic and biological probes to detect gene expression), hence the label of GeneSat mission due to the biological payload.

Figure 7 The GeneSat-1 spacecraft (image credit: Stanford University).



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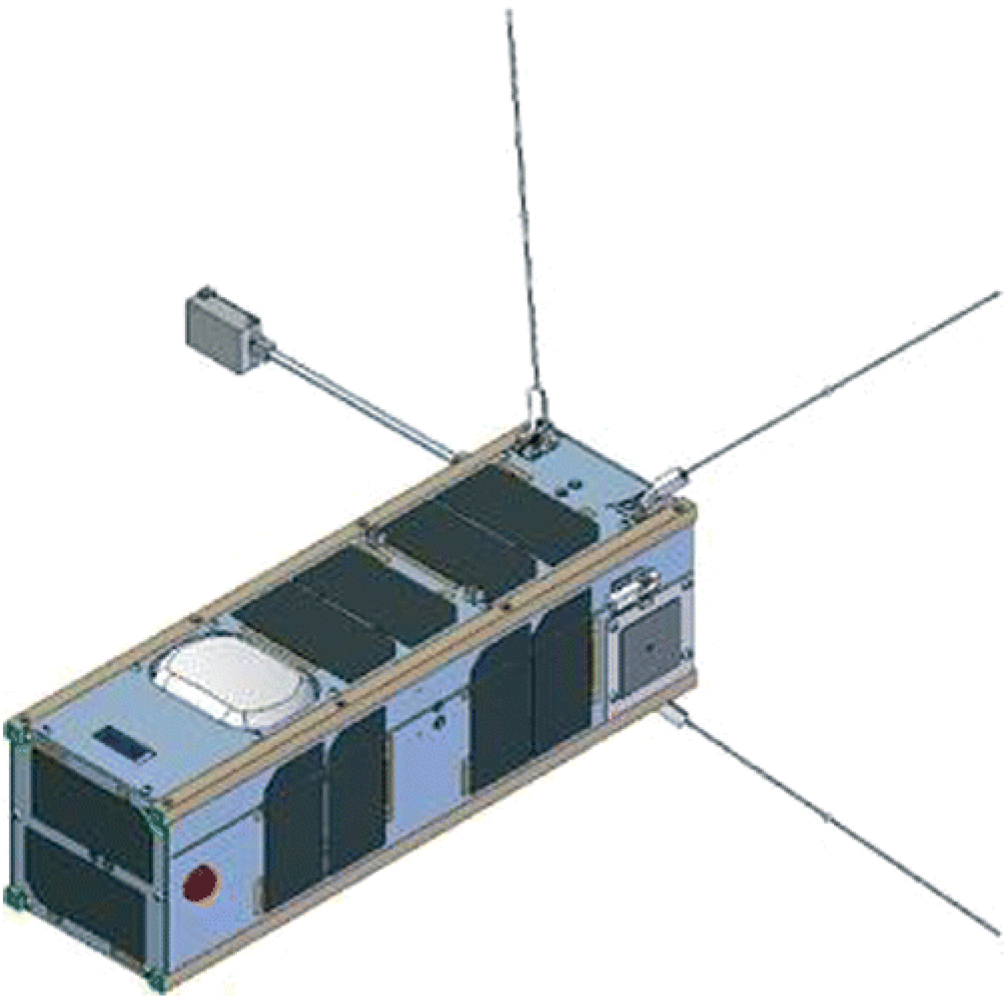
The entire satellite is about 100 mm×100 mm×340 mm in size with a mass of about 4.6 kg. The launch of GeneSat-1 as a secondary payload on a Minotaur launch vehicle of OSC (Orbital Sciences Corporation) took place on 16 December 2006 from NASA's Wallops Flight Facility, Wallops Island, Virginia, USA. As of late 2007, the spacecraft is operating. The GeneSat-1 biological experiment was initiated on 18 December 2006. After 96 h, the biological experiment was complete and all baseline data downloaded (22 December 2006). As of 17 January 2007, all operations for executing the primary mission criteria have been successfully performed, with results disseminated (http://genesat1.engr.scu.edu/log/opslog.htm).

CanX-2 (Canadian Advanced Nanosatellite eXperiment-2) (figure 8) is a nanosatellite mission of UTIAS/SFL (University of Toronto, Institute for Aerospace Studies/Space Flight Laboratory) within the framework of the CubeSat programme (see below). The objective of the triple-cube configuration is to demonstrate among other things a momentum-bias attitude control subsystem. The spacecraft measures 10 cm×10 cm×34 cm with a mass of about 3.5 kg (triple-cube standard); a launch is planned for 2008 (secondary launch on a PSLV vehicle of ISRO) (http://www.utias-sfl.net/nanosatellites/CanX2/CanX2Index.html#).

The standard ADCS (Attitude Determination and Control Subsystem) utilizes three magnetorquer coils. In addition, a momentum nanowheel reaction system provides a momentum-bias three-axis control system (maximum torque of 0.3 mN m and a maximum momentum storage of 10 mN m s).

Figure 8 Illustration of the triple-cube configuration of CanX-2 (image credit: UTIAS/SFL).



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DST (Dobson Space Telescope) is a research project at TUB/ILR, Berlin (figure 9). The overall objective is to introduce and demonstrate enabling technologies such as high-resolution (1 m GSD) Earth imaging from an orbital altitude of 550 km using the rather limited payload volume and mass of a microsatellite. This is done by employing a completely new type of self-deploying and self-collimating telescope system. The project started in 2003 and a patent of the deployment mechanism was granted in 2007. There are three versions of DST payloads, each with a larger telescope aperture, to be demonstrated in various small satellite missions:

in 2008. Imagery of 6 m spatial resolution on a FOV of up to 10 km (600 km orbit) is to be provided. The folded instrument size is 10 cm×10 cm×6 cm; the unfolded instrument size is 10 cm×10 cm×21 cm.

On DST 35 the telescope aperture is 350 mm and is to be flown on a microsatellite in 2010. The imagery resolution is 1.5 m in panchromatic mode and 6 m in multispectral mode on a swath of ~12 km. The folded instrument size is 40 cm×40 cm×25 cm; the unfolded size is 40 cm×40 cm×100 cm.

On DST 50 the telescope aperture is 500 mm and is to be flown on a microsatellite in 2012. The imagery resolution is 1 m in panchromatic mode and 4 m in multispectral mode on a swath of ~12 km. The folded instrument size is 60 cm×60 cm×30 cm; the unfolded size is 60 cm×60 cm×120 cm.

Figure 9 Artist's view of the DST deployment sequence (image credit: TUB/ILR, DST GmbH).

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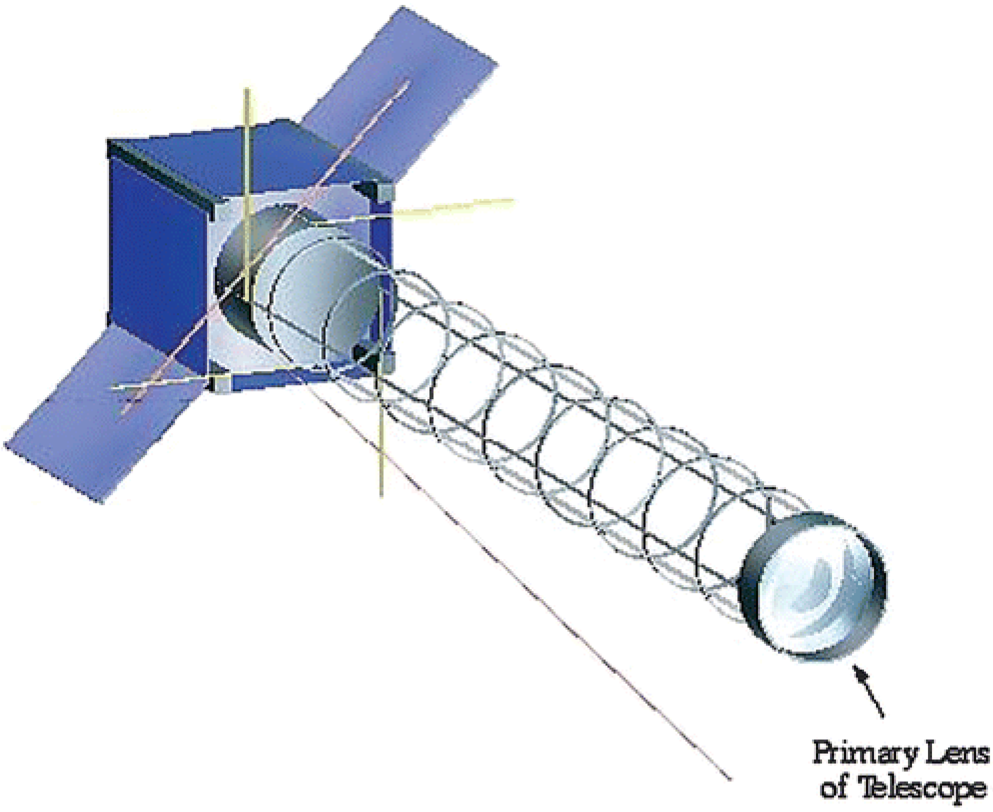
PRISM (Picosatellite for Remote sensing and Innovative Space Missions) is a pathfinder mission of ISSL (Intelligent Space Systems Laboratory) at the University of Tokyo (UT), Japan. The main mission objective is to demonstrate high-/medium-resolution imaging (of the order of 30 m from an orbital altitude of 800 km) to be done on a low-cost mission with a total spacecraft mass of 5 kg (i.e. a nanosatellite). The instrument design employs a telephoto digital camera system, based on deployable concepts (figure 10). A launch of PRISM as a secondary payload is intended for the period 2008/9.

Figure 10 Illustration of the PRISM satellite with deployed primary lens system(image credit: ISSL, University of Tokyo).



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The PRISM spacecraft bus structure is a cuboid of size 18 cm×18 cm×26 cm. The extensible boom design has a double function – to stabilize the spacecraft (passively), and to function as a placeholder for the primary lens of the optics subsystem (telescope). The extensible boom is deployed (after separation with the launch vehicle) with a lens attached at its tip. Deployment of the boom lengthens the distance between the lens and the imaging detector, which then realizes a long focal length. It implies also that the boom structure must be aligned accurately and remain stable (thermally) under the various orbital lighting conditions.

9.2 CubeSats

The CubeSat concept is a first attempt to standardize the bus structure and deployment of picosatellites for low-cost experiments and applications, in particular for student-built satellites at universities. CubeSat is the name given a cube-shaped picosatellite design of 10 cm side length and a mass of ⩽1 kg (figure 11).

The CubeSat idea, concept and programme began in 1999 at SSDL (Space Systems Development Laboratory) of Stanford University under the leadership of Robert J. Twiggs. The overall objective of the CubeSat programme is to provide an effective framework (including specifications and guidelines) for the design, construction and launch of picosatellites. Stanford University and California Polytechnic State University in San Luis Obispo, California (referred to as CalPoly) have combined efforts to develop a means of launching CubeSats. This involves all CubeSats featuring a standard form factor and sharing launches by using standard launch tubes, referred to as P-PODs (Poly Picosatellite Orbital Deployers) (Pranajaya et al. 2003).

The first multiple CubeSat mission, involving half a dozen picosatellites as secondary payloads, took place on 30 June 2003 on a Rockot vehicle (built by the Krunichev Space Center) of Eurockot (Eurockot Launch Services GmbH, Bremen, Germany) from Plesetsk, Russia. The CubeSat spacecraft were: XI (University of Tokyo), CUTE-I (Tokyo Institute of Technology), CanX-1 of UTIAS/SFL (University of Toronto Institute for Aerospace Studies/Space Flight Laboratory), AAUSat (Aalborg University of Denmark), DTUSat (Technical University of Denmark), QuakeSat (Stanford University, Stanford, California, USA).

The second multiple spacecraft launch, involving three CubeSats (UWE-1, XI-V and nCube-2), was released/deployed from SSETI-Express, a European student microsatellite, and itself a secondary payload on a multiple spacecraft mission. The launch of this spacecraft mission took place on 27 October 2005 (Cosmos-3 M launch vehicle of AKO Polyot from the Plesetsk Cosmodrome, Russia) involving the following spacecraft: TopSat of QinetiQ (UK), and China-DMC+4 (Beijing-1) of SSTL (UK) as primary payloads. The other secondary payloads on this multi-satellite flight were SSETI Express (European students), Mozhayets 5 (Russia), Sinah-1 (Iran) and Rubin-5 (OHB, Bremen, Germany).

Figure 11 View of some typical CubeSats.

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On 26 July 2006, a launch of multiple smallsats on a Dnepr-1 launch vehicle from Baikonur, Kazakhstan (launch provider: ISC Kosmotras), ended in a total launch failure after about 2 min of flight. The following CubeSats were on this flight: ION (University of Illinois), Sacred (University of Arizona), KUTESat (Kansas University), ICEcube-1, -2 (Cornell University), Rincon (University of Arizona), SEEDS (Nihon University), HAUSat-1 (Hankuk Aviation University), nCube-1 (Norsk Romsenter), Merope (Montana St University), AeroCube-1 (The Aerospace Corporation), PolySat-1, -2 (CalPoly) and Voyager (University of Hawaii).

Additional smallsats on the flight were: Belka (RKK Energia), 250 kg, the first remote sensing satellite of Belarus; Baumanets (NPO Mash), 80 kg; UniSat-4 (University of Rome, Italy), 12 kg; and PicPot (University of Torino, Italy), 3 kg. This launch failure represented a great setback and disappointment to all involved, in particular to the members of the 14 CubeSat projects. Years of work and effort from the many student satellite teams from around the world was lost in a single instant. The launch failure was due to a malfunctioning hydraulic drive unit in a combustion chamber on the booster's first stage. Unfortunately, occasional launch failures are simply part of spaceflight, in spite of careful launch preparations (David 2006).

The fourth multiple-launch CubeSat mission from the territory of the former Soviet Union (today Russia and Kazakhstan) took place on 17 April 2007 from the Baikonur Cosmodrome, Kazakhstan, on a Dnepr launch vehicle (launch provider: ISC Kosmotras). The launch involved seven CubeSats as secondary payloads. The CubeSat launch had been arranged by CalPoly and included three CubeSat P-PODs (Poly-Picosatellite Orbital Deployer), which were deployed after the primary payload in the predetermined deployment sequence (see table 15 and figure 12). All three P-PODs deployed the CubSats successfully (http://cubesat.calpoly.edu/pages/missions/dnepr-launch-2.php;

‘Russian booster puts batch of small satellites into orbit,’ 17 April 2007, URL: http://spaceflightnow.com/news/n0704/17dnepr/).

Table 15. Overview of CubeSat allocations on launch 4 on 17 April 2007. (http://cubesat.calpoly.edu/pages/missions/dnepr-launch-2.php).

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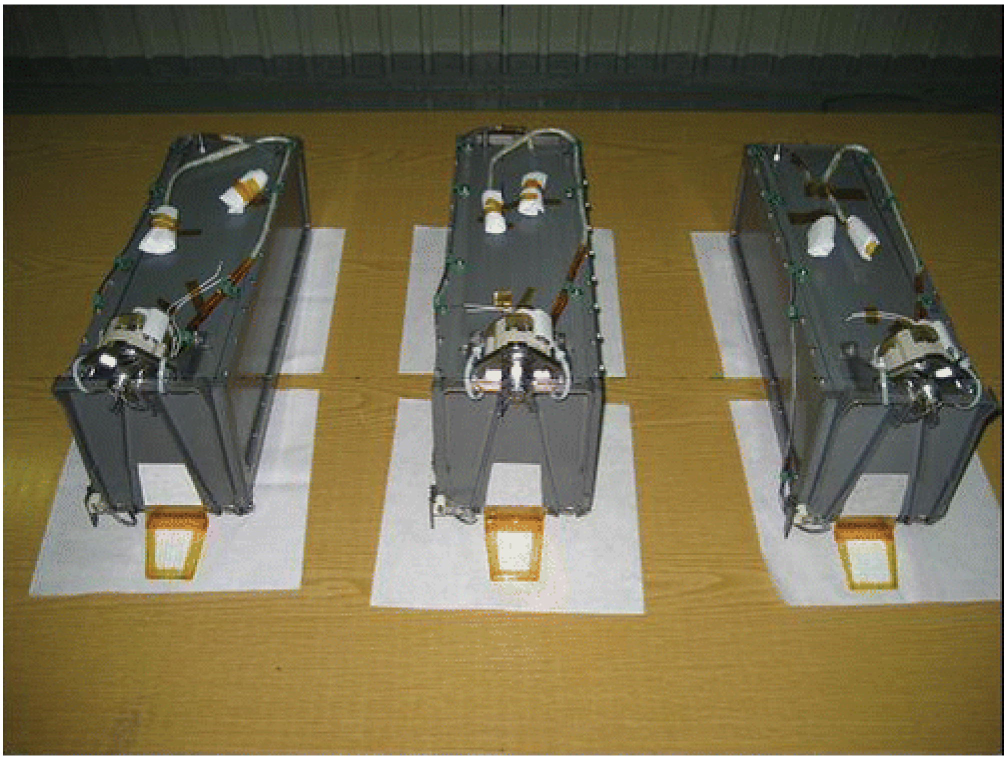
Figure 12 The three P-PODs for the seven CubeSats on flight 4 on 17 April 2007 (image credit: CalPoly).



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10. Current status and outlook in the small satellite service spectrum

Today, small satellites are changing the economics of space. These spacecraft embrace cutting edge COTS technology, permitting novel and less expensive ways to perform meaningful observation missions. In operation and in planning are SAR as well as hyperspectral imaging missions on minisatellites. A major challenge for high-resolution imaging missions or for hyperspectral missions on small spacecraft is the thermal stability on the imaging instrument and bus – to provide sharp imagery.

The SAR-Lupe constellation (five spacecraft, German Defense Ministry) developed by OHB-System, Bremen already has two minisatellites in orbit (both 770 kg). The complete constellation is planned to be in orbit by mid-2008.

The TecSAR mission of the Israel Defense Ministry (260 kg) was launched on 21 January by an Indian PSLV launcher.

An example of planned civil minisatellite SAR missions is the AstroSAR-Lite initiative of EADS Astrium Ltd and SSTL. The goal is to provide low-cost mission solutions with innovative designs to customers in the field of SAR observations.

The PROBA mission of ESA (launched on 22 October 2001) is flying CHRIS (Compact High Resolution Imaging Spectrometer), a UK hyperspectral imager developed by SSTL.

TacSat-3 is a DoD (USA) technology demonstration minisatellite with a planned launch in 2008. It carries ARTEMIS (Advanced Responsive Tactically Effective Military Imaging Spectrometer), a hyperspectral imager of AFRL and the US Army. An equally important aspect of TacSat-3 represents a first implementation of a demonstration of emerging avionics and interface standards as well as of modular spacecraft bus standards.

The EnMAP (Environmental Mapping and Analysis Program) mission of DLR is a small satellite hyperspectral mission (850 kg) under development with a planned launch in 2010.

ZASat-003 (South African Satellite-003) of SunSpace Ltd employs a multi-sensor imager for hyperspectral imagery in the region of 400–2350 nm. A launch of this minisatellite is expected in 2010.

HERO (Hyperspectral Environment and Resource Observer) is a CSA (Canadian Space Agency) minisatellite mission with a planned launch in 2010 (with 210 spectral bands in the very near and shortwave infrared).

In the early 21st century, the spectrum of microsatellite services is by all means as impressive as that of their bigger brother satellites, but at considerably reduced costs. Overall, microsatellites have experienced an impressive evolution from flying toys or gadgets to real and advanced service providers. In fact, microsatellites make it possible to open up new fields of services previously considered too expensive (in particular, well as the military establishments of the world have been (or are) re-evaluating their programmes, in favour of smaller systems, to offer a solution for ever tighter budgets (Lew et al. 2001 Sandau 2006b).

In their modern reincarnation, a worldwide community of innovators has chosen to leverage the technological advances in electronics, materials and sensors to create satellites that are physically smaller, technically simpler, and much more affordable to acquire, launch and operate. In particular, the technology of component/instrument miniaturization is making considerable progress in the field of integrated microsystems – the introduction of micro- and nano-technologies into space applications. The vision is to build modular microsystems, platforms on a chip, that integrate the domains of electronics, photonics, MEMS (Micro-Electro-Mechanical Systems), architectures, and algorithms into an intelligent set of tools. The future lies in reconfigurable and adaptable microsystems (Willey et al. 2001, Echersley et al. 2005, Zolper 2005).

With these developments in mind, there is definitely an exciting future ahead for small satellite missions in many fields of spaceflight. For instance, small satellites represent the only affordable and meaningful solution for the development of future cooperative distributed space systems – constellations and formations – to provide a new observational dimension in the field remote sensing (Saylor et al. 2007). Table 16 gives an overview of such constellations in operation as well as in planning or under development. However, in the vast field of Sun–Earth research, there are mission requirements that call for hundreds of near-simultaneous measurements at widely distributed locations within the Earth's magnetosphere. Obviously, these new constellations require a high degree of operational autonomy as well as new concepts in spacecraft deployment and manufacturing.

Table 16. Overview of small satellite constellation missions in remote sensing.

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Notes

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