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Technologies and Designs for Small Optical Missions

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ABSTRACT

The worldwide growing interest in small payloads and platforms require the use of solutions that are compact, cost effective and simple to align and test. In particular, the possibility to use constellations of small satellites require the payloads to be easily built in a relatively large number compared to typical space missions where only the flight model and possibly few flight spares need to be procured. This clearly drives the payload architecture towards solutions that can be easily manufactured, and in large quantities.
The recent progress of manufacturing techniques favours this rapid change. For instance, for some applications the possibility to use a spectrometer with a magnification different from one is a key factor to enable instrument designs that are compact, cost effective and with high performance. This can be for instance achieved by using freeform or aspheric mirrors and freeform or spherical gratings. Other compact designs use instead linearly variable filters as dispersive devices, pointing to a different set of applications and performance.
The progress on small satellites and payloads, especially in the vision of large constellations, also benefits from the rapid development of imaging processing and deep learning machines, for instance equipping the payloads with powerful on-board data processor for real time generation of Level 2 data to face the challenge of handling the huge amount of data that is produced on-board.
By combining all these developments, it is possible to produce a portfolio of innovative multi/hyperspectral payloads covering a broad range of applications, spanning from high spatial resolution to large swath width, from minisatellite to cubesat format. Exploiting the flexibility and interoperability of these payloads, the users will be provided with turnkey solutions and real time response to their specific needs.
The European Space Agency is leading several R&D activities in the field of compact multispectral and hyperspectral payloads, fit for small platforms. These activities encompass technology development of novel optical designs, materials and processes, including also engineering of detectors, EEE components and dedicated data processing to achieve innovative and cost-effective solutions.
The paper provides an overview of the technology developments, the status of the instruments manufactured so far and those in operation, their performance and their expected applications. An example of an imaging spectrometer design that is extremely compact, realized with only two spherical optical elements and with a magnification different from one (1:3) is also addressed.

Keywords: hyperspectral payloads, cubesats, innovative technologies

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1. INTRODUCTION

The trend in satellite earth observation towards smaller platforms and miniaturized instrumentation, as well as a demand for higher spatial and spectral resolution, is nowadays favoured by the increasing technological maturity in fields like CMOS detectors, hyperspectral filters, electronics miniaturization and optical quality. The possibility to obtain interesting hyperspectral data in several areas like climate changing, water quality, land cover and land use with a relatively small amount of investments, if compared to the traditional hyperspectral payloads, opens the way to new potential markets and data exploitations.

The European Space Agency (ESA) is involved in the development of several compact hyperspectral instruments. The activities running now under ESA contracts cover a wide range of technologies and specifications: from payloads with large swath width (HyperScout), to instruments with high spatial resolution (STREEGO), ideas for the combinations of different, inter-communicating payloads (HyperSTREEGO), compact hyperspectral imagers using Linear Variable Filters (LVF) (CHIEM) and free-form grating spectrometers (CHIMA) and concepts. Some of these activities are focused on the development of components and on the optical design. Others are developing, testing and – in some cases also flying – flight hardware to prove not only the technological challenges to build a performing compact (cubesat-size) payload, but also the on-board L0-L2 data processing feasibility and the delivery of the end data product, thus overcoming the major cubesat limitation, which is the downlink capability. The on-board processing allows continuously tuning the end data product to satisfy the needs of multiple users, even over the same area of interest.

2. HYPERSCOUT: ONBOARD PROCESSING OF HYPERSPECTRAL IMAGING DATA ON A NANOSATELLITE

HyperScout is a hyperspectral nanosatellite payload operating in the VNIR spectral range with very low mass and volume, fitting 1.2 Cubesat unit. It features a large field of view (31° across track x 16° along track), a spectral resolution of about 12 nm.

HyperScout takes advantage of technology developments performed in recent years in Europe, such as CMOS detectors, hyperspectral filtering technology, electronics miniaturisation and state of art microprocessors. The optics is formed by a wide field of view Three Mirror Anastigmatic (TMA) telescope, the hyperspectral filtering is produced with a Linear Variable Filter (LVF) deposited on a glass substrate. This optical system has been designed to be very compact and athermal, almost monolithic and easy to align, prerequisite for production in series. One of its key features is also the presence of an onboard intelligence, enabling a large variety of land and vegetation operational applications, for which cost efficiency and timeliness are of foremost importance.

First designed and build as EM in the frame of a concluded ESA GSTP (General Support Technology Programme) activity, the instrument design was then successively optimized, and a Proto-Flight Model (PFM) was manufactured and tested (Figure 1) in the frame of a GSTP IOD (In-Orbit Demonstration) activity, for flying as a payload on board of the Danish 6-units Gomx-4B cubesat, to prove hardware and processing functionalities. However, for the adaptation into this platform the across track field of view was reduced to 23°. With a pixel pitch of 5.5 µm, it now achieves a swath of 220 km and about 70 m ground sampling distance (GSD) from 500 km altitude[1]. In 2017 the payload was successfully manufactured, tested, assembled on the platform, and on February 2nd 2018 the Gomx-4B was successfully launched with the “Long March 2” Chinese rocket[2]. First light was acquired in summer 2018: a single frame with a footprint of about 200 x 150 km^2, proving that the full chain is operational[3]. Commissioning of the payload and the platform ended in Q2 2018 and HyperScout is now running nominal operations, as planned for the IOD.

Hyperspectral imaging with LVF in pushbroom mode acquires frame images that have a spatial and a spectral dimension; the second spatial dimension is built over time by sequentially recording a series of frames. The raw frame images are then processed into a hyperspectral data cube. The result is the generation of more than 1TeraByte per orbit. However, due to the platform power and size constraints of a typical cubesat platform, the downlink data rate is very low, around 1 Mbit/s. To overcome this constraint, HyperScout employs an on-board payload data processing chain that extracts relevant high-level information, reducing the hyperspectral data into high-level data products that can be sent down to Earth. More in detail, HyperScout features an optimized L0 to L2A processing chain resulting in a hyperspectral data cube, after which application specific processing is performed. Finally, a prototype end-application that extracts high level information from the data cube is produced. This application uses algorithms developed within the consortium to perform dimensionality reduction, segment classification and change detection. The resulting information can be sent to Earth within the downlink capacity of the nanosatellite, and during the same orbit as the data was acquired[4].

These processing capabilities will enable a large variety of land and vegetation operational applications of worldwide relevance, such as Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) calculations, and detection of anomalies such as flooding, forest fire, volcanic eruption, landslides within minutes from their occurrence, since timeliness is of foremost importance. The instrument, together with a distributed net of ground stations, can thus enable early warnings in a cost efficient manner. Furthermore, in a constellation scenario the revisit time can be greatly increased. For the purpose of this IOD, though, only some of these features will be tested.

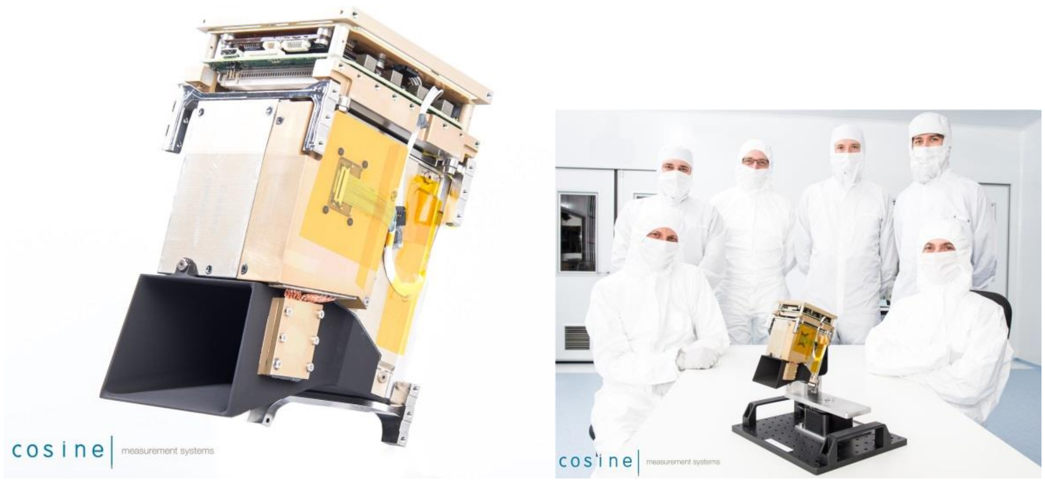

Figure 1. HyperScout. The flight model (left) and the payload with cosine team (right). Credit cosine.

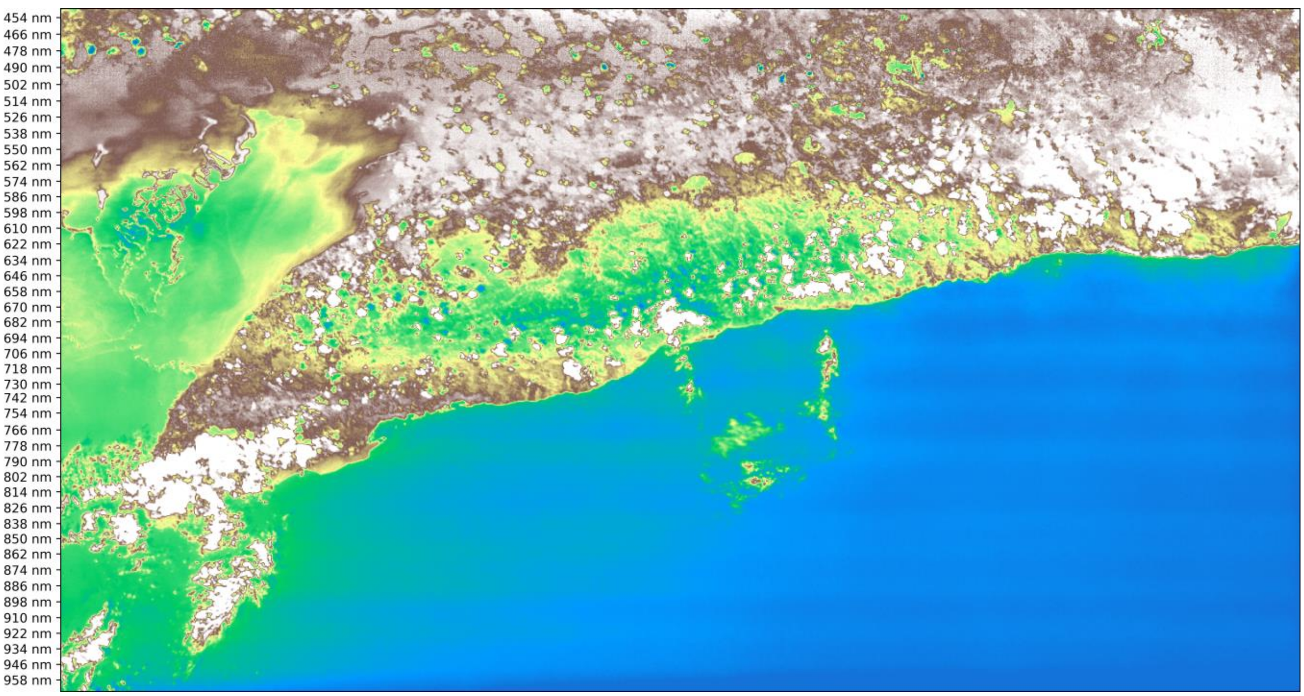

Figure 2. "First light" of HyperScout payload[3]

This system is extremely flexible and re-configurable in-orbit, resulting in a paradigm shift in the space asset use: different users may use the same sensor for different real time applications; the same nanosatellite can support precision farming in Northern America and flood monitoring in South-East Asia.
Within the GSTP programme, HyperScout is being developed by a consortium led by cosine Research B.V. (NL), including VITO NV (BE), S[&]T AS (NO) and TU Delft (NL).

3. HYPERSTREEGO: REACTIVE PAYLOAD

Thanks to its on-board image processing capability, HyperScout can be used as a viewfinder in the VIS-NIR for a high spatial resolution instrument, dubbed STREEGO. STREEGO is a multispectral/panchromatic (upgradable to hyperspectral) instrument for small platforms developed by Medialario (I) under a GSTP contract, working the wavelength range from 450 nm to 900 nm, with GSD in the meter range using the 5.5 µm pixel pitch CMOSIS CMV1200 commercial detector, and a field of view of 1.08° x 0.81°, consequently with a moderate swath. The optics configuration is a TMA with 200-mm aperture and f/#6; the nominal Modulation Transfer Function (MTF) at Nyquist frequency is 64% and in panchromatic mode the Signal to Noise Ratio (SNR) is >100. The system is athermal, mirrors and structure are realized with CTE-matched RSA443 Aluminum.

The concept proposed with the name of HyperSTREEGO is to couple the two instruments by placing a quad configuration of HyperScouts (renamed “Panorama”) in a slanted pointing direction of approximately 45° in front of STREEGO, which will be pointing Nadir. The idea is to use 2 HyperScouts working in SWIR to identify the cloud-free pixels to be used for the processing, the other 2 Hyperscouts working in VNIR range to detect real time anomalies and to point STREEGO on these anomalies within a minute, for higher resolution observations. This is possible because the hyperspectral instrument is conceived to have a pre-stored Earth map on the on-board computer that is used as comparison during observations, and whenever the land looks different an alert is raised to the AOCS.
The architecture of the HyperSTREEGO design (Figure 3) has been proposed[5], although it is not yet under ESA funded activities.

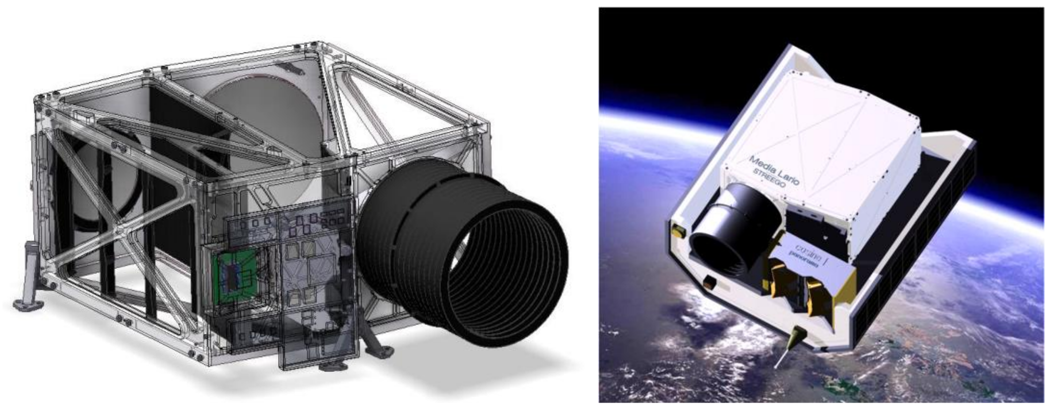

Figure 3. STREEGO system layout (left). HyperSTREEGO (right): The quad HyperScout configuration is visible on bottom right. Credits cosine and Medialario.

4. CHIEM: A NEW COMPACT HYPERSPECTRAL IMAGER

An engineering model of a new compact hyperspectral imager called CHIEM (“Compact Hyperspectral Instrument Engineering Model”) has been developed under a GSTP activity. It includes a LVF directly deposited on a CMV12000 2D detector array. The baseline instrument design is for a satellite mission operating at 600 km, offering a swath of 100 km and a GSD of 24.4 m[6].

Conventionally, LVF filters are deposited on a glass substrate, which is mounted on a detector afterwards. This technology has however some limitations, mainly on the accuracy for assembling the filter on the sensor. In the proposed new method, thin film Fabry-Perot interference filters can be deposited directly onto the detector at wafer level, thus eliminating alignment issues of a classical LVF filter and allowing more flexible geometric filter designs: the depositions can be varied from pixel to pixel. Selection of the filters material is strictly dependent on the refractive index and absorption coefficient needed, but also on the compatibility with CMOS material. This yields the spectral range in the CHIEM development to be from 470 nm to 900 nm, with a narrow spectral resolution (FWHM) between 4 and 10nm.

However, to achieve this waveband the sensor is integrating two LVF wedges, completely independent from each other: the first covers 470-620 nm with 50 spectral bands, the second 600-900 nm with 104 bands.
For the CHIEM project the 5.5µm pixel pitch, 4096 x 3072 pixels CMV12000 CMOS image array sensor was selected, on which both hyperspectral and panchromatic zones are created in line with the concept of a geo-spectral camera. The LVF was directly deposited on front side illuminated sensors, but the deposition process was tested also on the back side illuminated ones, being a new development and higher risk but providing higher optical efficiency.
The instrument development also includes the optical design of a front telescope in TMA configuration, which is very compact and allows a wide field of view in both across track and along track direction (> 9.5° x 7.2°). The readout electronics (ROE) provides all required sensor interfaces (power, control, data) enabling its full performance operation, and also a set of backend interfaces for system power, remote control, and backend remote data (to EGSE) and local storage interfaces.

During this activity, concluded in November 2017, an engineering model of the hyperspectral imager was successfully designed and built, suitable for a 12U cubesat platform. The core of the imager, i.e. the set of hyperspectral interference filters deposited on the CMOS sensor, was completed with a read-out electronics, capable of high speed operations, allowing also post-processing techniques to improve SNR.
A new GSTP activity is starting at the time of writing this article. It will focus on further improvements of ROE design, on a more detailed opto-mechanical design of the fore-optics and also on the accommodation study and a mission definition for a 12U cubesat. This activity will be followed by an IOD activity, with the defined and tested payload.
Within the GSTP programme, CHIEM was developed by a consortium led by VITO NV (BE), including AMOS (BE), IMEC (BE), CMOSIS (BE) and DELTATEC (BE).

5. FREE-FORM DIFFRACTION GRATING FOR HYPERSPECTRAL IMAGER

Free-form gratings (FFG) are a very promising solution to achieve compact and cost effective hyperspectral spectrometers with unprecedented SNR and spectral resolution, opening new opportunities to remote sensing from small satellites.
Although the design of such spectrometers is usually made possible by commercial optical software, the major limitation on the freedom of the development was found on the availability of manufacturing techniques to realize the free-form component. Nevertheless, most of the available manufacturing techniques, such as direct ruling, holography, lithography or e-beam writing, are typically applicable on simple shape of the grating surface, such as flat or spherical surface. This is a limitation of the degree of freedom offered for the optical design of compact and well-corrected spectrometers.
ESA is being investigating the possibility to overcome these technological limitations, with the goal to improve the performance of these grating-based hyperspectral spectrometers for various space remote sensing applications. Besides, such instruments can become quite light and compact, thus simplifying the overall constraints related to a space mission.
In the frame of ESA's Technological Research Programme (TRP), a few activities have been kicked off with AMOS (Belgium) on this topic. The first one addressed the technological feasibility of a spectrometer design based on a 3-mirror configuration, where all the optical elements, including the freeform grating, are built with Single Point Diamond Turning (SPDT). The configuration is a modified Offner, where primary and tertiary mirrors are separated to gain freedom in the optimization process for pushing the design towards low f/#, and the FFG is a convex grating. The target application was hyperspectral data collection of land observations, for which a spectral resolution <2.5 nm was desired in the spectral range of 450 nm to 900 nm. The grating, designed without any rotational symmetry, was successfully manufactured and characterized in terms of shape, diffraction efficiency, polarization sensitivity, scattering and operating spectral range[7]. The convex freeform grating has a diameter of 35 mm, a radius of curvature of 80 mm and a groove density of 104 lp/mm. It was fabricated by diamond machining on Nickel-plated Aluminum substrate. The improved manufacturing technique allowed to achieve extreme axes accuracy required to maintain low straylight and scattering (Figure 4).

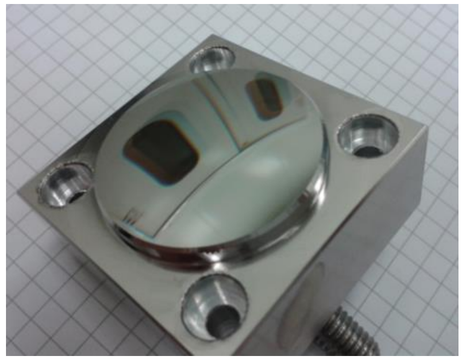

Figure 4. The Freeform convex grating. Credit AMOS.

The second TRP activity, still running, has the target to prove the feasibility of a more challenging compact spectrometer configuration with a new freeform grating with no rotational symmetry. The goal is to prove the potentialities of such a configuration for atmospheric chemistry observations in small satellites, which require high signal to noise ratio and very high spectral resolution.

The core of the activity is the design and the manufacturing of a free-form grating with around 1000 lp/mm and 0.5 nm spectral resolution, working in the 600-800 nm waveband. As for the previous study, the performances are achieved by means of the use of non-rotational symmetric substrate in a 3-mirror spectrometer (Offner-type) design, whose manufacturing and testing is also included in this development. The target is to manufacture and characterize a breadaboard of such a system. However, the need of such a high spatial frequency of the grooves prevents from using the SPDT manufacturing technique: the approach followed within this activity is freeform holographic replication. Analyses of the FFG, in terms of shape, diffraction efficiency, polarization sensitivity, scattering and operating spectral range, are under investigation. The activity is now finalising the proposed manufacturing technique for the gratings. At the time of writing the article, the testing phase of the grating and the complete breadboard is about to start.

Within the TRP programme, the activity named “Free-form diffraction Gratings and Mirrors - breadboarding” is being developed by AMOS (BE), in collaboration with Horiba Jobin-Yvon (F).

6. COMPACT HYPERSPECTRAL SPECTROMETER DESIGN

Despite the recurrent and widespread need of hyperspectral instruments for space missions, and in particular for Earth observations, the optical design is based on a relatively low number of concepts, most of them based on quite old designs, such as the Offner (1971) and the Dyson (1959). A drawback of these designs is that only magnification very close to one can be typically achieved. For some applications the possibility to have a spectrometer with a magnification value different from one is a key factor to enable instrument designs that are compact, cost effective and with high performance. ESA has recently patented a new design concept of an hyperspectral imaging spectrometer based on a reflective grating, with several remarkable properties as for instance the use of a very limited number of optical elements (only two) and the possibility to achieve magnification factors different from one (e.g. 1/3 or 3). The design is very flexible, extremely compact and it can be adapted on a case by case basis to different requirements (swath width, spectral resolution). In the most simple form the design consists of a spherical mirror and a spherical grating only, while more complex solutions can be defined using freeform optics but still using two optical elements and keeping the grating as spherical to ease manufacturing.

The proposed spectrometer design is based on a flat image anastigmat relay that is made by only 2 spherical mirrors. The layout of the relay design is shown in Figure 5.

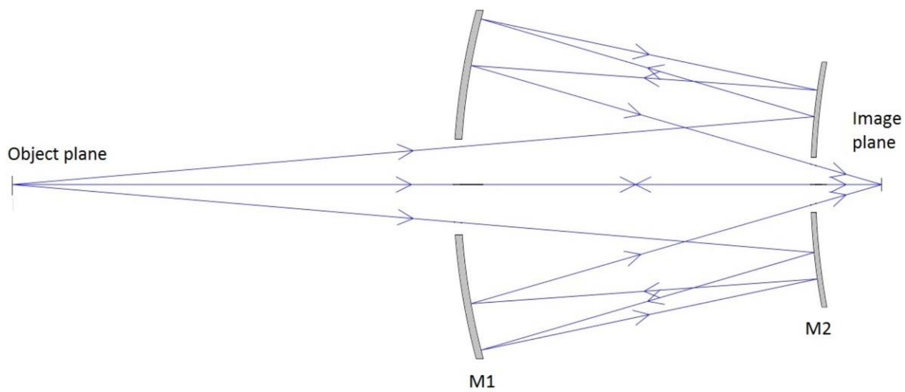

Figure 5. Flat image anastigmat relay

Light coming from the object passes through a central aperture in mirror M1, is reflected two times by mirror M2 and two times by mirror M1 before reaching the image plane. The special feature of this design is the “double reflection” from the two mirrors and the fact that the radii of curvature of M1 and M2 are equal but with opposite sign. The magnification of the relay is ~0.3 but a magnification 3 can be achieved just swapping the object and the image planes. In order to obtain a spectrometer from this relay concept it is necessary to replace at least one portion of the two mirrors with a reflective grating and to introduce a proper off-axis and tilt in order to achieve an unobstructed design.
One possible simple implementation is shown in Figure 6 using as main design parameters the values reported in Table 1. The spectrometer is composed by a convex and a concave spherical element with the same radius. In this specific example the concave element is a mirror and the convex element is composed by two parts, a mirror and an holographic grating. The aperture stop is placed on the holographic grating.

Table 1 - Spectrometer example parameters

Slit length	22 mm
Wavelength range	450 nm – 850 nm
Spectral dispersion	75 nm/mm
F#	3.2

The use of an optical element that is composed by two separate zones, one being a mirror and the other a diffraction grating may sound rather unusual. Nevertheless it has to be noted that the manufacturability of this element is not more complex than an typical holographic grating.

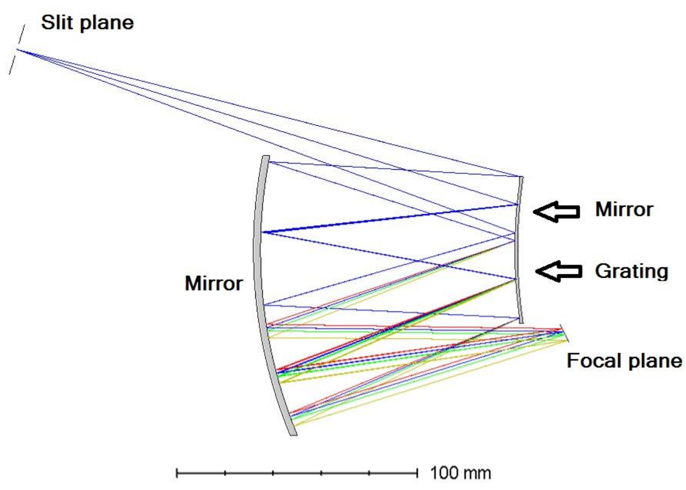

Figure 6. Spectrometer layout

The image quality is good as shown for instance in Figure 7 in terms of MTF plot for the central wavelength up to a Nyquist frequency of 25 cycles/mm (considering a typical pixel size of 20 μm). MTF is similar for all the wavelengths of the spectral range. Smile and keystone are also relatively small (respectively 7 μm and 6 μm). An even better image quality and full correction of residual smile and keystone can be achieved with a more complex design, using different radii for the different portions of the convex and concave elements or introducing aspherical components. Since the beam footprints on both convex and concave elements are well separated, another possibility that can be explored is the use freeform instead of spherical elements.

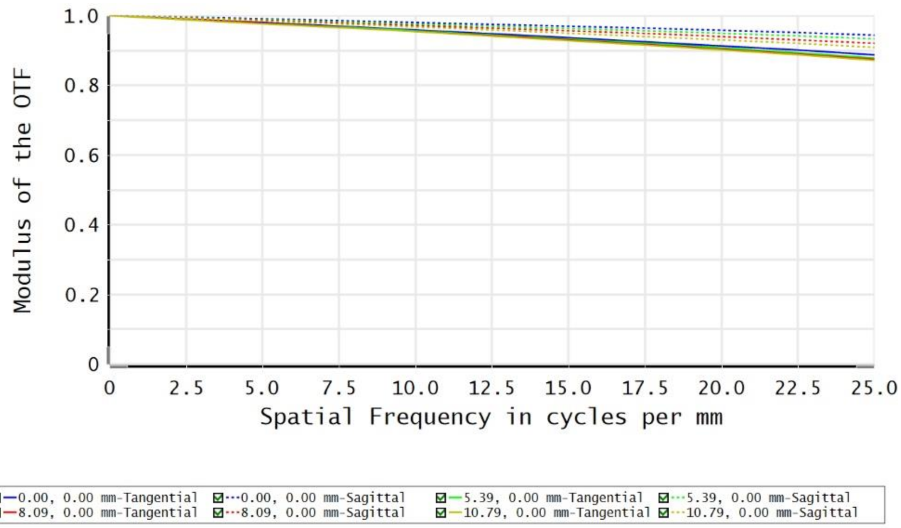

Figure 7. MTF plot for the central wavelength (650 nm) considering pixel size of 20 μm (Nyquist frequency 25 cycles/mm)

7. CONCLUSIONS

Different approaches to implement compact instrumentation for multi/hyperspectral imaging, in particular for Earth observation, have been introduced in this paper. These are the most recent developments that are being carried on within ESA's R&D activities: although at different development phases, their aim is to demonstrate that it is possible to obtain a portfolio of instruments, flexible and adaptable to a different set of requirements and applications.

8. ACKNOWLEDGEMENTS

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