First In-Orbit Results from the UoSAT-12 Minisatellite

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In 1995, having built and launched twelve 50-kg microsatellites, 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 325-kg satellite demonstrating key bus and payload technologies. On 21 April, a converted SS-18 Inter Continental Ballistic Missile (ICBM) placed Surrey’s UoSAT-12 minisatellite in a 650 km, 65° orbit. The in-orbit acquisition and check-out of the satellite have been successful. Engineers operating the satellite from Surrey’s mission control centre have received initial results from attitude control, remote sensing, Global Positioning System (GPS) orbit determination, L-to-S band communications and orbit station-keeping systems.

Surrey’s Minisatellite

UoSAT-12 Mission Background

In the past twenty years, microsatellites (10-100 kg mass) have repeatedly demonstrated their worth as vehicles for space science, technology demonstration, communications, remote sensing, education and know-how transfer. The Surrey Space Centre at the University of Surrey (UK), and its technology transfer company, Surrey Satellite Technology Limited (SSTL), have built 16 microsatellites, and amassed considerable experience with the strengths and weaknesses of this satellite class.

Figure 1 UoSAT-12 at Surrey

While developing these microsatellite missions, we observed that many interesting medium-sized payloads could not be accommodated on microsatellites, yet did not justify the expense of the 500-1000 kg “small satellite” platforms available from traditional suppliers. Also, many of SSTL’s know-how transfer customers were looking for an intermediate step (both financially and technically) between microsatellites and full-sized satellites. We saw the requirement for an inexpensive “minisatellite” in the 100-500 kg mass class.

A number of organisations in the US and Europe have approached this minisatellite market by decreasing the size of their large platforms or designing new platforms along traditional lines. At Surrey, we felt that we could build a useful minisatellite based on our existing low-cost techniques, engineered to produce a higher performance-to-cost ratio than available alternatives. In late 1994, we initiated the UoSAT-12 minisatellite mission as an internally funded research and development (IR&D) program.

Program Objectives

The top-level objective of the UoSAT-12 program is to demonstrate that Surrey’s newly developed minisatellite subsystems can be combined with existing microsatellite subsystems to create a cost-effective satellite in the 300-500-kg class.

In selecting equipment and subsystem designs, we specifically included features expected in a larger satellite, but impractical or undesirable in the 50-kg microsatellite:

- large, flexible payload accommodation,
- 28-V power subsystem with isolated distribution and regulation at the equipment level,
- expandable telemetry subsystem,
- high-speed S-band telemetry,
- 3-axis attitude stability and control,
• orbit station-acquisition and maintenance subsystem, and

• freedom from single-point failures.

To the greatest possible extent, the minisatellite was to be built using equipment developed at Surrey. Particularly on an IR&D mission, this policy increases our expertise while giving us detailed control over costs, risks, interfaces, import/export issues and schedules.

Some “black boxes” were purchased from external suppliers (Ithaco momentum wheel, Servo horizon sensor, Weitzman gravity gradient boom, MMS S-band antennae), but these are operating alongside Surrey-designed equipment fulfilling similar functions. This strategy ensures the fundamental functions of the minisatellite while permitting long term in-house technology development.

Mission Objectives

The UoSAT-12 mission objectives are primarily engineering experiments. They are not commercially “operational.” This reflects the nature of the mission, and Surrey’s top-level objective: to flight qualify minisatellite technologies and techniques which can subsequently be employed on operational missions. The payload compliment nevertheless makes severe demands on the space and ground segments, as required for a good in-orbit demonstration.

Surrey payloads were selected from our existing areas of interest: optical imaging and store-and-forward communications. Nanyang Technological University (NTU) in Singapore became a UoSAT-12 partner with an experimental communications payload, and ESA-ESTEC agreed partly to fund an in-orbit GPS attitude determination experiment. Interestingly, two partners were added late in the mission: Microcosm, Inc is contributing a software experiment which will be uploaded to UoSAT-12 in orbit, and EEV, Ltd. has supplied one panel of experimental solar cells for the satellite. Thus there are four external experiments on UoSAT-12 alongside Surrey’s own payload and bus experiments.

Structure

The UoSAT-12 structure employs some microsatellite heritage, while also providing the additional payload capacity required of a minisatellite. In order to most easily accommodate existing microsatellite printed circuit boards (PCBs), the satellite’s thrust bearing column consists of three stacks of Surrey’s standard microsatellite module trays. The stacks ($340 \times 340 \times 500$ mm) are joined around a triangular central void and placed on a honeycomb panel approximately 1.1 metres in diameter. This panel forms the attach frame. A similar payload frame sits above the stacks, and the payload bay is capped by a third panel, the Earth frame.

Equipment not housed in the module stacks is attached to the various frames. Module boxes are attached to hard fixing points inserted into the honeycomb during the manufacture of the frames. Important areas for payload accommodation are the large payload bay formed between the payload frame and the Earth frame, as well as the central void around which the stacks are connected. The central void provides an area particularly suitable for long focal-length Earth imaging equipment.

On UoSAT-12, body-mounted solar panels are fixed around the perimeter of the frames. With its solar panels mounted, the satellite main structure forms a nine-sided prism approximately 1.1 metres in diameter and 0.8 metres in height. Equipment on the nadir and zenith facets (antennas, lens baffles, sun sensors, etc.) take the total vertical envelope to 1.3 metres.

![Figure 2 UoSAT-12 Structure](image)

* In this case, “above” and “below” refer to the orientation of the satellite during integration. In orbit, the satellite is inverted so that the Earth facet is facing nadir.
Thermal Control

UoSAT-12 employs passive thermal control, based only on a careful structural design and on alteration of the thermo-optical properties of the external surfaces, with no heaters or coolers. The passive thermal design was complicated by uncertainties about orbit selection, the desire to operate the satellite in a 3-axis controlled mode, and the fact that thermal modelling was undertaken only after the main structural design had been completed. Thermica and Sinda/3D were used to model the thermal behaviour of the satellite and select first- and second-surface mirror materials for the large exposed facets of the satellite.

Power

The Surrey minisatellite power subsystem provides bus and payload equipment with dual-redundant, unregulated, 28-V switched power supplies. For operation in eclipse and for intermittent operation of high-power loads, the subsystem includes NiCd batteries. In keeping with design objectives the subsystem contains no single-point failure nodes.

Tracing the power from its source, each of the satellite’s nine solar panels is equipped with its own battery charge regulator (BCR), responsible for tracking the panel’s maximum power point and connecting the panel to a battery.

Each module stack houses a battery consisting of 22 NiCd F Cells. Surrey qualifies its own NiCd cells, starting out with industrial quality cells (KR-7000F) manufactured by Sanyo. For UoSAT-12, 66 cells were upscreened from roughly 100 candidates. The three batteries are connected in parallel (through isolating circuitry) to power the entire spacecraft. These batteries provide a total of 21 Ah capacity.1

Dual-redundant battery buses carry power to a power distribution module (PDM) in each module stack. Each PDM contains 19 power switches controlled by the satellite’s telecommand system. The power switches provide resettable over-current protection. Each PDM also monitors the state of the battery in its associated module stack.

Each item of power consuming equipment must regulate and condition the bus power as necessary. Early in the minisatellite design, we decided to use AC and DC isolated power conversion wherever possible. In most equipment, Interpoint isolated DC-to-DC converters are used, with their associated filters. UoSAT-12 carries approximately 200 such converters. The policy of local regulation and full isolation resulted in relatively few electromagnetic compatibility (EMC) problems being identified when UoSAT-12 was integrated. Given the fast-track nature of the UoSAT-12 mission, such problem avoidance techniques were essential. They are also a key component in any low-cost, fast response satellite mission.

Communications

UoSAT-12 carries five uplink receivers. Three are 10-kbit/second frequency-shift-keyed (FSK) channels in the VHF band. Two are L-band receivers integrated in the Merlion 1 Mbit/second transponder.

Two of the VHF receivers are intended for enhanced store-and-forward communications experiments. These receivers connect through dual-redundant low-noise amplifiers (LNAs) to a circularly polarised turnstile antenna. The remaining VHF receiver is the satellites safe-mode receiver, connected to a low-gain omni-directional antenna.

Five transmitters share downlink tasks. For safe-mode telemetry, a low power UHF transmitter is connected to the satellite’s omni-directional antenna.
For operation up to 76.8 kbit/second, dual-redundant UHF transmitters connect to a circularly polarised antenna. All three of these transmitters employ circuitry and FSK modulation systems with extensive microsatellite heritage.

A high-speed downlink more suitable for minisatellite payload operation is incorporated in the Merlion payload. The Merlion S-Band transmitters can transmit at a range of data rates up to 1 Mbit/second, and include options for binary phase shift keying (BPSK) and quadrature PSK (QPSK), with or without forward error correction (FEC).

Telemetry and Telecommand

UoSAT-12 retains the Surrey standard practice of providing numerous telemetry and telecommand paths. All of the receivers and transmitters on the satellite can carry out the basic telemetry and telecommand functions.

In a departure from previous designs, the Surrey minisatellite uses a fully distributed telemetry system. Each item of equipment includes its own telemetry/telecommand node, based on a microcontroller with ISO-11898 Controller Area Network (CAN) support. Any node on the CAN can interrogate other nodes for telemetry or issue telecommands to other nodes.

In normal operation, the satellite’s on-board computers (OBCs) collect telemetry for storage and transmission, and they also issue time-tagged or direct telecommands. Before OBC software is loaded, however, a ground segment computer is connected to the CAN using a radio bridge, allowing satellite controllers to execute telemetry and telecommand tasks directly.

UoSAT-12 uses three CAN buses in a redundant configuration. Most nodes on the CAN contain failsafe watchdog timers which will switch them to a functioning bus in the event of failure. No bus or payload function will be lost in the event of a single bus failure.

On-Board Computing and Networking

Apart from the 50 CAN node controllers, UoSAT-12 carries

- two primary OBCs based on the 386EX CPU, each with 387SL math co-processor, 128 Mbytes of software-protected data recorder RAM and 1 Mbyte of hardware-protected program RAM,
- one secondary OBC based on the 80C186 CPU, which has extensive flight heritage,
- four T-805 Transputers for imager control and image processing, each with 32 Mbytes of hardware-protected RAM,
- four Texas Instruments TMS-320C31 digital signal processors (DSPs) supporting the Merlion payload, and
- one ARM60 32-bit reduced instruction set computing (RISC) processor for GPS signal processing.

Each of these computers was designed for a specific task on the satellite, but CAN networking allows them to be used as general purpose OBCs should the need arise. In practice, functions have been shared and shifted, particularly amongst the primary OBCs and Transputers.
The UoSAT-12 CAN network provides a 400-kbit/second shared bus for the entire satellite. It is intended for telemetry and telecommand, and is not ideally suited to bulk data transfer.

High-speed bulk data transfer is provided by two means: 10 Mbit/second point-to-point links connect the Transputers to the imagers, and a 10 Mbit/second Ethernet local area network (LAN) connects the primary OBCs and the Transputers.

The inclusion of Ethernet in Surrey’s minisatellite design completed a simple, powerful interface specification. Equipment can connect to the system through three well-documented, well-supported interfaces: 28 V raw power, ISO-11898 CAN and Ethernet. Equipment with other interfaces can be easily adapted to meet this, and new equipment can be quickly and inexpensively developed to meet it.

**Attitude Determination and Control**

The UoSAT-12 attitude determination and control subsystem (ADCS) is both a bus subsystem and a critical experiment for Surrey. Although Surrey’s microsatellites have brought gravity-gradient and magnetic control to new levels of performance, minisatellites require the accuracy and flexibility of more-traditional, wheel-based control systems. UoSAT-12 provides us with a good opportunity to prove our competence in the hardware and software for wheel-based control. The ADCS was therefore designed to support as many experiments as possible.

Actuators include: two Surrey momentum wheels, one Ithaco momentum wheel, cold-gas jets, magnetorquers and a gravity gradient boom. Sensors include: Surrey magnetometers, sun sensors, GPS sensor and star cameras, a Servo Earth sensor and an Ultra magnetometer and a solid-state gyro. Control algorithms can be executed on any of the satellite’s computers, although the primary OBC is generally used. The ADCS can be operated in momentum biased mode, zero momentum mode or even gravity gradient mode (for end-of-life mission extension). Full details of the UoSAT-12 ADCS can be found in [3].

**Orbit Determination and Control**

Just as ADCS requirements can be more strict for minisatellites than microsatellites, minisatellites frequently need propulsion. Particularly in constellations, a propulsion system is used to place and keep the satellite in precisely the desired orbit. In the past few years, Surrey has experimented with a number of cost-effective propulsion techniques, and UoSAT-12 is our first opportunity to try them in orbit.

UoSAT-12 carries a traditional cold-gas system which can be used for attitude and orbit control. Surrey built this system from a components supplied by Ardé, Inc. Three spherical tanks store twenty seven litres of Nitrogen. The tanks fit in the gaps between module stacks. These tanks feed an accumulator, which is pressurised to 4-bar operating pressure by a simple bang-bang regulator. Eight attitude control thrusters and two orbit control thrusters complete the system.

Additionally, we have included an electric propulsion system on UoSAT-12. Surrey PhD student Dr. Tim Lawrence designed the 100-W resistojet, which uses Nitrous Oxide as its working fluid [4]. This thruster can impart 10 metres/second velocity change to UoSAT-12.

From this description of UoSAT-12, it can be seen that the satellite is very complex. Configuring, testing and operating UoSAT-12, both in orbit and during ground testing, challenged even Surrey’s experienced operators. The remainder of this paper describes the later phases of the mission.

**Test Campaign**

**Model Philosophy**

Project managers envisaged that UoSAT-12 would be built as a single, proto-flight model satellite. The proto-flight model would be subjected to qualification testing and subsequently launched into orbit. This would have provided the most rapid, least expensive mission—although at significantly increased risk.

In the event, a proto-flight approach was adopted at the satellite level. At the equipment level, however, most PCBs went through breadboard, engineering-model and flight-model phases. Some PCBs which were truly unaltered from their microsatellite heritage went directly to flight.

For the mechanics, a structural qualification model (SQM) was constructed as soon as major mechanical design decisions had been made. Vibrating the SQM validated finite element models of the structure, indicated where it should be strengthened, and significantly increased confidence in the new concept. Significant subassemblies which were not available for the SQM vibration were vibrated separately before flight models were manufactured.

Individual interfaces were bench tested during the prototype phase, but at no time was there an integrated prototype or engineering model of the satellite. Only a flight model of the wiring harness was constructed. The first large-scale interface tests were conducted in October 1998, during thermal
testing. During this initial integration, the spacecraft’s 100 equipment units functioned smoothly together, and this testifies to the robustness of the interface design.

**Integration**

33 weeks to launch.

One strength of the Surrey’s 50-kg microsatellite design is that it allows easy disassembly and integration of the satellite at any phase of the mission. This is most often an advantage early in the integrated testing of a satellite, when interface problems are identified. Components which fail in vibration or thermal vacuum can also be replaced without undue delays.

The first flight modules of UoSAT-12 were brought together in the Surrey clean room in September 1998, 33 weeks prior to launch. Modules were added to the satellite as they completed bench testing, throughout the next two months.

**Thermal Testing**

26 weeks to launch.

Surrey has on-site facilities to test microsatellites at ambient pressure over a temperature range of -20 to +50 C. These tests identify components, equipment or interfaces which are likely to experience problems in the later (more expensive and critical) thermal-vacuum tests. In the case of UoSAT-12, thermal tests had to be conducted at an external site because of the size of the satellite.

**Vibration and Mass Properties Testing**

19 weeks to launch.

The first full flight integration of UoSAT-12 was undertaken prior to the acceptance level vibration tests. These tests, at a Portsmouth facility hired from MMS, took the satellite to 1.2 times expected launch loads in all axes, measured first lateral mode, centre of gravity and three-axis moments of inertia.

In practice, most equipment in the satellite was readily accessible during final testing. Payload modules such as Merlion and the image processing Transputers were removed when necessary for late modifications. We were pleasantly surprised that we could extend the modular approach to such a large satellite as UoSAT-12.
Thermal Vacuum Testing

12-13 weeks to launch.

Surrey uses thermal vacuum testing as the major acceptance test for satellite electronics. It is also a point at which the satellite is operated solely over its radio links, in a flight-representative configuration.

UoSAT-12 thermal vacuum tests were conducted in a facility hired from Rutherford Appleton Laboratories (RAL) in Oxfordshire.

When UoSAT-12 was first placed in the thermal vacuum chamber and the chamber was evacuated, operators measured unacceptable levels of Helium coming from the satellite. Helium had been used during propulsion system leak tests, and had not been vented prior to thermal vacuum testing. It is obvious in hindsight that systems intended for Nitrogen have a significant leak rate for Helium—which is what makes Helium such an excellent leak-check gas. The chamber was returned to ambient pressure so that the Helium could be purged from the propulsion system, and no further major problems were encountered during the tests.

Electromagnetic Compatibility Testing

10 weeks to launch.

Surrey conducts electromagnetic compatibility (EMC) testing on its satellites in order to trim antennae, determine the satellite’s sensitivity to its own intended and unintended radiated emissions, and measure the satellite’s emission spectrum. UoSAT-12 EMC testing was conducted at ERA Technology Ltd. in Surrey.

The complexity of UoSAT-12 RF systems made EMC testing particularly difficult. Five receivers and five transmitters, not to mention the GPS receiver system, were to be tested during 3 days of tests. Tests included VHF, UHF, L and S band, using various configurations of the satellite’s on-board systems.

Due to limits on time and facilities, antenna pattern measurements could not be made and some optional tests were also cancelled. EMC testing had been scheduled last, in part because many of the tests are “optional” (strictly speaking) on an experimental satellite such as UoSAT-12. For operational missions, we reserve more time for these tests, particularly where complex RF systems are involved.

Launch Segment

Impact on Project

UoSAT-12 started as a mission in search of a launch, similar to many small satellite missions. It was also (largely) an internally-funded project, vying for resources in a commercial environment. Inevitably, this led to uncertainties in system design, delays of the schedule and the technical compromises. On the other hand, this uncertainty aided us in designing a general-purpose minisatellite bus suitable for many launches.

The overall structural envelope was chosen to be compatible with a wide range of launch vehicles, and launcher interfaces were kept as simple as possible.

Initially, we expected to launch UoSAT-12 on a converted SS-20 ICBM, hot-launched from its silo. This produces extreme acoustic loading, which necessitated specific acoustic tests of the solar panels. It also meant that our SQM was vibrated to 14 g (rms) in all axes. We felt confident that these tests would clear UoSAT-12 structurally for most potential launches.

Because we were looking for a very inexpensive launch, we knew that we were unlikely to control our final orbit. Thermal, optical, antenna and power budget designs were therefore subject to uncertainty in orbital characteristics. We designed the satellite for sun-synchronous low earth orbit (SS-LEO) in the range 600-800 km and attempted to restrict our search to vehicles which could take us into this orbit.

Ultimately, in April 1998, Surrey reached agreement with ISC Kosmotras to launch UoSAT-12. The launch was to be one year later, into roughly 650 km altitude and 65° inclination. This non-sun-synchronous orbit would stress thermal and power design of the satellite, but was within the design limits.
Under the conditions of international arms limitation treaties, the nuclear powers are decommissioning many of their ICBMs; fortunately for the small satellite industry, treaties permit destruction by orbital launch. Surrey’s partner, Commercial Space Technologies (CST)* identified such a launch opportunity on-board the Dnepr vehicle, and this ex-ICBM placed UoSAT-12 into orbit.

The Dnepr is a converted R-36M2 (15A18M) ballistic missile (NATO code-name SS-18 mod 4), developed by the Yuzhnoye organisation in Ukraine, and marketed by ISC Kosmotras. It is a two stage launch vehicle, and both stages employ nitrogen tetroxide and unsymmetrical dimethyl hydrazine (UDMH). The vehicle is 3.0m in diameter and has a capacity of 4 tons to a 300km, 46.2 degree orbit.

The Dnepr fairing is comfortably large enough to encompass UoSAT-12. Indeed, the vehicle could launch a minisatellite and one or two secondary microsatellites. UoSAT-12 connects to the Dnepr through a spacecraft adapter (S-adapter) provided by Kosmotras. The S-adapter includes the pyrotechnic separation actuators, separation confirmation indicator, a battery trickle charge connection, and a mechanical interlock which keeps the satellite inert while it is on the vehicle.

**Launch Campaign**

The UoSAT-12 launch was Surrey’s second launch from Baikonur Cosmodrome in Kazakhstan, following the 1998 Zenit launch of FASat-Bravo and Thai-Puhtt. Familiarity with the potential difficulties of shipping to Kazakhstan and logistical arrangements at the Cosmodrome helped us avoid delays and surprises during the UoSAT-12 campaign. A short launch campaign with smooth arrangements reduces costs significantly.

**Shipping**

7 weeks to launch.

Compared to previous, difficult, shipping experiences (FASat-Bravo and Thai-Puhtt took more than four weeks to clear Moscow customs), the UoSAT-12 ship-out was rapid and smooth. CST arranged customs transit through Moscow and subsequent flights to the Cosmodrome. The complete process took only one week from the time the satellite left Surrey until it was on site in Kazakhstan.

**On-Site Activities**

4 weeks to launch.

Surrey’s team of six travelled to Kazakhstan four weeks before launch. They were required to hand over the satellite to Kosmotras fifteen days later. During this period, they completed the following key activities:

- satellite electrical checkout,
- battery re-conditioning,
- final preparation of thermal surfaces,
- final assembly of the S-adapter,
- integration with the S-adapter,
- checkout of the propulsion system, and
- filling of the propulsion system.

Facilities in Kazakhstan are clearly not the same as those found in the west, but in the year between July 1998 and July 1999 site facilities had improved immensely. Team members maintained daily e-mail contact with Surrey, and even used their GSM mobile phones from the Cosmodrome base. Kosmotras

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provided clean room facilities for all pre-flight testing and preparation.

Surrey engineers handed the satellite over to Kosmotras on 13 April, and Kosmotras engineers integrated the satellite to the launch vehicle that day.

Launch

The launch itself took place as scheduled at 1100 local time in Kazakhstan, 0600 British Summer Time (BST) in the United Kingdom. Surrey’s team at the launch site were somewhat surprised by the ‘informality’ of the pre-launch announcements; most of the observers were not even looking when the missile rose from the silo.

At Surrey, we had established teleconference contact with all of the mission partners: Singapore, America and Europe. Although we were able to communicate with our Kazakhstan team as they drove to the launch site (by GSM mobile phone), this was not permitted when after they reached the silo. Unfortunately, a satellite telephone link which had been arranged for the day also fell foul of military regulations.

Immediately following the launch and the orbital insertion of UoSAT-12, team members in Kazakhstan were able to telephone Surrey to give us updates. When they reached the Cosmodrome base, digital images were sent back by e-mail.

Launch-day communications with the launch site and availability of accurate, timely information are critical to team morale and motivation. As remote launch sites are used more and more frequently (e.g. Alaska, Svobodny, Kaspuitin-Yar) the problem of finding reliable, accessible communications facilities will become a common one.

Orbital Insertion Accuracy

A satellite in a non-sun-synchronous orbit experiences wide variations in eclipse duration and ground-station window timing. Because UoSAT-12 was the only payload on the Dnepr, Surrey was given some control over the initial orbital parameters. We selected the UoSAT-12 launch window to place the orbit at a favourable sun angle during the early phases of the mission, and also to bring the satellite over Surrey during the daytime (initially).

Kosmatras placed UoSAT-12 into a $639.4 \times 653.4\text{km}$ orbit, inclined at $64.5478^\circ$. The goal was $650 \times 650$ inclined at $64.5^\circ$.

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<th>Table 1 Dnepr Orbital Insertion Performance</th>
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<td>Perigee radius (km)</td>
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<td>Apogee radius (km)</td>
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<td>Inclination (deg)</td>
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These results are excellent for a first orbital launch: slightly outside the Dnepr ±4-km specification for height, but well within the ±2.4° specification for inclination. Had it been critical, just 3.75 m/second velocity change would have placed UoSAT-12 in exactly the desired orbit.

Initial Acquisition Phase

During UoSAT-12’s first transits over Surrey, beginning six hours after launch, operators executed a series of critical tasks: initial activation of the satellite’s downlink, loading of flight software to OBCs and acquisition of nadir-pointing attitude.

Downlink Acquisition & Software Loading

Day 1-2

Initial plans called for downlink acquisition during the first transit of UoSAT-12 over Surrey. Difficulties with ground command sequences delayed this milestone, and the Surrey mission operations centre first received UoSAT-12 on the third transit.

It took several transits to isolate the command sequence problem. Once it had been isolated, controllers rapidly loaded the primary computer’s multi-tasking operating system.

Operating system software and applications tasks provide all of the satellite’s high-level functions. The software implements command diaries and macros, telemetry storage, downlink packet communication and attitude determination and control. Approximately 500 kilobytes of software implements these features. Ground controllers completed software loading midway through the second day of the mission.

Attitude Acquisition

Day 3-6

The Dnepr launcher released UoSAT-12 with essentially random attitude dynamics (although within specified constraints). As with all Surrey launches, ground controllers assume that the satellite is drifting slowly about all axes until active attitude control is initiated. Surrey designed UoSAT-12 to be safe in this arbitrary attitude state for extended
periods of time. Thus, the brief delay in signal acquisition did not stress on the satellite.

The attitude acquisition sequence called for three phases:

- reduction of all angular rates,
- placing the satellite in the Thompson-equilibrium—pitching with a controlled polarity and rate,
- activation of the satellite’s pitch axis momentum wheel and acquisition of nadir pointing mode

Surrey has extensive experience with the first two manoeuvres, which are based on magnetic control laws. The third manoeuvre was our first attempt at making a satellite stable in 3-axes using a wheel.

For UoSAT-12, all manoeuvres were implemented in new software. ADCS engineers had verified the software during extensive simulations, but some modifications due to in-orbit experience were anticipated.

The ADCS controller placed UoSAT-12 in stable nadir-pointing mode on the sixth day of the mission, clearing the way for full check-out of other spacecraft subsystems.

The attitude acquisition phase is reported fully in these proceedings.

Check-Out Phase

Because many of UoSAT-12’s bus systems are experimental, the distinction between the commissioning phase and the operational phase of the mission is not clear-cut. We elected to check-out all equipment as quickly as possible, exercising potentially risky payloads after those which posed less risk. As this is written (90 days after launch) check-out of the more complex payload and bus subsystems is nearing completion.

Remote Sensing Payloads

As soon as UoSAT-12 had been stabilised nadir pointing, controllers switched their attention to the satellite’s remote sensing system.

UoSAT-12 carries several high resolution multispectral and panchromatic Earth imaging cameras, designed and built at Surrey. Surrey engineers designed these cameras using advanced commercial off-the-shelf (COTS) optical, mechanical and electrical components, to deliver excellent imaging results at extremely low cost.

The Surrey High Resolution Camera (SHC) uses COTS optics (560 mm f/8) to achieve a ground resolution of 10 metres per pixel. Its area-array charge-coupled device (CCD) sensor has $1024 \times 1024$ pixels, covering just over $10 \times 10$ km per image. The camera can be programmed to capture a sequence of images thus allowing long swaths of imagery to be gathered.
UoSAT-12 also carries two Multispectral Imagers (MSI) working in tandem, angled so as to provide a combined coverage of 60 × 30 km. Each imager’s 180 mm f/3.4 COTS lens and 1024 × 1024 pixel CCD provides ground resolution of 32.5 metres per pixel. The MSI imagers use rotating filter wheels to image in 4 spectral bands (the classical LANDSAT-4 blue, green, red and near-infra-red bands).

The process of checking and commissioning the imagers involves taking test images to set CCD integration time and analogue-to-digital converter gain for each camera. With each image set generating up to 10 megabytes of data, and several test sets required, this was a lengthy process.

The first high-quality SHC images were captured just 8 days after launch.

MSI commissioning was complicated by the need to fully test the filter wheel synchronisation system. Ground tests with static images had been successful, but several days of on-orbit time were required to overcome some operating difficulties not apparent in ground testing.

High-quality MSI scenes were returned on the 19th day of the mission.

UoSAT-12’s imaging systems continue to produce outstanding results, demonstrating that the COTS approach to space remote sensing is very successful.

**GPS Orbit Determination Subsystem**

Day 12.

The European Space Agency (ESA) was one of the first external customers to become involved in the UoSAT-12 mission, through the Space GPS Receiver (SGR) payload.

Surrey designed the SGR to provide an experimental test-bed for GPS orbit and attitude determination. The receiver uses state-of-the-art commercial components, including the MITEL (formerly GEC Plessey) GPS chipset and the powerful ARM60 32bit RISC microprocessor. Radiation tolerance is inherent in the design, implemented through error detection and correction (EDAC) protected memory and a latch-up protected power switch. In collaboration with ESA, Surrey evaluated core components of the SGR for tolerance to both total dose and single event radiation effects. The receiver provides basic positioning services and supports software experiments in GPS attitude determination.

The SGR on UoSAT-12 has 5 GPS antennas, 4 of which can be used simultaneously to track GPS signals. The SGR requires only one GPS antenna to calculate UoSAT-12’s position and determine its orbit. With signals from multiple antennas, it is possible accurately to calculate the spacecraft attitude by measuring the phase differences between signals received at different antennas, and applying interferometry techniques. During the course of experimentation, data from the UoSAT-12 GPS receiver will be downloaded to the ground to permit research into orbit determination and attitude determination techniques. An important feature of the SGR is that newly developed code can be at any time to fine tune and upgrade the SGR capabilities.

The UoSAT-12 SGR was activated on the 12th day of the mission. It was operated in autonomous or ‘cold-start’ mode, where the receiver had no prior knowledge of its own position or the position of the

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**Figure 9 UoSAT-12 10-Metre Resolution Image of Ontario, Canada**
GPS satellites.

The SGR receiver was able to achieve its first fix after only 6.5 minutes, and it tracked up to 9 GPS satellites simultaneously.

This and subsequent tests have shown the SGR to be working as expected, producing accurate position fixes for UoSAT-12. During the experimental phase of the mission, SGR output will be compared with RADAR tracking, to measure the accuracy and precision of the receiver.

We will also use the SGR to measure the difference in phase of GPS signals received from several antennae—measurements which can show the satellite’s attitude.

**Merlion Communications Transponder**

Days 29-75

Merlion is an L-to-S-band transponder which will be used for communications experiments. The transponder also provides a 1 Mbit/second S-band downlink for transmission of spacecraft experiment data. Merlion was developed during a long-term collaborative program between Surrey and NTU Singapore.

Merlion is by far the most sophisticated communications equipment flown on a Surrey satellite. The experiment is fully dual-redundant. Each of the two transponders consists of an L-band front end and down-converter connected in parallel to a 9.6 kbit/second demodulator, a 1 Mbit/second demodulator and an S-band up-converter. The S-band up-converter can process either the L-band uplink signal or a 1 Mbit/second modulation source. The S-band signal is amplified by a linear power amplifier. Each transponder further connects by digital and analogue links to a TMS320C31 DSP. Simply checking the basic functionality of these transponders involves at least 30 tasks, each taking at least one satellite transit.

Operations are further complicated by safety considerations. Merlion draws 80 W from the bus, discharging the battery and increasing spacecraft temperatures. A special OBC software task controls and monitors Merlion in a closed-loop fashion. This task monitors the satellite’s power and thermal condition to ensure that critical parameters remain within acceptable limits. If limits are exceeded, the task places Merlion in a safe mode.

Because Merlion presents these safety concerns, operators elected to test it only after some high-quality images had been received from the remote sensing system.

As of this writing, basic functioning of the Merlion transponders has been confirmed. The check-out sequence deviated significantly from plan for a number of reasons. Firstly, the Surrey Mission Control Ground Station had not previously operated on L-band or S-band, so the check-out and fine-tuning of the ground station proceeded in parallel with the Merlion testing. Secondly, operators elected to move back and forth between the two redundant transponders in order to explore differences between the two units. Finally, a conservative approach to all operations was adopted, and this inevitably resulted in some pauses for data analysis and operations re-planning.

The Merlion communications transponder is the subject of a further paper in these proceedings.

**3-Axis Attitude Control**

Day 55

During the check-out of Merlion and the remote sensing payload, momentum biased attitude control kept UoSAT-12 nadir pointing. Momentum bias mode provides sufficient stability for many minisatellite tasks, but does not provide the attitude control agility required by some science and remote sensing payloads. Experiments with more agile 3-axis control modes commenced during the Merlion checkout phase.

Three-axis zero-bias attitude control experiments were executed 8 weeks after launch. The spacecraft pitch-axis wheel momentum was dumped completely and the roll- and yaw-axis wheels manufactured by SSTL were activated. Full results of this experiment are presented in these proceedings.

**Cold Gas Orbit Control**

Day 73-78

* To improve general spacecraft safety, the Merlion monitor was extended to monitor UoSAT-12’s power status at all times, and to shed nonessential loads should the power budget become negative.
The most recent achievement in UoSAT-12 checkout sequence is the commissioning of the cold-gas propulsion system and execution of a planned orbit change. This experiment met the following objectives:

- verification of thruster commands,
- verification of accumulator closed-loop control system,
- calibration of thrusts,
- verification of attitude control system in presence of thrusting, and
- execution of 120-second in-track propulsive manoeuvre.

The 120-second manoeuvre was designed to change the semi-major axis of UoSAT-12 by about 200 metres and to move the satellite closer to the frozen orbit conditions required for the Microcosm Orbit Control Kit experiments scheduled to commence this summer. GPS measurements from the UoSAT-12 SGR confirmed the success of this manoeuvre.

**On-Going Experimental Phase**

Ninety days after launch (July 1999), we are approaching the end of the check-out and commissioning of UoSAT-12. Experimenters in Singapore, the USA and Surrey will now undertake the “operational-experimental” phase of the mission.

Key goals for this phase are

- to continue gathering multi-spectral and panchromatic images, demonstrating the operational capabilities of the imagers and stimulating development of supporting ground and space systems,
- to fully characterise the Merlion system in-orbit and to use the transponders for experiments in a wide range of LEO communications technologies,
- to place UoSAT-12 in a frozen orbit and demonstrate fully on-board autonomous orbit station keeping through the Microcosm OCK experiment,
- to measure GPS phase differences for ground processing of the satellite’s attitude, and to produce on-board GPS attitude determination software,
- to activate the Nitrous Oxide resistojet thruster and demonstrate inexpensive electrical propulsion,
- to increase attitude control accuracy through application of Surrey’s star imagers and sun sensors, and
- to demonstrate attitude control agility, including ground target tracking, along-track and cross-track off-pointing manoeuvres.

**Summary**

The UoSAT-12 mission was a large investment of resources for Surrey and for our partners. We challenged ourselves to take our proven cost-effective engineering techniques and validate them on a new class of satellites. Further, it was essential to prove a new range of capabilities which would open the door to new mission opportunities.

UoSAT-12 has already achieved these goals. In the 90 days since launch, we have

- demonstrated three-axis attitude control with both momentum-biased and zero-biased systems, using both third-party and in-house wheels,
- demonstrated a 1-Mbit/second telemetry downlink to a low-cost ground station, exclusively through in-house technology,
- demonstrated the Surrey SGR GPS position receiver,
- returned outstanding 32-metre multi-spectral and 10-metre panchromatic images of the Earth from a COTS-based imaging system,
- planned and executed a propulsive orbit-change manoeuvre,
- brought a sophisticated payload through in-orbit checkout and to experimental readiness.

For Surrey, the significance of these achievements is clear. We have proven that our engineering techniques can be extended to a new class of small satellites. We will exploit this both commercially and academically.

For the small satellite community at large, UoSAT-12 demonstrates yet again what can be achieved with a small budget when this is employed by an expert team, supported by sympathetic management and appropriate levels of bureaucracy—and when equipment, payload, system, launch and operations teams work together to achieve the greatest return.
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References


