

Integrated Hyperspectral, Multispectral and Video Imager for Microsatellites

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ABSTRACT: The multi-sensor micro-satellite imager (MSMI) programme is developing an imager suitable for microsatellites, with multi-spectral, hyperspectral and video detectors on the same focal plane of a single telescope. It also contains the mass memory and high speed data compression capability to store any combination of the above sensor outputs on board. The imager is designed as a standard payload for the African Resource Management (ARM) satellite constellation and will be test flown as part of the ZASat programme (as part of the South African Space programme). Consortium partners include universities, private companies and research councils in both South Africa and Flanders in Belgium. The MSMI has standardized and modularized components and communication systems, which allowed the re-use of sensors, processors and mass memory on imagers for other small satellites produced by SunSpace in association with Stellenbosch University. Ultimately this opens up the possibility of affordable satellite constellations that can deliver remote sensing data to commercial and science users more frequently.

INTRODUCTION

The MSMI in Brief

The core innovative concept of the MSMI is a remote sensing satellite payload that combines dissimilar detectors on the focal plane of a single telescope in order to achieve high spatial resolution and high spectral resolution. A video sensor is the third detector class, that allows real time motion detection in the observed area or snap shots along the imager footprint, as well as measurements of imager bore sight motions. The combination of these sensors on a relatively small imager opens up opportunities for higher temporal resolutions by a constellation of microsatellites.

At present, many researchers find it relatively difficult to obtain hyperspectral data. The MSMI attempts to address this need in a limited frequency band from small satellite platforms. This approach will hopefully lead to better affordability in the same fashion as microsatellites have for other niche applications.

The combined imager is a “smart sensor” that incorporates its own data storage and data compression subsystems with the payload. It also assists satellite attitude control system and terrestrial post processing algorithms by providing imager bore sight motion information, derived from the continuous video sensor.

The MSMI sensor is designed to be compact and light so that it is suitable for microsatellite and minisatellite customers. To inform the design by a real need, a food security application is developed simultaneously, which also demonstrates the value of a multisensor imager.

South African Satellite heritage

During the early 1990's the South African government funded the development of a complete minisatellite from remote sensing, called Greensat. The satellite mass was approximately 350 kg and the main payload was a pushbroom imager with about 1.5 m ground resolution. Together with its ground station and data processing systems it was to provide services for cartography, agriculture and environmental protection. Unfortunately this programme was abandoned in 1994 due to a lack of funding.

Stellenbosch University, near Cape Town, was involved in several aspects of Greensat's development, including the control system and simulation models development. The university realized the benefits of such a challenging programme for research and education, and even before Greensat was shelved, the Stellenbosch Engineering Faculty commenced with the smaller scale SUNSAT programme. SUNSAT is an acronym for Stellenbosch UNiversity SATellite.

The SUNSAT programme set out with three major goals, namely to enhance the engineering graduate training programme, to expand international scientific co-operation and to stimulate interest in technical careers among school children. It was envisaged that the local development of a microsatellite with a number of novel subsystems would provide the technical challenge and excitement required to achieve these goals.

SUNSAT carried two main payloads, namely a camera and a communications system, which together with the bus system resulted in a total satellite mass of 64 kg. The camera system on SUNSAT was designed to

provide stereo or side view images in three colours, namely green, red and near infrared. Each color line covered a swath width of 51 kilometers at 15 m ground resolution from 800 km orbit height. At the time of SUNSAT's operation this ground resolution was of the same order of magnitude as the SPOT and Landsat satellites. The quality and types of SUNSAT images were unique for a university microsatellite of this size and weight.

The communications payloads on SUNSAT provided the service of receiving large data files from anywhere on earth as the satellite passed over a ground station, and retransmitting these files to other receiving station anywhere else on the globe (the so called "store-and-forward system" for data communication).

Apart from these payloads, SUNSAT also had on board computers and control systems designed and built by the research students. Despite the fact that it was not built by professional satellite engineers and on a shoe string budget supplied largely by partners in die South African electronics industry, SUNSAT was successfully operated in space¹ for nearly two years following its launch on 23 February 1999. The cost for the launched on board a Boeing Delta II rocket from Vandenburg Air Force Base in California, was sponsored by NASA in exchange for two NASA scientific instruments that were incorporated on SUNSAT. Figure 1 shows the flight model of the SUNSAT microsatellite.

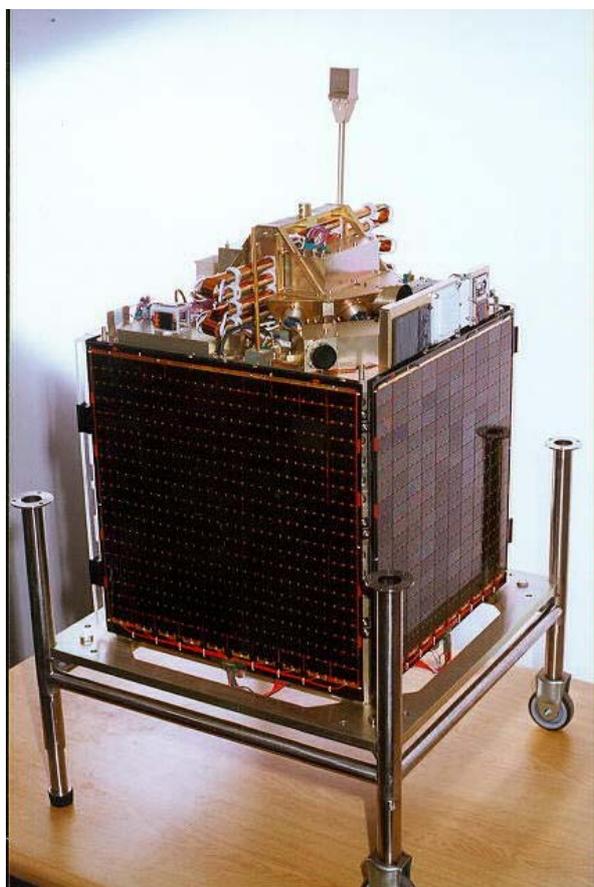


Figure 1. SUNSAT Flight Model in Handling Frame

Present EO Microsatellites from South Africa

Following the success of the SUNSAT programme, Stellenbosch University started receiving requests and orders for microsatellites subsystems, e.g. the imager, star camera, magnetometer and other attitude determination and control systems components. When an order for a complete remote sensing satellite was received, the university and founders of the SUNSAT programme decided to form a spin-of private company. SunSpace and Information Systems (Pty) Ltd was established in March 2000, and commenced with the development small satellites in two classes. Their 60 kg microsatellites are based on the SUNSAT concept and their somewhat larger satellites in the 200kg class are designed to carry approximately 5 m resolution multispectral imagers and/or hyperspectral imagers such as the MSMI. The latter class satellite already resulted in an international commercial sale and also forms the basis for the upgraded ZASat remote sensing satellite presently considered for a South African government initiative to strengthen the local aerospace capability. SunSpace had also registered other sales of satellite subsystems and technology transfer contracts with international clients.

In May 2005 the South African government Department of Science and Technology has commissioned Stellenbosch University to develop the ZASat Pathfinder satellite programme in conjunction with the South African industry. As the name indicates, this is a precursor to the ZASat programme, whereby a smaller (approximately 60 kg) remote sensing satellite is to be developed with SunSpace as the main subcontractor. The research and human resource development will be largely the responsibility of Stellenbosch University and stretches over a 4 year period during which large numbers of MScEng and PhD students will do their research on various aspects of remote sensing satellites. Special emphasis is placed on enrolling students from formerly disadvantaged communities in South African on the satellite development programme. On the technology development front, SunSpace will prepare the multispectral and continuous video elements of the MSMI as a payload for ZASat Pathfinder. The launch date for ZASat Pathfinder is intended for 2006.

SIMULTANEOUS APPLICATIONS DEVELOPMENT

Given the historical background of satellite development in South Africa, it is evident that the work was largely driven with a "technology push" approach, in order to strengthen human resource development and know-how in the local aero-space sector. A different approach, namely "applications-pull" was taken for the MSMI development.

Philosophy

From the inception of the MSMI project it was decided to select an application that would be relevant to the needs of Africa² and drive the requirement for a multisensor satellite imager. Food security, in particular the short term prediction of the food balance (i.e. the difference between the food supply and food demand), will benefit greatly from remote sensing data, even though the latter is by no means a sufficient input for the prediction models by itself³. The food security application places high demands on the spatial, spectral and temporal resolutions of satellite imagers. If this application can be adequately served by the MSMI, it would simultaneously open up other avenues for services in natural resource management that can be provided by the MSMI.

Applications and Developers

The MSMI Food Security Application⁴ calls for three types of data, to be carried on the same platform, along with onboard 'short message' data-uploading capabilities. The data types are:

1. 'Multi-spectral' data with a resolution of around 5 m and swath width about 25 km. The preferred band requirements, if exactly 3 bands are available, would be:
 - a. Red 630-685 nm: strongly absorbed by vegetation
 - b. NIR 845-890 nm: strongly reflected by vegetation
 - c. Water band 950-970: sensitive to moisture content of vegetation. The purpose of this data is to track crop development for predicting final yield.

For this purpose it needs cloud-free views of the target area (but not necessarily exactly the same fields) about once every 10 days.

2. A high-resolution panchromatic image. Resolution <3 m, image =3 km per side. The purpose of this sensor is to provide statistical estimates of cultivated area (not a wall-to-wall census), especially for the small field sizes typical of developing countries. It can also provide information on human settlement size, density and location, useful in determining population densities.
3. Hyperspectral array, 400-2350 nm in 10 nm steps. Resolution <50 m, swath >10 km. The purpose of this sensor is to identify the crop variety planted, using its spectral signature. There is a possibility that it may also be able detect crop health, nutrition and water stress, all of which affect yield.

The concept is that the panchromatic data maps out cultivated areas, based on pattern recognition and contextual information, possibly supplemented with multispectral data and data from other satellite and

non-satellite sources. On these cultivated areas (a small fraction of the landscape, thus greatly speeding processing time), the repeated views using the multispectral instrument are used to find the planting date and to estimate final productivity from the growth curve. The crop type is identified from planting date, context and the hyperspectral fingerprint. Productivity is a crop-specific function of an accumulated 'greenness' index, such as NDVI (i.e. $[\text{NIR-Red}]/[\text{NIR+Red}]$), modified by water availability (NIR/Water band) and possibly other bands derived from the hyperspectral sensor. The yield is scaled to the administrative unit using the estimated statistics of the planted area in the unit. Yield is continuously projected forward in time, using climate-scenario-based models, providing estimates (with broadening uncertainty bars) up to 6 months ahead.

On each pass, the satellite gathers uploaded data from key grain storage locations regarding stocks, and data from remote automatic weather stations. This capability is not part of the MSMI design, but could be provided by a separate store-and-forward payload on the same satellite or the data could be provided over landlines, cellular lines or via the internet. This information is integrated with consumption and distribution models, to give a surplus/shortfall projection at a scale of about a magisterial district, in good time to enact interventions. To deploy the full benefit of the food security application over Africa, a constellation of satellites with MSMI payloads would help to facilitate the regular observation of the growth cycle despite the prevalence of clouds.

In the MSMI project the responsibility for the development of the food security application and its testing with simulated MSMI data lies with the CSIR (Environmentek) and Agricultural Research Centre (Institute for Soil, Climate and Water), two parastatal research organizations in South Africa.

Multispectral frequency band specifications from additional considerations

A workshop with South African and international experts in vegetation remote sensing applications as well as sensor developers was held early on in the project (March 2004) to recommend the appropriate spectral bands for the multispectral detectors⁵. The workshop departed from the premises that primary application will be the monitoring of food security in the developing world, and particularly southern Africa. Secondary applications in rangeland monitoring, alien plant mapping, fire management and other environmental areas are also targeted where they are compatible with the primary application. The main purpose of the multi-spectral sensor is therefore the measurement of vegetation cover, vigour and phenology (the study of cyclic events of nature, e.g. plants, in response to seasonal and climatic changes to the environment).

The engineering design could incorporate 6 multispectral line detectors. Apart from the Red and

NIR bands required for vegetation indices, the following aspects were considered for selecting the remaining four bands:

The blue band is omitted by most multispectral sensors, because dust in the atmosphere interferes with it. However, reflectance in the blue can be used to correct for dust in the other bands. Aerosol absorption near 400 nm may be excessive, so a 440 to 510 nm band is selected.

The second priority is for true color imagery. Given that a red and blue band are already specified, this simply requires the addition of a green. The exact location and width are not very critical. A green band at 520-590 nm is widely used by heritage systems and is very close to that specified for Landsat continuity missions.

If there is scope for six bands, the priorities become those associated with particular features, especially those connected with leaf pigments.

The xanthophyll absorption feature at 520-540 nm is related to plant radiation use efficiency, an important variable. It can be proxied by the Photochemical Reflectance Index (PRI)⁶. The PRI needs a fairly narrow waveband (20 nm) centered around 531 nm, and a reference waveband, typically centered around 570 nm. The two bands together give a true color green band capacity.

The red-fringe area (about 680 to 750 nm) is strongly related to chlorophyll and protein content of the leaves and leaf vigour. A robust index requires several bands in this region, which makes it more suited to the hyperspectral than the multispectral sensors⁷. Nevertheless, the "red edge" contains valuable crop classification information if it can be sharply limited at the upper wavelength to somewhere just below the red edge inflection point.

Table 1. Selected Bands and Purposes

Band code	From	To	Primary use
	nm		
PAN	440	650	Spatial analysis
BLU	440	510	Aerosol correction, EVI, true colour
XAN	520	540	Photochemical reflectance Index
GRN	520	590	True colour, Photochemical Reflectance Index
RED	620	680	Vegetation index, true colour
REI	690	730	Red edge information
NIR	840	890	Vegetation Index

A Water Index (H2O/NIR) can be calculated⁸ using bands that take advantage of strong water absorption features. The water index correlates with Leaf Area Index (LAI), especially at high LAI where vegetation indices tend to saturate⁹. There are several water absorption bands in the infrared¹⁰, but none within the spectral sensitivity of the selected charge-coupled device (CCD) available for the MSMI sensor. The closest is at 970 nm, where the band is quite narrow and not ideal. Given the small signal and the doubtful sensitivity of the CCD in this range, a water band was considered unfeasible.

Hyperspectral considerations

The Hyperspectral MSMI component will make available spectral data, which depict the interaction between solar energy and plant material plus its environment¹¹. Simultaneously in-situ data will be collected, that are pertinent to the plant production system being studied. The data are integrated within a process-modeling context in order to model, monitor, and eventually have control over, economically important plant production systems, such as, for example, fruit orchards, vineyards, forests, agricultural crops, etc. The integrated data sets represent environmental conditions (e.g., air and soil humidity, hours of sunshine, pollen counts, wind regime, temperature below and above canopy, sugar content, osmotic pressure, ozone concentration, etc.) and the way plant production systems react to these factors (hyperspectral vegetation indices that correlate to plant vigor, plant vitality, leaf biomass, fruit production, fruit quality, etc.) in orchards, vineyards, forests, city parks and more, in order to optimize management interventions (establishment, irrigation, spraying, pruning, time of harvest, etc.).

The hyperspectral sensor is a Flemish contribution to the MSMI package, and entails the electro-optical components (imaging spectrometer, detector/read-out component) of a hyperspectral sensor, being built in Oudenaarde (in Belgium) by OIP. Based on this firm's experience with airborne hyperspectral sensors and other space borne sensors, the two spectrometers in the hyperspectral sensor were selected to cover the visible and near infrared frequency range (400 to 990 nm) and the short wave infrared frequency range (940 to 2350 nm). There is thus an overlap in the frequency bands of the multispectral and hyperspectral sensors, which will allow interesting research opportunities since the data is collected simultaneously. The hyperspectral sensor provides more than 200 spectral lines in bins of approximately 10 nm wide and it will have a swath of 15 km with GSD of 15 m.

Forward Motion Compensation (FMC) is defined as the pitch motion of a 3-axis controlled satellite that reduces the effective forward [ground/target scanning] velocity, increasing the possible exposure (integration) times to achieve higher SNR by effectively lowering the sensor line rate. The hyperspectral sensor requires

the use of FMC>10 in order to satisfy its minimum integration time requirements. This implies that viewing will not always be nadir pointing.

Furthermore, it is envisaged that the microsatellite host satellite will use oblique sideways viewing to roll angles of up to 30 degrees, in order to increase revisit times to targets. The interpretation of off-nadir hyperspectral images is one of the important research areas addressed by the Faculty of Applied Bioscience and Engineering at KU Leuven in Belgium.

MSMI SPECIFICATIONS

The complete technical specifications are provided in Appendix A. The frequency specifications were developed from the primary application, as described above. The decision to operate the sensor in the visible, near infrared and short wave infrared bands was largely influenced by the technology that was readily available in South Africa and Belgium.

The optical front end size was determined by the manufacturing capabilities that could be accessed in South Africa at present and the requirement to design for a micro-satellite payload. This limited the lenses and mirrors to spherical elements, with maximum diameters of about 300 mm.

The choice of particular detectors (linear detectors for the multispectral and panchromatic detectors, and area sensors for real time PAL video detectors and the hyperspectral detector) was determined by those component with which the MSMI consortium partners have previous experience in similar space imager products.

Since the MSMI is designed for use on a microsatellite or minisatellite, mass allowance, component volume and electrical power will be restricted for this payload when it is integrated with the satellite bus. The complete MSMI expected to weigh less than 60 kg, of which the hyperspectral subsystem comprises about 22 kg. For satellites where payload mass is severely restricted, an alternative solution is developed using the same components, but includes the multispectral line scan and continuous video detector with telescope and supporting electronics only. This solution is expected to weigh less than 40 kg.

The MSMI is designed as a payload for the ZASat series of South African microsatellites (see below). Based on the designs for like satellites built for clients of SunSpace and Information Systems (Pty) Ltd, certain assumptions (see Table 2) were made about the host satellite. In particular is it assumed that the host satellite will provide the imager attitude control, including forward motion control. For the line scan multispectral and panchromatic detectors, the imager should be kept nadir pointing (orbit synchronous rotation rate). In order to collect enough photons on the SWIR detectors of the hyperspectral sensor, forward motion compensation (FMC) is required to

increase the imager pitch rate by as much as 20 times the orbit synchronous rate.

Table 2. Host Bus Assumptions

Parameters	Value
Orbit(nominal)	660 km sun-synchronous
Forward Motion Compensation Capability	1 for multispectral Max. 20 for hyperspectral Infinite dwell for video
Micro satellite bus volume (launch)	ASAP5 (600x600x800mm)
Payload Power Budget	< 100W per orbit
Payload Mass Budget	< 50kg
Design lifetime	5 years

TECHNICAL SOLUTION

Block diagramme

The MSMI block diagramme is depicted in Figure 2. The camera includes the front end optics and refocus mechanism by which minor focus adjustments in orbit can be achieved if required. The focal plane electronics (FPE) include all the multispectral, panchromatic and continuous video detectors as well as the associated electronics close to the detectors. The hyperspectral optics and electronics is also included in the FPE of the block diagramme, but physically it is a separate unit adjacent to the telescope (see Figure 3).

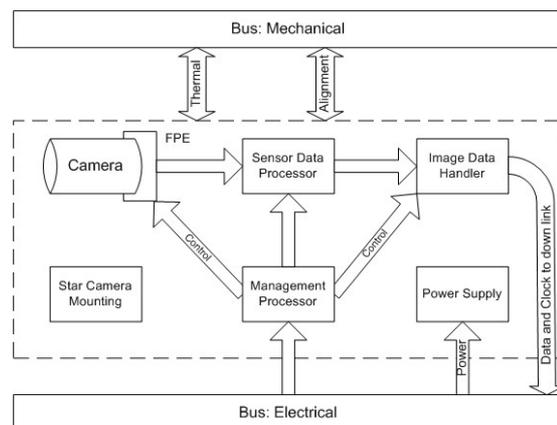


Figure 2. Block Diagram of the Imaging Payload.

The sensor data processor in the block diagramme can select any combination of data from the multispectral or hyperspectral bands for storage in the on board mass memory of the MSMI. Lossy and lossless compression

capability is for off-line processing of data once captured in the mass memory. The present configuration of mass storage unit (MMU) provides for simultaneous storage of 4 Gbyte of data for each multispectral channel and the panchromatic band, 8 Gbyte of hyperspectral data storage and 4 Gbyte for the matrix video detector output . The storage capacity of the MMU for the various spectral bands and ground sample distances are shown in Table 3 below.

Table 3. MMU Capacity, GSD and Swath at 660 km Altitude

Sensor	# of square scenes	GSD (m)	Swath (km)
Multispectral	50	4.6	27.6
Panchromatic	50	2.7	23.6
Hyperspectral	19 (containing all sampled spectral bands)	14.5	14.9
Video snapshot	1525	2.6	2.6 x 3.3

The download of the imager's data from the mass memory storage, is considered to be a satellite bus function. The imager data transmission rate is designed for downloading at a maximum of 200 Mbits/s via X-band.

Optical system

A single Catadioptric optical system is used since it offers a compact, light and robust system with good spectral performance, and with small and easily correctable vacuum focus shift. The optical system is mounted using iso-static techniques to avoid distortions due to satellite thermal variations, and will have to be thermally protected to minimize temperature gradients.

Figure 3 depicts the CAD drawing of the MSMI imager system. To the right is the carbon fibre structure containing the optical elements. The multispectral, panchromatic and video detectors are mounted in the central structure about one quarter distance from the bottom. The optics has a focal length of 1.72 m, folded into the telescope of physical length less than 800 mm.

The hyperspectral unit is the separate assembly to the left of the telescope in Figure 3 above. Light is reflected off a prism located near the focal plane of the multispectral detectors, onto the 40 mm x 40µm entry slit of the hyperspectral detector.

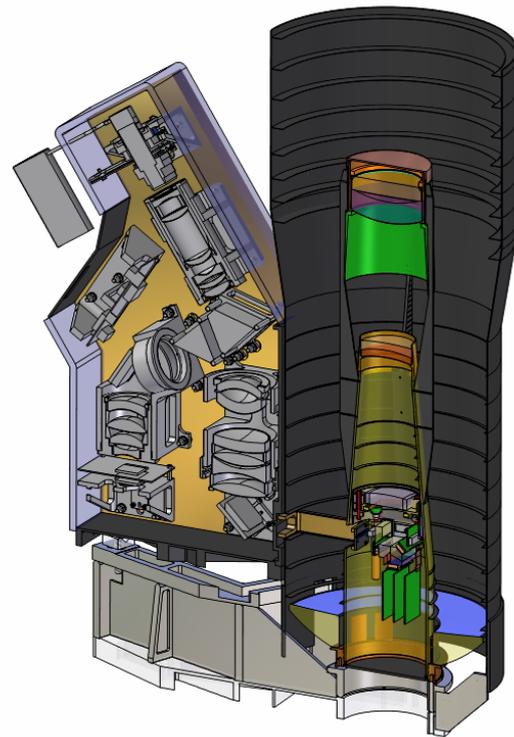


Figure 3. MSMI Optical System

Focal plane assembly

With the unique mechanical design of the focal plane, the various detectors are effectively located in the focal plane as depicted in Figure 4. The arrangement was made to maximize the use of the central part of the physical focal plane which is no more than 80 mm wide. During the line scan operational mode of the satellite, the instantaneous recordings of terrestrial "lines" will be separated by 3.2 km between multispectral and panchromatic detection and 5.3 km between panchromatic and hyperspectral detection.

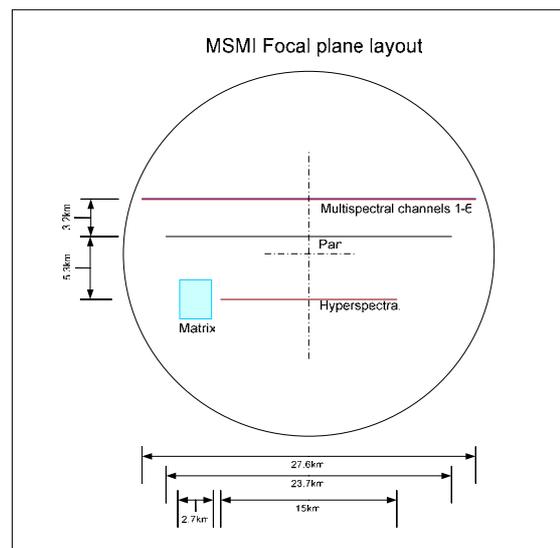


Figure 4: MSMI Focal Plane Layout

Across the scanning track, the various detectors have overlapping imaging strips as shown in Figure 5. The multispectral strip is the widest at 27.6 km swath. Within this strip the panchromatic swath of 23.7 km is fully contained and likewise the hyperspectral swath of 15 km. This arrangement will provide the unique feature of the MSMI, namely that overlays of combinations of multispectral, hyperspectral and panchromatic images, which were acquired virtually simultaneously, can be readily achieved by post processing.

The continuous matrix video detector's footprint also overlaps with both the multispectral and panchromatic sensors as shown in Figure 5. One of the main advantages of this arrangement is the bore sight motion detection can be achieved by means of real time processing, to provide information to the satellite attitude control system. It is envisaged that this can serve as valuable sensor information to assist forward motion compensation for the cases where it is required for the hyperspectral imaging modes.

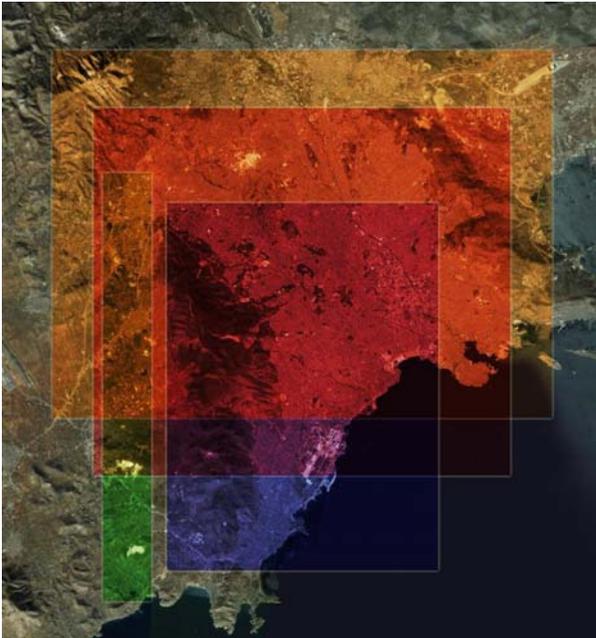


Figure 5: MSMI Ground Footprint for Different Ground Resolutions

MSMI ON ZASAT AND THE ARM CONSTELLATION

Having so far zoomed in on the details of the MSMI, the paper will now consider the South African approach towards a host satellite bus for the imager and the concept of the MSMI being used on the satellites of a consortium of remote sensing users.

ZASat Satellite Bus

ZASat in this context describes a satellite bus developed with funding from a unit of the South

African government. The ZASat microsatellite platform¹² has been designed as a multi-payload carrier that is eminently suitable for use by the MSMI imager. ZASat for MSMI will be based on the SunSpace180 platform (Fig. 6), an enhanced microsatellite bus developed subsequent to the SUNSAT programme. A satellite based on this bus has been qualified and is awaiting launch. Many of the subsystems have flight heritage from the SUNSAT bus.

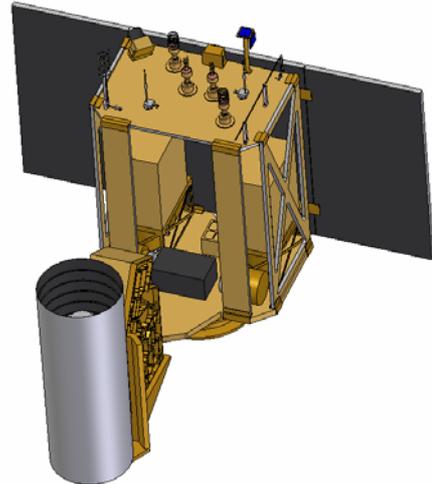


Figure 6: ZASat Based on the SunSpace-180 Bus and MSMI Payload Before Final Integration

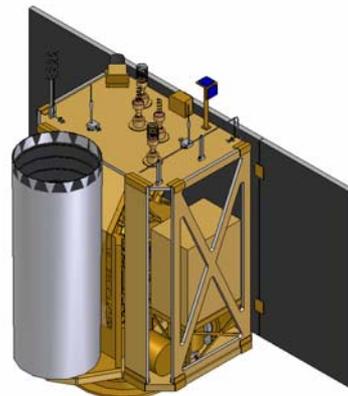


Figure 7: The ZASat After Integration with the MSMI

The characteristics and unique features of the SunSpace 180 bus can be summarized as:

- Designed for a Sun-synchronous circular orbit around 660 km altitude
- Designed for a 5 year orbit life
- Butane propulsion system to counter aerodynamic drag effects and maintain desired orbit
- GPS receiver and on-board orbit propagator to ensure 50 meter (1-sigma) orbit position accuracy
- Optional video joystick steering for manual target acquisition

- X-band Video transmission unit (VTU) with a data rate up to 105 Mbits/s
- Fully 3-axis reaction wheel stabilized satellite with magnetic momentum management
- Target off-pointing (roll), forward motion compensation and stereoscopic imaging capability
- Dual redundant onboard computers with EDAC protection and 32 Mbyte file system
- Triple redundant VHF/UHF telecommand and telemetry transmitters and receivers
- Triple redundant telecommand and dual redundant telemetry system
- Power system to ensure 70 to 100 Watt orbit average power to the imager payload at end of a 5 year life

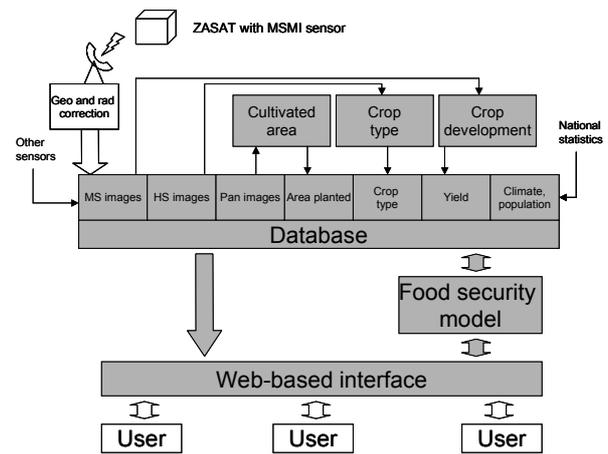


Figure 8. ZASat System Block Diagramme for Food Security

Orbit of a single ZASat for the Food Security Application and System to User Interface

The Food Security product does not require spatially contiguous coverage, either along track or between tracks. About 10% coverage of an administrative agricultural unit (100x100 km) within a 10 day period is perfectly adequate, provided it is well-distributed spatially, to provide the necessary statistics with acceptable accuracy. If a polar, sun-synchronous Low Earth Orbit (between 600 and 700 km altitude) for the MSMI host satellite and a $\pm 30^\circ$ off-nadir viewing by means of pointing of the microsatellite is assumed, the remote sensing data requirements for the food security application can be met with the particular MSMI multispectral and hyperspectral sensor swaths and spatial resolutions.

The food security model also accepts other satellite and in-situ sensor inputs as shown in Figure 8. Further input requirements for the model include long term weather forecasts, agricultural production statistics on a magisterial district basis, population statistics, household consumption survey data, etc.

The users of food security early warning information comprise mainly government officials responsible for food assurance and non governmental food relief organizations, which could be national or international. Because of the logistics and preparations required before interventions, these organizations need information on possible food shortfalls in quantitative terms a few months in advance. Information needs to be clearly and intuitively displayed, including maps, tabulations and trend maps³. This information needs to be accessible using standard interfaces to a web-based service, using standard modems and desktop computers without specialized software or user skills.

ARM Constellation

Apart from the single satellite applications, one should consider multi-satellite constellations, that would serve additional applications. The African Resource Management (ARM)¹³ constellation represents a novel utility concept, where African countries are getting together to deploy a constellation with African priorities in remote sensing. The MSMI technology is designed to form the back bone of the ARM constellation.

Five African countries have demonstrated access to space through a satellite programme by June 2005. This demonstration of commitment forms the basis of a collaborative programme where African countries can contribute to addressing its needs from an existing knowledge base, while developing capacity for growth. Furthermore, by operating their satellites in constellation, daily visits of targets in their own regions of interest is possible under certain orbit conditions.

One of the key motivators for frequent revisits is the fact that cloud cover obscures the ground for optical imagery. Daily coverage reduces the probability of a specific area being inaccessible to the imager for prolonged periods of time. Other applications that benefit from daily coverage include:

- Early detection of and rapid response to forest fires
- Other forms of disaster management
- Refugee monitoring and camp planning require up to date surveillance.

Daily coverage implies daily dissemination of satellite information. Daily high-resolution coverage supported by rapid dissemination of information is of crucial importance to several key resource management applications. Frequent cloud cover may mean that daily revisits are required in order to obtain a cloud free image of a given area within a reasonable period of time. This will speed up decision-making for applications such as:

- Infrastructure development
- Water resource management
- Agricultural resource management
- Renewable natural resources planning.

To have a daily revisit to any selected target area. The minimum number of satellites in a 600 km circular orbit constellation to satisfy this condition will also depend of the maximum roll off-pointing angle allowed for the imager. If a maximum distance to the ground target is chosen as 750 km (a 25% maximum reduction in nadir resolution), a roll off-pointing angle within the range -35° to $+35^\circ$ will be required. A solution will be to have a minimum of 3 satellites in the same orbital plane (with a 120° phasing angle between them) to ensure a daily revisit time to any target area [Mostert, Jacobs, Steyn and Milne: African Resource and Environmental Management Constellation, IAA, date]. Apart from the ZASat sponsored by the South African government, two other African countries are therefore required to allow daily remote sensor visits to any region of a participant.

A better alternative would be for 4 participating countries to have two launch opportunities for 2 satellites per launch (i.e. 4 satellites in total) in a 10h00-11h00 and 13h00-14h00 sun-synchronous orbit respectively. By a suitable relative configuration of the 2-satellite constellations a twice daily revisit can be obtained for most days, one visit before noon and another 2-4 hours later after noon. For the remainder of approximate 32 days per year only one visit per day will be occur. The great advantage of this arrangement is that only 4 satellites will give a twice daily revisit to any location on the globe more than 90% of the time with slightly different sun angle and shadowing conditions.

The satellite pairs and triplets will preferably be launched simultaneously to ensure the same orbital plane and initial orbit velocity. A limited amount of propellant will then be required to phase all the satellites appropriately in the circular orbit. The rest of the propellant will be used to do drag compensation and maintain the orbital phase of each satellite.

A number of meetings and workshops have occurred among African countries active in remote sensing satellites. Positive responses have resulted from these meetings, since the ARM system addresses core remote sensing needs of decision makers in Africa in a manner that is:

- retained for the priority use of African countries in the areas of natural resource management for agriculture and environmental management for tourism
- cost-effective for images and GIS compatible
- supportive of the retention of African talent in high-technology areas and,

- inspirational in terms of the cultivation of African role models in science, engineering and technology (SET) that inspire the larger SET African community in a sustainable way by setting examples of “can-do” attitudes.

PROGRESS TO DATE

The MSMI development commenced in July 2003 and will deliver its protoflight imager in June 2006. At this stage (June 2005) the following project milestones have been achieved:

- Detailed design of optical front end (telescope)
- Prototype electronics completed
- Detailed design of hyperspectral sensor
- Design of food security algorithms
- Surrogate data collected to test food security model
- System preliminary design review
- Opto-mechanical design completed
- Optical elements and mounting mechanisms manufactured
- Structural model completed and environmentally tested.

At present optical element assembly is taking place. Figure 9 shows the finite element analysis of the primary mirror under mechanical stress conditions. Figure 10 is a photo of the carbon fibre structure into which the lens elements are mounted. The mass equivalent element of the primary mirror can be seen at the bottom of the structure. Figure 11 is the structural model of the hyperspectral sensor unit. Finally, Figure 12 depicts several optical components and the alignment jig used for the assembly process that is currently (June 2005) occurring in the SunSpace clean room facilities.

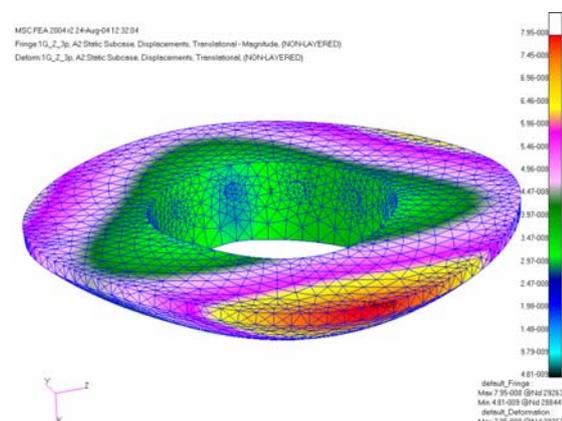


Figure 9: Primary Mirror Finite Element Deflection Analysis



Figure 10: Carbon Fibre Structure Containing Mirror/lens Elements



Figure 11: Structural Model of the Hyperspectral Sensor Unit

highly modular, customizable and reconfigurable system to emerge from the project. One such an example is the mass memory component that consists of identical memory units that in turn consist of identical memory banks. The memory units are combined on a higher level sub-system providing simultaneous storage of up to seven data streams. The sub-system is repeated again to provide for all the image channels that the MSMI requires. The units are completely interchangeable and intended for re-use in future systems.

The implementation of standard protocols and interfaces on the telecommand and telemetry level for each major component allowed MSMI team to build a test framework on an open-source script based language. The test framework is used by the product engineers from prototyping phase, through qualification to final unit testing of their components. Qualification and functional test procedures become highly automated and repeatable, thereby cutting the manpower effort during testing phases considerably. The modularity of the scripts and the hardware enabled the integration team of the project to build on reliable, repeatable and tested units, and in doing so reduced the testing effort during the integration phase extensively. The test framework will be carried right through to the integration of the satellite in which the MSMI will one day be incorporated.



Figure 12: Optical Assembly Jig (centre) with the Central Optical Element Structure (left), Outer Telescope Baffle (right) and Hyperspectral Unit (right front).

MODULARITY AND REDUCING TESTING DURING INTEGRATION

The imager system was designed with modularity as one of the goals in mind and using standardized interfaces between all major components of the imager system, for instance on their power, control, data transfer and even mechanical interfaces, enabled a

ADVANCED TECHNOLOGIES

The MSMI incorporates some very new and advanced technologies to fulfill its functions. For instance the onboard data processing unit is based on a high performance processor that is capable of running at high clock speeds while using low power. Complete support for the advanced commercial operating system

QNX is provided. Building on the operating system again greatly reduced the development time of the MSMI, providing the opportunity to focus on adding value to the system and its data. The embedded processors were radiation screened during the project execution and it passed with flying colors.

The method used to implement the customizable spectral filters for MSMI is also one of the main technologies developed during the project. A highly advanced commercially available optical process is used in manufacturing of the filters and then a proprietary process of integrating it with the detectors is carefully followed. Although this part of the MSMI project is one of the most expensive, it is also one of the most beneficial for the imager system.

Advanced techniques in modeling of the optical and opto-mechanical elements of the imager and their use in the thermal and structural analysis allowed for the design stage qualification and characterization of the imager rather than waiting for the physical models to be available for environmental testing. These modeling steps reduce risk very early on in the project.

CONCLUSION

The Multisensor Microsatellite (MSMI) imager represents a quantum leap in micro-satellite imaging performance. The unique combination of multispectral with hyperspectral sensors on the same compact optical system, sets a new benchmark for the imaging capability available to future micro-satellites.

The investment of the South African government in its own ZASat microsatellite programme to space qualify locally produced space technology will open up avenues for Africa and other developing countries to co-operate in the use of small satellites that specifically address locally relevant applications such as food security. At the same time it develops industrial and human resource capacity for advanced manufacturing and information and communications technology.

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On the Flemish side the technical contributions on the MSMI project are made by OIP for the hyperspectral sensor development and the Catholic University of Leuven (Faculty of Applied Bioscience and Engineering) for hyperspectral research in plant production systems modeling. Leuven is also responsible for the programme coordination from the Flemish side. The expertise for multi-spectral and video imagers is provided by Stellenbosch University and SunSpace, that is also the prime contractor for most of the electronics and mechanical development as well as systems integration and testing. The food security and agricultural applications expertise is contributed by two South African partners: Environmentek, a division of the CSIR, and the Agricultural Research Center.

APPENDIX A : MSMI TECHNICAL SPECIFICATIONS

MSMI Performance Specifications (preliminary Jan 2005)	
Item	MSMI Performance
Spatial Resolution	Linear detectors Panchromatic: (1 spectral band) 2.7m ground sample distance (GSD) at 660km altitude (IFOV: 4.068 urad) Multispectral: (6 spectral bands) 4.6m GSD at 660km altitude (IFOV: 6.97 urad) Hyper spectral: (>200 spectral bands) 14.5m GSD at 660km altitude (IFOV: 22.05 urad) Area detector Panchromatic: (1 spectral band) 2.6m ground sample distance (GSD) at 660km altitude (IFOV: 3.88 urad)
Spectral Resolution	Panchromatic Linear 480nm - 690nm Multispectral Linear 440-510nm (blue) 520-540nm (Xanthophyll) 520-590nm (green) 620-680nm (red) 690-730nm (red-edge) 840-890nm (near IR) Hyper spectral Linear 400-2350nm in 10nm bins (>200 spectral channels) Panchromatic Area 440-650nm
Ground Swath Width	Multispectral: FOV = 41.8 mrad (27.6 km cross track at 660km altitude) Panchromatic: FOV = 35.8 mrad (23.6 km cross track at 660km altitude) Hyper spectral: FOV = 22.5 mrad (14.9 km cross track at 660km altitude) Area sensor: FOV = 3.97 x 4.96 mrad (2.62 x 3.27 km at 660km altitude)
Data Acquisition Modes	Pushbroom imaging system for all bands
Operations	Snapshot and continuous area imaging in panchromatic band (matrix detector) Simultaneous imaging and storage of all bands Real-time PAL video system in panchromatic band Read-out of any one band at a time from memory Off-line data processing (for instance data compression) Optimisation of optical system using refocusing capability
Data Compression	Programmable lossy and lossless compression at various stages of the data flow.
Calibration	<5% relative
Design Life	>5 years achieved through redundancy and radiation mitigation strategies (hyperspectral sensor excl.)
Onboard Storage Capacity	4GB per band in standard configuration
Payload Mass	~60kg (telescope: 22 kg + hyper spectral sensor: 22 kg + electronics: 16 kg)
Power Consumption	< 150 W with full simultaneous system imaging < 40 W during data processing or retrieval Hyper spectral sensor needs 50W for cooling stage and 30W for imaging
Dimensions:	Telescope Size (include FEE): Dia = 300mm; length = 1050mm Hyper spectral sensor: 162mm x 345mm x 665mm Support Electronics: 2 units with dimensions of 240mm x 270mm x 400mm each
Telescope MTF	31% @ 72 lp/mm (on-axis) 17% @ 72 lp/mm (full field) 49% @ 42 lp/mm (on-axis) 35% @ 42 lp/mm (full field)
System MTF	>12% @ 42 lp/mm over the full field for all wavelengths >6% @ 72 lp/mm over the full field for the panchromatic band
Radiometric performance	Multispectral & Panchromatic bands: SNR>30 at 20% target reflectivity & FMC=1
Other features:	Reconfigurable memory configurations enabling failure redundancy and/or band capacity In flight upgradeable data processing algorithm capability Comprehensive telemetry feedback Bore-sight motion detection via area sensor Re-focus capability using area detector Inline ADCS and telemetry data (e.g. time stamping) insertion in image data Selective data storage for Hyper spectral sensor to reduce data volume

APPENDIX B: ZASat BLOCK DIAGRAMME

ZASat system layout and context diagram

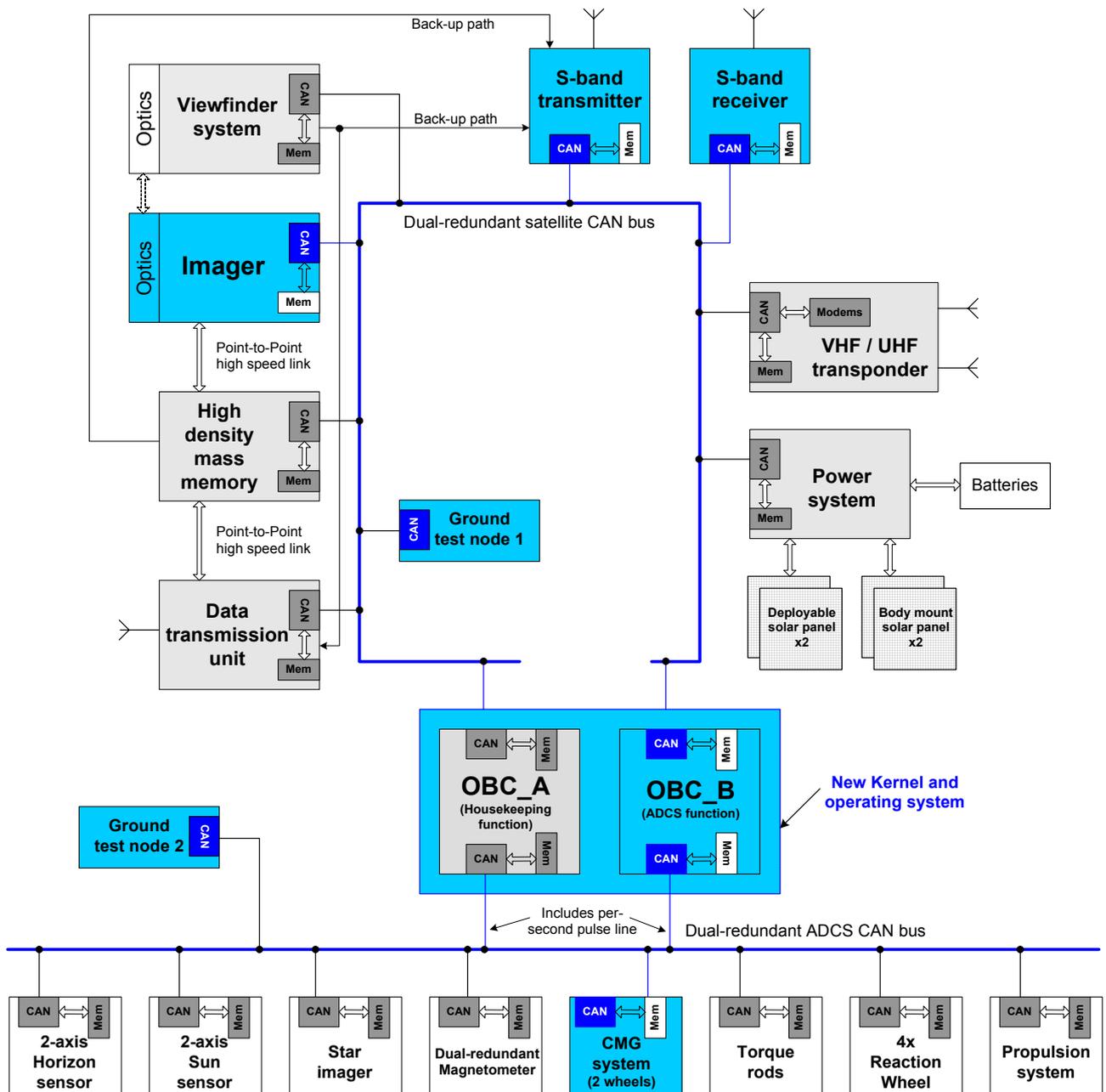


Figure 1 Block diagrammatic representation of ZASat layout

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