# The Engineering Model for the Multi Spectral Imager of the EarthCARE spacecraft

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The Multi-Spectral Imager (MSI) will be flown on board the EarthCARE spacecraft, under development by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). The fundamental objective of the EarthCARE mission is improving the understanding of the processes involving clouds, aerosols and radiation in the Earth's atmosphere. In addition to the MSI instrument, a Cloud Profiling Radar (CPR), an Atmospheric Lidar (ATLID), and a Broadband Radiometer (BBR) complete the payload of the EarthCARE satellite. By acquiring images of the clouds and aerosol distribution, the MSI instrument will provide important contextual information in support of the radar and lidar geophysical retrievals.

The MSI development philosophy is based on the early development of an Engineering Confidence Model (ECM) and the subsequent development of a Proto-flight Model, the model to be launched on-board the EarthCARE satellite. This paper provides an overview of the MSI instrument and its development approach. A description of the ECM and its verification program is also provided.

## Introduction

Predictions of future climate on planet Earth rely on global models all of which have limitations arising from deficiencies in the numerical representation of clouds, aerosols and radiative transfer in the atmosphere. The European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) are co-operating to develop the EarthCARE satellite to study clouds-aerosol-radiation interaction processes, to better understand the influence of these elements on weather and climate. The fundamental goals are to retrieve vertical profiles of clouds and aerosols properties and to simultaneously measure the radiative flux at the top of the atmosphere [1].

To meet the mission goals the EarthCARE satellite incorporates a complement of active and passive instruments [2]. A 94GHz Cloud Profiling Radar (CPR) procured by JAXA will provide information on the vertical structure of clouds as well as vertical velocity of cloud particles. The ATmospheric LIDar (ATLID) operating in the UV (354.8nm) will be employed to obtain information on the vertical distribution of aerosols and thin clouds. ATLID will also be used to determine the cloud top height. Measurements of the absolute upward short-wave (0.2µm-4.0µm) and long-wave (4.0µm-50µm) radiation will be performed with the Broad Band Radiometer (BBR). The Multi-Spectral Imager (MSI) will provide images of the horizontal distribution of clouds and aerosols that will be employed as contextual information for the processing of the data acquired by the other instruments. The MSI instrument is the subject of this paper.

EarthCARE will be launched into a polar sun-synchronous orbit at 400km height with a nominal descending node at 14:00 Mean Local Solar Time. Launch is foreseen in the second half of 2015.

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The MSI instrument will image of the Earth with a Ground Sampling Distance (GSD) of 500 m over a swath of 150 km [3]. Images will be acquired in 7 spectral channels centered at 0.67 µm, 0.865 µm, 1.65 µm, 2.21 µm, 8.8 µm, 10.8 µm and 12.0 µm. Absolute radiometric accuracy is required to be better than 10% for the visible-near-infrared channels and better than 1K for the thermal infrared channels. The Modulation Transfer Function (MTF) is specified to be better than 0.25 for all frequencies below Nyquist frequency. The required radiometric noise performance is shown in Table 1. To avoid the sun glint the MSI is tilted towards the anti-sun direction with respect to the sub-satellite point, so that the swath extends 115 km in the anti-sun direction and 35 km in the sun direction (Figure 1).

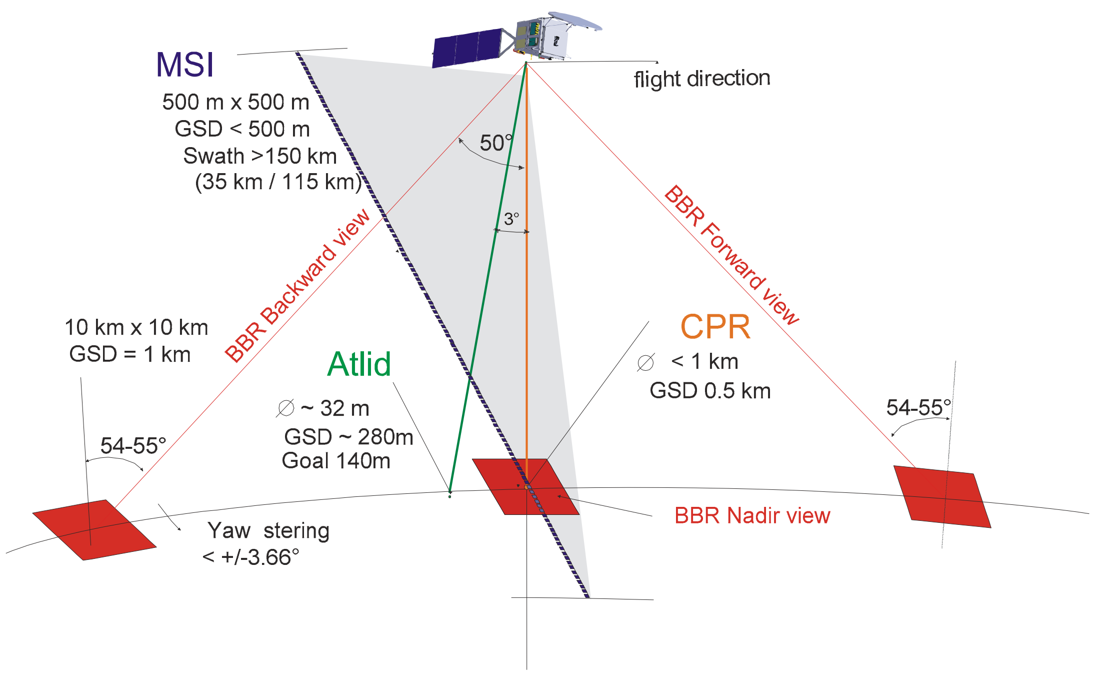


Figure 1. EarthCARE satellite observation concept showing the MSI swath with respect to the satellite ground track.

| Channel | λ (µm) | Δ λ FWHM | Low Scene: Low Scene Radiance W.m⁻².sr⁻¹. µm⁻¹ | Low Scene: SNR@Low | | High Scene: High Scene Radiance W.m⁻².sr⁻¹. µm⁻¹ | High Scene: SNR@High | |
|---|---|---|---|---|---|---|---|---|
| | | | | Goal | | | Threshold | |
| **Vis** | 0.67 | 20 nm | 30 | 75 | | 444.6 | 500 | |
| **NIR** | 0.865 | 20 nm | 17 | 65 | | 282.7 | 500 | |
| **SWIR-1** | 1.65 | 50 nm | 1.5 | 18 | | 67.9 | 250 | |
| **SWIR-2** | 2.21 | 0.1 µm | 0.5 | 21 | | 24.6 | 250 | |
| | | | **Low Scene Brightness Temperature** | **NEdT@Low** | | **High Scene Brightness Temperature** | **NEdT@High** | |
| | | | | **Threshold** | **Goal** | | **Threshold** | **Goal** |
| **TIR1** | 8.80 | 0.9 µm | 220 K | 0.8 K | 0.6 K | 293 K | 0.25 K | 0.10 K |
| **TIR2** | 10.80 | 0.9 µm | 220 K | 0.8 K | 0.7 K | 293 K | 0.25 K | 0.10 K |
| **TIR3** | 12.00 | 0.9 µm | 220 K | 0.8 K | 0.8 K | 293 K | 0.25 K | 0.10 K |

Table 1. MSI Radiometric performance requirements summary

**Instrument Design**

The MSI is a push broom imager designed to provide an across-track image line covering the entire swath (150km) at a constant rate while the motion of the satellite itself provides the along track scanning.

MSI consists of two separated cameras, one for the short wave channels, the so-called VNS camera, and another for the thermal infrared channels, the so-called TIR camera, mounted on a common optical bench. The cameras incorporate the optics, the calibration facilities and the focal plane assemblies including the optoelectronic detectors.

Mounted directly on the spacecraft panel is the Front End Electronics box (FEE), providing the power supply and control lines to the detectors located at the imaging planes of the cameras. The Instrument Control Unit (ICU), installed inside the satellite, realizes the interface to the spacecraft (Figure 2), including electrical interface, telecommand, telemetry interfaces, and overall instrument control.

In order to comply with its absolute radiometric requirements the MSI incorporates facilities to calibrate the instrument response in-flight. The VNS channels are calibrated using a solar light diffuser and the thermal infrared channels are calibrated with a black body whose temperature is accurately monitored.

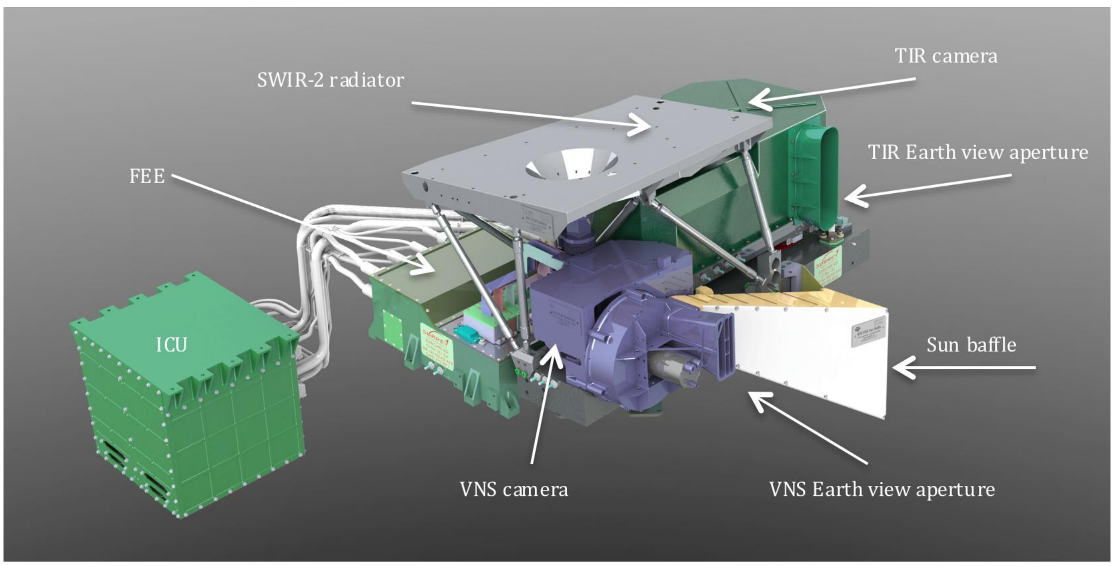


Figure 2. 3D CAD model of the MSI

***VNS Camera***

There are two apertures at the front of the VNS camera (Figure 2), one dedicated to the VIS (0.67 µm), NIR (0.865 µm) and SWIR-1 (1.65 µm) channels, while a larger aperture collects the weaker light coming from the Earth at the SWIR-2 wavelength (2.21 µm).

Figure 3 shows the disposition of the optical train within the VNS camera. Light collected in the VIS-NIR-SWIR-1 aperture is passed through a set of dichroics and filters to separate the beam into the three channels. The scene in all four channels is imaged with refractive optics onto the detectors at a focal length of 22.2 mm. The orbital height, the ground sampling requirements and the size of the detector photosites determine the required focal length of the imaging system. In addition the signal to noise requirements define the optical aperture. For VIS, NIR and SWIR-1 channels the diameter of the entrance pupil is 4.85mm corresponding to a numerical aperture of f/4.58. The aperture for the SWIR-2 channel is larger, 10.47 mm leading to a f/2.1 numerical aperture.

The detector packages are installed at the focal planes. Each package consists of a thick film hybrid circuit with a centered linear photodiode array and two readout integrated circuits (corresponding to odd/even photosites) encapsulated in a metal can package. Silicon photodiodes are employed for the VIS and NIR channels, while InGaAs photodiodes are used for SWIR-1 and SWIR-2. Each array consists of 512 photosites of 25μm x 25μm active area. Figure 4 shows a view of a detector and readout integrated circuits in its metal can package.

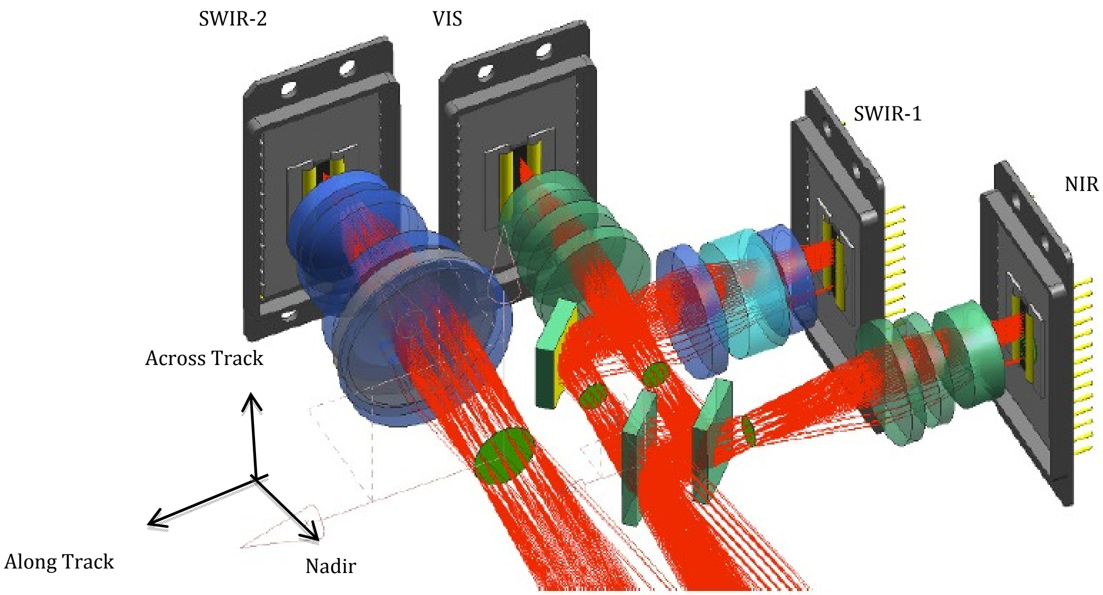


Figure 3. VNS camera ray tracing from aperture to imaging plane.

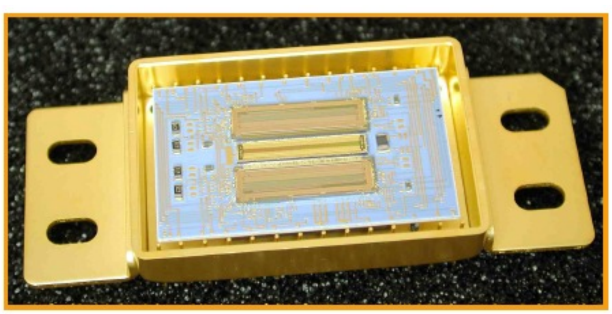

Figure 4. View of a 512 detector package showing the photodiode array and the two readout integrated circuits (manufactured by Xenics, Belgium).

VIS, NIR and SWIR-1 detectors are operated at room temperature. The SWIR-2 detector however, will be operated at 235K to reduce thermal noise. In order to reach the required operating temperature the SWIR-2 detector package is thermally coupled to a large passive radiator (Figure 1) via the so-called cold finger. The radiator panel, with an effective radiating surface of 0.175 $m^2$, is designed to reach a temperature well below the target. A dedicated active thermal control circuit operated from the ICU stabilizes the temperature of the detector at 235K.

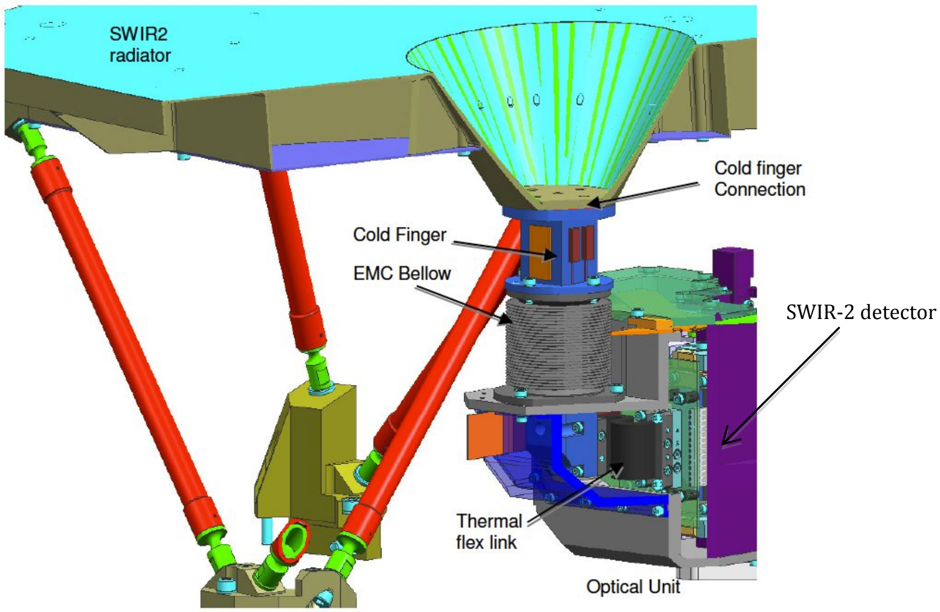


Figure 5. SWIR-2 detector thermal connection to the SWIR-2 radiator.

The VNS response will be regularly calibrated in flight employing the light from the Sun and a pair of Quasi Volume Diffusers (QVDs), one for the VIS/NIR/SWIR-1 aperture and one for the SWIR-2 aperture [4]. When the satellite flies over the South Polar Region the Sun will illuminate the diffuser through a Sun aperture. The diffuser, mounted on a rotating carousel will then be inserted in the optical path allowing recording of the instrument response to the Sunlight passed through the diffuser. In order to compensate for possible degradation of the QVD, two identical element sets are installed in the instrument so that one diffuser pair is employed up to once per orbit and the other much less frequently. Comparison of the instrument responses when using the different diffusers will allow any degradation effect to be monitored. The diffuser carousel will also allow closing of the instrument aperture to perform a zero illumination calibration, so-called dark calibration, necessary to correct the offset response of the instrument.

***TIR Camera***

Co-registered images in the thermal infrared will be acquired by the TIR camera in three spectral bands centered at 8.8 µm (TIR 1), 10.8 µm (TIR 2) and 12.00 µm (TIR 3), with a spectral bandwidth of 0.9 µm. A Time-Delay Integration (TDI) technique is employed in the TIR camera to reduce the noise contribution to the signal.

The optical layout of the TIR camera is shown in Figure 6. A mirror, known as the calibration mirror, on a rotating mechanism allows the input to the instrument to be selected from Earth view, space view or the internal black-body. The imaging system consists of two stages. In the first stage, an image of the scene is formed at a relatively long focal length by a simple lens system. The beam is then split by two dichroic beam-splitters located near the large primary image. Optical filters in the three separated beams further define the required TIR spectral response functions. The three beams, folded by mirrors onto parallel paths, are then re-imaged onto the single two dimensional detector array with a substantial de-magnification [5].

The detector array has 384 x 288 photosites on a 35 µm pitch (Figure 7). Different areas of the array are used to image the entire swath of each of the three channels. The Earth scene is imaged on the detectors with a focal length of 31 mm, the along track aperture is 30 mm wide corresponding to a numerical aperture of 1.0. Each spectral band uses 355 pixels across track and 20 pixels along track to image the 150km swath. As the satellite overflies the scene, the detector is sampled at a relatively high rate. A number of detector readouts are averaged to reduce noise. In this way an equivalent long integration time can be attained without compromising the linearity of the detector response due to self heating. The over-sampled image lines are further integrated whilst compensating for the shift of the scene due to the satellite orbital motion by use of the TDI, so that radiometric noise is further reduced.

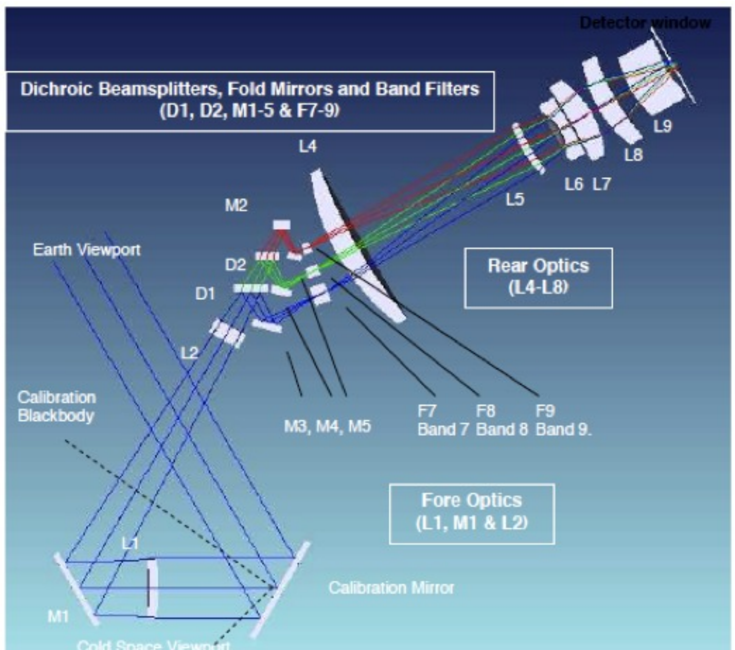


Figure 6. Optical layout of the TIR camera

The usage of microbolometers allows the radiometric requirements to be met without the need to incorporate a detector cooling system. However the signal generated by the microbolometers in response to the Earth signal contains a component originating from the thermal background of the instrument itself. In order to remove this temperature dependent background, a specific part of the instrument structure is imaged on certain regions of the microbolometer array not used for scene imaging known as reference detector areas, as shown in Figure 7. The data acquired in the reference detector areas is used to remove the instrument thermal background from the imaged Earth scene.

Absolute calibration of the TIR optical unit is performed in-flight by observing cold space and an internal warm black-body calibration target [4]. The instrument incorporates a specific aperture to acquire the signal of dark cold space. Inside the TIR camera a rotatable mirror allows selection between space view, black body view and normal Earth scene view. If the space view is selected, the radiation coming from deep space is directed into the imaging optical path of the instrument. Similarly the mirror may be used to select a view of the internal warm black-body which is made of black anodized aluminium and its temperature is accurately monitored with platinum resistance thermometers. In order to reduce as much as possible the data discontinuity due to calibration, TIR and VNS calibration will be performed almost simultaneously when the satellite is flying over the South Polar Region. A number of acquisitions will be performed in order to obtain a statistical ensemble so that calibration parameters can be calculated with as low an error as possible.

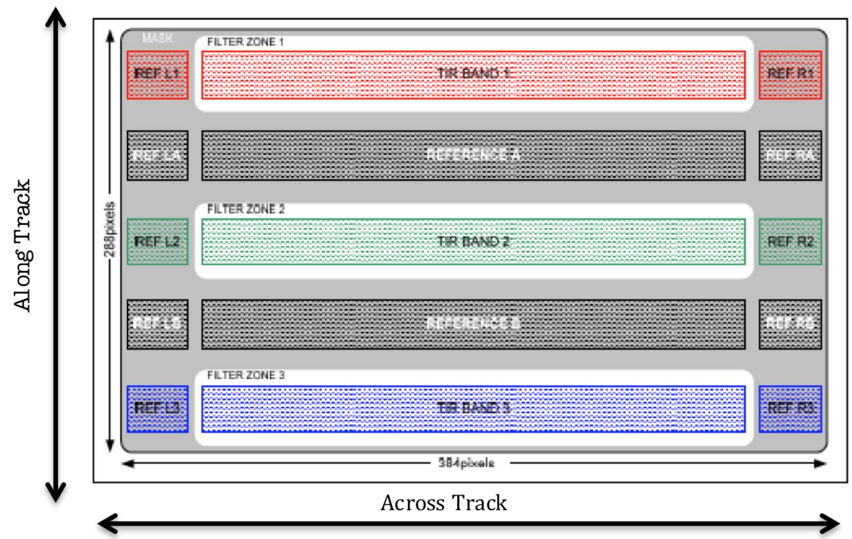


Figure 7. Distribution of microbolometer array photosites at the TIR camera focal plane

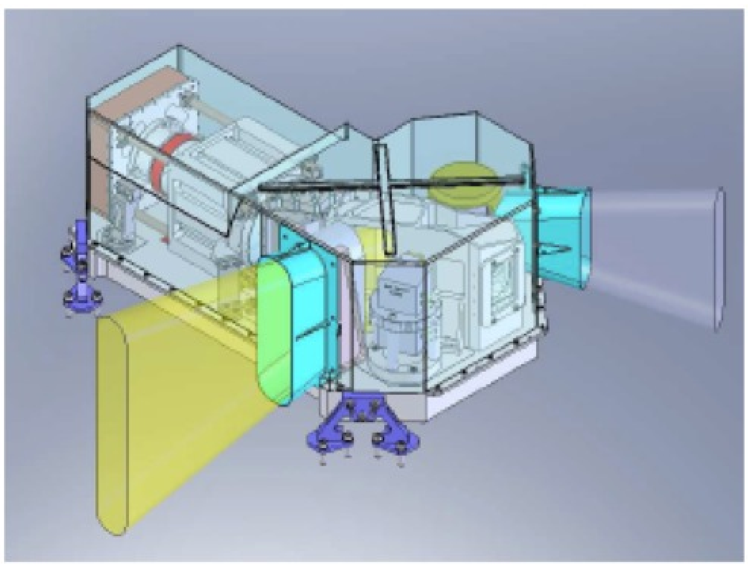

Figure 8. TIR camera

Analog image signals generated by the detectors of both cameras are converted to digital (14 bits) in the Front End Electronics unit. This unit is mounted on the satellite panel close to the Optical Bench Module. It also provides power lines and timing signals to the detectors. Image lines are acquired at a higher rate (oversampling) than required by the 500 m ground sampling distance. Oversampled image lines are co-added in the FEE to reduce readout noise. TDI processing of the TIR camera image lines is also performed in the FEE according to algorithms hardwired into a FPGA but with some freedom for adjustment when the instrument is in-flight. The digitized image data are packetized and delivered to the Instrument Control Unit. At the ICU the data are further packetized with other instrument telemetry and sent to the Mass Memory and Formatting Unit for relay to ground at the next suitable contact with the ground station.

### Instrument development

The development of the MSI instrument is based on a Proto-Flight Model (PFM) approach. Qualification is attained on the same model of the instrument that will be launched into space by subjecting the instrument during mechanical and thermal environmental testing to full qualification levels for a reduced duration (acceptance duration) so that materials fatigue is limited. The PFM approach differs from the classical approach in which qualification is attained in a non-flying model of the instrument, the qualification model.

However, in order to de-risk the development of the flight instrument a number of additional models have been developed. The Structural Model (SM, see Figure 9) was built as a structurally representative model of the PFM that allowed demonstration that the mechanical interface of the instrument was able to sustain the dynamical loads expected during launch.

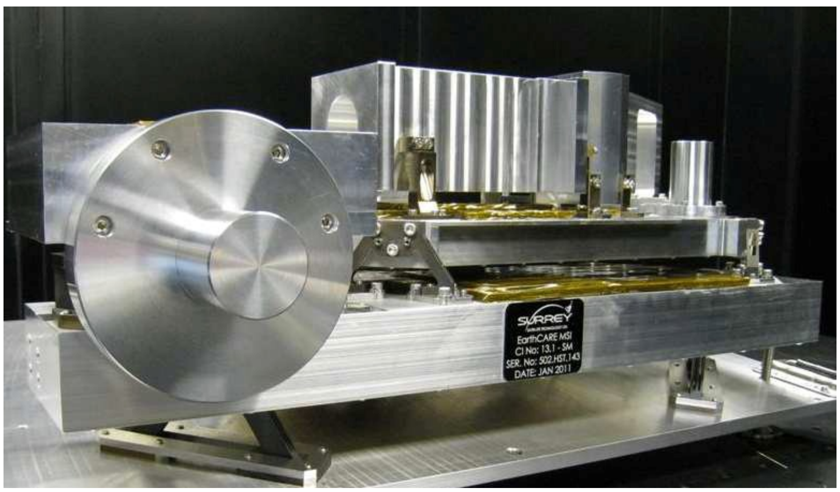

Figure 9. Front view of the MSI Structural Model

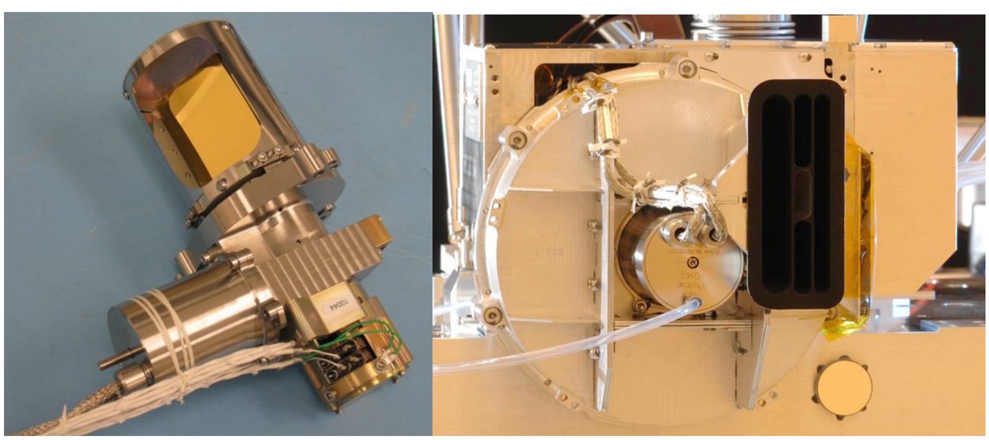
Figure 10. Calibration mechanism assembly Life Test Model (left: TIR camera, right: VNS camera)

Calibrating the instrument every orbit in-flight as described above requires high reliability mechanisms to deploy or to point to the calibration targets. In front of the VNS camera a calibration drum has to be rotated to introduce the Quasi-Volume Diffuser in the optical path. Within the TIR camera a rotatable mirror allows selecting the input radiance between Earth, Space or Black-Body views. These mechanisms will be activated a considerable number of times along the mission lifetime. In order to demonstrate the suitability of their design, Life Test Models (LTMs, see Figure 10) have been developed for each mechanism. That of the VNS camera calibration mechanism was successfully operated for a total of 56,000 cycles of orbital calibration and 560 cycles of monthly calibration. Furthermore the assembly was subjected to vibration qualification levels and thermal vacuum cycling. The Life Test Model for the TIR camera calibration mirror assembly has been subjected to qualification vibration levels and thermal vacuum cycling. The assembly was successfully operated for more than 60,000 cycles.

The purpose of the Engineering Confidence Model is to de-risk the development of the instrument. The ECM is intended to validate the overall instrument concept prior to proceeding with the Proto-Flight Model. It consists of an ECM TIR camera (Figure 11) and an ECM VNS camera (Figure 12). It also incorporates the Optical Bench Module and an Elegant Breadboard (EBB) for the Front End Electronics. The VNS ECM camera does not include the NIR and SWIR-2 channels. Both cameras will be subjected separately to functional, performance and vibration testing. Both will also be calibrated in a dry-run of the calibration campaign which will subsequently be applied to the flight cameras. Following the completion of the test campaign of the separated cameras they will be integrated into the MSI ECM. Testing at integrated level will include functional, alignment and performance checks. Furthermore, the integrated ECM will be subjected to shock, vibration and Thermal Vacuum testing. At the end of the ECM program the overall instrument concept will have been verified paving the way for the manufacturing and qualification of the PFM.

Testing of the ECM cameras have been started and will continue through the third quarter of 2012 with the testing of the integrated MSI ECM being completed by the end of 2012. The test results will be reviewed in the frame of the instrument Critical Design Review in 2013.

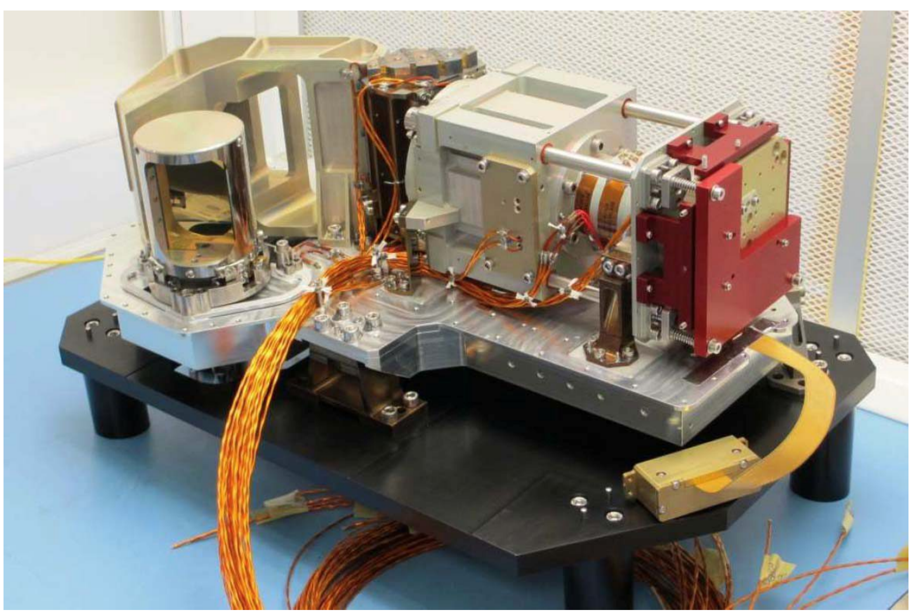

Figure 11. TIR ECM camera

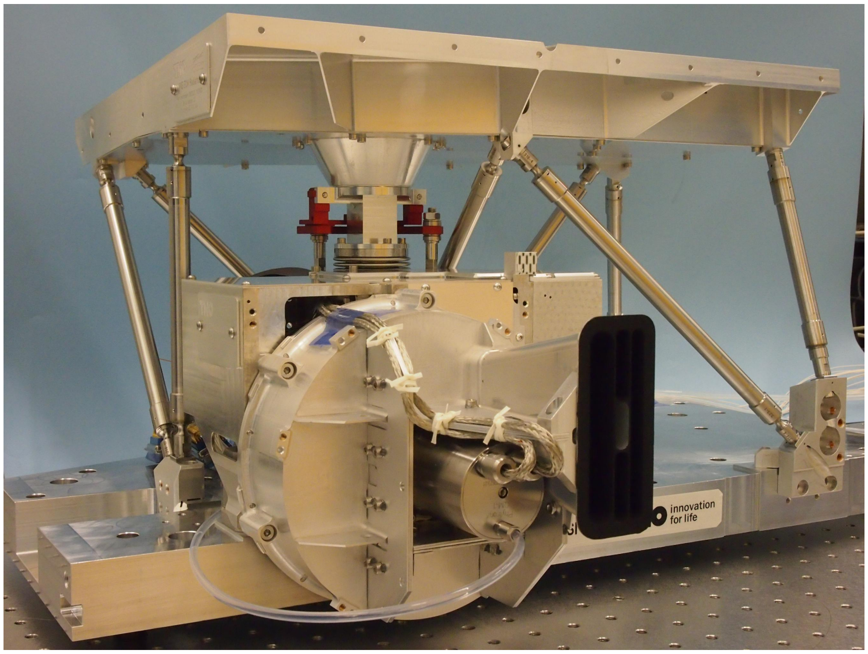


Figure 12. VNS ECM camera. Sun baffle not assembled.

**Conclusion**

A description of the MSI instrument and its development strategy has been provided in this paper. In particular the Engineering Confidence Model (ECM) has been described, including a summary of its verification program that will continue during the coming months, paving the way for the construction of the flight model along 2013.

**Acknowledgements**

The MSI instrument is being developed by Surrey Satellite Technology Ltd. (UK) under contract to Astrium GmbH (Germany). The VNS camera is developed by TNO (The Netherlands) under contract to SSTL. The EarthCARE satellite is being developed by Astrium GmbH under contract to the European Space Agency, responsible for the implementation of the overall EarthCARE Mission, including launcher facilities and ground segment.

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