

SUNSAT, STELLENBOSCH UNIVERSITY AND SA-AMSAT'S REMOTE SENSING AND PACKET COMMUNICATIONS MICROSATELLITE.

G.W. Milne*, P.J. Bakkes, A. Schoonwinkel*, J.J. du Plessis*, J.H.R. Enslin*,
W.H. Steyn, S. Mostert, K.D. Palmer, D.M. Weber.

Department of Electrical and Electronic Engineering
Stellenbosch University. 7600 Stellenbosch. South Africa
Fax: +27 2231 774981. Internet: milne@firga.sun.ac.za

19 August 1993

Abstract

The Engineering Model of SUNSAT, a 50 kg, 45 cm, Ariane ASAP-compatible microsatellite is scheduled for assembly in December 1993, permitting flight model completion early in 1995. Fifteen M.Eng. students, led by Computer & Control System lecturers at Stellenbosch University, began detail design in January 1992. Most prototype hardware was operating by July 1993, and assembly of the first final-sized PCB's started.

A packet radio service, a 2 m parrot speech transponder, and Mode A and S transponders, all defined and endorsed by SA-AMSAT, comprise the Amateur Radio communications payload. Verification of the 15-20 m pixel spacing, 3-color, 3456 pixel pushbroom imager capable of stereo imaging, is a major research goal. Data will be downlinked in S-band, or single images stored in a 64Mbyte RAM. Coarse attitude stabilization by gravity gradient and magnetorquing is improved by small reaction wheels during imaging. Continuous attitude sensing is by magnetometers. Sun sensors, visible band horizon sensors, and a star sensor provide 1 mrad accuracy when imaging from the sun-synchronous orbit. Average power of 30 W enables images of South Africa to be taken on a daily basis for real time downlinking.

Satisfaction of SA electronics companies on our Advisory Board with the engineering model will lead to continued student funding. Demonstration of a working engineering model will then hopefully provide the credibility we need to finalize a launch opportunity. The satellite's layout, block diagram, and expected performance of the imager, downlink, and Amateur packet communications payload are described.

1 Introduction

Sunsat is a 50 kg, 45 cm cubic microsatellite being

*Professor

developed in the Sunsat laboratory in the Electrical Engineering Department of Stellenbosch University. Planned for a sun synchronous orbit height of 800km, it will carry a 3-color pushbroom imager with 15-20 m pixel spacing, and a predominantly Amateur Radio packet communications payload. Manufacture of the first engineering model has started, and integration will begin in December 1993. Launch with Arianespace and others has been discussed, but is not yet secured.

South African company's sponsorship of Sunsat's concept study was announced in 1991 [1, 2], and communicated to the Amateur Radio fraternity [3, 4]. Progress and further system details were reported in 1992 [5]. This paper for the Seventh Annual AIAA/USU Conference on Small Satellites gives a comprehensive system description and progress report, and will possibly trigger new interactions.

This paper is jointly authored by academic staff members leading Sunsat's development, and is the most comprehensive description published to date. Section 2 gives our reasons for creating the Sunsat unit. Sections 3 and 4 give Sunsat's goals and the mission specification. Section 5 explains the overall satellite design concept. Sections 6 - 14 give detailed information on subsystems. Sections 15 to 17 cover management of the program and research unit.

2 Motivation for the Sunsat Unit

Doctors and electronic engineers require theoretical knowledge and practical skills to be proficient. Doctors gain experience as medical *interns* in academic hospitals, but electronic engineers involved in advanced degree programs seldom have equivalent practical opportunities. Design-oriented members of our computer and control group felt a need to increase

the level of design activity to which M.Eng. students are exposed, by establishing such an internship opportunity. The robotics laboratory in the Aero-Astro Department at Stanford University, and the Spacecraft Engineering Research Unit at the University of Surrey were identified as examples of the engineering activity we would like to emulate.

In 1990 we resolved to establish such an activity by focussing research-assistant time of approximately 30% of our Electrical Engineering M.Eng. students on a long-term project. New students joining such an established team at the start of their two-year M.Eng. programme absorb skills from their seniors, creating a positive feedback loop that makes the skills pool grow beyond the 'channel capacity' of the available academics.

Grinaker Electronics sponsored the first author's post to stimulate satellite activity in the department. South African electronics companies with space-related activities¹ agreed to support a first group of students, which enabled the laboratory to start operations in January 1992.

The Sunsat microsatellite was selected as the core around which to build the new activity. It was felt to be a project that would apply many of our existing skills in control, simulation and computers, and attract pre-competitive research support from local industry, and be of interest to the world. It also has sufficient interest to attract the number and quality of students we desire. From the start with fifteen students in January 1992, we overshot to twenty-one in January 1993, and plan to stabilise at a total of sixteen. The last eighteen months have seen us establish a graduate research unit and make significant progress towards the engineering model of Sunsat.

3 Sunsat goals

The goals of the Sunsat programme are:

- Be the core program establishing a microsatellite research group to enrich the graduate Electrical Engineering programme at Stellenbosch.
- Contribute to international microsatellite interest and research, thereby increasing international interaction with our department.
- Integrate with activities of the SA Amateur Radio League and SA-AMSAT in promoting technical career interest in the youth.
- Provide useful, though not necessarily profitable services to the southern African region, and potentially further afield.
- Promote contact with other satellite organizations.

¹Grinaker, Altech, Plessey Tellumat, AMS, Siemens,

- Achieve the above goals with the minimum of cost, and maximum technical input and reward for cooperating SA research organisations and industries.

4 Sunsat mission specification

The concept study evaluated orbits available for auxiliary payloads, value of services that can be provided from these, and compatibility with available skills and goals. We concluded that providing lower quality SPOT-type images from a microsatellite would be both a relevant research contribution and a useful service, particularly if stereo images *from the same pass* could be obtained.

A South African developed optical system and standard linear CCD sensors were found to comply with physical constraints and yield satisfactory performance with 15–20 m pixel size. Attitude control and downlink requirements were investigated and found to be achievable. When potential sponsors reacted favourably to the design concepts, the imaging role was added to the store and forward communications function originally considered.

The above conclusions and advice from many sources during 1990–1991 produced the following mission specification:

- Provide an Amateur Radio payload that supports worldwide activity, is approved by SA-AMSAT, and is particularly tailored for the SA situation.
- Design for a sun synchronous 10:30 a.m. orbit of 800 km altitude.
- Include the highest resolution stereo multispectral pushbroom imager possible within size and cost constraints.
- Provide for commercial store and forward data communications.
- Comply with the Ariane ASAP² specification of 50 kg and 45 cm maximum cube side.
- Provide communications, signal processing, and computing capability able to be exploited by software developed in future research projects.
- Avoid a propulsion system or other expendable systems.
- Use military/industrial components and design for graceful degradation.
- Maximize the performance/cost ratio.

²Ariane Structure for Auxiliary Payload

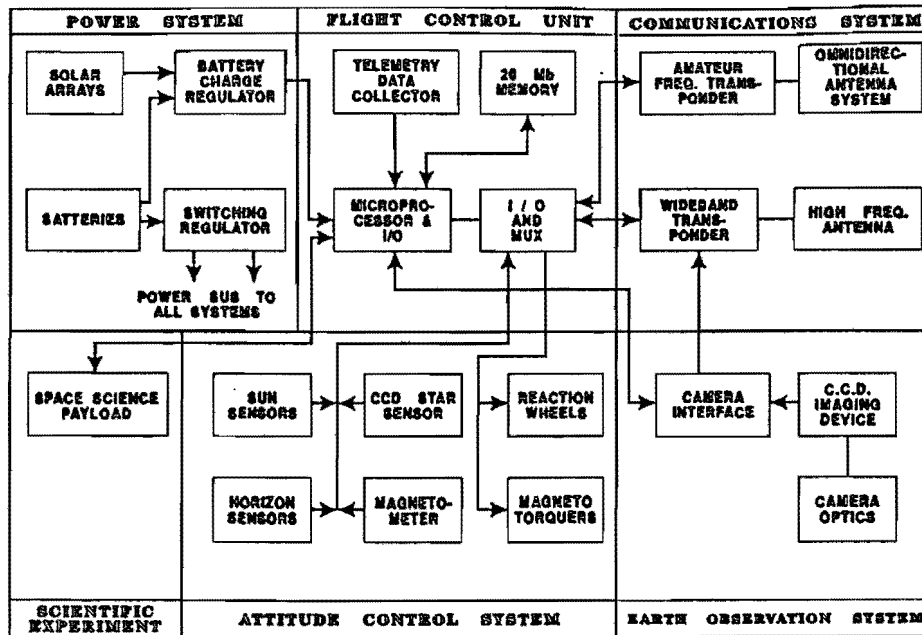


Figure 3: Simplified block diagram of Sunsat.

All subsystems are described in greater detail in the sections that follow.

6 Structure and layout

The structure supplies mechanical support during launch, and thermal and radiation protection in orbit. It also is an unavoidable part of the VHF and UHF antenna system. A guideline radiation requirement of 2 mm Aluminium between any electronic component and the exterior gives great stiffness to the layered box structure.

6.1 Composition of satellite

Figure 2 shows how the 10 trays are stacked on top of each other. The bottom and top trays (figure 5) are milled from solid aluminium for structural stiffness. The bottom tray includes one side of the attachment ring.

The bottom tray (figure 6) contains the batteries and the satellite bus regulator. The rest of the volume is used for the main payload which in SUNSAT 1 comprises the optical tube and the reaction wheels required to meet attitude control requirements of the imager.

The cabling between trays is divided into a slow bus and a fast bus on opposite sides of the satellite. Using subminiature 'D' connectors, a maximum of 250 wires can be connected to a side. The slow bus carries signals that produce little radio frequency interference. The fast bus carries signals such as micro-processor busses, and will be screened with great care.

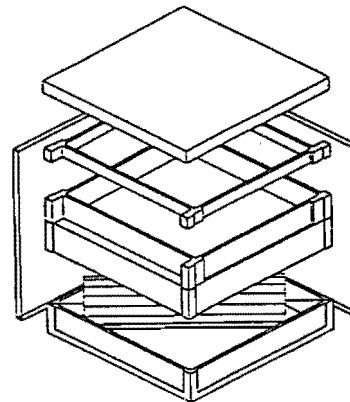


Figure 5: Exploded view of Sunsat mechanics.

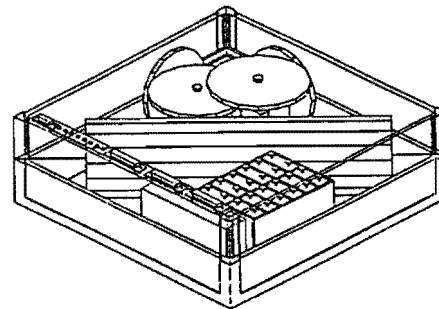


Figure 6: Bottom tray layout.

Four sides of the satellite are used for solar panels, the bottom (earth) side for antennas and launcher attachment ring, and the top side for attitude determination sensors.

7 Imager payload

Not having a commercial customer, we chose to produce images of interest to a wide community of users, and considered subjective quality and continuing interest in the data to be important. Since most users are interested in their local information, and seek the highest possible ground resolution, we aimed to provide this without sacrificing excessive swath width.

These considerations, and availability of excellent linear Silicon CCD sensors able to operate in the visual and near-IR band motivated a 3-color sensor system with bands similar to SPOT 4 and LANDSAT 6. These permit biomass production to be monitored, which is of continuing interest in our water-short country. The Texas Instruments TC104 linear CCD sensor with 3456 pixels of 10.7μ spacing was chosen since its MTF (modulation transfer function or spatial frequency response) does not degrade significantly in the near-IR band (0.9μ).

The imager will comprise a single optical tube assembly containing the 45° mirror, lens system, pentaprism with dichroic colour splitter, the three vertically mounted linear CCD's, and their drivers and output buffers. The optical tube will be mounted diagonally across the bottom of the satellite, which will fly with the optical tube horizontal, and normal to the velocity vector. The CCD pixels will thus form a line on the ground that is normal to the velocity vector, and is able to be pitched forward or backwards by up to 26.5° .

7.1 Optical resolution

The rectangular pixels of the CCD sensor reduce its MTF to $2/\pi = 0.63$ at the Nyquist frequency, N_f , of half a cycle per pixel. Specifications for the TC104 indicate the MTF as 0.63 from 0.5μ to 0.7μ with slow degradation at longer wavelengths.

Motion in the forward direction also degrades the forward MTF at N_f by $2/\pi$ since the sensor integrates incident illumination during the full aperture time. A reasonable compromise between magnification and visual quality of the image is obtained if the lens MTF at N_f approximates $0.63(0.63 + 1)/2 = 0.51$, this being the product of the CCD's MTF and the average of the forward motion MTF and the lateral motion MTF.

The diffraction-limited MTF's of 10 cm aperture lenses at 0.7μ fall approximately linearly from a max-

	Focal length in mm.					
	200	280	400	560	800	1200
MTF	0.91	0.87	0.82	0.74	0.64	0.52
MTF (obs)	0.80	0.72	0.60	0.49	0.37	0.33
Pixel (m)	43	30	21.4	15.3	10.7	7.1

Table 1: 46 cy/mm, 0.7μ m diffraction-limited modulation transfer function for 10 cm diameter optical systems. Ground pixel size is for 800 km altitude and 10.7μ m sensor pixel spacing.

imum of 1.0 at zero spatial frequency to the values given in table 1 at $N_f = 46$ cycles/mm. The obscured MTF's apply to reflective optical systems with typically sized secondary reflectors obscuring up to 50% of the entrance pupil diameter. Table 1 shows that a 560 mm reflective optical system can achieve the desired MTF.

The *Telemacro 3* lens developed by the Lasers and Optics Group of the CSIR³ has a 35 mm image format, 600 mm focal length, 10 cm aperture, 200 mm length, mass of 2.1 kg, and achieves near diffraction limited performance. Its specifications and characteristics provide a baseline for Sunsat's optical system.

The previous discussion only considers the image plane MTF, which fails to convey the effect of different magnifications. If we wish to see small ground features, it is more useful to plot MTF versus spatial frequency on the *ground*. Figure 7 shows the obscured lens MTF's as a function of spatial frequency on the earth (800 km height, 10.7μ pixels) for various focal lengths. The curves are plotted to the Nyquist frequency for each lens, and clearly show that longer focal length lenses give greater MTF's.

Sunsat's optics will thus be similar to a fixed focus version of the *Telemacro 3*. Being a predominantly reflective system, chroma distortions can be kept small. Calculated performance for the optics and TC104 CCD sensor at 0.7μ indicate a MTF dropping linearly from unity at zero spatial frequency, to 58% at 50 metres per cycle, and then to 32% at the Nyquist frequency, N_f , of 30 metres per cycle. At 0.9μ the MTF's become 50% and 27%. Motion will reduce MTF in the forward direction by a further factor of 0.9 at $N_f/2$, and 0.63 at N_f .

7.2 Spectral response

The TC104 sensor's response is good from 0.4 to 0.9μ . We are able to split the band into three sub-bands, with the 10% to 90% transition taking about 20nm. The 50% transition points will be set at 0.52, 0.61, 0.70, and 0.9μ , which are close to the LANDSAT 6

³South African Council for Scientific and Industrial Research

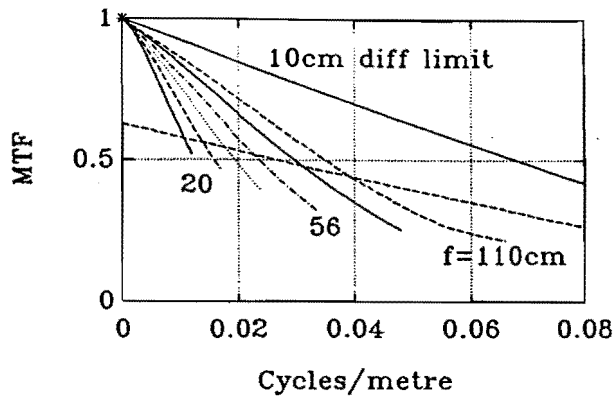


Figure 7: MTF of reflective optics and TC104 CCD at $0.7\mu\text{m}$, for focal lengths of 20, 28, 40, 56, 80, and 110 cm, and altitude of 800 km. A 10 cm aperture's diffraction limited MTF, and $2/\pi$ times this are also shown.

Linear CCD Sensors	Three x TC104
Filters, 50% transmission	0.52 - 0.61 μ
	0.61 - 0.70 μ
	0.70 - 0.9 μ
Sensor pixel size	10.7 x 10.7 μ
Number of pixels	3456 per band
Lens focal length	570 mm
Aperture diameter	100 mm
F number	1:5.7
Ground pixel size	15 m x 15 m
Image width	51.8 km
Max. stereo strip length	$\pm 700\text{km}$
Lens transmission	63%
Filter peak transmission	95 %
Line scan rate	331 lines/sec
Pixel rate/channel	1.14 M pixel/s
Total pixel rate	3.42 M pixel/s
Quantization	8 bit
Electronic gain	0 dB, +6 dB
Bit rate/channel	≥ 9.15 Mbit/s
Total bit rate	≥ 27.5 Mbit/s
CCD output 100% refl.	70% of saturation
Saturated sig./p-p noise	1000:1
30% refl. signal/p-p noise	210:1

bands 2, 3 & 4 of 0.52–0.60, 0.62–0.69, 0.76–0.90 μ .

7.3 Signal to noise, electronic gain and quantization

The TC104 is capable of a 1000:1 dynamic range (saturation signal/p-p noise). To maintain a small pixel size we plan to only use 20% of the saturated signal level on the CCD for a 30% reflective object. The signal to noise ratio will then be 210:1. A 2:1 switchable electronic gain will be included, followed by 8 bit digitization. If experiments show the signal to noise ratio to be too low, a pixel size increase to 20 m will raise the light level by $(20/15)^3 = 2.37$.

7.4 Imager specification summary

The imager's specifications are summarized in table 2.

7.5 Optics schedule and optimization

For financial reasons, final design and manufacture of the optical system will only start once a launch agreement is closed. Interim tests will be done with the *Telemacro 3* or a similar lens. Prototype hardware has already produced test images using the TC104.

8 Communications payload

8.1 System design

Image downlinking

The high resolution data will be transmitted in real time via the S-Band downlink to reception stations at Stellenbosch and Johannesburg. Small-area images stored in the RAM disk can be down-linked at much

Table 2: Summary of imager characteristics

lower rates. For example, a 40 kbyte image covering a 4 km x 4 km area can be downloaded at 9600 baud in about 100 s.

Data collection and transfer

At 800 km altitude, the 5° elevation footprint has a diameter of 5080 km, which spans 45° in longitude. Radio range varies from 800 km to 2800 km compared to the geostationary range of 36000 km. Data communication with 10 Watt or lower powered transmitters and dipole antennas is practical, permitting data interchange with low cost terrestrial transceivers. Since large quantities of data can be stored in the satellite, global data transfer is possible. AX25 data protocols will be used to ensure error-free operation.

Wideband downlink and transponder

At 27.5 Mbit/s the 5 Watt 0dBi S-band downlink will produce a 14.7 dB E/N_0 ratio at 2500 km slant range for a 3.7 m diameter 35K receiving station as planned for Stellenbosch. By adding an L-band receiver and appropriate switching, a transponder capable of 1 MByte/s with 2 m diameter ground stations can be implemented. Application of the system for Amateur Radio gateway service is intended.

Amateur Radio VHF and UHF payload.

The Amateur Radio payload definition was approved at the SA-AMSAT Spacecon 91 Conference [4]. Store and forward digital packet radio will be provided, in-

cluding 1200 baud AFSK for compatibility with terrestrial equipment common in SA. To provide sufficient uplink channels, one of the 2 m receivers has four IF sections displaced in 25 kHz steps, and connected to 1200 baud modems. Two 9600 baud modems compatible with the G3RUH standard are carried, and can be switched to various receivers and transmitters. Both 2 m up/down and 2 m up/70 cm down options will be included, together with full bulletin board facilities. The AMSAT Pacsat Standard Protocols can be supported.

The 2 m and 70 cm downlinks will be able to operate for short periods at 10 Watts output, producing a $0.5\mu\text{V}$ signal at 435 MHz and $1.5\mu\text{V}$ signal at 145 MHz with 0dBi receive antennas at full range. This power level will be used over southern Africa to provide signal to noise ratios approaching 15dB for easy reception.

A 2 m *Parrot* mode is intended especially for Novice category users (under 16). Up-linked speech will be digitally stored and retransmitted on the same frequency. Novice school users will thus hear the retransmission and know that they are getting through. The need to learn and apply operating protocols will definitely be experienced!

The 2 m down-link will also be used to distribute the SA Radio League's weekly bulletin. SA AMSAT will also provide a linear 10 m transponder tapped off the 2 m IF stage, and manage the bulletin board after launch. Since some of the above services are incompatible, they will be scheduled for use at different times.

Antenna pattern studies

The VHF and UHF radiation patterns must be smooth, with no holes, and with maximum gain at the horizon, which is 30° below local level. Circular polarization is required to avoid Faraday rotation induced nulls with linearly polarized ground antennas. Sunsat's structure has a major effect on the VHF and UHF antenna patterns, requiring use of NEC2 for numerical evaluation of various antenna configurations. Figure 8 shows results of a promising left-hand circular configuration. The importance of circular polarization is shown by figure 9 which compares predicted and measured signals from UoSat UO-22, and shows the polarization rotating at least once between 0° and 80° elevation.

8.2 Block diagram description

Figure 10 gives the full block diagram of the communications subsystem. The VHF and UHF modules will be completed in time for Engineering Model assembly in December 1993. The S-band system will be added later in 1994. We still have to finalize the VHF and UHF antenna configuration and feed system.

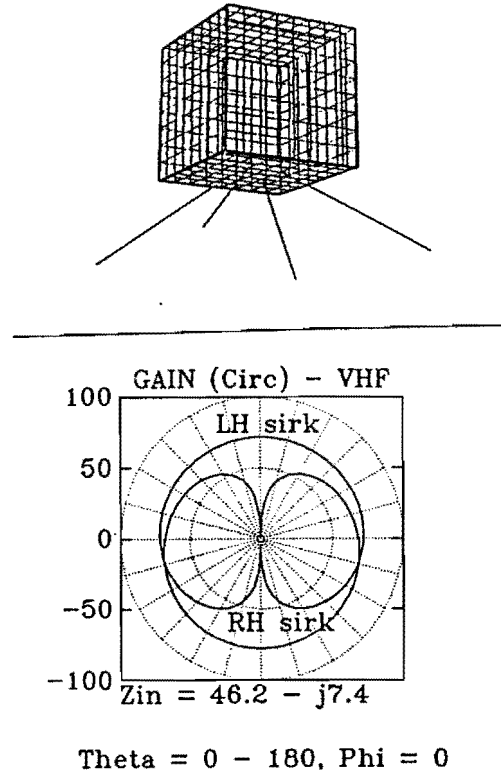


Figure 8: Pattern of candidate antenna for VHF links.

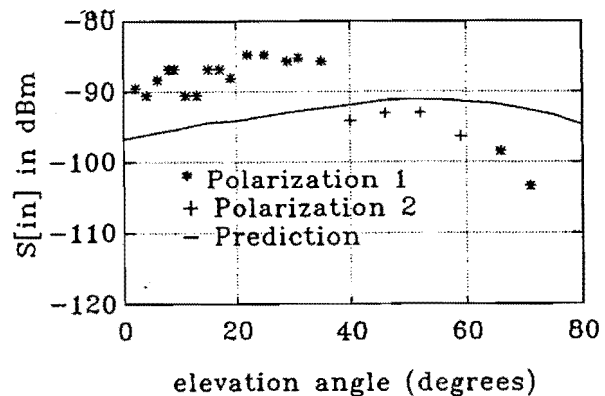
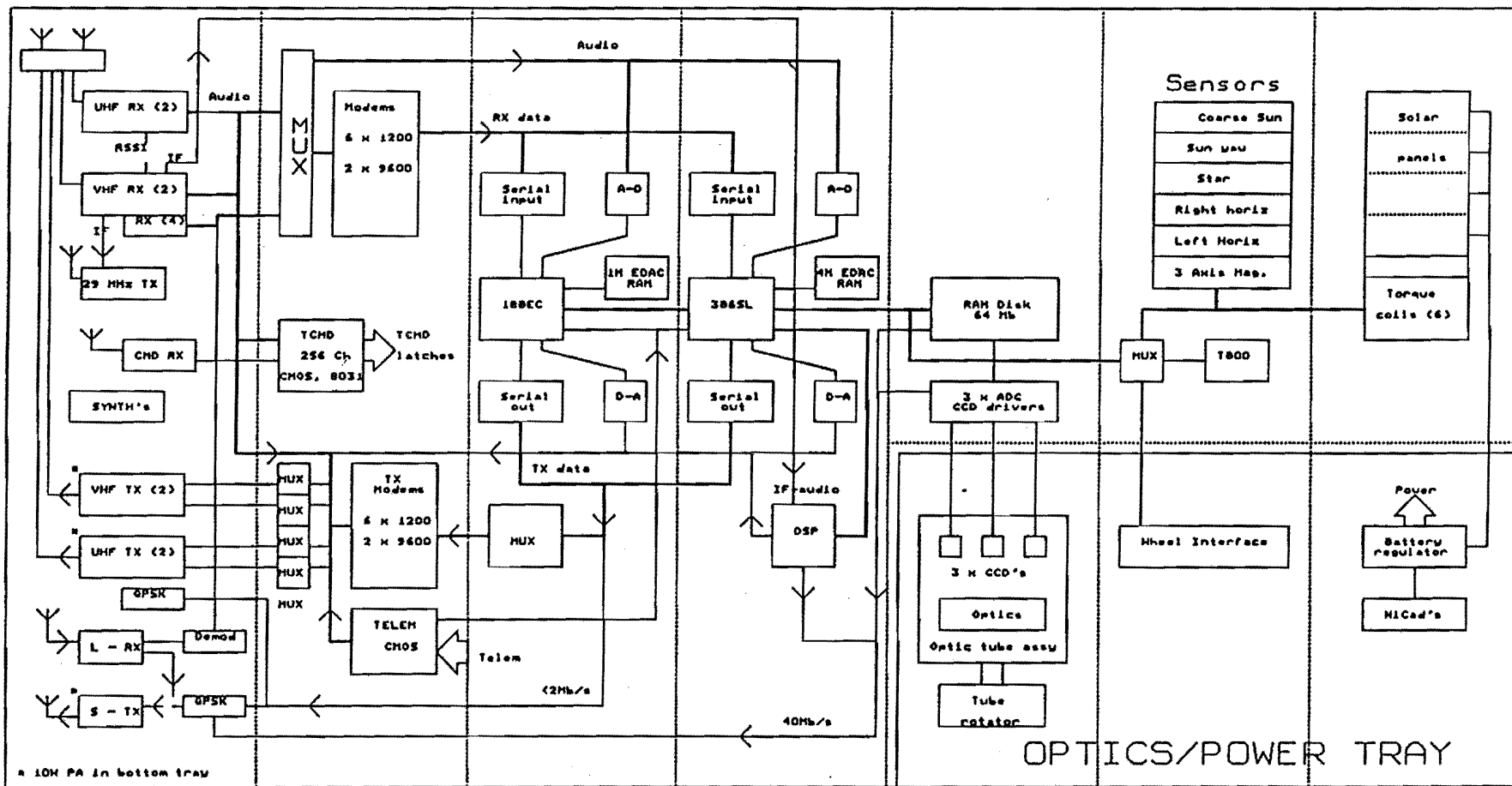


Figure 9: Measured and predicted signal strength from UO-22.

SUNSAT Microsatellite - Overall Block Diagram

RF TTMS 188 386 RAM ADCS Power



* 10W PA in bottom tray

Telemetry
Telecommand
Modems
Switching

Attitude determination
& control system

Drawn: CH Milne, Ver 1, 23/5/93

Figure 4: Detailed block diagram of Sunsat.

9 Attitude determination and control

9.1 Performance requirements

Stringent attitude requirements need to be satisfied for Sunsat, especially those imposed by the push-broom imager. Attitude measurements must ensure position determination accuracy better than 1 km at the sub-satellite point. At an orbiting altitude of 800 km, the pitch and roll attitude measurement error should be less than 1.25 mrad. The required yaw measurement accuracy is 2.5 mrad. The attitude must be *controlled* to ensure less than 5 km image overlap, i.e., less than 3 mrad pitch and roll error and 6 mrad yaw error. Additionally, to ensure less than 1% geometric distortion on images, the linear disturbance velocity at the sub-satellite point must be less than 66 m/s (1% of ground speed). The maximum satellite pitch and roll rates allowed are therefore 0.08 mrad/s and the maximum yaw rate is 0.16 mrad/s.

9.2 Subsystems

Design motivations

Sunsat will be an earth pointing satellite (body Z-axis towards nadir) to keep the imager in the nominal direction for usage and permit some antenna gain. A gravity gradient boom and tip mass will be deployed from the top of the satellite to earth-stabilize it using the minimum amount of control energy.

The satellite will be kept in a slow Z-spin during normal operation (not during imaging), for improved solar thermal distribution. The 4 solar panels on the X/Y facets will thereby receive an even solar illumination resulting in an improved life of the solar cells. A simple momentum transfer to a Z-axis reaction wheel will de-spin the satellite before imaging sessions.

9.3 Actuators

3-Axis reaction wheels

Four small servomotor-driven reaction wheels provide an accurate, continuous, and fast attitude control capability. A wheel is used for each of the body axes and an extra wheel is added for backup to the Z-axis. Our main concern about the reaction wheels is their operational life in vacuum, so they will only be used for pointing manoeuvres and stabilisation during imaging. Tacho feedback is used during wheel angular rate control. Digital counters clocked by optical sensors provide wheel angular position feedback during precise attitude manoeuvres. The maximum reaction torque per wheel is $3.5E^{-3}$ Nm. This permits a 180 degree slew around the Z-axis within 90 seconds, and a position control accuracy of 0.1 mrad.

3-Axis magnetorquer coils

Air core coils are wound into channels around the

X/Y solar panels and around the Z facets. They ensure a high reliability (lack of moving parts), long life (no expendables) and are digitally switched on/off with dual polarity. Magnetorquing is used as the primary active stabilisation method to do libration damping, Z-spin control and momentum dumping of the reaction wheels. Detumbling and attitude capture can also be done initially from simple and space proven control rules for magnetorquers [6]. Control torque is generated using a pulse width modulation method, the direction being dependent on the geomagnetic vector. Libration can be reduced to within 1 degree with control algorithms making use of full attitude information [7]. Pitch and roll libration is mainly caused by aerodynamic and solar pressure disturbance torques. The maximum torque obtainable from the Sunsat magnetorquers will be $1E^{-3}$ Nm at the polar region, mainly used for pitch and roll control and $0.5E^{-3}$ Nm at the equatorial region, mainly for yaw control.

Gravity gradient boom

The 4 m long boom with a tip mass of 2.5 kg will be deployed for passive attitude control. Gyroscopic torque will make it possible to create a constant roll offset angle (e.g. for imaging) by controlling the Z-axis angular momentum through Z-spin control. The tip mass will contain either an accurate magnetometer for scientific measurements or a school project experiment. To prevent any wires impeding boom deployment, the tip mass has to be a self contained unit.

9.4 Sensors

3-Axis fluxgate magnetometer

The magnetometer is used to measure the strength and direction of the geomagnetic field vector. This information is used to calculate the magnetorques and estimate the satellite attitude when in earth-shadow. Simple control rules using short term variations in magnetometer measurements can be used for initial attitude capture. The magnetometer has a dynamic range of $\pm 64\mu T$ and a resolution of 32 nT. With a power consumption of only 100 mW it is suitable for continuous operation.

2-Axis horizon sensor

Two orthogonal linear CCD and lens assemblies look 27.3° below local level to obtain orthogonal measurements of the sunlit earth horizon. A $\pm 15^\circ$ view on each 2048 element CCD is used to obtain pitch and roll attitude angles to an accuracy of 0.5 mrad [7]. This sensor is currently used on the UoSAT-5 satellite. The sensor consumes approximately 2 W when active and will only be used when both CCDs see a valid sunlit horizon, and accurate attitude information is needed. The rest of the time they will be inactive.

Fine sun sensor

Similar linear CCD technology is used to obtain a sun azimuth measurement within a 60° view with an angular resolution of 1 mrad. The sensor head consists of a slit aperture perpendicular to the CCD array. During imaging this sensor will face the sun and accurate yaw attitude information will be available. When the satellite is spinning, sensor data will be available for only 20% of each orbit. The active consumption of 1 W can therefore be reduced substantially by switching off the sensor when not needed.

Coarse sun sensor

Six cosine-law solar cells mounted on each spacecraft facet are used to obtain full attitude information to within ± 5 degrees with the aid of a sun and orbital model. The short circuit currents from each cell are compared to obtain the sun vector direction with respect to the satellite body. The temperature of each cell is also measured to make the necessary temperature sensitivity corrections to all measurements. The sensor consumes almost no spacecraft power and is very simple and reliable. It can be used directly after launch to determine the non-stabilized satellite's attitude during the sunlit part of the orbit.

Star sensor

A $10^\circ \times 10^\circ$ star image is projected onto a 192×165 pixel matrix CCD sensor, providing backup accurate 3-axis attitude information during earth imaging sessions. With a sensitivity of $4E^{-3}$ lux on the CCD pixels, V-6 magnitude stars can be detected. At least 2 separated stars will then be detectable within the sensor's field of view to enable an algorithm using a star catalogue to calculate the pitch, roll and yaw angles. The roll and yaw angular resolution will be at least 1 mrad and the pitch resolution will depend on the star separation distance. For example, 2 degrees will give a resolution of at least 30 mrad. During earth imaging, the star sensor will always be pointing towards the orbit anti-normal, so only a small part of a full star catalogue has to be present on board the satellite.

9.5 ADCS on board processors

Interface controller (IFC)

An 80C51 based micro controller is used to directly interface to all the actuators and the sensors. It supplies the reaction wheel speed reference signals to the analog wheel speed control system and switching pulses to the magnetorquers. The control command updates are received every 1 second from the attitude control processor (ACP). The IFC must also control the sensor hardware, for example, select illumination on the horizon and star sensors, low pass filter the magnetometer, horizon, and sun sensors, and read out the positions of detected stars from the star sensor. All the sensor data has to be send to the ACP

at 1 second intervals.

Attitude control processor (ACP)

A T800 transputer will be used to implement all the control system software. The ACP can take over most of the functions of the IFC if the 80C51 fails. If the T800 fails, the 80C386 OBC can implement most ACP functions. All these possibilities are selected using a multiplexer as shown in the ADCS system block diagram in figure 11. The ACP communicates to the IFC via a bi-directional UART and to the OBCs via its links and link adapters. The transputer can also reduce its own clock speed to save power. This feature will be used to dynamically adjust processing speed to any changing work load conditions.

Control system software

The control system software is implemented as tasks on the ACP which are scheduled by a hard real-time kernel. This will ensure that all asynchronous events (e.g., communication with IFC and OBC), timer driven events (e.g. discrete sampling periods) and message passing between tasks is done in an orderly manner. The tasks consist mainly of environmental models, sensor calibration, measured attitude computations, attitude estimators and controller algorithms. An extended Kalman filter will be used to extract full attitude data from the continuous magnetometer measurements and from all the accurate but intermittent sensors such as the horizon, fine sun and star sensors. Its output accuracy will be limited to approximately 1° [8] when in shadow, largely because of limitations in the IGRF geomagnetic model. When horizon sensors are operating, an accuracy of 1 mrad is expected and needed for 3-axis stabilization during imaging.

A few controller modes will be available using either the magnetorquers and/or the reaction wheels. After the initial de-tumbling phase, the boom will be deployed and gravity gradient lock achieved. The following modes will then be used during normal satellite operation:

1. A normal mode using only the magnetorquers to do libration damping and Z-spin control. Momentum dumping can also be done whenever this mode is entered with reaction wheels running.
2. A set-up mode to orientate the imager to the correct 3-axis stabilized attitude before imaging commences. The orientation maneuver will be done in a time-optimal manner using the reaction wheels.
3. A 3-axis stabilization mode, using the reaction wheels, to keep the push broom imager steady while scanning. Slow angular tracking will also be possible in this mode, e.g. to compensate for the earth rotation.

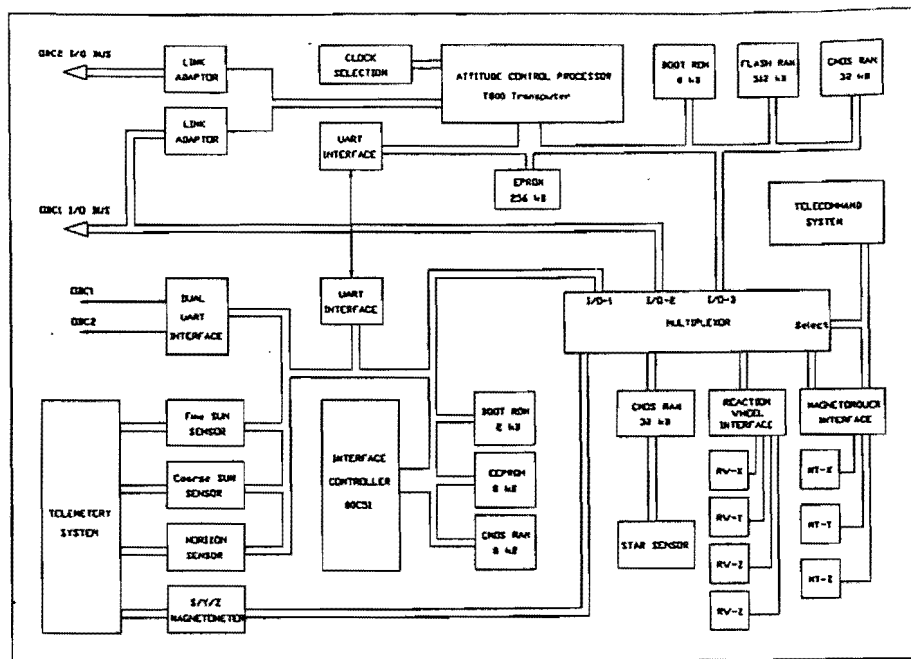


Figure 11: Attitude determination and control system.

4. A reset mode to return to the satellite's condition before the preparations for imaging had commenced (set-up mode). This can be achieved automatically by stopping the reaction wheels.

10 Flight management and communications computers

10.1 Choice of processors

The on board computer systems are based on a principle of moderate redundancy and heterogeneous technologies. A total of six processors are on board. Three of these are embedded 80C31 microcontrollers used for the telemetry, telecommand, and attitude control subsystems. The main flight management computer is an Intel 386-SL processor. Although originally designed for low power Laptop application the 386-SL is well suited for satellite use. An Intel 80C188EC processor functions as backup for the 386. Although not as fast as the 386, this processor has been well proven in space and runs compatible code. Figure 12 shows the main computer data paths in Sunsat

10.2 Functionality

The distribution of tasks amongst the processors is briefly as follows:

The two Intel processors are able to provide basically the same facilities although the 188 is much slower

than the 386. Both have access to all peripherals. The 386 is the preferred processor for general flight management tasks such as scheduling, CCD imager control, communications, etc., but if it fails, the 188 will take over these functions.

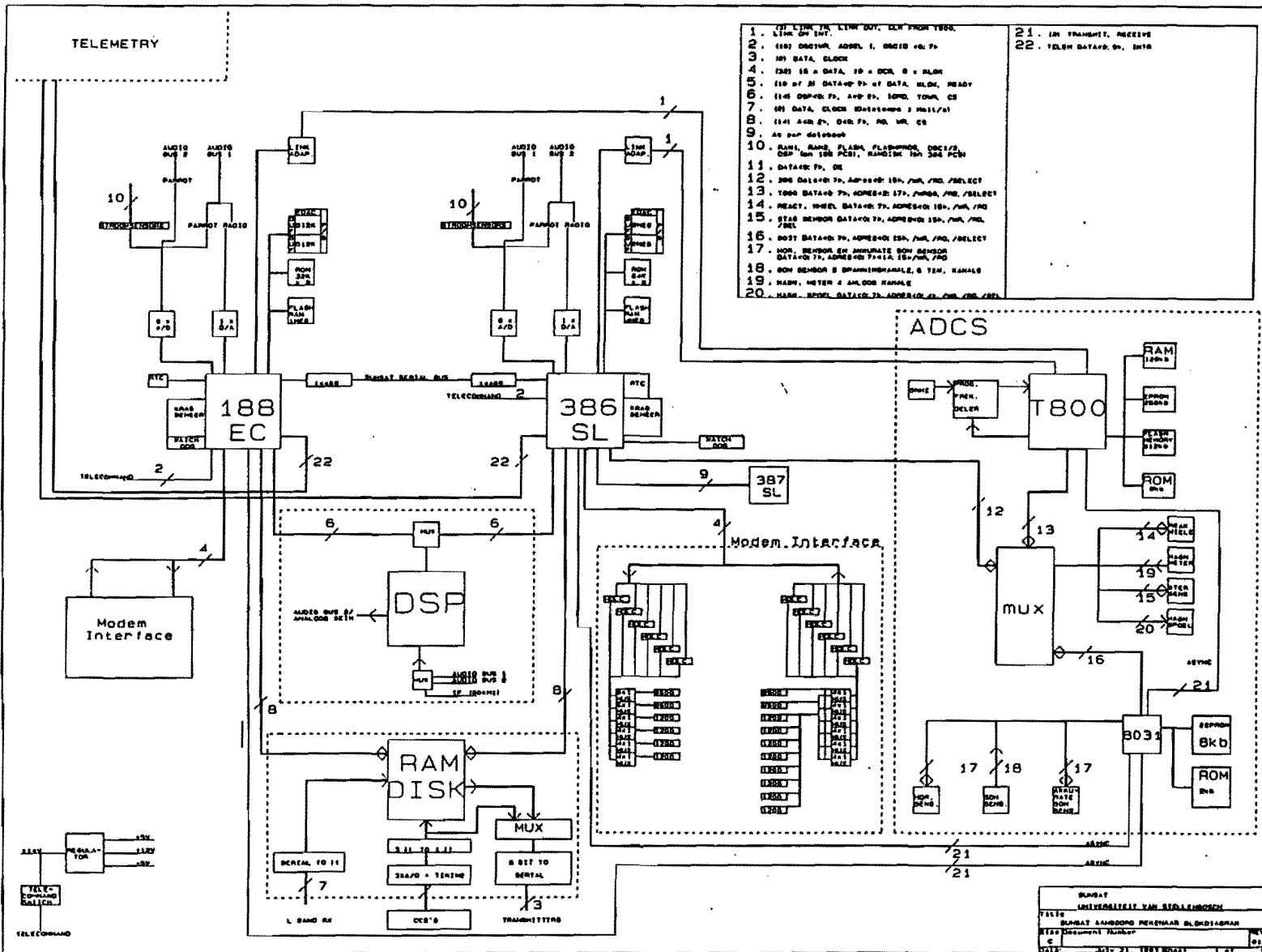
The transputer is dedicated to the processing of the star sensor positioning system and the fine orientation control algorithms, because of its high processing power. If it should fail, the 386 will take over these functions. The processing rate will be lower, but high enough to maintain the orientation of the satellite.

In case both the transputer and the 386 fail, the 188 will take over all functions. The 188 is however not fast enough to process the fine orientation algorithms and the accuracy of the orientation will therefore be reduced. Re-scheduling of tasks will also take place in order to reduce the concurrency of tasks and the possible suspension of noncritical tasks.

10.3 Memory structure

The structure of the private memory of the processors was chosen to consist of two rows of 1 M-byte static RAM, one row of FLASH RAM and a small PROM with basic boot code. The FLASH RAM will contain a copy of the code running in the RAM at any stage; if the RAM should lose any of the code it can be copied from the FLASH without having to reload from earth. The purpose of having two rows of RAM is to provide higher fault tolerance for permanent failure of a memory chip. In case of such a failure, one of the rows can be totally isolated from

Figure 12: Main computer signal flows.



the processor with a set of gates.

10.4 Ramdisc

The 64 M-byte RAMDISC will be used to store images from the imager. This memory must be accessed from both the Intel processors and the imager. It will not have EDAC, but redundant data will be stored in different parts of the memory for error checking and correction.

In order to conserve power the RAMDISC is divided into 8 blocks of 8 M-byte static RAM chips. At most only one of the rows is selected when reading or writing. Any subset of the rows can be turned off in case of a permanent failure. Special decoding logic will assure a continuous address space under such circumstances.

10.5 Software

Modula II and C have been chosen as the supported programming languages for the main processors.

Different real-time kernels are used on the different main processors. A locally developed kernel named Hybrid will execute on the 386 processor. This kernel is written in Modula II and supports a virtual machines structure through which new processes can elegantly be loaded dynamically. The Kodak AMX-86 kernel will run on the 188 processor. The transputer can either execute dedicated code or use the Virtuoso kernel from ISI.

11 Telemetry

11.1 Requirements

The telemetry system is conveniently split into a data collection function, which has to collect data from a large number of sources in the satellite, and a data transmission function. Both functions have to be redundant, to be able to operate flexibly when the computers are running, and also be able to run in a simple mode independently of any 'crashed' computer.

11.2 Design concepts

To minimize wires while still providing redundancy, a decentralized telemetry concept is used, involving *acquisition modules* in each tray which multiplex 32 analog and 32 digital channels, and duplicated *telemetry combiners* (figure 13) in the telemetry tray.

One set of carefully protected address lines is routed to each acquisition module, which contains a digital multiplexer and two analog multiplexers, each feeding one leg of the analog data collection system. Critical signals are connected to both legs of the telemetry system, ensuring full redundancy.

Time-multiplexed voltages are then fed to the telemetry combining tray. Here, in duplicated systems, the voltages from the acquisition modules are further combined and digitized into serial output data streams.

The data streams include a frame counter and frame synchronization information. Each is passed to a UART and 1200 baud modem, which can be switched to any of the transmitters by the telecommand system. This base level system uses standard async data formats, and can be read by any standard PC with 1200 baud modem. The unmodulated async format is also provided for use during integration, when a higher clock rate is used.

The base system provides 62 eight-bit analog channels in addition to 186 seven-bit channels and 186 one-bit status lines. The status lines are merged with the seven-bit analog lines together with synchronization information, to provide a standard telemetry frame of 256 bytes. The clock rate can be set for 1200 baud or 9600 baud, giving either 0.32 s or 2.56 s frame repetition periods.

Normally, the base system format will not be transmitted, since an 8031 microprocessor has been included to produce more conveniently formatted data. The 8031 has access to the A-D converter outputs, and can collect and format short lengths of data in any desired manner. It can produce outputs in async form or AX25 packet format, and can incorporate any desired standard broadcast messages which are obtained from the main computers. The 8031's 1200 baud modem output can be switched by telecommand to any of the transmitters to provide a background telemetry transmission function.

Both the 8031 and main computers, if so permitted by telecommand latches, can gain access to the telemetry address bus and A-D outputs, thereby accessing any signal in the satellite. Whole orbit telemetry data will normally be gathered by the flight computer as one of its tasks, formatted according to standards proposed by AMSAT[9], and treated thereafter as part of the packet radio bulletin board system.

12 Telecommand

12.1 Performance

The telecommand system is designed to provide both stored scheduled command sequences as well as direct ground-to-satellite commands at 1200 or 9600 baud. Reliability for guarding against natural occurring errors and illegal commands, was the main design objective. This reliability is obtained by completely duplicating the system as shown in figure 14, as well as by using keywords, BCH code for error

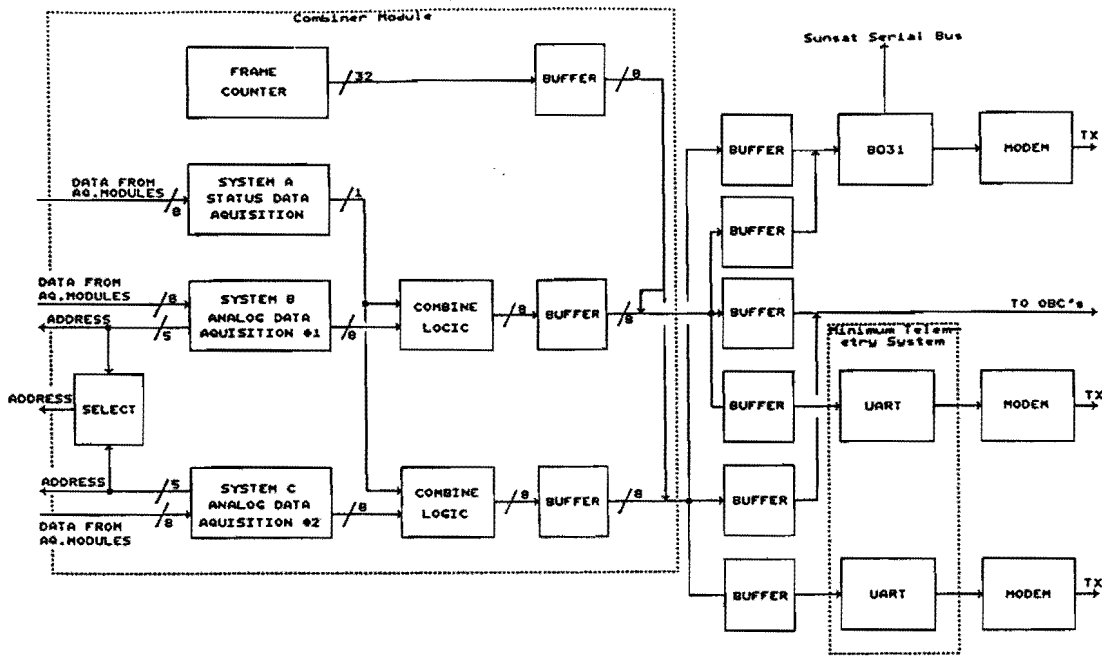


Figure 13: Telemetry combiner.

detection and time diversity mechanisms for security purposes. The telecommand system is considered as extremely critical, and the minimum system is therefore implemented with high-reliability discrete logic components, using a dedicated 1200/9600 baud receiver. Provision is made for 128 bit-addressable and 128 byte-addressable lines to the trays. Careful consideration is given to the possibility of open lines, stuck latches and failed components. All state changes of the final outgoing lines of the telecommand system are monitored by means of the telemetry system. As seen in figure 14, only the final exclusive-or gates are common, making it possible to correct for stuck latches in any one of the subsystems.

12.2 Subsystems

Each one of the duplicated systems consists of three parallel systems, i.e. the highly reliable discrete system, an 8031 micro based system, and an on board computer buffer. The first two systems are modem-driven and have therefore real time capability only. For the highest reliability, the discrete system use no other memory components than shift registers, and all keyword and error detections are done in a minimum of hardware. The 8031 system uses software for the same verification functions. Those two systems are limited to the receiver speeds of 1200/9600 baud. The last system operates through the on board computers and will be the system that is mostly used for scheduled commands, because the command rate is not limited by the modems. The same keyword and time diversity checks are done by this faster subsystem.

13 Simulation

The total system, including all the orbital kinematics, orientation dynamics and sensor measurements are simulated by means of a powerful proprietary block diagram language, SIMuPAC, that is marketed by the University. The total simulation runs more than 100 times faster than real time, with the capability to synchronize it with real time for hardware in the loop simulations and continuous mission simulations. The simulation is used to study mission command profiles, energy usage, imager coverage of any area on the globe and sensor placements during the design phase. After launch, it will be used as a continuous mission simulation, reacting to any telecommands send to Sunsats. The simulation is a high fidelity simulation, consisting of more than a thousand fundamental blocks, programmed as six levels in the hierarchical SIMuPAC block orientated language[10]. Figure 15 shows a typical simulation of the yaw dynamics and energy usage during a number of orbits. The effect of imaging and S-band transmitter power usage can be seen during orbits 13 and 14.

14 Power system

The power system comprises the solar panels, main regulator unit, battery, and distributed voltage regulator units as shown in figure 16.

Redundant compound power converters will be used for maximum power point tracking, battery charge regulation, and bus voltage regulation. Each converter will be able to handle 70 % of the peak power

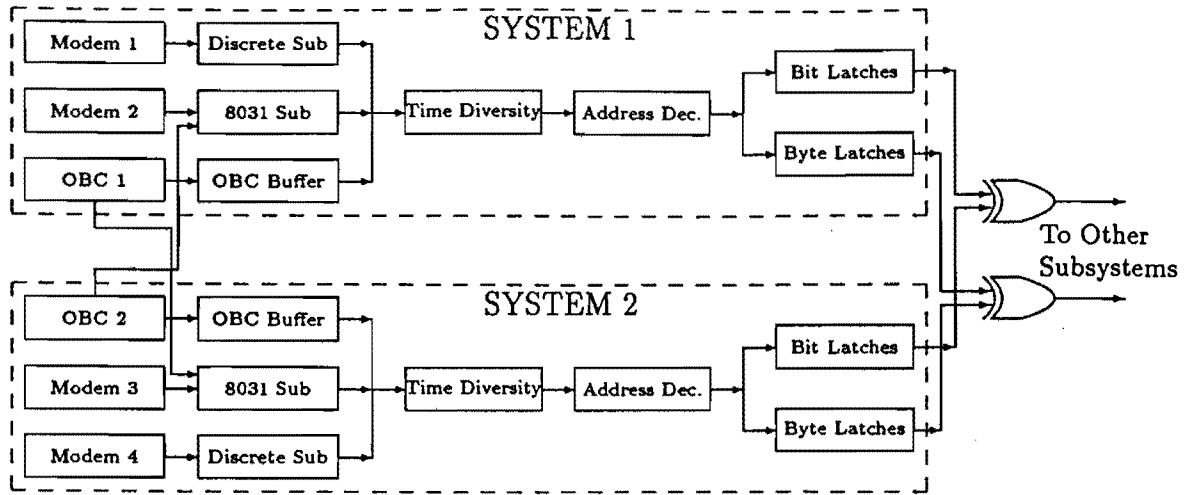


Figure 14: Block diagram of telecommand system.

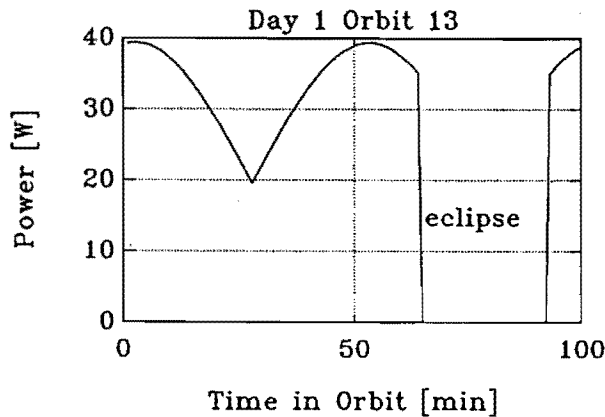


Figure 17: Simulated power from the PV Array

The power electronics will be designed for high efficiency. The main regulator's maximum power capability is 140W. The high peak demand rating is to handle peak loads during imaging data transfer.

14.3 Efficiency Improvement

The overall efficiency of a power system is the product of the efficiency of the subsystems. Converters designed to meet peak loads have lower efficiencies than if designed for the average load. By using the shared converters, one of which switches off when not needed, a higher average converter efficiency is obtained. The power converter uses the I-V characteristics of the PV panel in conjunction with a positive-feedback technique to track the maximum power point of the array.

15 Financing

consumption. Only one converter will be in operation at normal load conditions. On peak loads the second converter will automatically come into operation. If both regulators fail, unregulated battery-voltage will be supplied to the power busses.

14.1 Solar arrays, battery, and power simulations

Power system performance has been simulated [11, 12]. Power from the photovoltaic array is shown in figure 17. Four high-efficiency solar panels of 0.4 x 0.45 m will be used, with a maximum power point voltage exceeding 24V. The battery will use 11 8Ah NiCd cells for a nominal 12V supply. DOD will be limited to 20% for a lifetime of 5 years. There will be no active thermal control of the battery since the temperature is expected to be 0 - 10°C.

14.2 Power Conversion

The sections below describe the estimated costs for the completion of Sunsat model 1 from the announcement of the project in June 1991 till operational in orbit around September 1995. The first satellite is funded largely by sponsorships. However, Sunsat is an ongoing project and is expected to have successor satellites, funded on a more commercial basis. A description of the current sources of funds is given, as well as expected future sources. For this paper the budgeted financial figures are given in US dollars, using an exchange rate of 3 SA rands per US dollar.

15.1 Cost budget

The cost budget in table 3 includes all expenses actually incurred to date as well as future expenses up to launch. For convenience, it is divided into three project phases, namely prototype development, engineering model and flight model costs.

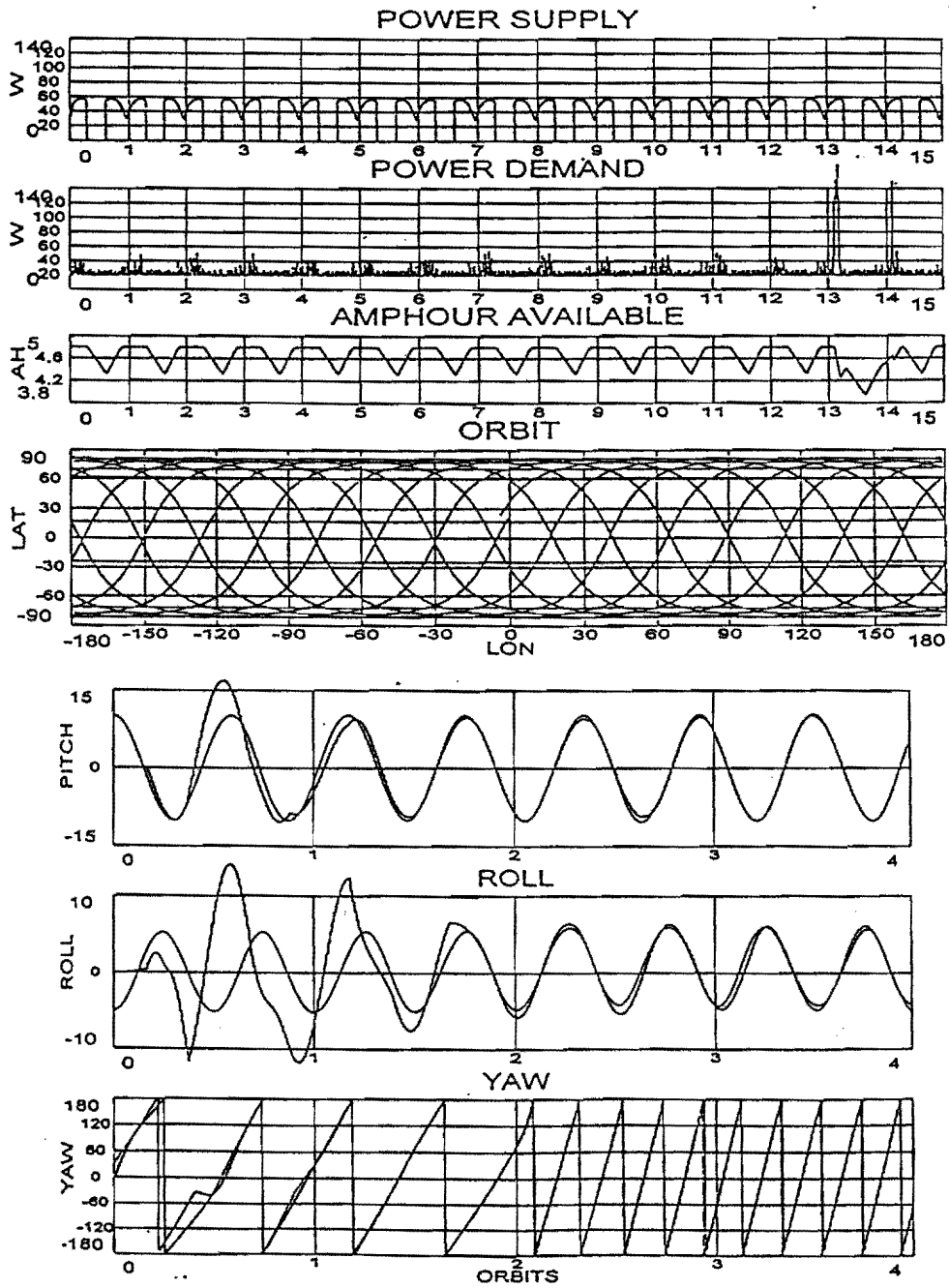
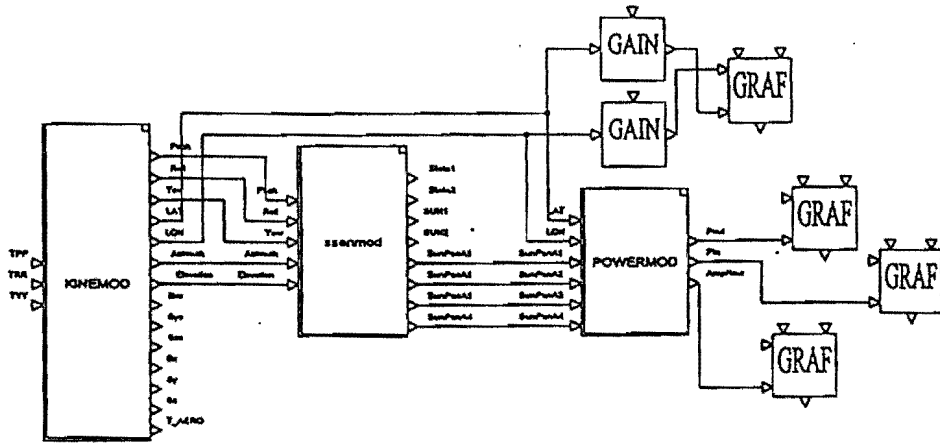


Figure 15: Yaw dynamics and power simulations using SIMuPAC.

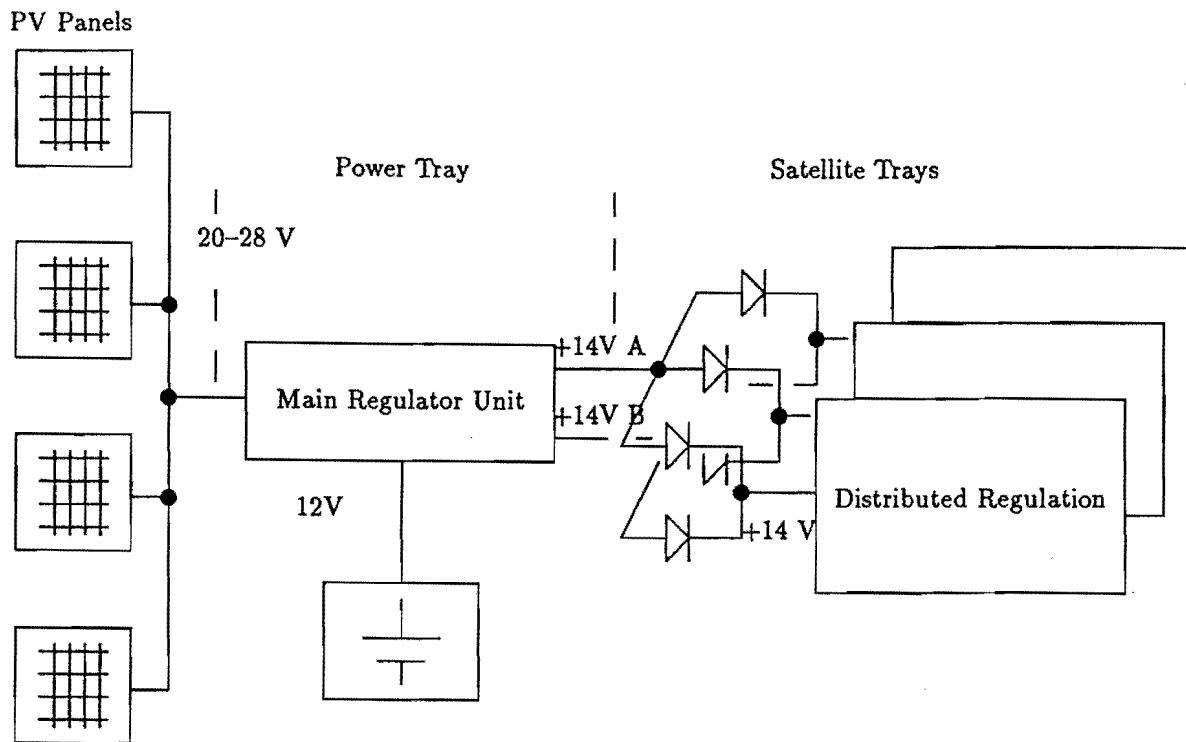


Figure 16: Sunsat power system block diagram

Prototype Development	
Systems engineering studies	\$ 65 000
Student internships	66 000
Material	23 000
TOTAL for Prototype	\$ 154 000
Engineering Model	
Student internships	\$ 133 000
Material	83 000
TOTAL for Engineering Model	\$ 216 000
Flight Model	
Student internships	\$ 77 000
Optics	50 000
Solar arrays	100 000
Space batteries	34 000
Other flight model hardware	83 000
TOTAL for Flight Model	\$ 344 000
TOTAL labor and material cost	\$ 714 000

Table 3: Sunsat cost budget

The labor costs are all in the form of scholarships paid to the student interns. The participating students are enrolled in a Master of Engineering course, and the bursary is adequate to cover their academic fees and on-campus residence costs. Academic staff participating in the Sunsat project do so as part of their normal research activities, and do not receive any remuneration for the labor hours invested. The material expenses listed above are for satellite components and structural parts development. Commercial quality components are used in the prototype models. The engineering model will contain a subset of flight quality components as required to perform the qualification tests. Purchase of the few expensive space quality components will be delayed until the flight model. Quotations have been obtained from several international launch agencies. Launch costs vary significantly. The upper limit is \$ 460 000 for a 'piggy back' launch by a launching agency that derives no benefit from the Sunsat satellite. Attractive negotiations are under way with organizations which are prepared to provide most of the microsatellite launch costs in exchange for access to scientific results from the Sunsat program.

15.2 Current sources of funds

The largest part of Sunsat income was derived from South African companies who are active or have an interest in space-related business. Grinaker Electronics has sponsored the Chair in Earth Satellite Engineering at Stellenbosch University since July 1991.

This initiated the first satellite research and teaching activity at a major South African university, from which the Sunsat project emerged.

Funding for student internships has also been provided by a number of South African high technology companies. In alphabetical order, with their main lines of business indicated in brackets, the companies are: Altech (electrical and electronic components and services), AMS (systems engineering services and product development), Grinaker Electronics (telecommunications systems development), Plessey Tellumat (telecommunications systems development), Siemens (electrical and electronic systems development).

The technology division of First National Bank has also sponsored a student on the Sunsat program. Regular feedback to these sponsors as part of the *Sunsat Advisory Board* has resulted in an excellent working relationship between the Sunsat team and industry. Their satisfaction with the Sunsat laboratory training methodology has resulted in a number of employment offers to the Sunsat students.

A further significant funding initiative has flowed from state sources in the beginning of 1993. A Technological Human Resources for Industry Program (abbreviated THRIP) was established by the Dept. of Trade and Industry. This fund is administered by the Foundation for Research Development which, among other activities, evaluates and awards grants in order to:

- promote the development of technological expertise in South Africa
- develop centers of specialization
- foster co-operation between universities and technikons on a regional basis

Grants from THRIP are allocated on the basis of 50% of the sponsorship received from industry. By basing the state funding on prior investments from industry, this formula effectively ensures the economic relevance of sponsored research.

16 Program management and control

Sunsat program management and control takes place at three levels, as discussed below.

16.1 Advisory Board

The *Sunsat Advisory Board*, comprising senior managers from South African high technology companies listed in the previous section, was established in June 1991. Their function is to evaluate the program at regular intervals from an industry perspective. They ensure that the Sunsat work is relevant to current market trends and that the technical performance

conforms to industry expectations. The Advisory Board members have provided the program with financial support and assisted with other funding and marketing drives.

16.2 Executive management

Program management within the Electrical Engineering Department is conducted by three professors, who have distinct responsibilities for financial management, industry liaison, and systems engineering. Together with six other academic staff members, they also serve as thesis and technical advisors for the students who work on the project.

16.3 Project management

A full time project manager has been appointed. He supervises the team of students, each of whom has project management responsibilities for a particular functional subsystem or hardware item of Sunsat. The program manager schedules design reviews as required for technical integrity verification. Finally, he places orders for technical work or component production by external suppliers.

The well defined management structure has not only served the Sunsat program well, but also exposed the student *interns* to working conditions similar to those encountered upon employment in engineering practice.

17 Acknowledgements

17.1 Sunsat Advisory Board Companies

Progress on Sunsat has only been possible because of the support of the companies mentioned previously. In a number of cases, their chief executives give time to monitor our progress and advise us both individually, and jointly through the *Sunsat Advisory Board*.

Our sponsoring companies have significant development and manufacturing expertise which enables them to support this graduate program as a long term strategy to maintain their attractiveness as international technology partners. The Sunsat program forms a breeding ground for engineers who will enter their space-related business activities. We also look forward to increased cooperation with the Houwteq Division of Denel, and appreciate their willingness to make their space qualification facilities accessible to Sunsat.

17.2 SA-AMSAT

Support from SA-AMSAT and the SA Amateur Radio League is of great value. We look forward to continuing the association.

17.3 Persona

The following students have done the majority of the design work on Sunsat, and have survived the creation of the new unit, and many design reviews! H.J. Beukes, R. Bootsma, N.J.J. Bornman, T.F. Botha, R.G.G Brune, H.S. Burger, C.A. Cilliers, I. de Swardt, R. de Villiers, F.E. du Plessis, J.H. du Toit, M. Eglington, H. Gouws, E. Jansen, L.J. Jordaan, F.G. Miedema, T. Niesler, M. Prinsloo, J. Rossouw, J.H. Tredou, P. v.d. Westhuizen.

P. Moon and Professor G. de Jager of the University of Cape Town have also contributed to the optical analysis.

Personnel of The Center for Electronics Services at the University play an important role on Sunsat's development. W. Amoraal is responsible for mechanical CAD design, and J. Grobbelaar has handled all complex PCB layout work.

17.4 University of Surrey

Many of the concepts being implemented in Sunsat have been used in the University of Surrey's UoSat's. We recognize their leadership with this type of satellite, and appreciate the technical interaction that has occurred.

18 Conclusion

This paper has given a detailed description of the design concepts involved in the Sunsat microsatellite. With a minimal budget we have been able to establish a unit and an initial design of a microsatellite that should be able to provide useful images of 20 m pixel spacing at approximately one percent of traditional satellite costs for such a purpose. Although the optical performance will not meet the exacting optical quality and calibration standards of the large satellites and only the silicon bands can be covered, we believe that Sunsat offers a useful price/performance option to the remote imaging community.

We still have a number of hurdles to overcome, particularly space environmental qualification, and launch financing. We hope that information in this paper will stimulate potential partners to consider joining the effort to turn Sunsat into an operational remote sensing microsatellite.

19 *

References

- [1] 'South Africans propose micro-satellite', *Space News*, Vol. 2 No.29, August 26 1991.

- [2] 'Sunsat Unveiled', *Space*, Vol. 7 No. 5, September 1991.
- [3] G.W. Milne, 'Sunsat — The Stellenbosch University Satellite', *AMSAT Annual Conference*, University of Surrey, July 1991.
- [4] G.W. Milne, 'Sunsat — Stellenbosch, SA Amsat, and Industry' *SA AMSAT Spacecon 91 Conference*, August 1991.
- [5] G.W. Milne. 'The Sunsat Microsatellite Program. Concepts, Progress, and Opportunities', *Proceedings of IEEE AFRICON'92*, September 1992, pp373-377.
- [6] M.S. Hodgart and P.S. Wright, 'Attitude determination, control and stabilization of UoSAT-2', *The Journal of the Institution of Electronic and Radio Engineers*, Supplement to Vol 57 No 5, Sept/Oct 1987, page S151 to S173.
- [7] W.H. Steyn, 'Attitude Control Algorithms and Simulation Programs for Low Earth Orbiting Spacecraft.' University of Surrey, 1990.
- [8] F. Martel, P.K. Pal, and M.L. Psiaki, 'Three-Axis Attitude Determination via Kalman Filtering of Magnetometer Data', Paper No. 17 for the *Flight Mechanics/Estimation Theory Symposium*, NASA/Goddard Space Flight Center, Greenbelt Maryland, May 1988.
- [9] J. Kasser, 'Telemetry, Past, Present, and Future'. AMSAT UK Space Symposium, July 1991.
- [10] O. M. Strydom. 'SIMuPAC: A Novel Interactive simulation Environment,' *Proceedings of the 1992 European Simulation Multiconference*, York, U.K.
- [11] H.J. Beukes, K.E. Dowson, JHR Enslin. 'Simulation and Analysis of the Stellenbosch University Satellite (Sunsat) Power System,' *Proceedings of IEEE AFRICON'92*, Sept 1992, pp 221-224
- [12] H.J. Beukes, K.E. Dowson, JHR Enslin, 'Simulation program for Stellenbosch University Satellite (Sunsat) Power System', *The Transactions of the South African Institute of Electrical Engineers*, March 1993, pp 32-36
- [13] H.J. Beukes, JHR Enslin, 'Analysis of a New Compound Converter as MPPT, Battery Regulator and Bus Regulator for Satellite Power Systems', *24th Annual IEEE Power Electronics Specialists Conference*, June 1993, pp 846-852