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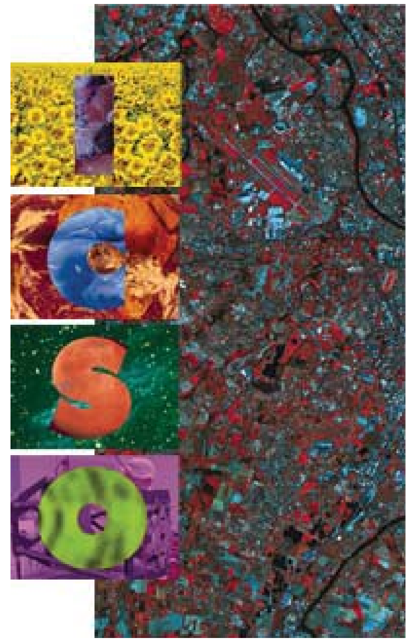

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THE ESA EARTH EXPLORER LAND SURFACE PROCESSES AND INTERACTIONS MISSION

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ABSTRACT : The European Space Agency (ESA) is defining candidate missions for Earth Observation. In the class of the Earth Explorer missions, dedicated to research and pre-operational demonstration, the Land Surface Processes and Interactions Mission (LSPIM) will acquire the accurate quantitative measurements needed to improve our understanding of the nature and evolution of biosphere-atmosphere interactions and to contribute significantly to a solution of the scaling problems for energy, water and carbon fluxes at the Earth's surface. The mission is intended to provide detailed observations of the surface of the Earth and to collect data related to ecosystem processes and radiation balance. It is also intended to address a range of issues important for environmental monitoring, renewable resources assessment and climate models. The mission involves a dedicated maneuvering satellite which provides multi-directional observations for systematic measurement of Land Surface BRDF (Bi-Directional Reflectance Distribution Function) of selected sites on Earth. The satellite carries an optical payload : PRISM (Processes Research by an Imaging Space Mission), a multispectral imager providing reasonably high spatial resolution images (50 m over 50 km swath) in the whole optical spectral domain (from 450 nm to 2.35 µm with a resolution close to 10 nm, and two thermal bands from 8.1 to 9.1 µm). This paper presents the results of the Phase A study awarded by ESA, led by ALCATEL Space Industries and concerning the design of LSPIM.

1. INTRODUCTION

This paper presents the results of a feasibility study awarded to ALCATEL SPACE INDUSTRIES by the European Space Agency (ESA) concerning the Land-Surface Processes and Interactions Mission (LSPIM). It briefly addresses the main mission requirements, the results of the mission analyses and the description of the satellite design. It is mainly focused on the design of the instrument.

The LSPIM satellite features an optical payload named PRISM (Processes Research by an Imaging Space Mission), a push broom multispectral imager providing reasonably high spatial resolution images (50 m over 50 km swath when looking at nadir) in most of the solar spectral domain (from 450 nm to 2.3 µm with a resolution close to 10 nm, and 2 thermal bands from 8.0 to 9.1 µm). This payload is implemented on a dedicated, intermediate class satellite.

The satellite provides access to any site on Earth within 3 days maximum. It is designed to provide in addition a directional sampling of the observed scenes, to contribute to the retrieval of the BRDF (Bi-directional Reflectance Distribution Function) of the surface of the sites of interest. The acquisition of such multidirectional, hyperspectral images on a series of pre-defined sites of major scientific interest, where ground and/or airborne measurements will be concurrently performed, will define the core of the LSPIM mission. The mission was one of the candidates for the ESA post ENVISAT « Earth Explorer » core missions. Though not retained as one of the 2 first missions to be launched, it was confirmed as a potential candidate for the next selection round.

2. THE MAIN SYSTEM REQUIREMENTS

Two types of missions are defined for the Land-Surface Processes and Interaction satellite : the principal mission provides systematic directional acquisition over a number of pre-selected sites, the exceptional mission provides on request acquisition on high priority sites, e.g. areas affected by natural disasters, using the spare capabilities of the system.

The nominal measurement mode is the directional (or BRDF) acquisition mode, which consists in acquiring images of the same site from a number of different directions, to provide directional sampling of the surface BRDF. Two temporal scales are involved in this acquisition : a sequence of 7 acquisitions, lasting about 400 seconds, and using different pitch angles during a single satellite pass, and a series of similar sequences from several satellite passes, using different roll angles, in a time frame of a few days. The required depointing range is typically ±35° in the cross-track (roll) direction, and ±58° in the along-track (pitch) direction.

For each angular acquisition, the instrument produces a set of spectral images of the sites, measured simultaneously in different wavelength regions. When looking at nadir, the image dimension is 50 km x 50 km, and the spatial sampling interval is 50 m. The images in all bands are spatially and spectrally co-registered for accurate exploitation of data. The instrument covers two main spectral regions. Region 1, from 0.45 to 2.35 µm covers Visible-Near InfraRed (VNIR) and the Short-Wave InfraRed (SWIR). In this region, the instrument operates as an imaging spectrometer with a spectral resolution of 10 nm to 15 nm. Region 2 covers the Thermal InfraRed (TIR), with two bands (8.0 -8.5 µm and 8.6-9.1 µm).The physical parameter directly measured by the instrument is the top of the atmosphere radiance of the selected ground sites. The images are calibrated so as to assign an absolute radiometric value to each of its picture elements. The main observation requirements are given in the table 1 :

DIRECTIONAL REQUIREMENTS	
Across-track depointing capability for 3 days access	± 35°
Directional sequence in BRDF acquisition mode	series of 7 elevation angles (from ground, nadir pass) : ± 70°, ± 60°, ± 45° or ± 30°, 0°
Hot spot sampling	Acquisition in the hot spot direction, compatibly with satellite agility capabilities
POINTING REQUIREMENTS	
Pointing error & Geolocation without ground control points	< 2.5 km
Pointing stability	Compatible with spatial registration requirements
SPATIAL REQUIREMENTS	
Swath width	50 km (at nadir)
Spatial sampling interval	50 m (at nadir)
Spatial registration within region 1 and region 2	< 0.2 spatial sampling interval
System Point Spread Function (PSF)	< 1.75 spatial sampling interval
SPECTRAL REQUIREMENTS	
Spectral range region 1	0.45-1.11 / 1.16-1.40 / 1.49-1.79 / 2.02-2.35 µm
Spectral sampling interval	< 15 nm, < 10 nm in range 680 ÷ 769 nm
Spectral registration	< 0.15 spectral sampling interval
Center line accuracy - Spectral width accuracy	0.5 to 1 nm - 0.5 nm
Spectral range in region 2	8.0-8.5 µm / 8.6-9.1 µm
RADIOMETRIC REQUIREMENTS	
Signal dynamic range in region 1	Specified Max. And Min. Radiance
Signal resolution in region 1	Effective 12 bits needed
Absolute radiometric accuracy in region 1	Goal : $< \sqrt{(\mathrm{NedL}^2 + (0.02 \text{ x Input radiance})^2)}$
Radiometric dynamic range in region 2	212-345 K

Radiometric resolution in region 2	NedT < 0.1 K
Absolute radiometric accuracy in region 2	1 K in nominal temperature range of the scenes
Polarisation sensitivity	< 0.03 (450 nm), < 0.1 (700 nm), < 0.3 (1 µm)

Table 1 : The main LSPIM observation requirements

3. THE MISSION PROFILE

The selected orbit is a 14 days cycle orbit at an altitude of 679 km at equator. This provides an ideal compromise between an access to any site on Earth within 3 days with a reasonable roll depointing of ±35°, and the high variability of the roll angle necessary to have access on the same site, thus improving the directional sampling on this site. The moderate altitude is also interesting for radiometric performance. The mission planning is optimized accounting for the observation requirements, the satellite resources (power, agility, on-board storage) and the downlink constraints. A single high latitude ground station is foreseen, with a limitation of about 3 downlinks per day for cost optimization. The figure 1 illustrates a typical scenario that was simulated, illustrating a possible repartition of reference sites, and materializing the orbital arc occupied by a directional (BRDF sequence).

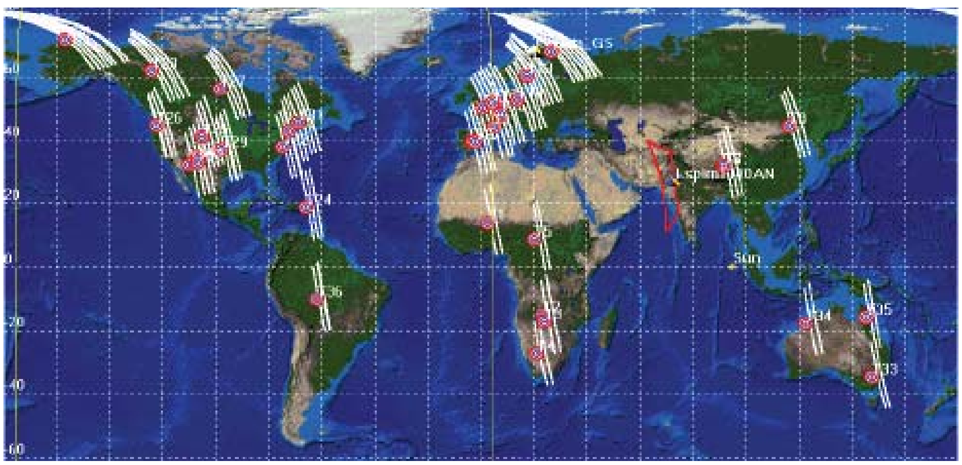

Figure 1 : An example of scenes distributions on a typical LSPIM mission scenario

The background programming of the satellite will be based on a 14 days cycle, with updating of the plan and uploading of commands every three days.

A typical orbital sequence will consist in a number of operations with transitions involving significant attitude changes of the satellite, as illustrated in the figure 2.The BRDF acquisition sequence allows the acquisition of 7 images and lasts about 450s. It involves both satellite maneuver (large angular range in pitch, line of sight control in roll, pitch and yaw), and a mirror depointing in the roll direction. Three such sequences per orbit can be handled at maximum by the satellite ; it is sized to acquire on average 2 such sequences. When the system is not in image acquisition mode, it will return to a Sun pointing mode, which allows battery charging. Once per week, when the satellite is at the south pole, it will perform region 1 radiometric calibration using diffusers, illuminated by

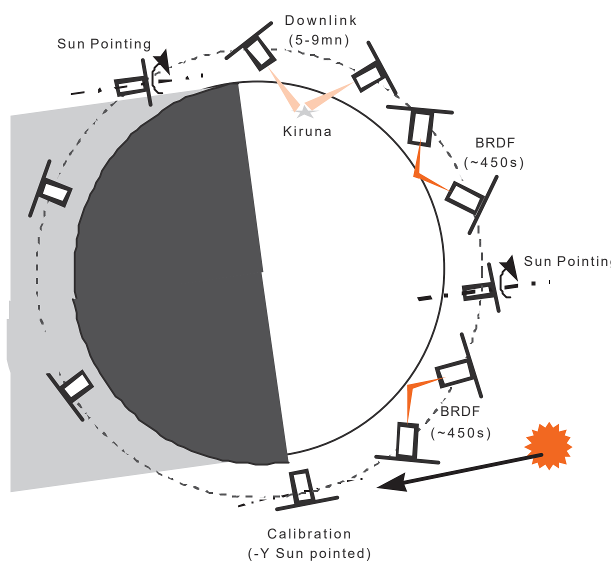

Figure 2 : Typical operations during an orbit with downlink

the Sun. During eclipse, images acquisition in the thermal infrared is possible. The downlink of the data is performed 3 times per day ; the satellite can perform a coarse pointing to the station to improve transmission.

4. THE LSPIM SATELLITE

An artist view of the satellite is shown in the figure 3. The satellite design is driven by a two main requirements : to provide the attitude agility required by the directional sampling, and to be compatible with medium to small class launchers. The overall system is furthermore a compromise between reasonable cost, acceptable risk and high level of performance.

The satellite is composed of two main modules : the payload module and the platform module. Both have hexagonal shape, which optimally fits the envisaged launchers fairing and leads to excellent inertia characteristics. One of the key subsystems of the satellite is the AOCS (Attitude and Orbit Control Subsystem), which provides both agility in the pitch direction and the accuracy required to dynamically control the line of sight in pitch, roll and yaw axes during image acquisition. This is possible thanks to an optimized skewed configuration of 4 reaction wheels (to produce high torques), use of high performance star-trackers and gyroscopes, and a satellite configuration with fixed solar arrays to minimize vibrations.

Though its architecture is fully optimized for the mission, the satellite benefits from a number of European on-going developments in the field of small satellites.

The maximum mass of the satellite is 788 Kg, including margins. Its maximum power consumption is 740 W.

The configuration is optimized to have low inertia moments for agility. It has been designed to be compatible with most of the medium and small launchers available on the market.

Figure 3 : Artist view of the LSPIM satellite

4. THE LSPIM IMAGING SPECTROMETER : PRISM

4.1. The Operating Principle and functional chains

The PRISM images in all the spectral bands are co-registered to a high accuracy so that an image acquisition of the same scene provides a set of so-called spectral images. In region 1, from 0.45 µm to 2.35 µm , PRISM is an hyperspectral imager, with a high spectral resolution (10 to 15 nm) and a high number of number of bands (up to 144 bands). In region 2, from 8.0 µm to 9.1 µm, PRISM is a multispectral imager providing 2 spectral bands.

Being a push-broom imager, the direction of the image normal to the satellite velocity is defined by the instrument field of view, whereas the direction along the direction of flight is defined by the duration of the image acquisition. A depointing mirror provides a ±35° accessibility in the direction across the satellite velocity. A common telescope collects the light from the useful spectral range onto an intermediate plane ; at that location, the optical path is separated within the field of view, in the direction of the velocity. The region 2 path is routed towards a dedicated focal plane, the region 1 path enters a spectrometer which disperses the light in the spectral direction, separates spectrally the VNIR and SWIR paths to direct them on 2D focal planes. At focal plane and analog chain level, the information is processed as follows. During each frame, i.e, during the elementary time corresponding to the sampling of 50 m on-ground, detectors are illuminated and the information collected is transferred towards the data processing chain. In region 2, each detector line corresponds to one of the two required spectral bands, the number of pixels (1000) defining the instantaneous swath.

In region 1, the VNIR and SWIR focal planes are two dimensional arrays, the larger dimension (1000 pixels) defining the instantaneous swath, the other dimension collecting the spectrally dispersed light. Such frame acquisition is repeated 1000 times to generate a set of 50 km x 50 km spectral images of the same scene (in nadir viewing case). Each frame is then processed and finally converted into digital counts that are stored in the solid state mass memory unit. At this level, the instrument transfers towards the mass memory all the accessible spectral bands : 57 spectral bands in VNIR, 85 bands in SWIR, 2 bands in TIR.

At mass memory level, the data are further processed until the next data down-link. Data are compressed using lossless compression algorithm, to reduce the size of the mass memory. The spectral bands can be selected (up to 60 bands in region 1 and 2 bands in region 2) in nominal BRDF acquisition mode, or kept in full spectral acquisition mode. Data are then formatted and encoded to be transmitted to the ground station using X Band communication.

After reception, the data are processed on ground with the following main steps. Data are decoded, uncompressed to generate raw data which are radiometrically and spectrally corrected, accounting for on-board calibration data transmitted with the image. The data are then geometrically calibrated, notably to provide geo-location projecting precisely the acquired images on a reference map.

4.2. Optical Architecture

The optical system is modular and involves a number of subassemblies, as illustrated in figure 4. The depointing mirror provides the double function of ensuring the roll depointing and the accessing of the front calibration sources.

The telescope covers the whole spectral range with a very high optical quality. The selected design is a TMA (Three Mirror Anastigmat which is presently well within the European manufacturing capability. Its low entrance diameter (100 mm) and reasonable f number (f/4) make it a very sound design, much insensitive to mechanical misalignments.

The region 2 relay optics is a fully refractive state-of-the-art system. It provides excellent optical performance (also including mechanical and thermal tolerancing), and the requested interfaces (dimension for accommodation constraints, cold exit pupil close to the focal plane for thermal reasons).

The spectrometer is the most challenging assembly of the optical system. The goal was to design a spectrometer as simple as possible while providing the required performance, to ensure its feasibility within a well controlled development effort. The design involves an Offner relay optics and curved lenses acting as image correction and dispersing elements. The structural concept selected for supporting lenses and mirrors will ensure high level performance.

The spectral separation between region 1 and region 2 is performed in-field at the telescope focal plane, using a slit/separation device that acts as the entrance slit of the spectrometer and reflects the TIR path.

The spectral separation between the VNIR and SWIR channels is performed by a dichroic plate that reflects the visible part of the spectrum and transmits the short wave infrared part. Since the spectral separation is located just before the focal planes, all the optical elements are common to both spectral domains thus strongly improve the image co-registration.

Both the telescope and the region 2 relay optics are diffraction limited. The spectrometer optical quality results from a system optimization between theoretical MTF (Modulation Transfer Function), spatial and spectral registration, and sensitivity to mechanical tolerancing.

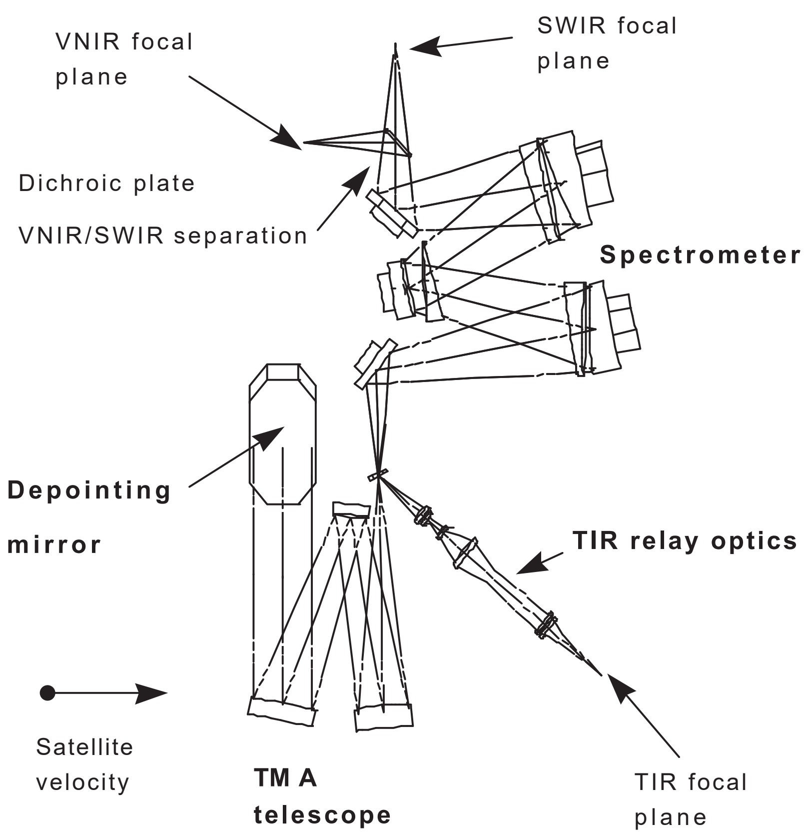

Figure 4 : PRISM Optical Architecture - The Earth is towards the reader.

4.3. PRISM electrical architecture

The detection chain involves 3 focal plane assemblies and their proximity electronics, which are physically accommodated on the optical bench.

The analog chain is physically located in the platform module and performs amplification, offset correction and digitization of the focal planes outputs. It is interfaced to the Mass Memory Unit using IEEE 1355 digital links.

The digital data handling chain mainly involves the 80 Gb Mass Memory Unit (MMU), which operates as a data storage and a processing unit, since it performs spectral band selection, data compression and formatting.

The command and control of the instrument is performed by the Instrument Control Unit (ICU), closely interfaced with the overall satellite controller, namely the Satellite Management Unit, via a 1553 bus. The ICU performs the instrument Telemetry acquisition and telecommand reception, the control of all the active equipment (thermal heaters, mechanisms, blackbodies, Peltier coolers).

A dedicated unit, the Cryocooler Control Unit (CCU) provides the power supply for the Stirling cycle cryocoolers used to cool the region 2 focal plane to 70K, and implements the regulation laws that minimize the microvibration of these devices. At last, the X band communication system downlinks the science data to the ground station at a 100 Mbps rate.

4.4. Focal Plane Assemblies

4.4.1.The VNIR focal plane

In visible and near infrared (VNIR), the focal plane will be a silicon, back-illuminated CCD. The selected technology and design will strongly benefits from the ESA MERIS (Medium Resoultion Imaging Spectrometer) CCD development. The main requirements for this CCD are given in the Table 2. The basic concept is a frame transfer 2 dimensional CCD. The larger dimension corresponds to the spatial direction (the field of view of the instrument), the smaller one to the direction of spectral dispersion of the spectrometer. For radiometric reasons, some spectral lines are summed at CCD level, so that 57 spectral lines are extracted among the 91 useful spectral pixels. The CCD topology involves two storage areas on each side of the sensitive area, each corresponding to half of the extracted spectral bands. This architecture presents the double advantage of limiting the so-called frame smearing effect, (detection of unwanted light during the frame transfer), and of providing dark pixel reference for each spectral line.

Parameter	Specification
Spectral range	0.45 to 1 µm
Number of useful lines	91
Number of spectral bands	57
Number of useful columns	1000
Pixel Dimension / Pitch (µm)	30 / 30
Mean dark current at BOL (pA)	< 0,05
MTF at Nyquist frequency (at 450 and 1000 nm)	0,5 / 0,45
Maximum data rate (MHz)	2,5
Stare time (ms)	7,4 to 10
Frame transfer time (µs)	< 70
Operating temperature (K)	293

Table 2 : The VNIR focal plane main requirements

4.3.2. The SWIR focal plane

The SWIR focal plane main requirements are given in the table 3. This detector is, like in VNIR, a 2 dimensional one. The spectral range led to the selection of HgCdTe technology, with the associated constraint of needing cooling to about 175 K. A trade-off was performed at system level between the radiometry and the operating temperature and 175 K was found to be a good compromise, within the capability of a cooling concept involving Peltier coolers and a 2 stage radiator. This concept gave origin to the use of a depointing mirror in the roll direction, to limit the variations of the thermal environment of the SWIR radiator.

Parameter	Specification
Spectral range	1 to 2.35 µm
Number of lines	105
Number of spectral bands	79 to 105
Number of useful columns	1000
Pixel Dimension / Pitch (µm)	30 / 30
MTF at Nyquist frequency	> 0,5
Quantum efficiency	> 0,5
Maximum data rate (MHz)	2,5
Stare time (ms)	7 to 10
Operating temperature (K)	> 175

Table 3 : The SWIR focal plane main requirements

4.3.3 The TIR focal plane

The main requirements of the TIR focal plane are given in the table 4. The detector material will be HgCdTe, cooled to 70K for radiometric reasons. In this spectral region, a single line is necessary for each of the 2 spectral bands. For cost saving and easier accommodation in the cryostat, the focal plane will be made of 2 lines, each corresponding to one of the required spectral bands. The spectral band definition is ensured by a filter in front of each line. One of the challenge is to make these lines close enough to allow an excellent co-registration, accounting for the satellite pointing stability. The physical separation between the lines will be less than 2.5 mm.

Parameter	Specification
Spectral range	8 to 8.5 µm 8.6 to 9.1 µm
Number of lines	2
Number of useful columns	1000
Pixel Dimension / Pitch (µm)	30 / 30
Max.Gap TIR 1 / TIR 2 lines (mm)	2.5
MTF at Nyquist frequency	> 0,5
Quantum efficiency	> 0,55
Maximum data rate (KHz)	400
Stare time (ms)	5 to 10
Operating temperature (K)	70

Table 4 : The TIR focal plane requirements.

4.4. Mechanical and Thermal Architecture

The external interfaces of the payload module are defined to combine the best utilisation of the volume under fairing with excellent inertial and mechanical properties. The module envelope fits within a 1.6 m larger dimension hexagon of 850 mm height. Its mass is 273 kg.

The internal accommodation is sketched in figure 7. The core element is the optical bench, which supports all the optics and the focal plane assemblies. The optical bench is iso-statically mounted on the interface baseplate. On the main frame are mounted the instrument and platform equipment with lower stability requirements: the radiators and active coolers for region 2, the calibration assembly, the antennas, the star trackers.

The thermal architecture provides an adequate thermal environment (temperature and stability) for the instrument equipment. These environment requirements are spanned over a wide range. The optics are controlled to about 20°C, with special gradient and stability requirements for the region 2 optics to guarantee the radiometric performance. This control is performed thanks to the very low dissipation within the optical thermal cavity, involving accurate temperature probes, adequate environment insulation and heater regulation. Stirling cycle active coolers are used to cool to 70 K the TIR detectors. They are mounted on the interface plate and associated to a dedicated radiator. The SWIR focal plane is cooled to 175 K using a Peltier cooler associated to a double stage radiator located on the coldest face. This solution brings the major advantage of avoiding a second set of Stirling cycle cryocoolers, thus avoiding strong interface issues (mass, vibrations, power, control) and improving the reliability in this region.

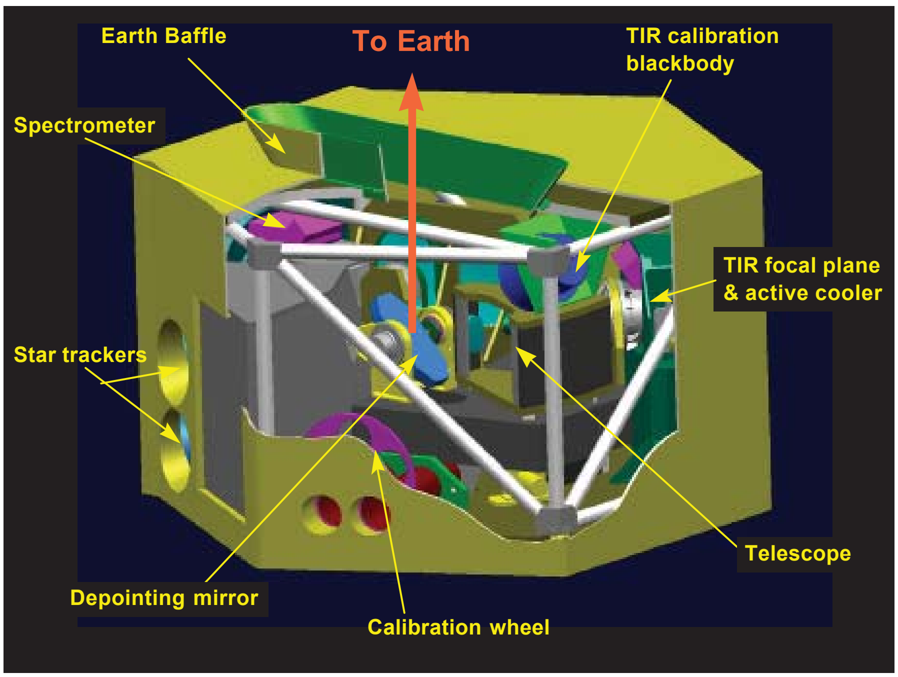

Figure 7 : Payload accommodation

4.5. PRISM Radiometric and Spectral Calibration

4.5.1 Radiometric and spectral calibration in region 1

Both the radiometric calibration and spectral calibration are performed involving a dedicated assembly that involves 2 sun diffusers as radiance calibration standards and a filter wheel. When the satellite passes over the South Pole, the sun light enters the calibration assembly through a filter wheel, before illuminating a sun diffuser.

For radiometric calibration, the filter wheel has three functions : 1/ provide a shutter for the offset characterization, 2/provide the adequate level of input sun irradiance to the diffuser to get calibration radiance, 3/ select one or the other of the two diffusers, one being routinely used, the other being used less often as a reference for monitoring possible degradations of the nominal diffuser.

For spectral calibration, the filter wheel introduces handles a rare earth transmission filter with well-known spectral lines used to characterize on board the wavelength associated to each pixel.

4.5.2 Radiometric Calibration in Region 2

The radiometric calibration in region 2 involves two assemblies.

The relative spatial calibration (equalization of the detectors response) is performed using 2 internal blackbodies that are accessed thanks to a deployable mirror inserted in the TIR relay optical path. These internal blackbodies provide a 2 point reference for an accurate calibration, performed before each image acquisition.

Absolute radiometric calibration is performed using a front end blackbody with a nominal temperature of 300 K, accessed using the depointing mirror. A multiple point absolute calibration is possible by varying this blackbody temperature.

5. CONCLUSION AND PERSPECTIVES

The study performed by ALCATEL SPACE INDUSTRIES and its partners for ESA has shown that the ambitious Land Surface Processes and Interactions Mission is feasible with low risk, thanks to the high level of maturity of the involved technologies.

The proposed satellite design largely benefits from on-going European developments for small class satellites. As regards performance, detailed simulations demonstrated notably the achievement of a high agility associated with high pointing stability.

Extensive analyses of radiometric, spectral and spatial performance of the payload were performed during this study showing compliance with the observation requirements, as summarized in table 1. The payload concept thus provides a high level of performance while remaining within a level of complexity compatible with a low risk, well controlled development.

The LSPIM would deliver products of high scientific interest, and implement concepts and technologies of major interest for future missions, notably operational hyperspectral or superspectral systems.

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