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DEVELOPMENT OF A CALIBRATION EQUIPMENT FOR SPECTROMETER QUALIFICATION

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ABSTRACT

With the development of new spectrometer concepts, it is required to adapt the calibration facilities to characterize correctly their performances. These spectro-imaging performances are mainly Modulation Transfer Function, spectral response, resolution and registration; polarization, straylight and radiometric calibration.
The challenge of this calibration development is to achieve better performance than the item under test using mostly standard items. Because only the subsystem spectrometer needs to be calibrated, the calibration facility needs to simulate the geometrical “behaviours” of the imaging system.
A trade-off study indicates that no commercial devices are able to fulfil completely all the requirements so that it was necessary to opt for an in home telecentric achromatic design. The proposed concept is based on an Offner design. This allows mainly to use simple spherical mirrors and to cover the spectral range. The spectral range is covered with a monochromator. Because of the large number of parameters to record the calibration facility is fully automatized.
The performances of the calibration system have been verified by analysis and experimentally. Results achieved recently on a free-form grating Offner spectrometer demonstrate the capacities of this new calibration facility.
In this paper, a full calibration facility is described, developed specifically for a new free-form spectro-imager [1].

Keywords: Testing and calibration, Free Form optics, Hyperspectral Imaging, Spectrometer

I. INTRODUCTION

The availability of free form manufacturing tools allows the development of new type of spectrometers. To be confident in these new designs and new manufacturing process, it is requested to develop metrology tools able to confirm/evaluate their performances. The basic performances are the spectral one as spectral response, resolution, and registration, but the geometrical one as MTF, the polarization and the straylight remains also important characteristics to verify. To reply to these new demands a dedicated optical ground system equipment (OGSE) has been developed at the Centre Spatial de Liège. The application case is a recently free-form grating Offner developed by AMOS[1]. This spectrometer is very compact and lightweight for an implementation on a small platform. The design offers an excellent image quality while maintaining very low spectral (smile) and spatial (keystone) distortions.
The metrology system needs to have better performances than the instrument under test and needs to simulate the geometrical properties of the front imaging system.

II. TRADE-OFF

A. Introduction

The guide line for the development of the test bench was to allow the full characterization of a spectrometer including a free from grating, part of a spectro-imager. The design of this spectrometer is shown in Figure 1 and is based on an original modified-Offner design for imaging spectrometer with a convex gratings ruled on a Free-Form surface [1]. This required an imaging system that shapes the input beam as the one provided by the imaging system.

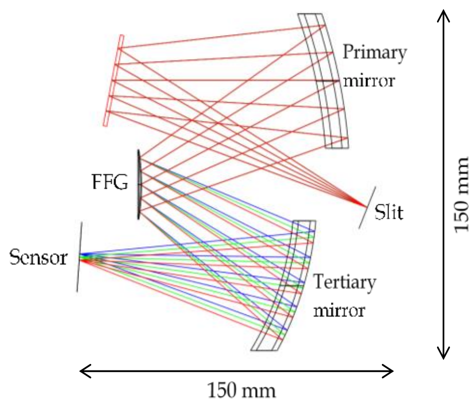

Fig. 1. Spectrometer optical design including a FFG (Free Form Grating)

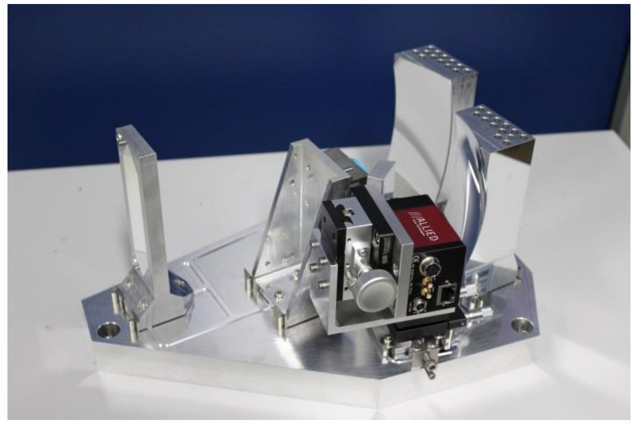

Fig. 2. Spectrometer breadboard

B. Tests to be performed

Imaging spectrometer main performances to be characterized are the following:

- Keystone
- Spectral response matrix
- MTF
- Polarization sensitivity
- Straylight

Each test will be briefly described in section V. To do these characterizations, the calibration setup needs:

- Different targets to be placed in the object plane,
- A displacement system to accurately superimpose the imaging spectrometer entrance slit and the Offner relay exit slit,
- A displacement system to scan the spectrometer slit,
- A spectrally wide light source, with the possibility of wavelength tuning ($\Delta\lambda$ and λ) and scanning,
- A polarizer.

The full calibration facility is described in next section.

C. Input light shape constraints

The input light should be similar to the output of the coming imaging system. In this case, it will be a TMA telescope. In particular, the design of the telescope is telecentric (the variation of the chief ray incidence along the FOV can be neglected), nearly achromatic, with a F/# = 5. Moreover, it is requested to illuminate in one shot the full spectrometer entrance slit (62 mm long).

D. Proposed solution

The calibration test setup has to image an object placed at a finite distance. A trade-off study indicates that no commercial devices are able to fulfill all requirements. It was thus necessary to go to an homemade telecentric achromatic design.

To be close as possible to the telescope properties at spectrometer entrance slit, the proposed concept is based on an Offner design (see Fig. 3).

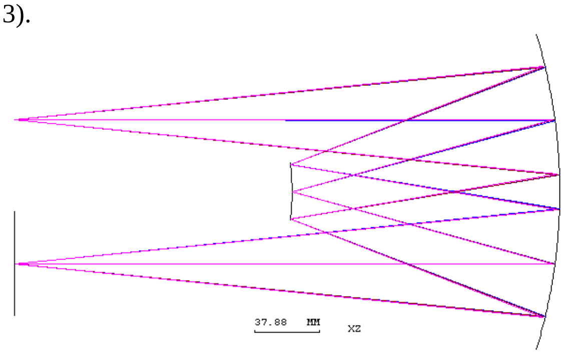

Fig. 3. Offner relay proposed for light shaping.

This design uses simple spherical mirrors. The system is achromatic, telecentric with a magnification of 1, and is designed with a F/# < 5 to fit with the imaging F/#.

III. CALIBRATION TEST SET-UP

A. Test setup elements

The final design and configuration is depicted in Fig. 4 and Fig. 5.
It is composed of:

- A light source: for $\lambda \in [400 - 900]$ nm, a 300 Watts Xenon lamp (6258) is used. This lamp can be replaced by an Halogen lamp for example to deal with larger wavelengths,
- A monochromator, $\Delta\lambda$ adjustable between 1 and 10 nm, central wavelength accuracy and resolution better than 0.1 nm, minimum spectral range from 350 to 1100 nm,
- An integrating sphere (IS) (62 mm output diameter) in order to enlarge and homogenize the output of the monochromator, coupled with a photodetector for monitoring,
- An entrance mount to receive adapted target objects according the performance under test,
- A fold mirror (needed for space management),
- An optical Offner relay (telecentric,F/#=5, magnification 1, see Fig. 3),
- A movable rotating polarizer,
- Motorized translation stages for spectrometer positioning in front of calibration setup exit slit, also used for slit scan.

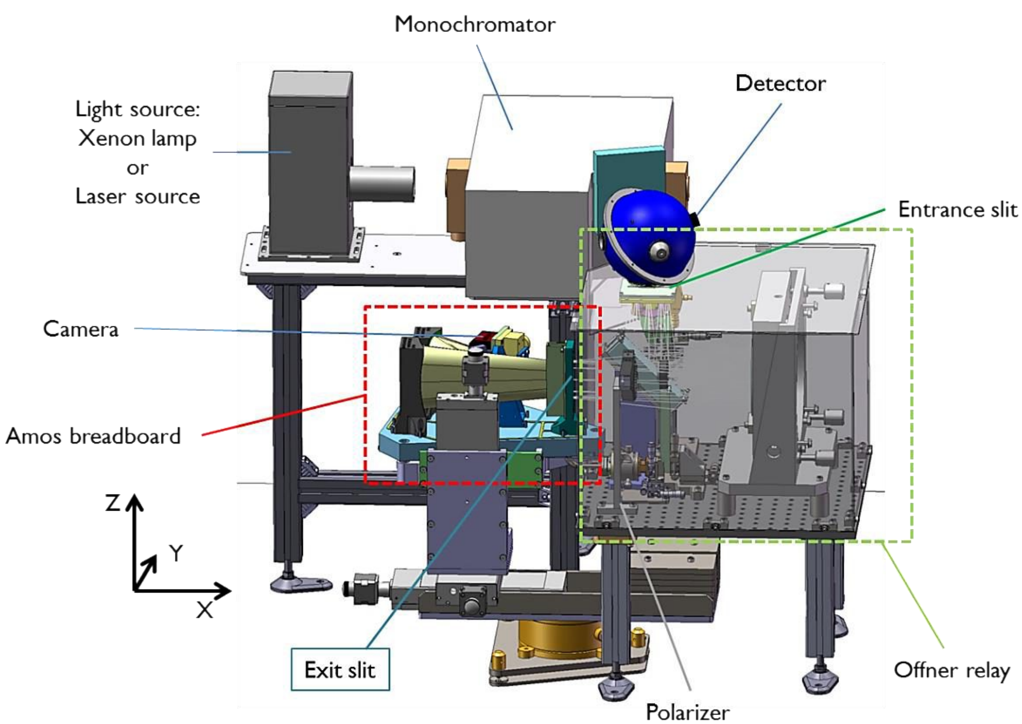

Fig. 4. Scheme of the test facility with an imaging-spectrometer placed at the exit.

The calibration facility generates a quasi-monochromatic (with tunable $\Delta\lambda$ and λ) and uniform (thanks to the IS) illumination on the entrance slit of the spectrometer under test. For each performance test, a dedicated object target is placed at the IS output (see section III.B): it will be imaged (ratio 1:1) exactly on the spectrometer entrance slit. Each element position is adaptable (with accurate translation/rotation stages) for fine tuning alignment.

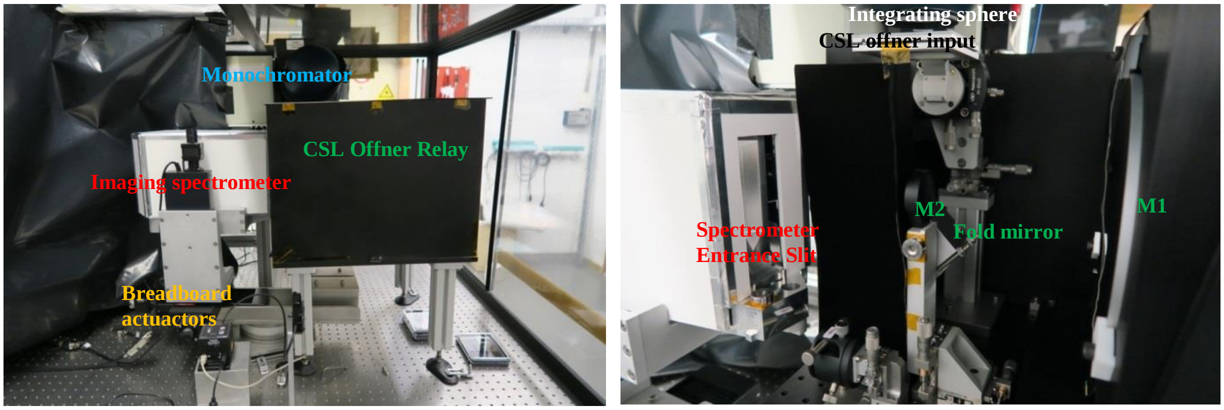

Fig. 5. Pictures of the calibration setup.

B. Target objects

For each performance test, a dedicated target object has been performed at CSL. Some pictures are depicted in Fig. 6. The targets are inserted in specific housing adapted for an accurate positioning in the mounting aligned in the calibration setup under the IS.

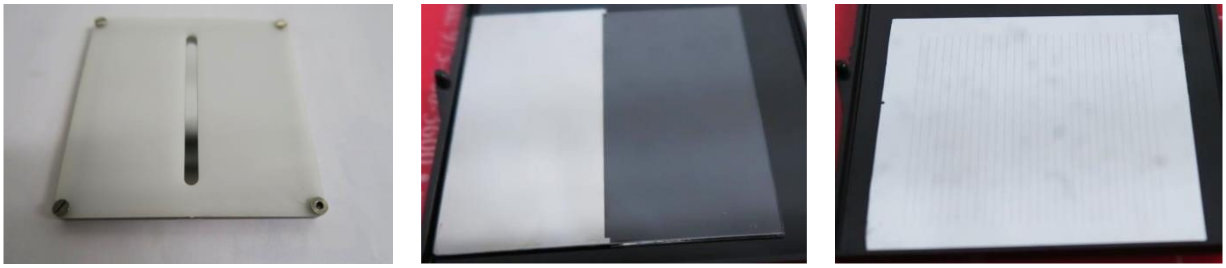

Fig. 6. Different objects that will be placed at the entrance of CSL Offner relay. (Left) 7.5µm wide slit for alignment and MTF. (Center) Knife-edge for the straylight measurement. (Right) Array of 50µm wide slits for keystone measurement.

C. Test setup fully automatized

Because of the large number of parameters to record, the calibration facility is completely automatized.

The Labview program controls:

- The monochromator: $\Delta\lambda$ (automated adaptation of slit width), λ scanning, grating (modification according $\Delta\lambda$ and λ), high order rejection filters (according λ).
- Motorized translations for breadboard accurate positioning: fine lateral and focus positioning, slit horizontal and vertical scan.
- Camera acquisition parameters: automated adaptation of integration time according λ.
- Polarizer rotation.

The program manages the positions and wavelength scanning for each test configuration. Images recorded by the camera at each step are automatically classified to be analyzed.

D. Setup alignment

Alignment consists mainly to co-align both mirrors (M1 and M2), and to localize exactly entrance and exit slits. For this purpose, slits are materialized by metallic spheres.

A first alignment was done with an API Radian laser tracker, completed after by an interferometric alignment. This interferometric alignment uses those metallic spheres to measure the WFE across the Offner Relay. The aberrations are minimized by tuning mirrors and entrance slit positions. At the optimum configuration, all positions are fixed. Metallic spheres at the exit of the Offner Relay are then placed at the focal point of the interferometer.

The WFE measurement for the final frozen configuration of the CSL Offner relay is shown in Fig. 7. Astigmatism is the main contributor to the WFE, but the RMS value is considered as sufficiently low.

Once Offner relay has been aligned, the second step is to align the spectrometer: its entrance slit shall coincide with the Offner relay exit slit (materialized by metallic spheres). A first alignment has been carried out by laser tracker: positions of the exit slit metallic spheres are recorded and entrance slit of the spectrometer is placed with the X,Y,Z motorized translation stages, at that position. Then, it is the image on the spectrometer camera that is used to refine the alignment: a slit theoretically thinner than a pixel is placed at Offner relay entrance, the focus is adjusted in order to image this slit on about 1 pixel on the camera.

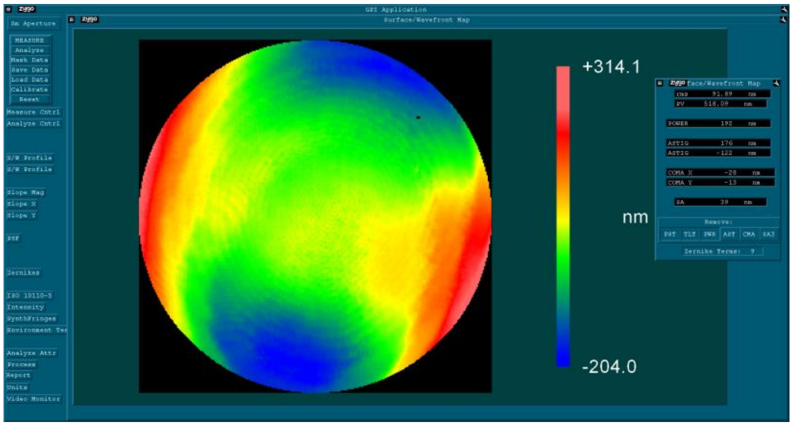

Fig. 7. WFE obtained after alignment adjustment.

IV. SETUP CHARACTERIZATION

A. MTF

The MTF curve corresponding to the WFE of the Fig. 7 is better than 88% at 15 lp/mm.

B. Spatial uniformity

The setup was designed to uniformly illuminate an exit slit around 60mm long.

The exit slit spatial uniformity of the Offner relay is mainly linked to the IS output. It has been measured with the set-up depicted in Fig. 8. The monochromator is working on the 0^{th} diffraction order, illuminating the slit with a polychromatic light. An optical fiber (20 µm width) with a NA=0.1 is used in order to analyze only in-field light (F/#~5, comparable to the spectrometer F/#). The fiber is connected to a photodetector, and fixed on a translation stage to scan the full exit slit.

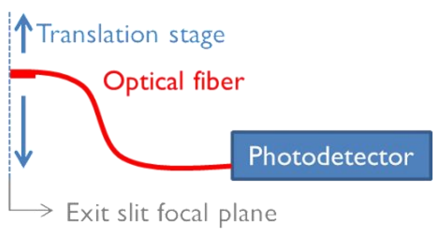

Fig. 8. Exit spatial uniformity measurement set-up.

Results are presented in Fig. 9: the Offner relay reaches 99% uniformity over 59mm.

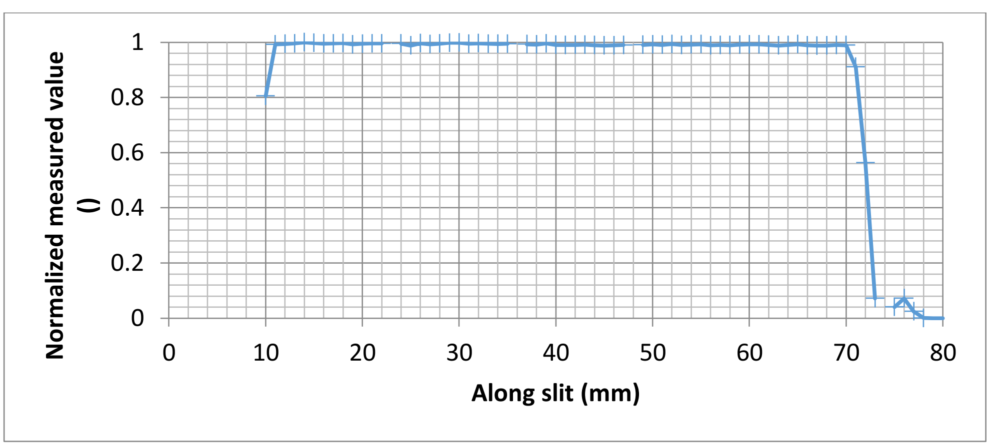

Fig. 9. Uniformity measurement at CSL Offner relay exit slit

C. Straylight

To measure Offner relay straylight at exit slit, for in field light, the set-up presented in Fig. 10 is used. It allows a scan of the Offner relay focal plane to investigate the transition of a knife-edge placed at the entrance slit.

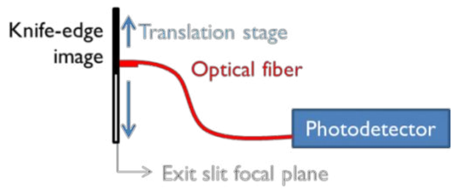

Fig. 10. Straylight measurement set-up, at the exit slit of the Offner relay. A knife-edge is placed at the entrance slit, its image at the exit slit is scanned by an optical fiber linked to a photodetector.

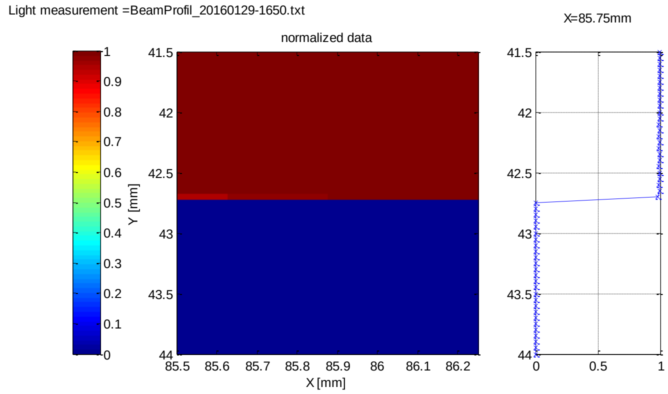

Fig. 11. Offner relay straylight measurement results.

Measurement results are depicted in Fig. 11. Averaged straylight at 250 µm from the cut is around 0.13% ± 0.01%.

D. Irradiance

Irradiance at spectrometer entrance slit (F/#5 field) has been measured with a calibrated photodiode, depicted in Fig. 12. Even if the irradiance is small, for the tested spectrometer, enough flux is collected by the camera in its focal plane to achieve good S/N image.

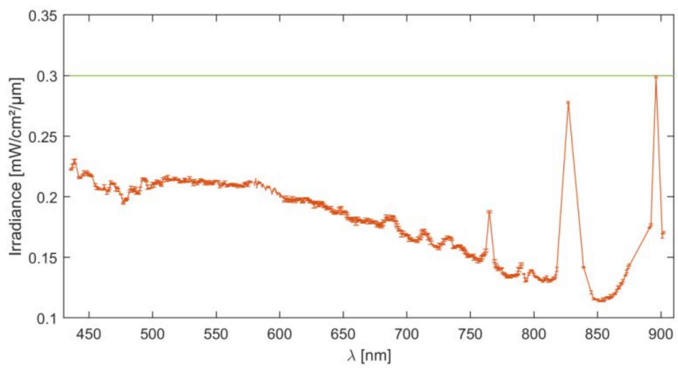

Fig. 12. Irradiance measurement at spectrometer entrance slit. The slit height seen by the calibrated detector has been measured at 7 mm. Slit width is fixed by the spectrometer entrance slit (30 µm width).

E. Polarization

To test polarization sensitivity, the input light has to be nearly non-polarized. Offner relay output light polarization has thus been measured. The set-up is depicted in Fig. 13, using a linear motorized rotating polarizer to scan polarization angles.

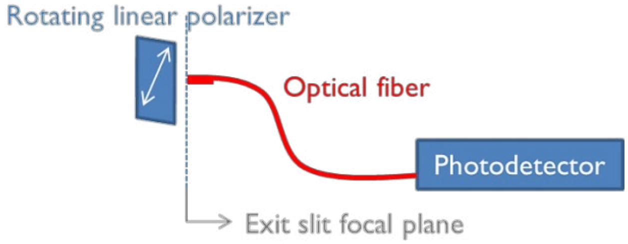

Fig. 13. Polarization characterization set-up. A rotating linear polarizer is placed in front of the Offner relay exit slit. Output light according to polarization angle is collected by an optical fiber linked to a photodetector.

Measurements are influenced by two main factors:

1. The rotation stage movement behaviour, modifying incident angles on the polarizer according the rotation position, see Fig. 14.
2. Detector polarization sensitivity. Measurements are depicted in Fig. 15.

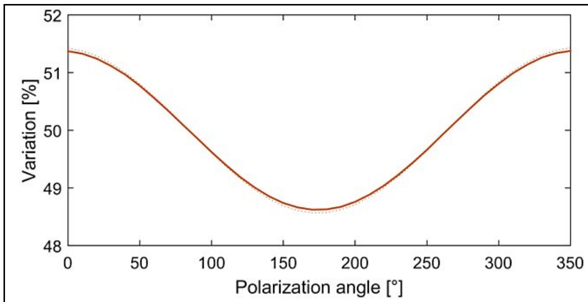

Fig. 14. Sinusoidal variation to be subtracted from polarization characterization measurements coming from rotating stage behavior.

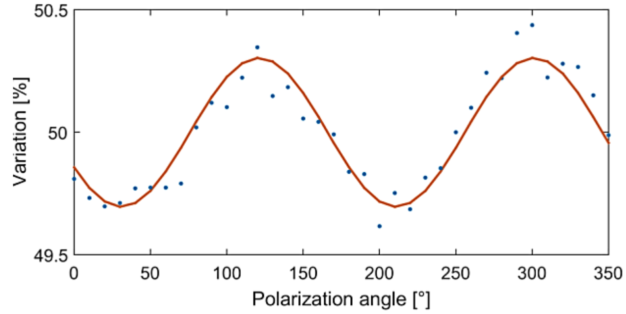

Fig. 15. Polarization sensitivity of Offner relay output light.

Since the Offner relay polarization is known (Fig. 14 and Fig. 15) it can be removed, and by this way the tested spectrometer (including camera) polarization behaviour is known with an accuracy of 0.5%.

V. TESTS DESCRIPTION

A. Keystone

The Keystone is defined as the departure from straightness and parallelism of line spectra from white point sources at various positions in the image field. For this test:

- Polychromatic light is obtained by using the 0^{th} diffraction order of the monochromator.
- A grid of 30 slits, 50 µm wide and 2 mm spaced, is placed in the object plane of the Offner relay (after the IS), shown in Fig. 6 (right picture). The grid is imaged on the spectrometer entrance slit, and finally its spectrally dispersed image is recorded by the camera. An example is presented in the first picture of Fig. 16.
- According to the distortion of the recorded grid on the camera, by post-processing, the keystone can be extracted.

B. Spectral response matrix

This characterization includes spectral range, spectral resolution, peak transmission, smile and tilt, and out-of-band rejection. The goal is to build a 3D spectral response matrix.
All this information can be extracted from a spectral scan ($\Delta\lambda$=2.5 nm, for λ=400 to 950 nm) performed by the monochromator. For this configuration, no slit in object plane is needed: a full line along geometrical dimension will be registered at different spectral positions according to λ.

C. MTF

Two kind of MTF can be measured: in spatial direction, or in spectral direction. MTF is extracted from LSF.
To do LSF measurement, there are two configurations:

- *Spatial LSF:* a small slit (7.5 µm width, determined to be smaller than the camera pixel for the studied spectrometer) is placed in the Offner object plane, perpendicular to the spatial axis. Polychromatic light (0^{th} diffraction order of the monochromator) is used. An example of image recorded at one position is depicted in Fig. 16 (right picture). The entrance spectrometer slit is then scanned by steps of 2 µm (respecting Nyquist criteria) by moving the spectrometer thanks to the translation stages. From the more than 40 images collected, the LSF can be derived, and finally the spatial MTF can be computed by Fourier transform.
- *Spectral LSF:* the small "slit" used to scan the focal plane is here defined by a very short spectral line ($\Delta\lambda < 0.6$ nm). By changing λ_c by step of 0.2 nm, the monochromator scans the spectral axis of the spectrometer focal plane. As for the spatial MTF, the spectral MTF is deduced from Fourier transform of measured LSF.

D. Polarization sensitivity

Polarization sensitivity measurement implies image registration according incident light polarization angle. For this purpose, a motorized rotating polarizer is placed in front of the spectrometer entrance slit. By removing the polarizer artifact and previously characterized Offner polarization signature (see section IV.E), the spectrometer polarization sensitivity can be extracted. This measurement can be done with polychromatic light or quasi-monochromatic light.

E. Straylight

In-field straylight is measured by placing a knife-edge in the object plane of the calibration setup in order to mask half of the image plane surface (along spatial direction), see central picture of Fig. 6. Images have been recorded for different wavelengths ($\Delta\lambda$~10nm) and for white light (example in the second picture of Fig. 16). Removing background, these images gives information on straylight with respect to the distance from the knife-edge.

VI. CALIBRATION CAMPAIN RESULTS EXAMPLES

This calibration facility was prepared and used to calibrate a new free-form compact spectro-imager. Some captured images are depicted in Fig. 16. Detailed analysis of performances, including their extraction methodology from measurement, can be found in Ref. [1].

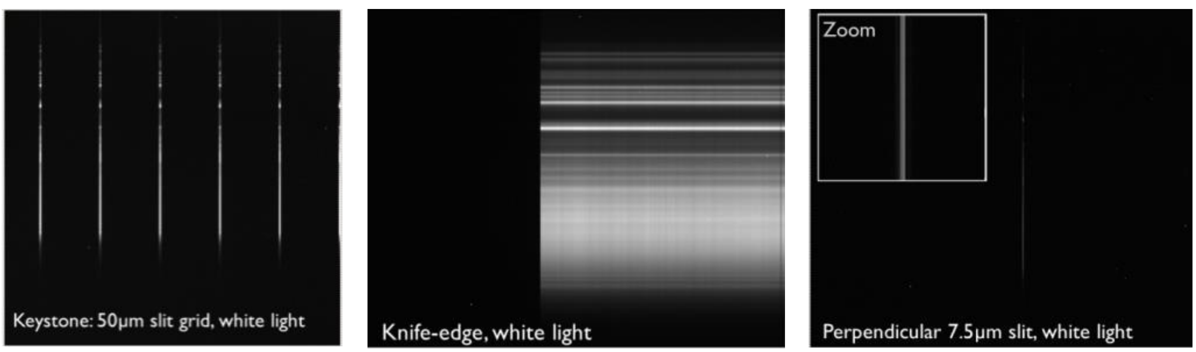

Fig. 16. Preliminary pictures capture on the spectrometer camera respectively for keystone, straylight, MTF and spectral registration configurations. Horizontal axis is the spatial dimension, vertical axis is the spectral dimension.

VII. CONCLUSION

New types of spectrometers for Earth observation are under development, modifying requirement for calibration facilities. Their designs become then more challenging.
In this paper, design and performances of a new calibration facility for spectro-imager has been presented. The developed calibration facility was certified fully compliant to characterize the new spectro-imager presented in Ref [1]. Collaboration will continue for the next spectrometer generation, which will be tested with the same calibration setup. An adaptation of this calibration setup will also be developed to perform calibration in vacuum environment.

VIII. AKNOWLEDGEMENT

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IX. REFERENCES

[1] V. Moreau, J. Versluys, M. François, M. Taccola, C. Michel, P. Blain, and Y. Stockman, “Tests and calibration of a free form compact spectro-imager”, in: Proceedings of 4S Symposium 2016, in press.