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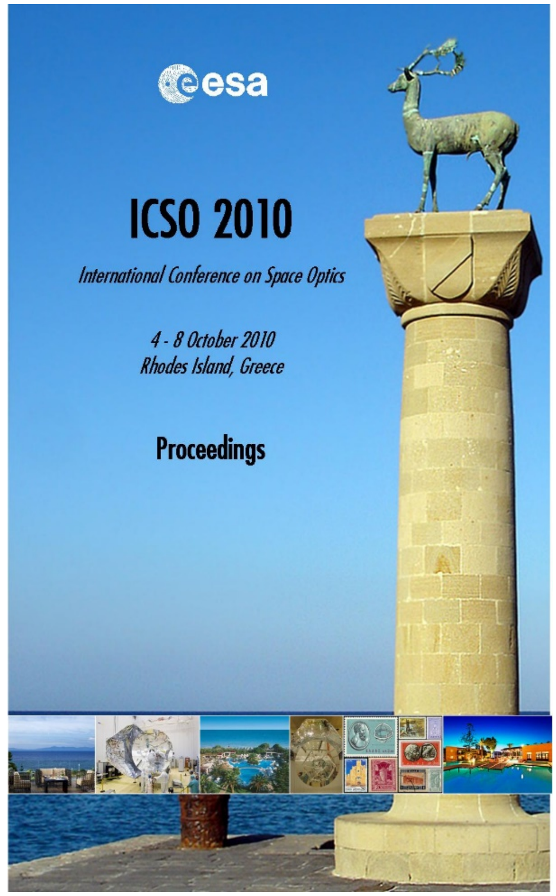

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THE EARTHCARE MULTI SPECTRAL IMAGER THERMAL INFRARED OPTICAL UNIT

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I. INTRODUCTION

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 4 instruments is the Multi-Spectral Imager (MSI), previously described in [1]. 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 7 spectral bands: one visible, one near-IR, two short-wave IR and three thermal IR. The instrument will be comprised of two key parts:

- a visible-NIR-SWIR (VNS) optical unit radiometrically calibrated using a sun illuminated quasivolume diffuser and shutter system
- a thermal IR (TIR) optical unit radiometrically calibrated using cold space and an internal black-body.

This paper, being the first of a sequence of two, will provide an overview of the MSI and enter into more detail the critical performance parameters and detailed design the MSI TIR optical design.

The TIR concept is to provide pushbroom imaging of its 3 bands through spectral separation from a common aperture. The result is an efficient, well controlled optical design without the need for multiple focal plane arrays. The designed focal plane houses an area array detector and will meet a challenging set of requirements, including radiometric resolution, accuracy, distortion and MTF.

II. EARTHCARE MSI ARCHITECTURE OVERVIEW

The MSI system comprises an Optical Bench Module (OBM) mounted on an external spacecraft panel, connected via a complex harnessing arrangement to the Instrument Control Unit (ICU) within the interior of the satellite. The OBM is a logical unit containing the TIR and the VNS mounted onto a single Optical Bench (OB) for accurate through-life alignment of the two instruments. It also contains the instrument Front End Electronics (FEE), which provides the drive and signal conditioning to the detectors in the two instruments. A sketch of the OBM can be seen in Fig. 1.

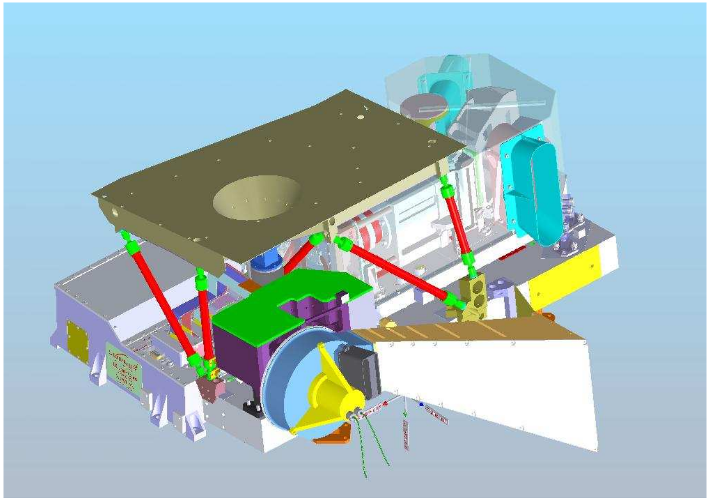

Fig. 1. MSI OBM oblique view

III. MSI TIR SPECIFICATIONS AND OPTICAL DESIGN

The TIR optical unit will provide co-registered images in three spectral channels. The spectral bands are detailed in Table 1. The other main requirements are on the swath width, ground sample distance, MTF and radiometric accuracy (<1K absolute accuracy and 0.1K interchannel relative accuracy). These are coupled with the constraints of a large range for the spacecraft orbit altitude and demanding temperature environment.

The TIR will use a single (microbolometer) area array detector within a two-stage imaging system. In the first stage, an image of Earth will be formed at relatively long focal length by a simple lens system. The beam will be split by two dichroic beam-splitters located near the large primary image, and optical filters in the three separated beams will define the required TIR spectral response functions. The three beams, folded by mirrors onto parallel paths, will then be re-imaged onto the area-array with a substantial de-magnification. This is shown in Fig. 2.

Table 1. TIR bands, reference scene brightness temperatures and NEdT specifications

Band	Centre Wavelength	Bandwidth	Ref. scene brightness temperature	Specified NEdT
7	8800nm	900nm	293K	0.25K
8	10800nm	900nm	293K	0.25K
9	12000nm	900nm	293K	0.25K

The TIR optics are designed to achieve the following optical parameters: Focal Length Target: 31.14 mm, Across Track Field of View: +/-11.5º, Along Track Field of View: +/-0.65º. The mask at the intermediate image plane reduces this to +/-11.3°. As such the system images a 156 km by 8 km ground area at minimum altitude.

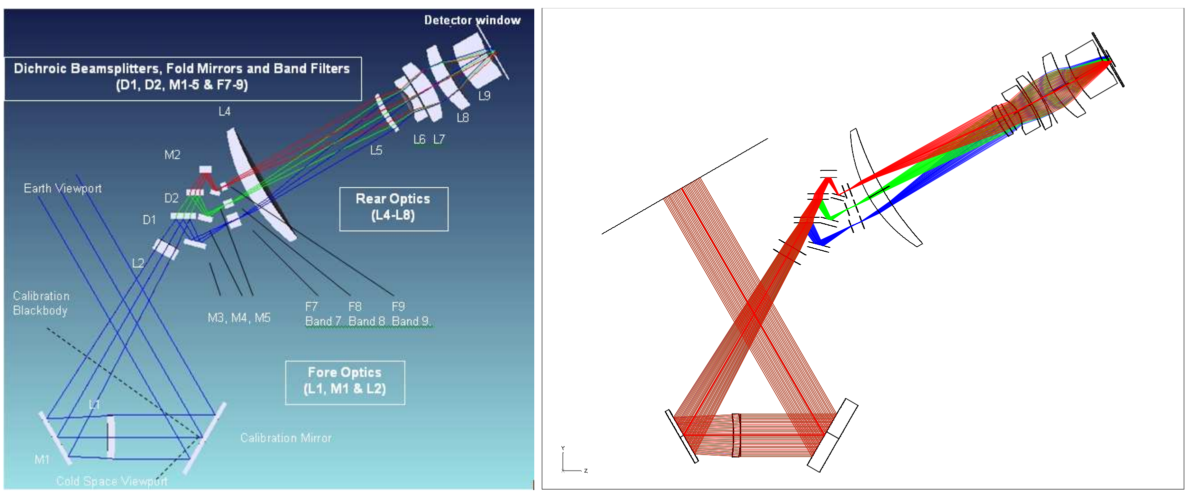

Fig. 2. TIR optical layout. The rear optics are defined downstream of F7, F8, F9.

Note that L3 was deleted during optimisation – the lens labels were retained as they had already been entered into the design database.

The simplest use of an area array imaging device is to accumulate an image by allowing scene radiance to fall upon the detector array for a desired integration time. Unfortunately this technique is extremely limited in scope for reducing the NEdT. The approach adopted to improve the NEdTs is to combine oversampling and Time Delay and Integration (TDI). Details of the focal plane array readout process can be found in [2]. The use of TDI demands an extremely tight control of distortion, much better than 1%. Moreover, the common optical elements operate over a wide bandpass of ~4µm.

With reference to Fig. 2, radiation from Earth is received through the Earth view port, and falls on the calibration mirror. The beam is reflected through an imaging lens (L1), which is nominally 30.6mm diameter. The beam is then reflected from a fixed fold mirror (M1), through a second lens element (L2), into a system of dichroics, fold mirrors and filters (D1, D2, M2, M3, M4, M5, F7, F8 and F9). The second lens element (Rear Optics L4 to L8) acts partly as a field lens, so that the system is close to telecentric in the region of the dichroics and filters. Two dichroics (D1 and D2) split the beam efficiently into three parts, working at ~30° incidence angle. The three beams are then folded through filters (F7 to F9) onto a common image plane. The primary images are formed within an f/5 beam within the fore-optics (L1 to L2). The filters define the required spectral bands. The system following the filters will be enclosed in a separate cavity – the rear-optics enclosure – with enhanced temperature control. The beams will pass into the enclosure through three slots in a temperature-controlled front plate or mask (Fig. 6). After the filters, the three beams are re-imaged onto the detector by a lens system. The magnification factor is nominally 0.2, so that the final image is formed at f/1.

The optics are designed to maintain MTF rather than focal length. The focal length becomes shorter with temperature, as shown in Fig 3. Athermalisation of the system design is achieved by structural means. A focal plane array metering rod set, constructed in Invar (a low thermal coefficient material) holds the detector at a fixed position relative to the rear optics lens barrel over a 50º temperature range. This is shown in Fig. 4.

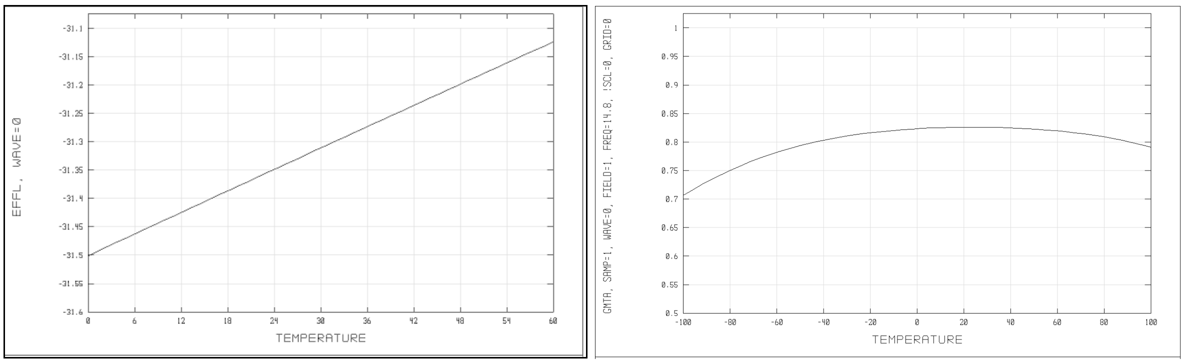

Fig. 3. (left) Focal length shift with temperature (right) Focus stability with temperature (ΔT = 60ºC)

Of the 8 lenses in the TIR, 2 surfaces are aspheres, in the rear optics. The number of aspheres have been minimised during the design process by ensuring that the start point of the solution is with spherical surfaces. The optical system operates near the diffraction limit, utilising a very restricted materials palette. Materials of the transmitting optical elements include Zinc Selenide (ZnSe), Germanium (Ge) and Gallium Arsenide (GaAs). Ge and GaAs have significant absorption in the bands, so the total thickness of these materials was a design constraint.

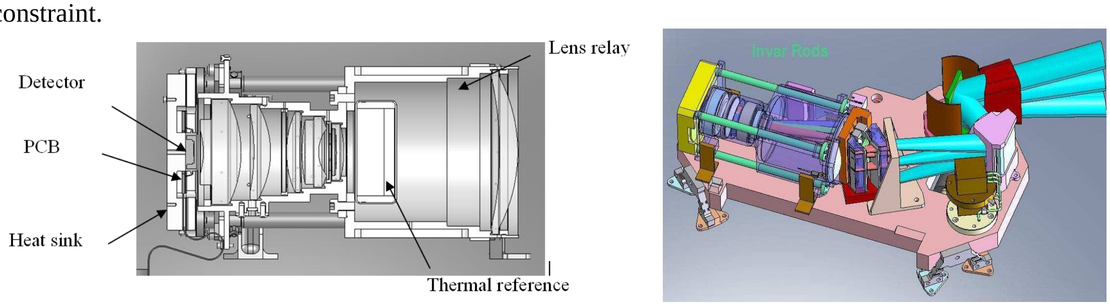

Fig. 4. TIR rear optics structural design – Invar rods maintain the system athermalisation.

In order to achieve the required radiometric performance, it is important to control errors due to background thermal radiation reaching the detector from internal surfaces of the instrument. High stability is required between absolute calibration procedures during calibration mode (see Section IV). Most of the background radiation reaching the detector comes from within the rear enclosure, which receives scene radiation only through the filters. Enhanced thermal isolation is provided for the rear enclosure via the thin flexures, limiting temperature variations through the orbit and stabilising the background. This adds to the justification for the more-complex relayed optical design compared to a direct design.

The reference areas on the detector, indicated in Fig. 6, will be used to provide a measure of the background radiation reaching the detector. The reference signals will be averaged and subtracted from image-area signals. The reference areas will be images of mask areas between the filters. To control the effective radiances of these mask areas, the masks will be mirrors reflecting a stabilised “internal thermal reference” (indicated in Fig. 4 and Fig 5). The filters will reflect from the same reference area.

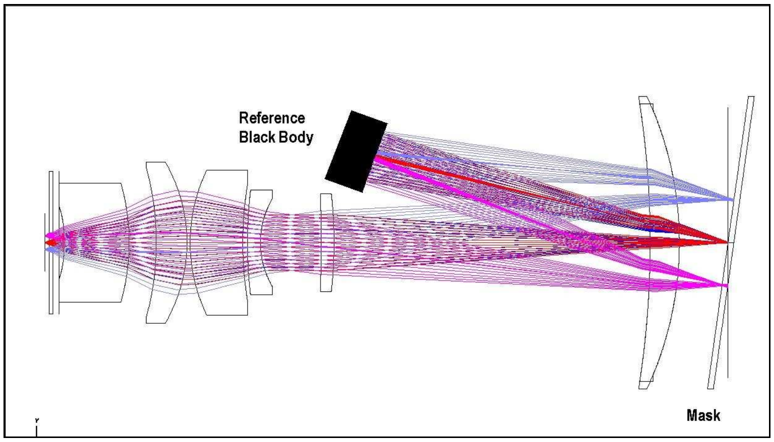

Fig. 5. TIR rear optics showing the internal thermal reference blackbody

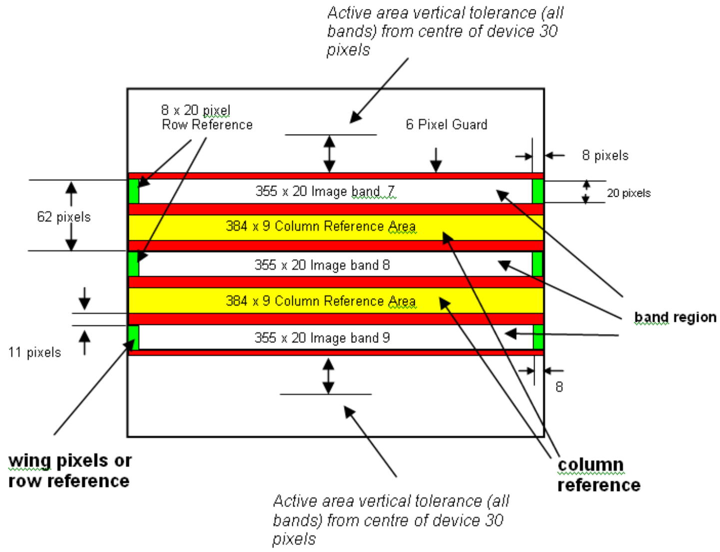

Fig. 6. Sketch of Operating bands for the TIR detector

IV. TIR MODES OF OPERATION

Radiometric calibration in-flight for the TIR will be provided using a rotatable mirror in the incident beam path, allowing the instrument field to be switched between Earth, cold space and an internal warm blackbody. Light enters the system aperture and is always incident on the calibration mirror. Two configuration modes are available to the TIR: imaging and calibration.

In imaging mode the scan mirror directs the light towards L1. The image of the ground therefore is relayed to the detector. In calibration mode, there are two view positions: the on-board blackbody (TIR-BB) and cold space (TIR-CS).

In TIR-BB view, the detector receives thermal radiation from the on-board blackbody source, providing a warm level reference. The blackbody is viewed by a concave rear face of the calibration mirror, which acts as a collimator for the black body emitting aperture. This allows the black body aperture to be small and thus a deep-cavity black body, with an emissivity that will always be very close to unity. The temperature of the blackbody is monitored to within 50 mK. The blackbody itself adopts the temperature of its interface to the TIR optical bench, targeted at room temperature. The calibration mirror temperature will always be very similar to that of the blackbody thereby introducing very little error by a change in mirror emissivity and reflectance, since the total radiance from the mirror will always be virtually the same as the blackbody radiance.

In TIR-CS view, the detector sees deep space. The calibration mirror is used at the same angle of incidence for cold space and Earth views, so that it has the same emissivity in these two configurations, providing a nearperfect zero radiance reference. The cold space aperture is closed by baffles located on the sides of the rotatable mirror.

V. OPTICAL PERFORMANCE SUMMARY

The TIR optics are diffraction limited by design. Even on Band 9, the longest wavelength, the design MTF is >0.75 at Nyquist (14.3 cycles per mm), as shown in Fig. 7.

In practice, MTF will be degraded by manufacturing and assembly errors. To validate the system MTF calculations, an optics tolerancing exercise was performed to determine the minimum feasible MTF. The results are that >0.65 should be the MTF goal. An MTF of >0.60 is a worst case figure as regards MTF budget. The budget is presented in Table 2 for across and along track values for the on-orbit system. The requirement to be met is 0.25 at Nyquist.

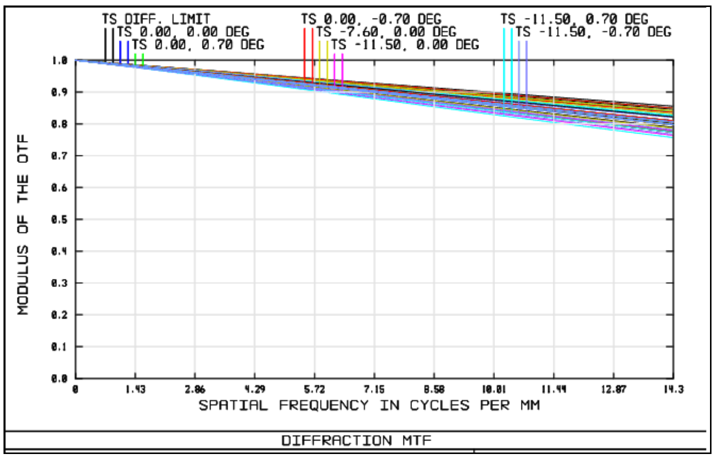

Fig. 7. MTF at 3 field points for Band 9, nominal design result

Table 2. MTF budget for across track (left column) & along track (right column)

MTF including manufacture aberrations [see 8.3.2.1]	0.6	0.6
Detector Cross-talk [see 8.3.2.3]	1	0.9
Detector MTF (finite element size) [see 8.3.2.4]	0.7	0.64
Platform Vibration (150μrad) [see 8.3.2.5]	0.993	0.993
Platform motion during the single-SSD integration period [see 8.3.2.6]	0.72	1
Time delay and integration: error in image direction [see 8.3.2.7]	1	0.995
Time delay and integration: error in image speed [see 8.3.2.8]	0.868	1
System MTF	**0.261**	**0.341**

Distortion control was highly weighted during the optimisation phase of the design. As a result the TIR design's distortion is minimal at <0.6%, shown in Fig. 8.

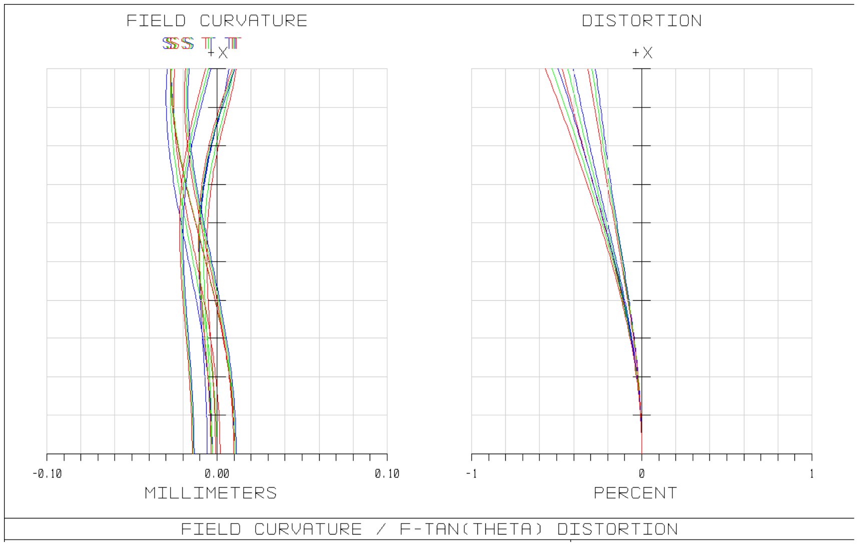

Fig. 8. Field Curvature and Distortion results from the TIR design

Predicted polarisation sensitivity for the bands are shown in Table 3. The requirement is <10% with a goal of <4%. The requirement is met comfortably for all channels. The goal is met with margin on 2 of the 3 channels and just met on the band 8.

Table 3. Predicted polarisation sensitivity

Band	Integrated Signal S	Integrated Signal P	Sensitivity
7	89.703	87.593	1.19%
8	77.468	71.895	3.73%
9	73.342	71.060	1.58%

VI. CONCLUSIONS

This paper has presented the EarthCARE MSI system and details of the basic optical design of its TIR optical unit. The optical system has been shown to meet its athermal MTF, distortion and polarisation requirements during analysis. The next step is to confront the practical technical challenges in the manufacture, alignment and validation of the design.

The MSI's other optical unit, the VNS is described elsewhere in these proceedings.

ACKNOWLEDGEMENTS

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