SCIENCE MISSION SCENARIOS USING "PALMSAT" PICO-SATELLITE TECHNOLOGIES

Dr. Craig Underwood*, Dr Vaios Lappas*, Dr. Alex da Silva Curiel+, Dr. Martin Unwin+,
Dr. Adam Baker+, Prof. Sir Martin Sweeting+

*PLANETARY ENVIRONMENTS GROUP, SURREY SPACE CENTRE,
+SURREY SATELLITE TECHNOLOGY LTD,

University of Surrey, Guildford, Surrey GU2 7XH, UK

Tel: (44) 1483 689278 Fax: (44) 1483 689503

Email: c.underwood@surrey.ac.uk

www.sstl.co.uk

ABSTRACT

The Recent efforts to provide low cost access to space for education and technology demonstration have led to the concept of the pico-satellite – a satellite of the order of 1 kg in mass. Students at the Surrey Space Centre, are developing such a satellite – PalmSat – which has a number of potential scientific applications when launched in a swarm, or alongside a micro-satellite "mother-craft". PalmSat builds upon the success of Surrey's 6.5 kg SNAP-1 nano-satellite, launched in 2000, and yet takes the concept of spacecraft miniaturization a step further, from a modular commercial-off-the-shelf (COTS) technology based spacecraft formed of "Eurocard" (165 mm x 120 mm) sized payload and bus-system modules, to one based on "credit-card" (90 mm x 55 mm) sized modules.

As with SNAP-1, PalmSat will carry miniature propulsion and attitude control systems. Its first mission is aimed at demonstrating spacecraft rendezvous and remote-inspection, using CMOS camera technology. However, other miniature payloads are under development, including ionising particle detectors, magneto-resistive magnetometers, GPS receivers, thermal-infra-red micro-bolometer imagers, near ultra-violet radiometers and multi-spectral imagers, which enable PalmSat-class spacecraft to carry out scientific investigations in a cost-effective manner. This paper describes these developments and the missions they can support.

1 INTRODUCTION

Rapid developments in the consumer electronics industry continue to drive up the performance, and drive down the cost, size, mass and power consumption of commercial microelectronics-based systems. There is therefore a direct synergy between the characteristics of state-of-the-art, commercial-off-the-shelf (COTS) technologies, and the needs of the small satellite community – i.e. to develop highly capable spacecraft systems under very severe mass, volume and cost constraints.

As spacecraft size is a large factor in determining space mission cost, there is a continuing interest – particularly among university research groups – in exploring the lower limit of the size of a spacecraft capable of achieving a significant mission aim. This has lead to a steady stream of increasingly diminutive satellites, ranging from the micro-satellites (i.e. sub 100 kg satellites) of the 1980's and 90's, to the nano-satellites (i.e. sub-10 kg satellites) of the turn of the millennium.

The cost of a typical (sophisticated) micro/nano-satellite mission is of the order of $1-10 million (US) – i.e. orders of magnitude lower than traditional space missions, but still beyond the reach of most educational organisations. However, recent developments in semiconductor and micro-electro-mechanical systems (MEMS) technology have made it possible to design ultra-small (*circa* 1 kg) satellites, which have mission costs of just a few tens of thousands of dollars (US), thus enabling educational institutes to have access to space – even within limited financial resources.

A number of universities are now engaged in designing and constructing (and in some cases have already launched) such satellites. A key development in this process has been the "CubeSat" concept proposed at the University Space Systems Symposium (USSS) in Hawaii in November 1999 by Robert Twiggs of Stanford University. The CubeSat programme has lead to an international collaboration between more than 20 educational institutions including ones from the US, Canada, Japan and Europe [1].

Pico-satellites have direct applicability to graduate and post-graduate engineering education. The relatively low cost of pico-satellite technology means that they become affordable within the context of "laboratory" equipment, and their relative simplicity means that systems and principles can be taught in a clear fashion with direct relevance to systems engineering as applied to major aerospace projects. Students are therefore encouraged to develop their own designs, with some companies providing suitable building blocks or complete sub-systems.

Uniquely, there is the added bonus, that the self-same equipment can be put together as part of a real spacecraft and flown! To this end, the CubeSat concept is accompanied by a standard set of launch interface specifications, limiting the spacecraft to a cubical volume of approximately 10x10x10cm, and to a launch mass of 1 kg, to enable their launch from the P-POD deployer (Fig. 1). The first of the CubeSats were launched in 2003.

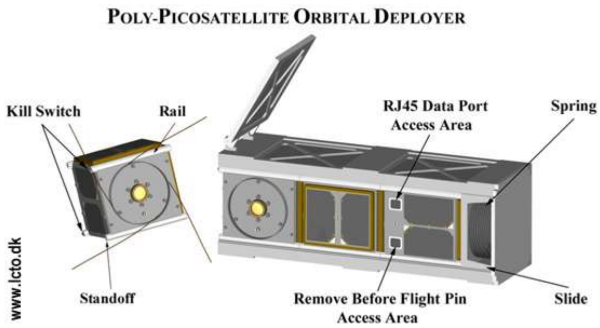

Figure 1. CubeSat and P-POD Deployer
http://www.cubesat.auc.dk/mission1.html

The University of Surrey has a similar pico-satellite programme – PalmSat – intended both as an educational vehicle, and as a demonstrator of advanced technologies for real mission applications. PalmSat builds upon Surrey's nano-satellite experience dating back to the mid-1990's, and whilst it aims at a vehicle of similar dimensions and mass to the CubeSats, it is not restricted to the CubeSat form factor. Surrey has regular access to space through the work of Surrey Satellite Technology Ltd (SSTL), and PalmSats may be launched singularly or in multiples using SSTL technology.

PalmSat's current design is as the result of a series of undergraduate and postgraduate engineering projects carried out since 2000 (typically 6-8 per year). The challenge to the students is to design a "pico-satellite" capable of carrying out a rendezvous and inspection mission similar to that of Surrey's SNAP-1 nano-satellite, launched in 2000 [2]. It is intended that this first PalmSat mission be carried out in 2005, and as with SNAP-1, it will be a collaborative venture between Surrey Space Centre (SSC) students and academics, and SSTL.

In the context of education, PalmSat-based projects and laboratory work are expected to play a key part in Surrey's new undergraduate and postgraduate *Space Technology and Planetary Exploration* Degrees planned for 2005.

Remote inspection is just one of the mission scenarios to which advanced pico-satellite technology is suited.

Pico-satellites also offer a relatively cost-effective way to demonstrate and test-out new technologies in space - particularly where such technologies would be considered too risky for conventional, more expensive, spacecraft. These new technologies (micro-electro-mechanical systems - MEMS, low voltage electronics, micro-propulsion, active surfaces, etc.) will in turn greatly enhance the capabilities of future pico-satellites - leading to a virtuous circle of technological development.

However, pico-satellites really start to come into their own when launched *en-masse*, thus spreading the relatively expensive launch and insurance costs over a number of individual platforms. It is therefore to be expected that pico-satellties will become a key enabling technology for cost-effective "swarm"-type missions, where many (perhaps 10's or 100's) of pico-satellites will be deployed to synthesise some mission function. Such missions might, for example, involve multipoint sensing for Earth observation or for space science. To this end, Surrey is also developing a series of miniature payloads for scientific and remote sensing applications, which will have utility in such scenarios.

Such missions will also require a degree of cooperation between the pico-satellites, hence autonomous attitude and orbit determination and control, and inter-satellite link technology will become key aspects of the pico-satellite bus. Surrey demonstrated such techniques and technology on SNAP-1, and is now adapting these to PalmSat .

2 THE SURREY EXPERIENCE

The University of Surrey has, over the last 25 years, been a pioneer of small satellite research – spinning-off the results into its commercial-industrial arm – SSTL, whilst also providing "hands-on" education and training to students at Surrey through the "UoSAT" micro-satellite/mini-satellite, "SNAP" nano-satellite and now "PalmSat" pico-satellite programmes.

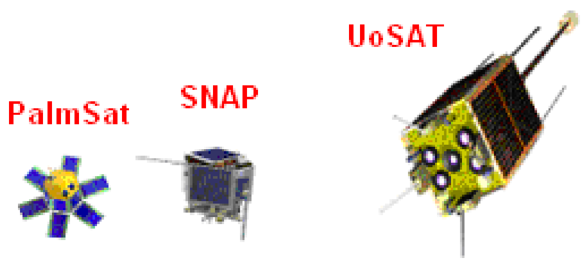

Figure 2. Surrey's Spacecraft Programmes

The UoSAT programme has its origin in the late-1970's, with the first satellite, UoSAT-1 (UoSAT-OSCAR-9) – a *circa* 50 kg micro-satellite – being launched in 1981. This was quickly followed by UoSAT-2 (UoSAT-OSCAR-11) in 1984. SSTL, formed in 1985, has gone on to develop this technology, and to market it world wide, launching on average just over one satellite per year.

The Surrey Nano-satellite Applications Programme (SNAP) was conceived in the mid-1990s as a means of demonstrating a low-cost COTS-based nano-satellite platform for both technological and educational use.

Work began as a series of design-studies and systems prototypes carried out in the context of undergraduate and postgraduate student projects within the Surrey Space Centre. However, in 1999, the programme was adopted by SSTL as part of its internally funded research and development activities, and this resulted in the final definition of the SNAP-1 mission, which was formally begun in October 1999.

The objectives set for the mission were to develop and flight-prove a modular COTS-technology-based nano-satellite bus and, in the process, evaluate new manufacturing techniques and technologies. The spacecraft was to be used to obtain images of the deployment of the SSTL-built Chinese Tsinghua-1 micro-satellite, launched alongside SNAP-1 using a machine vision system (MVS) comprising four miniature CMOS video cameras [3]. Following this, SNAP-1 was to demonstrate the systems and techniques required for future nano-satellite constellations – i.e. three-axis attitude control (using magnetorquers and a miniature pitch-axis momentum-wheel) [4]; precise on-board orbit determination (using a credit-card-sized global-positioning-system (GPS) system), and to carry out automated orbital manoeuvres (using a butane-propellant-based cold gas thruster) [5].

If propellant reserves allowed, SNAP-1 was finally to rendezvous with Tsinghua-1 and demonstrate 'formation flying'. SNAP-1 also carried a UHF inter-satellite link for communications with Tsinghua-1, and a VHF spread-spectrum communications payload.

The resultant 6.5 kg nano-satellite was completed in May 2000 and successfully launched on June 28th 2000 from the Plesetsk cosmodrome on-board a Russian Cosmos rocket – just nine months from definition-to-orbit!

SNAP-1 was deployed into a 700 km Sun-synchronous orbit from a Russian COSPAS-SARSAT satellite, called Nadezhda. As it deployed, its MVS automatically activated and it duly acquired an image sequence showing the deployment of Tsinghua-1 from the same vehicle. Once three-axis attitude control was established, the ~50 mN propulsion system was used to try to bring SNAP-1 and Tsinghua-1 back together. This was made difficult by the differential effects of atmospheric drag, which resulted in SNAP-1 falling approximately 10m per day with respect to Tsinghua-1. This, coupled with the initial orbital insertion conditions, meant that SNAP-1 started from a position approximately 2 km below Tsinghua-1, and some considerable distance ahead of it. Thus, SNAP-1's thruster had to be used extensively to regain altitude (Tsinghua-1 was a purely passive target). Therefore, a long sequence of firings was initiated under the automatic control of the OBC, and the GPS navigation system was used to keep track of the orbital changes.

Over a period of 30 days, the thruster was fired approximately four times per day, giving a change in velocity (ΔV) of approximately 10 cm s^{-1} per day, by which time SNAP-1 had climbed approximately 1 km above Tsinghua-1. High solar activity meant that a further sequence of firings was necessary to attain rendezvous, and unfortunately during this phase the propellant ran out. In total, the propulsion system raised the altitude of SNAP-1 by the equivalent of approximately 4 km (corresponding to a total ΔV of 2.1 m s^{-1}), all done with just 32.6 g of butane propellant.

At maximum separation, Tsinghua-1 and SNAP-1 were approximately 15,000 km apart but, by means of these manoeuvres, SNAP-1 brought itself to within 2,000 km of its target. Thus, while a true rendezvous was not achieved, the agility and manoeuvrability of SNAP-1 under automatic control was amply demonstrated, meeting its purpose of demonstrating that nano-satellites can be constructed rapidly to achieve sophisticated mission objectives at ~$1 million total mission cost.

The PalmSat-1 has similar mission objectives, but these must be achieved at lower cost and with a vehicle of only 1 kg mass!

3 DESIGN PHILOSOPHY

The design philosophy for the SNAP nano-satellites played a key role in enabling the SNAP-1 mission to be developed and executed so quickly. SNAP-1 used miniaturized but otherwise conventional mechanical and electronic "COTS" technologies within a "modular" framework. Thus, Surrey's approach to nano-satellite design can be regarded as a natural extension of the COTS-based modular design approach that it has applied so successfully to its micro-satellites [6].

The approach can be encapsulated in a few key principles, namely:

- To make the design modular, and to standardise both the electrical, and mechanical interfaces, facilitating concurrent design, and ensuring that assembly and test is as easy as possible.
- To use advanced COTS technologies, but to make the way that they are used (i.e. the spacecraft architecture) as robust as possible.

For SNAP-1, a simple standard electrical interface was prescribed for each module, consisting of regulated 5V and raw battery (V_{batt} ~7.2V) power connections, with a single bi-directional Controller-Area-Network (CAN) bus for data transfer. These connections are provided via a 9-way D-type connector, which is standard to all modules. An additional 44-way D-type connector was allowed for each module to provide for specific point-to-point connections (where absolutely necessary). This greatly simplified testing and harness design.

All modules used a standard Controller-Area Network (CAN) bus for on-board data handling.

A standard module box mechanical format was also defined at the beginning of the SNAP programme, thus, every module on SNAP-1 has the same external dimensions, sized approximately to house a standard "Eurocard" printed circuit board (160 mm x 100 mm, with ~13 mm of useable depth).

This approach allowed the mechanics, avionics and payload design to occur in parallel, and largely in isolation. It also allowed procurement to start at a very early stage in the programme. This was essential given the very tight schedule we had to work to in order to meet the launch date.

The lessons learnt from the experience of SNAP-1 mission were that all these were good decisions – although the engineers did complain about the tightness of fit to the mechanical envelope of the standard module!

So, is this approach still valid for PalmSat?

As spacecraft masses reduce and performance requirements raised, technologies such as MEMS and highly integrated electronics become increasingly attractive, if not essential.

Increased integration could ultimately lead to the spacecraft bus systems becoming a single unit – a single board (or even a single chip!).

Whilst Surrey is working on a fully integrated single-chip spacecraft concept [7], PalmSat is an intermediate stage. Thus, we shall still retain the modular design philosophy applied to SNAP – albeit with smaller, more integrated ("credit-card"-sized) modules. We shall also continue to advocate a simple payload interface of, (essentially), power, ground, data in and data out. PalmSats will therefore comprise two blocks of modules based upon credit-card-sized (i.e. 90 mm x 55 mm) circuits:

The "housekeeping" block comprises 7 modules:

- Power System
- On-Board Computer
- UHF Uplink/Downlink Transceiver and Modem
- VHF Uplink Receiver and Modem (optional)
- Attitude Control System (Magnetorquer Rods)
- Attitude Determination System (tri-axial Magnetometer – Sun-Sensors optional)
- GPS Receiver

The "Payload" block will similarly be credit card sized and will comprise (in the first instance):

- CMOS Camera (Pair for Remote Inspection)
- 2.4 GHz ISM Band Inter-Satellite Link.

A separate Orbit Control System (a water-based Resistojet) will be attached to the base of the spacecraft to provide propulsion.

Whilst the housekeeping block will have multiple internal connections, the interfact to the payload will be CAN data in and data out (2 wires), regulated +5V (or +3.3V), raw battery voltage (~6-8V) and ground.

4 PALMSAT'S CONFIGURATION

4.1 Structure/ Thermal Control

PalmSat's mechanical structural design is aimed at keeping size of the satellite at a minimum, whilst at the same time providing a maximum surface area facing the Sun for solar-power generation To this end, we have chosen to construct the satellite body as an hexagonal prism, with six rectangular faces and two hexagonal faces. Six rectangular "panels" deploy from this body to provide extra power-generating surfaces (see Fig. 3).

The size of each rectangular face is approximately 10 cm × 6 cm, and each can support two 4 cm x 4 cm cells per face, giving 12 body-mounted cells and 24 deployed panel-mounted cells. The body-mounted cells act as passive thermal control surfaces – as do the hexagonal end-facets, which support the antennae and payload cameras. The walls are formed from 2mm thick aluminium alloy to provide radiation dose shielding.

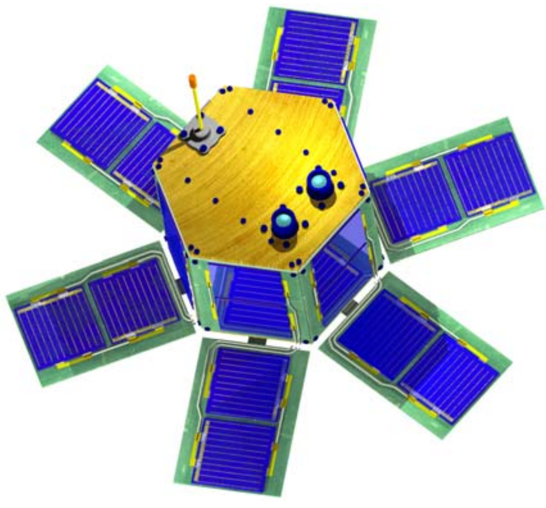

Figure 3. PalmSat with Deployed Panels

4.2 Power System

An unregulated power bus/ peak-power tracking topology has been adopted for the design of the power sub-system. Triple-junction solar-cells are used to maximize the power available. The use of two cells per panel (18 panels in all) gives a raw solar-panel operating voltage of approximately 4 V, which is sufficient to drive the internal DC-DC power converters (minimum input = 3.5 V).

Each panel gives ~210 mA at ~4.2 V under load (at a panel temperature of 28 ^{o}C), therefore the input power will vary between ~1.7W and 5.2 W, averaging ~4 W under sunlight – depending upon attitude.

To run the spacecraft's systems and to charge the battery, this raw voltage is stepped-up to ~6-8 V by a PIC-controlled boost battery charge regulator (BCR) regulator. This regulator also sets the operating point of the solar panels. Students have produced and examined BCR designs using a discrete power-FET solution, and an integrated COTS power regulator solution. The discrete solution gives better control over the maximum power-point-tracking of each individual panel and could obtain almost a 10% improvement in power availability. However, the COTS solution is simpler to implement. The final choice will depend upon the results of full-system tests planned for this summer.

Nickel-Cadmium (NiCd) batteries have been the technology of choice for low-Earth orbit satellites since the 1960's. However, newer battery technologies such as Nickel-Metal-Hydride (NiMH) and Lithium-Ion (Li-Ion) offer a far superior energy density. Table 1 gives a comparison between the candidate technologies *for small cell sizes*:

Table 1. Battery Technologies

Tech.	*Energy per unit mass Whr kg^{-1}*	*Energy per unit volume Whr dm^{-3}*	*Cell Voltage V*	*Cycle life*
NiCd	40	74	1.2 - 1.7	~1000
NiMH	55	111	1.2 - 1.5	~1000
Li-Ion	122	237	3.7 - 4.2	~500*

** until 20% loss of capacity*

Lithium-ion (Li-ion) batteries are clearly superior in terms of energy density, however there is currently little experience of the use of this technology in space – especially over the long term. Given that a spacecraft in LEO experiences more than 5000 eclipses (i.e. charge/ discharge cycles) per year, the apparently limited cycle lifetime of such cells is a concern.

NiCd and NiMH cells are usually quoted as lasting only up to a 500-1000 charge discharge cycles - but this is highly dependent upon the depth of discharge (DoD) used. For carefully matched cells which are only cycled through ~20% of their capacity, the lifetime can be considerably longer - indeed our own UoSAT-2 satellite (which flew COTS NiCd cells) has now operated for 20 years in space! Lithium ion cells also cannot supply large peak discharge currents - unlike NiCd and NiMH cells, and they have no safe over-charge regime. For these reasons, whilst we might consider using Li-ion cells as an experiment, for now we baseline NiMH or NiCd technology for PalmSat.

Indeed, we propose to use the same high-density Sanyo KR-1400AE "AA"-sized cells cells we flew successfully on SNAP-1. These cells are have a current-storage capacity of 1400 mAhr at 1.2V per cell, and thus a 5-cell pack provides ~ 8.4 Whr of energy in a 120g package (i.e.~70 Whr kg^{-1}).

The battery negative terminal is the star-point ground for the spacecraft.

The unregulated V_{batt} = 6-8 V is passed on to buck-regulators to provide regulated +5V or +3.3V lines to the other sub-systems as required. Further boost regulation is available for higher-voltage systems such as the transmitter.

4.3 On-Board Computer

The on-board computer (OBC) has also been the subject of much student development. An important requirement regarding the OBC design of a spacecraft is the selection of an appropriate processing unit. In the context of PalmSat, the major constraints are size and power. Thus, we looked for a low-power processor, with highly integrated peripheral handling features. The microchip "PIC" family of micro-controllers met this general requirement, whilst also being convenient to use in the context of a student project because of ready availability of low-cost development tools. We initially chose the PIC 16F877 as the core micro-controller for the OBC [8]. This was selected as it has a number of attractive features:

- Simple to program (in assembly language), with in-circuit serial programming and debugging.
- Variable clock rate up to 20MHz and power saving SLEEP mode.
- Low cost and development tools are readily available
- Has attractive peripheral features: USART (serial) port, synchronous serial Port (SSP) with SPI or I^2C interfaces, parallel slave port, for interfacing to other processors, 10-bit multi channel analog-to-digital converter (ADC), and pulse-Width Modulator (PWM) control
- Watchdog Timer (used to protect against single event effect failures), and interrupt capability.
- Wide operating voltage range: 2.0 to 5.5V and low power consumption

However, having decided to use the CAN-bus interface for the payloads, we have now selected the PIC 18F8680. This device has the additional advantages of being able to support 64K of program memory, and has a full CAN 2.0B interface.

The OBC uses its USART serial port to link to the radio-frequency communications system. This handles all the data flow between the spacecraft and the ground. This form of asynchronous serial communications makes testing and emulation with a

PC easy, but does introduce an overhead of start, stop and parity bits on every byte – i.e. 12 bits are required to send every 8-bit byte of information. Many spacecraft (including Surrey's own) use synchronous data links, where the receivers recover the data clock and can optimally sample the incoming digital bit stream. However, to do this requires extra hardware in the form of a Terminal Node Controller (TNC). This hardware could be added later to increase the effective data throughput between the ground and the satellite. For now, we have decided keep the communications simple, and to minimize the need for extra hardware.

Data needs to be exchanged with the spacecraft in an error checked form, so that commands and data are not corrupted by any bit-errors which might occur in transmission. To facilitate this, all data transfers make use of a standardized packet format, which was originally intended for use on the SNAP-1 nano-satellite. The format of the data packets is illustrated in Figure 4.

0	1	2	3	4	5	n	n+1	n+2
SYNC0	SYNC1	D	L	S	T	DATA	CRC0	CRC1

Figure 4. PalmSat Packet Format

- **SYNC0** and **SYNC1** are synchronization bytes to identify the start of the packet
- **D** identifies the destination address of the packet (ground-station, or satellite sub-system)
- **L** identifies the length – 1, thus enabling 256 bytes of data to be sent in a single packet
- **S** indicates the source address where the data originates and where to reply (ground-station or satellite sub-system)
- **T** is the type of packet (Telemetry, Command, Payload Data, etc.)
- **DATA** bytes comprise of the actual data to be transmitted, the maximum number of which is 256 which is represented by
- **CRC0** and **CRC1** are the packet checksum bytes used to check the validity of the packet against bit-errors.

This format was selected for its simplicity and relatively small overhead. The packet requires a cyclic redundancy check to handle the error detection problem. The generator polynomial used is based on CRC16 ($X^{16} + X^{12} + X^5 +1$), which is chosen for its ability to offer maximum detection rate against most kinds of "line" noise. The CRC polynomial chosen detects all single and two bit errors, all transmissions with an odd number of errors and all burst errors with bursts less than 16 bits in length. All bursts greater than this length stand a 0.0015% chance of going undetected. It can therefore be seen that longer the packet length, the greater chance of errors passing undetected.

The RF sub-system includes a minimum-shift-keyed (MSK) modem that operates at 9600 bps, allowing an uncompressed 640 x 480 pixel image to be downloaded in a single pass over a ground-station.

The OBC acquires, and monitors telemetry data from various nodes of spacecraft and handles the packet communications functions with the radio systems. To provide for the storage of telemetry, 8K bytes of external ferro-electric RAM (FRAM) is interfaced serially to the controller, via its I^2C bus. A seriall EEPROM is also used to provide initial operating code for the spacecraft.

The processor also has a link back to the power system controller, which is also linked to the communications system and which can act as a "back-door" into the spacecraft in case of OBC malfunction.

4.4 Communications System

Students have designed and constructed credit-card sized VHF amateur band receivers and and UHF amateur band transmitters. In addition we have also investigated COTS solutions such as the Tekk KS-960 UHF tranceiver. This requires some modification to be made suitable for spaceflight, but it dose provide a convenient basis for an uplink and downlink transceiver. It has a radio-frequency (RF) output power of 2-watts, and operates at a data rate of 9.6 kbps. As the transmitter and receiver share the same frequency, the transceiver is operated in half-duplex mode, with the OBC controlling the data flow via the tranceiver's push-to-talk (PTT) interface.

Half-duplex operation is not always convenient in a space communications context when the gropund requires the acknowledgement of packets. Also, there is a risk that the transmitter may fail stuck on – in which case it would not be possible to send the spacecraft a turn-off command. For these reasons we are also considering a VHF uplink – based on the VEC-1002K 2 meter-band FM receiver kit. This would provide either for full duplex command and control, or possibly form an emergency "back-door" link into the spacecraft.

As currently defined, the antenna is a simple base-loaded monopole deployed from the bas of the spacecraft. The deployed panels acting to some extent as a pseudo-ground plane. If the VHF uplink option is adopted, we propose to use the same antenna via a diplexer.

4.5 Attitude Determination & Control System

The attitude determination and control system (ADCS) primarily comprises a 3-axis magnetometer, and three magnetic torquer rods. This system matches the basic control set flown in SNAP-1, which was capable of independent basic control over the spacecraft without the need for OBC intervention. (SNAP-1 also had a momentum wheel, which provided fine control, albeit with control software running on the OBC).

Students have developed a miniature 3-axis magnetometer head based on the Honeywell HMC2003 magneto-resistive sensor. The sensor, and the 16-bit sampling system potentially gives ~30 μGauss precision, however, we only require ~100 μGauss resolution. The prototype system had a mass of 65 g and a power consumption of 163 mW.

They have similarly produced a miniaturised and improved torque-rod control system, capable of driving 3.8 times the coil current used in SNAP-1, with 43% of the power consumption.

As well as studying this basic system, students have also been developing sub-miniature digital Sun-sensor s based on CMOS diode array technologies. Sensors accurate to 0.1o have been developed based on CMOS cameras, but these are still a little bulky and power-hungry for PalmSat application. Sub-miniature CMOS linear arrays are now under study, which look more promising for PalmSat.

Ideally, the PalmSat ADCS will provide at least the same pointing and stability performance as that achieved by SNAP-1:

Table 2. SNAP-1 ADCS Performance (1-σ) [4]

Roll	Pitch	Yaw
2.9°	0.3°	2.6°

This task is a challenging task for a ~ 1kg spacecraft with ultra miniature sensors and actuators. However, with careful design and state of the art sensors, we believe this is possible [4,9]. Table 3 lists the additional ADCS actuators and sensors required, along with their characteristics. Preliminary analysis indicates that an ultra miniature Brushless COTS DC motor with a mass of 2.5g is feasible for PalmSat. Such a pitch momentum wheel will enable a pointing resolution capability of < 0.5°. The estimated inertia of the platform is $[I_x, I_y, I_z]$=[0.005, 0.005, 0.007] kg-m^2 which requires an 8 g inertia disk (1.9 x 10^{-6} kg-m^2) and thus provides a 0.001 Nms angular momentum.

This momentum wheel would enable slew rates up to 2°s^{-1} making PalmSat agile about its pitch axis.

Momentum dumping can be done via the torque-rods or the thruster. Power consumption of the wheel including will be less than 250 mW.

In order to achieve the specified attitude pointing requirements it is proposed to use a MEMS gyro in a skewed configuration. The SiRRS01 is a MEMS gyro currently in operation on-board the BILSAT-1 enhanced microsatellite [10]. With a low power consumption, the gyro could be adapted for PalmSat. This would require the packaging being modified and together with the removal of various shielding materials, in order to further reduce the mass and decrease the required dimensions of the gyro.

Table 3. PalmSat Advanced ADCS

	Momentum Wheel	**Gyro**
Manufacturer	SSC	BAE
Quantity	1	1
Type	DC Brushless	SiRRS01
Range	0-5000 rpm	18.2 mV/°/σ
Res/accuracy	0-0.001 Nms	ARW 0.2°/hr$^{-1/2}$
Mass	2.5 g	35 g
Size	20xΦ6 mm	31x31x17.3 mm
Power	< 250 mW	250 mW

4.6 GPS Orbit Determination System

Although SNAP-1 already carries a credit-card-sized GPS receiver for orbit determination, SSTL have continued to develop the system. The resulting SGR-05U receiver is based upon a commercial MG5001 OEM GPS board manufactured by an Australian company called Sigtec.

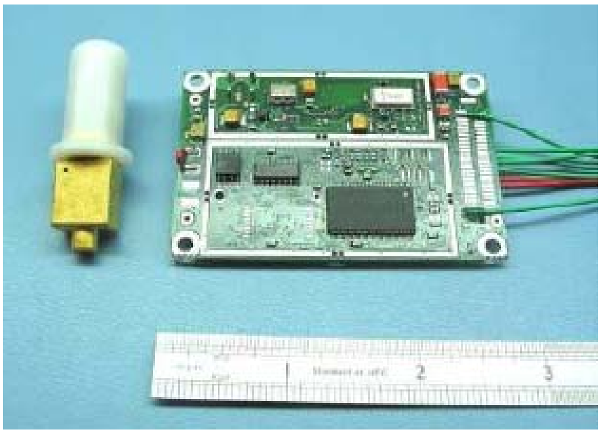

Figure 5. SGR-05U GPS Receiver System

Whilst the SGR-05U is only the core engine of a GPS receiver, its positioning performance is very similar to those systems used on other SSTL spacecraft. It has, however, the advantage of offering very low power consumption (less than 0.8 W) and has small physical dimensions:

- Dimension 70×45×10 mm
- Weight 20 g
- Operation Temperature 0 C to +50 C
- Power Supply 0.5-0.8 W at 5 V

The navigation accuracy has been evaluated using a GPS simulator (Table 4):

Table 4. SGR-05U GPS Navigation Accuracy

	Position [m]	Velocity [cm s^{-1}]
Radial	+0.16 ± 0.49	+0.20 ± 1.91
Along-Track	-0.08 ± 0.21	-0.42 ± 0.72
Cross-Track	-0.00 ± 0.18	-0.32 ± 0.83

SNAP-1 used a patch antenna for its GPS system, however, for PalmSat, a miniature antenna solution has been derived from Sarantel's PowerHelix antenna range (originally intended for portable GPS products or other mobile wireless products).

4.7 Propulsion System

There are a number of candidate propulsion systems under consideration at the moment for PalmSat

The SNAP-1 mission used small solenoid valves manufactured by Polyflex Aerospace in the UK, these are 40mm long, 16mm ∅ and weigh ~42g each. They are rated to 18Bar, and draw ~13W when opening and 0.75W when held (open), with a leak rate when closed of <5cm^{3}He/hr. SNAP-1 used butane as its propellant.

An alternative valve suitable for PalmSat is the Lee Products Extended Performance Solenoid Valve (EPSV) which is ~6mm diameter x 33mm long, is rated to 375psi (25Bar) has a mass of less than 6g with an average draw power of 0.75W. The EPSV valve is shown below (Fig. 6):

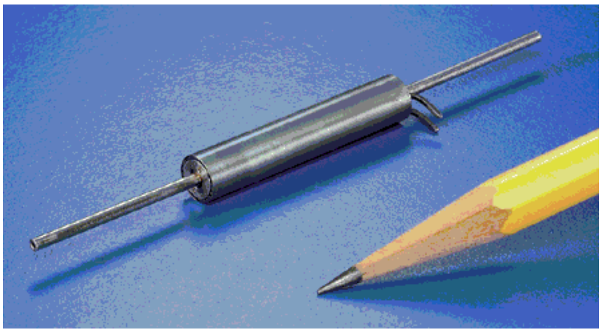

Figure 6. Image of the Lee Products EPSV

This is the basis for an ultra-miniature propulsion system, based on water as a propellant (Fig. 7).

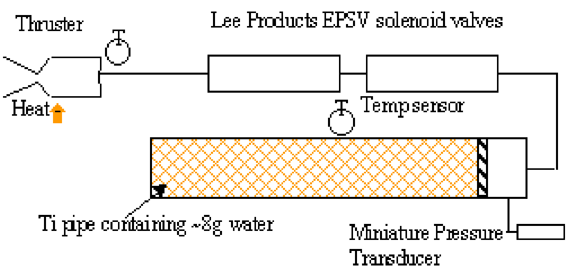

Figure 7. Schematic of the Conceptual PalmSat Propulsion System

The integral filament wound resistive heating element is as an effective means of increasing specific impulse by heating propellant (Fig. 8).

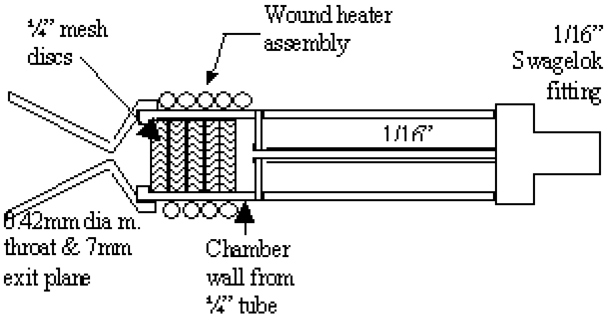

Figure 8. Schematic of Miniturised Low Power Resistojet

Just 8 g of water would give ~3 ms^{-1} ΔV to PalmSat.

SSTL have already test-fired an experimental version of this thruster in orbit on the UK-DMC micro-satellite.

Table 5 summarises the system.

Table 5: PalmSat Propulsion Characteristics

Component	Palmsat proposal
Propellant	Water (8g + 2g propellant management device)
Propellant tank	Ti tube as per SNAP-1, 180mm long, (~15g)
Thruster & isolation valves	The Lee Co. EPSV solenoid valves (~12g/pair)
Thrust chamber	Estimated 20g
Pressure sensor	Kulite XCQ-77-062 ultraminiature pressure transducer (0.1g ex-leads)
Temperature sensor	as per SNAP-1
Control electronics	PIC (<20g?)
Mounting structure	Estimated at 20g
Total mass	*<100g*

5 PAYLOADS

5.1 Remote Inspection Cameras

PalmSat's first mission is to provide a remote inspection capability, similar to that demonstrated on SNAP-1. It will therefore acquire images of a target spacecraft (and later the Earth) via a miniature digital CMOS camera system – similar to, but updated from, the cameras used on SNAP-1 (Fig. 9).

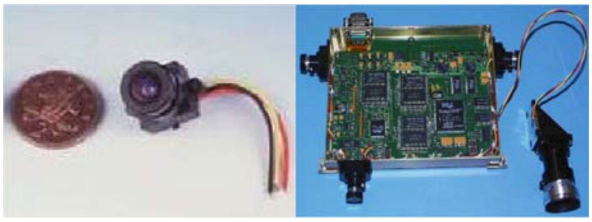

Figure 8. SNAP-1 Miniature CMOS Video Camera and Machine Vision System (MVS)

The PalmSat camera has a 640 x 480 pixel grid array forming 4.8 mm x 3.6 mm imaging surface. The pixel size is 7 microns. Exposure control is electronic, and the payload is operated by a dedicated payload-controller, with 2 Mbytes of image storage memory.

Work is in progress in using such a system to determine the relative pose and range of a target spacecraft [11]. The full Rendevous Camera Payload would consume approximately 5W, and is designed to fit a standard SSTL "nano-tray" – approximately 200 mm x 150 mm x 20 mm – with additional mechanical housings needed for the remote camera heads. These heads comprises four cameras, each with a different field of view (FoV):

- Long Distance Camera (LDC)
  75 mm focal length, f/4, FoV: 3.7^o x 2.8^o
- Medium Distance Camera (MDC)
  25 mm focal length, f/4, FoV: 11^o x 8.2^o
- Short Distance Camera (SDC)
  2.9 mm focal length, f/2, FoV: 79^o x 63^o
- Close Proximity Camera (CPC)
  2.1 mm focal length, f/2.5, FoV: 98^o x 81^o

PalmSat will fly a cut-down version of this, probably encompassing just the SDC and MDC components.

5.2 Multi-Spectral Imagers

SSC is also working on multi-camera radiometric imaging sensors, based on CMOS technology. The prototype for this has already been developed as part of the NigeriaSat programme (Fig. 10). This is aimed at such applications as ocean colour sensing, and meteorological scale imaging at moderate-to-low ground-sample distances (100~200m).

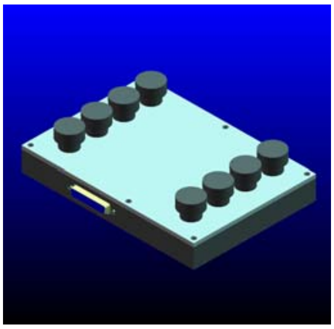

Figure 10. The "Nano-Tray" Sized CMOS Camera-Based Modular Multi-Spectral Imager (MSSI)

5.3 Inter-Satellite Link

The first PalmSat's other payload is expected to be a COTS 2.4 GHz ISM-band data transceiver, to be used for inter-satellite link experiments. A 200 mW output RF power device from Aerocomm is currently under study. This has a mass of 20g, a power consumption of 2W in transmission mode and 575 mW in receive mode. It can support 115 kbps links over 3 km.

5.4 Thermal IR Camera

Students at SSC are currently developing the Surrey Thermal Infra-Red (TIR) Imaging Array. This is a staring 2-D array type imager with 320 x 240 pixels based on uncooled microbolometer technology [12]. The prime sensor has sensitivity over the 8-12 μm band (LWIR), although we are currently investigating its possible application to the 3-5 μm (MWIR). This technology has been used extensively in ground-based applications, but it is a new technology for space.

A single imager would be similar in size to one of the current DMC micro-satellite cameras, and would have a mass of 1-3 kg (including the germainium or GaAs refractive optics). Its power consumption is ~2W. Further miniaturisation may enable this to fit on a future PalmSat.

The camera currently has the following specification :

- NETD: in the range 0.4 - 0.8 K
- SNR: in the range 150 – 250
- Minimum detectable fire area: in the range 25m x 25m to 50m x 50m (900 K fire) from 700 km
- GSD: ~260 - 500 m depending on swath width requirements (700 km altitude)
- Swath: ~ 85 km – 160 km.

It has application to forest-fire and volcanic plume detection, as well as potential application to sea-surface temperature monitoring (for observing ocean currents, etc.), and meteorological temperature mapping. The instrument is expected to be flight ready in 2005.

PalmSats equiped with such a sensor could provide a cost effective way of providing a continuous "fire-watch" from orbit.

Figure 11. Early Test Image from the Prototype Surrey Thermal Infra-Red (TIR) Imaging Array

5.5 Near Ultra-Violet Radiometers

SSC developed the Ozone Mapping Detector (OMAD) instrument for the FASAT series of micro-satellites, to monitor UV light backscattered from the atmosphere [13].

The payload comprised four UV sensitive PIN-diodes each viewing an area of 150 km x 150 km, and set to narrow wavelength bands at 289 nm, 313 nm, 334 nm and 380 nm.

Data from this instrument were used to primarily to recover global total ozone data, although it does also have application to monitoring aerosols in the stratosphere.

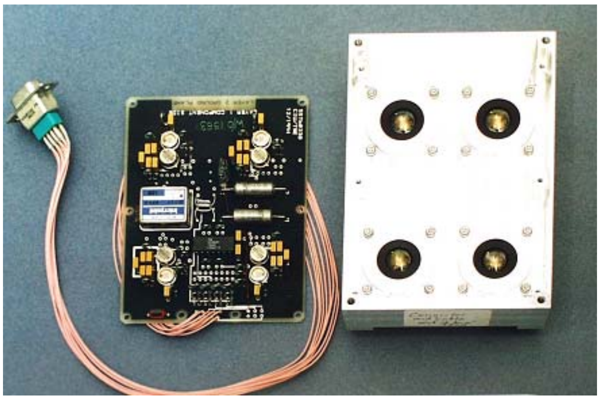

Figure 12. OMAD UV Radiometer Instrument

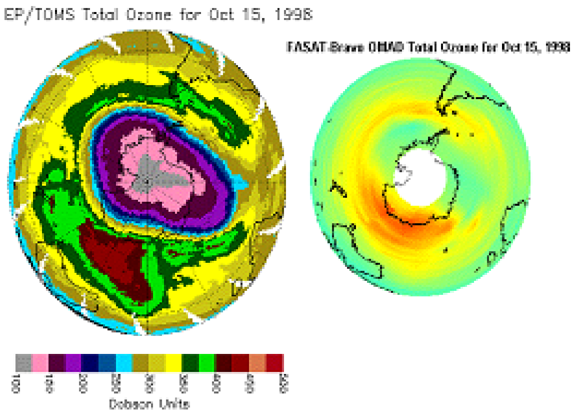

Figure 13. OMAD Ozone Data for 15/Oct/1998 in Comparison to NASA TOMS Data

The OMAD payload mass (including structure) is ~200g and the power requirement is 500 mW. The data-rate is ~64 kbyte per day. This instrument could therefore be easily adapted to fit PalmSat.

5.6 Ionising Radiation Detectors

SSC has also developed the CEDEX Cosmic-ray Energy Deposition Experiment, which detects protons and heavy ions > 30 MeV energy [14]. This payload flies on the TiungSAT micro-satellite, and has a mass (including mechanical housing) of ~ 600g, and a power consumption of ~2W. The data rate is up to ~ 200 kbytes per day.

It is capable of detecting up to 200,000 particle hits per second in a 3cm x 3cm PIN diode detector/ particle telescope arrangement, and it records the pulse height spectrum over programmable integration periods, for a particle linear-energy-transfer (LET) range of 64 to 8400 MeV cm^2 g^{-1}.

Equipped with such a payload, a swarm of PalmSats could be used to investigate the Van Allen belts, and solar particle event phenomena in some detail. Such a radiation environment mapping mission would be valuable as our current models are known to lack accuracy, and in any case, do not take note of the dynamic nature of this environment, which needs further characterisation [15].

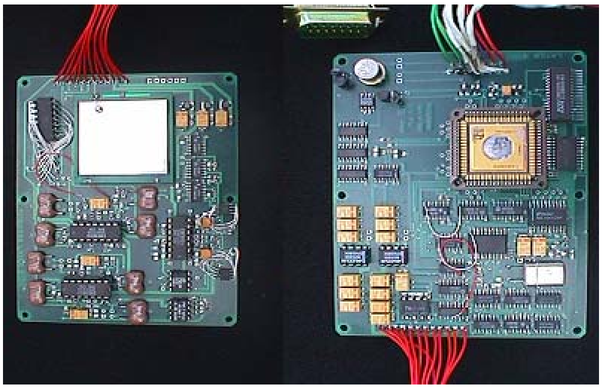

Figure 14. CEDEX Particle Detector (Prototype)

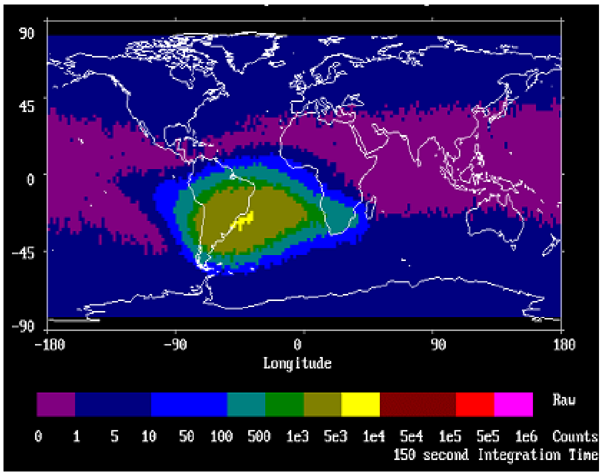

Figure 15. CEDEX Proton Data for 700 km Altitude

6 CONCLUSIONS

Advances in miniaturised electronics and MEMS technology enable pico-satellites to become important tools in the scientific exploration of the Earth and its environments - especially when used in swarms.

Swarms will require sophisticated technology to enable the appropriate level of cooperation between the vehicles in the swarm.

The University of Surrey's PalmSat pico-satellite is being developed to support such an endeavour, with the first launch expected in 2005.

Already, the PalmSat programme has enabled many students to gain practical "hands-on" experience of spacecraft engineering, as well as to contribute towards the development of a sophisticated pico-satellite platform.

As with the SNAP nano-satellite programme before it, the PalmSat programme shows the benefit of collaboration between academics, students and engineers, working in a "real-world" environment.

7 ACKNOWLEDGEMENTS

I should like to thank the many students who have worked on "SNAP" and "PalmSat" projects over the years. I should also like to acknowledge the contribution of SSTL engineers to these programmes.

8 REFERENCES

1. http://cubesat.calpoly.edu/

2. Underwood, C.I., Richardson, G. and Savignol, J. (2001) "SNAP-I: A Low Cost Modular COTS-Based Nano-Satellite – Design, Construction, Launch and Early Operations Phase". Paper presented at the 15th AIAA/USU Conference on Small Satellites, Logan. Utah, 2001. Published in Proceedings of the 15th Annual AIAA/USU Conference on Small Satellites, SSC01-V-1a, AIAA/ Utah State University, 2001.

3. Lancaster, R. and Underwood, C.I. (2000) "The SNAP-1 Machine Vision System", Paper presented at the 14th AIAA/USU Conference on Small Satellites, Logan, Utah, 2000. Published in *Proceedings of the 14th Annual AIAA/USU Conference on Small Satellites,* **SSC00-III-6**, AIAA/ Utah State University, 2000.

4. Steyn WH., Hashida Y., Lappas V., "An Attitude Control System and Commissioning Results of the SNAP-1 Nanosatellite", *14th AIAA/USU Small Satellite Conference proceedings*, **SSC00-VIII-8**, August 20005.

5. Gibbon, D. and Underwood, C.I. (2001) "Low Cost Butane Propulsion Systems for Small Spacecraft". Paper presented at the 15th AIAA/USU Conference on Small Satellites, Logan. Utah, 2001. Published in *Proceedings of the 15th Annual AIAA/USU Conference on Small Satellites,* **SSC01-XI-1,** AIAA/ Utah State University, 2001.

6. Underwood, C. I., Crawford, M. & Ward, J. W. 1998 A low-cost modular nanosatellite based on commercial technology. In *Proc. 12th Annual AIAA/Utah State University Conf. on Small Satellites*. Paper no. SSC98-V-4. Reston, VA: American Institute of Aeronautics and Astronautics.

7. Vladimirova, T. (2003) "Next Generation Satellites: Picosatellties and Satellites-on-a-Chip" Paper presented at the 18th Annual AMSAT-UK Colloquium, University of Surrey, Guildford, UK, July 2003.

8. Maqbool, S., Underwood, C. and Suddle, M. R. (2003) "An On-Board Computer (OBC) System for 'PALMSAT' – a Pico-Satellite". Paper presented at the International Workshop on Satellite Imaging Technology and Applications", Karachi, Pakistan, 22nd-28th January 2003.

9. Steyn, W.H., Hashida Y., "In-Orbit Attitude Performance of the 3-Axis Stabilised SNAP-1 Nanosatellite", Proceedings of the 15th Annual AIAA/USU Conference on Small Satellites, Utah State University, August 2001, **SSC01-V-1**

10. Gomes, L., Yuksel, G., Lappas, V., da Silva Curiel, Bradford, A., Ozkaptan, C., Sweeting, M**,** "BILSAT-1: Advancing Smallsat Capabilities", *17th AIAA/USU Small Satellite Conference proceedings*, **SSC03-VI-4**, August 2003.

11. Cropp, A., Palmer, P., Underwood, C.I. (2000) "Pose Estimation of Target Satellite for Proximity Operations", Paper presented at the 14th AIAA/USU Conference on Small Satellites, Logan, Utah, 2000. Published in *Proceedings of the 14th Annual AIAA/USU Conference on Small Satellites,* **SSC00-III-7**, AIAA/ Utah State University, 2000.

12. Oelrich, B.D. and Underwood, C.I. (2003) "Low-Cost Thermal-IR Imager for an Earth Observation Microsatellite", Paper presented at the SPIE 2003 Remote Sensing Conference, 8th-12th September 2003. Barceló Sants Hotel, Barcelona, Spain. To be published in Proc. SPIE, Vol. 5234.

13. Underwood, C.I., Valenzuela. A., Schoenherr. M., Arancibia. M. and Fouquet, M. (2001) "Initial In-Orbit Results from a Low-Cost Atmospheric Ozone Monitor Operating On-Board the FASat-Bravo Micro-Satellite". Published in *Phil. Trans. R. Soc. Lond. A* (2003), **361**, 1802, pp. 71-76, January 2003.

14. Underwood, C.I., da Silva Curiel. A. and Sweeting, M. (2002) "A Double-Peaked Profile of the Inner Radiation Belt - First Flight Results from the AMSAT-OSCAR-40 Cosmic-Ray Experiment". Paper presented at the 53rd International Astronautical Congress, October 10th – 19th 2002, Houston. USA. (**IAC-02-IAA.11.1.02**)

15. Da Silva Curiel, A., Meerman, M., Liddle, D., Schwartz, S., Underwood, C., Sweeting, M. (2003) "FRISBEE – A Platform for Small Satellite Science Swarms". Published in *Proceedings of the17th Annual AIAA/USU Conference on Small Satellites,* **SSCO3-IX-6**. AlAA/ Utah State University, 2003.