Advancing Small Satellite Earth Observation: Operational Spacecraft, Planned Missions And Future Concepts

A Wicks
A da Silva-Curiel
Dr. J Ward
Dr. M Fouquet

Surrey Space Centre
University of Surrey
Guildford, Surrey GU2 7XH, UK
Tel: (44) 1483 259278 Fax: (44) 1483 259503
Internet: a.wicks@eim.surrey.ac.uk
WWW: http://www.sstl.co.uk

Abstract. The launch of Surrey's UoSAT-12 in April 1999 heralded a new era in small-satellite Earth observation. The UoSAT-12 mission, Surrey's first mini-satellite, supports a variety of payloads, including a 10-m panchromatic imager and a 32-m multispectral imager - both built at Surrey using COTS technology. In building these imagers, Surrey applied the lessons learned over sixteen microsatellite missions, and took advantage of the minisatellite class platform, which can support larger payloads and more complex missions.

In the year since launch, UoSAT-12 has succeeded in a series of demonstrations of key remote-sensing technologies and techniques including autonomous station keeping, repeat ground track maintenance, high-speed communications, slewing and ground target tracking. This paper reviews these operational achievements and also describes next-generation remote sensing missions under development at Surrey.

Spurred by the outstanding success of UoSAT-12, Surrey is already planning more ambitious remote sensing missions. Already, minisatellite advances are feeding back into microsatellites, such as an enhanced microsatellite with 12-m panchromatic and 24-m multispectral imaging. Future minisatellite missions are pushing the boundaries further, including 4-m panchromatic and 13-m multispectral payloads based on COTS technology.

Planned missions and future concepts are presented which include use of pushbroom imagers, development of new imagers, Earth observations constellations and improved data handling as applied to small satellites.

UoSAT-12 has proven that small satellites can offer rapid development, cost-constrained Earth observations missions. These affordable missions offer the opportunity for governmental and commercial organisation to target specific applications and provide emerging space nations with independent Earth observation.

Introduction

From the early 1980's, advances in microelectronics and their mass production, as well as improvements in Commercial-Off-The-Shelf (COTS) component reliability, have enabled small satellites to be manufactured and launched within short time-scales and on tight budgets. As the commercial arm of the Surrey Space Centre in the University of Surrey, Surrey Satellite Technology Ltd. (SSTL) in the UK has pioneered the use of modern micro-satellites weighing less than 100kg. In the early 1990's it had established through its first five experimental space missions that small inexpensive space missions could contribute significantly to space science and education, and enhance spacecraft technology. Subsequent missions have employed this technology to enable a wide range of applications including Store and Forward Communications, Low and Medium resolution Earth Observation, and Space Science.

Figure 1 summarises the SSTL missions. As regular missions are flown, small evolutionary steps can be made in technology, thus enhancing and improving the performance and specifications in every new mission. SSTL's recent missions Clementine, FASAT, TMSAT, and UoSAT-12 are well into their operational phases now. Most recently, July 2000, the Tsinghua-1 microsatellite and SNAP-1 nanosatellite, have been launched and have yielded positive results during their commissioning phase.

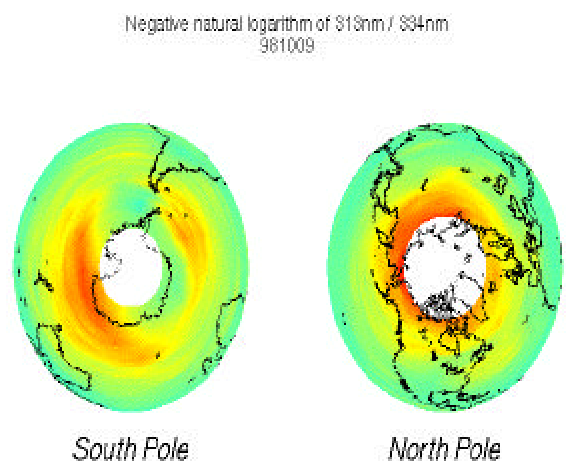
#	Launch	Satellite	Orbit	Mission (primary, secondary)	Primary customer
1	'81	**UoSAT-1**	540km, 97.5° (SS)	Education	Univ. of Surrey
2	'84	**UoSAT-2**	690km, 98° (SS)	Digital Comms, Space science	Univ. of Surrey
3	'90	**UoSAT-3**	780km, 98° (SS)	Digital Comms	VITA, SSTL
4	'90	**UoSAT-4**	780km, 98° (SS)	Imaging, Space science	SSTL (UK)
5	'91	**UoSAT-5**	780km, 98° (SS)	Earth Observation, Digital Comms,	SSTL (UK)
6	'92	**KitSat-1**	1325km, 66°	Earth Observation, Tech.Demo	KAIST (S.Korea)
7	'92	**S80/T**	1325km, 66°	Comms	MMS (France)
8	'93	**KitSat-2**	810km, 98.6° (SS)	Earth Observation, Tech.Demo	KAIST (Built in S.Korea)
9	'93	**HealthSat-2**	810km, 98.6° (SS)	Digital communications	Satelife, VITA, DataTrax (US)
10	'93	**PoSat-1**	810km, 98.6° (SS)	Tech.Demo	PoSAT consortium (Portugal)
11	'95	**CERISE**	670km, 98.1° (SS)	ELINT	Alcatel Espace (France)
12	'95	**FASat-Alfa**	675km, 82.5°	Tech.Demo	Chilean Air Force
13	'98	**FASat-Bravo**	821km, 98.6° (SS)	Tech.Demo	Chilean Air Force
14	'98	**TMSat**	821km, 98.6° (SS)	Tech.Demo	TMC (Thailand)
15	'99	**UoSAT-12**	650km, 64.5°	Earth Observation, Tech. Demo	SSTL, ESA, NTU (Singapore)
16	'99	**Clementine**	670km, 98.1° (SS)	ELINT	Alcatel Espace (France)
17	'00	**TiungSat**	Awaiting launch	Earth Observation, Space Science	Malaysian Government
18	'00	**PICOSat**	Awaiting launch	Technology Demonstration	SMC/TEL, FCT (USAF)
19	'00	**SNAP**	Awaiting launch	Technology Demonstration	SSTL (UK)
20	'00	**Tsinghua-1**	Awaiting launch	Earth Observation, Tech. Demo	Tsinghua Univ. (China)
(21-26)	'01-'02	**ESAT**	Under construction	Digital communications.	DBSI (US)
27	'01	**BILTENSAT**	Contract signed	Earth Observation, Tech. Demo	BILTEN Tubitek (Turkey)
(28-31)	'02	**RapidEye**	Under development	Earth Observation (4 satellites)	Rapideye AG

Figure 1 Spectrum of Surrey Satellite Platforms

FASAT-Bravo

The FASAT-Bravo microsatellite mission was launched together with TMSAT (renamed **Thai Phutt** in orbit), for the Chilean Air Force. It is a Space science and technology demonstration mission, carrying a digital store and forward payload with an experimental Digital Signal Processing payload, and panchromatic narrow (120m GSD) and wide angle (2km GSD) cameras of similar technology to TMSAT. The primary science instrument is the Ozone UV Backscatter Instruments (OUBI). This comprises two UV sensitive cameras and four photodiodes, which permit global ozone levels to be inferred and monitored. This experimental instrument and has already returned valuable scientific data on global ozone levels and its seasonal variation. The characteristics of the Ozone Mapping Detector (OMAD) payload are illustrated in Figure 2, together with a snapshot of a year long sequence of backscatter measurements over the two poles, showing areas over the South pole with a clear lack of ozone concentration.

The two cameras are tuned to 380 and 313nm and cover an area of 560x400km each at a Ground Sampling Distance of 1.4km. By processing the differences between the two images, an instantaneous ozone concentration images can be collected for the first time, and sample output of the two channels is presented in Figure 4.



No. of Channels	4 linear radiometric channels
Optical Band Centre	380 nm, 334 nm, 313 nm, 289 nm
Optical Bandwith	10 nm per channel
Field of View	11° x 11°
Coverage Area	150 km x 150 km per channel
Lens	12.5 mm, f/1.1
Filter	AR-coated fused silica bi-convex (4)
Sensor	UV-enhanced photodiode (4)
Sensor Size	2.4mm x 2.4 mm
Sample Rate	1-15 seconds (typical)
Digitisation	12 bits
Payload Power	0.5 W continuous operation

Figure 2 OMAD characteristics and typical output over a single day

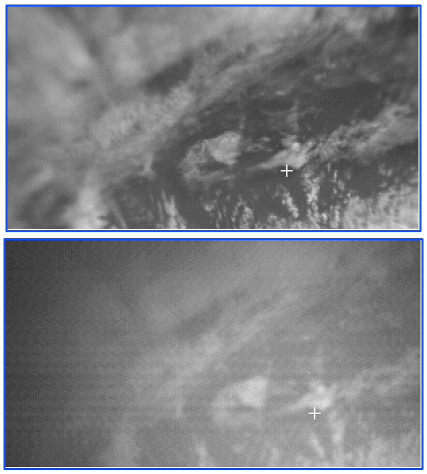


Figure 3 OMAD data in albedo and ozone channel

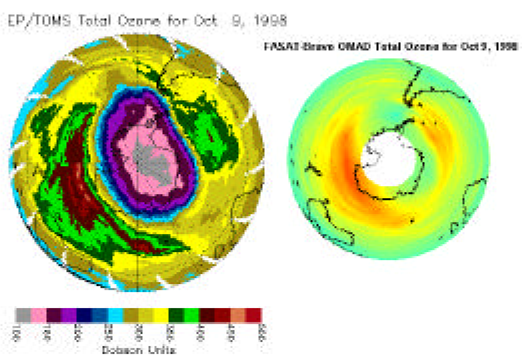


Figure 4 Agreement between TOMS and FASAT data

The instrument relies on measurement of UV backscatter in 4 bands over the sunlit part of the orbit. The ratios of backscatter in bands are a guide to ozone levels in the upper atmosphere, and the photodiode channels permit regular in-orbit calibration. The instrument is constructed using low cost techniques based on existing SSTL camera hardware, and simple dye based filters are employed and applied to conventional array CCD's. Altogether the instrument was developed and built within a US$50k budget, but it was also carefully calibrated at NASA facilities. The data compares closely with the data from the NASA TOMS-EP mission. In addition seasonal polar ice growth has also been observed via the albedo channel.

UoSAT-12

Following the successful build and launch of twelve 50-kg microsatellites by 1995, the Surrey Space Centre made a strategic decision to develop and demonstrate a larger low-cost satellite platform. This internally funded project became the UoSAT-12 research and development minisatellite, a 312-kg satellite demonstrating key low-cost platform and payload technologies. The US$8M mission was launched on the 21st April 1999 on a 'DNEPR' converted SS-18 Inter Continental Ballistic Missile (ICBM), and placed into a 650 km, 65° orbit. The mission carries largely technology development payloads to pilot future Surrey small-satellite applications, alongside proven microsatellite systems. Experiments include an attitude control test bed, remote sensing systems, Global Positioning System (GPS) orbit determination payload in collaboration with ESA ESTEC, L-to-S band communications transponder in collaboration with Nanyang Technological University in Singapore, orbit station-keeping systems, as well as various trials and flight qualification of new components and equipment. As SSTL owns the spacecraft, most of its in orbit resources are available for experimentation, and since its launch a significant number of experiments have been performed.

A year in orbit, UoSAT-12 has demonstrated some key technologies for furthering small satellite Earth observation capability:

- The new minisatellite platform, capable of offering more power, mass and volume to payloads and sub-systems
- High resolution imagers: the 10 m panchromatic and 36 m multispectral imagers having increased SSTL mission performance and provided invaluable experience in dealing with more sophisticated payloads
- Full 3-axis control and off-pointing capability has increased performance, revisit rates. The ADCS is also suitable for missions using high resolution pushbroom imagers.
- On-board orbit control: SSTL's own GPS receiver, resistojet, cold gas propulsion system and software have been qualified.
- Orbit manoeuvreing, orbit maintenance (including autonomous orbit control) and orbit determination capability necessary for constellations.

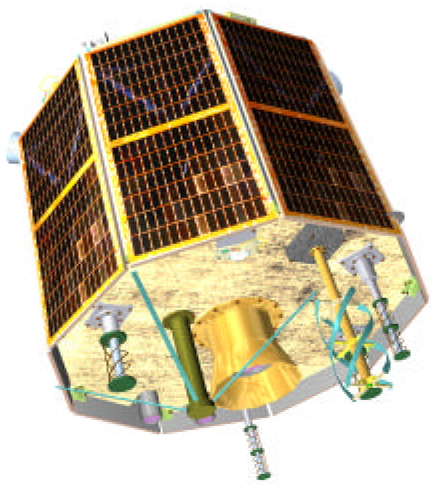


Figure 5 UoSAT-12 external view

The spacecraft structure comprises a baseplate with three load-bearing microsatellite stacks, permitting existing microsatellite designs to be employed alongside new developments. As a consequence the structure has 9 solar panels. The baseplate also has the attach fitting and integrates the cold gas propulsion system. A payload compartment is carried on the top of the stacks and is nominally Earth Facing on UoSAT-12. The central core of the spacecraft is hollow, and carries the 10 m panchromatic imager.

Despite its appearance as a spinner, the Attitude control and Determination system provides full 3-axis control. Actuators include three orthogonal reaction wheels, magnetorquers and cold gas thrusters. Sensors include magnetometers, a quartz rate gyro, two star cameras, fine sun sensors and a horizon sensor. A gravity gradient boom is carried on the space facing side to permit continuation of the digital Store and Forward mission for many years after the cold gas has run out and reaction wheels have failed. Modes developed include nadir, sun and inertial pointing, inertial tracking (moon). To support the Earth imaging payload, roll slewing and Earth target tracking have been developed. Spacecraft yaw manoeuvres have also been developed in order to orient sensors and actuators. The spacecraft is generally operated in a sun pointing mode to provide greatest power, and is actively manoeuvred during the orbital imaging season.

The SSTL GPS payload [3] was developed in collaboration with ESA ESTEC and combines 24 channels with five antennas, and in-orbit programmable software code to provide an attitude determination test bed. The receiver has been successfully employed in orbit determination, with a Time to First Fix from cold standby of 4 minutes, and 90s for an initialised receiver. The most dramatic data is plotted in Figure 6, which shows the point in time as Selective Availability was removed. Individual position fix accuracy improves from 100m to better than 25m (3-sigma), when compared with an Epicycle orbit filter. Work on attitude determination is continuing, and post processed data has shown that Roll/Pitch can be determined to better than 1-degree (1-sigma). It is likely to lead to a system capable of 0.1° attitude measurement on board.

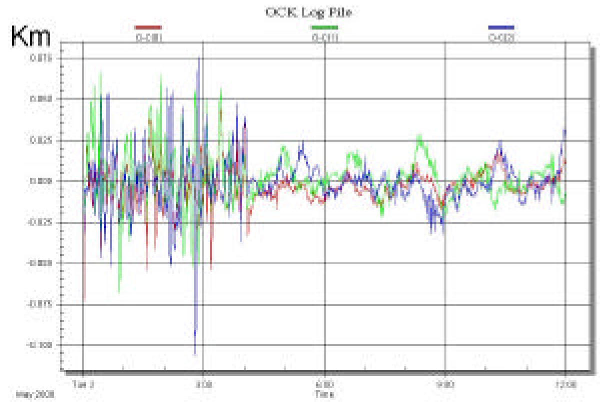


Figure 6 GPS on UoSAT-12: before and after SA was switched

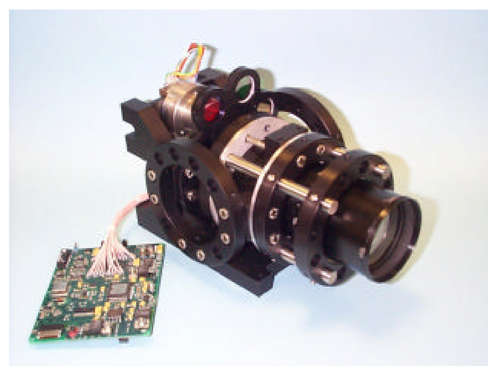


Figure 7 UoSAT-12 multispectral imager

The mission carries a 6 band multispectral imager with 60x30km Field Of View and 30m Ground sampling distance. The camera instrument has been completely manufactured using Commercial Off The Shelf (COTS) optics and optical test bench equipment, and employs two 1024x1024 array CCD's and filter wheels.

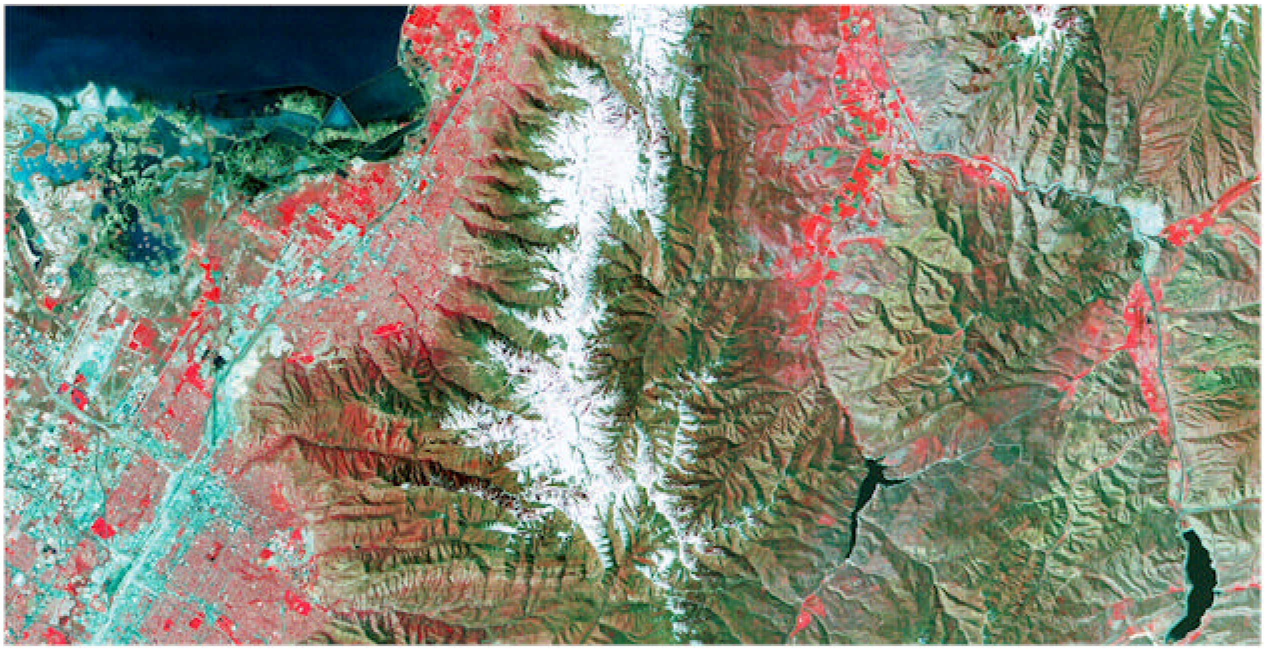


Figure 8 Salt lake city: NIR and Green bands

Figure 9 Panchromatic Image: Damn at Aswan in Egypt

A panchromatic imager is also carried with 10×10km Field Of View and 10m Ground Sampling Distance. As the spacecraft is in 65-degree inclined orbit, it experiences different lighting conditions during the orbital seasons, which is ideal for experimentation with exposure times and different remote sensing applications. A typical image is shown in . Recent images can be found in [10].

An advanced ADCS provides flexibility in the system, which can particularly benefit communications and imaging. Target pointing (off-pointing) and target tracking, including moon tracking, have been demonstrated with UoSAT-12. The image sequence below shows a pass over the UK, when the spacecraft was tracking the Surrey Space Centre in

Guildford. Currently off-pointing and target tracking is limited to 1°, a figure solely limited by the accuracy of the on-board sensors. Following commissioning of the star cameras, much higher accuracy is expected.

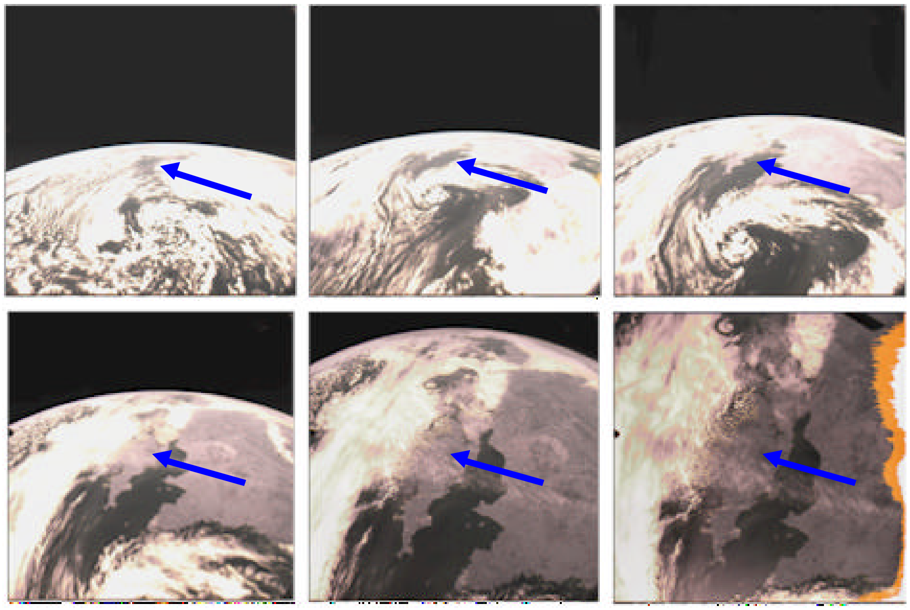


Figure 10 Target tracking by UoSAT-12 of Surrey Space Centre in Guildford (UK)

A conventional cold-gas propulsion system is carried, but also an experimental resistojet electric propulsion system. Water or nitrous oxide is super-heated over a resistive heater element, and the resulting hot gas is expelled through a nozzle to produce low-level thrust at moderate specific impulse. The UoSAT-12 thruster delivers 93mN of thrust, for 90 watts of input power, with a Specific Impulse (Isp) of 127 seconds. A total ΔV capacity of 10.4 m/s is carried by a 2-litre tank of self-pressurising nitrous oxide. The engine is ideally suited to station keeping applications where low cost and safety are primary drivers, and was developed and for some SSTL's proposed constellations.

The resistojet has also been actively employed in a successful flight demonstration for Microcosm of their Orbit Control Kit, which uses the GPS receiver in conjunction with the Resistojet in order to actively control the orbit so that the satellite position can be accurately predicted far ahead in the future. A high precision propagator is used to predict the spacecraft position, and in comparison with the GPS position measurement, the unpredictable elements such as drag are compensated. A frozen orbit is maintained for this.

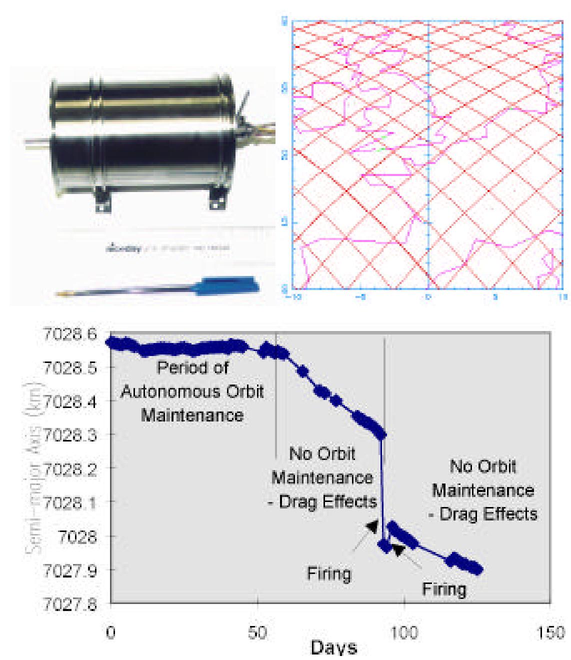


Figure 11 UoSAT-12 drag compensation

UoSAT-12 carries three on-board computers, and although standard SSTL equipment, their processing capability has been exploited in an experiment [7] in collaboration with VyTek LLC and NASA (represented through the project contractor Computer Sciences Corp). An IP stack was ported to the spacecraft computer to allow the groundstation receiver to be connected to a low cost IP router, thus making the spacecraft an active node on the Internet. Experiments have reached a point where the spacecraft has been 'pinged' from NASA Goddard as the spacecraft was in range of the SSTL station, and file transfers and blind commanding trials are in progress. Eventually full Store and Forward protocols and Simple Mail Transfer Protocols (SMTP) mission data delivery will be implemented. It is anticipated that these COTS techniques may extend low cost operations to complex distributed or collaborative missions, and allow existing global infrastructure to be used seamlessly to deliver data to the Virtual Control Centre of the Principle Investigator.

Tsinghua-1

With the experiences gained on the TMSAT, FASAT and UoSAT-12 missions, a number of new small-satellite applications have been enabled by following an evolutionary path. TiungSat and Tsinghua-1 are the latest steps in the evolution of small imaging microsatellites.

Tsinghua-1, launched July 2000 on the Cosmos launcher, is the forerunner of the Disaster Monitoring Constellation mission which aims to place up to eight satellites in orbit to provide global daily revisit for disaster management through provision of medium resolution imagery. It carries a multispectral imager with 36m GSD and a full three-axis control attitude system, for Tsinghua University in China.

SNAP-1

The Surrey Nanosatellite Applications Platform (SNAP) mission is largely an internally funded SSTL technology development mission. The 6.5kg spacecraft has been designed and built in under a year, with the aim to develop a small platform for technology demonstration, space science, space education, and effective in applications requiring large constellations or in swarms. In education, the small platform has proven to be an excellent tool as a focus for short courses and post-graduate student projects.

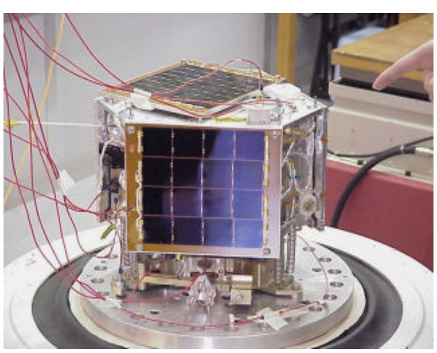


Figure 12 SNAP undergoing testing

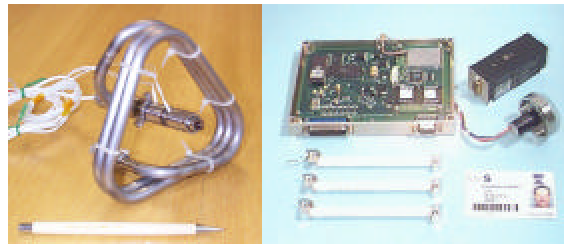


Figure 13 (L) SNAP butane propulsion system (R) SNAP ADCS

SNAP-1, was launched in July 2000 with the Tsinghua-1 microsatellite. It carries a micro-propulsion system and cameras in order to demonstrate formation flying techniques, inter-satellite communications and remote inspection. The mission size has been carefully balanced to permit common COTS technology to be applied so that the spacecraft can be employed in a typical 1-year University course.

The spacecraft carries a VHF receiver and an S-band downlink, as well as an intersatellite link to communicate with Tsinghua-1. A StrongArm OBC offers significant processing power at very low power, and includes 16Mbytes of Flash memory and 4Mbytes of EDAC protected code memory. A miniature reaction wheel and magnetorquer and magnetometer combination will offer full three axis control. A miniaturised GPS receiver will be carried based on the one flown on UoSAT-12, and employed to perform differential orbit determinations in conjunction with Tsinghua-1. A 30mN butane cold gas system has 3m/s capacity, and allows SNAP to be flown in formation with Tsinghua-1. Payloads include four CMOS cameras as demonstrated on Thai Phutt, in order to validate the remote inspection capabilities and applications of the spacecraft.

Current Projects and Future Missions

At the same time, UoSAT-12 experience is leading to a class of 100kg enhanced microsatellites to carry out similar imaging missions. For instance the BiltenSat mission aims to perform 13m panchromatic imaging using an agile 3-axis stabilised platform. The same enhanced microsatellite platform is baseline for use with the six-satellite ESAT constellation to provide store and forward messaging for DBSI (US). The 125kg satellites will be deployed in 2 planes of 3 satellites, and use cold gas propulsion for station keeping. It carries a payload to remotely read utility meters via a 1.5m antenna, and will be gravity gradient stabilised.

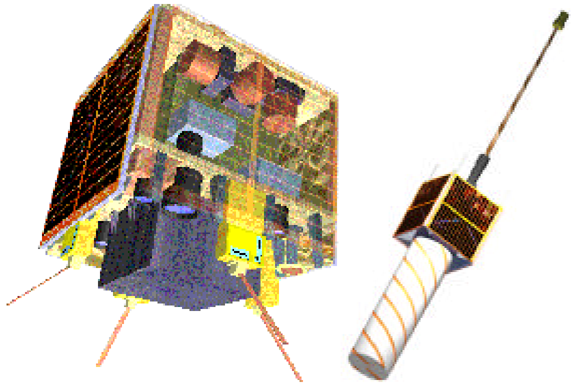


Figure 14. Enhanced Microsatellite

Results from UoSAT-12 are stimulating further Earth observation missions, and the platform is slated to be used in the RapidEye constellation of four Earth observation satellite to carry out 6m pan-chromatic imaging. The platform also forms the basis of a proposal for a Geostationary small spacecraft to serve niche communications, science and meteorological applications.

A new generation of microsatellite has been developed to serve small satellite constellations in particular. The 'Constella' platform is aimed at mass production and for launch in batches. Canted body-mounted solar panels offer a good power profile in non-sun-synchronous orbits, and provide a large instrument platform.

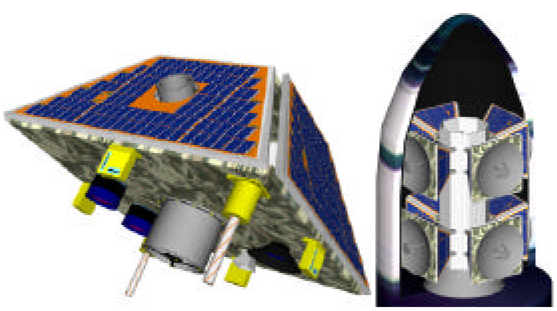


Figure 15 Constella platform and launch configuration

The platform has been selected as the baseline for the 16-satellite GANDER constellation [9], each of which will carry a radar alimeter in order to measure global daily sea state on a commercial basis to the shipping and offshore industry.

Figure 16. Geostationary Minisatellite

Conclusions

The major recent results of the SSTL Earth observation missions have been presented. It can be seen that performance boundaries have been pushed by the qualification of new nano and minisatellite buses and advanced on-board sub-systems and operations. At the same time existing performance levels can be achieved on smaller and cheaper platforms, opening up new opportunities for business and education.