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EnMAP – Hyperspectral Imager (HSI) for Earth Observation: Current Status

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ABSTRACT

The Environmental Mapping and Analysis Program (EnMAP) is a German space borne science mission that aims at characterizing the Earth's environment on a global scale. The single payload of the satellite is the Hyperspectral Imager (HSI). It is capable of measuring the solar radiance reflected from the Earth's surface as a continuous spectrum in the spectral range of 420nm to 2450nm, with a spectral sampling of 6.5nm (VNIR) and 10nm (SWIR). The EnMAP swath of 30km is sampled in spatial direction with 30m GSD.

In this proceeding, we give an overview of the design and current integration status of the HSI instrument optical unit with additional focus on measured optical and electro-optical performance.

Keywords: EnMAP, hyperspectral remote sensing, earth observation.

1. MISSION CONCEPT

The Environmental Mapping and Analysis Program (EnMAP) is a German space borne science mission that aims at characterizing the Earth's environment on a global scale. The applications range from climate change impacts, the monitoring of large ecological systems, land cover changes, biodiversity processes and natural resources, to geohazard and risk assessments [1].

The satellite is based on a push-broom type concept and will operate in a polar, sun-synchronous, low earth orbit in 652km height. Crucial for the scientific aims of EnMAP are the short target revisit times requiring an agile satellite pointing up to 30° off-nadir. This allows for revisit times of maximum 4 days with a single satellite. The EnMAP swath width of 30km is sampled in spatial direction with 30m ground sampling distance (see Figure 1 for illustration). The data handling capacity is designed in order to allow for individual swath lengths up to 1000km and a total data of 5000km per day. The single payload of the satellite is the Hyper Spectral Imager (HSI). It is capable of measuring the solar radiance reflected from the Earth's surface as a continuous spectrum in the spectral range of 420nm to 2450nm, with a spectral sampling of 6.5nm (VNIR) and 10nm (SWIR).

The launch of the satellite is planned for 2020, with a design mission lifetime of 5 years.

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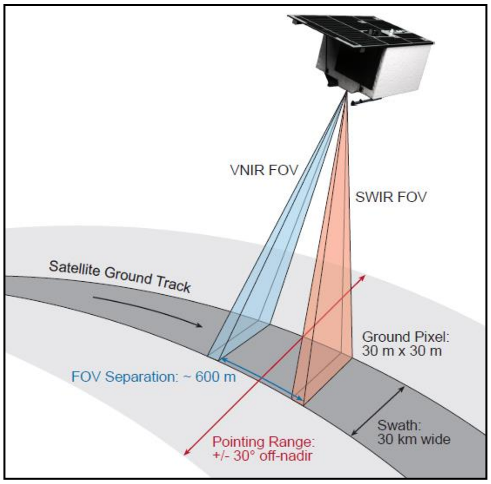

Mission Requirements	
Altitude	652km
Orbit	Polar, sun synchronous, 11:00 local time
Target revisit time	4 days (30° off nadir)
Pointing accuracy (knowledge)	500m (100m) at sea level
GSD	30m
Swath width	30km
Swath length	up to 1000km

Figure 1. **Left:** Representation of an EnMAP overpass featuring the dual-spectrometer instrument concept. The field-of-views (FOVs) of the visible near-infrared (VNIR) and shortwave infrared (SWIR) spectrometers are separated by ~600m on-ground track and are represented in blue and red, respectively. **Right:** Selected EnMAP mission requirements.

Table 1. EnMAP HSI instrument key requirements.

Instrument Key Requirements	
Spectral range	420-2450nm
Spectral Sampling Distance	VNIR: 6.5 nm SWIR: 10 nm
SNR	VNIR: 500:1 (@ 495nm) SWIR: 150:1 (@ 2200nm)
Radiometric resolution	14bit
Radiometric accuracy	<5%
Radiometric stability	<2.5%
Spectral accuracy	VNIR: 0.5nm SWIR: 1.0nm
Spectral stability	<0.5nm
Smile / Keystone	<0.2 pixel
Co-registration	<0.2 pixel

2. INSTRUMENT DESIGN

The relevant top-level requirements for the Hyper Spectral Imager are summarized in Table 1. The key design drivers are high optical throughput and low image distortion. A schematic view of the instrument design is presented in Figure 2. The instrument features a nearly diffraction limited three-mirror anastigmatic telescope (TMA) with an across-track field of view (FOV) of ±1.3°. The TMA has a 18cm entrance aperture and focusses the light from the earth's surface onto a field splitter slit assembly (FSSA). The FSSA includes two separate micro slits for in-field separation of the light and a micro-mirror to redirect the SWIR field into the SWIR spectrometer. Both, VNIR and SWIR spectrometer optics have unit magnification and are derived from an Offner relay imaging concept and employ curved prisms in dual pass configuration as dispersive elements. Light from the spectrometer is finally focussed on VNIR and SWIR focal planes arrays that acquire images at a frame rate of 230 Hz with 14-bit resolution. All optical elements are mounted to a monolithic 3-dimensional Aluminum structure. For fulfilling the stringent requirements on overall pointing stability, the star tracker sensor assembly is directly attached to the optical unit.

In addition to the optical key elements, the instrument also features a calibration device as entrance port, which allows switching between Earth view, full-aperture Sun diffuser calibration and launch protection modes. Furthermore, different on-board calibration sources can be fed into both spectrometers by means of a rotating mirror wheel mechanism. The whole instrument carries dedicated baffling systems ensuring good out-of-field stray light suppression.

In our chosen design, the required geometrical and spectral stability directly transfers to stringent requirements on thermal stability of the instruments optical unit. The thermal stability is achieved by heater control in combination with an actively controlled, sophisticated loop-heat pipe system.

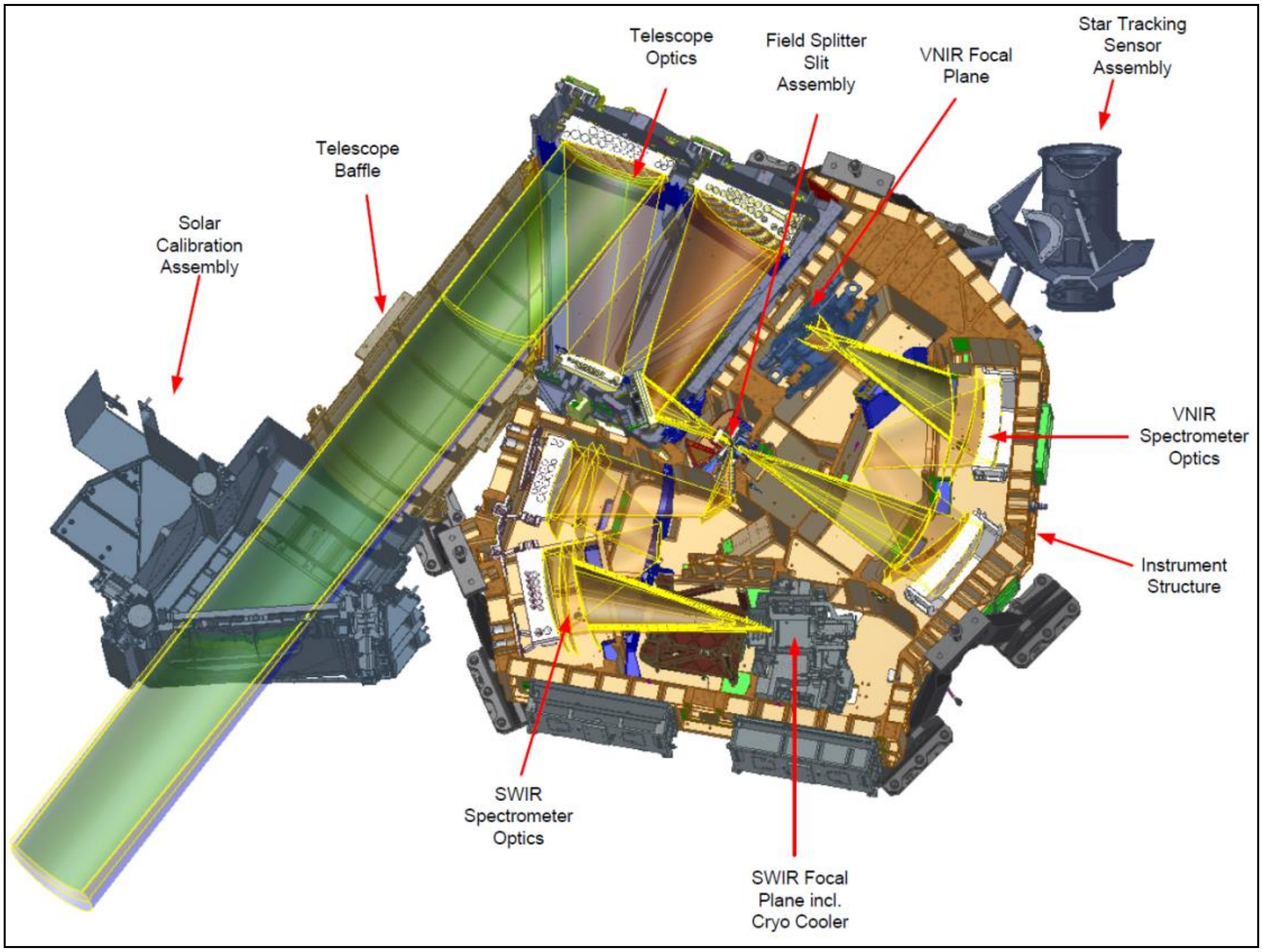

Figure 2. Schematic view of the main components of the EnMAP double-spectrometer instrument concept.

2.1 VNIR Focal Plane

The VNIR focal plane subsystem consists of a highly functionally-integrated back-illuminated complementary metal-oxide-semiconductor (CMOS) imager. The pixel design is based on a 5 transistor design and fabricated in 180nm technology. The detector has 1056x256 pixels with 24µm x 24µm pixel size. Each pixel column features an on-chip dual gain amplifier and an dual single slope column analog-to-digital converters (ADCs). Correlated double sampling in terms of separate reset & image frame readout is provided for improved read noise performance. The detector temperature setpoint is 21°C and actively controlled within ±50mK by means of a thermo-electric cooler (TEC).

2.2 SWIR Focal Plane

The SWIR focal plane system features a mercury-cadmium-telluride (MCT)-type detector (cut-off wavelength 2.55µm) coupled to an integrated read-out circuit. The detector has 1024x256 pixel with 24µm x 32µm pixel size. The necessary readout speed is provided by 8 parallel analog video output channels. The detector is operated at 160K by the use of a pulse tube cryocooler and stabilized within ±25mK during operation.

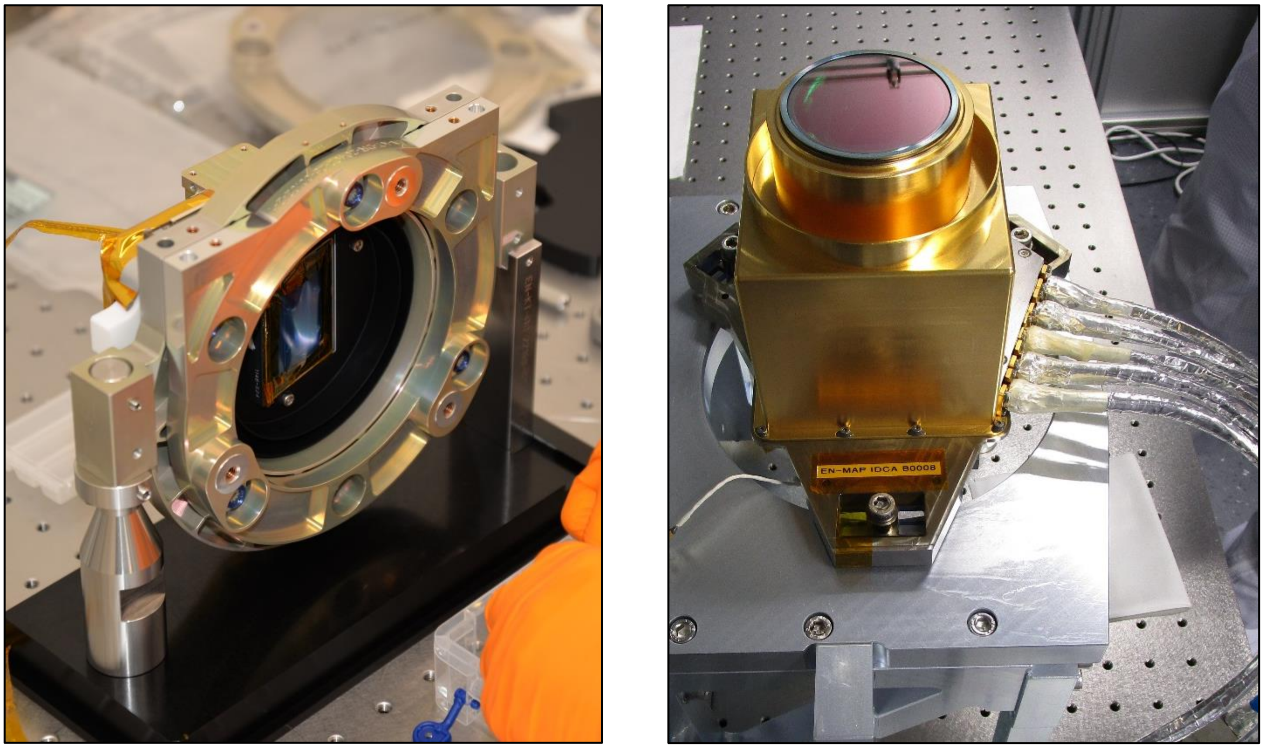

Figure 3. **Left:** VNIR-FPA flight model before integration into the instrument optics unit. **Right:** SWIR-FPA qualification model in the FPA electro-optical test lab at OHB.Schematic view of the main components of the EnMAP double-spectrometer instrument concept.

2.3 Field Splitter Slit Assembly (FSSA)

The FSSA forms the two separate entrance slits for the VNIR and SWIR spectrometer. The two slits are of dimension 24µm x 24mm and separated by 480µm. In order to fulfill the instrument requirements on image quality and performance, very stringent manufacturing tolerances have to be achieved. Therefore, the slits are manufactured from a Silicon wafer applying micro structuring (etching) techniques. More details on the design and performance of the FSSA can be found in [2]. Figure 4 is depicting the FSSA flight model after integration inside the instrument optics unit.

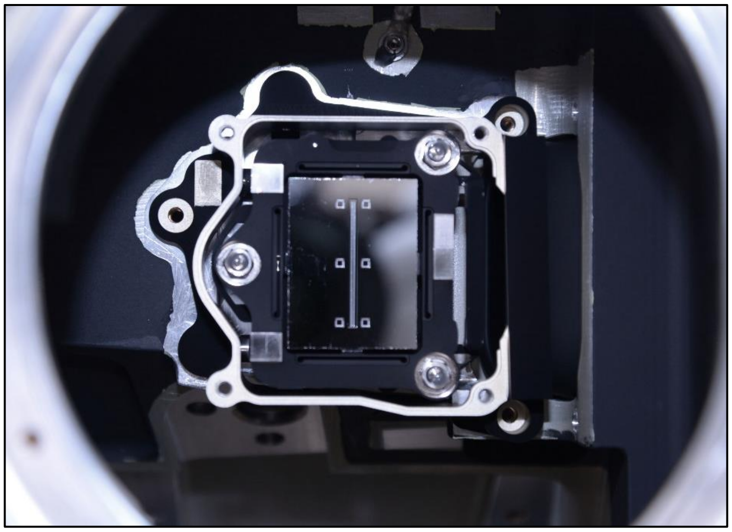

Figure 4. The field splitter slit assembly (FSSA) flight model after integration into the instrument optics unit.

3. CALIBRATION APPROACH

During EnMAP in-orbit operations, a series of spectral and radiometric characterization activities will be carried out based on the on-board calibration facilities. Detector linearity calibration, pixel response measurements and suspicious pixel mapping will be performed using light-emitting diodes (LEDs) mounted in front of the detectors in conjunction with the ability of the focal planes to control integration time in a wide parameter range.

Spectral calibration in-orbit will be performed using the spectral mode of the on-board calibration device (see [3] and Figure 6) where a rare earth-doped diffuser is used to illuminate the spectrometer entrance slits with a radiance spectrum with well-defined and stable spectral structures (see Figure 7). The shift in spectral parameters up to second order can be retrieved by comparing the predicted system performance with on-board measurements.

The calibration system based on an Ulbricht integrating sphere will be used in its radiometric mode to create repeatable and smooth spectral radiance for assessing the radiometric properties of the spectrometers. This facility allows the monitoring of the instrument at small time intervals in order to confirm the validity of the radiometric calibration.

Primary radiometric calibration will be achieved by using a full-aperture diffuser system (FAD). It carries a Spectralon diffuser with a bidirectional reflectance distribution function that has been characterized with high accuracy on-ground. A mechanism introduces the diffuser into the optical beam and opens the diffuser protection hatch to allow for direct sun illumination. In this respect, a well-known spectral radiance is generated at the entrance pupil of the instrument.

Finally, a shutter calibration mechanism allows the blocking of all light from entering the spectrometers in order to perform frequent dark signal calibrations. These measurements are complemented by deep space observations during commissioning and earth observation in different modes during night.

The same mechanism switches the optical path from the telescope view (Earth observation and Sun calibration) to the Ulbricht integrating sphere (spectral calibration and radiometric validation). A schematic view of on-board calibration devices is displayed in Figure 5.

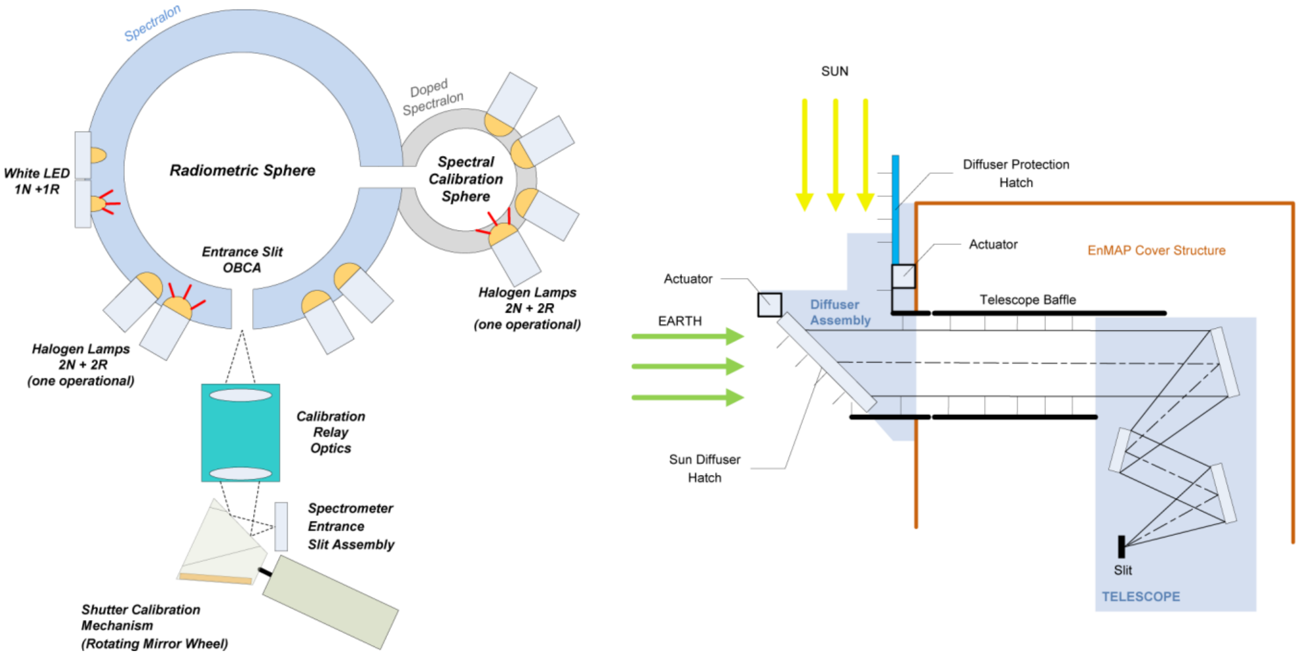

Figure 5. Schematic of on-board calibration sources.

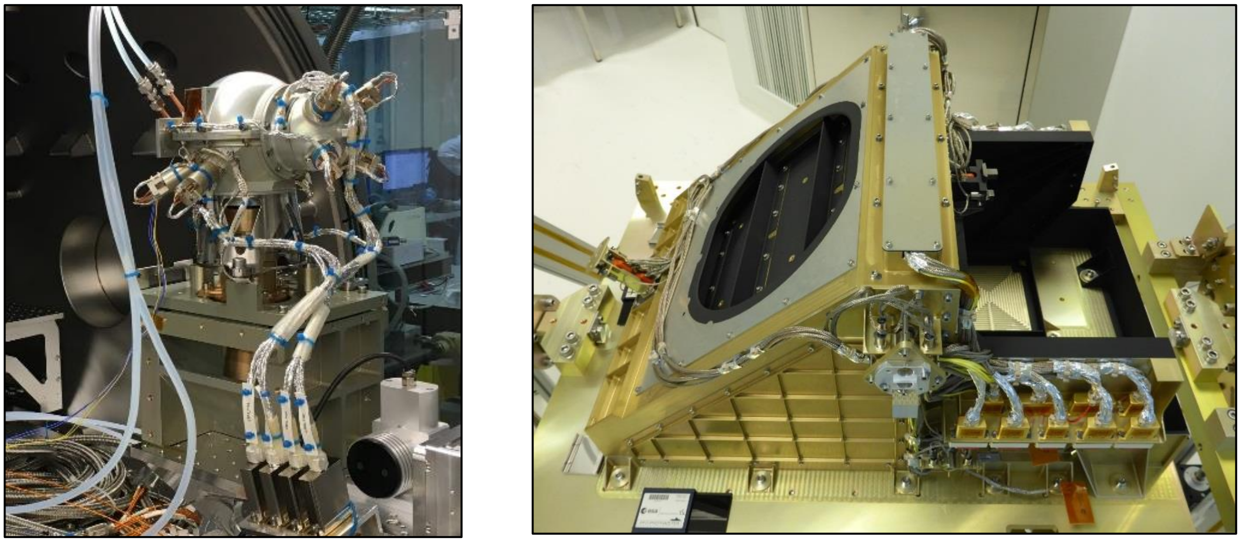

Figure 6. On-board calibration units of the EnMAP instrument. **Left:** For spectral and relative radiometric calibration, the Ulbricht integrating sphere provides a homogeneous source of illumination for the spectrometer entrance slits via coupling optics and a mechanism that introduces a mirror into the telescope beam. Photograph shows the flight unit during on-ground spectral/radiometric calibration campaign on unit level. **Right:** Absolute radiometric calibration is performed by using the sun to illuminate the entrance pupil of the telescope via a Spectralon full-aperture diffuser. Photograph shows the flight unit during final integration stages.

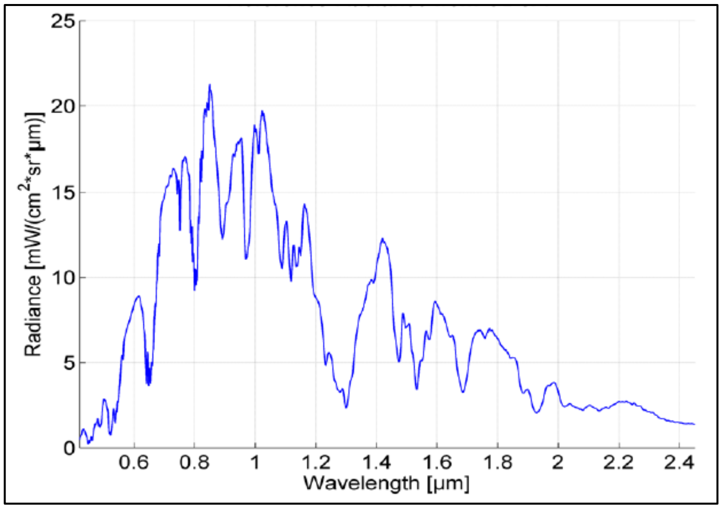

Figure 7. Emission spectrum of the rare earth-doped Spectralon Ulbricht sphere used for in-orbit spectral calibration of the instrument.

4. CURRENT INSTRUMENT INTEGRATION & ALIGNMENT STATUS

Telescope Assembly

The TMA telescope as the first optical sub-assembly has been aligned to design performance with residual (single pass) wave front error of 28nm rms (equivalent λ/25). After the telescope mirrors have been placed with high precision in the telescope structure, the subsequent alignment concept uses monochromatic light illumination at several field points and measures the corresponding wave front error in double-pass configuration. The measurement data is processed using a proprietary custom-developed software package for optical fine alignment (SOFA). The software calculates relative compensator movements based on the known properties of the optical design. In a second step, the compensator movements are translated into shim thicknesses that are integrated for correction of the mirror position [5, 6].

Instrument Spectrometer Unit

Photographs showing the activities on the spectrometers can be seen in Figure 7. Based on the same alignment concept as described above for the telescope, both spectrometer optics have been aligned and minimized with respect to optical wave front error.

The initial wave front error after placement for the SWIR spectrometer has been between 160 and 305nm rms (single pass) depending on the chosen field point. With a single alignment iteration with shim exchange on one mirror element, the wave front error has been reduced to 85-177nm rms (single pass), hence, achieving the success criterion for desired SWIR spectrometer performance. The remaining wave front error is dominated by astigmatism and some trefoil.

For the VNIR spectrometer the starting conditions for alignment have been more challenging. The initial wave front error has been in the order of 440nm rms (single pass) and showed a dominant high order aberration (trefoil) which was unexpected. The alignment was therefore extended to a double-prism correction (shim exchange on two prism elements). The success criterion for the VNIR spectrometer alignment was achieved with remaining wave front errors of 78-203nm rms (single pass) depending on the chosen field points. Calculation of the corresponding modulation transfer function (MTF) of the spectrometer shows a very decent MTF performance fully in line with the performance predictions.

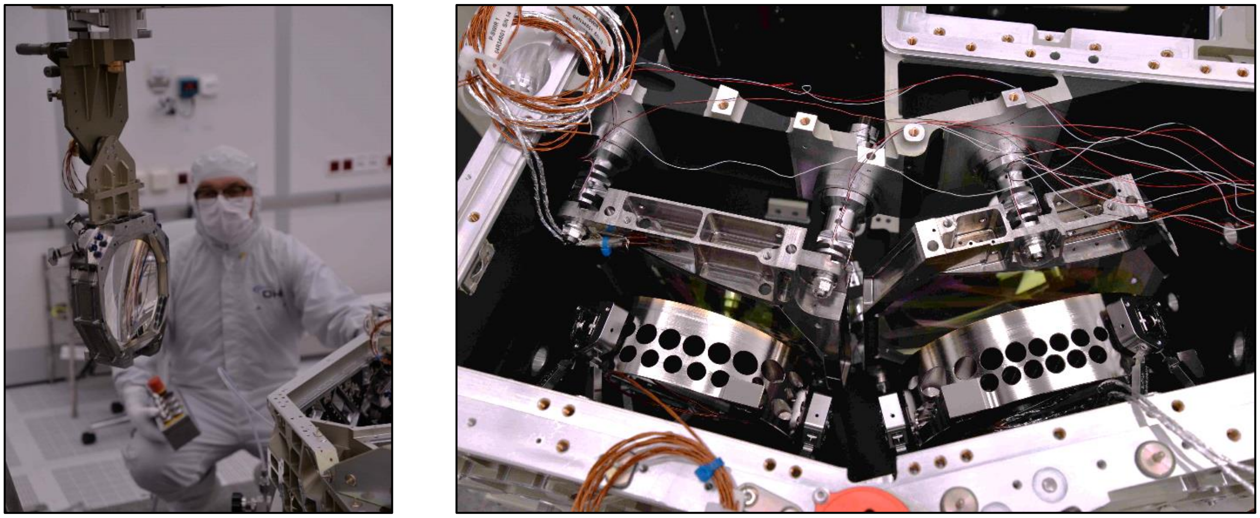

Figure 7. **Left:** Integration of a prism assembly inside the instrument optics unit using a precision insertion tool. **Right:** SWIR spectrometer compartment inside the instrument optical unit. Photograph shows the two mirrors and prisms in Offner configuration after placement.

During time of writing, the VNIR focal plane assembly has been placed inside the instrument. By illuminating the field splitter slit assembly (FSSA) with selectable wavelengths and at different field points, the optimum correction on position and orientation of the VNIR detector plane will be measured and finally implemented by means of shim exchange.

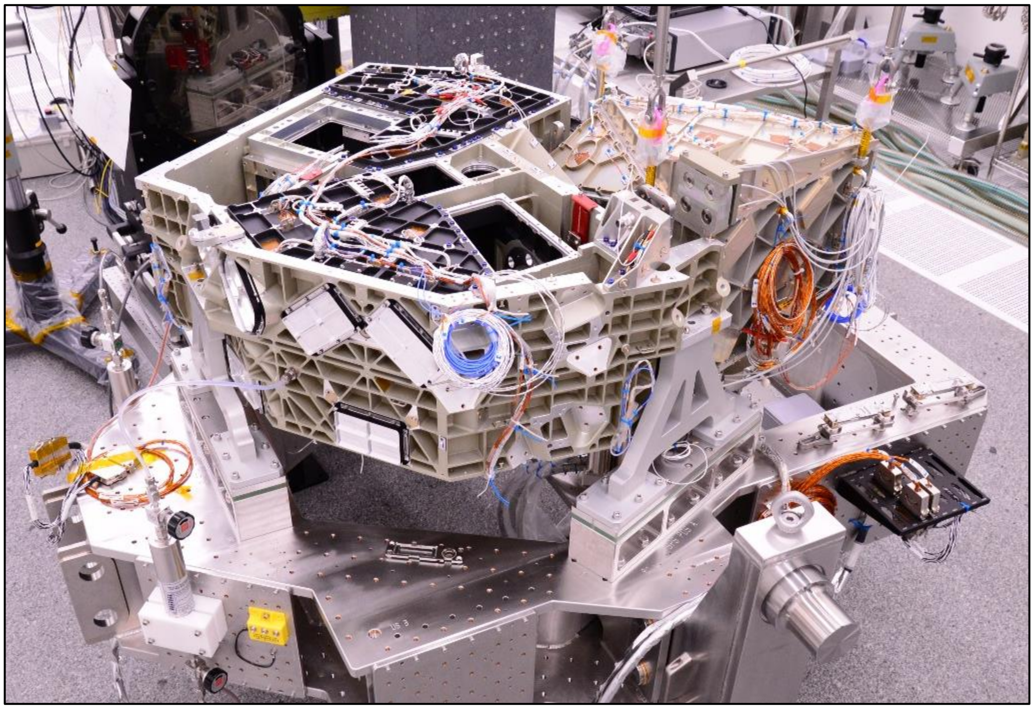

Figure 8. Instrument optics unit with the (closed) VNIR and SWIR spectrometer compartments and the telescope unit to the right. Photograph has been taken in the context of telescope to spectrometer alignment activities.

5. CONCLUSION AND OUTLOOK

With completion of the instrument optics unit planned for end of this year, the in-depth characterization of the complete optical chain will start. These test activities will make use of a highly modular, custom made optical GSE concept [4]. After finalization of the instrument optics unit the remaining functional subunits will be integrated. This integration phase will be followed by the instruments environmental test campaign and the instrument calibration. In this respect, the instrument is further progressing towards the final satellite integration currently planned in early 2020.

ACKNOWLEDGEMENTS

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