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Overview of the EarthCARE Multi-Spectral Imager and Results from the Development of the MSI Engineering Model

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***Abstract*—The EarthCARE satellite mission objective is the observation of clouds and aerosols from low Earth orbit. The key spatial context providing instrument within the payload suite of four instruments is the Multi-Spectral Imager (MSI). The MSI is intended to provide information on the horizontal variability of the atmospheric conditions and to identify e.g. cloud type, textures, and temperature. It will form Earth images at 500m ground sample distance (GSD) over a swath width of 150km; it will image Earth in seven spectral bands: one visible, one near-IR (NIR), two short-wave IR (SWIR) and three thermal IR (TIR). The instrument therefore comprises four key parts:**

- **The Visible-NIR-SWIR (VNS) optical unit radiometrically calibrated using a sun illuminated quasi-volume diffuser and shutter system,**
- **The thermal IR (TIR) optical unit radiometrically calibrated using cold space and an internal blackbody,**
- **Front-end electronics (FEE) which performs the readout and digitisation of the images recorded in each of the seven spectral bands**
- **The MSI instrument control unit (ICU) of MSI that operates, controls and powers the**

The MSI development philosophy is based on the early development of an Engineering Confidence Model (ECM) and a subsequent development of a Proto-flight Model, the model to be launched on-board the EarthCARE satellite. Within the ECM development phase qualification and life tests have already been performed on the mechanisms used within the TIR and VNS, qualification of the TIR blackbody and qualification of the VNS detectors and TIR detector.

This paper provides an overview of the MSI instrument design and further details both the VNS and TIR. The achieved performance from subassembly qualification and life tests are presented together with the status of the TIR ECM and VNS ECM test campaigns that are to be completed prior to integration into the MSI Engineering Model.

***Index Terms*—EarthCARE MSI, EarthCARE, Multispectral, Imager, VNS, TIR, ECM.**

I. Introduction

The EarthCARE Multispectral Imager is a radiometric imager that is intended to remotely determine cloud cover and cloud top surface temperature. The detailed design concepts have been reported at an earlier stage [1].

This pushbroom radiometer employs 5 detectors working across 7 spectral bands, from visible through to long wave thermal infrared. These spectral bands are handled by two separate optical units, named the VNS and the TIR. The EarthCARE satellite platform will fly in a sun-synchronous low earth orbit, giving rise to a clear operational distinction between dayside and eclipse Earth observation periods [2].

The instrument is comprised of two major modules: the Optical Bench Module (OBM) and the Instrument Control Unit. The two cameras mentioned are sited within the OBM. The weight of the flight model of the OBM is estimated to be no more than 44.5 kg and the ICU is estimated to be just less than 10 kg. The full instrument will come in around 56 kg.

The instrument configuration is shown in Fig. I-1. The OBM is located on the exterior, anti-sun side of the EarthCARE satellite platform. The ICU is mounted on the interior of the platform, on the same anti-sun panel.

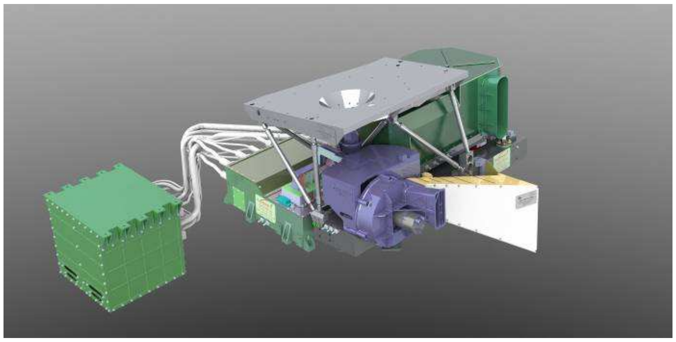


Fig. I-1 3D rendered model of the MSI

The MSI instrument development philosophy is a hybrid of the more standard Engineering Qualification Model (EQM) + Flight Model and the Proto-Flight Model (PFM) approaches. The objective is to design and manufacture a complex, advanced technology instrument for flight with the minimum possible risk, yet achieve a challenging set of schedule and cost targets. At the same time, the programme must rise to meet a demanding set of technical constraints. The result has been an early development of a product de-risking model, termed the Engineering Confidence Model, prior to the development of the Proto-flight Model for the mission. The key to the ECM is that only critical items are qualified, rather than the whole model. The overarching development philosophy is illustrated in Fig. I-2.

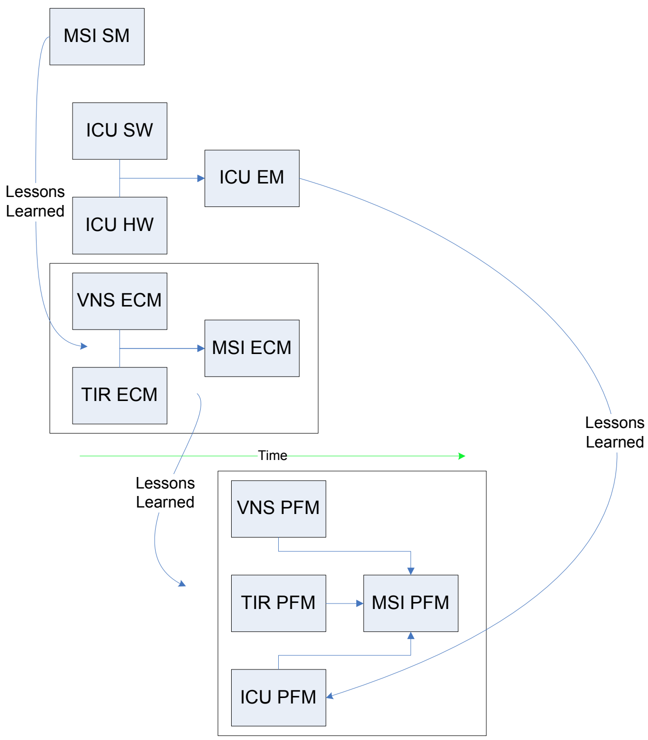


Fig. I-2 Schematic of development philosophy

A structural model (SM), see Fig. I-3, and an ICU engineering model (EM) form a part of the development programme. These allow for the major mechanical interfaces and software/hardware interfaces to be de-risked separately.

We note that neither the TIR nor VNS are passive camera systems. They both make use of mechanisms to enable camera calibration; these assemblies require qualification and life testing. Other critical components of the optical units are also qualified within the ECM development phase, specifically the detectors, and in the case of the TIR, the on-board blackbody calibration reference.

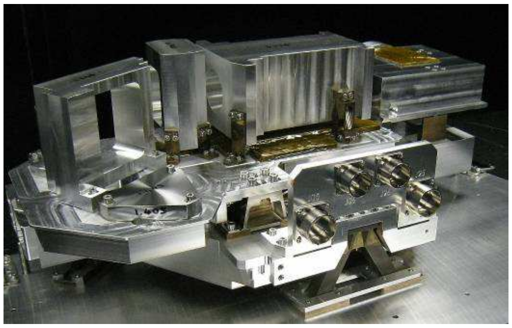


Fig. I-3 MSI Structural Model representing the OBM

II. VNS Optical Unit

A. VNS Driving Requirements and Constraints

The VNS shall provide co-registered images of four spectral channels. The required spectral bands are detailed in TABLE I. The other main requirements are a swath width of 150km, ground sampling distance of 500m, MTF larger than 0.25, polarization sensitivity below 2.5% and a radiometric accuracy better than 10% absolute and 1% relative between the channels.

The requirements are coupled with the constraints of a large range for the spacecraft orbit altitude and a demanding temperature environment.

TABLE I. VNS Spectral Bands

VNS channel	Central wavelength [nm]	Spectral width [nm]
Visible (VIS)	670	20
Near infrared (NIR)	865	20
Short Wave Infrared 1 (SWIR-1)	1650	50
Short Wave Infrared 2 (SWIR-2)	2210	100

The combination of demanding requirements and constraints result in a challenging opto-mechanical design with strict constraints on temperature stability, mechanical alignment and mechanical stability [3].

B. VNS Design

The VNS consist of the following three assemblies, which are directly mounted on the MSI Optical Bench:

- VNS Camera with integrated VNS Calibration Mechanism
- VNS SWIR-2 radiator
- VNS Sun Calibration Baffle

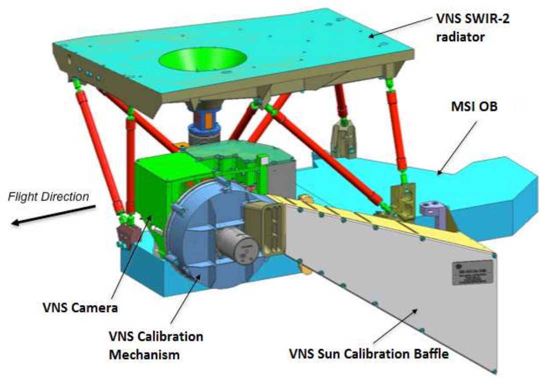


Fig. II-1 3D CAD model of the VNS

The VNS has two separate apertures (Fig. II-2), one 4.85mm diameter aperture for the VIS, NIR and SWIR-1 channels, and a second 10.47mm diameter aperture for the SWIR-2 channel. The larger aperture for the SWIR-2 channel compensates for the weaker light levels coming from the earth. The light collected through the VIS/NIR/SWIR1 aperture is separated in different spectral regions using a set of dichroics.

The scene of the four channels is imaged on linear detector arrays using refractive telescopes. Inside of the telescopes a spectral band filter ensures the required wavelength range. The focal length (22.2mm) of the telescopes is based on the orbit height, ground sampling distance requirement and the 25µm detector pixel pitch.

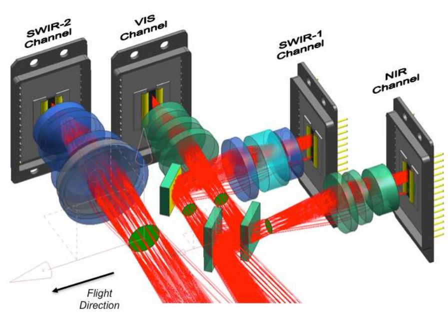


Fig. II-2: VNS camera optical configuration

The four detector arrays are developed and manufactured by Xenics (Leuven, Belgium). The detector packages consist of a thick film hybrid circuit with a centered 512 pixel linear photodiode array and two readout integrated circuits (corresponding to odd/even photosites). The VIS and NIR channel detectors employ silicon photodiodes, while the SWIR channels employ InGaAs photodiodes.

The in-orbit operating temperature of the VIS/NIR and SWIR-1 detectors are 300K, while the operational temperature of SWIR-2 is 235K. The reduced SWIR-2 temperature is implemented to achieve the required signal to noise levels and radiometric accuracy. In order to reach its operating temperature the SWIR-2 detector is thermally isolated from the VNS camera and thermally coupled to the VNS SWIR-2 radiator using a flex link and cold finger (see Fig. II-3). The thermal isolation of the SWIR-2 detector is achieved by the implementation of titanium flexures in the camera design.

The radiator panel, with a surface of 0.175m^2, is designed to reach temperature well below the target. An active thermal control circuit stabilizes the detector temperature at 235K.

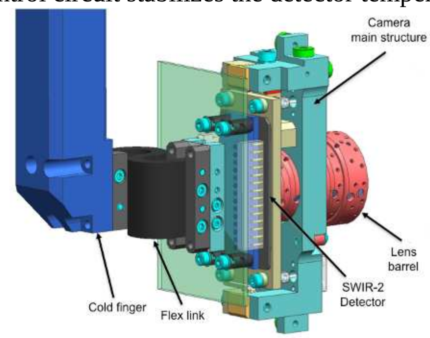


Fig. II-3 SWIR-2 camera assembly

During the in-flight operations the VNS will be regularly calibrated. Dark measurements will be performed for offset corrections during eclipse of the orbit; sun calibration will be performed for response calibration during passes over the South Pole region. During the sun calibration the sun light will illuminate a pair of Quasi Volume Diffusers (QVD). The QVDs are mounted on a rotating carousel (see Fig. II-4), which is used to switch between dark, sun and earth viewing modes.

The rotating carousel is driven by a Phytron VSS-43 motor and is guided by ESTL procured bearings.

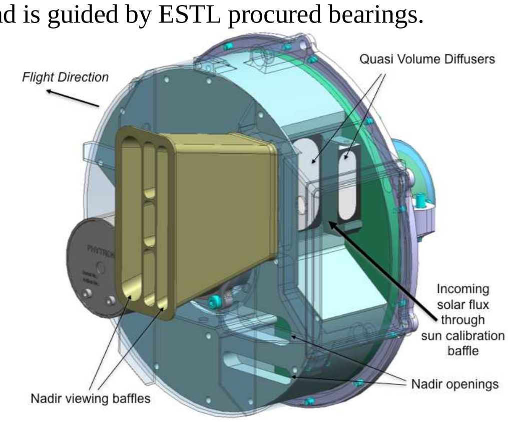


Fig. II-4 VNS Calibration mechanism

C. *VNS Calibration Mechanism Life Test*

The first physical model built of the VNS is the Life Test Model (LTM), see Fig. II-5. The LTM consists of the VNS Calibration Mechanism Assembly (CMA) and is used to perform an accelerated life test on the Mechanism.

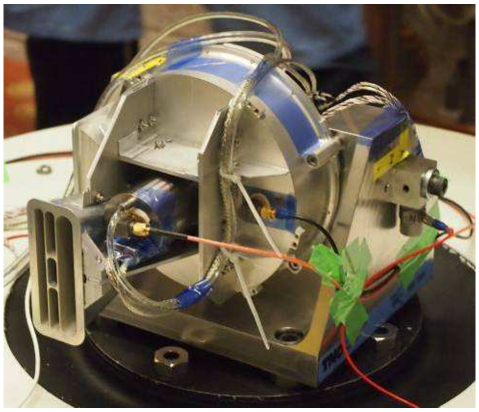


Fig. II-5: VNS life test model during vibration test at CSL

The test program of the VNS LTM consisted of:

- Qualification level vibration testing.
- Thermal Vacuum cycling (-30°C - +70°C).
- Operation of the Mechanism for 56000 orbital calibration cycles.
- Operation of the mechanism for 560 monthly calibration cycles.

The VNS LTM successfully passed all these tests maintaining the required performance and is therefore considered qualified for the MSI program.

D. VNS Engineering Confidence Model

The second physical model built is the Engineering Confidence Model (ECM), see Fig. II-6. The purpose of the ECM is to validate the overall instrument concept prior to proceeding with the Proto-Flight Model (PFM). The VNS ECM is mechanically and electrically representative. Two of the four optical channels (VIS and SWIR1) and the Calibration Mechanism are fully functional.

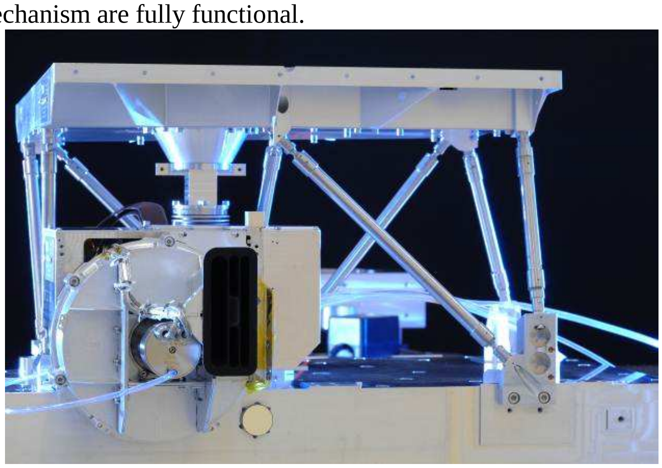


Fig. II-6 VNS ECM (Sun Baffle not assembled)

During the assembly of the VNS ECM, the assembly and alignment procedures have been checked and refined. Using the refined alignment procedures, the scene can be imaged at the detectors within a position accuracy of a few micrometers. These accuracies result in a VNS instrument pointing and channels co-registration well within the requirements.

After full assembly the VNS ECM has been subjected to a qualification level vibration campaign. The pre and post vibration performance checks show that the pointing and co-registration shifts are well within the requirements. This validates the mechanical integrity and stability of the VNS concept.

At the moment of writing this paper the full performance test campaign on the ECM are being carried out. The performance tests already completed show:

- Focal length = 22.2mm
- Field of View > +/-11.5 degrees of arc
- Detector noise is well below the required 5000 electrons per read-out.
- MTF performance above 0.4
- Polarization sensitivity below 1.5%

All these performance parameters are within their respective requirement.

Before the end of the third quarter of 2012 all performance test and a dry-run calibration will be concluded on the VNS ECM.

III. TIR OPTICAL UNIT

A. TIR Requirements and Design

The TIR provides the other 3 spectral bands of the MSI instrument. Its optical design has been reported before [4]. To recap, the spectral bands are shown in TABLE II.

TABLE II. TIR SPECTRAL BANDS

TIR channel	**Central wavelength [nm]**	**Spectral width [nm]**
TIR1	8800	900
TIR2	10800	900
TIR3	12000	900

As with the VNS, the system constraints lead to a significant design challenge which the unit's external appearance (Fig. III-1) belies.

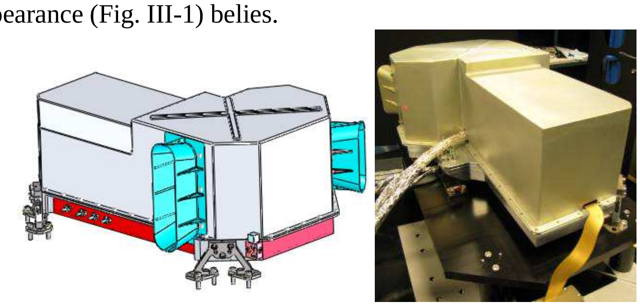


Fig. III-1 TIR (left) CAD (right) ECM

The internal layout of the TIR comprises an f/8 telescope upstream of a dichroic and filter assembly which provides the spectral division into the 3 TIR bands. Downstream of this assembly is an f/1 relay lens, responsible for directing the 3 colour channels onto a 2D α-Si microbolometer detector. This system is read out in Time-Delay-Integration (TDI) mode by the front end electronics (FEE) such that the output is a linear co-added, background subtracted image suitable for the instrument's pushbroom operation in flight.

Fig. III-2 shows the TIR located on the OBM, with its outer shroud removed. The unit has three target apertures – the primary science Earth (nadir) viewing port, the Cold Space viewing port for dark scene reference and an on-board calibration blackbody aperture providing the bright scene reference. The blackbody is a passive component, thermally tied to the TIR optical bench and will be monitored by high precision platinum resistance thermometers in the PFM. In the ECM, these PRTs are substituted by thermistors.

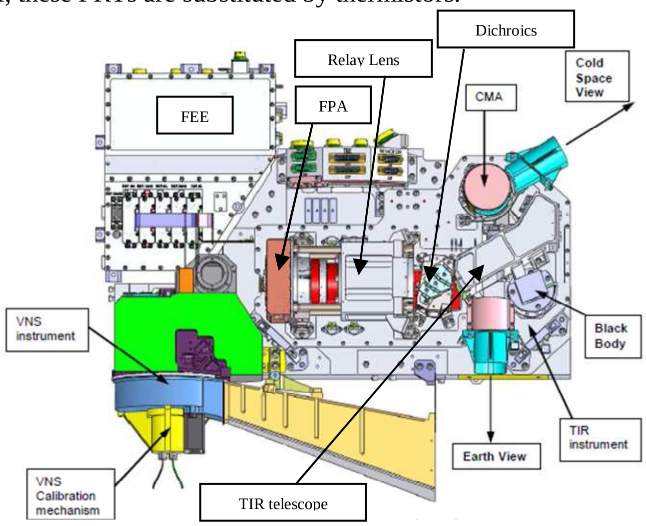


Fig. III-2 MSI OBM from above: TIR cover, SWIR2 radiator, harnesses omitted

Selection of one of 3 target apertures directed through the optical chain onto the focal plane assembly is performed by the TIR calibration mechanism assembly. The focal plane array (FPA) and relay lens system design have been described in detail [5].

B. TIR Calibration Mechanism Assembly

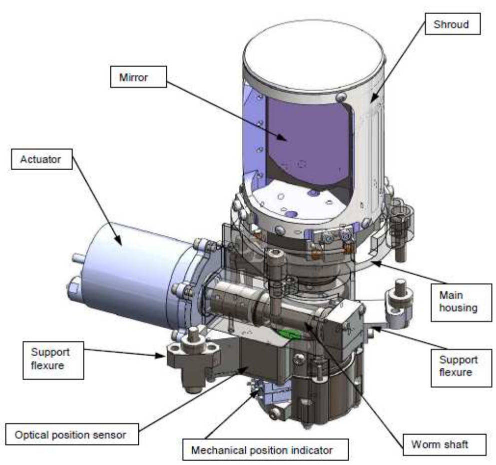
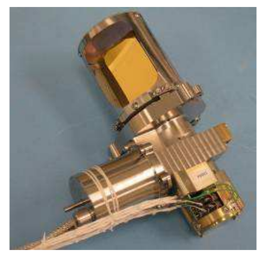


Fig. III-3 TIR CMA ECM design

The TIR requires regular calibration, by pointing the optical beam at an on-board blackbody source and to a cold space viewport. After viewing and recording the reference sources, the optical beam is then aimed back at Earth for science data acquisition. This motion is carried out by reflecting the beam off a rotating calibration mirror. The mirror is a two surface, front coated item. One side of the mirror is plane, and this is used for Earth view and cold space view. The other side of the mirror is concave, providing focusing down on to the TIR blackbody aperture. To perform its function, the mirror has to be flipped through more than 180º. The stability and positional repeatability of the mirror for Earth viewing is very strict, so there is a hard end-stop at that point.

The TIR CMA ECM is based around a Phytron VSS-42 motor. The shaft assembly and other components are SSTL design. The ECM equipment is used as a qualification model; it diverges from the traditional mechanism life test model in that it is used in the next level assembly, the TIR ECM, and is not intended to be subjected to post-test constructional analysis.



Test	ECM	PFM
Ambient functional test	X	X
Qualification level vibration test	X	-
Ambient functional test	X	-
Thermal vacuum test to qualification levels	X	-
Thermal vacuum test to acceptance levels	-	-
Ambient functional test	X	-
Life test	X	-
Final ambient functional test	X	-

Fig. III-4 TIR CMA ECM and the equipment test campaign per model

At the time of writing, the TIR CMA ECM has withstood a combined xyz random vibration response of 65.7 g_{rms} at the motor. In the life test, the CMA has experienced 44117 cycles; 40000 cycles were the target to meet the orbit lifetime under qualification conditions.

The TIR CMA ECM has also undergone an exported torque (microvibration) test, illustrated in Fig. III-5. The results are expected to be finalized by September 2012. The measurements and specific analysis approach used show that the CMA exports very low moments (<0.04 Nm) and low forces (<0.12 N) between 1 Hz and 1 kHz.

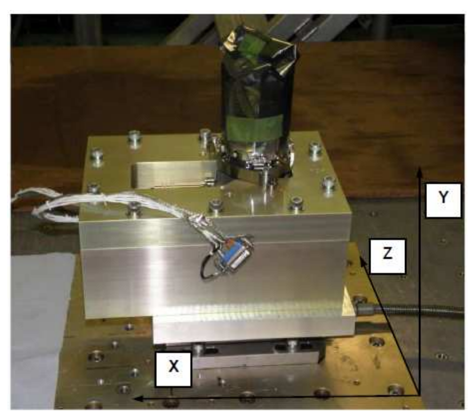


Fig. III-5 TIR CMA ECM microvibration test

C. TIR Calibration Blackbody (TIR-BB) EQM

As with the TIR CMA ECM, the TIR-BB is qualified at subassembly level. The blackbody is a standard qualification model, with only the temperature sensors differing from the flight model. The primary motivation for qualification is the black coating response within the specific internal geometry afforded by the TIR-BB to environmental testing.

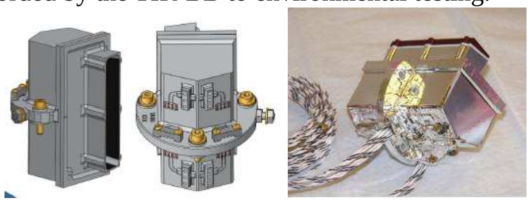


Fig. III-6 TIR CMA (left) design (right) EQM

The test flow is shown in Fig. III-7. The thermal test extrema were -40ºC to +70ºC.

The TIR-BB EQM passed its qualification at equipment level and has been incorporated into the TIR ECM.

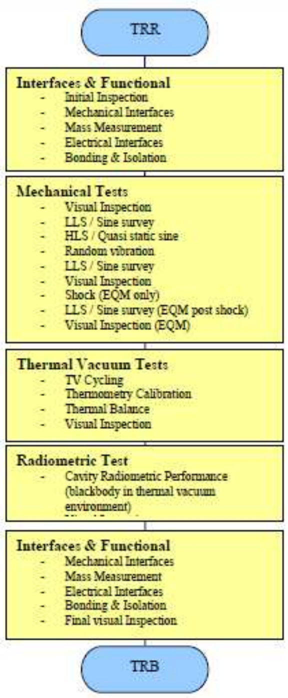


Fig. III-7 TIR CMA qualification testing campaign

D. TIR ECM

The purpose of the TIR ECM is to address the structural and performance risks prior to entering the PFM phase of the instrument programme.

Structurally the major risks arise in integration of key subassemblies of this unit. Specifically, the risk of misalignment of the components within a subassembly, and of subassemblies to each other is significant enough to warrant a high fidelity ECM to rehearse on.

The use of TDI as the readout configuration also demands excellent optical aberration control; again the principal risk here is judged to arise from assembly activities.

Strict control of the background pedestal on the signal is necessary to sustain the required radiometric accuracy over an orbit interval before recalibration. The TIR is designed for thermally stability rather than thermal control responsivity.

With all this in mind, from a structural viewpoint the TIR ECM is equivalent to a prototype.

The ECM serves to prove the assembly and integration processes and trial the bespoke ground support equipment made to enable the functional and performance tests. It also provides a base for the development of user friendly data acquisition and processing software for the future stages of the MSI and EarthCARE programme.

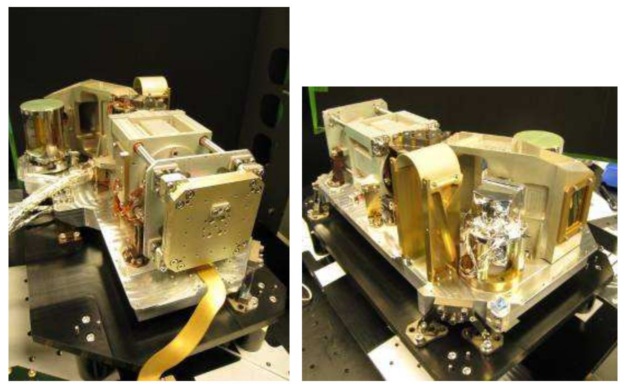


Fig. III-8 TIR ECM internal (left) FPA end (right) from TIR-BB end

At present the TIR ECM is undergoing its performance tests prior to mechanical environment testing. First interface and functional tests have been completed, with the unit passing. The test programme for the TIR ECM is expected to be complete by the last quarter of 2012.

IV. FRONT END ELECTRONICS

The FEE is an integral part of the MSI OBM as it serves to drive the detectors and acquire all video signals and key telemetries associated with the 5 focal planes of the MSI.

The optical unit ECMs are supported by 2 FEEs, as both units are manufactured and tested in parallel. These FEEs are not environmentally tested with the unit cameras and so are provided at breadboard maturity.

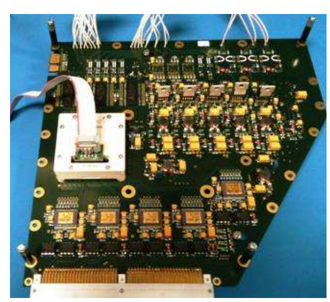


Fig. IV-1 FEE breadboard - FPGA being programmed

Both breadboards have been performance tested and have passed. One of the breadboards will be upgraded to an elegant breadboard for MSI ECM level testing once the TIR and VNS are integrated.

A third FEE breadboard serves as part of the ground support equipment for the ICU EM described in the next section. This has the added benefit of proving the FEE-ICU interfaces and confirming that the ICU EM performance is not affected by the FEE breadboard design.

V. INSTRUMENT CONTROL UNIT

The ICU is responsible for handling all the spacecraft interfaces as well as ensuring the correct function and health of the instrument by performing the data handling, monitoring and control activities.

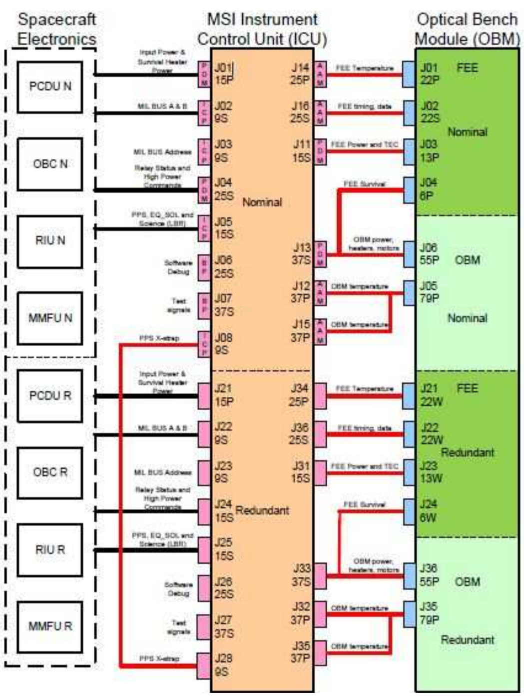


Fig. V-1 Spacecraft – ICU – OBM schematic

The ICU plays no direct part in the MSI OBM ECM. As mentioned in Section I there is an engineering model which serves to verify hardware requirements and interfaces. Fig. V-1 illustrates the OBM to Spacecraft connectivity provided by the ICU. Note that the ICU EM provides only the nominal components.

The EM also verifies and validates the hardware/software interfaces. The ICU software is split into two separate components – boot software and application software.

The boot software is intended to run for a short time after an ICU reset. It controls the start-up of the ICU into instrument initialisation (INS-INI) mode. It will load and start the ICU application software on command. Naturally it has no operating environment and starts from a PROM.

The application software is simply a fixed priority static cyclic scheduler, based around the ICU processor's interrupts. This means that there is no runtime kernel.

At the time of writing, the ICU EM has completed its initial integration tests and is proceeding with the main electrical tests. Boot software is present on the ICU EM, as is an unvalidated version of the application software. The electrical and functional tests will make use of an OBM simulator, comprising a fully functional FEE breadboard. The results of these tests will feed in to the FEE breadboard upgrade to an elegant breadboard, ready for the MSI ECM campaign.

VI. CONCLUSION

The units that go to make up the MSI ECM have been discussed. The design specification has been provided, or referenced. The latest status resulting from the test campaigns that are complete or are now ongoing has been described. The results of the unit level ECM tests are expected by the last quarter of 2012, which should be followed closely by the independent ICU EM electrical and functional test results. The outcome will put the EarthCARE MSI project in a good position to move to MSI ECM integration; it will have the best information in the shortest practical timeframe.

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REFERENCES

[1] D. Lobb, I. Escudero Sanz, M. Chang and S. Gode, "Development of Detailed Design Concepts for the EarthCARE Multi-Spectral Imager" in proceedings of the *International Conference on Space Optics*, October 2008.

[2] A. Pérez Albiñana, R. Gelsthorpe, A. Lefebvre, M. Sauer, E. Weih, K-W. Kruse, R. Münzenmayer, G. Baister, M. Chang, "The multi-spectral imager on board the EarthCARE spacecraft", Proc. SPIE 7808, 780815 (2010); http://dx.doi.org/10.1117/12.858864

[3] J. Doornink, B. de Goeij, O. Marinescu, E. Meijer, R. Vink, W. Van Werkhoven, A. van 't Hof, "The Visible, Near-Infrared and Short Wave Infrared Channels of the EarthCARE Multi-Spectral Imager" in proceedings of the *International Conference on Space Optics*, October 2010

[4] M. P. J. L. Chang, D. Woods, G. Baister, D. Lobb, T. Wood, "The EarthCARE Multi Spectral Imager Thermal Infrared Optical Unit" in proceedings of the *International Conference on Space Optics*, October 2010

[5] L. Gomez Rojas, M. Chang, G. Baister, G. Hopkinson, M. Maher, M. Price, M. Skipper, T. Wood, D. Woods, "The EarthCARE multispectral imager thermal infrared optical unit detection system design", Proc. SPIE 7826, 7826H (2010); http://dx.doi.org/10.1117/12.869250