ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

Instrument pre-development for flex mission

Matteo Taccola

C. Gal

M. Kroneberger

D. Lang

et al.

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 105622H · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296239

INSTRUMENT PRE-DEVELOPMENT FOR FLEX MISSION

M. Taccola[1], C. Gal[4], M. Kroneberger[4], D. A. Lang[4], A. Taiti[3], P. M. Coppo[3], E. Battistelli[3], D. Labate[3], L. Pettinato[3], E. Fossati[3], J. Caron[2,] , U. Del Bello[1],S. Kraft[5],J-L. Bézy [1]
[1]*ESA-Estec, The Netherlands.* [2]*ESA-Estec, co RHEA System BV, The Netherlands.* [3] *Leonardo Company, Italy.*
[4]*OHB System AG, Germany,*[5]*ESA-Esoc, Germany.*

INTRODUCTION

FLEX (Fluorescence Explorer) has been recently approved by the Earth Observation Programme Board as the next Earth Explorer 8 mission.

The contract for the Phase B2/C/D/E1 of the payload is currently in the negotiation phase with Leonardo Company (prime contractor) and OHB AG System (sub-contractor).

The FLEX pre-development has been addressed from the very beginning by ESA toward an experimental validation of the optical concept, the related alignment and test procedures and the early risk retirement of the most critical technologies as for instance detectors and gratings. An extensive breadboard development has been initiated since the phase A/B1 study of the mission, and its refurbishment is currently in progress for an Elegant BreadBoard (EBB). The complete development and successful test of the EBB is part of the FLEX instrument development plan and it is considered by ESA a key aspect for the success of the FLEX project.

This paper will provide first a very brief overview of the mission objectives and a description of the instrument, in particular concerning the High Resolution Spectrometer designed by Leonardo and the Low Resolution Spectrometer, recently optimised by OHB System AG. A full description of the optical design and performances of the other subsystems is not part of this paper because subject of previous comprehensive publications [1, 2].

The pre-development activities are then addressed in more detail and the current status of the EBB is presented.

FLEX MISSION OBJECTIVES

After Sun or artificial illumination green plants re-emit part of the light absorbed by chlorophyll molecules (Fig.1). The fraction of energy emitted as fluorescence and lost as heat with respect to the energy used for carbon assimilation (photochemistry) depends on the physiological status of the plant. Fluorescence is therefore a directly measurable index for photosynthetic activity. The aim of FLEX mission is to quantify photosynthetic activity and plant stress by measuring vegetation fluorescence with a 10% accuracy.

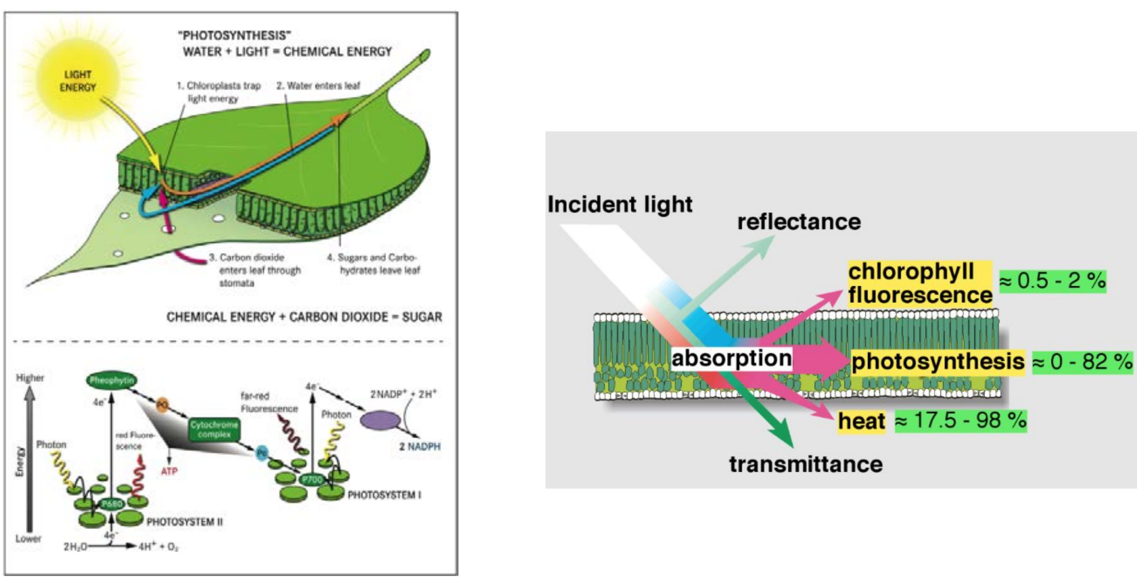


Fig. 1. **-** Plant fluorescence [3]

FLEX INSTRUMENT

The fluorescence signal emitted by vegetation is rather weak and therefore the ideal condition to observe it from a satellite is looking at the dark absorption lines of atmospheric gases in the optical spectrum of sunlight.

The FLEX instrument accommodate an imaging spectrometer with a very high spectral-resolution (0.3 nm), to measure the fluorescence spectrum within two oxygen absorption bands (O2A and O2B), and a second spectrometer with lower spectral resolution to derive additional atmosphere and vegetation parameters.

Both spectrometers operate in a pushbroom configuration and with a common telescope (Fig.2).

The telescope is based on a dioptric Petzval design. It collects the radiation from 2 regions on ground (150 km x 300 m with a separation of ~14 km in the along-track direction) onto a double slit assembly composed by two identical slits. A dual Babinet scrambler is placed in front of the telescope to achieve the polarisation sensitivity requirement (less than 1% for the HR spectrometer, 2% for the LR spectrometer).

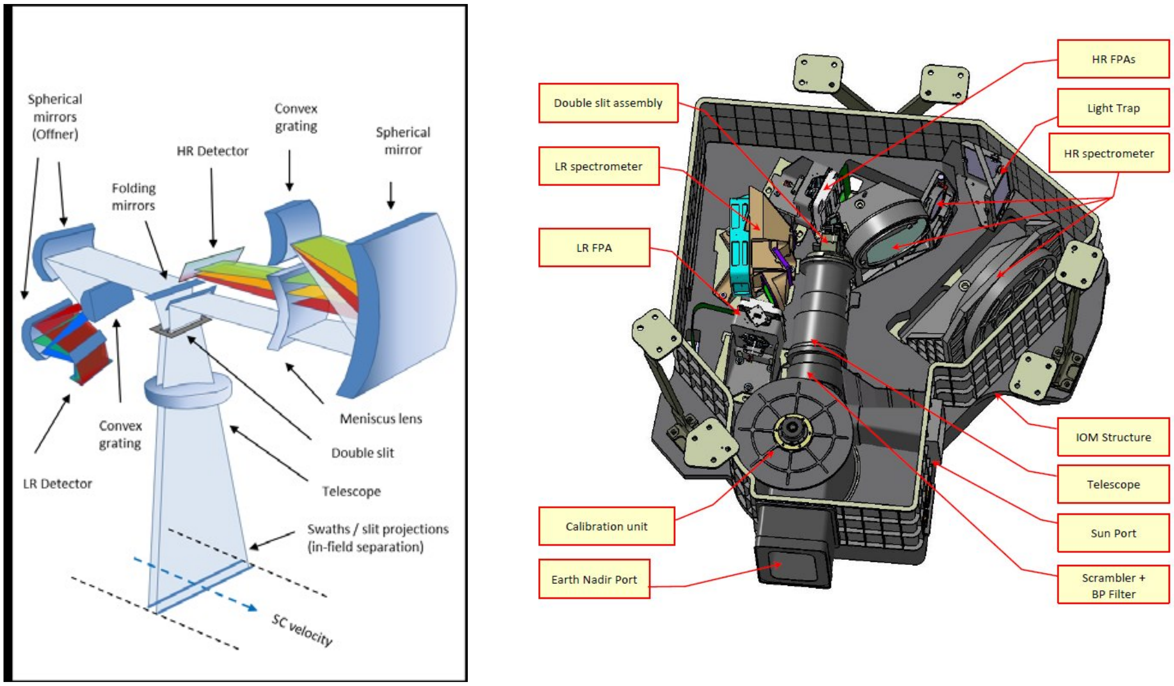


Fig. 2. Conceptual instrument design (left [3]) and CAD view of the opto-mechanical design showing the sub-systems

Both spectrometers have unitary magnification and are based on adaptations of the Offner design [4]. For both designs the optical performances are enhanced by the introduction of meniscus lenses.
Three CCD detectors are required with one covering the low resolution spectral range (500nm to 780nm) and two covering the O2A and O2B oxygen absorption bands (740-780 nm and 677-697 nm respectively). The CCDs are back side illuminated to enhance the quantum efficiency and cooled to reduce the detector noise. A calibration unit with a baffle is placed in front of the telescope in order to allow the observation of a dark reference every orbit and of a Sun illuminated diffuser every two weeks (two points radiometric calibration) (Fig. 2). The spectral calibration is achieved by means of vicarious technique observing the atmospheric gas or the sun Fraunhofer lines.

LOW RESOLUTION SPECTROMETER

The key requirements for the design definition are the spectral range (500 – 758 nm), the spectral sampling interval (0.6 nm), the WFE, MTF, and ensquared energy at focal plane. Two of the most stringent requirements are the spectral- (smile), and spatial co-registration (keystone) errors, which are defined to be <15 µm, and 4 µm, respectively at focal plane level. Both requirements drive the optical and mechanical tolerances, as well as the alignment accuracy requirements. Even if the operational temperature range is rather small (22±3°C) the spectral stability requirement of 2.8 µm at focal plane is a driver for the thermal design.
The mechanics of the instrument and all optical mounts are designed to withstand the heavy vibration loads during launch and adequately protect the optical components. Due to the different thermal expansion of the optical and mechanical materials, flexure joints are implemented to reduce the surface deformation of the optical elements.
The need to control straylight require the use of several internal baffles and a tight control of contamination.
The optical design of the LR spectrometer is illustrated in Fig. 3.

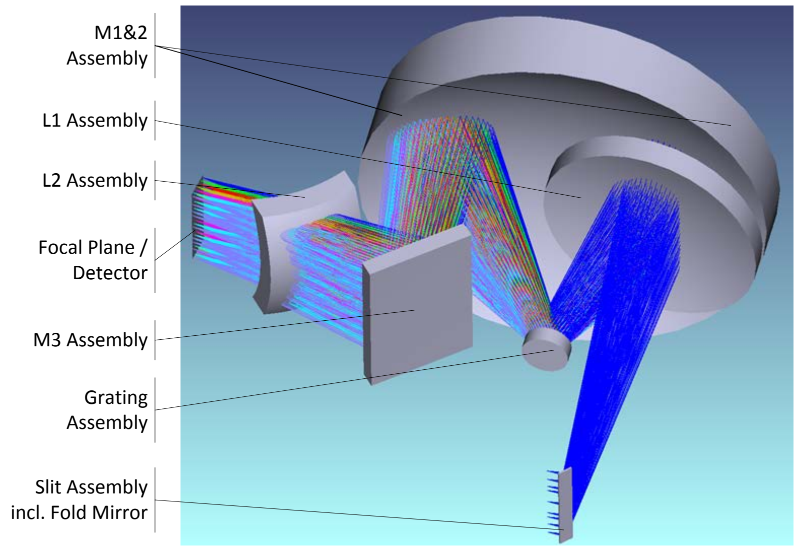


Fig. 3. Optical layout of the low resolution spectrometer of the FLEX instrument

The primary and tertiary mirrors of the Offner are merged into one single mirror piece. This has the benefits of a simplified alignment procedure and a lower tolerance sensitivity. Two additional spherical meniscus lenses are introduced into the optical system in order to improve image quality and in particular smile and keystone. The lens close to the focal plane is both tilted and off-axis.

The required F# of the spectrometer is 6.5. Since the spectrometer has 1x magnification, the input F# is matched to the telescope F# (F#=3.1). All the optical elements between the slit and the spectrometer pupil (close to the grating) are designed for this F#. This is essential to control straylight. The pupil reduces then the beam size to the required value.

The spectral dispersion of the instrument is provided by a blazed holographic grating with a spherical convex surface. The groove density is 500 grooves/mm to achieve the required spectral resolution and the grating has a saw-tooth blaze profile to increase the diffraction efficiency. The fold mirror behind the tertiary mirror is needed for envelope constraints.

Structural Analysis

A structural model has been developed for design validation and in particular for derivation of eigenfrequencies, stiffness, thermo-elastic stresses and margins of safety as well as the impact of different environmental loads, such as gravity, vibration, quasi-static, interface, glue shrinkage and thermal loads. The structural analysis shows that the current light-weighted design is compliant with all structural requirements.

The impact of load deformations on image quality is investigated feeding back the outcomes of the structural model into the optical model. In order to demonstrate the complexity of the analytical calculations, an example of the interface (I/F) tolerance load calculation is presented in Fig.14, where all the mounting interfaces are considered at component, assembly, and sub-system levels. Applying Monte Carlo (MC) simulation each mounting I/F of the optical elements are displaced and rotated within the tolerances. The used uniform distribution histogram is shown in Fig. 4 (left). Thousands of different optical systems are generated and for each system the RMS surface form deformation is calculated. The histogram of the distribution is shown in Fig. 4 (right).

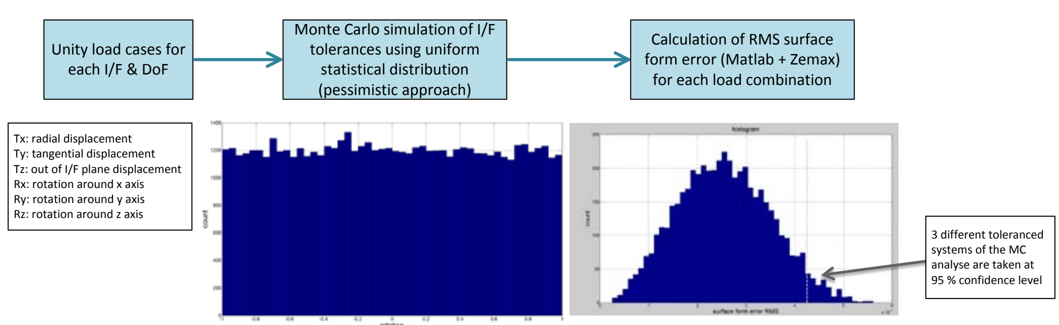
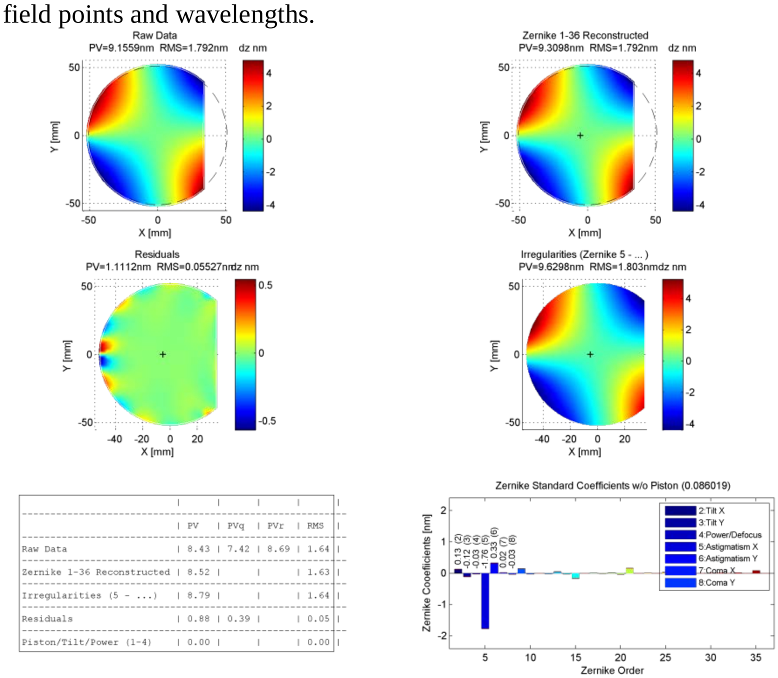


Fig. 4. Example of distribution of I/F tolerances for the generated systems (scale factor is uniformly distributed)

From the result of the MC simulation 3 toleranced optical systems are selected close to the 95% confidence level, where all optical surface deformations and element displacements are considered in all 6 degrees of freedom. The selected 3 different systems are analyzed in terms of optical quality degradation with respect to the nominal case.

Optical Performance

The optical performance is assessed considering surface deformations and element displacements of all optical components caused by various environmental influences. Environmental loads such as gravity, glue shrinkage, thermal gradients, and different interface tolerances introduce deformation and displacement of the optical elements. The effect of stress due to glue shrinkage during curing has also been analyzed. Based on the thermal model the temperature gradients on the mechanical structure and optical elements are assessed, and hence, deformations of the optical surfaces are implemented in the optical model. The lens displacement and surface deformation is calculated with a tool (MultiPAS) developed by OHB. A typical result of such a surface analysis is presented in Fig. 5. The surface deformation is implemented in the optical model and the image quality is assessed for several field points and wavelengths.



	PV	PVq	PVr	RMS
Raw Data	8.43	7.42	8.69	1.64
Zernike 1-36 Reconstructed	8.52			1.63
Irregularities (5 - ...)	8.79			1.64
Residuals	0.88	0.39		0.05
Piston/Tilt/Power (1-4)	0.00			0.00

Fig. 5. Surface deformation of LRL1 cc surface due to I/F tolerances (upper left), reconstructed SFE using Zernike polynomials (upper right), residual error of Zernike reconstruction (middle left), irregularities assessed by Zernike fit (middle right), summary table of SFE (lower left), Zernike polynomial distribution (lower right)

The WFE is evaluated replacing all the optical components in the nominal design with the deformed ones. In agreement with the alignment procedure the optical quality is re-optimized adjusting the detector position (shift along the optical axis and tilt angle) and mirror assembly position and tilt. The adjustments are done considering 10 µm shimming accuracy. The main results for the hot case are reported in Table 1.

Transmitted RMS WFE at 740 nm for combined hot load case [nm]			
Field #	Nominal System	Nominal + Deformed LRS optics	Delta WFE of LRS optics
1	18,4	70,1	67,6
2	23,8	76,4	72,6
3	56,1	104,4	88,0
Ensquared Energy at 740 nm for combined hot load case [%]			
1	93,10%	92,09%	1,0%
2	93,08%	92,00%	1,1%
3	92,54%	91,73%	0,8%

Modulation Transfer Function at 740 nm for combined hot load case [%]			
1	92,70%	87,89%	4,8%
2	92,72%	87,77%	5,0%
3	90,51%	87,31%	3,2%
Smile and Keystone Performance for combined hot load case [µm]			
Smile	0.25	7.03	
Keystone	0.22	1.61	

Table 1 Optical performances for the nominal and for the system under environmental loads

The performance degradation is small compared to the nominal system performance.

<u>Straylight Analysis</u>

A detailed straylight analysis has been performed during the breadboard (BB) design phase in order to determine the critical contributions. The results gave further feedback for a better straylight control, e.g. more stringent contamination control, adequate surface treatment (blackening) , baffle installation and design improvement.

The requirement at spectrometer level is defined considering half slit bright and half slit dark and imposing that the ratio of the stray light irradiance at a distance of 20 SSD (Spatial Sampling Distance) from the bright-dark border shall not exceed 0.07% of the irradiance level in the bright region. This requirement guarantees to achieve the radiometric accuracy for all LR spectral channels. The analyses are performed for wavelengths in the range of 500 to 740 nm at steps of 0.5 nm and with an irradiance spectrum according to the requirement, as illustrated in Fig.16.

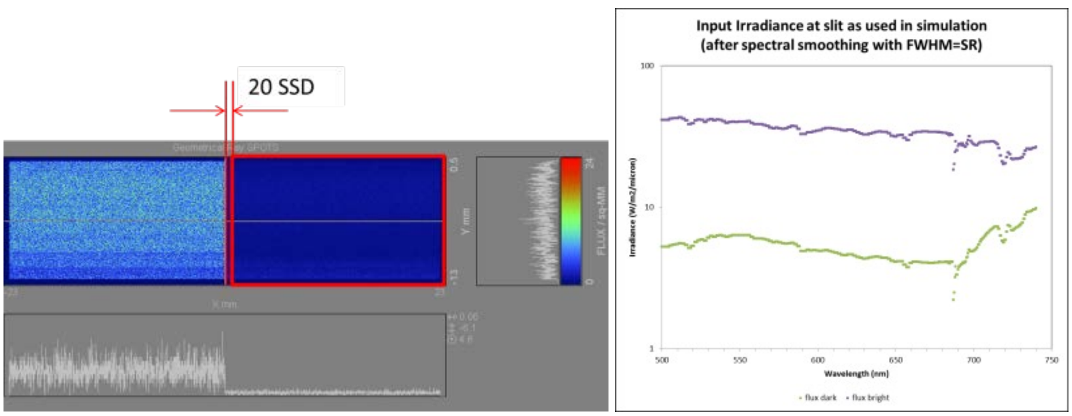


Fig. 6. Post processing areas as defined by requirement (left), irradiance used for slit illumination (right)

The light source used for the model is defined by 4 rectangular sources (2 half slits bright and 2 half slits dark for the 2 slit assembly) . The full simulation geometry consists of the optical surfaces imported from Zemax in ASAP and the full, yet simplified CAD geometry neglecting any screws and washers.

The analysis considers in-field straylight contributions (ghost, scattering due to roughness and contamination, grating diffraction orders) and straylight originating from the mechanical parts illuminated by the oversized beam. All contributions are analyzed separately and then summed pixel-by-pixel to get the overall result.

An important result of the analysis is that the requirement is not met with the BB design (Table 2) due to a ghost originating from the lens assembly LRL1. By removing the lens and re-optimizing the design the ghost stray light can be scaled down by more than one order of magnitude. In addition, a relaxation of the requirement to 40 SSD exclusion zone where the irradiance distribution reaches a plateau level (Fig. 7), reduces the stray light contribution by 17%. This optimized design is the current baseline for the flight model.

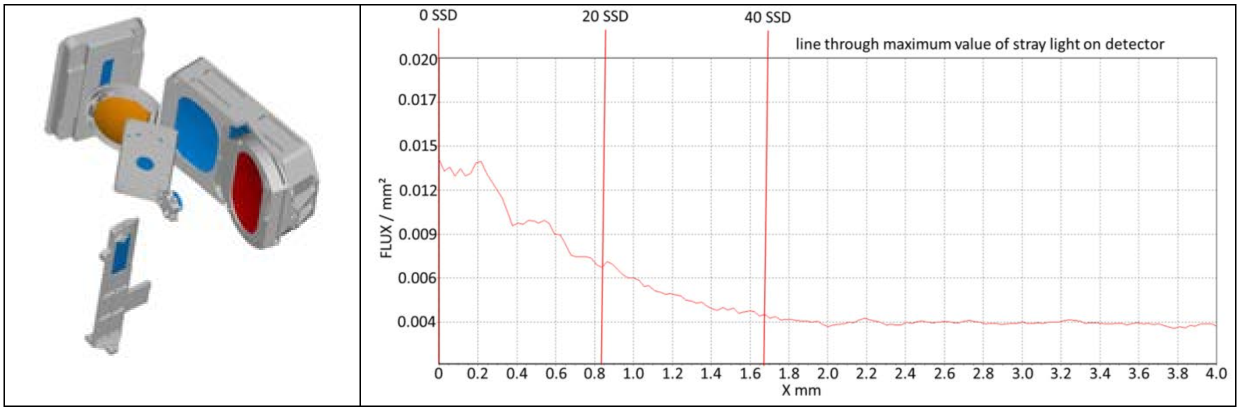


Fig. 7. Simplified CAD model for straylight analysis (left). Stray light irradiance profile (right). The analysis shows that at a distance of 40 SSD the irradiance profile reach a plateau level.

The analysis shows that with a roughness of σ_{LM}=0.5nm for the optical surfaces and σ_G=2nm for the grating the flight baseline has a straylight level comparable with the requirement (Table 2).

Optical configuration	Contamination	Roughness	Ghosts	Sum	Mechanics	Requirement
Flight design	2.18E-04	6.37E-04	3.54E-05	8.21E-04	9.96E-5	7.00E-04
BB design	3.46E-04	7.71E-04	8.98E-04	1.65E-03	9.96E-5	7.00E-04

Table 2: Summary of stray light analysis of the BB and Flight Design

Polarisation Sensitivity Analysis

The analysis is performed for various wavelengths and FoVs considering a linearly polarized input source. The Jones matrix of each element is used including wavelength dependent efficiency measurements for the grating. The polarisation sensitivity curves as a function of the wavelength for different FoV's are plotted in Fig. 8.

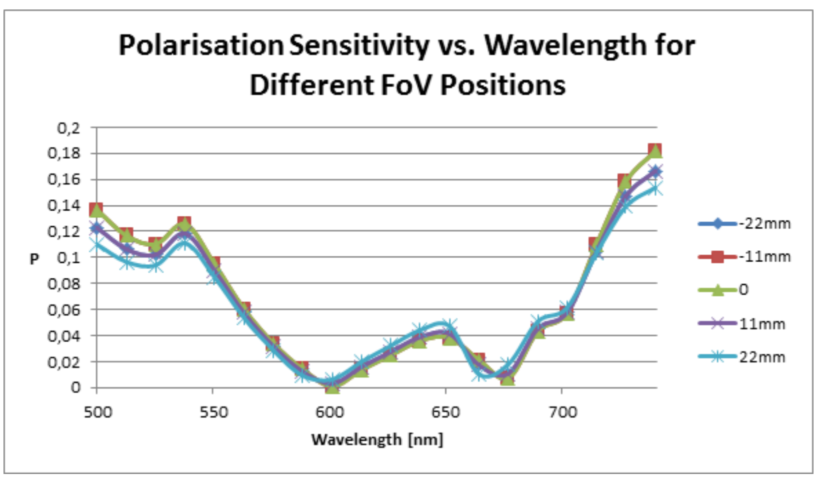


Fig. 8. Polarisation sensitivity as a function of the wavelength for different FoV points including the grating performance and the rest of the LRS optical system

As expected, the main contributor for polarisation sensitivity and transmission loss is the grating. The polarisation sensitivity variation over the FoV is very limited (few percent) meaning that there is no need for special coatings. The polarisation sensitivity as a function of the wavelength shows a quite large variation from almost zero to a worst case value of 18% (therefore with good margins with respect to the 22% requirement).

HIGH RESOLUTION SPECTROMETER

The key driver requirements for the design of the high resolution spectrometer are the spectral range, spectral resolution, image quality (WFE) and distortions (smile and keystone). The design is based on a 1x Offner relay with image quality enhanced by the use of a concentric meniscus lens (Fig 19). The spectrometer is derived

from the relay replacing the convex spherical mirror with a convex grating. A folding mirror is introduced after the slit to accommodate the spectrometer on the optical bench.
The spectral dispersion is obtained with a spherical holographic mirror to achieve the required spectral sampling of 0.0933 nm/28µm . The required F# of the spectrometer is 3.1to meet the signal to noise ratio requirement.

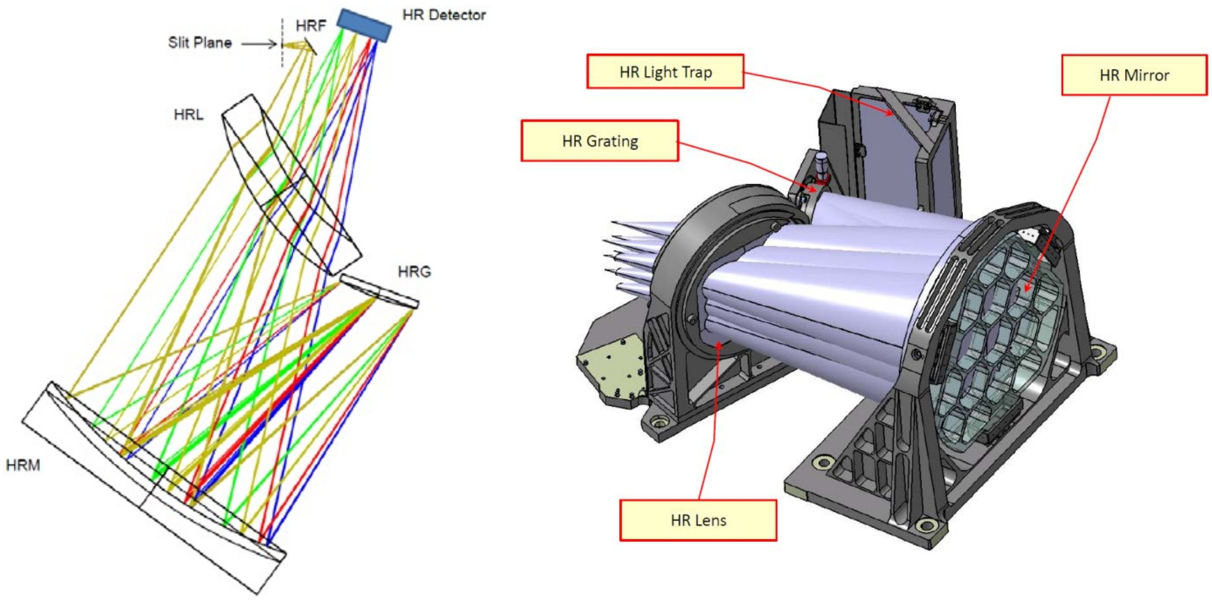


Fig. 9. Optical (left) and opto-mechanical (right) layout of the spectrometer.

The lens and the grating are mounted on the same mechanical support while the mirror with its support constitute a stand-alone group. Both lens and mirror operate in a double pass configuration.
A light trap is also implemented to block unused grating orders and in particular the order zero.
The nominal image quality of the telescope is excellent as shown by the spot diagrams (Fig. 10). Also smile and keystone are by design extremely low (both less than 1 µm)

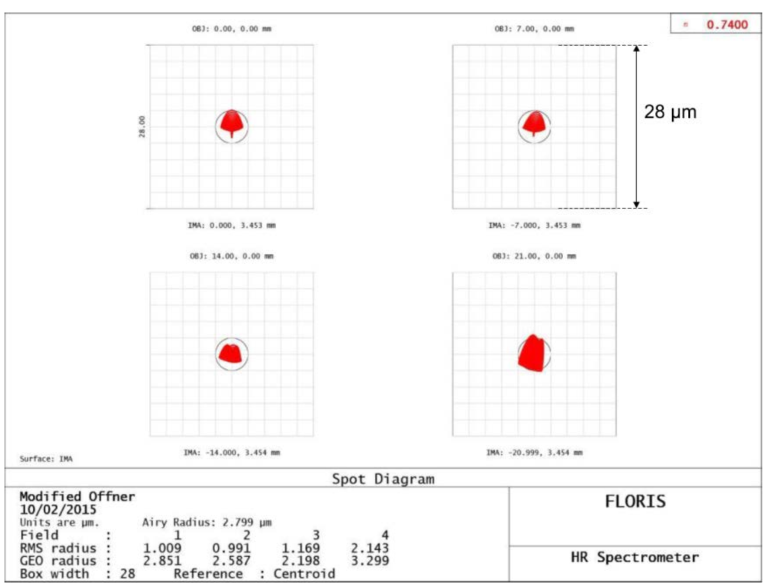


Fig. 10. Spot diagram at 740 nm. The spot size is comparable with the circle size (Airy disk) and much smaller than the pixel size (28 µm x 42 µm). Spot sizes at both edges of the spectral range are larger but still well contained in the pixel size.

Similarly to the Low Resolution Spectrometer thermo-mechanical and tolerance analyses have been performed showing that the HR spectrometer is very stable in terms of optical (MTF, smile and keystone) and spectral performances.

The polarisation sensitivity analysis shows results similar to the low resolution spectrometer. The dominant contributor is the grating and the overall polarisation sensitivity of the spectrometer is below 22% (less than 1% at instrument level considering the dual Babinet scrambler).

Straylight Analysis

Straylight is very critical for the high resolution channels because it directly impacts the accuracy measurement of the weak fluorescence signal.
Considering a non-uniform scene composed by two spatially uniform zones with respectively a bright cloud radiance spectrum and a reference vegetation spectrum, the instrument requirement at Level 0 ask for a maximum straylight radiance of 0.2 mW/(m2.sr.nm) after a distance of 40 SSD from the transition.
The requirement at Level 1, after straylight correction of Level 0 data is 0.04 mW/(m2.sr.nm).

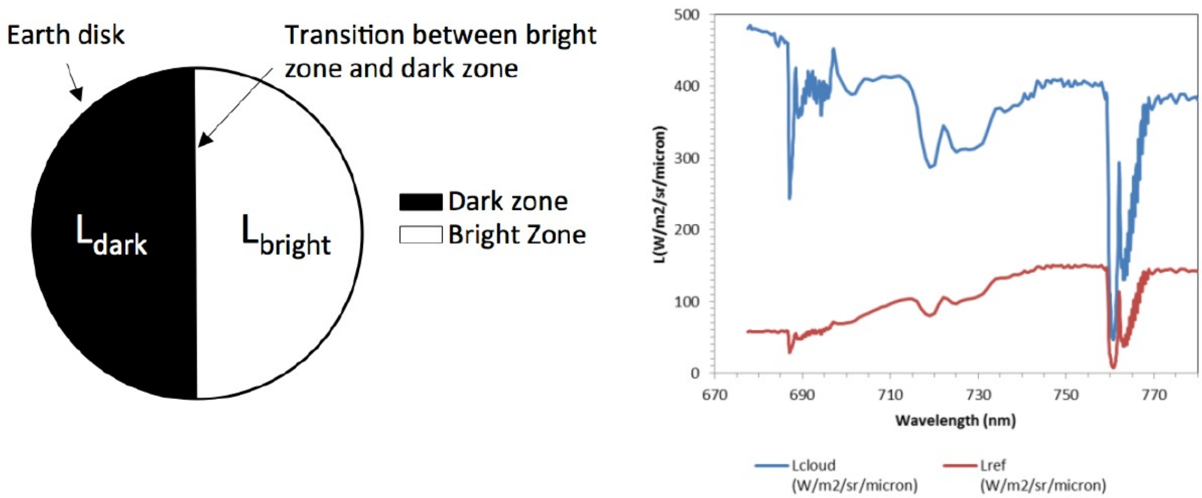


Fig. 11. Non uniform scene spatial (left) and spectral (right) definition

The results of the straylight analysis show that for the worst case wavelength the Level 0 straylight is 5 times larger than the required value. Concerning the spectrometer the most critical contribution is the scattering due to grating imperfections followed by the scattering due to particle contamination of the optical elements.
A special effort is currently put in place to reduce the Level 0 straylight and to develop a correction algorithm to reach the requirement at Level 1.

FLEX BREADBOARD

The breadboard of FLEX includes the optical bench, the common telescope and the 2 spectrometers.
Service detectors with a pixel size comparable to the flight detectors are implemented in the breadboard. A pre-development activity is currently in progress with e2v for the flight representative CCD detectors [5].

Telescope

The telescope design for the breadboard is based on a dioptric solution with 8 spherical lenses (Fig. 12). The telescope has a real entrance pupil located 75 mm in front of the first lens and is telecentric for a pupil match with the spectrometers. The opto-mechanical assembly has been built and fully characterised by Leonardo. It shows a good image quality over the entire field of view. Focal length, distortion and chromatic aberrations are well controlled and in line with the expectations (Fig. 13).
The flight design of the telescope will most probably differ from the current breadboard implementation due to the need of reducing the number of lenses to reduce the in-field straylight introduced by the telescope.
Despite the possible different design the breadboard telescope is fully representative for the purpose of validating the assembly, integration and test of the FLEX flight instrument.

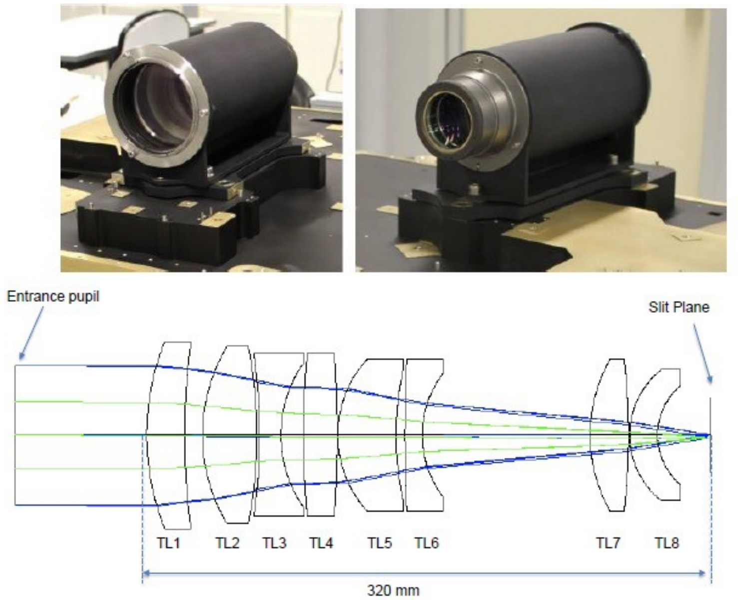


Fig. 12. Telescope opto-mechanical assembly (2 views) and optical layout

Telescope Optical Quality Budget		
	WFE rms	MTF @ 16.67 (cycles per mm)
Design + Manufacturing + Integration and Alignment	355 nm	> 0.62

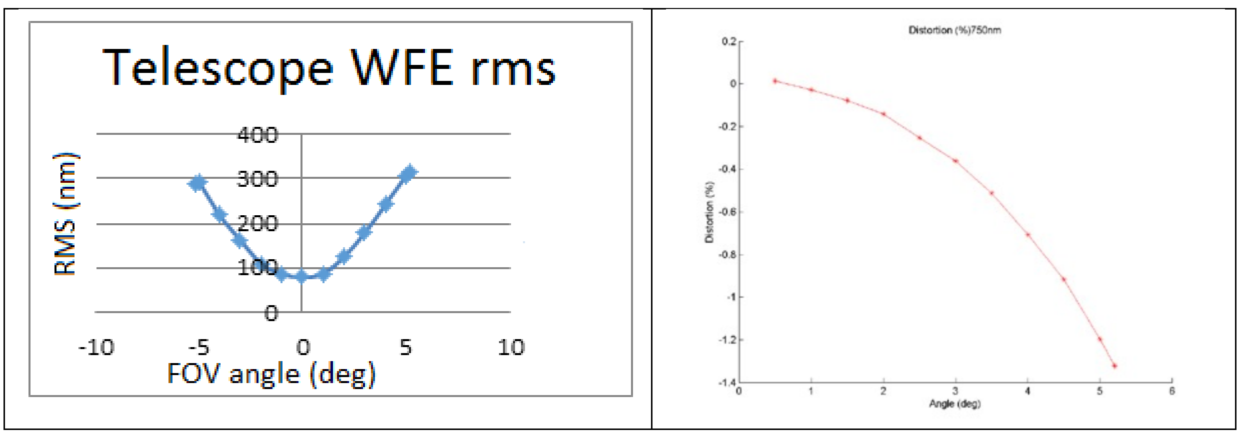


Fig. 13. Telescope measured WFE (in nm rms) and measured distortion as function of the across track angle. Both figures are in line with the optical analysis expectations.

<u>Slit assembly</u>

The slit assembly is a critical element for every pushbroom spectrometer and for FLEX this criticality is even more enhanced. The main reason is that for the HR spectrometer the spectral sampling is 1/3 of the spectral resolution meaning that the slit width is 3 times the pixel size in the along-track direction. Being the slit much wider than the pixel size it drives the shape of the ISRF (Instrument Spectral Response Function) and consequently the spectral resolution. A good knowledge of the ISRF is crucial for the retrieval of Sun induced fluorescence using spectral fitting methods [6]. Therefore FLEX has very stringent requirements concerning the shape and knowledge of the ISRF and also concerning the smoothness of spectral resolution variations between two adjacent spatial samples (less than 0.005 nm). These requirements have a direct correspondence on the required precision and characterization of the slit geometry.

A further complexity is the need to achieve a very good relative orientation between the 2 slits.

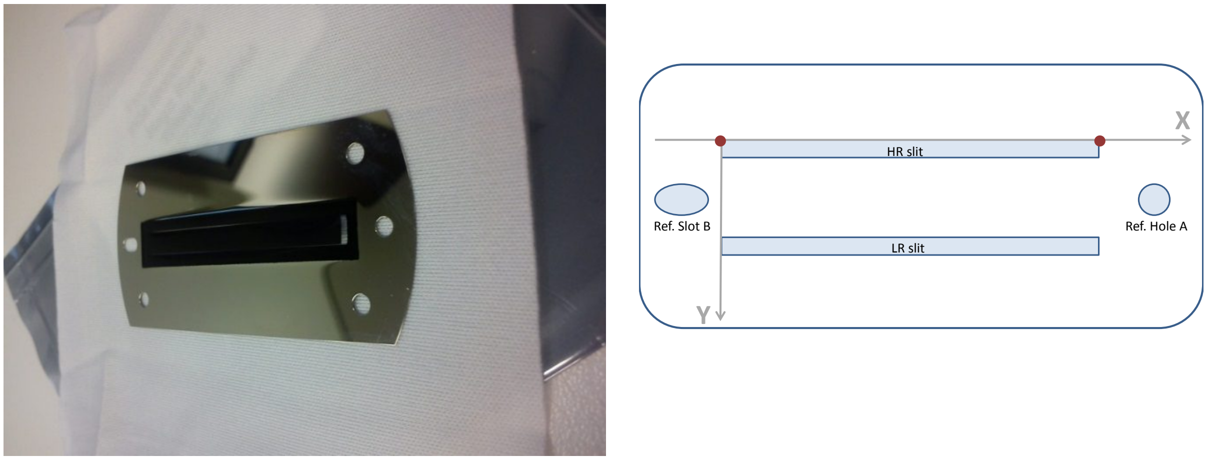


Fig. 14. FLEX double slit assembly for breadboard and drawing showing the geometry of the 2 slits. The slit assembly is black coated (reflectivity below 2%) to reduce straylight due to ghosts that are originated by slit plane reflections

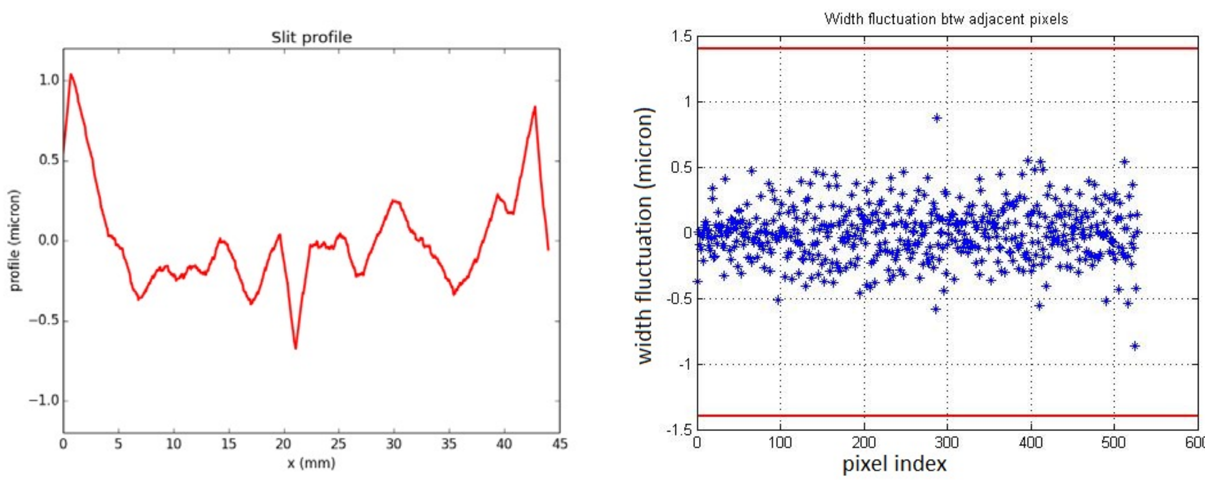


Fig. 15. Slit profile and width variation between adjacent pixels. The red lines on the right plot (±1.4 µm) correspond to 0.005 nm variation of the spectral resolution

Several slit assemblies have been manufactured by Leonardo and black coated by Acktar in order to reduce potential ghosts in the telescope linked to reflections from the slit plane (Fig. 14).

The microscope inspection shows that the slit assembly features excellent geometrical performance. The slit profile has been obtained measuring first the coordinates of the two edges of each slit and computing the average value. In particular the HR slit of the assembly selected for EBB integration has a maximum deviation from a straight line of 1 µm (over 45 mm length) and a very limited width fluctuation (less than 1 µm corresponding to ~0.0036 nm of spectral resolution fluctuation) (Fig. 15).

<u>HR spectrometer optics</u>

All the optical elements and mechanical mountings of the spectrometer (Fig. 16) have been procured and individually tested. At the time of writing this paper the integration and alignment of the spectrometer is in progress in the Leonardo clean room facilities.

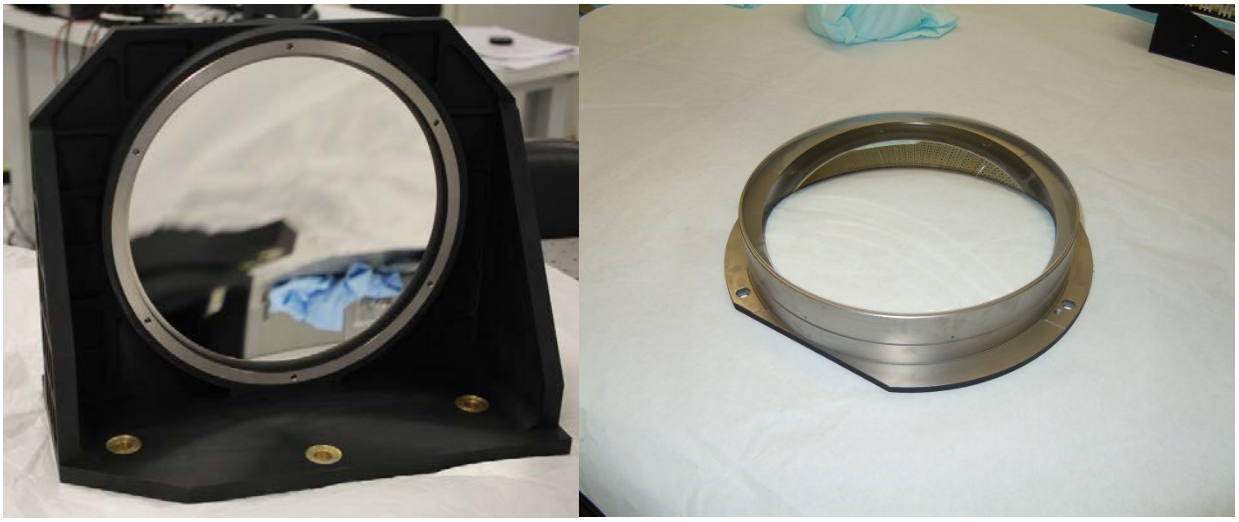


Fig. 16. HR spectrometer mirror (left) and meniscus lens (right)

HR grating

The grating of the HR spectrometer is holographic because it requires a relatively high groove density (1450 grooves/mm) and a very good control of imperfections (roughness, ghosts, profile errors) in order to limit the spectral straylight. The grating has been manufactured by Carl Zeiss Spectroscopy after a proper design and optimization of a bi-directional opposing wave holographic setup required to achieve an asymmetric blaze profile (Fig. 17).

The substrate of the grating is made of fused silica. After deposition of the photoresist material, holographic exposure and ion beam etching of the grating into the substrate a gold coating has been deposited in order to achieve a good reflectivity in the O2A and O2B bands.

Despite the challenging requirements the results obtained are very good in terms of grating efficiency (close to 80% with respect to 60% requirement) (Fig.18). A secondary beneficial consequence of this high efficiency at the first diffraction order is the lower energy at other unused grating orders that could have potentially contributed to straylight.

The measured polarisation sensitivity exceeds the current requirement (25% at the extreme of the band compared to 20% requirement) (Fig.18). The possibility to improve this figure is considered feasible by Zeiss with a slight increase of the blaze depth obtainable with a tuning of the etching parameters. Anyhow the impacts of this higher polarisation have been analysed and deemed fully acceptable for the purposes of the breadboard.

As previously discussed the grating is the most important element contributing to in-field straylight for the spectrometer. Therefore the measurement of the grating scattering is of paramount importance. A test of the grating BRDF is currently under discussion with the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF).

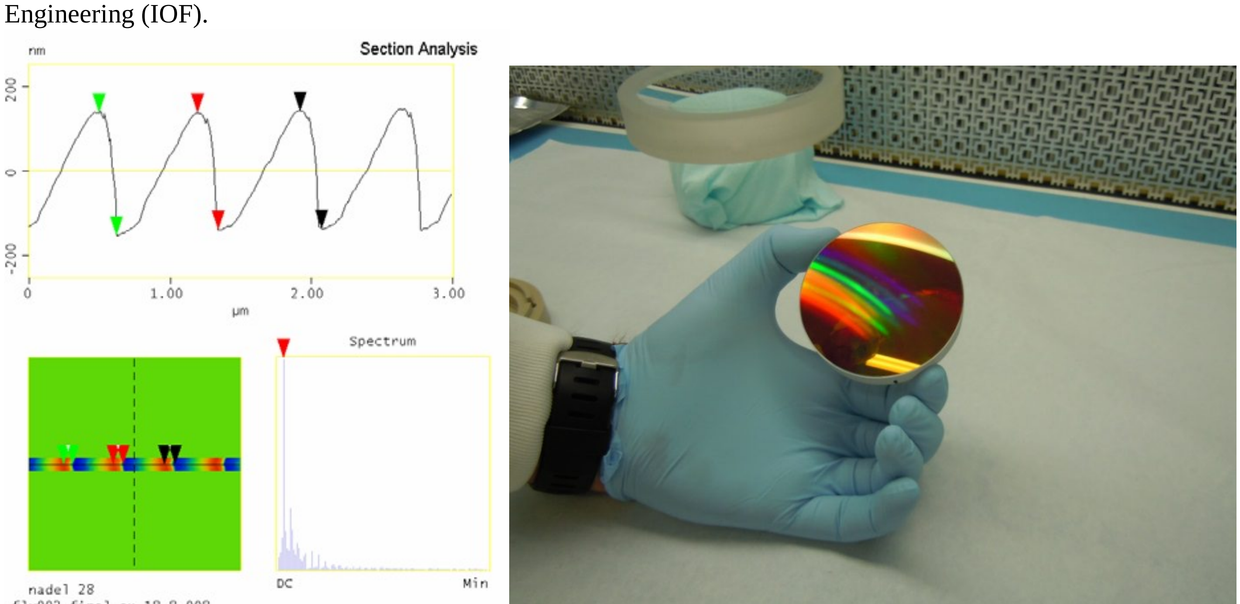


Fig. 17. HR grating picture (right) and blazed profile measured with AFM (left)

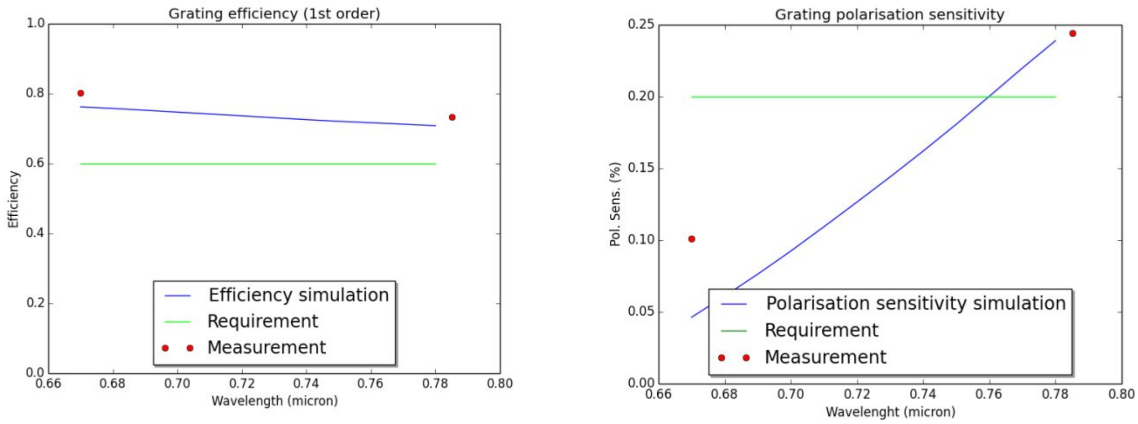


Fig. 18. HR un-polarised grating efficiency and polarisation sensitivity. Measurements are performed at two wavelengths and simulations are derived from RCW analysis of the actual measured grating profile

<u>OGSE</u>

A complex OGSE has been built to perform the optical tests of the elegant breadboard (Fig.19). The OGSE has a modular design. The input light source comes from a tunable laser that is then spectrally filtered by a monochromator to have a narrow band tunable source. The source is then linearly polarised with a selectable polarisation angle. Off axis parabolas are used to generate a collimated beam with an aperture larger than the entrance pupil aperture of the instrument.

The entire instrument is mounted on an hexapod and can be oriented with respect to the collimated beam to perform along track and across track measurements.

The OGSE will be used in particular for the two most important measurements that are the Instrument Spectral Response Function (ISRF) and the in-field straylight.

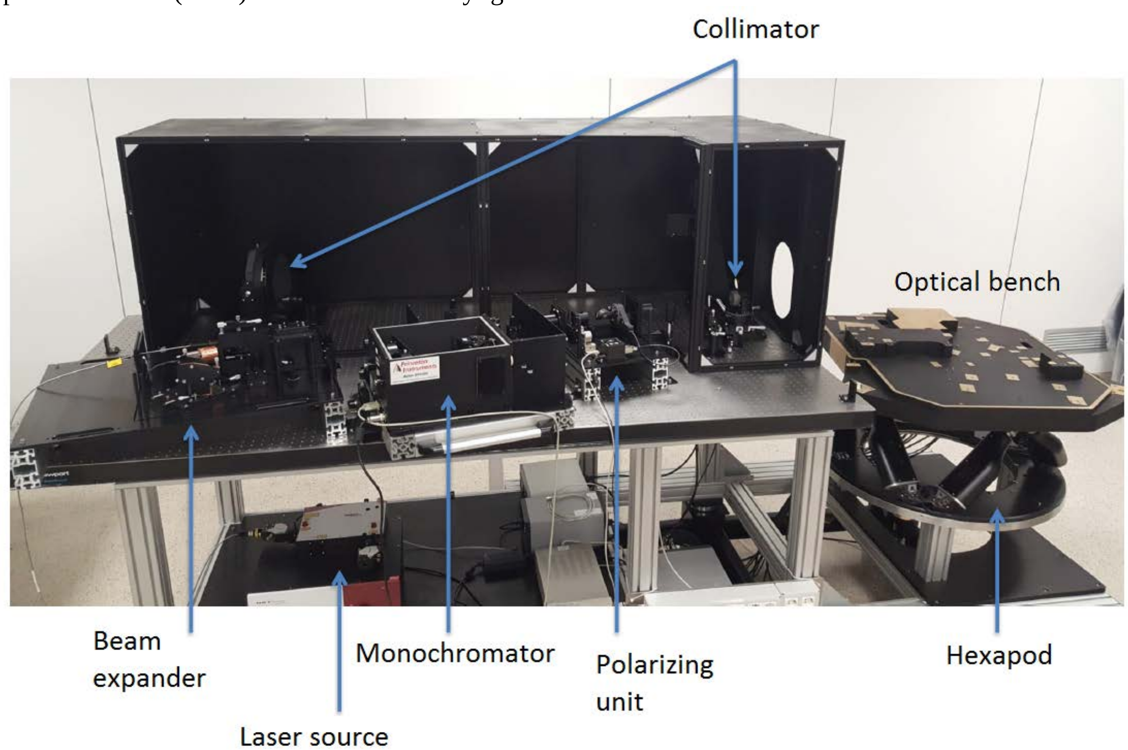


Fig. 19. OGSE developed for the breadboard test

CONCLUSION

An overview of the FLEX instrument and a description of the two spectrometers has been addressed.
The status of the FLEX Elegant BreadBoard (EBB) has been presented. The alignment of the High Resolution Spectrometer and the integration with the telescope on the optical bench are currently in progress. All the measurements performed at subsystem level (telescope, slit assembly, grating) indicate very good performances of the breadboard. In particular the HR convex holographic grating features efficiency as high as 80%. The activities related to the Low Resolution Spectrometer started later. The detailed design phase has been finalized and the manufacturing of the spectrometer is currently being initiated. The test of the fully integrated FLEX breadboard is expected to be completed by summer 2017.

ACKNOWLEDGEMENTS

The FLEX Predevelopment Breadboard has been developed by LEONARDO Finmeccanica with OHB System AG in charge of the Low Resolution Spectrometer (subcontract FLEX-OM-OHB-CT-001) in the framework of the ESA Earth Explorer EO8 program for the FLEX/Sentinel 3 tandem mission. The authors would like to acknowledge all people staff in LEONARDO and OHB for their cooperation, and Carl Zeiss Spectroscopy GmbH Jena for providing the gratings of the instrument.

REFERENCES

[1] A. Taiti, P. Coppo, and E. Battistelli, "*Fluorescence imaging spectrometer optical design*" *Proc. SPIE 9626, Optical Systems Design 2015: Optical Design and Engineering VI, 96261N (September 23, 2015)*

[2] P. Coppo, A: Taiti, M. Rossi, E. Battistelli, *"Fluorescence Imaging Spectrometer (FLORIS): A High Accuracy Instrument with proven technologies and robust design"*, Proceedings of 66 International Astronautical Congress, Jerusalem, 12-16 October 2015, IAC-15-B1.3.5, x29991.

[3] ESA, *"Report for mission selection – flex"*

[4] D. Lobb *"Theory of concentric designs for grating spectrometers"* Applied Optics, 33, 2648–2658, 1994

[5] R. Meynart, T.Phillips, R.Wheeler *"Pre-development of the CCD detector of the FLEX mission"* ICSO 2016

[6] S. Cogliati etc, *"Retrieval of sun-induced fluorescence using advanced spectral fitting methods"* Remote Sensing of Environment Vol. 169, November 2015, Pages 344–357