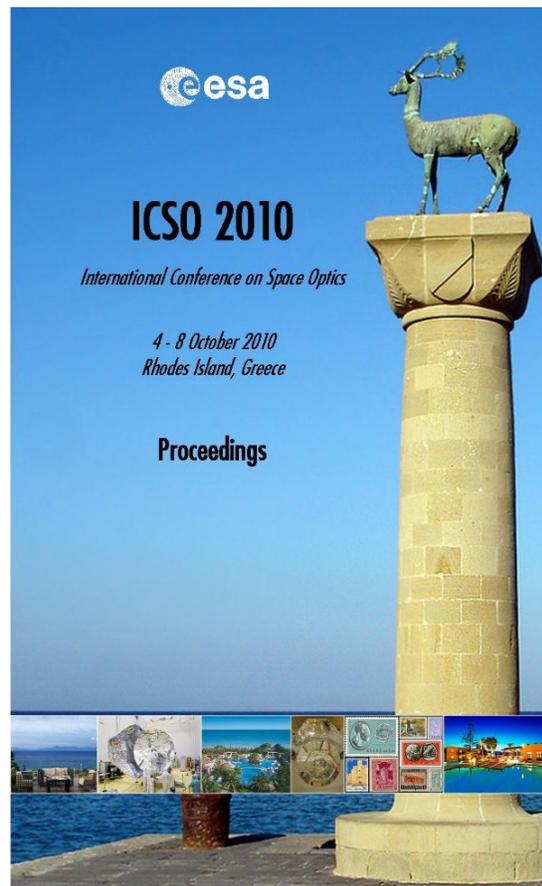


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THE VISIBLE, NEAR-INFRARED AND SHORT WAVE INFRARED CHANNELS OF THE EARTHCARE MULTI-SPECTRAL IMAGER

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I. INTRODUCTION

The EarthCARE satellite mission objective is the observation of clouds and aerosols from low Earth orbit. The payload will include active remote sensing instruments being the W-band Cloud Profiling Radar (CPR) and the ATLID LIDAR. These are supported by the passive instruments Broadband Radiometer (BBR) and the Multispectral Imager (MSI) providing the radiometric and spatial context of the ground scene being probed. The MSI will form Earth images over a swath width of 150 km; it will image the Earth atmosphere in 7 spectral bands. The MSI instrument consists of two parts: the Visible, Near infrared and Short wave infrared (VNS) unit, and the Thermal InfraRed (TIR) unit. Subject of this paper is the VNS unit.

In the VNS optical unit, the ground scene is imaged in four spectral bands onto four linear detectors via separate optical channels. Driving requirements for the VNS instrument performance are the spectral sensitivity including out-of-band rejection, the MTF, co-registration and the inter-channel radiometric accuracy. The radiometric accuracy performance of the VNS is supported by in-orbit calibration, in which direct solar radiation is fed into the instrument via a set of quasi volume diffusers.

The compact optical concept with challenging stability requirements together with the strict thermal constraints have led to a sophisticated opto-mechanical design.

This paper, being the second of a sequence of two on the Multispectral Imager describes the VNS instrument concept chosen to fulfil the performance requirements within the resource and accommodation constraints.

II. IMAGING CONFIGURATION

As part of the EarthCARE Multi-Spectral Imager (MSI), the VNS is a Nadir viewing push broom imager instrument with a swath width of 150 km. The EarthCARE orbit is sun-synchronous with an altitude of 391-434 km and 14:00 mean local time of the descending node. VNS is located at the -Y side of the spacecraft, which is permanently shielded from solar flux. The instrument line of sight is tilted 5° with respect to Nadir around the flight direction in order to reduce sun glint from the Earth's surface.

In swath direction the spatial sampling distance is 500 m, to be met for a range of orbital heights. The spatial sampling distance has to be for the maximum orbital height, while the 150 km swath width has to be met for the lowest orbital height. Due to this the maximum number of active pixels is 360. The EarthCARE spacecraft ground speed combined the 70 ms dwell period lead to 500 m sampling distance in flight direction as well.

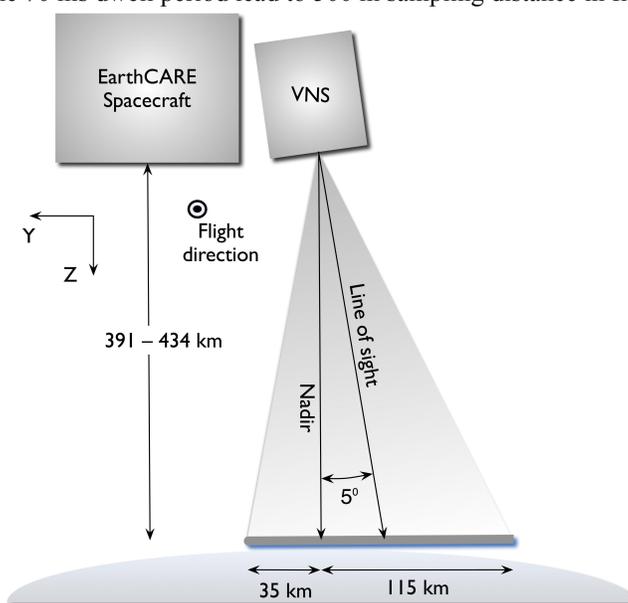


Fig. 1. VNS observing configuration

III. VNS PERFORMANCE REQUIREMENTS AND CONSTRAINTS

VNS shall provide images of the ground scene in four wavelength bands.

Table. 1. VNS spectral bands.

<i>VNS channel</i>	<i>Central wavelength [nm]</i>	<i>Spectral width [nm]</i>
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 spectral response per channel is constrained within a predefined parameterised shape. Out-of-band rejection is limited to 3%.
- Along track and across track MTF are both specified at 0.25. This instrument level MTF requirement is budgeted in allocations for detector level MTF, channel optics MTF and allowable tolerances in optics manufacturing.
- Polarisation is required to be below 1%. Based on an instrument level analysis of polarisation sensitivity, this is divided into contributions from the optics and detectors and specified accordingly.
- Stray light is specified in terms of measured crosstalk between illuminated and dark parts of a scene. Stray light is minimised by application of absorbing coatings and by slits in front of the detector arrays.
- Radiometric accuracy requirements impose strict constraints on temperature stability and on-ground calibration of the instrument.
- Instrument level channel co-registration and pointing requirements are budgeted in lower level requirements on alignment accuracy and stability of the optical components.
- The envelope available to VNS and the accommodation on the MSI instrument have determined the VNS configuration already at an early stage of development [1].

III. INSTRUMENT OVERVIEW

Together with the TIR unit, the VNS instrument is mounted onto the MSI bench [2].

- The Optical Unit contains the imaging optics and the detectors.
- The SWIR-2 Radiator cools down the SWIR-2 detector via a cold finger and a flex link.
- The calibration unit selects the optical input for the instrument.
- The sun calibration baffle provides a view on the sun while blocking earth radiation and spacecraft reflections.

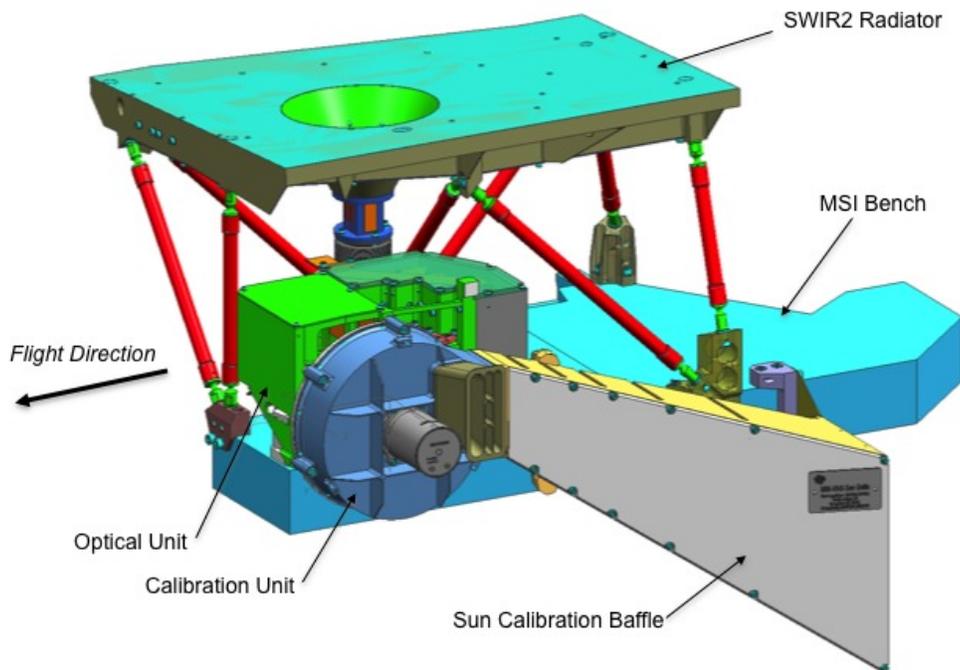


Fig. 2. The VNS instrument

III. VNS OPTICAL DESIGN

Orbit height and spatial sampling determine the minimum required effective focal length for a given detector pixel: 21.7 mm for the baseline 25 μm pixel. For the design a nominal focal length of 22.2 mm has been chosen, which includes margin for the manufacturing of the optics. Volume constraints have led to a configuration with common apertures. Orbit height, spatial sampling together with the detector noise define the required aperture diameters: 4.85 mm for the combination of the VIS, NIR and SWIR-1 channels and 10.47 mm for SWIR-2.

The VIS, NIR and SWIR-1 channels are spectrally separated using dichroic beam splitters and a folding mirror. The SWIR-2 channel has dedicated aperture. The two apertures are located close to each other to minimise the size of the calibration mechanism. The VIS, NIR and SWIR-1 channel optics each include three elements of which one is aspherical. The SWIR-2 channel optics includes 5 spherical elements. All filter coatings are applied on lens elements. The compact optical concept does not include a field stop. Out of scene radiation entering the instrument is absorbed on the black instrument interior and on a narrow slit in front of the detector.

V. VNS DETECTORS

The ground swath is imaged on linear detector arrays with a pixel size of 25 μm square. InGaAs detectors are applied for the two SWIR bands, while Silicon detectors are applied for the VIS and NIR bands. The SWIR detectors are modified version of existing 512-element InGaAs arrays from Xenics of Leuven, Belgium. In the standard version the detectors are hermetically sealed packages with Sapphire detector windows. To improve stray light performance the detector windows and the package lid had to be removed. The open packages now are mounted on a plate, which includes a narrow slit in front of the detector array for suppression of stray light and ghosts.

The Xenics InGaAs photo diodes normally are applied in the 1.7 μm SWIR-1 spectral band. For application in the 2.1 μm SWIR-2 channel several modifications were required, both at detector and at instrument level.

- Optimisation by band gap engineering: modification of doping levels to suppress dark current,
- Reduction of SWIR-2 detector temperature to 230 K in order to reduce both dark current level and its sensitivity to temperature fluctuations. Unlike the SWIR-2 detector, the VIS and NIR and SWIR-1 detector all operate at a temperature level of 300 K.
- F/2.1 optics for SWIR-2 to improve signal to noise ratio, as opposed to F/4.6 for the other channels.

For the VIS and NIR channels, Silicon photo detector arrays are applied. The VIS and NIR PDAs only differ in their anti-reflective detector coating.

All four detector types share the same read-out integrated circuits. The detectors will undergo a dedicated extensive test program to qualify them for this application.

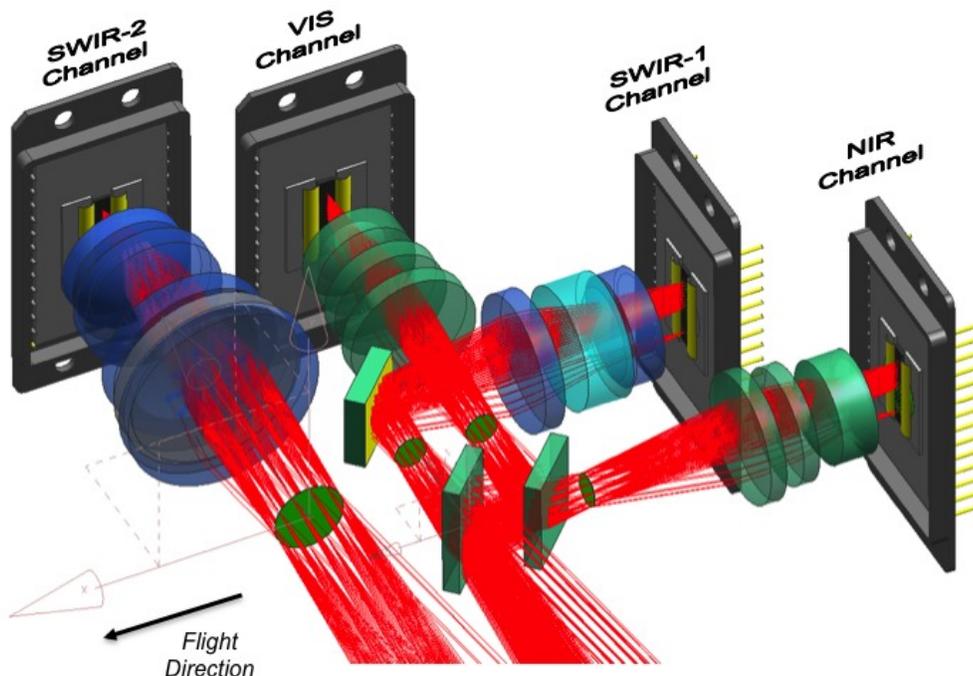


Fig. 3. VNS optical configuration

VI. IN-ORBIT CALIBRATION

Each orbit the VNS performs a solar and a dark calibration procedure. After the ground scene has gone into eclipse, nominal imaging stops and a prismatic diffuser is brought into position to view the sun through the sun calibration baffle. When the solar calibration procedure is completed, the calibration mechanism closes the instrument aperture and the spacecraft enters eclipse. Subsequently the dark calibration procedure is initiated. At the end of eclipse, the calibration mechanism opens the Nadir view for the aperture again and nominal observation is resumed.

The sun calibration baffle as shown in Fig. 2 is designed to block Earth radiation and reflections from the spacecraft. Within these elevation constraints, the time interval for the solar calibration procedure is chosen such that it ends before atmospheric effects become significant just prior to eclipse. Baffle dimensions in azimuth direction are determined by the seasonal variations of the beta angle of the EarthCARE orbit. At the inside of the baffle a set of vanes prevents radiation originating outside its field of view from reaching the diffusers via a single reflection.

The layout of the calibration mechanism is provided in Fig. 4. Two sets of Quasi Volume Diffusers (QVDs) are applied. These grounded quartz prisms provide a uniform illumination of the instrument aperture and are able fill the entire field of view. They transform the irradiance of the sun to radiance, thereby reducing the flux to avoid saturation. Specific advantages of QVDs are that they offer a very smooth spectrum to the instrument, lacking spectral features and their tolerance to contamination. One diffuser set comes into action every orbit, while the other set is active only once a month. This allows for compensation of any ageing effects. Experience past applications of QVDs in space instruments [3] learn that their degradation is very low anyway.

The diffusers and openings are locating on a rotating part inside the calibration mechanism housing that is supported on a pair of ball bearings and is driven by a stepper motor. The calibration mechanism performs a very critical function for the instrument and is tested thoroughly to ensure its dependability in orbit.

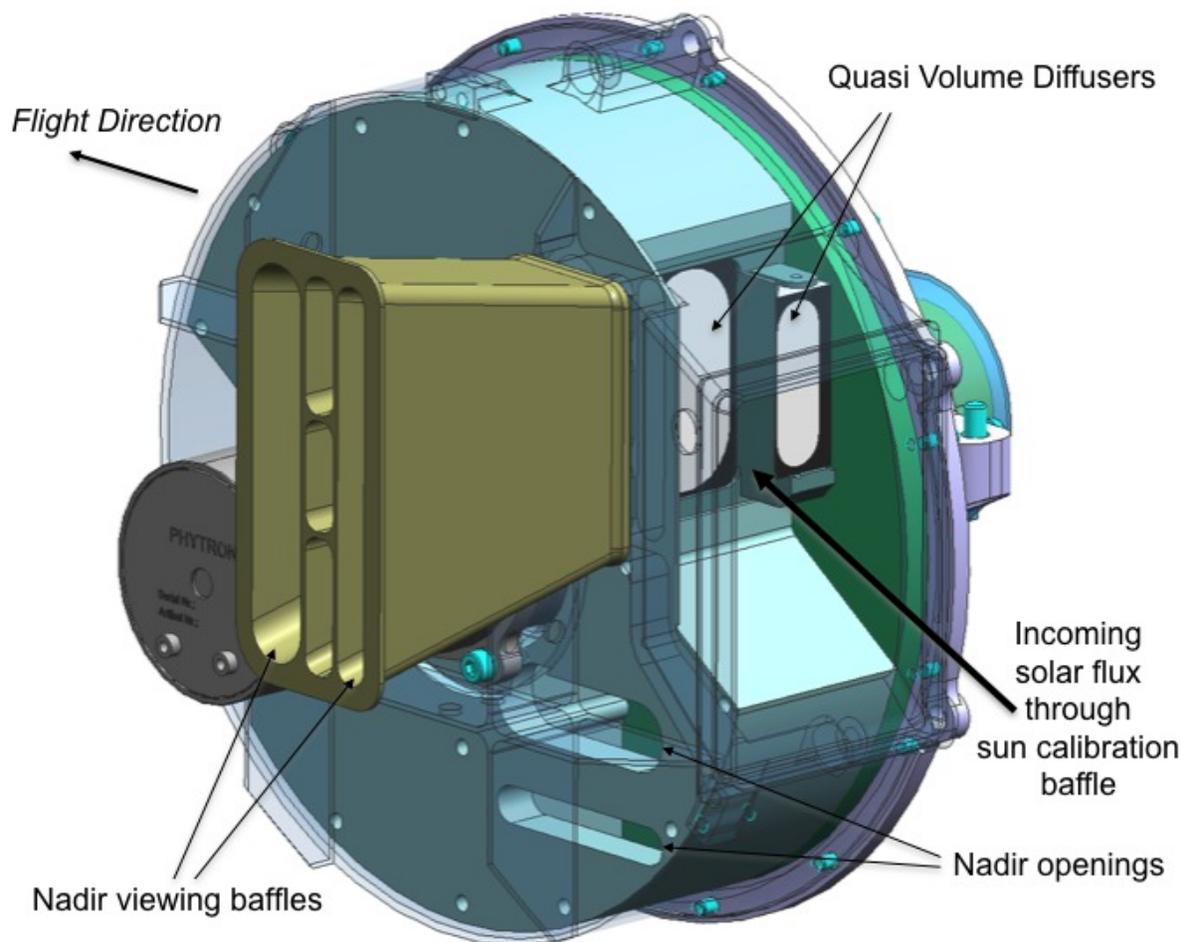


Fig. 4. VNS calibration mechanism

VII. STRUCTURAL DESIGN

As usual for this type of instrument the structural design is facing challenges in achieving sufficient stiffness and strength while still obeying requirements on optical alignment stability. For the VNS the severe volume constraints add to these challenges.

Within the VNS structural concept, the following principles have been applied to achieve this:

- Avoid over-determination of structural parts. This reduces stresses due to thermal and mechanical loads and improves position repeatability under cyclic loads.
- Attachments between parts shall not rely on friction only.

As an example the concept of supporting the detector assembly on the camera with the channel optics is taken. The design of the SWIR-2 and VIS camera assemblies is shown in Fig. 5. The principle is applied for all four channels. The basic support elements are four Titanium spokes which are adjustable in focus direction by shimming. Three additional spokes restrict the residual movement of the detector assembly with respect to the camera and are adjustable by shimming as well. This concept allows achieving repeatable sub-micrometer stability for the position of the detector with respect to the camera optics. For the VIS, NIR and SWIR-2 channel the thermal loads do not play a large role in the overall stability budget. However in the SWIR-2 detector assembly thermal loads are significant and thus the spokes perform a dual function:

- They provide thermal insulation between the SWIR-2 channel optics at 293 K and the SWIR-2 detector assembly at 230 K, which is essential for the passive cooling concept as applied in VNS.
- They compensate for thermal stresses in the structure due to this large temperature gradient and therefore provide the required positional stability.

The principle of reducing stress build-up often includes the application of flexures and elastic hinges. Another application of this principle is shown in Fig. 5 in the camera design. The lens housings are mounted on the camera main structure using a configuration of flexures that minimises stresses and enhances stability.

One final remark on the structural concept: VNS volume constraints have led to a very compact design. The camera assemblies in Fig. 5 are shown in their actual size. Next to all other considerations, accessibility and integration aspects play a significant role in the design of this instrument.

VIII. THERMAL DESIGN

In the VNS thermal design obviously there is a focus on the cooling to 230 K and temperature regulation of the SWIR-2 detector. In early design phases cooling of the SWIR-2 detector with a thermo-electric cooler has been considered. Due of issues with power demand and technology qualification status of thermo-electric coolers, passive cooling has been preferred in this application.

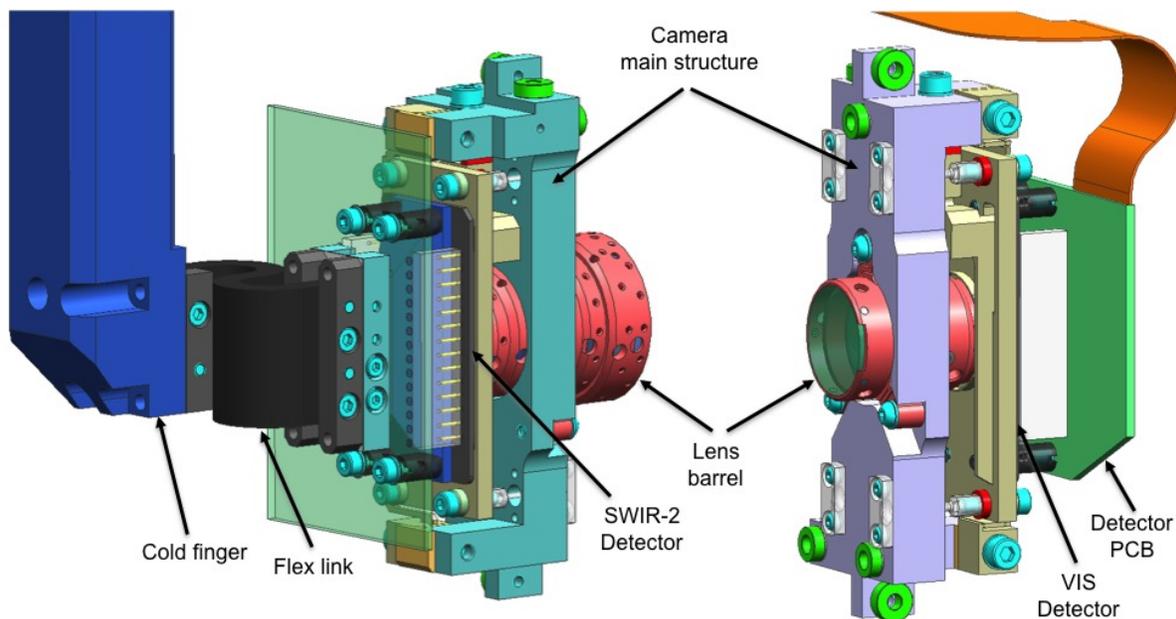


Fig. 5. SWIR-2 and VIS camera assemblies

The SWIR-2 radiator as shown in Fig. 2 rejects the sum of internal dissipation and all parasitic heat loads on the SWIR-2 detector assembly. The thermal design aims at minimising heat load and maximising radiator performance:

- With respect to the VNS mounting interface plane on the MSI bench the SWIR-2 radiator is tilted towards cold space to maximise its heat rejection capability.
- The SWIR-2 radiator is supported on struts with a low thermal conductance.
- The heat from the SWIR-2 detector is transferred to the radiator through a cold link. This cold link consists of a solid aluminium cold finger combined with a thermal flex link, shown in Fig. 5. The thermal flex link is a package of bent aluminium foils that conduct heat but minimise mechanical loads on the SWIR-2 detector.
- The suspension spokes reduce parasitic heat loads on the detector assembly as shown in Fig. 5. In addition, the flex rigid connecting the detector to the front end electronics is an excellent thermal insulator. Finally the detector assembly will be wrapped in low emissivity foil to reduce radiative heat leaks from its environment.

Driven by radiometric accuracy requirements, the SWIR-2 temperature level is controlled within less than 0.1°C by an active temperature control loop. Two more active temperature control loops in the optical unit and in the calibration unit reduce the impact of external sources of temperature fluctuations. For non-operating modes the VNS unit is equipped with two thermostat-controlled level heater circuits.

With the exception of the SWIR-2 radiator and the baffle openings, the entire VNS unit is covered with multi-layer insulation blanket to minimise the influence of the external flux environment.

CONCLUSION

This paper describes with a selection of design highlights how in the VNS design a combination of optical, mechanical and thermal challenges in a very limited envelope are met. Although the main function of the VNS unit is optical imaging and detection, many other engineering disciplines need to contribute to the design in order to be able to meet the performance requirements.

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TNO Science and Industry and Dutch Space B.V. jointly develop the VNS instrument in an integrated team in which complementary engineering disciplines of both partners are represented.

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