

Opto-Mechanical Design of an Imaging Spectrometer for the Thermal Infrared

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ABSTRACT

The current paper presents the activities in the development of a prototype imaging spectrometer for the thermal infrared (TIR). Requirements for the spectrometer are similar to ESA's Nitrosat [1] mission candidate: a fast optical system (F/2), a wavelength range of 10 μm - 11 μm , a spectral resolution of 10 nm, and a spatial resolution below 500 m from an 800 km orbit.

The optical concept relies on two similar Korsch [2]-type Three-Mirror-Anastigmats (TMA) used as collimator and camera in combination with a flat, reflective grating. The focal length of the TMA of 125 mm was chosen to provide the required spectral resolution, allow for a compact mechanical design and good manufacturability of the grating. The distortion of the optical system is reduced by a freeform modification of the surface on the middle mirror of the camera.

An athermal design is reached by making, mirrors, grating, and housing from the same material. The optical elements including the grating [3] will be manufactured by Single-Point Diamond Turning (SPDT) and Milling. The technology used also allows mounting and reference surfaces to be manufactured in the same production run, which considerably simplifies the later alignment of the system[4].

For a future flight model, the spectrometer will be combined with a TMA-type entrance telescope with a focal length of 75 mm.

Keywords: Imaging spectrometer, thermal infrared, three mirror anastigmat, single-point diamond turning

1. INTRODUCTION

The thermal infrared range allows the investigation of important atmospheric trace gases, such as ozone or Ammonia. The latter one as well as its sources in agriculture and chemical industry were a target for the activities of ESA in the framework of the Nitrosat [1] proposal.

Previous spectrometers in this spectral range primarily used the Fourier-transform (FT) concept, which provides high spectral resolution and good sensitivity. However, the FT concept uses multiple exposures and thus, always mixes up spatial and spectral information, which compromises the spatial resolution. High spatial resolution is required to identify individual sources of atmospheric pollution.

In the current project this issue is addressed by using the concept of a conventional, dispersive imaging spectrometer. The respective requirements were inspired by ESA's Nitrosat [1] mission candidate. A summary of the key parameters of the optical system is given in Table 1 below.

In the first phase of the project different spectrometer concepts have been compared wrt. their applicability for the TIR spectral range as well as their manufacturability. The preferred concept uses a first TMA to collimate the light coming from the slit of the spectrometer. A plane, reflective grating in the collimated beam provides the required dispersion, while a second TMA focuses the light onto the detector.

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Table 1. Key parameters of the TIR instrument.

Parameter	Value
Orbit height	800 km
Ground sampling distance	160 m
Field angle	$\pm 2.88^\circ$ (across track)
Spatial channels	503
Focal length of the entrance optics	75 mm
Numerical aperture	0.243 (F/2)
Pixel pitch	15 μm (Nyquist freq. 33 LP/mm)
Spectral range	10 μm ... 11 μm
Spectral channels	300
Spectral resolution	10 nm

2. OPTICAL DESIGN OF THE SPECTROMETER

System concept

The optical design of the spectrometer relies on two similar TMA. This approach considerably simplifies manufacturing, assembly and testing and allows to reduce the number of OGSE needed. The system pupil is located at the cold stop in front of the detector. Because of the symmetric layout, another pupil plane is located shortly behind the slit. It is used as an additional, potentially cooled stop in order to minimize false light. A sketch of the optical design is shown in Figure 1.

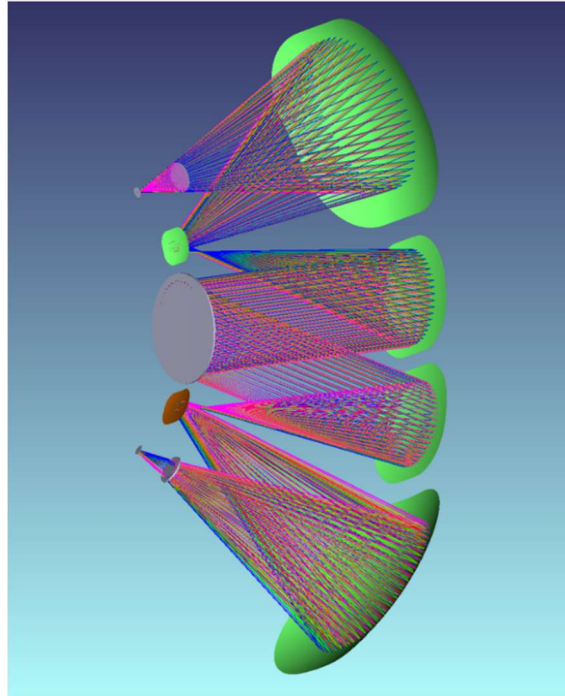


Figure 1. Optical design of the spectrometer. The slit is located on the top left, the detector on the bottom left side.

The mirrors are rotationally symmetric off-axis aspheres, except for the middle one in the camera TMA, which carries an additional freeform correction, which will be described later. The mirrors in each subsystem have a common optical axis. The optical elements will be made from Aluminum Al6061-T6 with a fine grain structure by SPDT. The material for the housing is conventional Al6061-T6.

A detector window with a thickness of 1.1 mm, made from Germanium, has been taken into account in the optimization of the spectrometer system.

Performance

The performance of the optical design is diffraction-limited over the complete spectral range as demonstrated by the MTF results given in Figure 2. The corresponding spot images are shown in Figure 3.

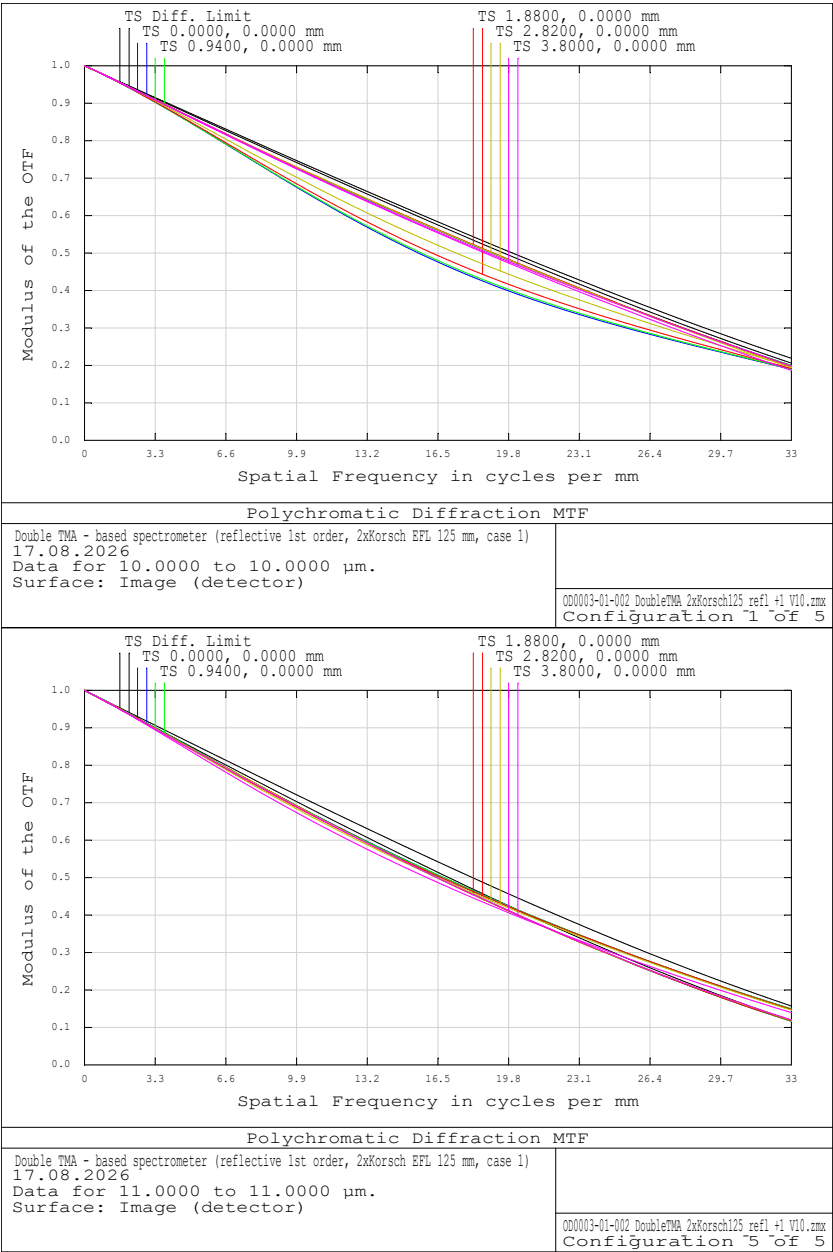


Figure 2. MTF of the spectrometer prototype. The upper image shows the performance at 10 μm, while the lower one corresponds to a wavelength of 11 μm.

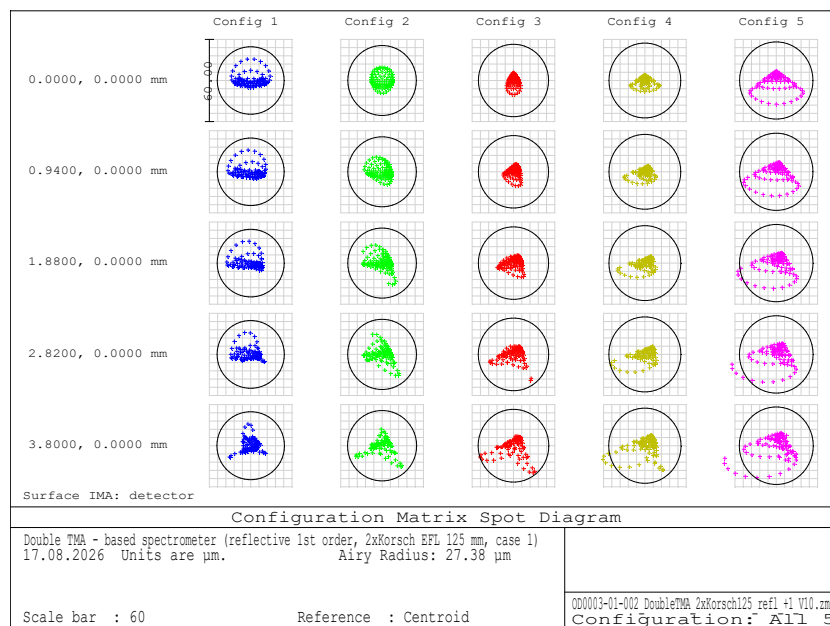


Figure 3. Spot images of the spectrometer prototype. The configurations correspond to different wavelengths (10 μm left, 10.25 μm , 10.5 μm , 10.75 μm , and 11 μm right, respectively).

The middle mirror in the TMAs is located close to an intermediate image plane, which allows it to be used for distortion compensation. In the current design, a free-form modification has been applied to the middle mirror in the camera TMA. The corresponding deviations from rotational symmetry with an amplitude of appr. 380 μm p.-v. are shown in Figure 4. Using this approach the remaining distortion of the spectrometer could be reduced to 1.3 μm of “smile” and 4.7 μm of “keystone”, respectively.

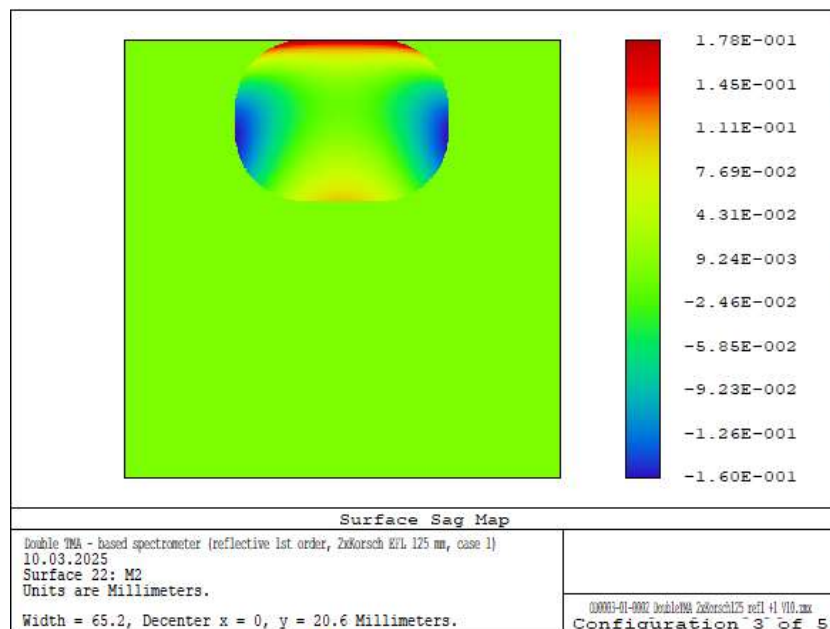


Figure 4. Freeform modification of the middle mirror in the camera subsystem.

Grating

The grating of the spectrometer will be made by diamond machining, as well [3]. The key parameters are listed in Table 2. The substrate is made from Aluminum and is covered with a thin coating of Nickel-Phosphorous, which is used to improve the reachable surface roughness and, hence, increase the efficiency of the grating. The final high reflective coating will be Gold.

Table 2. Key parameters of the grating.

Parameter	Value
Diffraction order	1st
Pitch	30.8 μm
Blaze angle	10.4°
Angle of incidence	3.5°
Diameter	77 mm

Simulation results of the grating structure show that an average diffraction efficiency of 90% may be expected. Diffraction efficiency is shown in Figure 5. The polarization sensitivity reaches 9% at the longest wavelength.

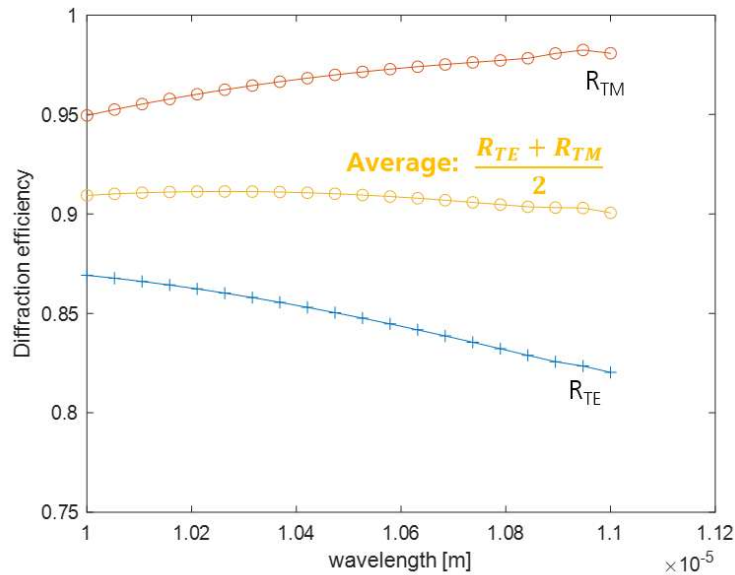


Figure 5. Simulated diffraction efficiency of the grating structure.

Tolerancing

Because of the complexity of the spectrometer, each subsystem (collimator/camera) will be adjusted separately. This approach is reflected in the tolerance simulation, where each subsystem has been analyzed separately.

The assumptions for tolerancing rely on the intended method of manufacturing by SPDT. Reference and interface structures on the mirrors will be manufactured by diamond milling in the same manufacturing run. This approach ensures tight position tolerances between the optical surfaces and the housing [4].

The assumed tolerances are listed in Table 3. The shape error of the mirrors has been chosen such that the overall wavefront error requirement (WFE) can be met, while keeping the manufacturing effort in a reasonable range.

Table 3. Assumed tolerances for the spectrometer mirrors.

Component	Variable	Value
Mirror positions	Lateral (x, y)	$\pm 20 \mu\text{m}$
	Axial (z)	$\pm 50 \mu\text{m}$
	Tilt (Rx, Ry)	$\pm 0.01^\circ$
Mirror form	Radius error	$\pm 0.1 \text{ mm}$
	Shape error	200 nm r.m.s.

The lateral positions of the middle mirrors have been used as compensators. During the alignment process, the mirrors will be shifted laterally (i.e. in x- and y-directions) to remove astigmatism, if present. The respective positions will be controlled by height gauges placed between reference surfaces on the mirror and corresponding surfaces on the housing.

The axial position of the detector, as well as its tilt, have been assumed as compensators, i.e. the interface between the spectrometer and the detector will be shimmed during the alignment process.

A separate Monte-Carlo analysis has been performed for each subsystem. The respective results were combined. Additionally, a surface error of 200 nm (r.m.s.) is assumed for the grating. The resulting budget for the wavefront error of the spectrometer is listed in Table 4. The resulting WFE of approx. $\sim \lambda/15$ is compatible with a diffraction-limited performance of the spectrometer.

Table 4. Summary of the tolerancing results.

Contribution	WFE [nm] r.m.s.	Weight
Nom. system	280	1
Collimator TMA	246	1
Camera TMA	243	1
Grating surface error	200	1.91
Detector window (Ge)	400 (est.)	1
Total (r.s.s.)	660 ($\sim \lambda/15$ @ $10 \mu\text{m}$)	

3. MECHANICAL DESIGN

The mechanical concept is based on the optical design with six reflective optical surfaces and one reflective grating. It is also driven by the manufacturing and alignment technology used for the mirrors and the grating [4]. An athermal design is ensured by using the same material (Al 6061-T6) for both mirrors and housing.

The spectrometer housing is milled from bulk Aluminum. The inner surfaces wrap around the optical path and act as straylight baffling as well. The interfaces to the optical elements are reworked by SPDT to ensure tight positioning tolerances. To simplify manufacturing and alignment, the housing is split into separate collimator and camera subsystems. The slit and the grating will be attached to the collimator housing.

The aspheric, off-axis mirrors are manufactured on-axis, i.e. using a free-form process. Free-form manufacturing allows, that their substrates also carry mounting interfaces, which are decoupled by solid-state hinges and reference surfaces for lateral positioning [4]. These references, as well as the mechanical interfaces of the mirrors, will be reworked in the same process, together with the optical surface. Corresponding reference surfaces are integrated in the respective housing. Top and bottom sides of the housing carry interfaces for thermal straps.

The whole assembly is connected to the optical bench by isostatic mounts. The housing parts, as well as the largest mirror, are lightweighted. The total mass amounts to approx. 15 kg. A simplified view of the mechanical design without bolts and thermal straps is shown in Figure 6.

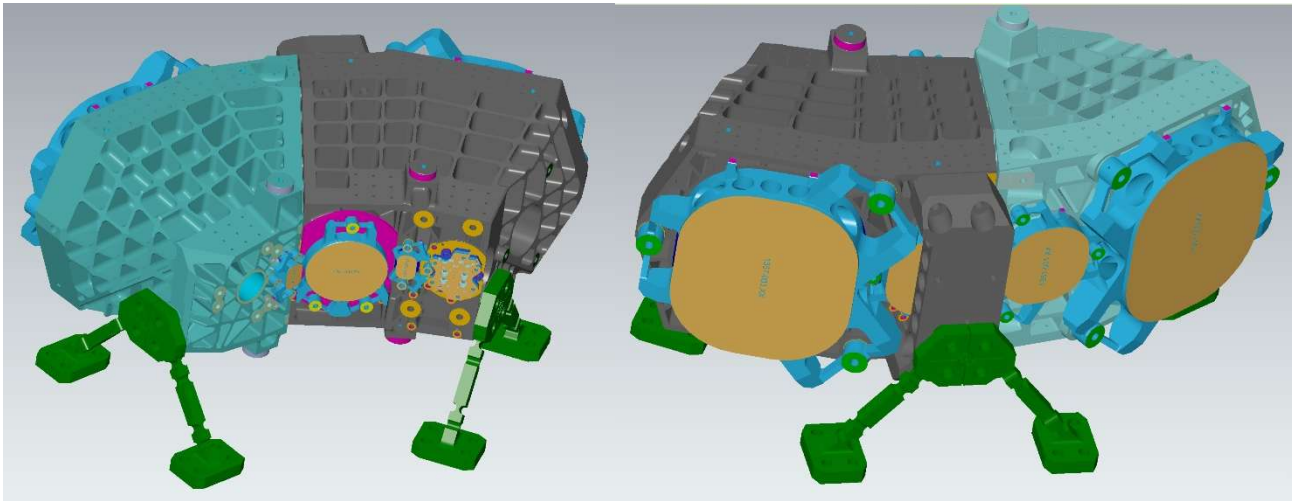


Figure 6. Mechanical design of the spectrometer (left: view from the entrance side, right: opposite side). Interface and reference structures are marked by yellow and pink colors. The isostatic mounts are marked green.

Slit assembly

The slit assembly is attached to the entrance side of the collimator subassembly. The slit is formed by two blades with an adjustable distance. Its edges are formed by a SPDT process. A thin Nickel coating is applied to the slit blades in order to improve their sharpness. A straightness tolerance of approximately 1 μm can be achieved for the slit edges, and a parallelism of approximately 3 μm can be reached during adjustment. The complete slit assembly is shown in Figure 7.

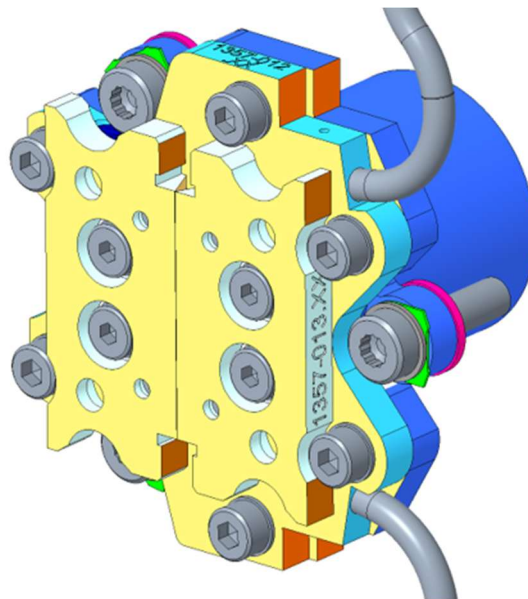


Figure 7. Mechanical design of the slit assembly. The stop is shown in dark blue.

The back side of the slit assembly carries a stop for false- and straylight suppression. The whole slit assembly including the stop can be cooled separately.

Thermal and mechanical analysis

The behavior of the prototype under mechanical and thermal loads has been analyzed by Finite-Element simulations of static acceleration, modal behavior, and thermo-mechanical effects. Some results will be shown below.

The first Eigenfrequency of the prototype reaches 250 Hz. The respective mode shape is given in Figure 8. The allowable quasistatic acceleration loads exceed 78 g, which is calculated by Miles equation for the current design.

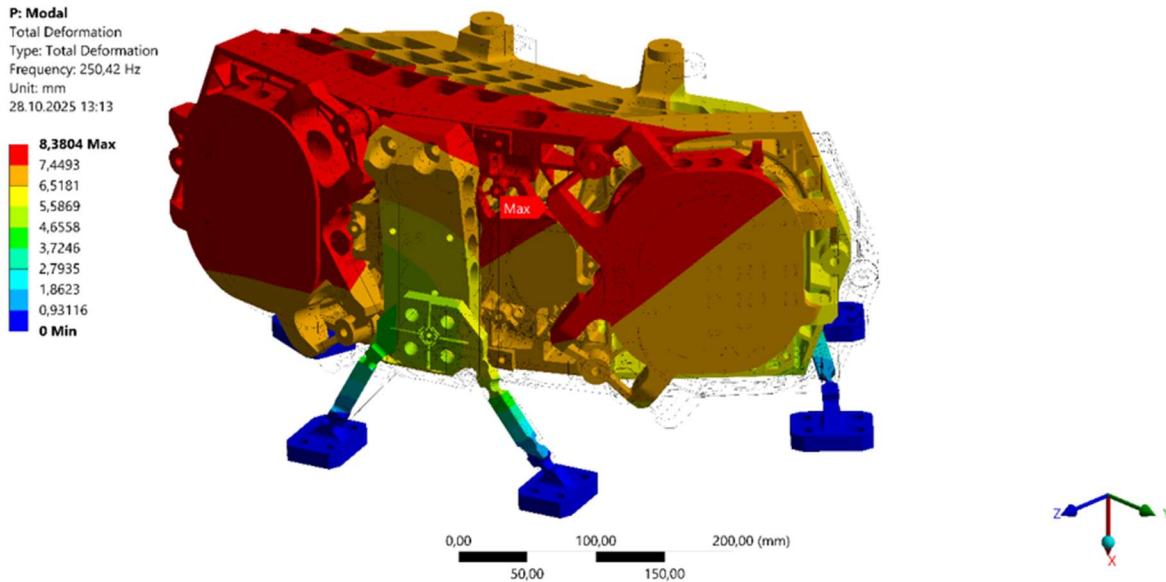


Figure 8. Shape of the fundamental Eigenmode of the prototype.

A thermo-mechanical simulation of the prototype under the expected cryogenic operating conditions also demonstrated diffraction-limited performance.

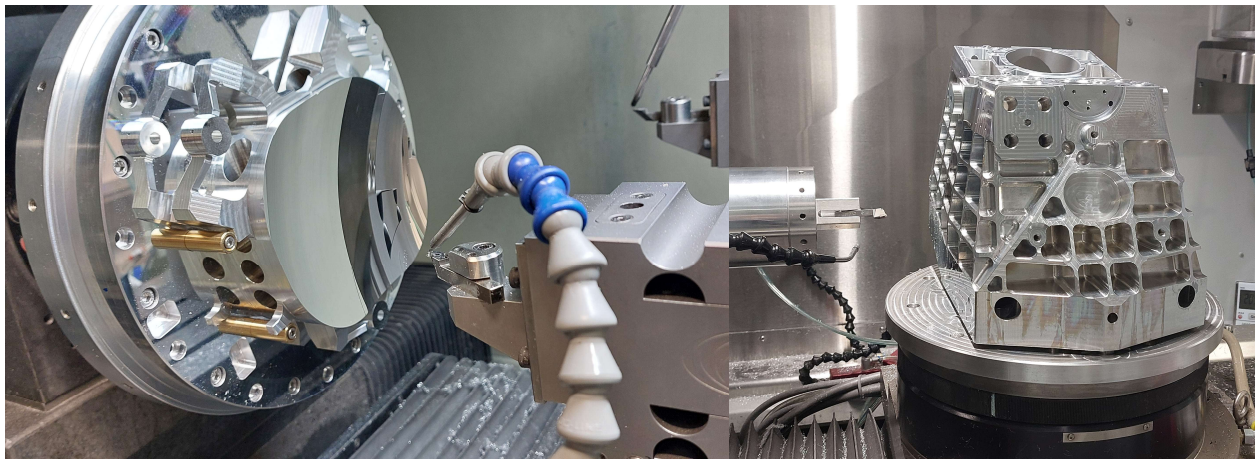


Figure 9. Parts of the spectrometer prototype during manufacturing. The left image shows one of the large spectrometer mirrors during SPDT. The right image shows the collimator body during diamond machining of the reference surfaces.

4. SUMMARY

In the current paper we present an opto-mechanical design of an imaging spectrometer for the thermal infrared. A laboratory prototype of the spectrometer is manufactured currently. Taking into account the performance of the system as designed, the influence of expected manufacturing and alignment tolerances, the optical requirements for the system will be fulfilled.

Currently the components of the spectrometer prototype are manufactured at IOF (see Figure 9).

As a result of the FE simulations, we assume that the current spectrometer design can be transferred into a flight model with only minor modifications. In flight configuration, the spectrometer will be combined with an adapted entrance telescope, which is under development.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] ESA (2023). Report for Assessment: Earth Explorer 11 Candidate Mission Nitrosat, European Space Agency, Noordwijk, The Netherlands, ESA-EOPSM-NITR-RP-4373.
- [2] Korsch, D., “Closed Form Solution for Three-Mirror Telescopes, Corrected for Spherical Aberration, Coma, Astigmatism, and Field Curvature”, *Appl. Optics* 11, 2987 (1972).
- [3] Ralf Steinkopf, et al, “Optimization of diamond machined gratings for low light scattering and highest diffraction efficiencies”, *euspen’s 23rd International Conference & Exhibition*, Copenhagen, DK, June 2023.4. Scheiding, S., Damm, C., Holota, W., Peschel, T., Gebhardt, A., and Risse, S., “Ultra-precisely manufactured mirror assemblies with well-defined reference structures”, *Proc. SPIE 7739*, 773908, 2010.
- [4] Scheiding, S., Damm, C., Holota, W., Peschel, T., Gebhardt, A., and Risse, S., “Ultra-precisely manufactured mirror assemblies with well-defined reference structures”, *Proc. SPIE 7739*, 773908, 2010.