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DESIGN OF AN IMAGING SPECTROMETER FOR EARTH OBSERVATION USING FREEFORM MIRRORS

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I. INTRODUCTION

In 2017 the new hyperspectral DLR Earth Sensing Imaging Spectrometer (DESIS) will be integrated in the Multi-User-System for Earth Sensing (MUSES) platform [1] installed on the International Space Station (ISS). The instrument is developed under the responsibility of the DLR. It will deliver images of the earth with a spatial resolution of 30 m on ground in 235 spectral channels in the wavelength range from 400 nm to 1 µm. As partner of the development team Fraunhofer IOF is responsible for the optical system of the imaging spectrometer, which consists of two primary components:

1. a compact Three-Mirror-Anastigmat (TMA) telescope which images the ground strip under observation onto a slit, and
2. the following spectrometer which reimages the slit onto the detector and performs the spectral separation using a reflective grating.

The whole optical system relies on metal-based mirrors. An athermal design is provided by using the same material for the instrument housing as for the mirrors.
The mirror surfaces are made by Single-Point-Diamond Turning (SPDT). Since the required spectral range is in the visible, a post-processing of the surfaces by Nickel plating [2] is necessary. The final surface shape and roughness are realized by a second SPDT step, subsequent Magneto-Rheological Finishing (MRF), and a post-polishing process [3].

II. OPTICAL DESIGN

A. Three-Mirror-Anastigmat (TMA)

The focal length of the telescope of 320 mm is determined by the required ground resolution of 30 m, the orbit height of the ISS of 400 km, and the pixel size of the intended detector which amounts to 24 µm. The aperture was chosen as F/2.8 in order to fulfil the signal to noise requirements for the instrument.
Though the TMA has a relatively large aperture its optical design follows a conventional strategy (see Fig. 1): All three mirrors are standard aspheres aligned on a single optical axis. The large mirrors share a common vertex in order to ease their manufacturing and the alignment of the instrument.
The theoretical performance of the telescope is close to diffraction-limited (see MTF in Fig. 2), leaving a considerable margin for possible fabrication tolerances.

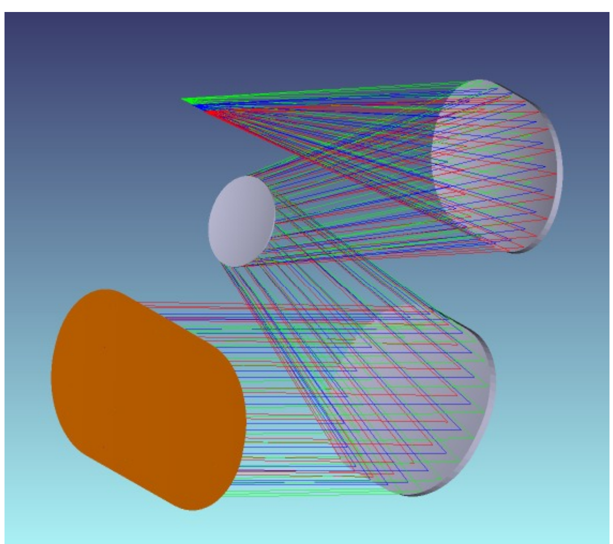

Fig. 1. Lay-out of the TMA.

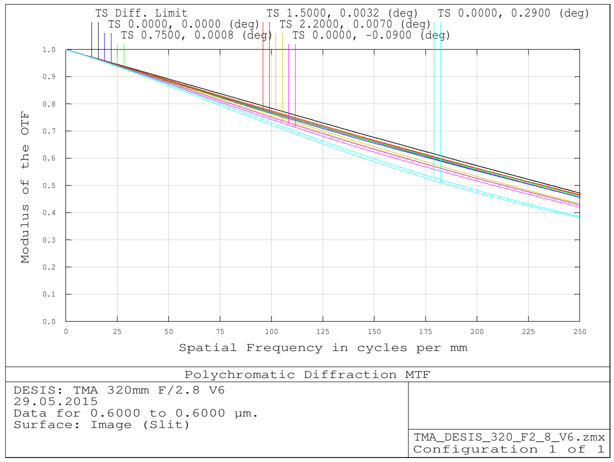

Fig. 2. Modulation transfer function (MTF) of the TMA.

B. Spectrometer

The spectrometer was designed on the basis of the so-called Offner scheme [4]: Light from the slit falls onto a large, concave mirror, which images the pupil onto a smaller, convex mirror, which is nearly concentric to the first one. A second reflection at the large mirror forms an image of the slit on the detector. The Offner scheme represents an excellent re-imaging system, because the aberrations, primarily astigmatism, caused by the three reflections on the spherical mirrors cancel each other nearly perfectly.

In order to convert this system into a spectrometer a grating is added on the convex surface of the central mirror (see Fig. 3) [5]. However, the spectral shift of the output beam disturbs the aberration balance of the original Offner scheme. The resulting astigmatism can be countered for a single wavelength by making the grating surface a toroid, by changing the mirror distance, or by splitting the large mirror [6]. However, in a conventional Offner-Type spectrometer with spherical mirrors considerable aberrations will remain. The dominant wavefront error is an astigmatism the size of which changes with wavelength (see Fig. 4).

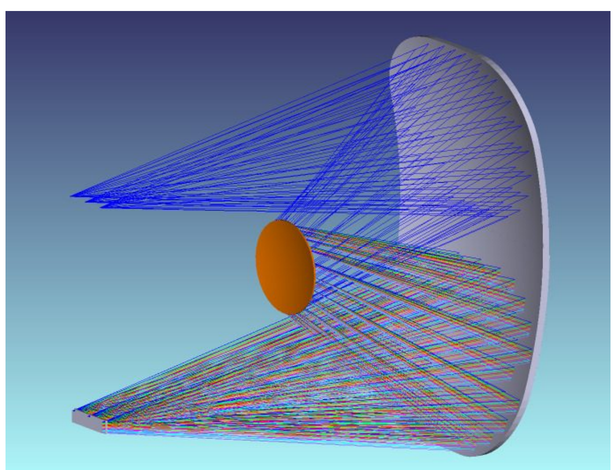

Fig. 3. Scheme of the Offner-type spectrometer.

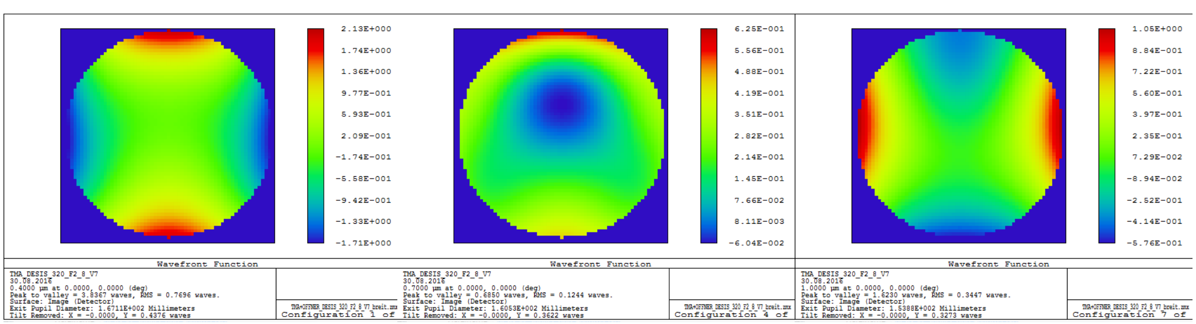

Fig. 4. Wavefront errors of an Offner spectrometer with spherical mirrors. Values are given for 400 nm, 700 nm, and 1 µm, respectively.

For the current instrument we chose a different approach that allows for the compensation of aberrations over the whole spectral range. Our concept relies on using a freeform surface on the large "Offner" mirror. The shape of the deviation from the sphere is depicted in Fig. 5.

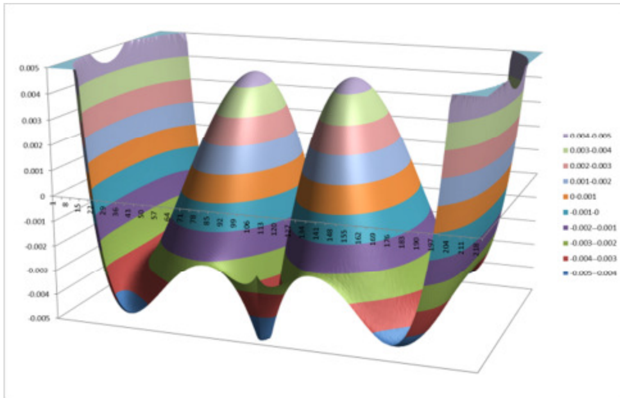

Fig. 5. Freeform part of the surface shape of the Offner mirror (average curvature subtracted).

The freeform part of the surface was described in terms of Zernike polynomials using the ZEMAX "Zernike Fringe Sag" surface type [7] with two patches on the Offner mirror centered on the incoming and outgoing beams, respectively. Optimization of the freeform resulted in a structure that is mirror-symmetric about both the x- and y-axes. The dominant contributions to the freeform deviation on the input side of the mirror are given in Table 1.

Table 1. Amplitudes of the dominant Zernike terms.

Zernike Fringe Polynomial	Amplitude [µm]
5	1.1
8	-3.7
11	2.2

The magnitude of the resulting freeform part of the surface is relatively moderate: The deviations from the sphere amount to 10 µm peak to valley.
The resulting wavefront errors are given in Fig. 6. At the edges of the spectral range aberrations reduce considerably compared to the all-spherical design, while the wavefront error remains practically unchanged in the center of the spectral range (compare Table 2).

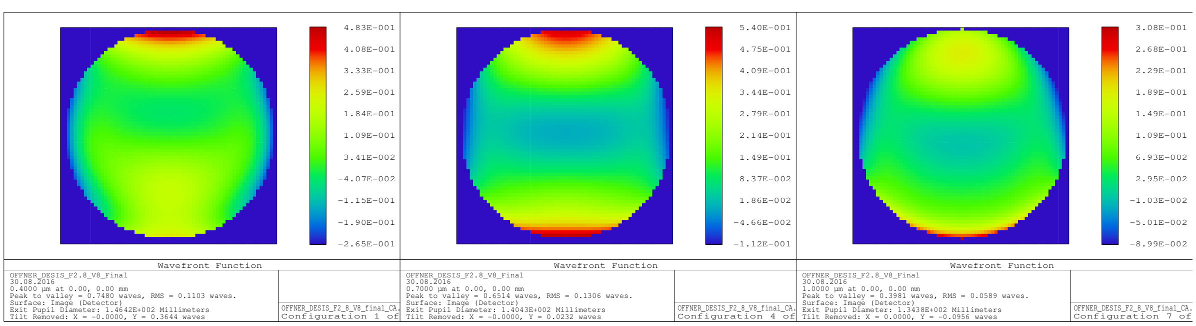

Fig. 6. Wavefront errors of an Offner spectrometer with a freeform mirror. Values are given for 400 nm, 700 nm, and 1 µm, respectively.

Table 2. Comparison of remaining wavefront errors of freeform and spherical designs, respectively.

Configuration	Spherical			Freeform		
Wavelength [nm]	400	700	1000	400	700	1000
Wavefront error (λ r.m.s.)	0.77	0.12	0.34	0.11	0.13	0.06

The mechanism of compensation can be explained as follows: The freeform deformation is imprinted into the incoming wavefront during the first reflection at the Offner mirror. Due to the spectral dispersion of the grating

the beam footprint on the output side of the mirror will suffer a wavelength dependent shift with respect to the second freeform pattern.
The overall wavefront deformation may be described roughly as an overlap of two mirror-symmetric patterns, which have a wavelength-dependent shift with respect to each other. In particular, the overlay of the shifted Koma (Z8) terms is responsible for the wavelength-dependent astigmatism needed.
The combination of both surfaces in a single mirror allows for an excellent alignment of the two freeform surfaces.

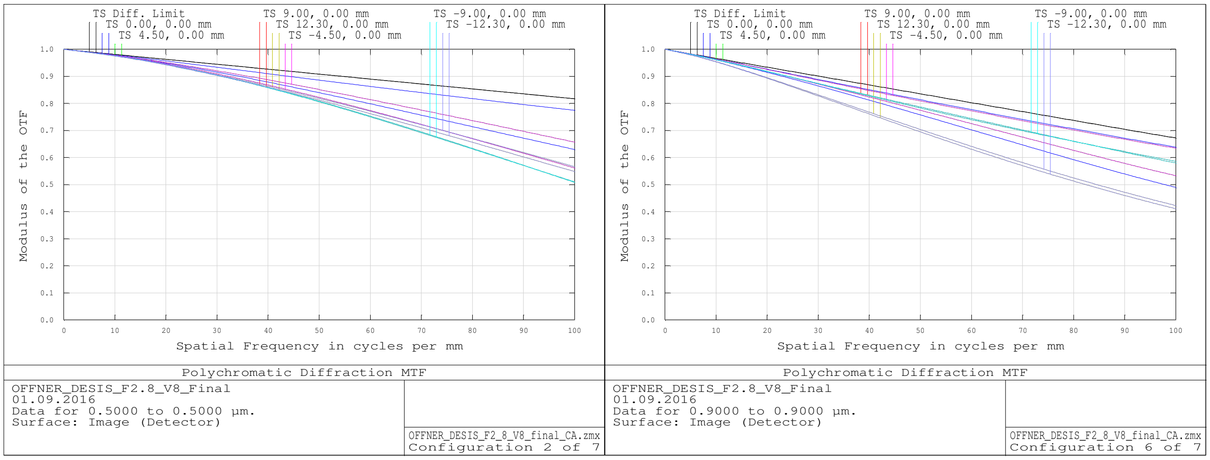

Fig. 7. Modulation transfer function (MTF) of the spectrometer for wavelengths of 500 nm (left), and 900 nm (right), respectively.

Due to the use of a freeform mirror a good imaging quality of the spectrometer in combination with a high throughput could be maintained over the whole spectral range. Respective MTF values at the edges of the spectral range (500nm and 900 nm) are presented in Fig. 7.

III. MECHANICAL DESIGN OF THE INSTRUMENT

The whole optical system relies on metal-based mirrors. Similar materials are chosen for the mirror mounts and the instrument housing in order to obtain an athermal behaviour of the complete opto-mechanical system.
The instrument is divided into a TMA and a spectrometer part, respectively, connected by a central mounting block.
The system concept is shown in Fig. 8. The housing elements are designed to wrap the light path. Their inner surfaces are designed to act as baffles.

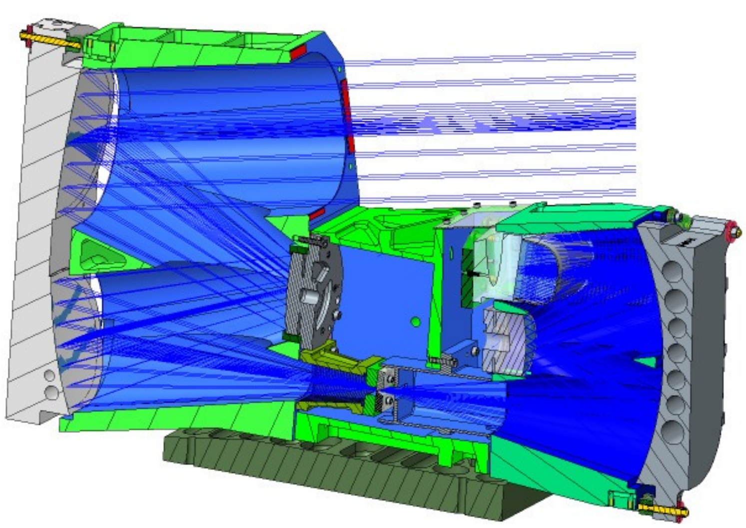

Fig. 8. Cut-view of the opto-mechanical system. The TMA is on the left side, the spectrometer on the right one.

A. Mirror design

The surfaces of metal mirrors are usually prepared by Single-Point Diamond Turning (SPDT). Since the required spectral range is in the visible, the surface roughness achievable by SPDT is not sufficient. Thus it is necessary to add a polishing step. On the other hand polishing requires a hard surface material like an electroless Nickel coating [2, 3], the thermal expansion of which does not fit to conventional Aluminum. In order to avoid bimetallic bending effects that would limit the usable temperature range we use an Aluminum-Silicon alloy [8] the CTE of which matches that of the Nickel coating.
The mechanical design of large mirrors for the TMA and the spectrometer relies on the Duolith-technology of IOF combined with freeform manufacturing technology [9, 10]. It allows for an excellent alignment of the respective mirror surfaces with respect to each other. In particular this is important for the freeform-based concept of aberration compensation used in the spectrometer.
Furthermore, optical and mechanical reference structures on the mirrors may be manufactured in the same SPDT run. This strategy allows for a significantly simplified adjustment of the optical system [11, 12].

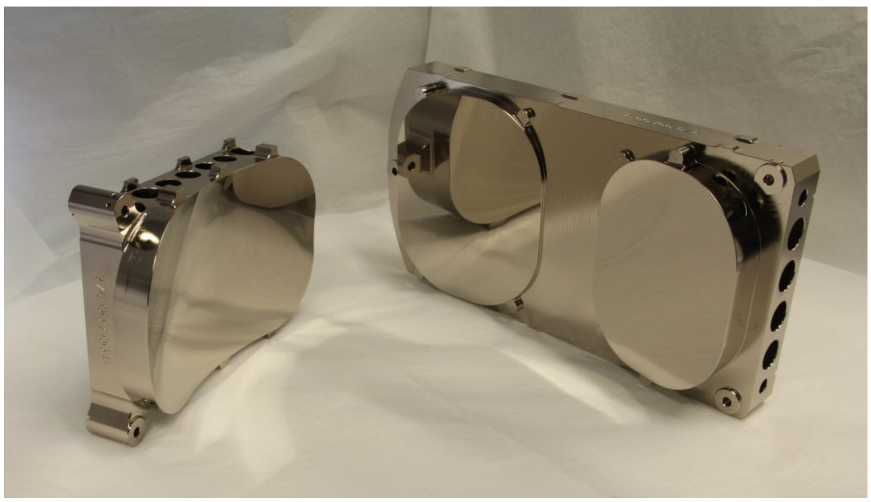

Fig. 9. Offner (left) and combined M1/M3 mirrors of the TMA (right).

The respective duolith mirrors of the DESIS instrument are depicted in Fig. 9. Reference surfaces can be seen on the sides of the actual mirror surfaces as well as on the side faces of the mirror substrates
Light-weighting of the mirrors is achieved by drilling of holes through the middle of the substrates.
The mirrors will be connected to the instrument housing via kinematic mounting elements.

Fig. 10. TMA (top) and spectrometer (bottom) housing elements prior to coating.

B. Instrument housing

The mechanical design uses light-weight housing elements which wrap the optical path to suppress stray light. This approach allows for a stiff mechanical set-up of the system, which is compatible with the harsh requirements of a space flight.
The actual housing elements for the DESIS instrument are depicted in Fig. 10. They were manufactured using a combination of eroding and CNC milling processes.
To provide high adjustment precision, the housing elements carry reference and mounting features similar to those on the mirrors. These elements will be finished by single-point diamond fly-cutting [11, 12] in a single machining run. They will be used to define a high precision starting point for the adjustment of the mirrors.

C. Alignment concept

The alignment of the DESIS instrument will be carried out in three major steps:

1. alignment of the TMA and the slit
2. alignment of the spectrometer
3. alignment of TMA and spectrometer w.r.t. each other.

For both TMA and spectrometer the integration of the optical components starts at the nominal position which are defined via mechanical stops attached to the reference surfaces at the respective housing. The actual position is controlled by inserting length gauges between the components and the respective stops.
Fine adjustment will be performed under interferometric control. In order to test the performance for different field angles the assembly under test will be placed on a movable table in front of the interferometer. The measurements will be performed in a double-pass configuration using a reference sphere centered on the respective image point. A reproducible positioning of the component under test w.r.t. the table is guaranteed by using a kinematic mount with balls and V-groves.
According to the results of the measurements a new position of the optical elements will be calculated. This new position will be reached in a controlled manner by changing the length gauges between the element and the respective mechanical stops.

IV. STRUCTURAL ANALYSIS OF THE OPTO-MECHANICAL SYSTEM

In order to verify the stability of the opto-mechanical setup of the DESIS instrument under launch and operational conditions a Finite-Element (FE) analysis has been performed using the simulation system ANSYS [13]. Targets of the analysis were:

1. the Eigenfrequencies of the instrument,
2. the response to acceleration loads as well as
3. the response to heat flow through the system.

A. Modal analysis

The Eigenfrequencies of a system to be used in space are crucial for its response to the shock and vibration loads during launch.
For the optical system of the DESIS instrument we found a fundamental frequency of 123 Hz which is a reasonable value taking into account the mass of the instrument of approximately 25 kg.

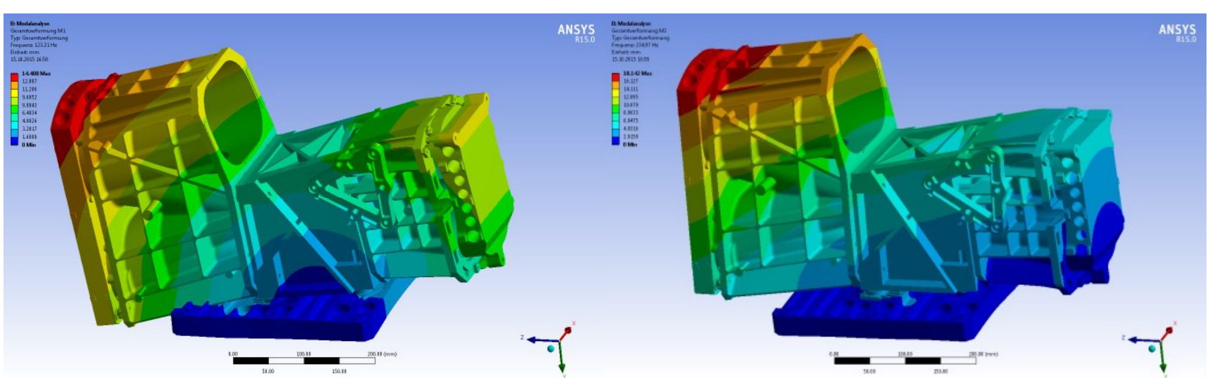

Fig. 11. Vibrational Eigenmodes of the opto-mechanical system. The fundamental mode at 123 Hz is shown in the left, while the second mode at 235 Hz is shown in the right picture.

The corresponding deformation pattern is depicted in Fig. 11. The fundamental mode is associated with a rocking motion of the whole setup about its transversal axis (X-axis in Fig. 11). The respective frequency is limited primarily by the stiffness of the instrument's mounting plate.
Higher modes have frequencies of 235 Hz, and 353 Hz, respectively. They also represent rocking modes of the whole instrument about its Z- and Y-axes, respectively. Significant mirror bending only starts at frequencies as high as 680 Hz.

B. Response to acceleration loads

Acceleration loads influence an opto-mechanical system in two ways. On one hand they introduce stresses in the mechanical components. On the other hand gravity induces deformations that will be released when the system enters weightlessness. In order to address those effects analyses have been performed with accelerations of 1 g acting in all three directions of space.

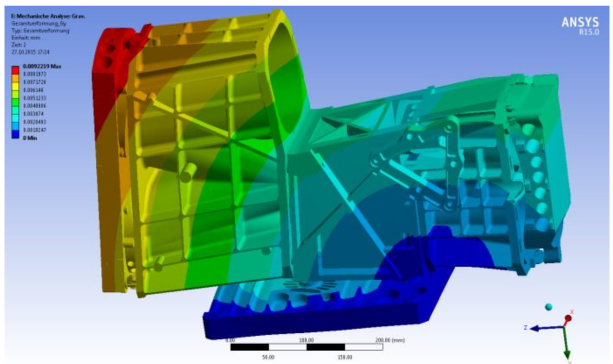

Fig. 12. Deformation (mm) of the system under gravity load in Y-direction (vertical).

An example of the results is given in Fig. 12. The maximum resulting gravity release effect reaches 2.4 nm r.m.s. on the mirror M1 of the TMA.
From the simulated stress levels a maximum acceleration load of 80 g is derived. This load is limited by the strength of the used Aluminum-Silicon alloy.

C. Response to thermal loads

Under operational conditions radiation may cause heat flow from its surrounding into the instrument. Since the thermal expansion of the used materials is not negligible, induced thermal gradients may deteriorate the performance of the optical system. In order to determine limits on allowed heat flow we simulated the response of the system to different types of radiation loading.
An example of the respective simulations is presented in Fig. 13. A heat flux of 10 W/m² (corresponding to 1.34 W total) falls onto the top side of the instrument, while the mounting points remain at reference temperature.

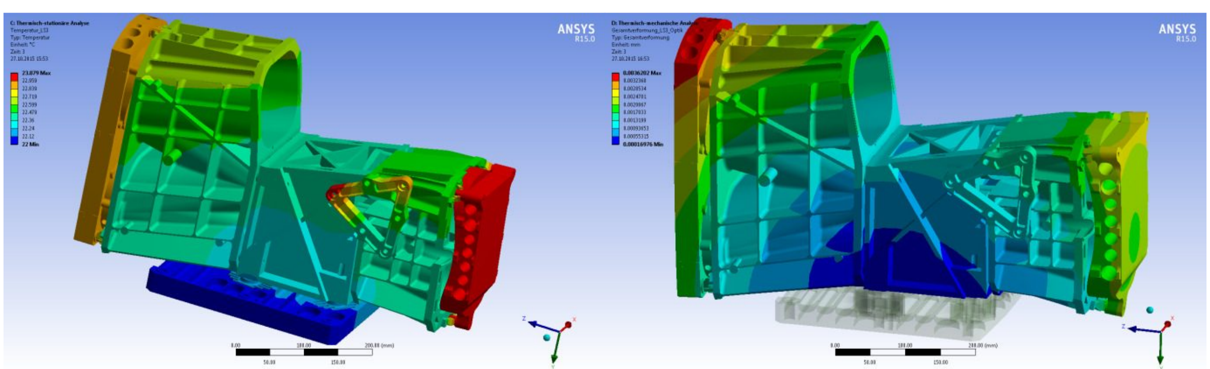

Fig. 13. Temperature distribution (K, left) and deformation pattern (mm, right) due to a thermal flux of 10 W/m² onto the top side of the instrument.

Under the above load the surface deformations of the mirrors will reach up to 4.5 nm r.m.s. on M3 of the TMA, and 9.7 nm r.m.s. on the Offner mirror, which is close to the tolerable limit. As a rule of thumb, gradients in excess of 35 mK in the large mirrors should be avoided.

V. SUMMARY

The current paper described the opto-mechanical system of the DESIS instrument and its two major components:

- a fast Three-Mirror Anastigmat telescope with a focal length of 320 mm, and
- a corresponding Offner type grating spectrometer.

While the performance of the TMA is close to the diffraction limit, astigmatism limits the resolution of the spectrometer. It is demonstrated, that this obstacle may be overcome by using a freeform mirror as a key element in the spectrometer. This strategy allows to increase the spectral resolution to 235 channels.
An all-metal design of the opto-mechanical system is proposed, which is compatible with the manufacturing of the mirror surfaces by single-point diamond turning and appropriate post-polishing.
Reference structures on the mirror bodies will be manufactured in the same production run as the optical surfaces. Corresponding reference surfaces on the housing elements allow to simplify the alignment process considerably.
Finite-Element Analysis of the optomechanical system demonstrated that it is compatible with the required operational and launch conditions and defined limits for allowable thermal radiation loads.

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