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Versatile full Aperture Illumination OGSE Setup for Alignment and End-to-End Calibration of the EnMAP Hyperspectral Imager

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ABSTRACT

The EnMAP hyperspectral Imager (HSI)[1] will allow to acquire Images of the Earth surface in a push broom configuration. 230 wavelength bands between 420nm and 2450nm are simultaneously recorded with a ground resolution of 30m x 30m.

The entire satellite is designed and built by OHB-Systems.

Characterizing and calibrating a state-of-the-art hyperspectral instrument as the EnMAP HSI requires to establish measurement setups that outperform the test object in all relevant performance aspects to achieve the required measurement accuracies.

At the same time technical as well as economical considerations yield to develop measurement equipment that can support multiple use cases throughout the Alignment integration and Test (AIT) Process of the Instrument.

This paper reports on development and commissioning activities of optical ground support equipment (OGSE) for full aperture testing of the EnMAP HSI. Design requirements as well as measured setup performance is reported.

The overall OGSE-system has been set-up and commissioned at OHB in Oberpfaffenhofen. It supports the following measurement cases:

- Double-pass wave front measurement of the HSI-Telescope for alignment to the HSI-Spectrometer Module
- Line of sight characterisation of the HSI with sub-arcsecond accuracy
- Scanning knife edge modulation transfer function (MTF)-Measurement of the HSI in the entire field-of-view
- Spectral response characterisation of the HSI in the entire spectral range with sub-nanometer wavelength accuracy.

The OGSE consists of several modules. The core component, a highly stable diffraction-limited 200 mm Collimator including a movement system and a scene generator was designed and built by Bertin Technologies upon OHB specifications.

Keywords: EnMAP, Hyperspectral, Satellite, OGSE, Calibration

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1. INTRODUCTION

1.1 Flight System Description

The EnMAP Hyper Spectral Imager (HSI) is a state-of-the-art satellite-based hyperspectral Instrument for Earth observation in Push Broom configuration. The main geometrical and spectral performance Parameters are summarized in the following Figure and Table:

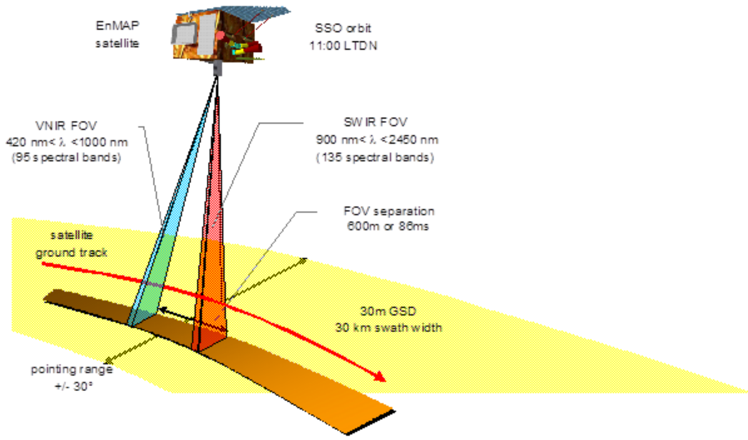


Figure 1 The EnMAP satellite

Table 1 Geometrical and spectral key Specifications.

EnMAP Geometrical and spectral key Specificaitons	
Parameter	Value
Instantaneous field of View (IFOV)	9.5 arcsec
Instrument field of View (FoV)	2.63° (across track)
spectral sampling distance SSD	VNIR 4.7nm – 8.3nm
	SWIR 7.4nm – 12.1nm
Bandwidth	1 to 1.25*SSD
spectral smile	< 20% of SSD
spectral calibration accuracy	VNIR 0.5nm
	SWIR 1nm

It has to be noted that delivering accurate radiometric data is also a key feature of the EnMAP mission and thus there are stringent requirements on Radiometric performance of the Instrument. Radiometric calibration is however not within the scope of the OGSE setup presented in this paper and will not be discussed in the following.

For more detailed information the reader is directed to Guanter et al:, The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation.[1]

The EnMAP instrument optical system consists of a common three mirror anastigmat (TMA) telescope, a field splitter and two separate prism-based spectrometers. Figure 1 shows a schematic of the optical layout:

In addition an On-board calibration system will be used for recurring in-flight radiometric and spectral calibration. It consists of a diffuser reflecting sunlight into the Telescope entrance aperture as well as a calibration light source that can be fed into the beam path in front of the Spectrometer entrance slits.

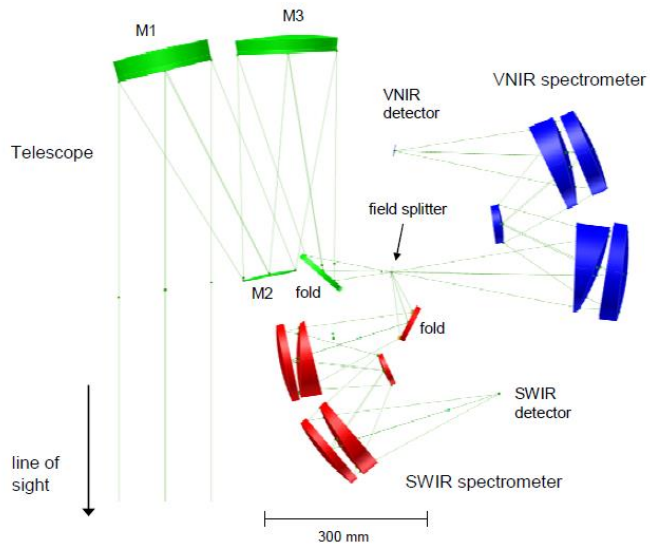


Figure 2 EnMAP HSI Optical beam path

1.2 On-Ground characterisation

In order to verify the System Performance on ground as well as to acquire relevant calibration data an extensive on-ground characterization campaign is performed employing various optical Ground Support Equipment (OGSE-) setups. Apart from functional testing aspects the activities can be split into three main blocks aiming to measure:

Table 2: main parameters subject to on-ground verification and calibration

Radiometric parameters	**Spectral Parameters**	**Geometrical and Image quality parameters**
• Radiometric response, • dark signal, • Polarisation sensitivity	• Pixel center wavelength • Bandwidth • Smile • Spectral response function	• Line of sight of individual pixels • Spectral channel co-registration • Field-of-view (FOV) • MTF • Keystone • Line spread function (LSF) across and along track • Instrument/star sensors alignment

Radiometric characterisation is split into activities on detector level and System level. The latter will be performed in a dedicated measurement setup employing a 1.5m diameter integrating sphere[2] already used for Ground Calibration in other programs. Description of this setup is not within the scope of this contribution.
In the course of the HSI integration several alignment steps precede the final end-to-end characterisation mentioned above. Some of them require Full aperture illumination of the Telescope and hence are to be done in a very similar setup as the End-to-End characterisation activities mentioned above. It was thus a natural decision to look for an OGSE solution that could already be employed during these alignment steps

2. MEASUREMENT CASES

The following measurement use cases were defined by analysing the Calibration and alignment requirements. They formed the basis for developing and specifying the OGSE elements described in Section 3

2.1 Telescope assembly(TA) to spectrometer alignment:

Requirement.

- Find the best focus location of the TA for collimated input with respect to the Spectrometer entrance Slit plane.
- The best focus position shall be derived better than 10µm for several field points distributed in the Spectrometer Focal plane.

Method:

- The TA is mounted on a piece of MGSE and moved in front of the Spectrometer.
- The TA entrance pupil is illuminated using Collimated light, which is reflected back by micromirrors on the Spectrometer entrance Slit structure. There are 6 Mirrors corresponding to extremal field points. The Mirrors are aligned in the Entrance Slit plane of the Spectrometer.
- The reflected light is analysed for collimation. And the best focus position of the TA is derived

2.2 Spectral response Function (SRF) characterisation

Requirement:

- Determine the Pixel Spectral response Function (Signal of a single pixel as function of the input wavelength) of the Complete Instrument.
- for several pixels in the entire Spectral range (420nm-2450nm)
- For several input field points in the Instrument Field of View
- With an accuracy of 5% (amplitude value for each measurement point)
- With a maximum wavelength uncertainty of 0.1nm (420nm-1000nm) / 0.2nm (1000nm-2450nm) traceable to national standard.

Method:

- The telescope entrance is illuminated with light of low spectral bandwidth covering several detector pixels in across track direction.
- Bandwith is set to be smaller than 10% of the instrument spectral sampling distance. (typically 0.5nm -1nm)
- Absolute knowledge of the Illumination central wavelength traceable to national standards is better than 0.05nm
- The central wavelength of the Illumination is scanned in sub nm steps and detector images are synchronously taken using the EnMAP Flight detectors.
- The SRF and other relevant parameters are derived.

2.3 Line of sight (LoS) and Imaging contrast (MTF) characterisation

Requirement (LoS)

- Determine the field angle at the telescope entrance corresponding to a detector Pixel with respect to the Instrument master reference (mirror Cube)

- For any selected detector pixel
- With an accuracy of 5µrad

Requirement (MTF)

- Determine the 2-dimensional MTF in a frequency range corresponding to 0.25 – 1 x Detector Nyquist frequency.
- With an accuracy of 5% (absolute MTF)

Method:

MTF and LoS characterisation are derived from the same measurement:

- The Telescope entrance is illuminated with a broad band divergent beam.
  - Angular divergence corresponding to approximately 10 detector Pixels.
  - Spectral bandwidth corresponding to 5-10 spectral channels
- A knife-edge-like structure situated in the OGSE is imaged onto the Detectors, partially covering the illuminated field.
- The knife edge structure is stepped across the illuminated field in sub pixel steps and detector images are synchronously taken using the EnMAP flight detectors.
- The illumination angle corresponding to a certain knife edge position in the OGSE is characterized with respect to the Instrument Master reference with an accuracy <5µrad.
- LoS and MTF values are derived (see also Figure 3)

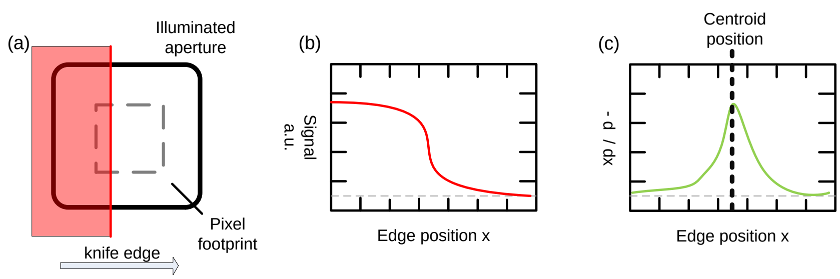


Figure 3 Determining the LoS of a pixel using a knife edge. (a) the image of a knife edge is scanned across the pixel of interest (b) the signal of the pixel as function of the knife edge position is the ESF of the imaging system including detector (c) the derivative of the obtained signal wrt the knife edge position yields the LSF again convoluted with the pixel size. The pixel LoS is defined as the centroid position of this function

3. OGSE DEVELOPMENT APPROACH

3.1 Goal

It was the goal to develop a modular OGSE Architecture that maximizes synergies of recurring tasks and requirements between spectral and geometrical characterisation as well as certain alignment activities.

Reducing the overall amount of OGSE Items for alignment and test has clear commercial advantages. In addition the Integration and alignment team benefits from working with a multi-purpose setup. It allows to thoroughly understand the systematic behaviour and technical peculiarities of the involved devices prior to the final calibration campaign which typically suffers from significant schedule pressure.

3.2 OGSE Elements Overview

To give a full picture of the modular approach advertised in the previous section Figure 4 shows an overview of all involved OGSE devices and optical interfaces. The individual devices are detailed in Section 4. Some Items are grayed out as they have only been used in earlier steps of the integration and alignment process which is outside the scope of this paper.

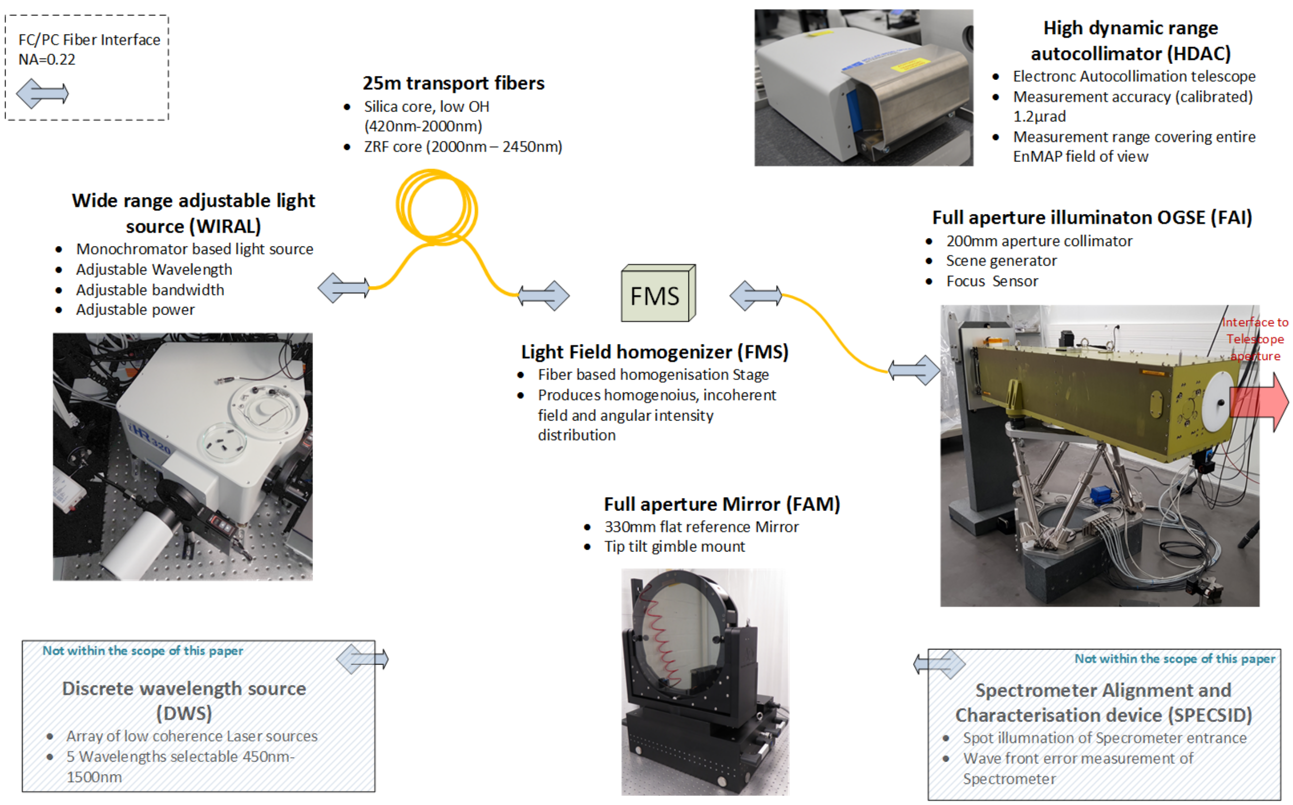


Figure 4 Overview of the general OGSE architecture. For a more detailed description of the individual Items c.f. Section 4 The Items DWS and SpecSid are shown for completeness only, they are not within the scope of this paper..

The Items FAI (scene generator) & WIRAL (monochromator) can be remotely controlled using a central control authority which also controls the HSI focal plane detectors. This way time synchronized batch script operation involving flight detectors and OGSE is possible. Synchronization lags are typically <10ms between the individual devices, which is sufficient for the envisaged use cases.

3.3 Optical Fiber Interface

In a modular setup as described above it is crucial to use an easy to control yet flexible optical interface. In our case Silica-core step gradient Multimode fibers where chosen to transport light from the Light source (OGSE) to the OGSE element interfacing with the flight hard ware. All fibers are equipped with standard FC/PC connectors. This sets some constraints on the design of the individual components but pays off in terms of flexibility and compatibility of the Setup.

Main Advantages:

- Possibility to physically separate Light source and high performance optical system in terms of heat transfer and Cleanliness classes.

- Convenient Numerical aperture of NA=0.22, almost constant over the entire relevant wavelength range at all optical interfaces.
- Wide range of commercially available Fibers (at moderate cost) with various core dimensions and shapes.
- Excellent mode-mixing properties in terms of polarization and light field homogeneity.

IR-Damping:

One major drawback about using Silica-core fibers is the high damping rate at wavelengths >2µm. for this reason, which essentially limits the Silica core fiber length to ~ 1m for all practical purposes. To overcome this limitation a ZrF Fiber was used to transport the light across the distance between Light source and Illumination OGSE (~25m) however to maintain interface compatibility small pieces of Silica-core fiber were used at both ends interfacing with the OGSE devices

Etendue matching

Unobscured, unobstructed optical imaging systems as e.g. the FAI or the HSI optical system have the property to conserve the illumination etendue ε defined as the product of illuminated area and illuminated solid angle.

In our case the required illumination etendue at the Telescope entrance $\varepsilon_{Telescope}$ is set by the dimensions of the telescope pupil and illuminated area on the HSI focal plane detector. Given that full aperture illumination by the FAI needs to overfill the Telescope entrance pupil and corresponding field for the individual measurement cases, the optical fiber interface at the FAI input has to provide an etendue $\varepsilon_{Fiber} > \varepsilon_{Telescope}$.

As mentioned above the Fiber NA (and thus the illuminated solid angle) is kept constant for technical reasons, the only possibility to adjust the etendue is to select a Fiber with a sufficiently large core (i.e. illuminmated area). Fortunately cores up to 1mm diameter are available which is sufficient for all practical purposes.

Homogenisation:

For Knife edge measurements (as well as for spectral characterization) a very homogenious light field, both in real (focal plane-) space as well as in angular space is desirable. In addition the light field must be incoherent.

In reality using a monochromator like the WIRAL as light source the intensity pattern as well as the spatial coherence properties of the light exiting the monochomator depend on the selected wave lengths and monochromator slit widths.

A well-established technique to homogenize light fields and get rid of spatial coherences is to couple the light into an Ulbricht sphere. In our case however this would have led to inacceptable losses in the overall optical path. A convenient overview of technologies for fiber-based light field homogenization is given in[3]. Here an optical throughput well above 50% was achieved. At the same time homogenous and incoherent illumination scenarios at the fiber exit could be created, independent of the input light field. Figure 5 shows measurement examples of pupil and focal plane intensity patterns measured at the FAI input fiber port.

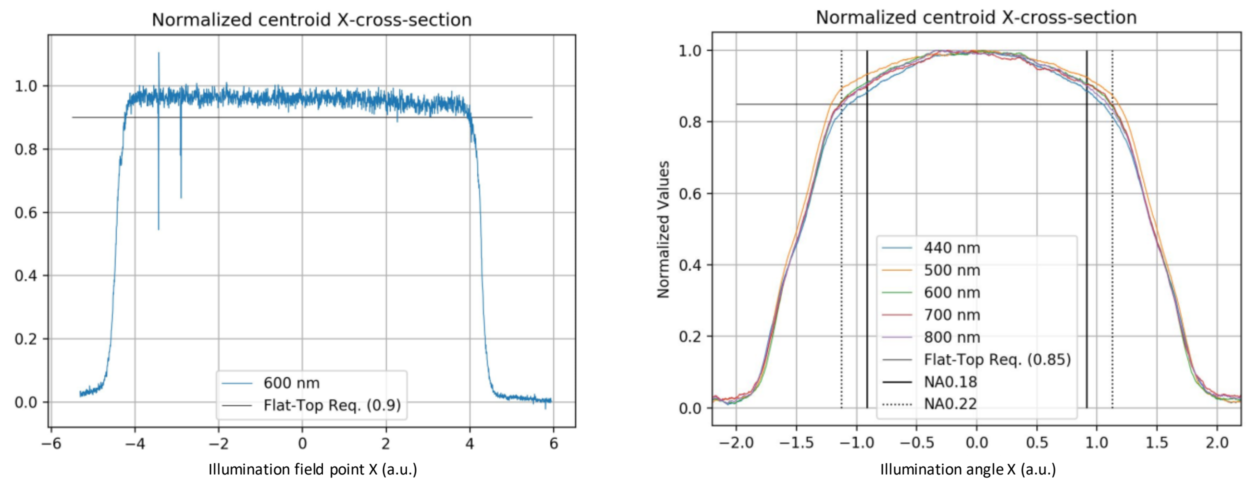


Figure 5 Intensity profiles at the FAI input Fiber port. Left: cut through the focal plane intensity pattern, Right: cut through the angular intensity pattern.

4. OGSE ITEM DESCRIPTION AND PERFORMANCE

4.1 High dynamic Range optical Autocollimator (HDAC)

The HDAC is a custom developed electronic Autocollimator and as such is used as master reference for angular measurements in the frame of Line of sight characterisation. The device was developed by Möller-Wedel-Optical GmbH upon OHB specifications. It is based on a standard platform used in the commercial line of Electronic autocollimators offered by Möller-Wedel-Optical. An important aspect of the Project was to calibrate the Autocollimator traceable to national standards with sufficient accuracy. This task was also performed by Möller-Wedel-Optical GmbH.

Key performance parameters are:

- Measurement range: +/- 23mrad (1.32°) x +/- 0,5µrad (0.03°)
- Accuracy calibrated traceable to national standards: < 1.2µrad separately in each axis
- Measurement resolution: < 0.25µrad

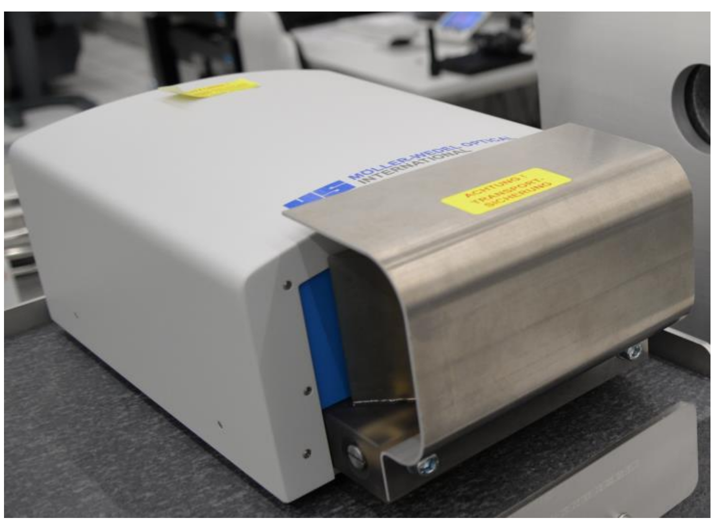


Figure 6 High dynamic range Electronic Autocollimator (built by Möller Wedel Optical GmbH)

4.2 Full aperture Flat mirror (FAM)

The FAM consists of a precise two sided reference Flat in a tip-tilt gimbal mount. It has two main purposes:

a) transfer line of sight angles between the FAI output (Instrument illumination) and the HDAC (measurement device)

b) Serve as a flat reference surface for Wave front error measurements of the optical system. This function is not needed for the tasks described in this paper but has been previously reported[4]

The FAM was developed upon OHB Specifications by Airbus-DS in collaboration with Aperture Optical Sciences Inc.

<u>Key performance parameters</u> are:

- Mirror clear aperture: 330mm
- Mirror surface form error: < 6nm (rms)
- Gimbal mount strokes: +/- 2° in all directions
- Gimbal mount controlled incremental movement steps: < 1µrad

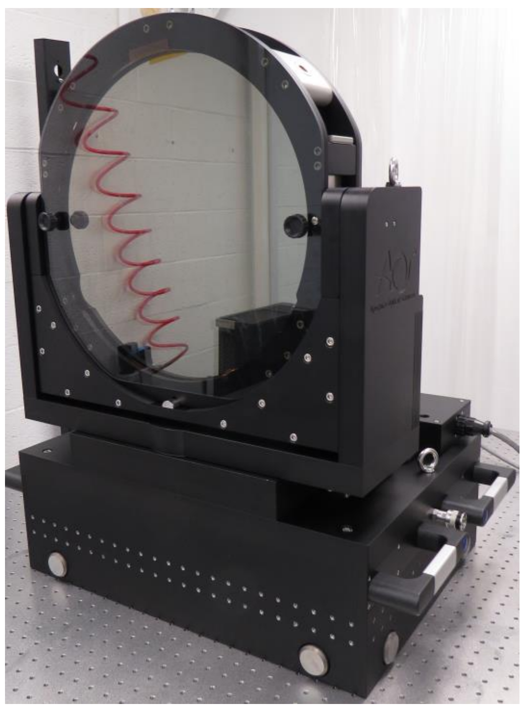


Figure 7 Full aperture mirror FAM

4.3 Wide Range adjustable Light Source (WIRAL)

The Wiral consists mainly of a commercially available Grating Monochromator (iHR320) by HORIBA Scientific, fed by several light sources and a fibre coupling interface.

The WIRAL serves as spectral reference for the described measurement cases it is calibrated traceable to national standards using a PTB-calibrated Echelle spectrometer (GWU_LambdaScan_Spectrometer, provided by DLR-IMF[2]). A dedicated recurring calibration plan employing Gas-Cell line sources ensures validity of the calibration throughout the EnMAP on-ground calibration campaign.

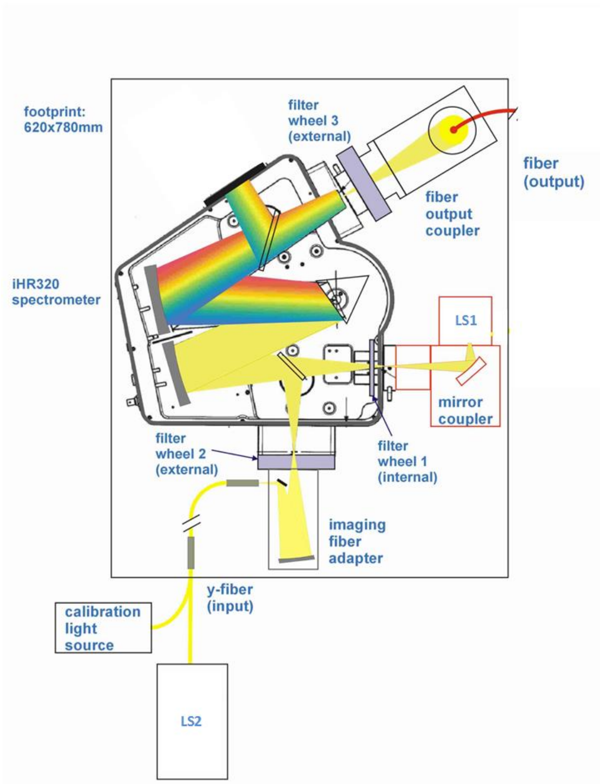
Key performance aspects include

- A wide wavelength range continuously covering 382 nm to 2481 nm;
- A precise bandwidth control from 0.5 to 2 nm within <±3% across the entire wavelength range;
- Absolute wavelength calibration and repeatability with better than 50pm across the entire wavelength range;
- A smooth change of radiometric flux across the used wavelength ranges;
- Relative radiometric fluctuations of <±0.5% between two scans;
- At least 0.3 µW and 0.05 µW in the VNIR and SWIR spectral ranges respectively coupled into multimode fibre.
- A white light mode to be used for imaging performance and geometrical characterisation measurements.
- A control-software, which provides full control of all system parameter, both locally and remotely, including versatile logging capabilities for the intended system level characterisation and calibration campaigns

The monochromator is equipped with three Gratings that allow to cover the entire EnMAP spectral range with sufficient throughput. In addition the gratings can be exchanged by a mirror, allowing to use the monochomator in a white light configuration. Bandwidth and power of the emitted light can be adjusted by choosing the entrance and exit slit width of the monochromator in conjunction with the used grating. Several filter wheels are installed to block higher diffraction orders of the gratings and select additional attenuation factors.

The light source can be selected by actuating an automated fold mirror. Currently two distinct Light sources (LS1 and LS2) are installed along with a gas-cell based line source for Spectral calibration verification.

The core parts were procured as pre-aligned off-the-shelf products. Fine alignment and thorough characterisation as well as integration with the HSI functional environment was done by OHB.



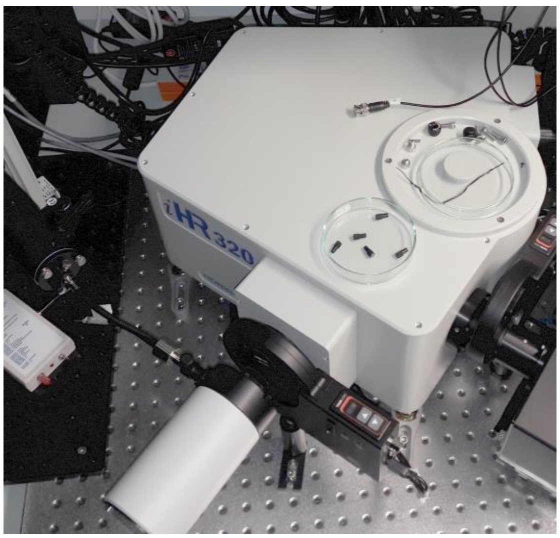


Figure 8 Wiral OGSE. Left: schematic overview of the architecture as designed by HORIBA, Right: Foto of the monochromator Setup

4.4 Full Aperture Illumination OGSE (FAI)

The FAI is the Core Part of the OGSE Setup presented in this paper. It was developed, manufactured integrated, aligned and tested upon OHB Specifications by Bertin Technologies.

System architecture

The Full Aperture Illuminator (FAI) (Figure 9) is composed of :

- A collimator system including a pattern plate system (ALIO translation stage and Optimask pattern plate) and a source assembly (wavelength range : 400– 2470 nm). These elements are at the focal object plane of a 200 mm diameter output pupil, two mirrors unobscured collimator manufactured by Winlight System now part of Bertin Technologies.
- A scanning system manufactured by Symetrie, to displace angularly the collimator system to scan the HSI field of view.
- A monitoring system, to measure the angular stability of the collimator system with respect to the granite base on which the FAI is mounted.
- A control unit and 20m length wires.

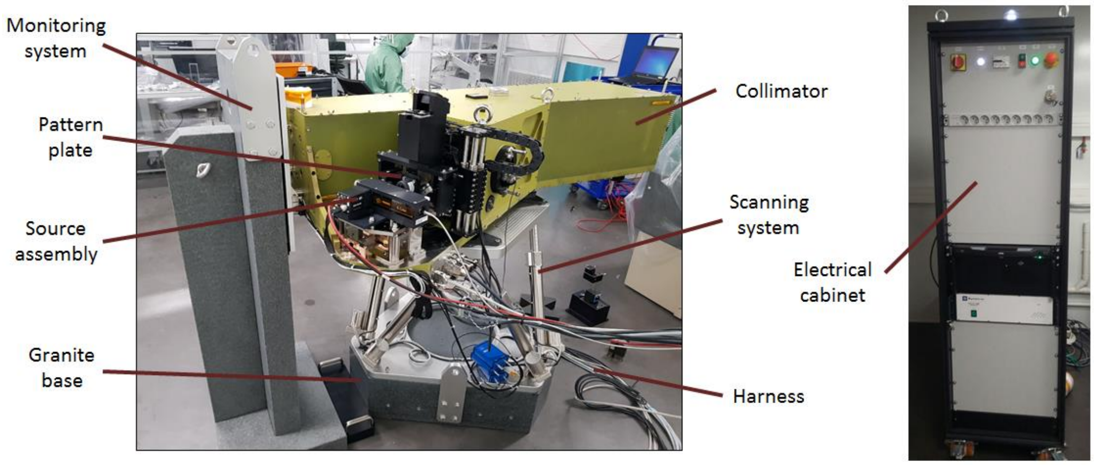


Figure 9: Architecture of FAI OGSE

Main functions

The FAI is a Swiss Army Knife that is used during several steps of HSI integration through several configurations:

- An autocollimation mode aiming at measuring the focus error of the TA in front of the Spectrometer in double pass configuration.
- An M-mode aiming at making MTF measurements of the instrument. This is done by projecting and displacing a knife edge at sub-pixel level. The pattern is displaced thanks to a high performance translation stage and projected by the Winlight System collimator.
- The L-mode whose goal is to make Line of Sight measurements of the instrument relative to a reference frame internal to the FAI. The FAI is projecting an edge pattern with an angular direction which is known with high accuracy in the FAI reference frame. (C.f. Section 5.2 for more information on line of sight referencing)
- A spectral characterization mode which aims at calibrating the spectral response of the HSI. In this configuration, light coming from WIRAL source is reshaped by FAI to overfill both pupil and required focal plane area of the instrument.

Key performance

The FAI needs to provide a highly stable illumination situation and at the same time keep its very small wave front error. This led to an All-Invar-structure for the collimator with Zerodur® selected as mirror material.

The optical system has been manufactured and aligned to provide a wave front error on the order of λ/20 for the shortest measurement wavelength (see Figure 10). Including all other relevant contributors, the FAI Illumination provides a collimated beam with a guaranteed Wave front performance <40nm(rms) including Focus.

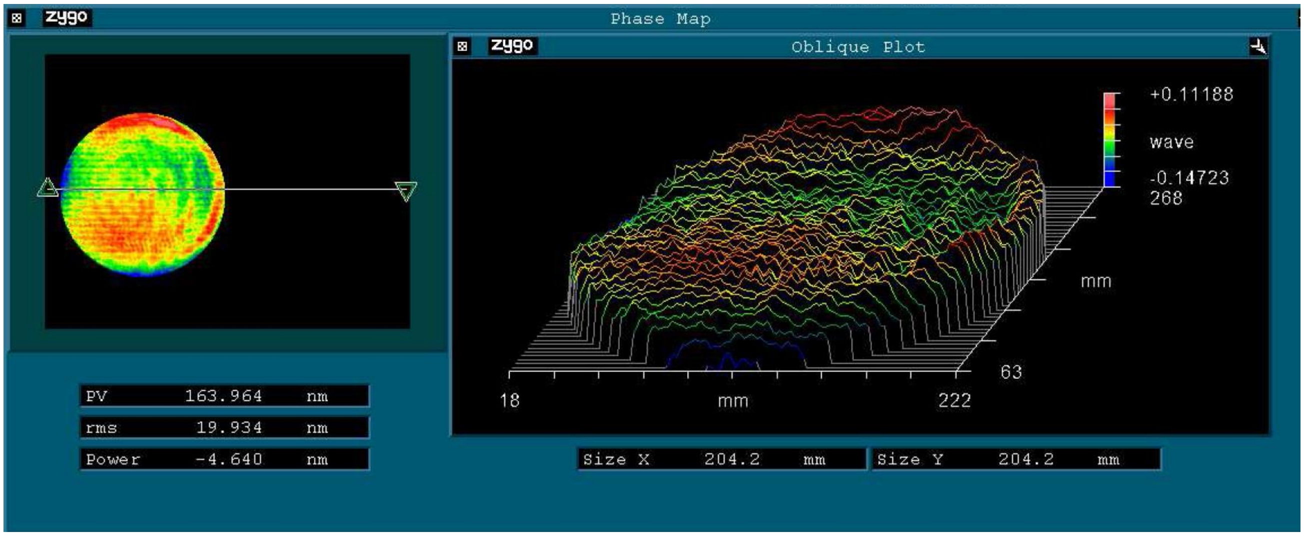


Figure 10 Wave front error map of the Collimator optical system for a central field point

Table 3 summarizes the most demanding performance requirements of the FAI and their link with each configuration.

Table 3. Key performances of FAI and relations with the different use cases

FAI	Achieved performance	A mode	M mode	L mode	Spectral mode
Output wavefront planarity	<40 nm rms		X		
Wavefront measurement sensitivity	22 nm PTV	X	X		
Accuracy of pattern angular positioning	<1µrad			X	
Pupil & Field uniformity	>99%		X		
Angular Stability	<1µrad		X	X	
Transmission	>83% @440-2400 nm				X
Pattern plate translation stage jitter	< 200 nm		X	X	
Pattern plate geometrical accuracy	< 1 µm		X	X	

The FAI is fully compliant to all these requirements.

5. RESULTS

5.1 Wiral working parameters

During the final commission phase, the radiometric and spectral performance of the WIRAL was optimized with an additional emphasis to run the individual measurements with optimal efficiency.

It was the goal to balance the output bandwidth versus the emitted power. While the bandwidth is required to be < 10% of the EnMAP Spectral channel width for the respective wavelength, the power needs to be sufficient to produce high-SNR signals on the illuminated Focal plane detectors. In total 6 wavelength ranges were defined, in which single values for the monochomator slit widths choice of grating and filters were applied. The wavelength is set by turning the monochomator grating. Figure 11 shows the results of this effort confirming that for almost all wavelengths sufficient margin is present both for power as well as for bandwidth with respect to the required values.

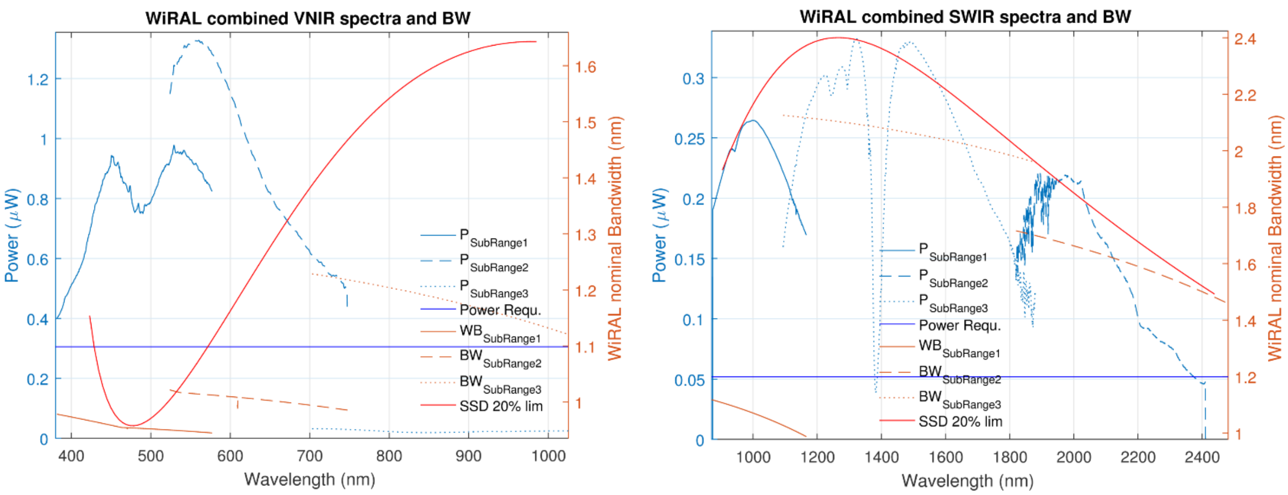


Figure 11 WIRAL wavelength ranges. Measured Power (light blue) and Spectral bandwidth defined as FWHM of the emitted spectrum (orange) are plotted against the minimum required power (solid blue) and the maximum required bandwidth (solid red)

The WIRAL absolute wavelength accuracy after calibration is determined by the reproducibility of the wavelength setting. Figure 12 shows that typical drifts of the bandwidth are on the order of 5% whereas the wavelength reproducibility is 50pm and thus <1% of the smallest EnMAP spectral channel width.

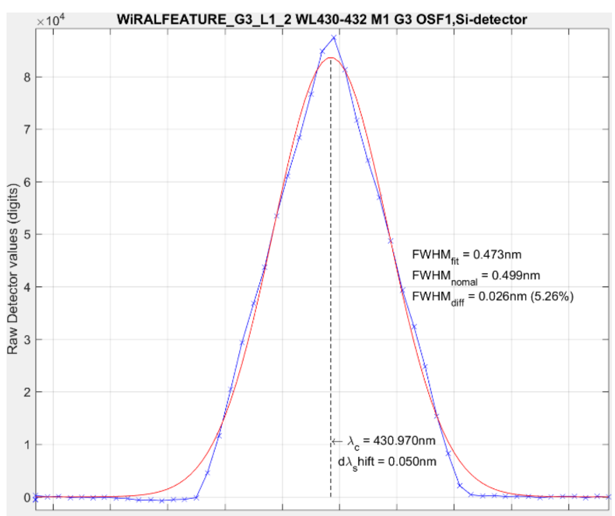


Figure 12 WIRAL bandwidth verification and wavelength drift characterisation based on Gas Cell reference lamp.

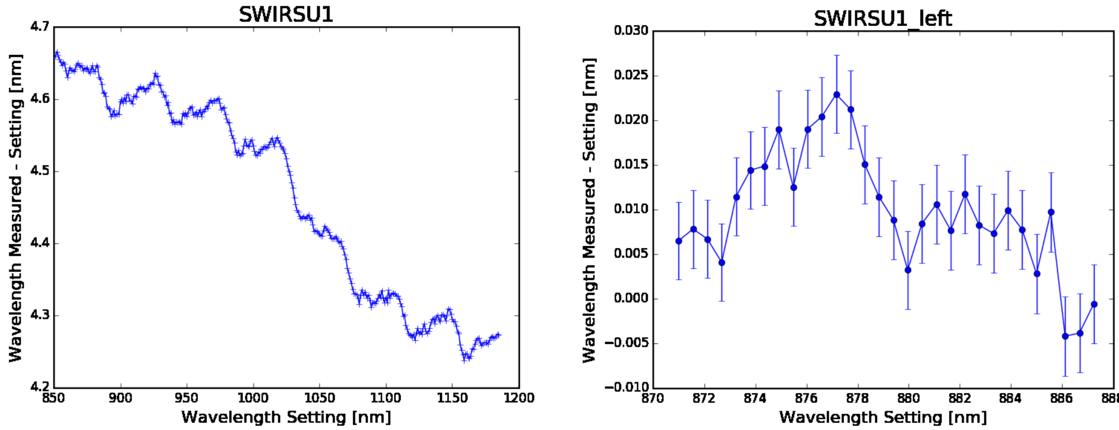


Figure 13 Wiral calibration results for one of the SWIR wavelength ranges. Measured Wavelength of light exiting the Wiral by a calibrated echelle spectrometer (GWU_LambdaScan_Spectrometer) before (left) and after (right) applying a calibration table. Please note the different x-scale of the two plots. (measurements performed by A. Baumgartnder (DLR-IMF))

5.2 Geometrical referencing Strategy

For line of sight characterization of the HSI the direction of the collimated input beam produced by the FAI must be referenced in the Telescope Line of Sight coordinate system CS_o_TA#1. The latter is operationally defined by a mirror reference cube (TA_RC#1) located next to the telescope entrance (Figure 14).

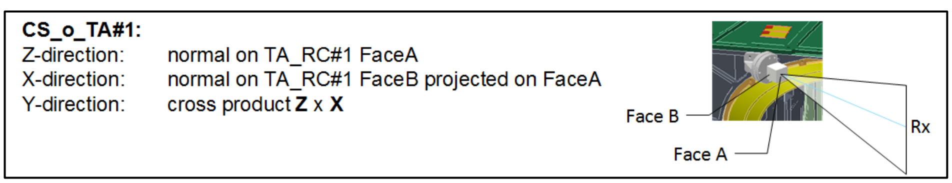


Figure 14 Operational definition of the Telescope Line of Sight coordinate system CS_o_TA#1 employing a mirror cube (TA_RC#1) next to the telescope entrance

Referencing is performed in a two-step process as illustrated in Figure 15

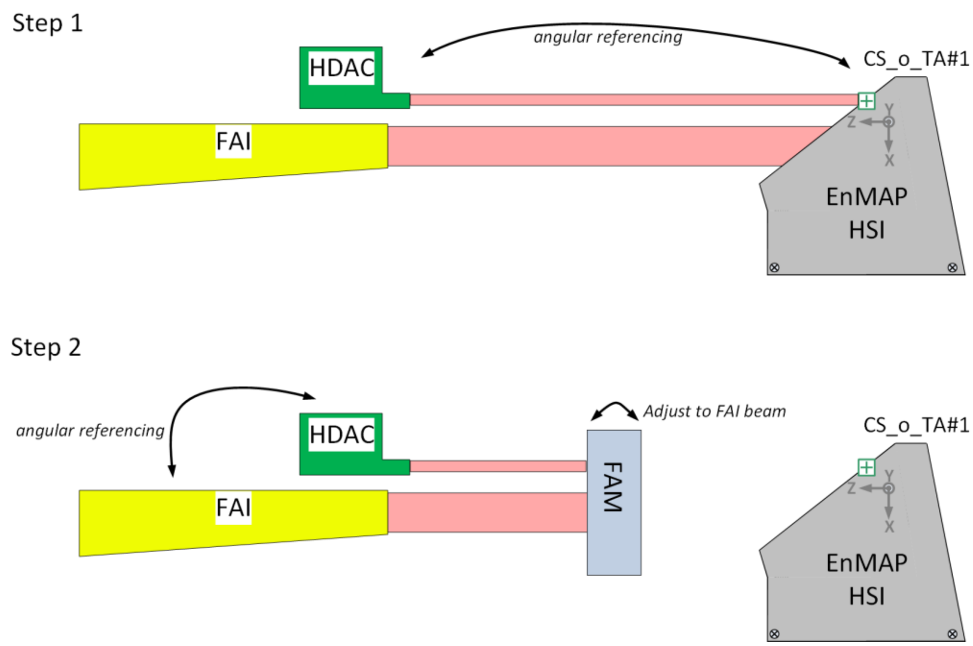


Figure 15 Schematic procedure to reference the FAI input beam with respect to the Telescope line of sight coordinate system CS_TA#1

<u>Step 1</u>: a) illuminate the telescope with collimated light at a defined angle in the FAI internal reference frame and measure response of the HSI Focal plane detectors. b) At the same time measure the TA_RC#1 front surface in the HDAC autocollimator internal reference frame.

<u>Step2:</u> Introduce the FAM reference flat in both Beam paths and align mirror surface to be orthogonal on the direction of the FAI beam. Measure the FAM mirror orientation in the HDAC internal reference frame.

The total accuracy of this procedure is analyzed in a budget to be <1arcsecond. Main contributors are:

a) measurement accuracy HDAC

b) FAM adjustment accuracy

c) FAI Stability between Step1 and Step 2

Contributors a) and c) have been experimentally verified to be on the 1µrad level.

In order to assess the FAM adjustment accuracy b) measurements have been performed that show that thermal drifts within the FAM gimbal mechanics are limiting this accuracy. However if either sufficient time for thermalisation is given or the measurements of Step2 can be performed in a time synchronized manner, accuracies on sub µrad level are possible. Both options are currently under investigation.

6. CONCLUSION

A highly modular OGSE Architecture for on-ground characterization of the spectral and geometrical properties of the EnMAP Satellite has been developed and implemented at OHB System. High emphasis was put on creating a highly modular and versatile setup that can be used in different measurement cases for calibration and alignment. A central feature is the use of a standardized optical fiber interface to interconnect the different modules. Key performance figures of the individual components have been tested and show to be fully in-line with the requirements for the upcoming end-to end tests of the EnMAP Instrument.

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Image of WIRAL architecture Figure 8 based on footage provided by HORIBA inc.

REFERENCES

[1] Guanter, L., Kaufmann, H., Segl, K., Foerster, S., Rogass, C., Chabrillat, S., Kuester, T., Hollstein, A., Rossner, G., Chlebek, C., Straif, C., Fischer, S., Schrader, S., Storch, T., Heiden, U., Mueller, A., Bachmann, M., Mühle, H., Müller, R., Habermeyer, M., Ohndorf, A., Hill, J., Buddenbaum, H., Hostert, P., van der Linden, S., Leitão, P., Rabe, A., Doerffer, R., Krasemann, H., Xi, H., Mauser, W., Hank, T., Locherer, M., Rast, M., Staenz, K., Sang, B., „The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation.“, Remote Sens. 7(7), 8830-8857. (2015), doi: 10.3390/rs70708830.

[2] Gege, P., Fries, J., Haschberger, P., Schötz, P.. Schwarzer, H., Strobl, P., Suhr, B., Ulbrich, G., Jan Vreeling, W., “Calibration facility for airborne imaging spectrometers.”, ISPRS Journal of Photogrammetry & Remote Sensing. 64. 387-397. (2009), doi:10.1016/j.isprsjprs.2009.01.006.

[3] Avila, G., “FRD and scrambling properties of recent non-circular fibres”, Proc. SPIE. 8446 (2012)

[4] Godenir, A.M.R., Kolmeder, J., Kuisl, A., Sang, B., Lettner, M., Balbi, M., Küchel, C., Mayer, R., Sornig, M., “Fine alignment of Aerospace Telescopes for the Earth observation Satellite Mission EnMAP”, Proc. SPIE. 10562 (2016)