The SUNSAT Micro Satellite Program:

Technical performance and limits of imaging micro satellites

Sias Mostert, Thys Cronje and Francois du Plessis

Department of Electrical and Electronic Engineering
Stellenbosch University. Private Bag X1, MATIELAND, 7602. South Africa.
Fax: +27 21 808 4981. Internet: mostert@firga.sun.ac.za. http:\\sunsat.ee.sun.ac.za

ABSTRACT *- This paper examines the technical performance of the SUNSAT micro satellite bus, which is supporting the high resolution imager (HRI) payload on the micro satellite which is scheduled for launch in December 1998. A number of existing remote sensing satellites are investigated to determine some key parameters by which a micro satellite remote sensing mission should be evaluated. The SUNSAT 1 HRI instrument is then evaluated in this context and future possible missions suggested which is suitable for micro satellite missions.*

1. INTRODUCTION

SUNSAT, a professional micro satellite developed by a team of graduate students and engineers at Stellenbosch University in South Africa, is scheduled for launch from Vandenberg Airforce Base on a Delta II rocket, currently manifested for December 1998. The Flight Model hardware is complete and the pre-flight testing is drawing to a close.

This paper examines the technical performance and capabilities of SUNSAT 1 micro satellite supporting the high resolution imager (HRI). Laboratory measured performance data are provided for the 15 m resolution 3 color CCD imager of SUNSAT, developed jointly by Stellenbosch University, the Council for Scientific Industrial Research (CSIR) in South Africa and the Korean Advanced Institute of Science and Technology (KAIST). The performance of the Attitude Determination and Control System (ADCS), which is required to support the imager, is described. An overview of the satellite bus to support the high-resolution imager is provided.

Former and present remote sensing missions are examined to determine essential parameters by which the current SUNSAT 1 and future missions should be evaluated. The SUNSAT 1 imager, in its intended mission, is then compared to these parameters.

The contribution of this paper is to consider the SUNSAT micro satellite bus as a high accuracy and high data rate platform and show to what extent the HRI imager payload should provide useful remote sensing information. The expected mission profile for the imager due to the non-optimal orbit will also be analyzed. The paper closes by considering follow-on missions possible with micro satellite remote sensing.

2. SUNSAT TECHNICAL PERFORMANCE OVERVIEW

The 63kg SUNSAT microsatellite is composed of six major subsystems [MIL]. In this section we discuss the subsystems of the bus that support the payloads and science experiments, especially SUNSAT’s ability to carry a high resolution imaging payload.

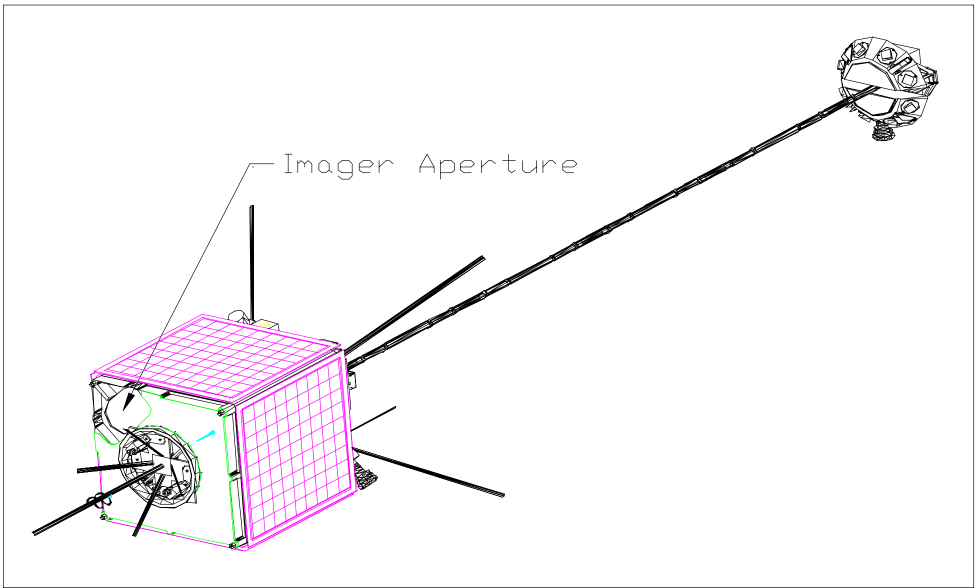

Figure 1: SUNSAT 1 with deployed boom.

2.1. Attitude Determination and Control System (ADCS)

The attitude determination and control specifications on SUNSAT are stringent for a microsatellite. To point the imager accurately, the following specifications must be satisfied:

- To determine the imager boresight position to within 1-km accuracy, pitch and roll attitude measurement error must be less than 1.2-mrad and a yaw error less than 2.4-mrad.
- To ensure less than 5-km image overlap between imaging sessions, pitch and roll attitude control accuracy must be less than 3-mrad, and yaw accuracy less than 6-mrad.
- To reduce the geometric distortion of images to below 1%, the maximum allowed pitch and roll rates must be less than 0.08-mrad/s and the yaw rate less than 0.16-mrad/s.

Five types of attitude sensors are used. A 3-axis magnetometer is used to measure the strength and direction of the geomagnetic field. This low power (100-mW) device can be operated continuously to provide attitude accuracy to within 1°. Coarse attitude information is also derived to within 5 degrees from six cosine-law solar cells mounted on each facet of the satellite. Horizon sensors, a fine sun sensor and a star sensor serve as the accurate attitude measuring devices. Attitude control is achieved through a passive gravity gradient boom, combined with two redundant active actuation methods. Slow attitude motions and coarse pointing to within 1 degree is achieved through magneto torquers and are mainly used for libration and momentum damping of the reaction wheels. Accurate pointing and stabilization during imaging is provided by 4 servomotor driven reaction wheels. The position control resolution of the satellite is 1mrad.

2.2. Communication links

The data downlink must be able to transmit the imager output in real-time to provide long length images when within range of a receiving station. Various communication systems are present, of which the 60Mb/s downlink is the most important for direct image data transmission. Small area images stored in the RAM disk can be downlinked at much lower rates. The communication links available on SUNSAT are:

- VHF 2m transmitters at 9600 bps
- UHF 70cm transmitters at 9600 bps.

- S-band 60Mb/s transmitter at 5W.

2.3. Flight control and data storage

Redundant computers of differing type provide flight control. General flight management tasks such as scheduling, CCD imager control and communications management are performed by an Intel 386EX processor, backed up by an Intel 80C188EC processor. A T800 transputer is dedicated to the fine attitude control system, but its tasks can be taken over by the 386 in case of failure. Seven additional embedded micro controllers provide further support for telemetry, telecommand, power control and attitude control subsystems. A separate RAM disk of 64 Mbytes, which is accessible by both processors, is provided for storage of imager data or large files for store-and-forward applications.

2.4. GPS

NASA's (National Aeronautics and Space Administration) TurboRogue/Turbostar GPS receiver and a set of laser retro-reflectors will support experiments in gravity recovery, atmospheric occulation science and ionospheric tomography. The GPS receiver provides three-dimensional positional and velocity data of the satellite, together with UCT (Universal Time Co-ordinate) time to the telecommand, all in digital format. Accuracy of positional information is expected to be within 60m, which can subsequently be recalibrated to provide 1-m accuracy.

2.5. Scan Control

The scan controller is adaptable to support variations in the satellite height, the number of colors and the extend of data compression used. Each image line contains the number of lines, the line number, the pitch, roll or yaw of the satellite, the time, temperature and gain settings.

2.7. Telemetry and telecommand

The telemetry data collection function and the data transmission functions are replicated for redundancy.

2.8. Power system

The power system is controlled by a simple but reliable shunt-regulator. The four solar panels are able to provide an average power of 23W. The peak power capability is 90W to handle peak loads during imaging data transmissions. Depth of discharge of the batteries is limited to 20% to ensure a lifetime of 5 years.

3. IMAGING MISSIONS

Remote sensing of the earth from space generates useful data that can be used in areas like forestry, agriculture, geology, hydrology, planning and many others. The cost and risk associated with large satellites have limited remote sensing to governmental organizations paying for weather services, military observation and mines paying for images for prospecting purposes. The major space faring nations and space companies do however have continued to invest in remote sensing, i.e. SeaStar 1, WorldView 1 and 2, Ofeq 3, Clark and Lewis.

The role of a microsatellite in remote sensing is to provide a very inexpensive platform that can be configured and launched for a very specific mission in a short time. Other roles include dedicated constellations for specific application areas due to the low cost of one such satellite.

3.1. Remote Sensing Satellites

Since the mid-1960's, a variety of remote sensing systems have been launched for imaging the earth. In this section these space sensors will be examined to see how they are supporting earth resource management applications. The key question to ask would then be if micro satellites are able to carry remote sensing payloads with significantly useful data.

3.1.1. Meteorological Observation

Low resolution remote sensing information for weather forecasting is available meteorological satellites, e.g. the **NOAA**'s with their AVHRR (Advanced Very High Resolution Radiometer), **GOES** (Operational Geostationary Satellite) and **DMSP** (Defense Meteorological Satellite Program) [MAN].

3.1.2. Oceanographic Programs

The ocean has a very big influence on the world's weather patterns and provides us with food and transport. Satellites are ideal to monitor this inaccessible area. Some examples are **Seasat**, **SeaStar** with its SeaWiFS (Sea-viewing Wide Field of View Sensor), **Nimbus-7** with its CZCS (Coastal Zone Color Scanner) and **MOS-1b** with its VTIR (Visible and Thermal Infrared Radiometer) [LIL].

3.1.3. Landsat

Landsat-1 was launched in July 1972 in a sun synchronous orbit. Onboard sensors was the RBV (Return Beam Vidicon) with three spectral bands between 475nm and 830nm and a resolution of 80m, and the MSS (Multispectral Scanner) with 4 bands between 500nm and 1.1µm with a resolution of 79m. **Landsat-5** was launched in March 1984. An MSS with the same characteristics of the previous Landsats were used. The onboard TM (Thematic Mapper) has 7 bands between 450nm to 12.5µm and a ground resolution of 30m, except in the thermal infrared band where the resolution is 120m.

The **Landsat-6** launcher failed in October 1993. The performance of its ETM (Enhanced Thematic Mapper) was identical to the TM except for a panchromatic band with a resolution of 15m. Table 1 gives the measured characteristics, wavelength, resolution and MTF, of Landsat-6's sensors.

Band	Pan	1	2	3	4	5	7	6
Wavelength [µm]	0.5-0.9	0.45-0.52	0.52-0.60	0.63-0.69	0.76-0.90	1.55-1.75	2.08-2.35	10.4-12.5
Ground Resolution [m]	15	30	30	30	30	30	30	120
MTF at Nyquist [%]	38.31	40.26	40.96	39.15	34.05	34.30	32.08	29.00

Table 1: Characteristics of Landsat-6 sensor as measured in the laboratory.

3.1.4. IRS

In 1988 **IRS-1A** (Indian Remote Sensing Satellite) was launched with remote sensing payloads LISS-I and LISS-II (Linear Imaging Self-Scanning Sensor). Both instruments have four separate scanners with its own refractive optics, optical filter and 2048 element CCDs are used to cover four optical bands. LISS-I and LISS-II have respective ground pixel sizes of 73m and 36m[REM].

The **IRS-1C** satellite has several improved sensors, with a panchromatic resolution of 10m, visible bands of 20m, near-infrared bands of 70m and a wide angle, wide spectrum instrument with a 188m resolution[KAS].

3.1.5. SPOT

SPOT-1 (Sysètme Probatoire d'Observation da la Terre) was launched in February 1986. **SPOT-2** followed in January 1990 and **SPOT-3** in September 1993 with identical orbits and remote sensors. Two HRV (Haute Résolution Visible) instruments per satellite are used. Each instrument contains three linear CCDs with 3000 pixels for multispectral imaging at a resolution of 20m, and one linear sensor of 6000 pixels for panchromatic imaging at 10m resolution was used [LIL].

SPOT-4 has an additional fourth band operating in the short-wave infrared portion of the spectrum (SWIR - 1.5 to 1.75 µm). The new SWIR band will make **SPOT-4** more sensitive to soil moisture content, vegetation cover and leaf moisture content. The HRV (high-resolution visible) optical instruments on **SPOT-1**, **2** and **3** have been superseded by HRVIR instruments (High-Resolution Visible and Infrared) for the SWIR channel.

The SPOT family will provide service continuity with **SPOT-5**, to be launched in 2002, with the new High Resolution Geometry or HRG imager. **Table 2** shows the measured specifications of **SPOT-5**'s spectral bands.

Band	Pan	B1	B2	B3	MIR
Resolution [m]	5	10	10	10	20
Wavelength (µm)	0.49 - 0.73	0.50 - 0.59	0.61 – 0 .68	0.79 - 89	1.58 – 1.75
MTF between lines [%]	19.6	34.3	31.9	26.6	27.1
MTF in line [%]	11.9	28.8	26.4	24.7	18.1

Table 2: Specifications of SPOT-5's bands and MTFs**.**

3.1.6. Other:

MOS-1b is a Japanese satellite launched in 1990 with two optical remote sensor instruments, VTIR (Visible and Thermal Infrared Radiometer) with a visible and three thermal infrared bands and MESSR (Multispectral Electronic Self-Scanning Radiometer) with two visible and near-infrared bands. In 1992 Japan launched **JERS-1** with a SWIR (Short-wave Infrared Radiometer) with four mid-infrared bands, well as an optical sensor with two bands in the visible and two in the near-infrared bands[BEL].

From 1998 an international effort in remote sensing, EOS (Earth Observing System), is planned. This is a NASA project consisting of several satellites with payloads sponsored by several governments [ZOR]. The **EOS-AM** satellite has six types of sensors of which three are of interest for remote sensing of rural areas:

- MODIS (Moderate-Resolution Imaging Spectroradiometer), with 36 spectral bands with a resolution of 250 to 1000m.
- ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), with the same spectral bands as MODIS, but with a resolution of between 15 to 90m.
- The "Multi-Angle Imaging Spectroradiometer" have bands in the visible and near-infrared wavelengths.

3.2. What is important in remote sensing products?

Satellite remote sensing has the fundamental advantage that it is available on a regular interval. This enables remote sensing to be used for the monitoring of environmental processes that change with a period of between 5 days and one year. The following parameters are important when deciding on a remote-sensing payload.

Remote Sensing Parameters	Limiting and Determining Factors
Spatial Resolution and Swath Width	• Ground pixel size needed • Available data rate • Sensor characteristics • Optical limitations (f-number) • Number of pixels
Radiometric Resolution	• Signal-to-noise ratio of sensor • Available bandwidth
Temporal Resolution	• Environmental changing period • Orbital Parameters • Off-nadir imaging capability
Spectral Resolution	• Sensor characteristics • Imaging Application (see Table 3) • Available data rate
Pointing accuracy, stereo off-nadir imaging	• Imager configuration (pushbroom or area sensor) • Imager ground resolution • Imager/Optics orientational capabilities
Lighting conditions	• Similar or variable illumination conditions • Orbital parameters

4. THE SUNSAT 1 IMAGER

The Sunsat I high resolution imager (**HRI**) will be able to collect and store three color stereoscopic images with ground pixel size of 12.4m at a height of 650km [DUP] with a swath width of 42.9km and length of 39.8km (stereo and color). The imager has the ability to look forward and backward for stereo imaging or sideways. A variable base-height ratio from zero to one is possible for stereo imaging.

Three linear CCD sensors with pixel spacing 10.7μm are used. Each sensor contains 3456 imaging pixels with a total of 3490 pixels. The output of the three linear CCDs - each covering a separate spectral band - are digitized to 8 bits each, resulting in a 24-bit color picture.

Spectral Region	Wavelength (μm)	Primary Application	Resolution (m)
Blue, Green	0.47-0.57	Water penetration	10
Red	0.57-0.69	Vegetation and cultural features discrimination	10
Near IR	0.76-1.05	Land, water interface and vegetation discrimination	10
Short Wave IR	1.55-1.75	Vegetation type, soil moisture	10 – 30
Panchromatic	0.51-0.73	Topographic mapping	5
Short wave IR	2.08-2.35	Mineral exploration, soil types	

Table 3: Spectral regions useful for mapping, interpretation and Earth science applications.

The actual imager comprises a single optical tube assembly mounted diagonally in the bottom tray of the satellite. It contains a 45° mounted mirror, a catodioptric lens system and a pentaprism with dichroic beam splitter. The three vertical mounted linear CCDs, the clock drivers and output video processing circuitry are also housed inside the imager tube. A small stepper motor can rotate the tube

±25° enabling the imager to take stereo-scopic images of the earth with a maximum base-height ratio of one.

4.1. Spectral Resolution

The SUNSAT imager is a three band spectral imager with spectral bands green (510-590nm), red (600-685nm) and near-infrared (710-900nm). The respective 10%, 50% and 90% transition points of the three channels are given in Table 4.

	Green	Red	NIR
10%	495-610	580-710	695-920
50%	510-590	600-685	710-900
90%	530-570	615-660	720-890

Table 4: The spectral transition points (nm) are given for the three spectral bands [CRO].

In Figure 2 the measured spectral responses are shown together with the spectral bands of other remote sensors. The main difference is that the measured near-infrared band includes the H_2O-absorption band at 0.75µm. Figure 2 shows clearly that most of the other remote sensors avoid these wavelengths.

4.2. Spatial Resolution

The instantaneous field of view (IFOV) and the resolution limit as determined by the Modulation Transfer Function (MTF) are the two most common methods to define the spatial resolution of the imager.

The IFOV in meters is defined by the area subtended by the angular field of view of a single detector projected onto the ground at nadir from the nominal altitude of the spacecraft. For an altitude of 650km the angular field of view is 20µrad for each pixel in the linear CCD array. This angular field projected at a distance of 650km subtends 12.4 meters square. The unique design of the imager tube will permit omnidirectional viewing with off-nadir angles extending in excess of 23° to both sides. This increase in FOV also increases the revisit frequency of the satellite.

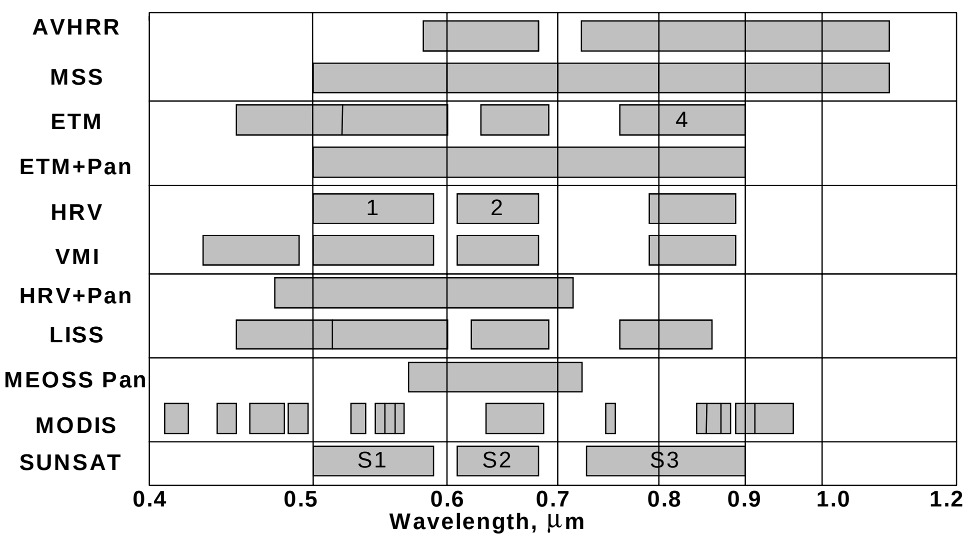

Figure 2: The spectral bands of SUNSAT and NOAA AVHRR, Landsat MSS and ETM, SPOT's HRV and VMI, IRS's LISS and MEOSS, and EOSs MODIS are shown.

The MTFs for the three channels of the imager was measured with a collimator and slit, in the first 5%, middle, and last 95% of the CCDs, to verify the optical quality. The results of the MTF measured at Nyquist and half Nyquist spatial frequency are listed in Table 5.

	Green			Red			NIR		
Cy/mm	5%	50%	95%	5%	50%	95%	5%	50%	95%
MTF at ½ Nyquist [%]	36	42	40	34	38	30	31	40	32
MTF at Nyquist [%]	12	15	13	11	11	10	9	11	10

Table 5: SUNSAT MTFs at half and Nyquist frequency [CRO].

4.3 Orbital Parameters

SUNSAT will be launched on a Boeing Delta II rocket with the Argos P91 mission in an elliptic orbit that varies between 520km and 850km. The inclination of 96.5° results in an orbit plane drift of 0.79°/day and is equal to a drift of –0.19°/day with reference to the sun-earth direction, resulting in a drift of one hour earlier every 76 days. The illumination of the earth from the satellite's viewpoint is thus not sun-synchronous.

The orbit for SUNSAT was simulated for a mission life of 42 months and the elevation of the sun was calculated for every crossing of the satellite over South Africa [SIM]. The results of the simulation are presented in Figure 3. Useful conditions for taking images is when the solar elevation angle from the sub-satellite point is between 40° and 70°. From the simulation results in Figure 3 it can be seen that there is a period of approximately 500 days after launch during which the solar elevation will vary between approximately 40° and 70°. For the period between day 150 and day 200, the large sun elevation-angle will result in unfavorable condition for useful imaging. Between days 500 and 850 the sun angle is too low for useful images. From day 630 to day 700 the satellite will always pass over South Africa either during nighttime or close to dawn. After

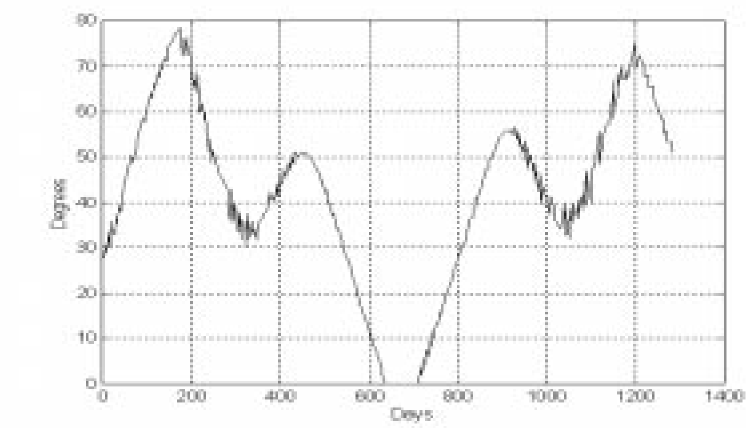

Figure 3: Sun-elevation angle during a pass over South Africa

day 850, the lighting conditions will gradually increase until it is once again possible to take images with good lighting conditions over South Africa.

5. EVALUATION OF SUNSAT 1 IMAGER

Figure 2 compares SUNSAT 1's spectral bands with some of the major remote sensing satellites. These bands are comparable with band 4 of Landsat and band 1 and 2 of SPOT. The first two bands (S1 and S2) are the same as SPOT's HRG instrument. For the third band (S3) Landsat's ETM band was recommended. However, the S3 band includes the O_2 and H_2O absorption bands at 750nm and

760nm. The appearance of O_2 in the atmosphere is much more stable than H_2O and would not have such a big influence on the signal intensity levels. The inclusion of the H_2O absorption band could result in signal variations.

In Table 6 SUNSAT HRI instrument's resolution, swath width and revisit time are compared with some of the major remote sensing satellites. From this information it is clear the micro satellite's ground resolution compares good with these traditional large remote sensing satellites. From Table 1 and 2 it is clear that measured Landsat-6 and expected SPOT-5's MTF at Nyquist is better than SUNSAT's and is more capable of recording spatial detail than SUNSAT's HRI. Swath width with instrument side viewing capability is similar to the SPOT 5 capability.

6. FUTURE IMAGING MISSIONS

SUNSAT 1 is an engineering experiment satellite undertaking to prove that high resolution remote sensing is possible on such a small platform. The development of new technology micro satellites will be done in parallel with the exploitation of the current SUNSAT technology to specific missions [MOS]. Three particular follow-on remote sensing missions are briefly mentioned.

Instrument	Resolution	Swath width	Height	Inclination	Revisit time
AVHRR	1.1km	2400km	833km	98.9°	1d
MSS	82m	185km	705km	98.2°	16d
TM	30m				
ETM (Pan)	15m	185km	705km	98.2°	16d (38°: 3d)
HRMSI (Multi)	10m	60km			
HRMSI (Pan)	5m				
HRG (Multi)	10m	60km	832km	98.7°	26d (27°: 5d)
HRG (Pan)	5m				
VMI	1km	2000km			
VTIR	900m	1500km	909km	99.0°	17d
MESSR	50m	100km			
SWIR	18×24m	75km	568km	97.7°	44d
LISS-I	73m	148km	900km	99.0°	22d
LISS-II	36.5m	2×74km			
HRI	12.4m	43km	650km	96.5°	64d (25°: 5d)
	16.2m	56km	850km		50d (25°: 4d)

Table 6: Characteristics of NOAA 6 to 12's AVHRR, Landsat 4&5's MSS and TM, Landsat 7's ETM and HRMSI, SPOT 5's HRG and VMI, MOS-1b's VTIR and MESSR, JERS-1's SWIR and optical sensor, IRS-1B's LISS, and SUNSAT's HRI (High Resolution Imager). Thermal infrared band information is not shown. The revisit times in brackets shows the angular displacement of a directional sensor as well as the reduced revisit time.

6.1. Auroral imaging

The development of an imager to capture auroral displays assisting the South African Antarctic team in their research is investigated. Micro satellites with a polar orbit are ideal for capturing and assist with auroral research.

6.2. Water Resource

One of the applications being investigated is the possibility of multi spectral imaging, up to wavelengths of 1.8µm, targeted for the management of water resources. Water has major spectral features in this band, to the extent that the various phases of water can be distinguished. The water absorption features are centered at four major wavelengths, 0.97µm, 1.2µm, 1.45µm and 1.9µm.

6.3. Agriculture Resource

The SUNSAT 1 HRI imager with SPOT's bands 1 and 2 and Landsat's band 4 can be augmented with an extended short-wave infrared band (1.55-1.75µm) to provide an instrument optimized for vegetation and hence agricultural applications.

7. CONCLUSION

This paper describes the fundamental constrains of the SUNSAT micro satellite on imager payloads. It illustrates that the first high resolution imager on the SUNSAT micro satellite compares favourably with past large satellites in terms of resolution and a subset of the spectral bands.

The innovative combination of a high accuracy attitude determination and control system with a high resolution pushbroom imager on a micro satellite of 63kg opens up new opportunities for the application of micro space real-size problems. The performance of the SUNSAT micro satellite imager payload were investigated as a means of providing specific solutions for short term remote sensing problems.

The SUNSAT 1 orbit, although not an ideal remote sensing orbit, does provide unique opportunities to do imaging under various sun angle conditions.

With the SUNSAT 1 micro satellite readied for launch, the next generation micro satellite technology is being developed to improve the already advanced capabilities of the SUNSAT micro satellite bus. A number of possible follow on missions are described which will be pursued further as a baseline for the SUNSAT 2 mission.

REFERENCES

[BEL] Bell, T.E. Remote Sensing. *IEEE Spectrum*. March 1995: 24 – 31.

[CRO] Milne, G.W. and Cronje, M.L. Kitsat Flight Model Imager Optical Test Results, Electronic Systems Laboratory, Department of Electrical and Electronical Engineering, University of Stellenbosch, South Africa, 9 May 1997.

[DUP] Du Plessis F.E. Electro-Optical Analysis and Development of a High Resolution Imager for the SUNSAT Microsatellite (Afrikaans), Masters dissertation, University of Stellenbosch, October 1997.

[KAS] Kastuirangan, K. Aerospace technologies: a terrestrial focus. IEEE Spectrum, March 1994.

[LIL] Lillesand, T.M. and Kiefer, R.W. *Remote Sensing and Image Interpretation.* John Wiley&Sons, New York, 1994.

[MAN] Colwell, R.N. (Editor) *Manual of Remote Sensing, Volume I&II.* American Society of Photogrammetry, Virginia, 1983.

[MIL] Milne GW; Bakkes PJ; Schoonwinkel A; du Plessis JJ; Enslin JHR; Steyn WH; Mostert S; Palmer KD; Weber DM. SUNSAT, Stellenbosch University and SA-AMSAT's Remote Sensing and Packet Communications Microsatellite. Proceedings of the Conference on Small Satellites #7, Utah, USA, September 1993.

[MOS] Mostert S. SUNSAT 2R: Mission Analysis, Resources and Architecture. IEEE and SAIEE Small Satellites and Control System Symposium, Stellenbosch, October 1994.

[REM] Cracknell, A.P. (Editor) *Remote Sensing Yearbook 1990.* Tailor & Francis, Londen, 1990.

[SIM] Simulations done with Satellite Toolkit and Matlab

[ZOR] Zorpette, G. Sensing climate changes. *IEEE Spectrum*. July 1993: 20 – 27.