

International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas



Wedge filter imaging spectrometer

Pernelle Bernardi

M. Bonafous

M. Motisi

J-M. Reess

et al.



WEDGE FILTER IMAGING SPECTROMETER

P. Bernardi¹, M. Bonafous¹, M. Motisi¹, J-M. Reess¹, J. Tanrin¹, D. Laubier²
¹LESIA - Observatoire de Paris - CNRS, 5 place Jules Janssen, 92190 Meudon, France.
pernelle.bernardi@obspm.fr
²CNES, 18 avenue Edouard Belin, 31400 Toulouse, France.

I. INTRODUCTION

LESIA (Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, Observatoire de Paris-Meudon) has an extensive experience in visible and infrared imaging spectrometry with several instruments onboard planetary space missions (MarsExpress/OMEGA, VenusExpress/VIRTIS, Rosetta/VIRTIS). These instruments demonstrated high performances on wide spectral bands [0.4-5.0 μ m] with spectral resolution up to 2000 and good spatial resolution. However, designed for large orbiters, they are in the 30kg range. In the actual competitive context, instrument miniaturization is an essential effort to provide to be onboard a rover or a mission of opportunity. A first Research & Technology (R&T) program was conducted by LESIA and CNES (Centre National d'Etudes Spatiales) in the 2000s to study a new concept of miniaturized imaging spectrometer using a linear variable filter (LVF) and a dispersive system in the fore-optics, dedicated to low resolution imaging spectroscopy. The efforts were focused on the characterization of the LVF and the establishment of a numerical model of the instrument, as described in [1]. With a spectral resolution of about 100, and an estimated mass lower than 1.5kg, this instrument is suitable for investigating the composition of small bodies, in particular the detailed mineralogy, organics and water-altered materials.

This paper presents the results of a second R&T program dedicated to the setting of a mock-up. The measured performances (spectral resolution, field of view) are compared to the expected values from the numerical instrument model.

II. CONCEPT

A. Spectrometer concepts

The classical imaging spectrometers mentioned in the introduction, are based on the pushbroom principle in which both dimensions of a detector array give: (1) a spatial dimension (one sample line) and (2) a spectral dimension (one spectrum per spatial sample). The motion of the vehicle or a scanning mirror usually recovers the second spatial dimension. The optical principle of such an instrument is given in fig.1 (layout 1). The slit determines the field of view of the instrument. The collimator and the dispersive system make images of the slit in all the wavelengths spread over the spectral direction, and these images are focused on the detector pixels using the objective.

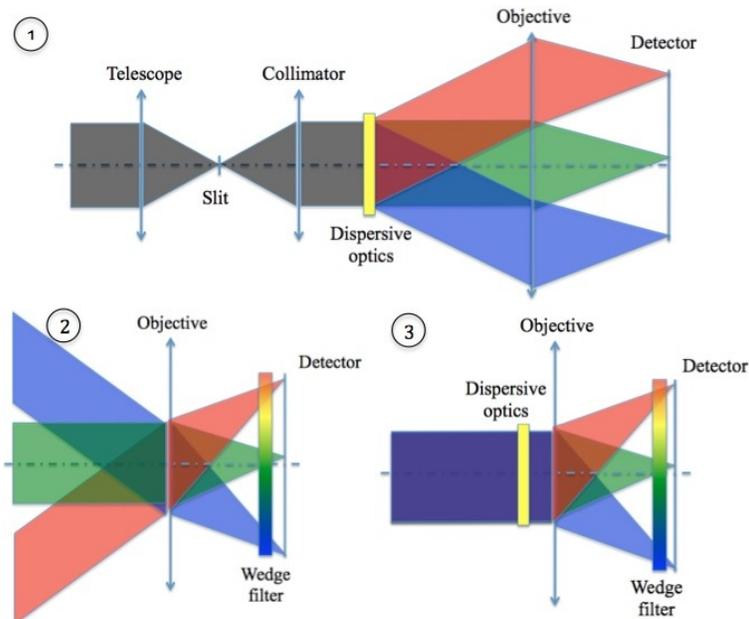


Fig. 1. Spectrometer concepts.
Proc. of SPIE Vol. 10563 1056335-2

A LVF is a narrow-band transmission filter with a peak wavelength varying linearly along one dimension of the filter. Coupled to an array detector, it forms a simple and compact imaging spectrometer as drawn in fig.1 (layout 2) and described in [2]. Besides the compactness, another advantage of this system is the reliable spectral registration, due to the rigid connection between the filter and the detector array, which allows getting rid of an internal calibration device. This concept is also interesting for infrared spectroscopy as it reduces the thermal background. Indeed a pixel sees only its useful narrow wavelength band, whereas in a classical spectrometer, a pixel sees the background in the whole spectral range. The main drawback of the system is that at a given time the pixels see different lines of sight. Image resampling can correct this misregistration, well noticed in [3], but needs very precise geometry information.

Adding a dispersive system in front of the objective, with the same dispersion law than the LVF, allows the pixels to point the same line of sight. In this system drawn in fig.1 (layout 3), the dispersive optics work in a collimated beam, thus in the best conditions. The alignment between the two optical groups {dispersive system + objective} and {filter + detector} is not stringent because a decenter creates an offset of the line of sight that can be calibrated.

B. Choice of the dispersive system

We have basically the choice between a diffraction grating and a prism. Considering its linear dispersive law and mass criterion, the diffraction grating would be the preferred solution. However the absence of field stop at the entrance of the instrument prevent from using a grating. Indeed, for a wavelength λ_0 diffracted in the direction β_0 in the first order of the grating, there are several angles of incidence (thus fields) for which rays at λ_0 are diffracted in the same direction β_0 . This is due to the existence of multiple diffraction orders of the grating and there is no solution to avoid them.

A prism is therefore chosen as dispersive system. The main concern of the prism is its non-linear dispersive law. This will be discussed later in the paper. A typical optical design of a wedge filter imaging spectrometer is illustrated in fig.2. The optical elements are limited to a prism and the four lenses of the objective. The folding mirror is added to compact the instrument volume.

C. Linear variable filter

Off-the-shelf LVF are available, for example at JDS Uniphase (fig.3 left). They supplied several units of LVF working in the [620-1080nm] range. The substrates dimensions are $15.0 \times 5.5 \times 1.5\text{mm}^3$. The local bandwidth is of the order of 1% of the central wavelength and the peak transmission is higher than 50%. Fresnel Institut in Marseille characterized the LVF (fig.3 right) to verify the spectral resolution and the wavelength gradient (40nm/mm).

Other spectral bands are available up to $14\mu\text{m}$. The spectral band of a filter is limited due to the absence of blocking filter.

III. INSTRUMENT MODEL

The instrument model is necessary to predict the spectrometer behavior (that is not so intuitive), and to assist us in the alignment procedure of the breadboard. It will also be used for a first instrument dimensioning given the scientific requirements.

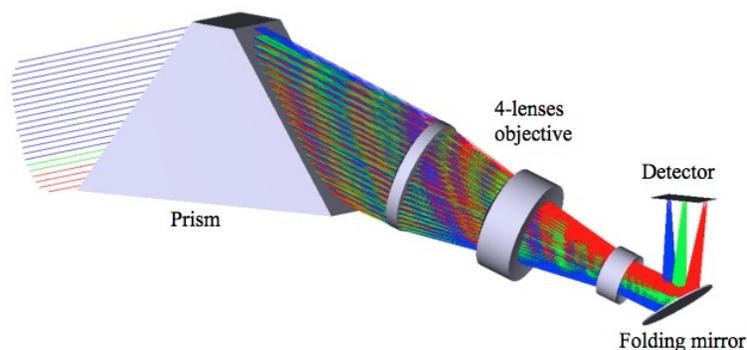


Fig. 2. Optical design of a wedge filter imaging spectrometer.

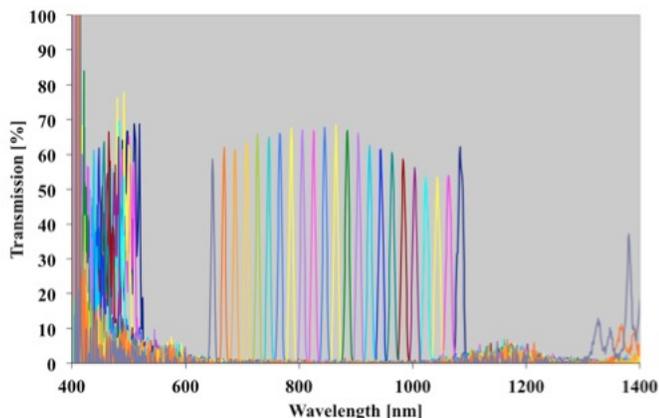
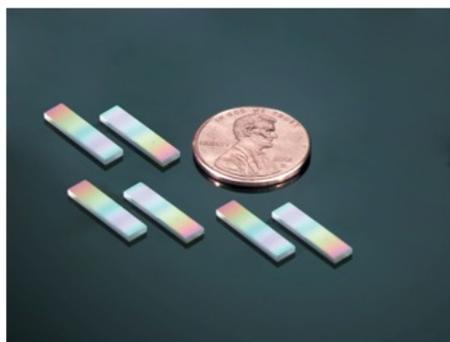


Fig. 3. Left: Linear variable filters from JDSU (Courtesy JDSU). Right: Characterization of a linear variable filter by Fresnel Institute.

A. Numerical simulations

A Mathcad tool runs analytical simulations of the system, and in parallel, an IDL program models the instrument. Both models compute the total field of view (FoV) of the instrument, the instantaneous field of view (IFoV) of each pixel and the spectral resolution (R) of each pixel. The entrance parameters are the spectral band, the optical data (prism material, angles, focal lengths, apertures), and the filter characteristics (dimensions, spectral resolution, wavelength gradient). Two other parameters are adjustable:

- The relative position of the prism and filter along the spectral direction,
- The distance between the filter and the detector.

The principle of the Mathcad model (fig.4) is to take the origin on the detector surface and describe the optical path until the entrance of the prism to retrieve the desired parameters (FoV, IFoV and R). Conversely, the IDL program samples the object spatially and spectrally and computes the detector response.

B. Instrument behavior

Due to the deviation of the prism and filter dispersion laws, each pixel of the detector matrix points a line of sight, θ_2 in fig.4, slightly different from its neighbors. The FoV is defined as the variation of θ_2 along the spectral dimension of the detector. The Mathcad tool models this effect (fig.5 left) and allows estimating the best relative position of the filter and the spectrum dispersed by the prism, i.e. the position minimizing the FoV. For a position where the dispersion laws are fitted, the FoV is about 12mrad (0.7°). A way to reduce the deviation of the dispersion laws is to linearize the prism dispersion by coupling two prisms. However the improvement is not so interesting compared to the increase of the mass. Another solution would be to design non-linear variable filters adapted to the prism dispersion law.

Unless the filter is directly deposited on the sensitive area of the detector, which is not the case here, the distance between the filter and the detector is not null. Indeed, coupled to the aperture of the beam, the surface intercepted on the filter increases with the distance between the filter and the detector.

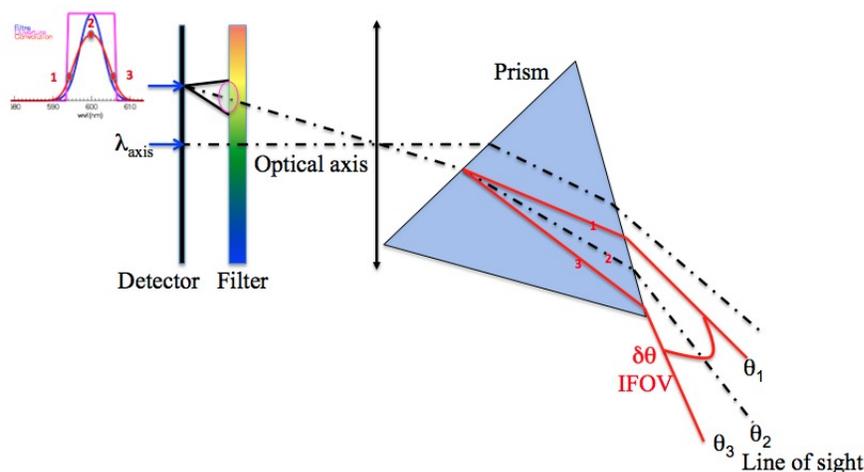


Fig. 4: Principle of Mathcad simulation.

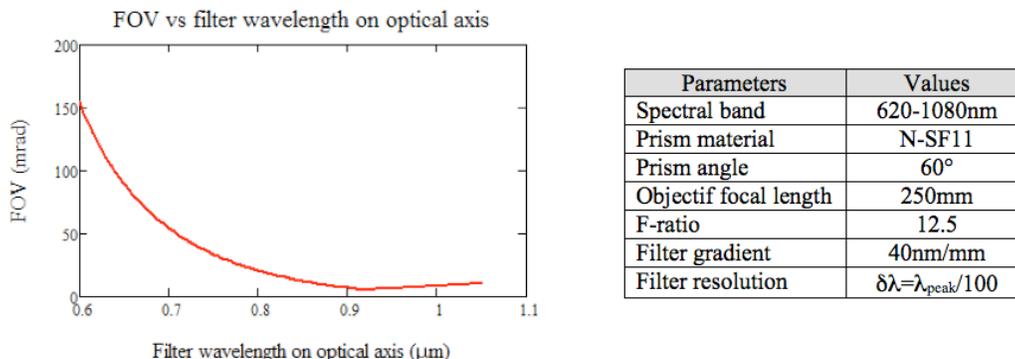


Fig. 5. Left: FoV versus relative position of the filter and prism spectrum. The optical axis is defined as the direction of the rays at 850nm dispersed by the prism. The x-axis represents the wavelength transmitted by the filter on the optical axis. Right: Optical parameters used for the simulations.

This results in an increase of the IFoV (fig.6 left) and a decrease of the spectral resolution (fig.6 right). Thus, the distance between the filter and detector should be minimized. For a distance of 100μm, the expected IFoV is about 2.2mrad @650nm and 0.9mrad @1050nm.

The spectral resolution of the instrument is defined as $\lambda/\Delta\lambda$, where $\Delta\lambda$ is the spectral band contributing to 90% of the energy registered by a pixel. As the filter transmission profile is gaussian, $\Delta\lambda$ is equal to 1.4 times the full width at half maximum of the gaussian function (FWHM). For a filter to detector distance of 100μm, the expected spectral resolution is equal is about 68. Note that the filter resolution, defined as λ/FWHM , is equal to 100, thus 1.4 times higher than the spectrometer resolution. This is just a consequence of the different definitions.

Adapting the dispersion laws of the filter and prism, as described above, would allow reaching IFoV of about 1mrad. The IFoV would still vary with wavelength, though to a lower extent, because it is proportional to the spectral band locally transmitted by the filter FWHM ($R = \lambda/\text{FWHM}$ is a constant for the filter, thus FWHM is varying). A minimum spectral resolution of 150 could be easily achieved with better resolution of variable filters (typically 200).

C. Example of instrument

LESIA has proposed a "classical" infrared imaging spectrometer for the Binary Asteroid in-situ Explorer (*BASiX*) Mission [4], based on prisms dispersion. *BASiX* will make the first quantitative measurements of a near-Earth asteroid's strength and seismic properties, and be the first to explore a binary asteroid system's mass morphology (target 1996 FG₃). A near infrared imaging spectrometer is classical and unavoidable instrument for remote characterization. This instrument covers the [0.4-4.0μm] band, with a spectral resolution of 200, a mass of 7.5kg and an optical head volume of 400 x 300 x 128mm³ (fig.7 left).

Focusing on the main scientific goals, and thus reducing the spectral band ([2.7-3.8μm] typically), a wedge imaging filter spectrometer would comply with the scientific requirements with a mass in the 1.5kg range and dimensions within 160 x 230 x 54 mm³ (fig.7 right).

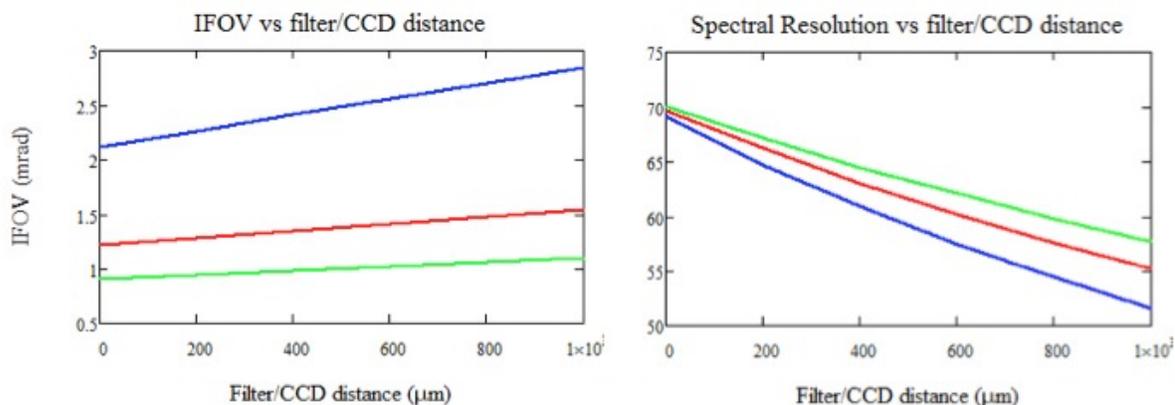


Fig. 6. IFoV and spectral resolution versus distance between filter and CCD.

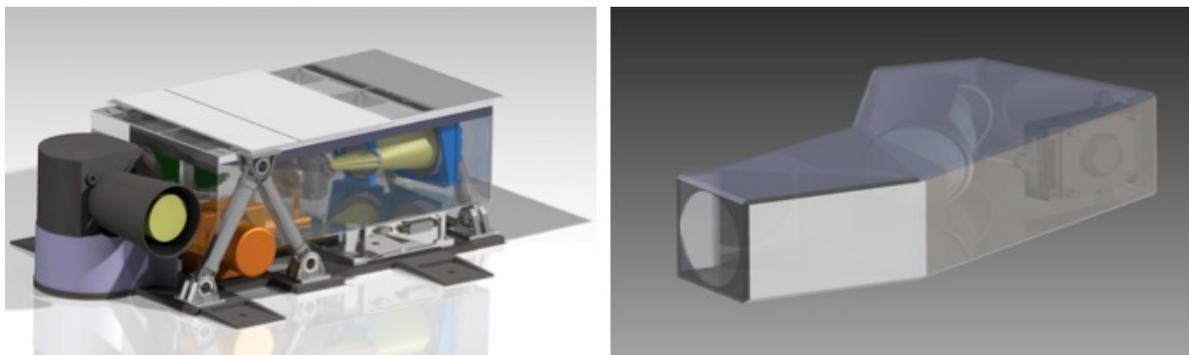


Fig. 7. Left: Opto-mechanical design of a classical imaging spectrometer. Right: Opto-mechanical design of a wedge filter imaging spectrometer.

IV. SPECTROMETER BREADBOARD

A. General description

The objectives of the spectrometer breadboard (fig.8) are to integrate a LVF in a camera, align the assembly with respect to a prism and characterize the performances in terms of spectral resolution and field of view.

Locating a slit at a collimator focus creates the artificial object at infinite distance. A monochromator (spectral resolution better than 2nm) and its output optics illuminate homogeneously the slit. The slit is mounted on a translation stage to explore the field of view. The off-the-shelf prism (N-SF11 glass) works at its minimum deviation. An objective focuses the dispersed beam onto the detector.

B. The camera assembly

In order to reduce the cost, we chose to supply a commercial camera and integrate the filter close to the detector in our laboratory. The camera must comply with several requirements: (1) no cover glass for the CCD, (2) no window at the entrance of the camera, (3) a CCD area and detector package large enough to locate the filter (15.0mm length) at 100 μ m distance from the CCD sensitive area. The camera Insight IN1400 from SPOT Imaging Solutions (fig.9 top left) complies with all these requirements. The Kodak CCD KAI-4021-M, with 2048 x 2048 pixels (7.4 μ m pitch), leads to a 15.2 x 15.2mm² sensitive area. SPOT kindly accepted to deliver a CCD without cover glass and to remove the camera window.

The LESIA design department developed a custom mechanical mount to maintain the filter close to the CCD sensitive area (fig.9 top right). The filter is glued on a mount that can be translated from 100 μ m to 2mm from the CCD, with a \pm 10 μ m precision. The filter mount assembly uses the F-mount of the camera as mechanical interface (fig.9 bottom).

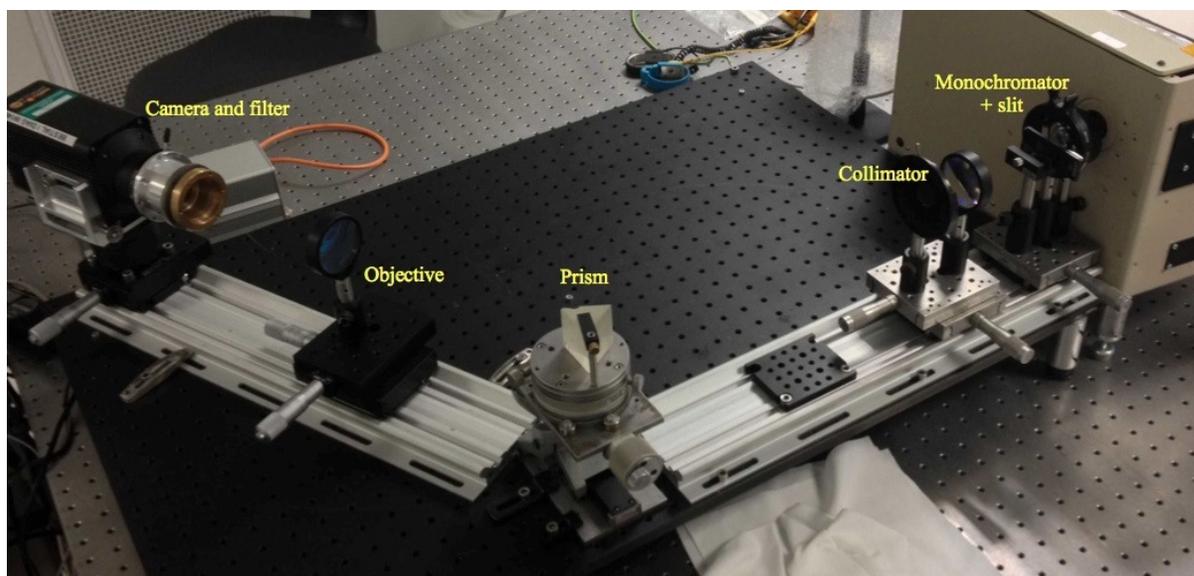


Fig. 8. Spectrometer breadboard.
Proc. of SPIE Vol. 10563 1056355-6

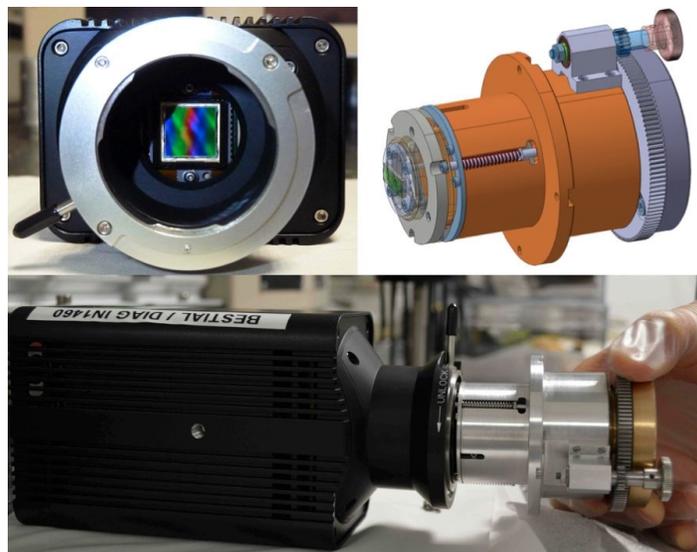


Fig. 9. Camera assembly. Top left: front view of the camera with unprotected CCD. Top right: mechanical interface between filter and camera. Bottom: integration of the filter assembly in the camera housing.

C. Metrology

The distance between the filter and the CCD is an important parameter to monitor, not only because the filter must not touch the CCD sensitive area, but also because it directly impacts the spectrometer performances. Thus we need to have at our disposal a non-contact distance sensor with a precision better than a few microns. We chose the confocal-chromatic sensor and controller from Micro-Epsilon. The confocal chromatic measuring principle works by focusing polychromatic white light onto the target surface using a multi-lens optical system. The lenses are arranged in such a way that the white light is dispersed into a monochromatic light by controlled chromatic deviation (aberration). A certain deviation (specific distance) is assigned to each wavelength by a factory calibration. Only the wavelength that is exactly focused on the target surface or material is used for the measurement. This light reflected from the target surface is passed through a confocal aperture onto a spectrometer, which detects and processes the spectral changes.

The filter mount was adapted to point successively the detector surface and the filter first face (fig.10). The filter thickness was previously measured with several methods, and in particular using the confocal-chromatic sensor that measures transparent elements thicknesses (knowing the refraction index of the material).

The distance between the filter rear face (where the filter function is located) and the CCD sensitive area is measured with a precision better than $\pm 3\mu\text{m}$.

V. RESULTS

The measurements consisted in scanning the field of view (translation of the slit) and the spectral band (with the monochromator) to assess the IFoV and the spectral resolution. We favored the spectral band with the best signal to noise ratio on the images ([800-900nm]) and tested two distances between the filter and the detector: 124 μm and 480 μm .

The results for the spectral resolution are presented in fig.11. We observed a very good coherence between the Mathcad and IDL models. The measured spectral resolution is nevertheless lower than expected. Moreover we didn't find a variation with the filter to CCD distance.

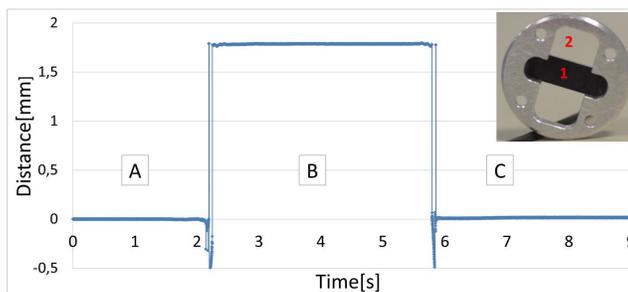


Fig. 10. Distance measurement between the LVF and detector.
Proc. of SPIE Vol. 10563 1056355-7

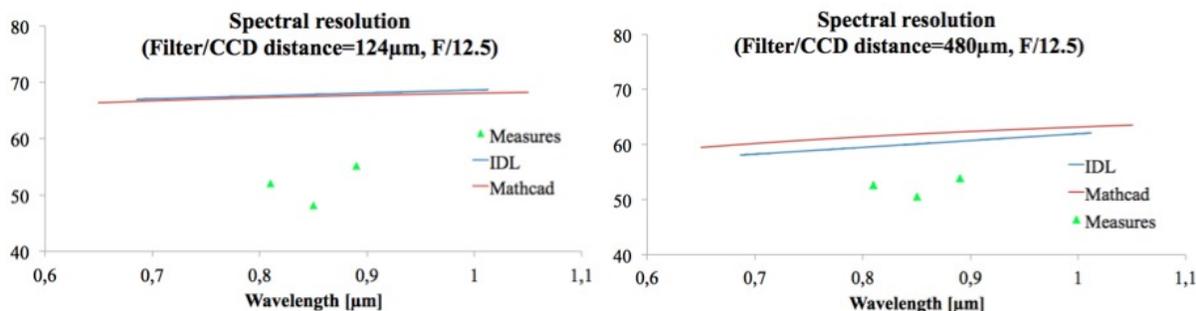


Fig. 11. Green triangles: Measurement of the spectral resolution for 2 distances between the filter and the CCD (left: 124μm, right: 480μm). Comparison with the expected values from Mathcad model (red) and IDL model (blue).

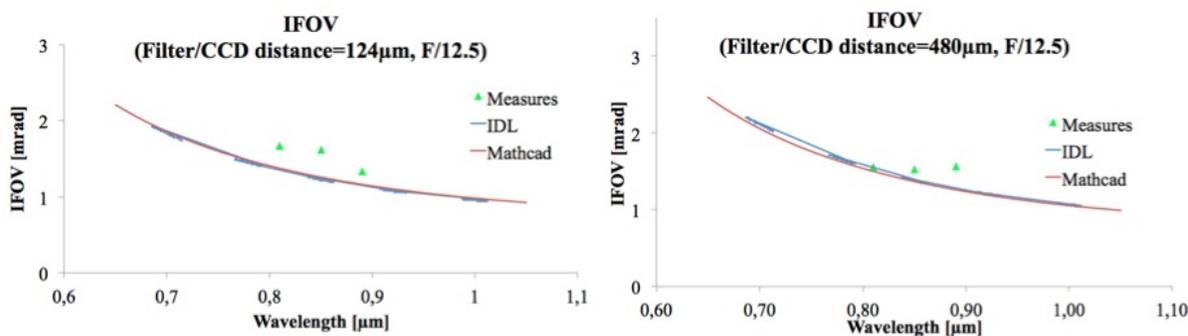


Fig. 12. Green triangles: Measurement of the IFOV for 2 distances between the filter and the CCD (left: 124μm, right: 480μm). Comparison with the expected values from Mathcad model (red) and IDL model (blue).

The results for the IFOV are presented in fig.12. Once again, the two models are coherent and the variation of the measured IFOV with the filter to CCD distance is not the expected one.

We assume that the effect of the filter to CCD distance is hidden by the diffraction effect that has not been taken into account so far in the models. We estimate working at F/12.5 on the breadboard, which corresponds to a 24μm diameter Airy disk in the focal plane. This is equivalent to 3 pixels and thus non negligible. Furthermore, we suspect a poor optical quality of the objective, which would worsen the diffraction effect.

VI. CONCLUSIONS AND PERSPECTIVES

The feasibility of the wedge filter imaging spectrometer is demonstrated. An instrument model is available to achieve a first dimensioning of the instrument. This model will be improved by implementing the diffraction effect. We plan to upgrade the breadboard to have a more compact mock-up and a better optical quality. The mechanical interface between the filter and the camera will be re-designed to reach a faster F-ratio, and a Nikon objective will be used to ensure a good optical quality in the focal plane.

The numerical simulations and tests on the breadboard have highlighted the main issues limiting the performances. We have identified three ways to improve the performances: (1) Increasing the spectral resolution of the filters (up to 200), (2) Adapting the dispersion law of the filter to the prism, (3) Increasing the spectral band by adding a variable blocking filter. A proposal for a new CNES R&T program in collaboration with Fresnel Institut in Marseille has been prepared to develop non-linear variable filters fulfilling these requirements.

REFERENCES

- [1] A.Semery et al, "Wedge filter imaging spectrometer", *ICSO 2006*.
- [2] A.Piegari et al, "Compact imaging spectrometer with visible-infrared variable filters for Earth and planet observation," *Proc. of SPIE*, vol. 8172. Optical Complex Systems, October 2011.
- [3] J.Jeter and K.Blasius, "Wedge spectrometer concepts for space IR remote sensing," *Proc. of SPIE*, vol. 3756, pp. 211-222, July 1999.
- [4] R.C.Anderson, D.Scheeres and S.Chesley, "Binary Asteroid in-situ Explorer Mission (BASiX): A Mission Concept to Explore a Binary Near Earth Asteroid System", *45th Lunar and Planetary Science Conference*, 2014.