SSC19-VII-08

Freeform grating-based hyperspectral instruments: when SmallSat solutions benefit to big missions.

Vincent Moreau, Benoit Borguet, Jean-François Jamoye
AMOS, Rue des Chasseurs Ardennais 2, B-4031 Angleur, Belgium; +32 4 3614040
Vincent.moreau@amos.be

Luca Maresi, Alessandro Zuccaro Marchi, Micael Miranda
ESA European Space Research and Technology Centre, Keplerlaan 1, 2201 AZ
Noordwijk, The Netherlands;
Luca.maresi@esa.int

ABSTRACT

Hyperspectral Earth Observation is a fast-growing field requiring high performing imaging spectrometers.

Since 2010, the European Space Agency has initiated a series of developments demonstrating the feasibility of miniaturized hyperspectral instruments on mini- and nano-satellites [1].

Among them, ELOIS and CHIMA are two innovative full Aluminum instruments based on diffraction gratings ruled on a freeform surface (FFG : Free-Form Grating). That solution offers a reduction of about a factor of 4 in volume with respect to a Offner-Chrisp spectrometers with equivalent performances.

The Spectrometers combines three promising new technologies for future hyperspectral instruments: complex blazed grating, freeform optics and backside-illuminated hyperspectral CMOS sensor. With an image space F-number of 2.1, ELOIS is also one of the fastest instrument of this type. The ratio between Swath and Ground Sampling Distance is about twice as big as currently planned hyperspectral missions.

Breadboards of these spectro-imagers, limited to the visible and NIR spectra, has been manufactured and tested. This breadboard program confirmed the achievement of the challenging design specifications.

Based on these demonstrations, a complete payload is now developed to cover the VNIR and SWIR spectral ranges (400nm to 2450 nm) with a spectral resolution of 10 nm.

The proposed technologies are now studied in the context of the “Copernicus Space Component Expansion” program. Six candidate missions have been identified by the European Commission (EC) as priorities for implementation in the coming years. Among them, the CHIME mission (Copernicus Hyperspectral Imaging Mission for Environment) aims to provide precise spectroscopic measurements in the VNIR/SWIR spectral range. Those data will be used to derive quantitative surface characteristics supporting the monitoring, implementation and improvement of a range of policies in the domain of raw materials, agriculture, soils, food security, biodiversity, environmental degradation and hazards, inland and coastal waters, snow, forestry and the urban environment.

1. INTRODUCTION

The Instrument ELOIS, i.e. Enhanced Light Offner Imaging Spectrometer, is a compact lightweight high performing hyperspectral imager with a spectral resolution of 10 nm (2.5 nm in un-binned mode) [2]. It resolves ground-projected pixels of 35m at Nadir in the VNIR and 70m to 35m in the SWIR (depending on sensor availability) over a swath of 70 km. With a platform roll viewing agility of ±30 degrees, this leads to less than 5 days revisit time for any location on earth.

The original objective of the partners was to demonstrate that smart optical design combining Freeform gratings and highly aspherical mirrors allowed for an important mass and volume reduction of high-performance hyperspectral imager, compatible with Small Sat (~100kg) constraints. We also aim to validate that all the critical components (grating, mirrors, slit) can be accurately manufactured with techniques based on single point diamond turning.

The instrument is specified as described in Table 1 to provide high SNR hyperspectral images of medium spatial resolutions from the earth canopy for a series of applications including agriculture, vegetation, forestry, land cover use, and geological mapping as well as water management. The Instrument is targeted to operate on a Sun Synchronous near polar earth orbit between 590 and 670 km with a reference at 642 km.

Table 1 : ELOIS Payload Specification

Specification	Requirement
Reference orbit	642 km
Ground Sampling Distance	35 m - 70m
Swath	70 km
SNR (alb. 0.3)	>400(VNIR); > 150 (SWIR)
Spectral Range	400-2450 nm
Spectral bands	Up to 210
Spectral resolution	2.5 nm – 10 nm
Mass	40 kg
Volume	640 x 700 x 550 mm³
Power consumption	<60 W in operation (<7 W in stand-by)
Image data rate	500 Mbps

2. COMPACT DESIGN FOR HIGH RADIOMETRIC PERFORMANCE

The Freeform Grating design offers increased flexibility and throughput performances in the sense that it combines imaging, de-magnification and dispersing functions in a system with only three power surfaces enclosed in a compact volume. In addition, the design offers the excellent keystone and smile performances required by the application. It has been demonstrated recently that the use of free-form surfaces allows a reduction of about a factor of 4 in volume with respect to the classical Offner-spectrometer design [3].

The radiometric performances rely on a very small F-number (F/2.1) and complex blazed grating design to maximize the grating efficiency over the broad spectral range covered by the spectroscope. A beam splitter is implemented in front of the focal plane for addressing respective spectral ranges to VNIR and SWIR detectors.

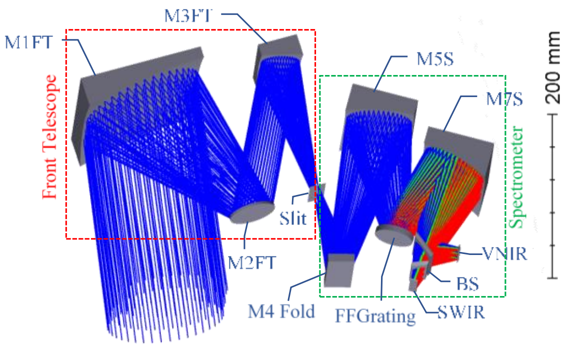

Figure 1 : Optical design of the ELOIS Spectro-Imager. It is composed of a front telescope with a large diameter pupil, of a compact free-form spectroscope and a dual sensors focal plane.

The SNR is the principal metric that has guided the configuration selection. Three main sources of noise can be identified: the shot noise, the read-out-noise, and the dark noise. At relatively high frame rate, the shot-noise remains the largest contributor when dealing with high photon statistics. The 140mm pupil diameter of the instrument, the optimized efficiency of the grating and the large full-well capacity of both detectors contribute to a good SNR, in line with the specification of the envisioned hyperspectral Copernicus mission (CHIME).

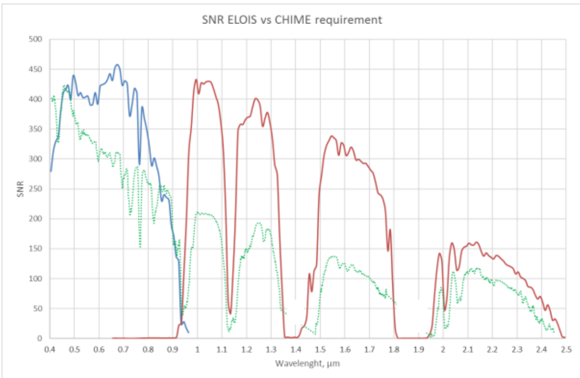

Figure 2 : ELOIS SNR (Blue and Red curve) compared with initial CHIME instrument requirement for the Copernicus Expansion Program (Green)

The complete optical chain achieves a Modulation Transfer Function of 0.8 in the VNIR and 0.65 in the SWIR, allowing for a total MTF budget of about 0.3 including smearing, jitter, sensor, manufacturing and thermos-elastic errors.

The distortions of the image in spatial and spectral directions are also critical for high-end applications and must be controlled very carefully especially for an extended swath as proposed. The spectral smile is

direct quantification of the spectral shift induced by the variation of the spectral magnification along the slit position. As a result, the sensor does not respond to the exact same wavelength across an individual scan line. The smile affecting the VNIR and SWIR channels of ELOIS is reduced to 1.75 µm PtV which is corresponding less than 3% of the spectral resolution.

The keystone quantifies the spatial distortions affecting the focal plane of a Spectro-imager. The keystone characterizes a chromatic dependence in the optical magnification: it is a measure of the spatial shift between pixels at different wavelengths. As a result, the pixels along a sensor column do not correspond to the exact same across track location. On ELOIS, we report a keystone of about 30% of the GSD while in the context of the CHIME mission Phase A study, considering slightly more complex surfaces, a keystone distortion of less than 10% of the pixel size have been achieved.

3. MODULAR FULL ALUMINUM CONCEPT

The opto-mechanical architecture of the payload is intentionally design as simple and modular as possible, taking a maximum advantage of the full aluminum approach and Single Point Diamond Turning of optical surface and mechanical interfaces. It is based on a main optical bench, supporting all the opto-mechanical elements. The Front Telescope mirrors are directly mounted on the bench while the spectroscope and its focal planes are assembled as a stand-alone sub-system on a second-stage board. For best thermos-elastic stability of the line-of-sight, the star tracker heads are directly attached to the telescope bench with a specific thermal decoupling bracket.

A breadboard of the freeform grating spectrometer, limited to the VNIR channel only, has already been manufactured (see Figure 3) and successfully tested [4].

The instrument is fully athermal as all elements are made in the same aluminum material. The optics were manufactured economically with excellent quality and they were aligned easily thanks to ultra-precise interfaces and “snap-together” assembly.

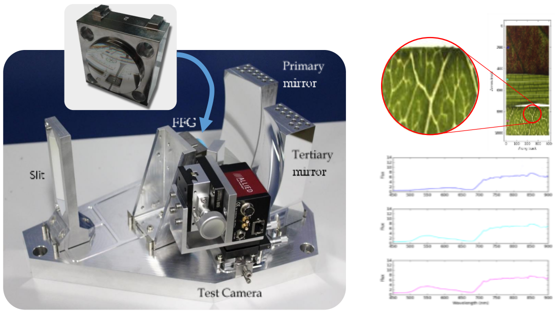

Figure 3 : Full aluminum Breadboard of the VNIR channel Freeform Grating based spectrometer.

4. CHIMA: THE HIGH SPECTRAL RESOLUTION IMAGER

The CHIMA instrument is an ELOIS-inspired spectroscope concept, targeting atmospheric applications. The accurate estimation of atmospheric components typically requires for extreme signal-to-noise ratio (> 1000) coupled with a sub-nanometric spectral resolution altogether with a good control of the optical distortions (<0.1 pixel). These performances can be achieved through the innovations introduced by ELOIS and the addition of advanced distortion control mirrors.

The optical design is based on a heavily customized Offner-Chrisp layout (see Figure 4). The stringent SNR requirement is fulfilled by the conjunction of the binning of 3x3 standard 15 µm pixel, and a built-in 3:1 slit demagnification, allowing the use of an extra wide input slit. The high spectral resolution is ensured by the use of ~1000 groove/mm diffraction grating. The resulting large diffraction angles require the folding of the original spectroscope layout in order to make use of the m=+1 diffracted light. The field independent aberrations introduced by the atypical system configuration are balanced at the pupil stop by allowing a slight freeformity to the grating surface (4 µm PtV with respect to the best fitting sphere). This slight deviation is sufficient to insure the demanding image quality requirement over the full 60 mm long input slit.

One of the key issue during the design optimization was the control of both original focal plane keystone (> 130 µm) and smile (~ 200 µm) without requiring strong freeformity of all the surfaces. The adopted solution for the keystone management is the introduction of an additional freeform surface

Table 2 : CHIMA Specifications

Parameter	Value
Spectral range	600 to 800 nm
Spectral Resolution	0.6 nm
Length and Width of Entrance Slit	60 mm x 135 µm
Magnification	3:1
F-Number (Image)	4
Keystone	<0.1 pixel
Smile	<0.1 pixel
MTF	> 0.5 @ Nyquist

A full breadboard of the instrument has been manufactured in Aluminum through Single Point Diamond Technique (SPDT). First order baffling has been produced via 3D printing. The 22 mm diameter blazed diffraction grating has been manufactured through holographic replication process at Horiba Jobin-Yvon. The replication process is flexible enough allowing for the accurate replication of both the grating grooves and the surface free-formity to a simple spherical substrate. All the elements were tested, and then integrated and aligned in the breadboard thanks to the diamond turned interfaces.

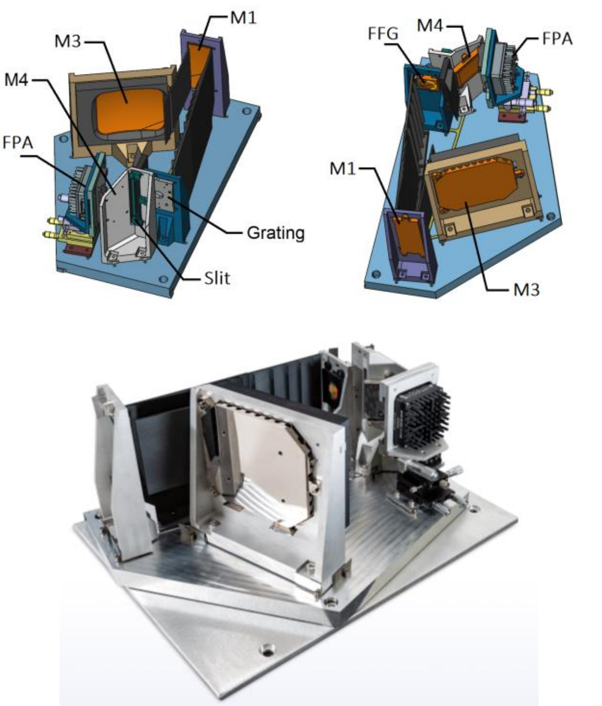

Figure 4 : Top: Opto-mechanical drawings of the CHIMA breadboard. Bottom: Assembled CHIMA Spectro-imager.

The performances of the CHIMA instrument have been characterized with a 12Mpixel CMV12000-based off the shelf camera. The test setup, located at the Centre Spatial de Liège, included a Xenon arc lamp, a monochromator and an integrating sphere, as well as a 1:1 Offner relay, allowing the use of a series of test patterns during the characterization. The keystone has been measured to be within the optical design values (±2 µm) and the smile to be less than 0.18 nm (~0.3 nominal pixel) see Figure 5. These performances underline the efficiency of the distortion control mechanisms implemented within the CHIMA design. The system MTF has also been measured and shown to be in agreement with the optical model.

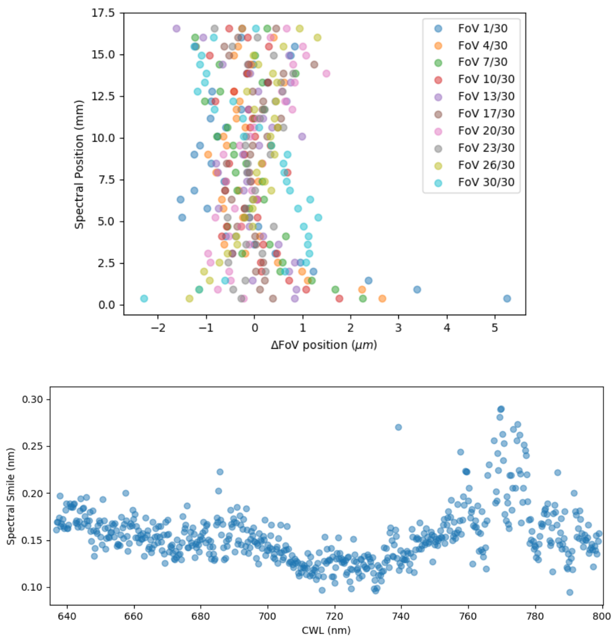

Figure 5 : Keystone (top) and smile (bottom) affecting the CHIMA focal plane.

5. CONCLUSIONS AND PERSPECTIVES

We propose an original design for a VNIR/SWIR compact hyperspectral imager with excellent imaging, spectral and radiometric performances. This design benefits from using a Free Form Grating instead of a planar or spherical grating. We have confirmed experimentally the feasibility and the performances of cost-effective manufacturing of the instrument by diamond machining on aluminum substrate. The instrument is fully athermal as all non-flat elements are made in the same material.

In addition, the range of applications of FFG-based instrument has been recently extended to atmosphere monitoring and chemistry. We manufactured and tested a compact instrument with spectral resolution in the

sub-nanometer range (typically 0.5 nm) along with whopping signal to noise ratios (> 1000) and excellent correction of the optical distortion over a large swath.

This new family of compact Spectro-imager can offer valuable solutions for high performances hyperspectral missions on small satellites for earth observation and planetary exploration. The cost-effective approach is also an important advantage in the perspective of the development of future satellites constellations.

While this instrument was originally designed for small satellite, the innovations introduced for combining performances and compactness are today considered for future flagship ESA hyperspectral mission within the Sentinel Expansion program.

Acknowledgments

The authors would like to thanks Arnaud Cotel from Horiba Jobin Yvon, for its work on freeform holographic gratings, Stefano Santandrea, Karim Melab, Mateo Taccola and Jorg Versluys from ESA for their support and expertise, Jean-Marc Schumacher and Vigil Monamy for the Mechanical and Thermal design as well as Arnaud Bourdoux (Spacebel), Dirk Van Aken (Caeleste) and Eric Callut (Deltatec) who manage the development of the sensors and imaging chain.

Support for this study was provided by the Service Public de Wallonie (SPW-DGO6) through the “Technologies for Hyperspectral Earth Observation” (THEO) project and by The Belgian Science Policy through ESA GSTP Program.

References

[1] A. Zuccaro Marchi, “Compact Hyperspectral Instrument – Status and Outlook” Small Satellite for Earth Observation, R.Sandau ed., Wissenschaft und Technik Verlag (2017), pp 63-66

[2] C. DeClercq, V. Moreau, J.-F. Jamoye, A. Zuccaro Marchi, P. Gloesener, “ELOIS: an innovative spectrometer design using a free-form grating”, Proc. SPIE 9626 (2015)

[3] J. Reimers, A. Bauer, K. P. Thompson, J.P. Rolland, “Freeform spectrometer enabling increased compactness”, Light: Science & Applications, vol 6, pp e17026 (2017)

[4] V. Moreau, J. Versluys, M. François, M. Taccola, C. Michel, P. Blain, Y. Stockman, ”Tests and Calibration of a Free Form compact spectro-Imager”, Proceedings of the 4S Symposium Small Satellites Systems and Services (2016)