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Integration and testing of an imaging spectrometer for earth observation

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ABSTRACT

The DLR Earth Sensing Imaging Spectrometer (DESIS) is a space-based hyperspectral instrument developed by Deutsches Zentrum für Luft- und Raumfahrt (DLR). The optical system of the spectrometer was fabricated and pre-aligned by the Fraunhofer-Institut für Angewandte Optik und Feinmechanik (IOF).

The paper describes the manufacturing, integration, and testing of this optical system. It was realized as an all reflective system using metal-based mirrors and a modular, so-called snap-together approach, which allows to simplify the integration of optical systems considerably. Measured r.m.s. wavefront errors of the complete system are in the range of 63 nm to 120 nm, which is compliant with the instrument's requirements.

Keywords: DESIS, ISS, MUSES, TMA telescope, imaging spectrometer, metal optics, freeform mirror, snap-together.

1. INTRODUCTION

The DLR Earth Sensing Imaging Spectrometer (DESIS) is a hyperspectral imaging system which is currently integrated on the Multi-User-System for Earth Sensing (MUSES) platform[1] of the International Space Station (ISS). The DESIS instrument was developed under the responsibility of Deutsches Zentrum für Luft- und Raumfahrt. It will deliver images of the earth with a spatial resolution of 30 m on ground in 235 spectral channels in the range from 400 nm to 1 µm.

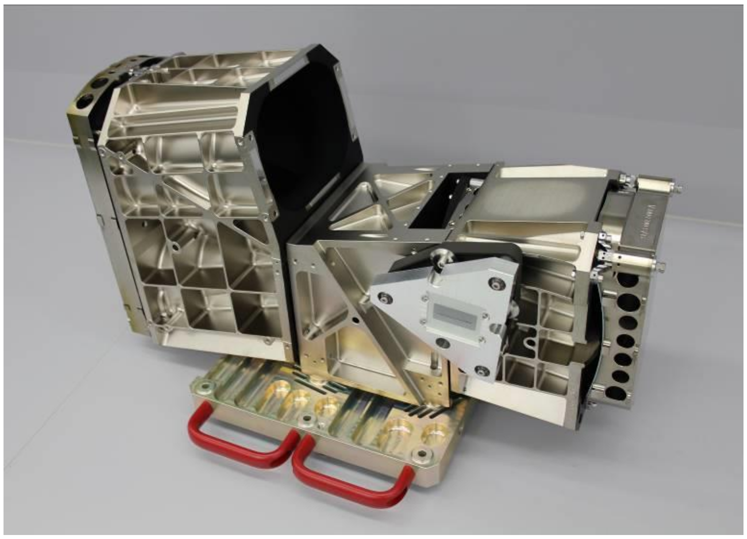

Figure 1. Optical system of the DESIS instrument. The telescope is on the left side, the spectrometer on the right. The light gray, triangular body is a detector dummy.

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As a partner of the development team Fraunhofer IOF was responsible for the development, manufacturing, integration, and test of the optical system, which consists of a telescope, a slit and the actual spectrometer module. The complete system is depicted in figure 1.

The optical as well as the mechanical design of the optical system were described in an earlier paper[2]: The telescope is a compact, fast Three-Mirror-Anastigmat (TMA) with a focal length of 320 mm and an aperture of F/2.8, which images the surface of the earth onto a slit. The spectrometer relies on a modified Offner type[3] design. The key components are a grating on the curved central mirror and a large outer mirror, which is modified by a freeform shape in order to reduce wavelength-dependent aberrations.

The concept of the optical system bases completely on metal mirrors, which were manufactured by single-point diamond turning[4]. Where possible, two mirrors were grouped into a module and fabricated in a single manufacturing run together with the respective mounting and alignment features[5]-[7].

The current paper summarizes the manufacturing, integration and test of the optical system of the spectrometer. In summer 2017 the optical system was shipped to DLR for integration into the DESIS instrument. The results of the calibration campaign and the concepts for in-flight calibration were published in [8], and [9], respectively.

2. COMPONENT MANUFACTURING

2.1 Mirrors

The complete optical system relies on metal-based mirrors, which were fabricated by Single Point Diamond Turning (SPDT) and subsequent surface correction using Magnetorheological Finishing (MRF). In order to make use of the high precision of the SPDT process, pairs of mirrors were grouped as modules according to the so called duolith-technology of IOF, if possible. In addition to the optical surfaces, their substrates carry optical and mechanical reference structures[6], which were manufactured simultaneously with the mirrors. Typically, this strategy reduces the lateral misalignment between the respective mirrors as well as between mirrors and reference surfaces to well below 5 µm. In the case of the DESIS instruments we used two mirror modules: Mirrors 1 and 3 of the TMA as well as the large mirror of the Offner spectrometer (see figure 2).

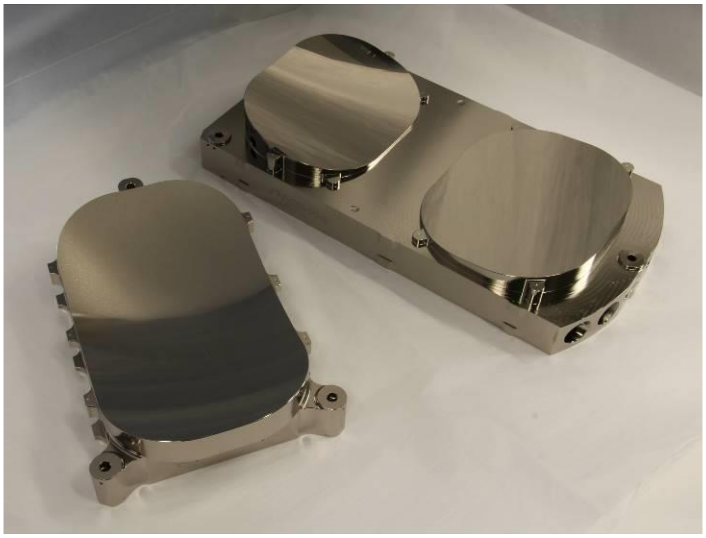

Figure 2. Offner (left) and M1/M3 mirror module of the TMA (right).

If the mirror surfaces of a duolith are dissimilar, the SPDT machine must be capable of freeform-manufacturing in order to cut both surfaces in one machining run. In order to reduce the stroke and acceleration of the freeform tool, it may be favorable to displace the machining coordinate system with respect to the optical one. In the case of the M1/M3 module the machining coordinate system was shifted by 20 mm and tilted by 1° w.r.t. the optical axis. Figure 3 shows the map of the respective tool path. The tool stroke could be reduced to 4 mm.

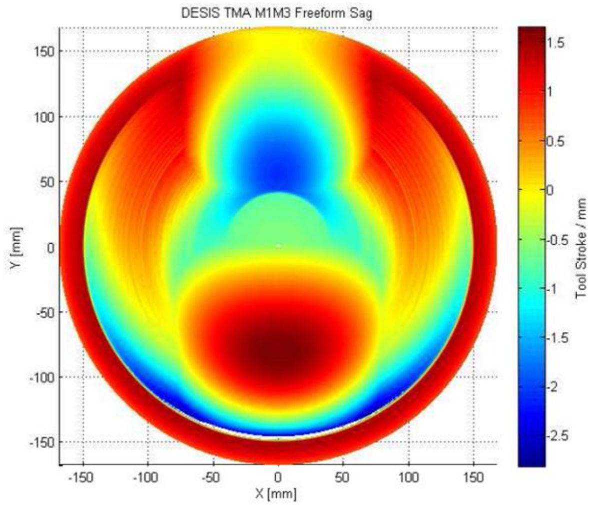

Figure 3. Map of the tool path used for the fabrication of the M1/M3 mirror module.

2.2 Component housing

In order to avoid thermally induced deformations, the housing of the components were manufactured from the same material as the mirror modules. The housing wraps around the optical path to suppress stray light.

In order to make use of the high precision of the reference surfaces on the mirror substrates, a similar precision is required for the corresponding surfaces of the housing. That’s why the respective surfaces were finished by a Single Point Diamond fly-cutting process.

2.3 Grating

The optical design of the DESIS spectrometer requires a reflective grating on a curved surface. Because of the large spectral range of the instrument a symmetric, binary grating was chosen in order to suppress the second diffraction order. Key parameters of the grating are a period of 13.4 µm, a grove depth of 137 nm and a duty-cycle of 1:1.

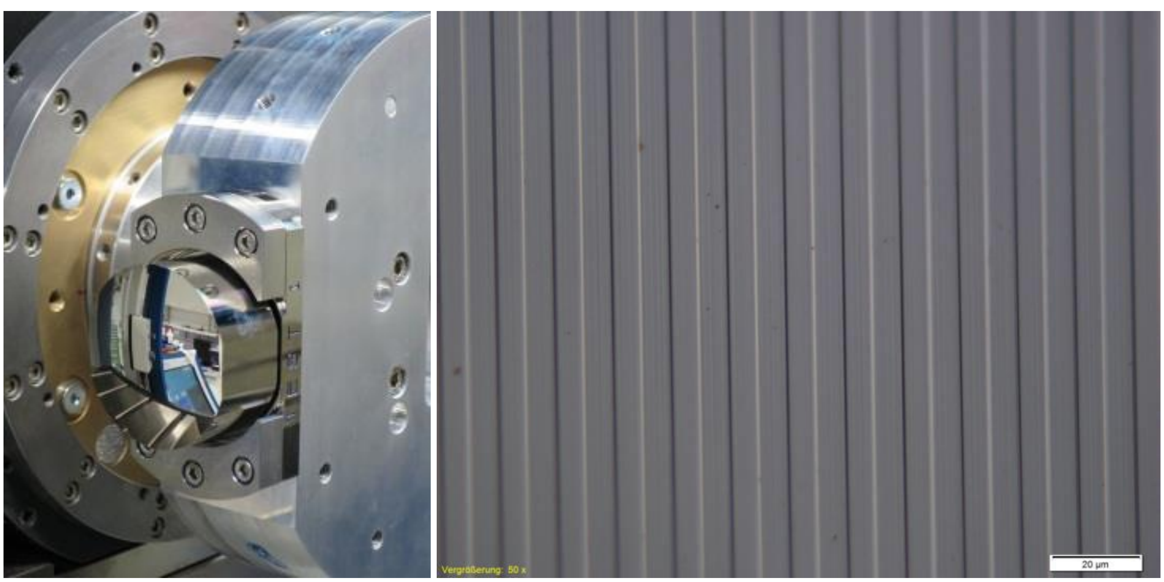

Figure 4. Manufacturing setup for the reflective grating (left) and microscopical image (right).

Two manufacturing technologies for the grating were tested: Ruling on a Single Point Diamond Turning (SPDT) machine (see figure 4) and laser-based lithography.

The grating used in the flight model was a ruled one. The period of 13.4 µm and the depth of 137 nm are well within specification. The profile shows ridges with a width of 4.5 µm and grooves having 5.6 µm. The slopes account for 1.6 µm each. At a wavelength of 633 nm the measured diffraction efficiencies for the first order are in the range of (32.5 ± 2.5)%, which is close to the theoretical limit for this type of grating.

The remaining form error of the grating amounted to 36 nm (r.m.s.). Due to the manufacturing technology astigmatism is the dominant aberration.

In a parallel effort, similar gratings were manufactured using a lithographical process. Though they yielded similar performance those gratings could not used for the flight model because of time constraints.

2.4 Slit

The slit forms the separation between the telescope and the spectrometer module. For compatibility with the rest of the optical system, we chose a metal-based slit design. The blades were manufactured by Single Point Diamond fly-cutting and aligned on a carrier frame with the help of gauge plates. Figure 5 shows the design of the slit assembly as well as a view of the assembled system.

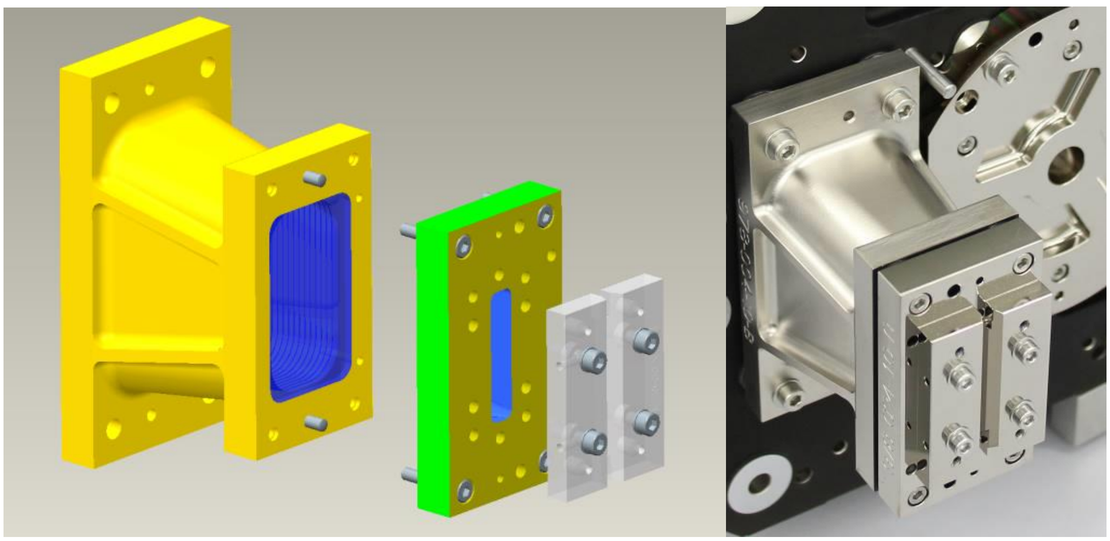

Figure 5. Exploded view (left) and image of the slit assembly mounted to the TMA (right).

After fixation by gluing the dimensions of the slit were measured with a camera system. The width amounts to 23.9 µm with a variation of 0.5 µm over a slit length of 24.6 mm. The straightness of the individual blades amounts to 1 µm.

3. INTEGRATION AND TESTING

3.1 Integration and alignment concept

In a first step each subsystem of the optics was assembled separately. Initially the components were placed on their nominal positions with the help of mechanical stops and gauge plates. Then the optical system was placed in front of an interferometer. The wavefront error was measured in a double-pass setup against a reference sphere. In a succeeding step the mirror modules were moved using gauge plates in order to reduce the aberrations.

Due to the high precision of the SPDT process, this strategy allows for a significantly simplified adjustment of the optical system[6]-[7]. An interferometric image could be acquired immediately after mechanical assembly and few iterations were necessary to find the optimum position for the mirror modules. In the case of the DESIS optics each subsystem could be aligned within 2 days.

Finally, both subsystems were mounted on a central, connecting block and characterized interferometrically.

3.2 Subsystem integration and test

The results of the interferometric characterization of the TMA and the spectrometer are presented in figure 6 below:

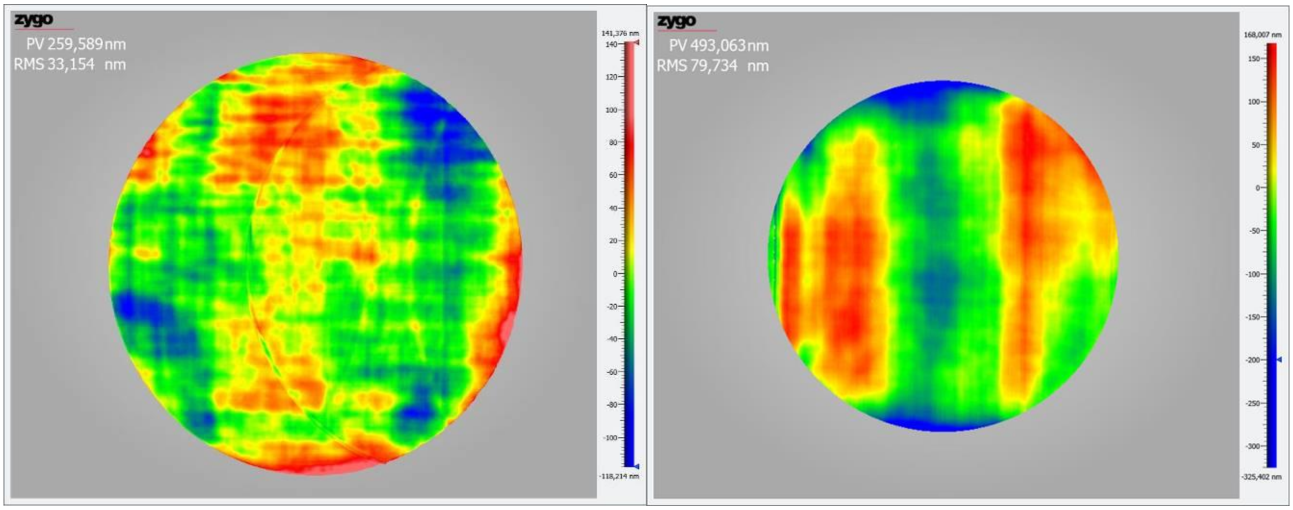

Figure 6. Measured wavefront errors of the TMA (left) and the spectrometer (right). The measurement position is in the center of the field of view.

The measured r.m.s. wavefront quality of the TMA is in the range of 33 nm to 81 nm depending on the respective position in the field of view. The corresponding results for the spectrometer are in a range between 70 nm and 114 nm. The best results are obtained in the center of the field while the wavefront error deteriorates towards the edges of the field.

3.3 Complete system

After integration the complete optical system was characterized interferometrically in a double-pass setup against a reference sphere. Depending on the respective position in the optical field the measurement results span a range between 63 nm and 120 nm r.m.s. (compare figure 7). The respective results and are close to the design limits and fully compliant with the requirements of the instrument.

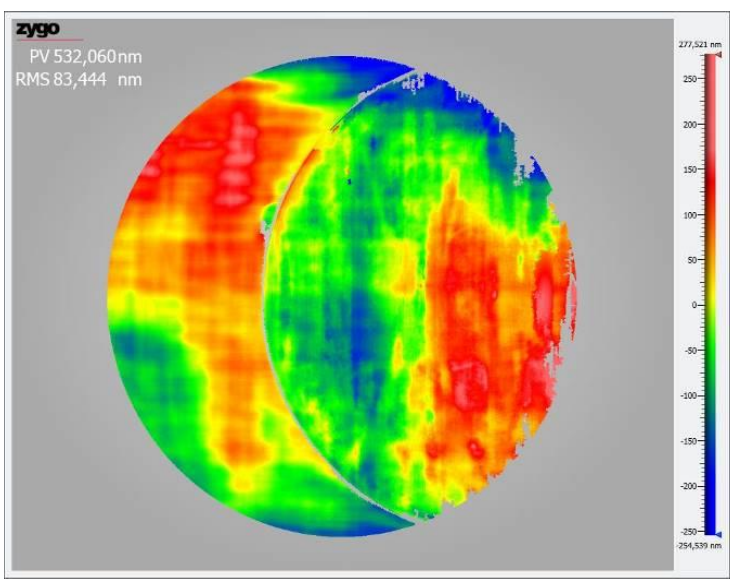

Figure 7. Measured wavefront errors of the complete optical system measured in the center of the field.

4. SUMMARY

The current paper describes the manufacturing, alignment and testing of the optical system for 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.

An all-metal design of the opto-mechanical system was realized. Single-point diamond machining in combination with Magneto-Rheological Finishing were used for the manufacturing of the mirror modules, the grating, and the slit blades.

By using mirror modules (duoliths) with ultra-precisely manufactured reference features the system integration could be simplified considerably.

The residual wave front error of the complete optical system is below 120 nm, which is fully compliant with the requirements of the instrument.

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