International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas

Development of detailed design concepts for the EarthCARE multi-spectral imager

Dan Lobb

Isabel Escadero

Mark Chang

Sophie Gode

International Conference on Space Optics — ICSO 2008, edited by Josiane Costeraste, Errico Armandillo,
Nikos Karafolas, Proc. of SPIE Vol. 10566, 105660I · © 2008 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308230

DEVELOPMENT OF DETAILED DESIGN CONCEPTS FOR THE EARTHCARE MULTI-SPECTRAL IMAGER

Dan Lobb (1), Isabel Escadero (2), Mark Chang (1), Sophie Gode (2)

(1) SSTL, Rayleigh House, 1 Bat and Ball Road, Sevenoaks, TN14 5LJ, UK, d.lobb@sstl.co.uk, m.chang@sstl.co.uk
(2) TNO, Stieltjesweg 1, P O Box 155, 2600 AD Delft, The Netherlands, isabel.escaderosanz@tno.nl, sophie.gode@tno.nl

ABSTRACT

The EarthCARE mission is dedicated to the study of clouds by observations from a satellite in low Earth orbit. The payload will include major radar and LIDAR instruments, supported by a multi-spectral imager (MSI) and a broad-band radiometer. The paper describes development of detailed design concepts for the MSI, and analysis of critical performance parameters. The MSI will form Earth images at 500m ground sample distance (GSD) over a swath width of 150km, from a nominal platform altitude of around 400km. The task of the MSI is to provide spatial context for the single-point measurements made by the radar and LIDAR systems; it will image Earth in 7 spectral bands: one visible, one near-IR, two short-wave IR and three thermal IR.

The MSI instrument will be formed in two parts: a visible-NIR-SWIR (VNS) system, radiometrically calibrated using a sun-illuminated diffuser, and a thermal IR (TIR) system calibrated using cold space and an internal black-body. The VNS system will perform push-broom imaging, using linear array detectors (silicon and InGaAs) and 4 separate lenses. The TIR system will use a micro-bolometer array detector in a time delay and integration (TDI) mode. Critical issues discussed for the VNS system include detector selection and detailed optical design trade-offs. The latter are related to the desirability of dichroics to achieve a common aperture, which influences the calibration hardware and lens design. The TIR system's most significant problems relate to control of random noise and bias errors, requiring optimisation of detector operation and calibration procedures.

1. MSI on EarthCARE – requirements

A multispectral imager (MSI) instrument forms part of the payload complement for the EarthCARE mission. EarthCARE is dedicated to improving the understanding of cloud, aerosol and radiation interactions, with the aim of improving climate and weather prediction models. The MSI will support two major active instruments on the EarthCARE platform — a cloud-profiling radar and a back-scatter LIDAR. It will provide context for the point measurements of the active instruments, providing images of Earth over a relatively wide swath, and adding data on cloud types, textures and temperatures.

The MSI will provide images in seven spectral bands, ranging from visible through to thermal infrared. Four solar-band channels are listed in Table 1, and three thermal IR bands in Table 2.

Table 1 Visible, near-IR and short-wave IR bands, reference radiances and SNR targets

Centre wavelengths and band widths, nm		Reference radiance, W per m^2.sr.µm	Target SNR
Centre	Width		
670	20	444.6	500
865	20	282.7	500
1650	50	67.3	250
2210	100	24.6	250

The same tables give the main targets for radiometric resolution: signal to noise ratios at reference scene radiance levels for the solar bands and noise-equivalent temperature differences (NEdT) at reference scene brightness temperatures for the thermal IR bands.

Table 2. Thermal IR bands, reference scene brightness temperatures and NEdT targets

Centre wavelengths and band widths, µm		Reference scene brightness temp.	Target NEdT
Centre	Width		
8.8	0.9	293K	250mK
10.8	0.9	293K	250mK
12.0	0.9	293K	250mK

Other main constraints and requirements on design and performance include:

Orbit altitude:	400km to 450km
Swath width:	150km (20° field)
Spatial sample:	500m
MTF:	>25% at Nyquist
Optics distortion:	<1%

- Temporal registration is all bands is required
- Radiometric accuracy

VNS absolute	<5%
VNS inter-channel	<1%
TIR absolute	<1K
TIR inter-Channel	<0.1K

2. MSI ARCHITECTURE, LOCATION AND IMAGING METHODS

The MSI instrument will be constructed in three main units:

- The visible/near-IR/short-wave-IR (VNS) sub-system, providing data from the four solar spectral channels,
- The thermal IR (TIR) sub-system,
- The instrument control unit (ICU) that drives both the VNS and the TIR sub-systems.

The VNS and TIR parts will be mounted on a common optical bench module (OBM) that interfaces to the EarthCARE platform. The OBM will be located outside the main platform structure, with the ICU inside. As indicated in Figure 1, the MSI is a very small unit compared with other instruments and the platform. It will be placed on the cold (anti-sun) face of the platform, which is in a sun-synchronous polar orbit; it will be close to a corner of this face, near the trailing and nadir faces. The trailing face is preferred to provide a view to the sun, for calibration of the VNS sub-system as the platform passes over a polar region, and the nadir face is of course convenient for the view to Earth.

The MSI system will operate as a pushbroom imager, instantaneously forming the image of a line of pixels across the 150km swath width; platform motion will sweep the field along-track to provide a continuous strip image (centred on the line of samples measured by the LIDAR and radar systems). The platform will not perform any significant attitude manoeuvres during data-gathering periods, so that the MSI system will be continuously nadir-viewing. (However, the 20 degree field will be offset 5 across-track in the anti-sun direction.) The nominal dwell period – i.e. the time taken for the swath to track through the along-track sample interval – will be approximately 70ms.

The VNS and TIR concepts will be described separately in the following chapters.

3. VNS SUB-SYSTEM

3.1. VNS detectors and optical parameters

For the solar-band channels of the VNS sub-system the detectors will be simple linear arrays. InGaAs detectors are preferred for the two short-wave IR bands, developed by modification of existing 500-element arrays from XenICs. The main modifications will include reduction of rectangular elements to 0.025mm squares, and some bandpass engineering, particularly to limit dark noise in the longer wave (2210nm) channel. It has been decided to use the same format and ROIC for the visible and near-IR channels, with silicon diodes replacing InGaAs, in order to make use of similar drive and analogue signal processing units for all four VNS bands. The VNS detector will be read-out up to 7 times during the 70ms dwell period, to avoid saturation.

The detector element size dictates the optics focal length of around 23mm (for the highest platform altitude). For the longer-wave SWIR band, optics aperture size is driven by the radiometric resolution (SNR) requirement: an aperture diameter of 10.5mm is needed. For the other three VNS channels, a 5mm aperture allows the SNR targets to be met with relative ease.

3.2. VNS optical design

Since all the VNS optics can in principle be quite small, it is reasonable to assign a separate lens to each of the four channels, and refractive optics can be used since the four channels are each relatively narrow. A separate filter will be mounted with each lens to define the required spectral band.

The main trade-off in optical design relates to use of dichroic beam splitters, to allow common apertures to be used for some or all channels. It is not in principle necessary to include dichroic splitters: the four lenses and detector can simply be placed side-by-side. However, a side-by-side arrangement tends to increase the necessary size of an external calibration source – typically a sun-illuminated diffuser that must be deployed in front of the optics. Dichroics can reduce the size of the calibration diffuser by providing a common aperture for some or all of the four channels. However a common entrance pupil is necessarily remote from the lenses, so that addition of dichroics tends to add to lens system size and to difficulties in design for the MTF and distortion targets.

The complex detailed-design trade-off currently favours an arrangement using two separate apertures as indicated in Figure 2: one assigned only to the long-wave SWIR band, while the other aperture serves three channels via 2 dichroic splitters. The diagram includes a schematic representation of the calibration diffuser, which takes the form of a reflecting prism with ground surfaces.

3.3. VNS calibration

Figure 3 shows the construction of the VNS sub-system, including the calibration assembly. The cylindrical housing contains two prism diffusers rotated on a common axis. Rotation of the calibration body selects either an open aperture for normal Earth view, or a shutter for protection and dark field, and or either of the two diffusers. The grey envelope on the left of the picture indicates the path of sunlight onto a diffuser, when the diffuser is deployed in front of the optics. Calibration data using diffuser radiance will be recorded when the platform is over a polar region, with sunlight illuminating the trailing face of the platform. One diffuser may be deployed up to once per orbit. The second identical diffuser will be deployed less frequently – comparison of images from the two diffusers will be used to detect a difference in degradation rates associated with exposure to solar UV radiation.

4. TIR SUB-SYSTEM

4.1. TIR detectors and optical parameters

The TIR design is based on use of micro-bolometer array detectors. These detectors are much less sensitive than photon detectors, but they offer a much lower-cost solution than photon detector options since (a) they do not require cooling, and (b) they do not require special developments to provide arrays capable of working at wavelengths up to 12µm. Simple pushbroom operation would probably not allow the NEdT requirements to be met. However, it is possible to use area-arrays in a time delay and integration (TDI) mode: TDI allows the targets for radiometric resolution to be met with confidence. The preferred device for the EarthCARE MSI is the ULIS 03 04 1, which has 384 columns and 288 rows; the detector element size is 0.035mm. The detector has undergone extensive testing at SSTL to provide data for optimisation of the operating modes applied in the MSI.

The optics focal length dictated by the element size is 31.5mm (for maximum altitude). The micro-bolometer array is normally operated at around f/1: the current design provides an f/0.9 aperture, slightly truncated in the along-track direction. The nominal aperture diameter is therefore 35mm.

The detector area will be read out in a five sets of rows and three sets of columns, as indicated in Figure 4. In general, 300 columns – plus some margin – must be assigned to across-track spatial resolution. Signal from reference columns on either side is also collected and averaged to provide calibration data. Threes sets of detector rows – nominally 16 rows per set – are assigned to the three TIR spectral channels. These rows provide for time-delay and integration over a total of 16 dwell periods. However, signal is also collected from spare “reference” detector rows – this signal is also averaged to provide calibration data.

The detector frame-read rate will be adjusted such that the time taken for the image to move across one image row width (the dwell period) is an integral number N of read periods. As for the VNS system, the detector will be read out N (typically 5) times during the dwell period and the results averaged to improve SNR. The TDI process involves averaging of signals from row 1 in dwell-period 1, row 2 in dwell period 2 etc, for 16 rows and dwell periods.

4.2. TIR optical design

The TIR system optical design is shown in figure 5. A key driver for the design is the requirement for temporal registration of all MSI channels: this means in effect that we cannot use separated areas of ground to image the three TDI channels. There is an option to use three separate detectors with separate optics (as for the VNS channels). However the optical apertures are relatively large for TIR channels, and separate apertures would have a fairly severe impact on the size of the external calibration hardware. A single aperture and a single detector is preferred in the system design trade-off, partly for control of system size but also since a single calibration source and a single detector are likely to provide optimum inter-channel relative accuracy.

The single-aperture/single-detector approach demands use of dichroic beam splitters, as indicated in Figure 5, to achieve temporal registration of the three TIR channels. It is convenient to introduce the dichroics near an intermediate image formed at relatively low aperture. This is also a convenient location for the three filters that define the spectral bands. Following the filters, in a “rear optics enclosure”, the large intermediate image is imaged onto the detector by a relay lens.

4.3. TIR fore optics and calibration method

Light from ground enters the TIR sub-system through the “Earth window” indicated in Figure 5, and is reflected into the imaging optics by a calibration mirror. The flat calibration mirror reflects the light through a weak fore optics lens, by which it is focused onto the filters, via a fixed fold mirror and the dichroic assembly. A field lens precedes the dichroic assembly: this effectively images to the fore optics aperture onto the relay lens in the rear enclosure. The intermediate image at the filters is formed at approximately f/4.5.

The calibration mirror is rotatable, as indicated in Figure 6 to provide views (a) of cold space and (b) of a “warm” black-body. These two views provide the two known radiance levels required for absolute calibration of all TIR channels. The 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 near-perfect zero-radiance reference. Dumb-bell structures on the mirror are used to block the cold space aperture during Earth view.

The warm black body 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 – it can therefore be a deep-cavity black body, with an emissivity that will always be very close to unity. The black body temperature will be monitored precisely, but will be allowed to drift with the fore optics structure temperature. This is done so that the calibration mirror temperature will always be very similar to that of the black body – in this condition, very little error will be introduced by a change in mirror emissivity and reflectance, since the total radiance from the mirror (reflected plus emitted) will always be virtually the same as the black body radiance.

It will be 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 referring to cold space and the black body. Two features of the design provide confidence in effective stability of the instrument:

(a) Most of the background radiation reaching the detector comes from within the rear enclosure, which received scene radiation only through the filters. It will be possible to provide enhanced thermal isolation for the rear enclosure, to limit temperature variations through the orbit and stabilise the background. (This is another partial justification for the more-complex relayed optical design.)

(b) The reference areas on the detector, indicated in Figure 4, 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 in practice 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 reference". This reference area may be isolated from the rear enclosure main structure to provide a further level of temperature stabilisation. The filters will reflect from the same reference area.

5. MSI performance

The MSI instrument is currently expected to meet all of its performance requirements, as outlined in Chapter 1. A possible exception (too complex to detail in this paper) is the requirement on stray light. The requested limits will be exceeded due to the diffraction effects and, at least for the TIR system, due to reflections between the detector and the optics (including the detector window). There is a route to compliance involving deconvolution of image data, using the instrument stray light functions measured pre-flight.

ACKNOWLEDGEMENTS

SSTL and TNO acknowledge the direction and support of the Astrium EADS in the role of prime contractor for the EarthCARE Mission, and of the European Space Agency.

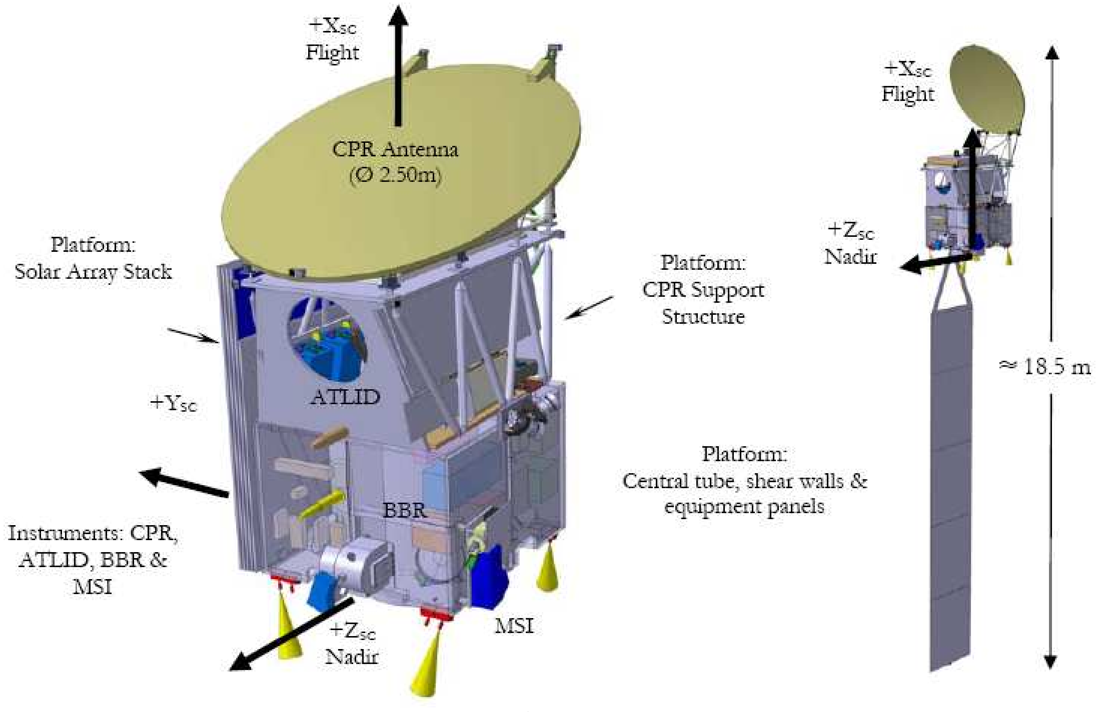

Figure 1 EarthCARE platform, indicating MSI location

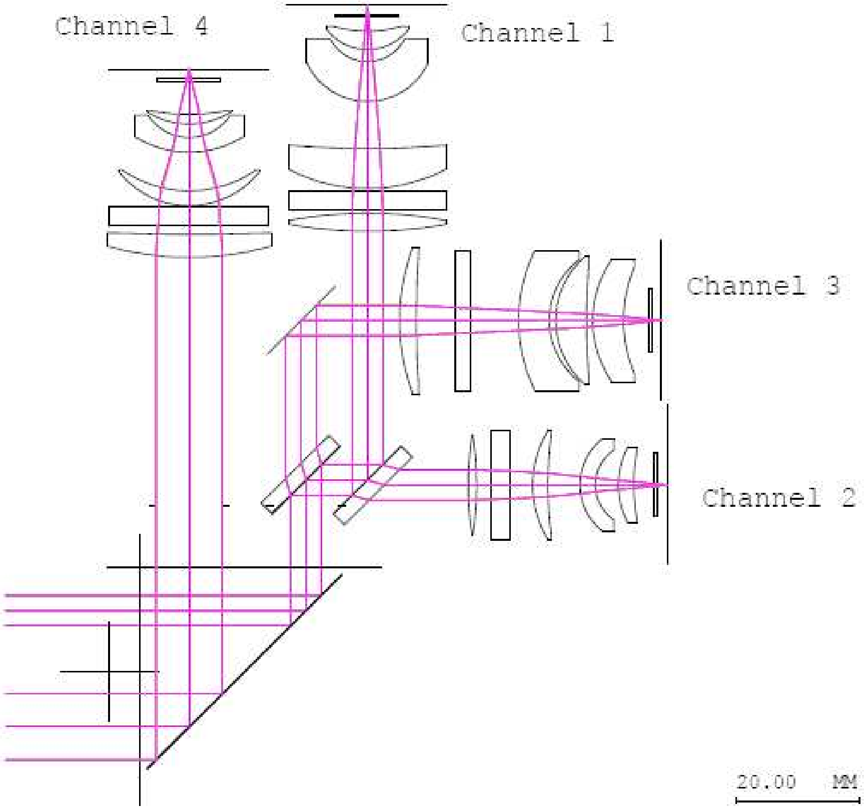

Figure 2 VNS optical design: channels wavelengths 1: 670nm, 2: 875nm, 3: 1650nm, 4: 2210nm

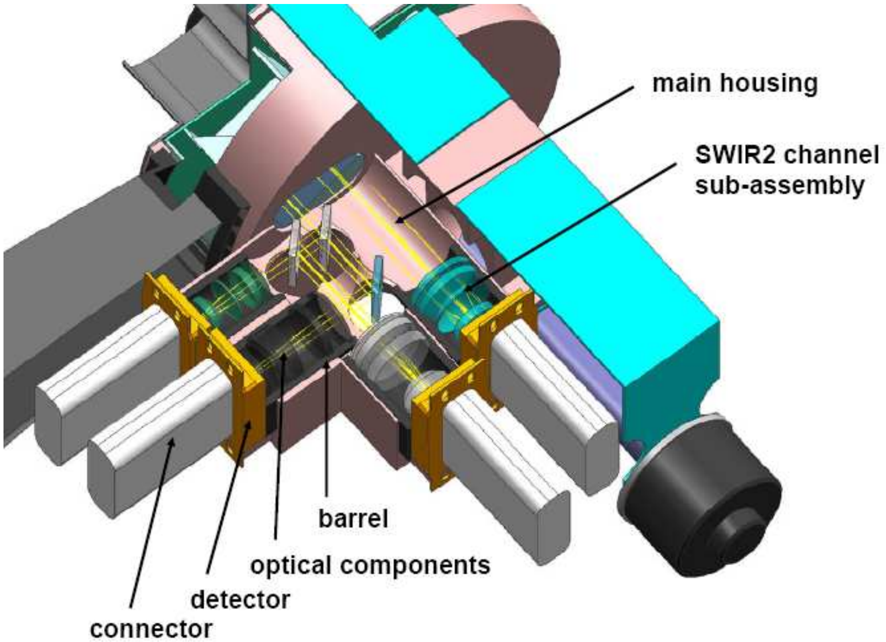

Figure 3 VNS structural layout, showing optics, focal plane assemblies and calibration assembly

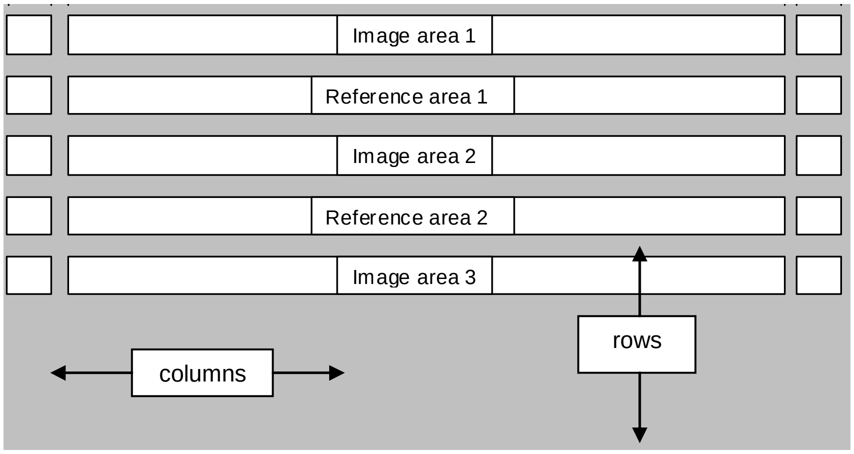

Figure 4 TIR detector – image and reference areas

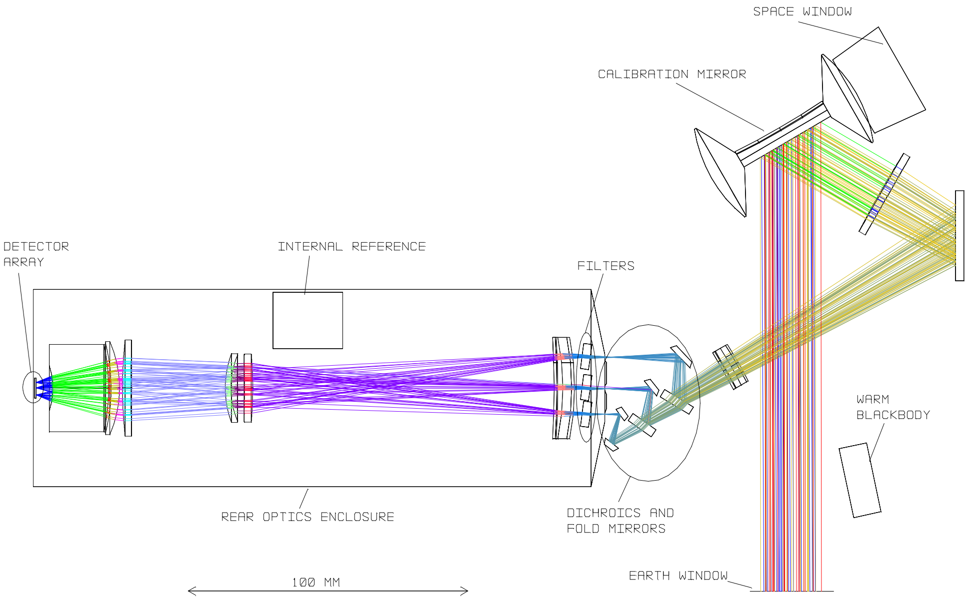

Figure 5 TIR optical design

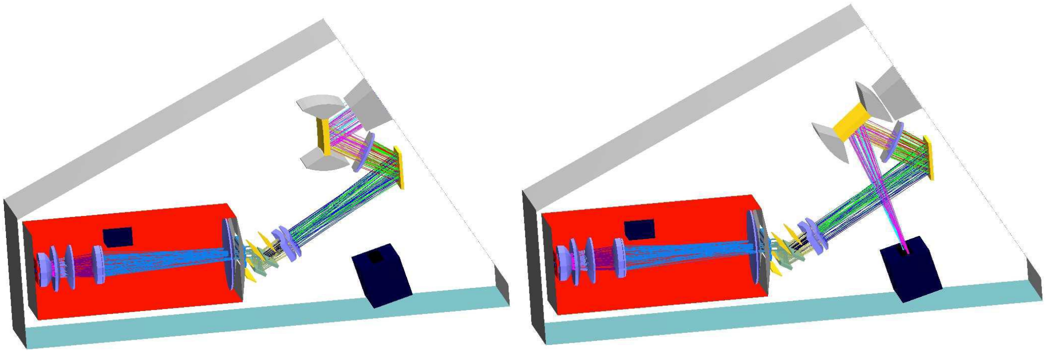

Figure 6 TIR system calibration: cold space and black-body views