SUNSAT - Launch and First Six Month's Orbital Performance.

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Abstract. South Africa's first satellite, SUNSAT, has been operating in orbit since a NASA-sponsored launch on the USA Air Force P91-1 Argos Delta II mission on February 23, 1999. SUNSAT is a graduate student-developed satellite from the University of Stellenbosch in South Africa, and includes a NASA GPS receiver for occultation research, laser reflectors, magnetometers, star cameras, Amateur Radio communications, and a 15-m resolution, 3456 pixel, 3-band, stereo-capable push broom imager. SUNSAT is controlled from the University, and most functions were operating in June 1999. Live PAL TV earth images are received well at Stellenbosch on a 4.5 m diameter antenna, and good quality test images from the 15m imager have been obtained. As OSCAR-35 (SO-35), SUNSATs Amateur Radio FM audio transponders provided strong signals on scheduled passes over South Africa and the USA. http://sunsat.ee.sun.ac.za

1 - Introduction

On February 23 1999, a USA Air Force Delta II lofted SUNSAT, South Africa's first micro-satellite, into a precise 96.4 degree polar orbit. Cheers from staff, students and many others watching the live TV broadcast of the launch, heralded South Africa's entry into space.

The 64 kg satellite (Figure 1) has become OSCAR 35 (SO-35) after starting South African and international Amateur Radio activities, and has begun returning 15-m resolution, 3456 pixel/line, 3-band stereo imagery.

The successful commissioning of arguably the most complex student-developed satellite in space, has opened the door for South Africa and the University of Stellenbosch to future space co-operation.

The SUNSAT programme has also achieved its engineering educational goal by involved over 96 graduate students, who have competed over 45 graduate degrees. The programme has produced numerous spin-offs, including components in orbit on satellites of three countries.

This paper reviews the program's goals and history, and records and evaluates the orbital experiences from launch until 14 July 1999.

Background

In 1991, the first four authors, who are in the Computer and Control Group in the Department of Electrical and Electronic Engineering at the University of Stellenbosch, decided that a micro-satellite project could satisfy the goals of:

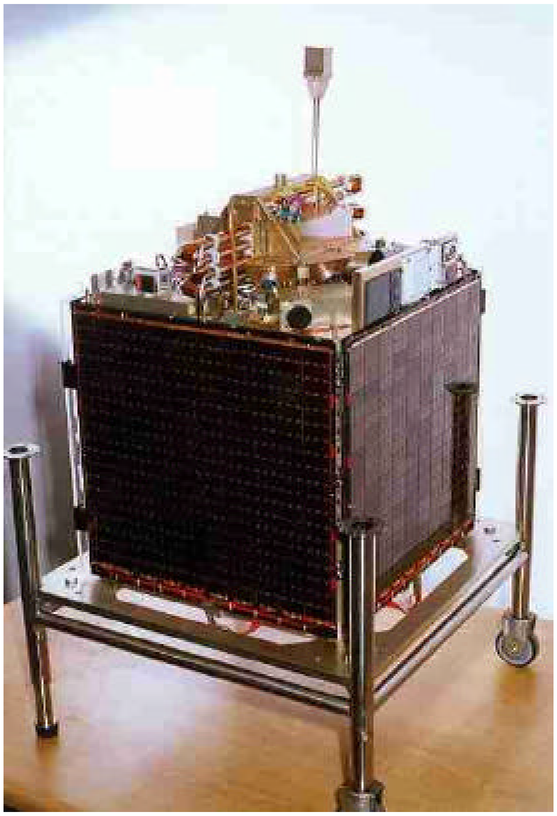

Figure 1 SUNSAT in Handling Frame

- Adding a multi-disciplinary engineering research opportunity to the graduate portfolio.
- Stimulating significant international interaction through a challenging research initiative.
- Helping stimulate interest of the youth in science and technology through media exposure and schools programs.

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The initial goal was to launch a satellite in three years, but funding and launch delays stretched SUNSAT's development until launch in February 1999.

Over 96 students were involved, and schools technology stimulus activities spawned the MTN-SUNSTEP schools programme that has seen over 25000 children assemble schools electronic kits (http://www.sunstep.sun.ac.za).

Educational aspects of the programme are covered in previous papers.[1, 2] The present paper concentrates on the satellite engineering aspects of SUNSAT.

Section 2 reviews SUNSAT's goals, while section three describes funding and schedule consequences. Sections four and five describe satellite development and environmental testing. Sections six through eight cover launch vehicle integration, the launch campaign, and early orbit operations. Sections seven and eight describe and evaluate the orbital status of SUNSAT in mid-July 1999. Sections nine and ten give lessons learned, our interest in SUNSAT 2, and the conclusion.

2 - Goals of the SUNSAT satellite

The Master's degree in the Department requires 2400 hours of student effort. SUNSAT provided a vehicle to stimulate this resource into creating a significant engineering product.

A decision for in-house development of all electronic systems and software except where facility requirements would be unreasonable, significantly expanded the system-wide understanding in our group's Electronic Systems Laboratory (ESL).

Industry sponsors also saw value in our students working on systems that could possibly be launched, thus developing engineers with increased concern for the quality and reliability of their work.

Implications of success or failure

Success of SUNSAT was expected to have a significant effect on possible future satellite developments in our country, so there was a strong motivation to succeed. This implied a satellite with many functions, that would not become value-less if a single failure occurred. To reduce risks and space radiation environmental effects, a LEO satellite with basic gravity gradient stabilisation was a logical starting point.

A challenging main research payload was identified, and options were reviewed for additional functions. Amateur Radio's track record and resources for stimulating interest in communication-based electronics led to a rewarding partnership. A modular design approach had been selected, so an extra tray was easily added to accommodate NASA's GPS when their launch offer arose. Our own boom design could also be exploited to add wiring and a tip mass magnetometer, star camera, and laser reflectors when the symbiosis with the Ørsted satellites data was appreciated.

Satellite engineering research goal

The research goal of SUNSAT is to demonstrate that a student-developed 50kg-class micro-satellite can produce remote sensing imagery approaching that of the SPOT-2 class of large remote sensing satellites.

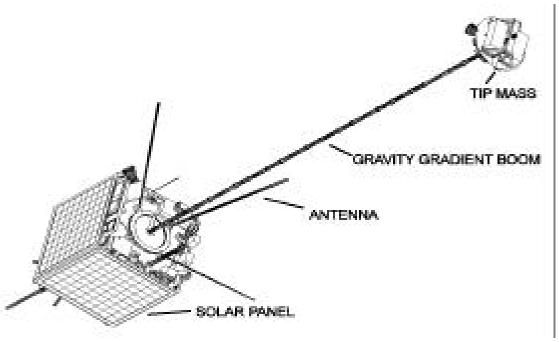

Figure 2 SUNSAT in-orbit configuration

Choosing the satellite engineering research goal.

Completing, launching and operating a first satellite would have met our training goals, but was insufficient for our research requirements. We thus sought further challenges to make a research contribution to satellite engineering. The following thought process led to SUNSAT's satellite engineering research goal.

Imaging in L.E.O.

The short visibility time in low earth orbits is a great disadvantage for communications and operations. The major attraction of this orbit for a single satellite is for imaging.

In 1991 the SPOT-2 satellite was producing the highest resolution remote sensing data over South Africa. SPOT-2 has a 20m multi-spectral resolution, while similar-sized intelligence satellites achieved meter-level resolution. There seemed to be a great opportunity to increase the resolution of imaging micro-satellites to well below the 100m levels then common in microsatellites.

Lower cost and calibration need.

We met numerous SPOT-2 users in South Africa who indicated a need and use for imagery that was *visually* similar to SPOT-2, but of lower cost. Users often did not utilise the accurate calibrations, and believed that lower cost data with less calibration would permit work that was precluded by the high cost of SPOT data. We also learned that a stereo capability *in the same pass*, with SPOT's green, red, and near IR bands would be an attractive combination of capabilities.

Sensors

High-resolution imagery needs both small pixel spacing, and many pixels. CCD TV sensors were limited to below 1000 pixels, but linear CCD sensors with up to 5000 pixels were available. At wavelengths longer than visible light, (near-IR), photons penetrate deeply into Silicon sensors, and generate photo-electrons that can diffuse to adjacent photo-sites. The MTF (Modulation Transfer Function ~ resolution) of sensors with fine pixels thus drops significantly at longer (NIR) wavelengths. To obtain good Chlorophyl-band imagery, we chose a TC104 3456 pixel linear CCD Silicon sensor with 10.7µm pixel spacing rather than a sensor with a larger number of smaller pixels.

Optics

Optics development was beyond our skills goal, so we teamed up with the Optical Engineering Group of the CSIR in Pretoria. They had developed a series of compact and light TeleMacro lenses which were a good starting point for a micro-satellite imager. They also proposed how to optically combine three linear CCD's into a single optical unit meeting the focus, alignment, and filtering needs for a pushbroom imager.

The real LEO!

The LEO acronym is quite appropriate for SUNSAT's imager since a lion at the Pretoria zoo played a role in the imager's history. The CSIR had taken a photograph of this lion using a 10cm diameter, 1200mm focal length TeleMacro lens. The lion's whiskers (estimated but not measured! as 1mm diameter) were in sharp focus. Simple scaling showed that 10m objects should be clearly visible from 700km. (1mm from 70m subtends the same angle as a 10m object seen from 700km.)

Figure 3 The SUNSAT LEO!

Armed with MTF calculations, the 3456 element linear CCD's performance, the CSIR's optical capability, and the lion's personal endorsement, we became confident of producing an imager for SUNSAT that would produce imagery that would be visually similar to that from SPOT-2. A joint development with the Kitsat-3 project[3] resulted in common imagers which have been successful on both satellites.

Trade-off and consequences

A trade-off study of light levels, MTF of optics, motion and CCD performance finally led to an optical system of 10cm diameter and 570mm focal length, using TC104 sensors. The pixel spacing of 10.7µm subtends 18.7µrad (10.7µm/570mm), or 15.01m from 800km. The swath is 3456 * 15.01 = 51.9 km, and the field of view is 3.717 degrees. An 8-bit image data handling system with independent electronic gain control in each channel was designed, and a 64Mbyte RAM disk was added as an on-board image store.

While converging to a research goal of demonstrating 15m resolution, 52km swath imagery from a microsatellite, we had considered the implications on other satellite subsystems. The real time downlink capability of over 40 Mb/s could be met with a 5W transmitter and a realistically sized 4.5m ground station antenna. Demands for 1mrad ADCS accuracy when imaging could be met with fine visible-band horizon sensors, and reaction wheels that only needed to run when imaging. Coarse attitude control when not imaging could still be maintained with magnetorquing, which reduced the consequences of reaction wheel failure.

3 - Program scheduling and completion

The concept design of SUNSAT as a sun-synchronous imaging micro-satellite was described earlier.[4] Funding has remained a major issue throughout the program, and influenced many design, contracting, and scheduling decisions. The first consequence was that the planned auxiliary payload launch on the Ariane Helios mission could not be funded and was missed, placing the whole programme in jeopardy.

NASA-sponsored launch

NASA saved the SUNSAT programme by offering a launch on the US Air Force P91-1 Argos Delta II mission if SUNSAT could carry a JPL Turbo-Rogue GPS receiver for geodynamic research. Denmark's Ørsted magnetic research satellite was already scheduled as a secondary payload, and SUNSAT could be carried in the opposite sector instead of a balance weight.

The interaction with Boeing and NASA has been one of the major learning experiences of the SUNSAT programme. NASA was extremely supportive, but realistic and strict on SUNSAT's launch integration. This resulted in a smooth final integration process with Boeing's Delta II rocket, and a perfect launch.

The 857 x 655 km elliptical polar orbit was dictated by science requirements of the Oersted satellite which was the initial secondary payload. The orbit plane drifts an hour earlier every seventy days, and was aligned with the sun in mid-July 1999.

The orbital drift makes long-term repeated imaging impossible, and lowered the expected output of SUNSAT to demonstrating what the satellite would be able to achieve in a true sun-synchronous orbit. We retained the sun-synchronous design for the drifting orbit, and intend to concentrate on communication activities when the sun angle becomes unsuitable for imaging, but provides more average solar power.

Following a first technical integration meeting at Boeing in May 1994, a NASA visit in July 1994 produced a series of technical milestones that were successfully met. A launch MOU was signed in July 1996. The originally intended launch date of September 1996 slipped on numerous occasions because of delays with the prime payload. Launch eventually occurred on 23 February 1999.

4 - Satellite final development

NASA took immediate control of the launch integration process via a schedule of documents verifying SUNSAT's design. The most urgent requirement was a correlated dynamic model of the spacecraft. The launcher interface design was finalised, a finite element model was completed and modal survey tests were performed at a daunting schedule. Figure 4 shows one of the finite element model printouts.

Tray structure

SUNSAT is formed by a number of trays containing the various subsystems. Figure 5 shows the mechanical model of SUNSAT undergoing modal survey tests, and clearly shows the tray structure.

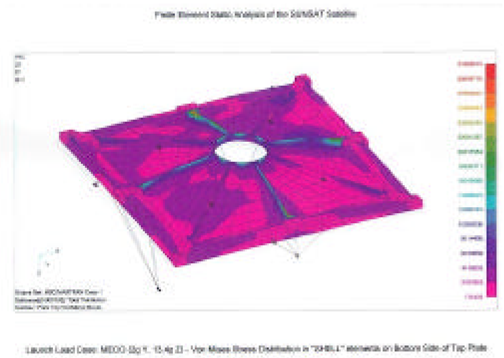

Figure 4 FEM analysis

Bottom tray

The bottom tray is the deepest and most complex tray since it has to carry components that need the view, a low position for C.G. reasons, or the mild temperature and heat dissipation capability. It also has to incorporate the payload attach assembly (PAA). The bottom view in Figure 7 shows the lower mechanical components, including the large threaded hole to accept the PAA.

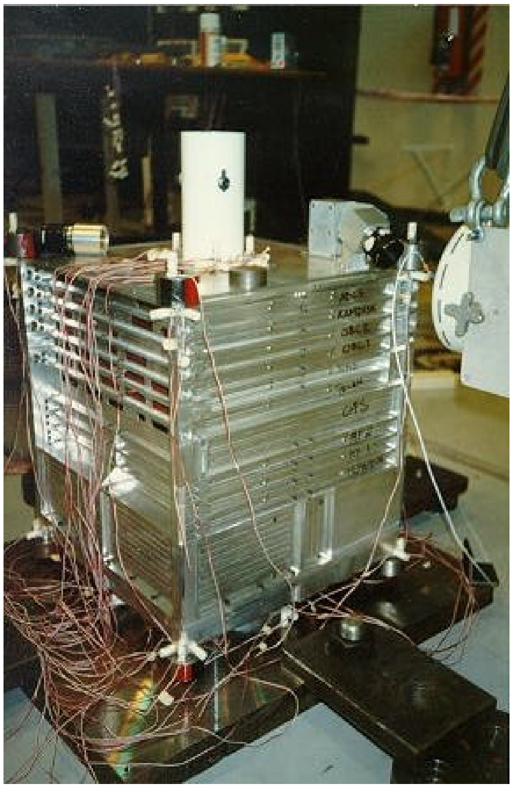

Figure 5 Modal survey tests

The lower tray is 12cm high to contain the imager, which fits diagonally across it, and views the earth below via a 45-degree mirror. The imager mechanics can be seen through the imager aperture in the corner of the bottom tray in the Figure 7.

Imager mechanics

Figure 8 gives the top view of the base plate and the imager mechanics at the beginning of lower tray assembly. The fused quartz optical system in Figure 9 was potted into mounting rings. It and the electronic circuit boards were then mounted inside the imager tube and subjected to comprehensive optical and environmental test before being handed over for integration with the lower tray.

Imager rotation

For stereo imaging along the ground track, the satellite is flown with the imager normal to the velocity vector. An approaching-image strip of up to 700km length is scanned with the imager pointing 24 degrees ahead of the sub-satellite point. The imager is then rotated 24 degrees behind the sub-satellite point, to take a receding image of the same area.

For imaging to the side of the ground track, the satellite is flown with the imager pointing in the direction of the velocity vector. Rotating the imager left or right allows scenes up to 350km away from the ground track to be imaged.

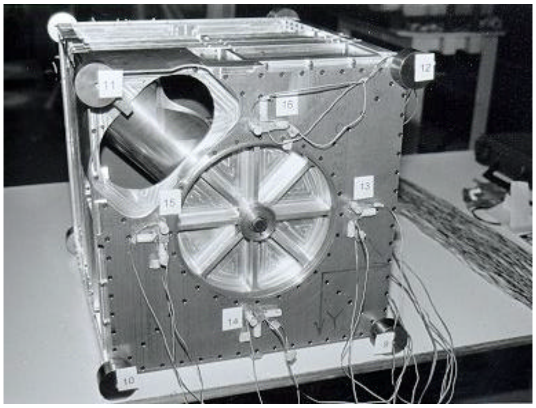

Figure 7 Underside of base plate.

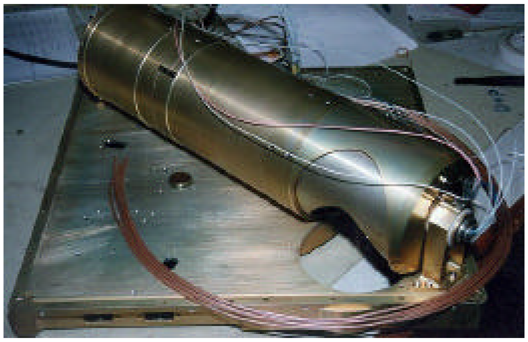

Figure 8 Base plate with imager.

Figure 9 Optics package inside imager.

The inner rotating tube in Figure 8 is needed to correct the orientation of the linear CCD's which differ by 90 degrees in the two cases. A potentiometer measures the coarse position of the imager, while fine wires passing through an optical interruptor's beam give precise angular information at a few specific angles.

Lower tray wiring

Figure 6 shows the lower tray after more items and the wiring harness were added. SUNSAT's S-band PA and the UHF transmitter PA's are mounted in the lower tray for heat dissipation reasons. These all require cables, which add to those for reaction wheels, batteries, and solar panel strings to make the harness a challenge.

Figure 6 Base plate with wiring harness.

Integrated lower tray

The complete lower tray seen in Figure 10 was more cluttered than desired. This resulted from thermal and view-port needs of some components, and the need to place large mechanical components in the single 'high bay'. Spot the four reaction wheels! In addition, the bottom plate represents 50% of the antenna mounting area of the satellite, so had to carry its fair share of RF cables and connectors.

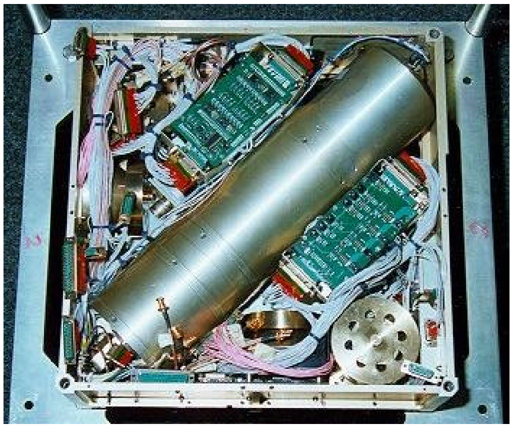

Figure 10 Complete lower tray.

Standard trays

The remainder of the trays in SUNSAT were less difficult to package. Figure 11 shows the satellite after the power, telecommand, and UHF communication trays had been added. The first two trays

Figure 11 Lower four trays of SUNSAT.

contain large motherboards with two crossbars supporting them via a number of screw attachments.

The RF trays used two crossbars to support a motherboard which carried the different RF subassemblies, each in their own aluminium-screened boxes.

The construction of other trays followed the same crossbar and large board concept with piggyback board in the RAM tray and on the ADCS tray.

The S-band tray had to be at least 50mm high to accommodate NASA-JPL Turbo-Rogue GPS receiver. The non-Turbo-Rogue area was split with a mezzanine floor, allowing two 25mm-high areas to accommodate the L- and S-band modules and the school experiment tray.

The top plate

The top plate of the satellite in its launch configuration is crowded, as can be seen in figures 12 - 15. The tip-mass occupies the center, and is attached with a single stainless steel bolt. The bolt passes through two pyrotechnic-activated guillotines that cut it to release the tip mass.

The tip mass comprises two halves and a bridge that straddles the folded boom, which deploys using its own stored energy. Screened signal leads pass through the interior of the boom to the star camera and 3-axis magnetometer in the tip mass.

Figure 12 shows the fine roll and pitch sensors. These are only needed during imaging, so use visible-band linear CCD sensors. Their black lenses are seen pointing 30 degrees downward. The fine yaw sensor used a similar CCD behind a split.

The phasing network for the VHF canted turnstile antenna is in the box at the lower right of Figure 12, while the downward facing holes in the tip mass are to receive the laser retro-reflectors.

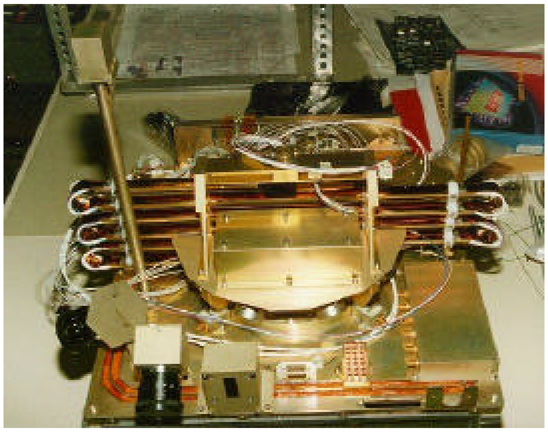

Figure 12 Mechanical components of top plate.

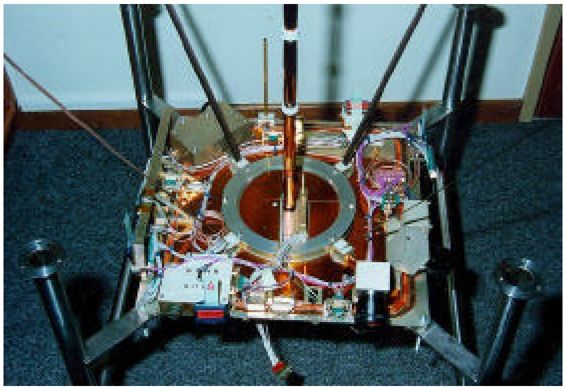

Figure 13 Top plate during electrical wiring.

The tip mass is also an ideal place for a web-camera to view future satellites in orbit and monitor surface degradation. The small size and mass of recent matchbox or smaller cameras makes them very useful for health and even attitude checks.

VHF Antennas

SUNSAT has two VHF antenna systems. The simplest is a monopole at the center of the lower surface which passed through apertures in the PAA and PAF. The second system is a canted turnstile, radiating circular polarization below the satellite. Flexible 50cm Beryllium Copper ‘tape measures’ were rolled up inside brackets on the tip mass during launch, and deployed once the tip mass was released. Figure 13 shows these antennas, plus the short UHF monopole on the far side of the top plate.

Boom deployment test

Firing the guillotines while the boom’s elbows were suspended with fine elastic in a high bay enabled deployment to be tested. Figure 14 shows the top plate with deployed VHF turnstile and boom. The boom is stiff enough to support its own weight (but not the 4kg tip mass) under 1 g’, which eases ground processing.

Figure 14 Top plate with boom deployed

The tip mass carried the eight NASA laser reflectors. These were mounted in 2.5 cm round housings that can be seen on the downward pointing edges of the tip mass. The baffle of the tip-mass star camera can be seen aimed at the rear of the white GPS antenna above the right solar panel in Figure 15. Flanking the GPS antenna are the micro-meteoroid sensors from the Peninsula Technikon (Pentech) in South Africa and NASA in an experiment run by Pentech. (www.EE.pentech.ac.za)

The closest corner in Figure 15 shows the top plate's star camera, while the solar cells on the coarse sun sensor can be seen above the top of the left solar panel. The figure also shows the short boom carrying the ADCS magnetometer.

Tray interconnections.

Interconnection of the many telemetry and telecommand wires was a problem. The width of all trays except the bottom tray was reduced to provide a wiring cavity under a solar panel. This cavity carries all 'slow' signals. A similar cavity on the opposite side was provided for data and address bus interconnections between the OBC's RAM, and ADCS. The separation of computer buses and signals entering the analogue trays was implemented to reduced the level of RFI and EMI.

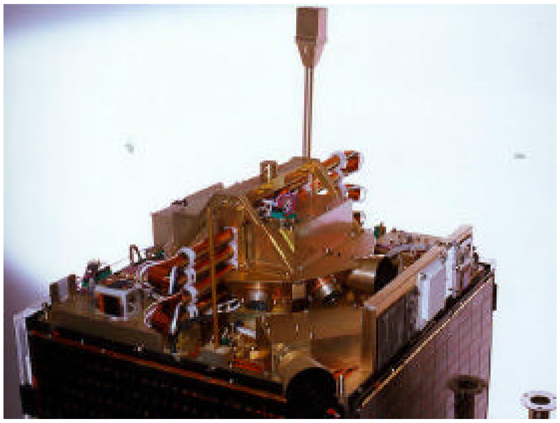

Figure 15 Top plate before thermal blanket installation.

Figure 16 shows the satellite inverted in its handling frame, with the solar panel removed to show the slow bus area. In later RFI correction measures, the wiring in the figure was totally covered by a 0.3-mm Aluminum plate. It was regularly grounded to screen the VHF antennas from RF noise generated inside the satellite.

RFI

The payload function on SUNSAT that is considered to be the most important for stimulating technical interest in young children is the VHF Parrot. Significant benefits accrue if the VHF receivers are sensitive enough to receive uplinked signals from 1.5W hand-held radios.

Significant attention was given to receiver spurious and image responses, and maintaining noise figures near 2 dB. However, RFI radiated from computers and in particular, from switching regulator packages, was extremely difficult to control. To reduce costs, unshielded regulators were used in most locations in SUNSAT. In the VHF tray, this proved inadequate, and the only way of controlling RFI was to mount the regulator in its own Aluminum filtered box that was attached to the sidewall of the tray.

The level of shielding needed is illustrated by a simple test done with an isolated 5V switching regulator fed from a well-bypassed and choked supply. A 0.5m antenna mounted 50cm away from the regulator received a 650 kHz comb-spectrum with -85 dBm spectral lines. This level is 44dB above the -129 dBm noise floor of SUNSAT's VHF receivers!

The switching regulator problem was very difficult to analyse and solve because the switching frequency changes slightly with supply voltage. Ten-

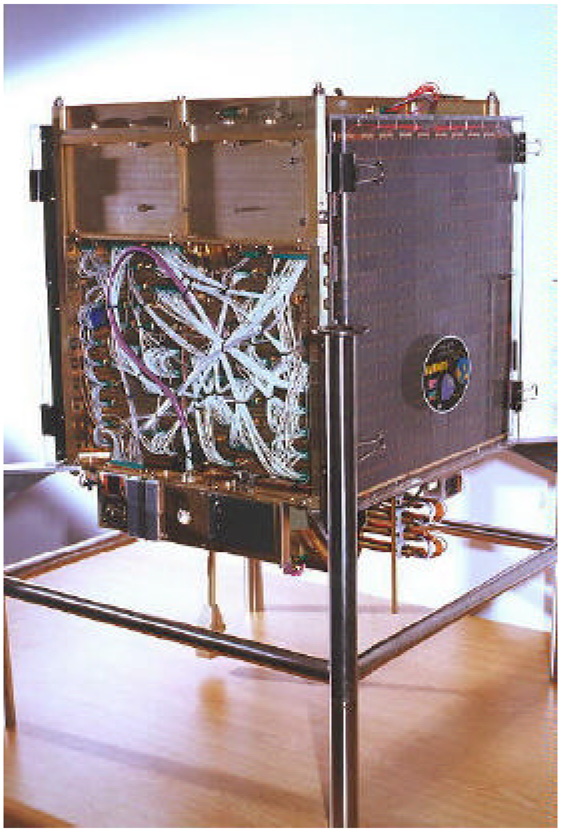

Figure 16 Slow bus wiring area.

millivolt changes in the supply, possibly caused by activating other payloads, caused the spectral lines (± 223 harmonic) to drift through the receiver passband, making measurements inconsistent.

RFI tests and diagnosis proved to be very difficult as reported previously[5]. At one stage we were not sure if the RF filtering on leads to the top plate and through-seam leakage between trays would be adequate to reduce satellite emissions to a point where our own receivers would not be de-sensitized by the RFI.

The Faraday screens shown in Figure 17 were thus made and attached around the satellite. With these we managed to prove that metallic screening of the bus cavities would be adequate to make our antennas noise-free.

5 - Environmental testing.

Thermal tests had to be done at affordable costs. We managed to obtain, and repaired a thrashing pump and diffuser vacuum pump and built the vacuum chamber shown in Figure 18. Heater plates were made to fit around SUNSAT as shown in Figure 19, and could fit into the vacuum tank. With these we could do room temperature and hot vacuum tests and bake-out.

Cold thermal vacuum tests required additional facilities and complications, so we reviewed their necessity. We knew that the internal temperature of SUNSAT would not become very low, and we provided no heaters except to heat the imager optics in an attempt to dislodge any condensed outgassing products from the satellite.

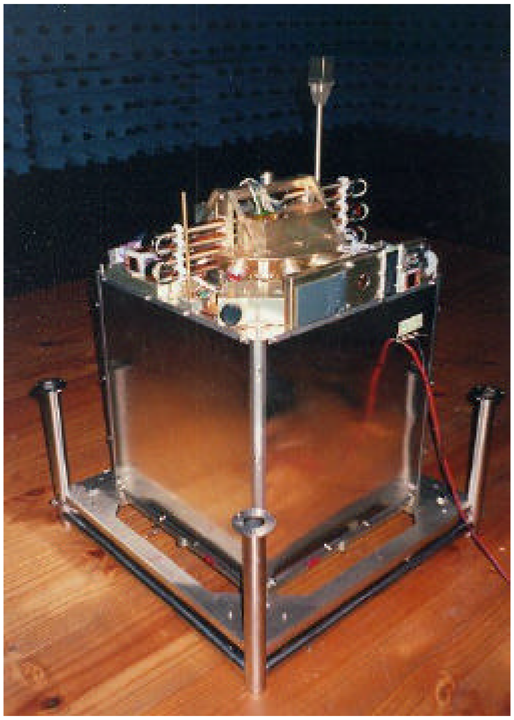

Figure 17 Faraday screen during RFI diagnosis.

We reasoned that high temperature tests needed to be done in vacuum to prove that losing the thermal transfer properties of air would not cause local overheating. We could not see the need to do cold tests in vacuum if we had no heaters to test, so decided to do all cold testing at atmospheric pressure.

Figure 18 Vacuum chamber.

Vibration tests

Full level, 3-axis random and sine vibration tests had been completed on sub-assemblies and the complete engineering model of SUNSAT. These had verified the packaging concept and identified isolated component mounting problems, which

Figure 19 Heater jacket around SUNSAT

were corrected. The flight model experienced no failures during its vibration test series at the Houwteq test facility. (Figure 20)

6 - Launch vehicle integration

Launch vehicle physical integration was done by Boeing, initially by design drawings and then confirmed by a fit check of a volumetric model to the second stage flight hardware. The location on the second stage is shown later in Figure 23.

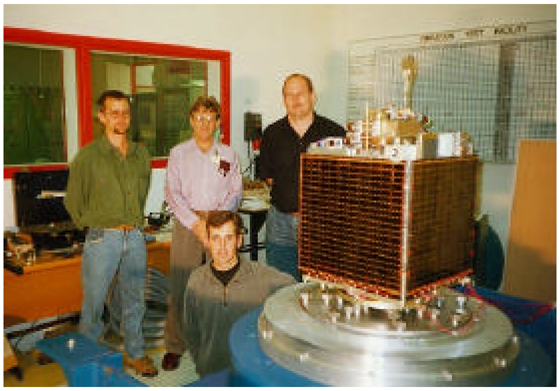

Figure 20 Flight model vibration tests.

Fit and shock tests

The flight PAF and flight PAA were integrated in South Africa during a visit by NASA and Boeing. A separation shock test was also completed to assess clamp-band firing shock loads. Figure 21 shows SUNSAT suspended with PAF attached and being readied for clamp band firing.

Figure 22 shows the separated PAF after the clamp band firing, and with SUNSAT's VHF monopole and UHF canted turnstile antennas in their orbit configuration. Shock levels were monitored and found to be within normal ranges, and no damage to optical components occurred.

7 - Launch campaign

Our mission nearly set the record for the launch campaign length. Our four-man launch team ar-

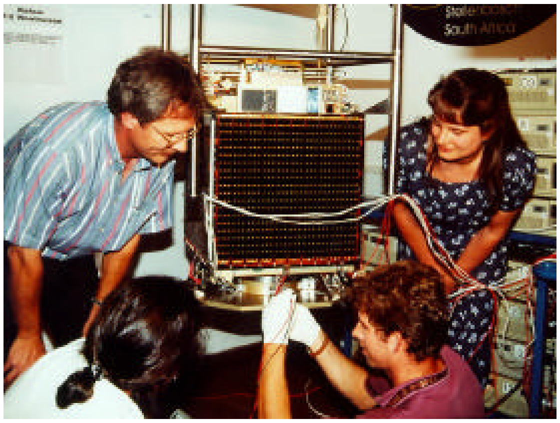

Figure 21 Preparations for clamp band firing.

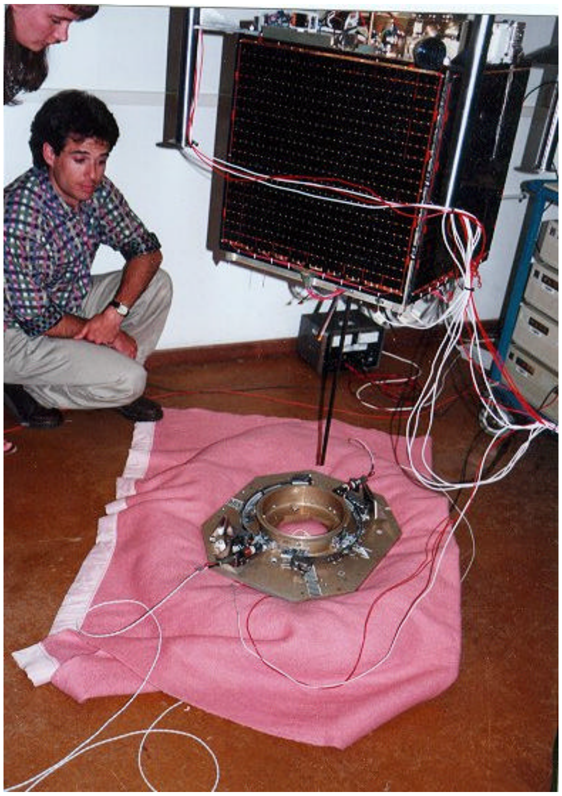

Figure 22 Hey guys -- it worked! No glass!

rived at Vandenberg on 23 November 1998, and proceeded with satellite checkout. The NASA Resident Office and its contractors, and the whole Boeing team, have become our reference standard for willingness and quality of support. Ørsted and SUNSAT were mated with the launch vehicle on December 8 and 9 (Figure 23), and left on monitored trickle charge over Christmas, with launch scheduled for 12 January 1999.

Figure 23 shows SUNSAT installed on the launch vehicle, with Ørsted on the opposite sector. The Argos satellite is attached on top of the white support ring, but is not visible because of the intervening floor of the mission support tower.

Figure 23 SUNSAT and Ørsted in place!

Launch

A number of Danish and South African visitors, including a cabinet minister attended, making for a busy public affairs programme. The 30-th Space Wing at Vandenberg made all visitors extremely welcome, and did a great job handling VIP's and rockets alike!

Waiting

Weather and two technical hitches caused ten launch scrubs, with launch eventually occurring on 23 February 1999. By that time, even the keenest academics had returned to South Africa and undergraduate classes, and only a single SUNSAT engineer was left monitoring trickle charging. The rest of the team watched the launch attempts via the TV link, and each time experienced the anticipation of launch as LOX vented and then puffed from just under the SUNSAT insignia on the launch vehicle (Figure 25).

Go go

The simplicity of the go, go, go on the countdown net on 23 February was almost an anti-climax after the dramas of earlier occasions. The auditorium at our Department was full of students and the die-hard launch watchers. The auditorium erupted as the Delta ignited and lifted smoothly into the night sky. We then watched in awe as the solids separated, and the range cameras tracked the Delta up until second stage shut down. We waited, doubting velocity vectors, Kepler and Newton, until the Hartbeesthoek tracking station in South Africa received confirmation of Argos' separation, and then until the words 'secondary separation confirmed' were heard from Vandenberg. Then it was up to us!

8 - Initial commissioning

Immediately after separation, our launch team member hosted at W6AB, the Vandenberg Satellite Amateur Radio Club, uplinked commands to SUNSAT to activate its power relays and telemetry transmitter, but no downlink was heard. Half an orbit later, over Stellenbosch -- still no telemetry, and yet again for the next pass. Joy of joy's, telemetry was received during the night pass, and indicated that battery voltage and temperature were fine. Life started again!

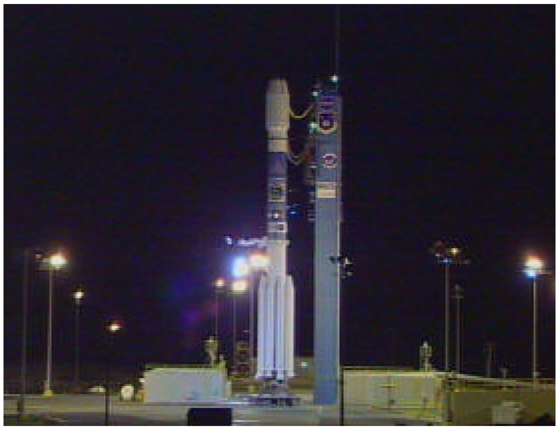

Figure 24 A beautiful sight.

Being our first satellite, we were extremely careful of any action that could cause us to lose the satellite through command lock-out by on-board transmitters. SUNSAT has time-outs on all transmitters to prevent lock-outs but we weren't prepared to risk the satellite on their unproven post-launch performance.

Figure 25 LOX venting below SUNSAT emblem

Figure 26 Go!

Figure 28 Solids separate

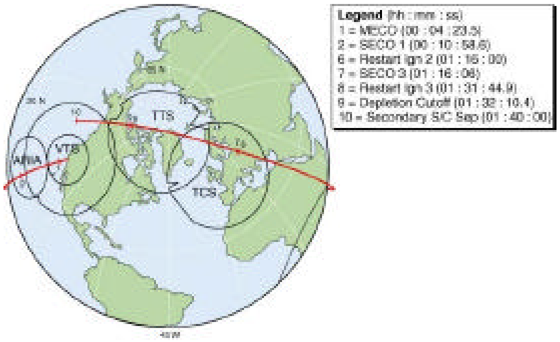

Figure 27 Orbit trace until secondary separation

The delayed telemetry had stalled our commissioning sequence, and allowed the satellite temperature to rise. It had also made us nervous and scared of losing telemetry or tele-command. Great joy occurred when we booted OBC1 for the first time and it transmitted it's 'I'm alive' audio signal.

The handicap of short passes and marginal communications was sorely felt in the first few days. The extra accesses from W6AB proved invaluable in understanding what was happening on board SUNSAT. OBC1 started collecting whole orbit telemetry (WOD) reliably, and our insight increased to a point where we could re-consider de-tumbling and boom deployment.

Initial ADCS activation

SUNSAT's 3-axis magnetometer from Hermanus Magnetic Observatory of the CSIR performed flawlessly and showed that SUNSAT was coning with its lower plate exposed to the Sun, and with its temperature rising. Our attitude control system was started and slowed the Z-spin using the torque coils. Figure 29 shows WOD magnetometer data as the Z-spin was controlled. The large square wave signal that starts at 20% of the time axis is magnetorquer current, which clearly reduces the frequency of the spin shown by the sinusoidal x-axis magnetic field.

We experienced some resets on OBC1 which then reset the ADCS computer (this has now been changed by software upload). It was thus impossible for the ADCS to enter the planned boom deployment process. Meanwhile, we had an increasing satellite temperature because of the attitude-stabilizing spin, and no gravity moment to break this pattern

Boom deployment

We reviewed our options, and concluded that the lowest risk strategy would be to deploy the boom, even though SUNSAT's was pitching at one degree

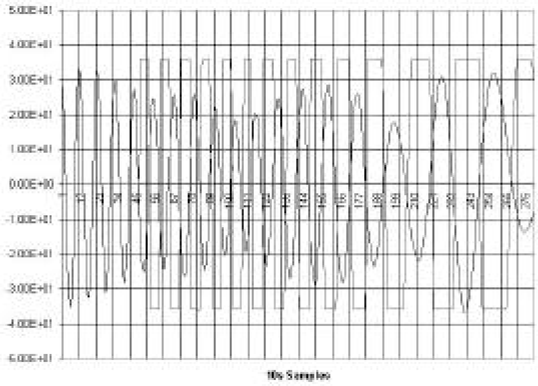

Figure 29 X-axis magnetometer during de-spinning

per second. We translated the rotational energy of 0.3 mJ, into the energy of one gram at three centimeters height, or a 6 μF capacitor charged to 10 Volts. We decided this could not damage anything, particularly since our boom deployment tests had shown the boom to straighten out in less than 5 seconds, and decided to deploy the boom.

The Z-axis magnetometer readings during boom deployment that are given in Figure 30 show how the angular rate normal to the Z-axis dropped by a large factor as the boom deployed. This particular telemetry trace caused great relief since it confirmed that our own-developed boom had deployed. Our communications team wanted deployment to occur to release the VHF turnstile antenna which immediately improved uplink telecommand performance.

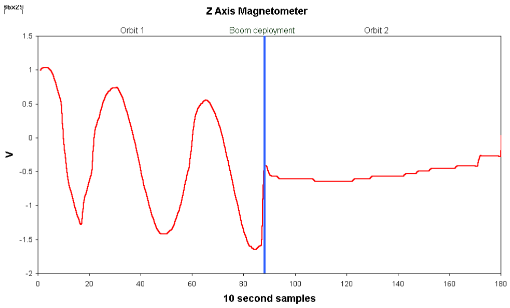

Figure 30 Z-axis magnetometer during boom deployment

The first action after boom deployment was to activate the libration damper controller on the ADCS. The satellite managed to establish gravity-gradient lock in the correct orientation within a few orbits.

With SUNSAT earth-pointing with a slow yaw spin for temperature equalization and a stable and satisfactory temperature, our thermal concerns were over. The main battery voltage was in limits, the battery charge controller was cycling correctly, and the state of charge indicator was giving credible information. It was time to celebrate a successful initial commissioning phase.

First software update

Prior to shipping SUNSAT, we knew we were running behind schedule on real-time software, and had to choose between completing a reliable kernel and AX25 communications software and drivers, or testing the applications to run on this. The kernel got preference, and proved able to boot OBC1 from simulated intermittent RF links, even if all flash memories had been erased, and then re-program the flash memories.

This effort, plus code for other controllers absorbed more software effort than was expected or available, so we missed a bug in our Diary command system which triggered crashes in OBC1. These were first blamed on SEU's, but the correlation with diary execution was noted, and then reproduced on the ground. Our first software upload corrected this simple bug and made other small improvements which left the software on OBC1 in a good condition.

9 - Orbital status

SUNSAT is a complex satellite with a number of redundancies. Apparent failure of the high-speed S-band modem will significantly reduce the imaging throughput of the satellite, but hasn't prevented us achieving our main research goal.

The high-speed modem failure has been located to the QPSK S-band exciter, which no longer drives the S-band PA (power amplifier). The same PA carries the live PAL TV signal, and on three early occasions transmitted an un-modulated carrier to the OTB ground station in South Africa. No modulation was possible at that stage since the RAM tray had not been commissioned, and our own S-band reception system was not operating. There is thus still a remote possibility that the exciter may be coaxed back into operation by some sequencing combination.

Failure of an interface to two of the four reaction wheels will also complicate ADCS operation. We have wheels operating in yaw and pitch, which is adequate for fine pointing control. This work was still in process in July 1999.

The pitch reaction wheel has also proved to be invaluable when inverting the satellite during a single pass, following occasional inverted gravity lock conditions that have followed computer crashes.

General performance

SUNSAT is functioning well as an Amateur communications satellite. The bus is in good condition with typically 20 degree-C temperature, and the power, charge-control, and monitoring system working well. Telecommand is reliable, and whole orbit data gathering works well. OBC1 has no known faults but crashes about once per week, possibly as a result of SEU's. After improving the ground station performance, we have reliable communications from horizon to horizon.

SO-35

SUNSAT has been allocated the Amateur designation of SO-35 (SUNSAT OSCAR 35) and has been supporting Amateur radio FM repeater operations in South Africa and the USA since mid-June and July respectively. The 436.291 MHz uplink is transponded down onto 145.825 MHz, giving a strong signal (-101 dBm) even on a hand-held re-

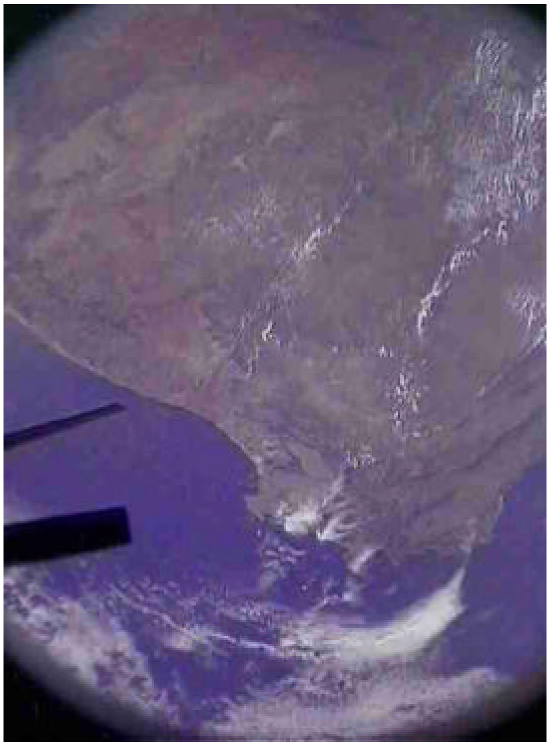

Figure 31 PAL TV frame of the Western Cape

ceiver. Initial USA Amateur QSO's were recorded and made available on the www.amsatnet.com web site, and other links are on the SUNSAT web site http://sunsat.ee.sun.ac.za.

The UHF transmitters can also be heard on hand-helds, but are weaker, as expected. We have also successfully tested a VHF uplink to SUNSAT from a 1.5W VHF hand-held transmitter and obtained a clear UHF return from the satellite when at 18 degrees elevation. The implication of the good VHF uplink and downlink performance is that the VHF Parrot system should work well when its software is installed.

Ground station downloads

Our ground station has a 4.5-m diameter tracking dish that we have started using for the UHF downlink. The additional gain relative to a set of Yagi antennas means that we get constant –98 dBm signals from SUNSAT for virtually any elevation, and have been able to download over 710kB at 9600 Baud in a single pass.

Payloads

SUNSAT's PAL TV camera is working well, and downlinks S-band images of South Africa that are received with no speckles on the 4.5m S-band dish at Stellenbosch. Figure 31 shows an image grabbed from this video stream. Note the tape antennas on SUNSAT protruding into the picture.

The NASA/JPL Turbo-Rogue GPS receiver is working and software updates are being prepared to support full instrument operation.

Figure 32 1000 x 350 pixels from a SUNSAT image of 3456 pixel width

The push-broom imager is working well, and in early July 1999 was storing 3456 pixel by 3500 pixel images on the 64 Mbyte RAM tray. The RAM is used simultaneously as a file system and to store raw image data.

With the high speed modem malfunction, the great stream of real-time image data expected from SUNSAT has not occurred, so we have had to download images at 9600 Baud over a number of passes. The process will be speeded by uploading JPEG image compression software.

Sample high-resolution images.
This section presents some image samples gathered from SUNSAT in the first two weeks of imager commissioning. SUNSAT's image width of 3456 pixels rapidly fills disk space, and cannot be adequately communicated without photographic quality reproduction. Small sections of magnified images are presented to aid assessment.

Figure 33 147 x 172 pixel segment of image

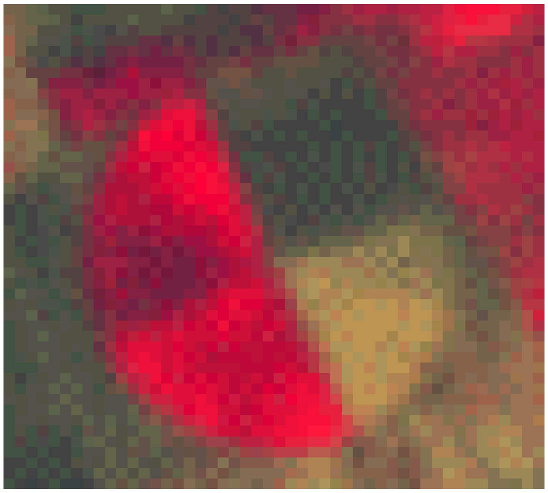

Figure 34 48 x 46 pixel segment of irrigator.

Figure 32 is a 1000 x 350-pixel excerpt from an image of mountains near Riviersonderend in South Africa.

Figure 33 was taken over the Middle East and shows varying fields and a round irrigation system. The irrigator is expanded further in Figure 34

The full color versions of these images are in the electronic version of this paper and on the web site http://sunsat.ee.sun.ac.za, They show the near-IR band in red, clearly highlighting the growing vegetation in the sector from 5'o clock to 11'o clock, and the worse development at the 9'o clock position.

10 - Preliminary evaluation of SUNSAT

After four and a half months orbital experience of a new satellite design and a still-evolving ground station, it is too early to give a full evaluation of SUNSAT. Performance is improving on a weekly basis.

The commissioning pace is slow because of SUNSAT's complexity; initial ground station problems, short LEO access times, and the small operating team that has other normal university responsibilities.

SUNSAT OSCAR 35 is a great success with Radio Amateurs, as evidenced by e-mail and on-air reactions of American and South African Radio Amateurs. VHF up-link tests using VHF hand-held transceivers show that the Parrot should work well when its software is activated. At present, power is needed for commissioning support.

The Middle East and Riviersonderend images show that SUNSAT is able to take 15m resolution images. The quality of the S-band TV link indicates that the S-band link margins for the data downlink would be adequate for regular image data transmission.

By mid-July, the accurate ADCS performance of SUNSAT was not what was desired, but we expect to bring this to full performance in due course.

11 - Lessons learned

Good things.
We feel good about a number of features on SUNSAT that are worth sharing.

1. Survive-all RF boot capability for OBC's.
2. Good performance of the AX25 software.
3. Good performance of the RAM disk and FTP.
4. Ability to upload new software into FLASH.

5. Our boom that deployed well.
6. Audio boot messages on the OBC's.
7. Using high-power VHF and UHF transmitters.
8. Multiple antennas avoid single point failures.
9. Excellent images produced by our jointly developed imager on KITSAT. (Identical to SUNSAT's imager.)
10. Good sample images from SUNSAT's imager.
11. Sub-sampling software for quick-look images.
12. A simple reaction wheel in pitch plane for inverting upside-down gravity locked satellites.
13. State-of charge integrator in power system.
14. Deploying the boom early with no problems.
15. Time-outs on all transmitters.
16. Periodic time-ins on de-activated receivers to provide backup comms in case of need.
17. 1200-Baud telemetry is a good wake-up call.
18. Redundant audio buses enabling audio signals to be 'patched' around the satellite.
19. Redundancy in, and by means of the VHF and UHF systems.
20. Apparently successful RFI measures resulting in good receiver sensitivity on VHF and UHF.
21. Positive feedback from Amateurs using SO-35.
22. Live TV from SUNSAT, and noise-free.
23. Solithane'd commercial TV camera works.
24. Befriending folks at NASA, Boeing, and USAF.
25. Sharing much with the Ørsted launch team.
26. Our students performed like stars!

Difficult things.
We found the following to be difficult

1. Stopping RFI from de-sensitizing VHF receivers due to stray coupling and via antennas.
2. Meeting software milestones with adequate testing.
3. Unwanted power consumption or latch-up from driving unpowered logic.
4. S-band QPSK modulators and demodulators, particularly without QPSK test equipment.
5. Incidental phase modulation on the QPSK synthesizer and modulator.
6. Maintaining continuity of knowledge with a student-manned project.
7. Funding.

Regrets.
We are sometimes sorry that:

1. The bottom tray was so tightly packed.
2. Harnesses were so complex.
3. The batteries are difficult to remove for conditioning.
4. We didn't do RFI tests on the VHF tray on its own.
5. We didn't build a sensor stimulation simulator facility to be able to do full ADCS tests before launch.
6. We didn't have time to operate SUNSAT remotely for a month before shipping.
7. We didn't account for magnetic torques from solar panel currents in design. (Are OK.)
8. We didn't include a simple high speed FSK modulator.

Next time we will:
1. Add a 'spy' TV camera on the tip mass.
2. Add an IR earth-sensor
3. Appreciate that VHF receivers imply high RF cleanliness, and use S-band uplinks if possible, with UHF as backup.
4. Do RFI tests with prototype hardware, satellite receivers and antennas.
5. Plan on 2-month EMC testing and problem solution with the Engineering Model.
6. Make an extra set of flight-identical computers for software testing only.
7. Split OBC processors and I/O multiplexers by modularizing or by serial bus systems.
8. Put micro-controllers on most UART's to reduce interrupt load on main processors.
9. Specify brownout performance of all modules.
10. Plan to allow all uplink receivers to be powered down to save power, but automatically cycle on for 5% of the time.
11. Get software finished earlier.
12. Incorporate JPEG in imaging system design.
13. Don't make it all yourself.
14. Arrange additional telemetry and ground control stations for early orbit operations.
15. Ensure all power consuming items driven by computers time-out if not regularly triggered.
16. Ensure all processors signal the main OBC that they are alive so they can be reset and logged.
17. Develop a standard timeout circuit and apply.

12 - SUNSAT 2

After the positive experiences with SUNSAT, our group is exploring options for an upgrade to a larger format. Research work is also in progress on improved imagers, ADCS and data handling systems.

In the last five years, the University of Stellenbosch has demonstrated its ability to participate successfully in international missions. These include carrying piggyback instruments for NASA, supplying instruments for other satellites such as Safir-2, and consultation to various organisations around the world.

The SUNSAT program looks forward to maximising the return from SUNSAT, and to participating in future satellite missions with international partners.

13 - Conclusion

SUNSAT is a successful start to South Africa's micro-satellite activities and has brought many benefits. It has succeeded in training graduate students, stimulating international interaction between our Department and other significant space entities, and stimulating interest in science and technology at schools --- the three original goals.

We are supporting the NASA payload and international Amateur Radio services, and are able to demonstrate our highest goal of returning 15-m resolution images from SUNSAT.

SUNSAT has been a wonderful journey. We have shared common goals and loads with hobbyists and professionals from many parts of the world. We have experienced the satisfaction of achieving with them, what to a new nation in space, are wondrous things. NASA, Boeing, and Vandenberg have become words that mean wonderful friends, partners, and shared experiences. Thanks, 73's and HOO - AAAH

Acknowledgements:
SUNSAT has been completed through friends and colleagues in many organisations. The following organisations have supplied funds or facilities:

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Colleagues at the university have built capabilities that were used on SUNSAT. Students and support organisations have done great work.

The first four authors have had the joy of leading a historic project. To Marisa, Gil, Larry, John L, John D, Bill, Sybrand, Tjaart, Christo, and Hans, -- you are the tops!

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