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FLEX instrument: status, performances and lessons learnt

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FLEX instrument: status, performances and lessons learnt

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ABSTRACT

The FLuorescence Explorer (FLEX) is the 8th Earth Explorer mission currently being developed by ESA with the objective to measure solar induced vegetation fluorescence. This will advance our understanding of photosynthesis and the health of vegetation. Vegetation fluorescence is a very faint signal, and this brings many challenges for the instrument design, development and test, in particular for the very stringent straylight requirement.

The development of the FLEX payload (FLORIS instrument) is led by Leonardo (Italy) with OHB (Germany) in its core industrial team. A major milestone has been achieved by completing the instrument Critical Design Review beginning of 2022, allowing now to move into the phase of flight hardware integration.

Most of the instrument flight components and subsystems are already manufactured and ready for integration.

An extensive test campaign has been already performed on an optically representative engineering model. This campaign provided very useful results in particular for the validation and optimization of the instrument alignment procedures, of cleanliness & contamination preventive measures and the assessment of the optical performances predictions, in particular straylight in flight representative conditions.

In this paper an overview of the instrument design, status and development progress is provided including an outlook of the follow up project activities to get ready for FLEX mission launch in 2025.

The main results of the engineering model test campaign will be provided with emphasis on the achieved optical performance results.

In addition to the project status this paper highlights also some of the most important lessons learnt during the project development as reported in section 4.

Keywords: Imaging Spectrometer, Earth Explorer, Fluorescence

1. INTRODUCTION

The main mission objectives of FLEX are to provide a quantitative assessment of photosynthetic activity of terrestrial ecosystems and physiological indicators for vegetation health status. This is achieved with a direct spectral measurement of vegetation fluorescence.

1.1 What is vegetation fluorescence and why we measure it?

Vegetation fluorescence is a by-product of photosynthesis activity. Photosynthesis (Ref. 6) is an extremely complex chemical process used by plants to produce chemical energy from water and light. But not all the energy of the radiation involved in the process is used and a residual is re-emitted by the plants as fluorescence.

Measurements of vegetation fluorescence allows quantifying the photosynthesis activity and hence the plant health status (the higher the emitted fluorescence, the less efficient the photosynthetic energy conversion).

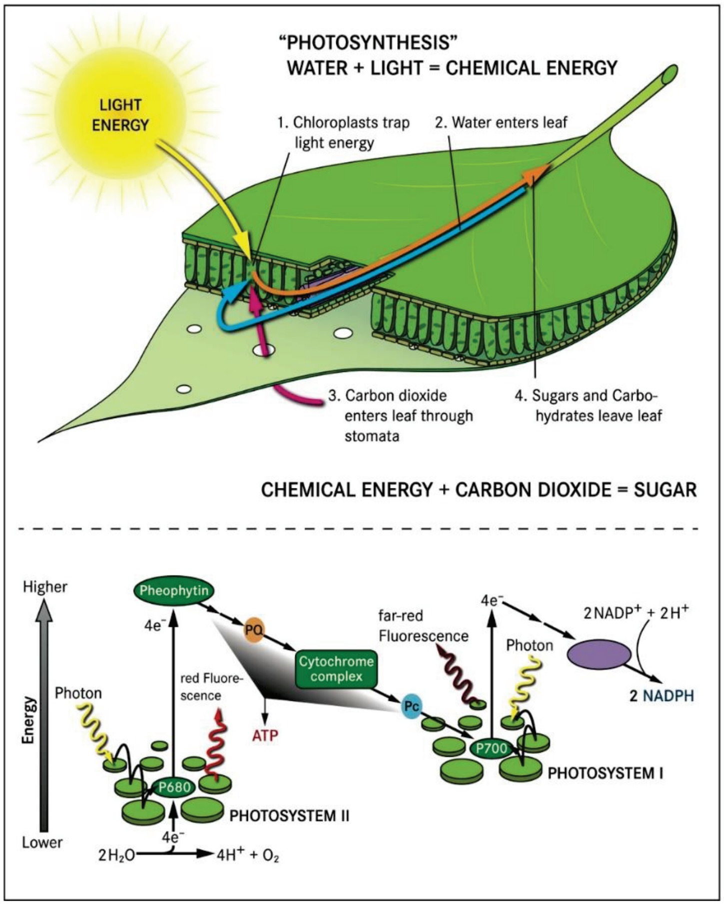


Figure 1. Photosynthesis is a highly regulated process that involves a complex cascade of electron transfers. Fluorescence is emitted from the cores of the photosynthetic machinery: Photosystems I and II. Fluorescence changes reflect the functional status of the photosystems

1.2 Measurement concept

The typical spectrum of vegetation fluorescence extend in the red and near infrared and it is characterized by two peaks that are generated by the two photosynthesis mechanisms shown in Figure 1. As an example in Figure 2 it is shown the fluorescence spectrum of cabbage (left) compared with the classic reflectance spectrum (right).

The typical value of the fluorescence peak induced by solar illumination is typically less than 1 mW/m2/sr/nm and it is therefore much lower than the typical reflectance radiance. Therefore the capability to disentangle fluorescence from reflected and background radiation is the main challenge of this kind of measurement.

The most favorable spectral regions to measure fluorescence from Space are the two absorption bands of the atmosphere originated from O_2 gas. In these spectral regions the reflectance signal is attenuated both during the Sun to Earth path and the Earth to Space path, while the emitted signal is attenuated only from Earth to Space. Therefore the ratio between emitted and reflected signal is more favorable if measured in these absorption bands.

The spectrum measured in the two absorption bands is not sufficient to derive photosynthesis from fluorescence. The measurement of additional spectral bands is required for the characterization of several plant properties (e.g. leaf chlorophyll content, leaf area index) and for the correction of the atmospheric effects. (Ref. 1)

The FLEX instrument (FLORIS) is composed of two imaging spectrometers. FLORIS HR cover the two oxygen absorption bands (O2A: 740 nm–780 nm, and O2B 677 nm–697 nm) with high spectral resolution (0.3 nm). FLORIS LR has a lower spectral resolution but it covers continuously the range between 500 nm to 740 nm. Additional bands required for atmospheric correction and temperature evaluation are obtained by flying Flex in tandem with Sentinel 3 satellite and taking advantage of its OLCI and SLSTR instruments.

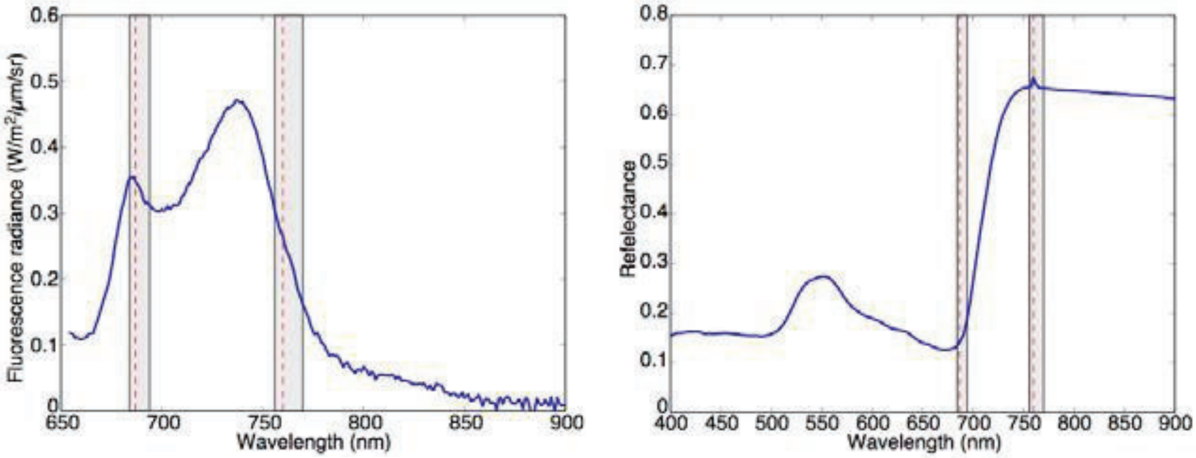
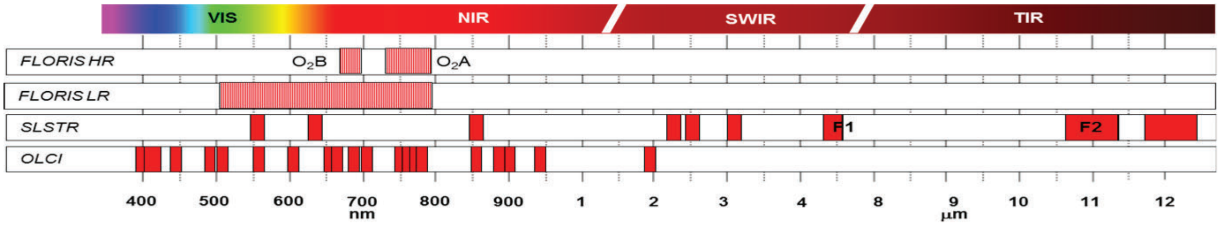


Figure 2. Cabbage fluorescence spectrum (left) and reflectance spectrum (right). The two grey vertical bars correspond to the two oxygen absorption bands.

Figure 3 provides an overview of the spectral bands covered by FLORIS and the two instruments onboard Sentinel 3 (OLCI and SLSTR) together with a reference to main physical parameters derived from the different instruments.



FLORIS (300 m SSD*)
- Fluorescence
- Photochemical Reflectance Changes
- Atmospheric correction
- True reflectance

S-3 OLCI-4 (300 m SSD)
- Aerosols and water vapour
- Biophysical variables (Chlorophyll, LAI, …)
- Reflectance
- Cross calibration
- Context information

SLSTR (500m – 1 km SSD)
- Aerosols,
- Surface Reflectance
- Surface Temperature
- Clouds (cirrus)

Figure 3. Spectral bands used for FLEX and list of main physical parameters required for fluorescence retrieval. Bands from two additional instruments onboard S3 are needed mainly for atmospheric correction and target temperature. SSD (Spatial Sampling Distance)

2. INSTRUMENT DESIGN AND KEY INSTRUMENT REQUIREMENTS

2.1 Key requirements

The main driving instrument requirements are reported mainly as reference in Table 1 but not further discussed. A good discussion of requirements and design aspects can be found in Ref. 2. The most challenging instrument requirement is straylight.

Table 1. Summary of main instrument requirements. Orbit is reported as a complement.

Requirement	Specification	Comment
Orbit	Sun-synchronous, 805 Km altitude	same as Sentinel 3 for flight tandem config.
Swath width	>150 Km	telescope FOV > 10.8 degree ACT (ACross Track)
SSD (Spatial Sampling Distance)	<300 m	Define instrument focal length
SSI (Spectral Sampling Interval)	<0.1 nm HR channel <2 nm LR channel	SSI specified to different values in different spectral regions. The numbers reported are the most stringent. Driver for spectrometer sizing and grating line density
SIE (System Integrated Energy)	>0.7 (area 1.2 SSD ALT x 1.1 SSD ACT) >0.9 (area 1.6 SSD ALT x 1.5 SSD ACT)	translated to instrument MTF budget Input for image quality req. of each subsystem ALT (ALong Track)
Spatial co-registration (within HR and LR channels)	<0.15 SSD	driver for spectrometer keystone and telescope lateral color
HR versus LR spatial co-registration knowledge	<0.1 SSD	
Spectral coregistration	<2 SSI	driver for spectrometer smile, focal plane and grating alignment
Spectral stability	<0.1 SSI (within 1 orbit) <1 SSI (lifetime)	driver for instrument thermal control
Polarization sensitivity	<2% (LR) <1% (HR)	define need for a polarization scrambler
SNR	>115 (in HR channel between 759 nm to 762 nm)	SNR specified to different values in different spectral regions. The number reported is the design driver
Straylight in HR channel (mW/m2/sr/nm)	<0.8 (at L0) <0.04 (L1b, after straylight correction)	requirement defined for spatially uniform scenes and for non uniform scene at 40 SSD from the edge of a bright region.

2.2 Instrument design

The FLORIS design is based on two separate pushbroom imaging spectrometers sharing the same telescope fore-optics. The conceptual instrument scheme is depicted in Figure 4 (left) while on the right it is shown the optical layout and the raytracing through the different optical subsystems. The separation between the two spectrometers is in field (in the along track direction) and it is implemented with a double slit assembly (SLITA) that includes two folding mirrors.

In front of the telescope there is a polarization scrambler assembly (PSCA) implementing three important functions:

1. Define the instrument optical aperture for the HR channel with an aperture stop. The LR channel can work with a reduced aperture and this is obtained with aperture stops inside the LR spectrometer.
2. Preselect the useful spectral range that is allowed to enter into the instrument rejecting light below 500 nm and above 780 nm. This is achieved with a bandpass filter.

3. Depolarize the incoming radiation with a dual Babinet scrambler. This is essential to achieve the challenging requirement of instrument polarization sensitivity.

Both spectrometers are based on the Offner design concept (magnification -1x) that guarantee very good image quality and very low distortions. The LR spectrometer has a corrective lens before the focal plane to improve image quality while the HR spectrometer makes use of a large meniscus lens in double pass. Both spectrometers implement holographic gratings to perform the spectral dispersion. The gratings are the outcome of specific developments with the objective to reduce spurious light.

The two focal plane assemblies for the HR and LR channel are based on cooled back size illuminated high speed CCD detectors. A linear variable filter (LVF, Ref. 4) is placed in front of the HR detector to act as a barrier for spectral straylight.

A calibration unit mechanism based on a rotating carousel is placed in front of the scrambler assembly. It allows to place a Lambertian diffuser illuminated by the Sun as the first element in the optical path in order to perform an absolute radiometric calibration or a black target for dark acquisitions.

The spectral calibration is achieved by observing the atmospheric and the sun absorption lines and it doesn't require specific on board sources or filters.

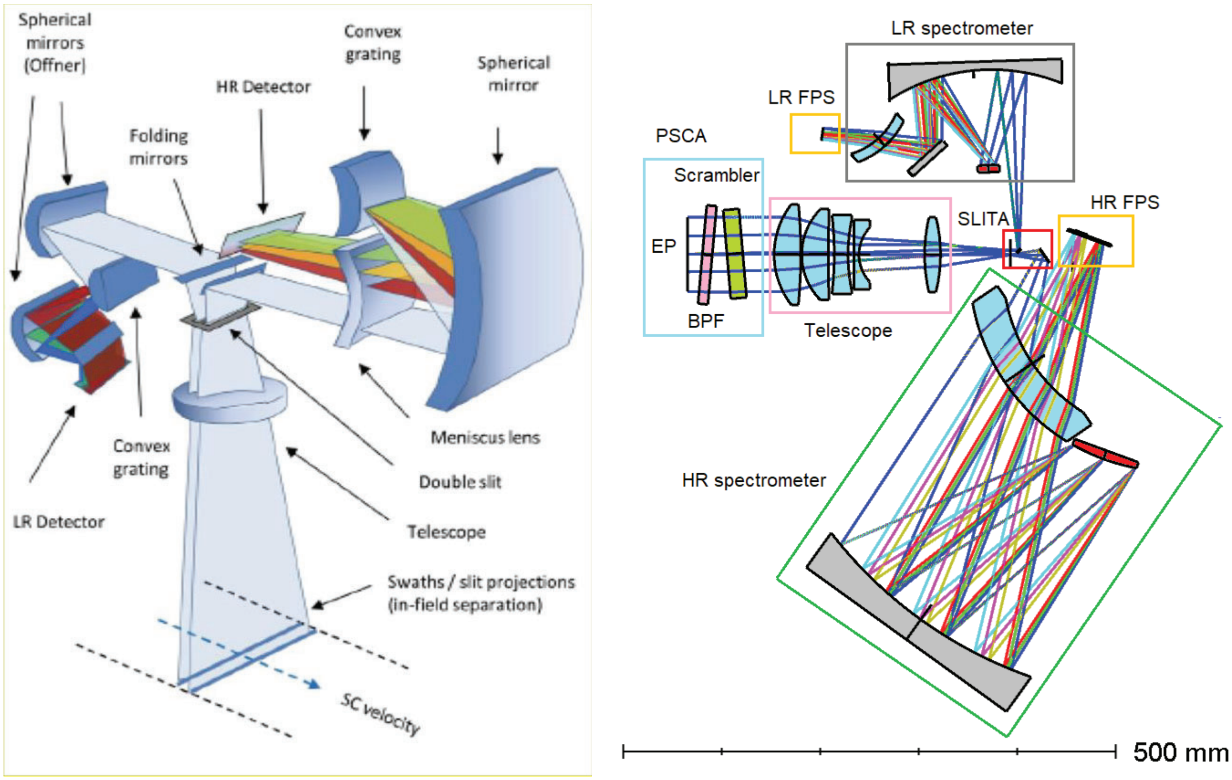


Figure 4. FLORIS conceptual scheme (left) and optical layout including raytracing (right).

All the optical subsystems are mounted on the same side of an aluminium optical bench (Figure 5, left) that is fastened to the supporting structure of the spacecraft by means of 3 flexible bipods made of titanium. The other side of the optical bench is oriented towards cold space when installed on the platform. It is used to mount the radiator and the 3 detector Video Acquisition Units (VAUs) (Figure 5, right).

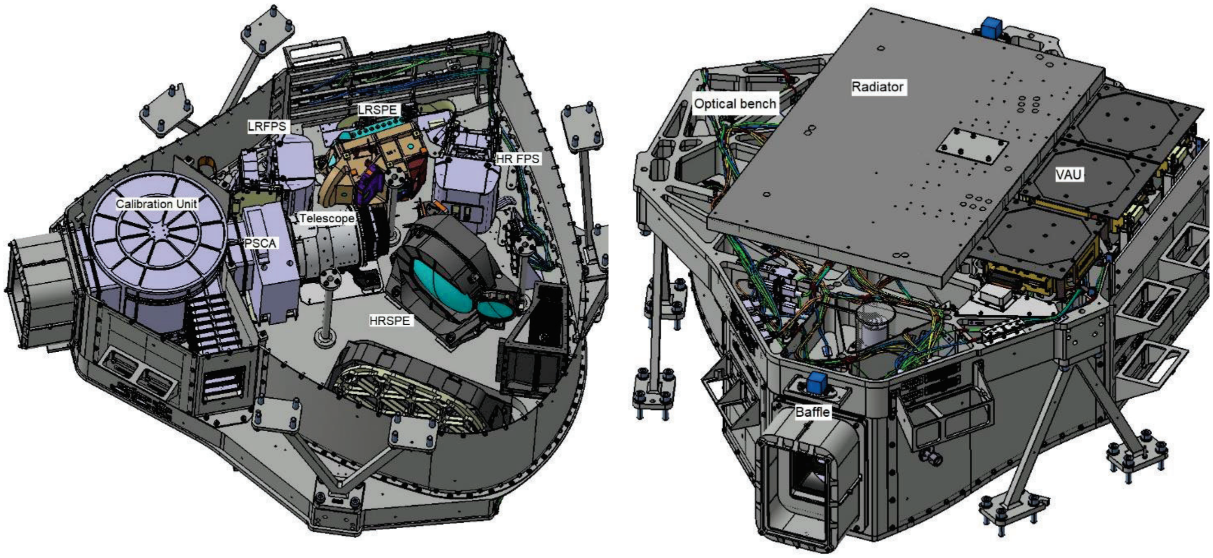


Figure 5. FLORIS mechanical accommodation.

3. INSTRUMENT STATUS AND PERFORMANCES

3.1 Instrument team

The mission prime is Thales Alenia Space (FR). The instrument prime is Leonardo Company (IT) leading a team of industries with OHB (DE) as main partner.

Besides the instrument prime role Leonardo is responsible for the HR spectrometer development.

OHB is leading the development of three important subsystems: the focal plane assemblies, the LR spectrometer and the slit assembly.

The optical bench is developed by Sener (ES), the telescope by Micos (CH) and Toptec (CZ), the Calibration Unit mechanism by Almatech (CH) and the polarization scrambler assembly by Sodern and Fichou (FR).

Several other companies gave a very important contribution to the development of the optical subsystems. Just to mention few of them Horiba Jobin-Yvon (FR) developed the HR grating and Zeiss (DE) the LR grating. IOF (DE) developed the double slit chip and the mirrors of the SLITA. Materion Balzers developed the LVF and the bandpass filter of the PSCA.

3.2 Status of subsystem procurement

Almost all flight models of the optical subsystems are manufactured and with performances in line or exceeding expectations.

The optical bench, the HR spectrometer and the telescope are already available and at least partially integrated in the instrument flight model. The SLITA and the LR spectrometer are completed and undergoing the final acceptance tests. The focal planes will be ready by the end of the year. The manufacturing of the PSCA and CU flight units is still in progress. These units will be ready next year and are the last to be integrated in the instrument flight model.

3.3 Polarization scrambler assembly

The bandpass filter, the aperture stop and the mechanical housing are ready. The manufacturing of the dual Babinet scrambler is currently in progress.

3.4 Telescope

The telescope is based on a Petzval design with only five lenses. It requires an aspheric lens to achieve the required image quality.

The telescope flight model has been manufactured and it is ready for integration on the flight optical bench. The image quality of the telescope is good and in line with the as built optical model.

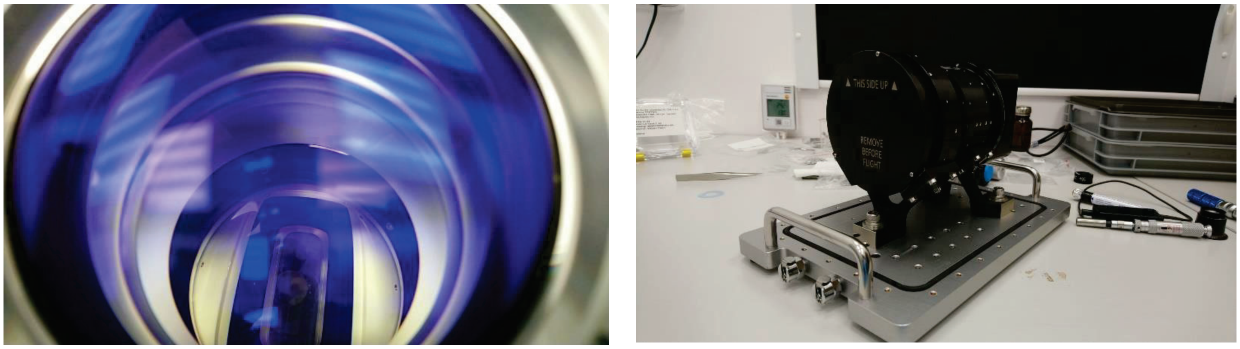


Figure 6. Telescope flight model.

3.5 Slit assembly

The SLITA is a complex assembly implementing a double slit device and two folding mirrors achieving both spatial channel separation and spectral filtering with the implementation of specific bandpass reflective coating.

The double slit device is based on a silicon double slit chip manufactured by a dedicated lithographic structuring process chain to fulfill a number of challenging requirements; i.e. the absolute slit width accuracy of less than 2 µm peak to valley and slit planarity of less than 10 µm peak to valley (Ref 3).

Figure 7. SLITA flight model compared with the SLITA structural model (left). SLITA detail showing the double slit device (right).

3.6 High resolution spectrometer

The HR spectrometer is composed by two subsystems. The grating and lens assembly (figure 8, left) and the mirror assembly (figure 8, right). Both have been already integrated and aligned in the flight optical bench. A light trap used to block the zero order of the grating is currently under manufacturing. It can be integrated on the bench at any stage.

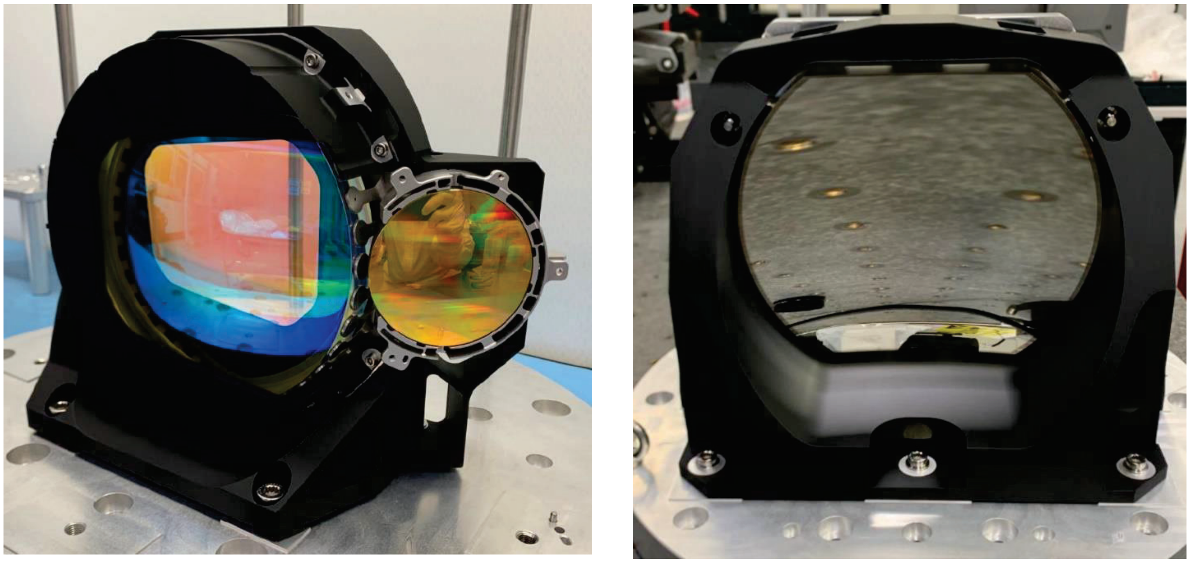


Figure 8. HR spectrometer lens and grating assembly (left) and mirror assembly (right).

3.7 Low resolution spectrometer

The LR spectrometer is also fully manufactured and currently undergoing the last thermal acceptance test. The image quality is excellent and the optical distortions (smile and keystone) are very low.

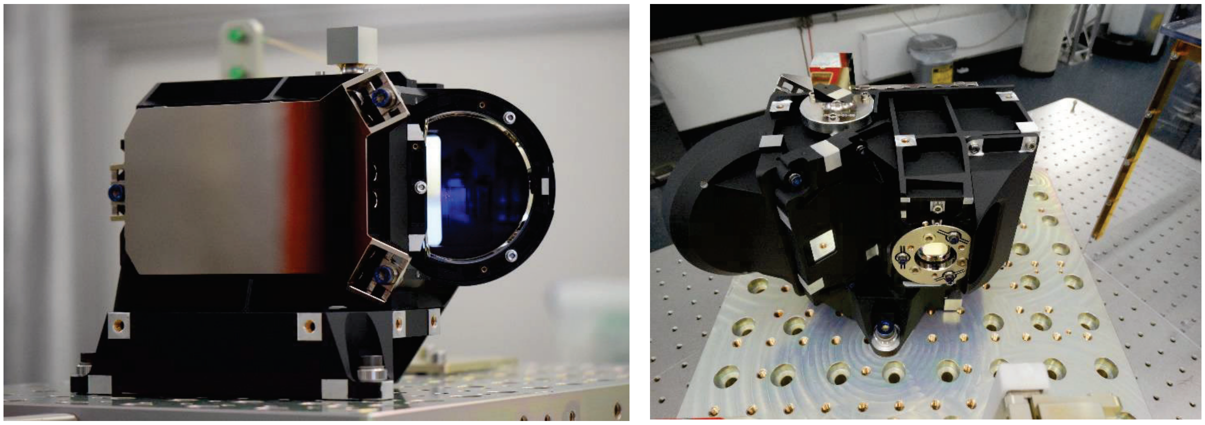


Figure 9. LR spectrometer flight model seen from two different orientations.

3.8 Focal plane assembly

The focal plane assembly of the HR spectrometer is currently undergoing all the electro-optical tests first without the LVF mounted. After this activity the filter will be mounted and the unit will be subject to mechanical and thermal tests and further electro-optical characterization before integration in the flight instrument.

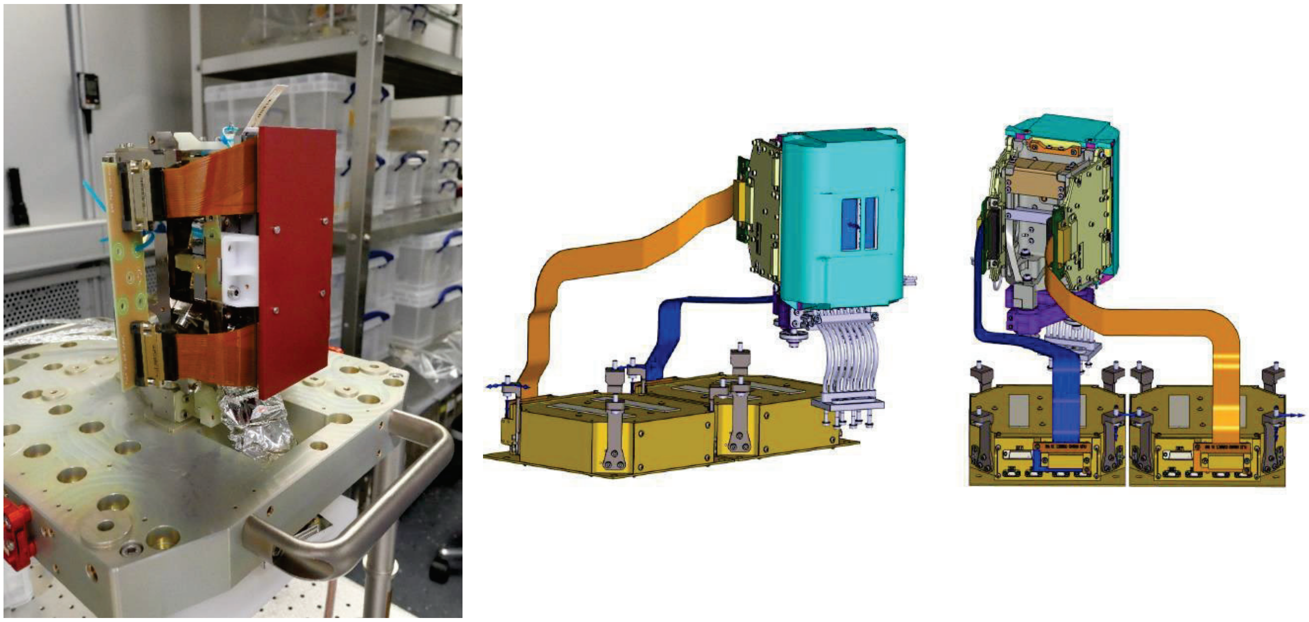


Figure 10. Focal Plane System (FPS).

3.9 Calibration unit

Almost all flight parts of the calibration unit are manufactured and under integration. How it will look in the final assembled state can be seen in figure 11 (left) showing a picture of the CU qualification model. Figure 11 (right) illustrates the mechanism positions during nadir view (nominal Earth observing mode) and Sun view for in flight radiometric calibration.

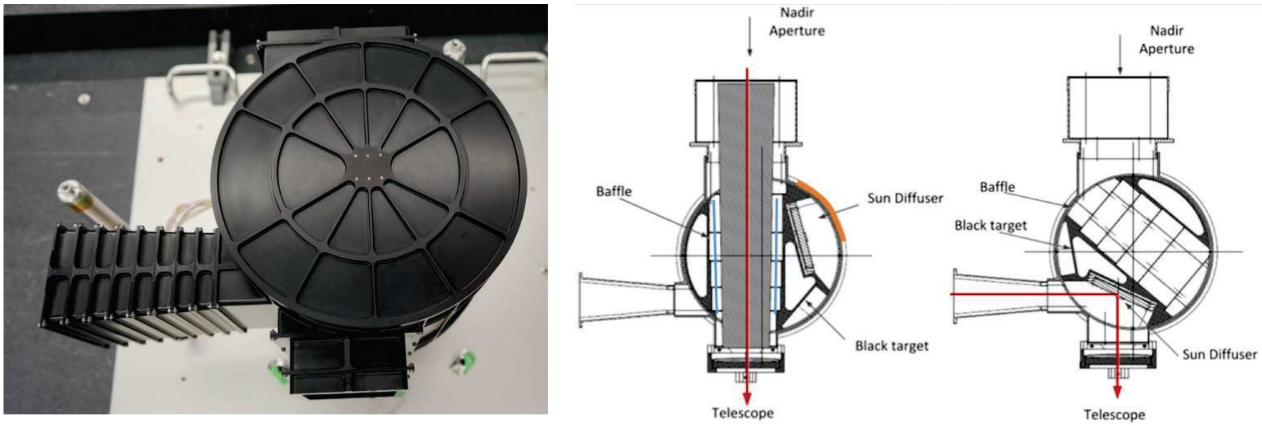


Figure 11. CU qualification model (left) and sketch of two mechanism positions (right). The third mechanism position allow to put a black target in front of the instrument for dark acquisitions and also as a mean to protect the instrument from contamination

3.10 Engineering model results

A complete engineering model of FLORIS has been built and tested with the objectives to validate all the optical performances and to validate and train the instrument alignment procedures, as well as cleanliness & contamination prevention measures that are key to keep straylight within the requirements.

The activity performed with this model was very valuable in particular to assess the instrument limits in terms of straylight and to perform a full correlation of the straylight model that is needed to implement the post processing straylight correction.

It also allowed to discover well in advance few weaknesses of the instrument design that were corrected for the flight model.

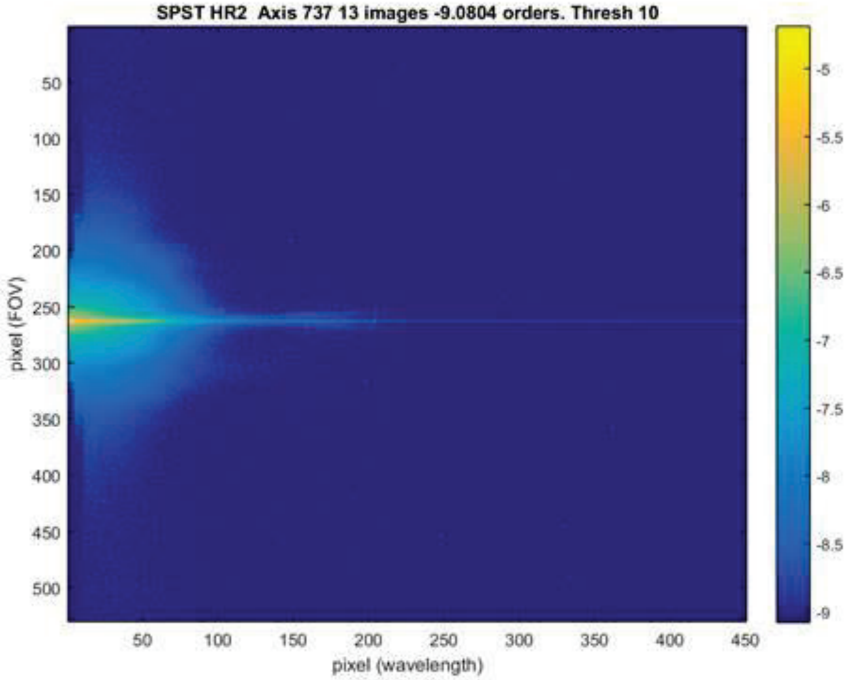


Figure 12. Example of straylight kernel measured with the FLORIS engineering model

3.11 Flight model status and next steps

The integration of the FLORIS flight model is currently in progress.

The HR channel is fully aligned using the SLITA qualification model for schedule optimization reasons. This will be then swapped with the SLITA flight model in September 2022.

A picture of the current flight instrument status is shown in Figure 13.

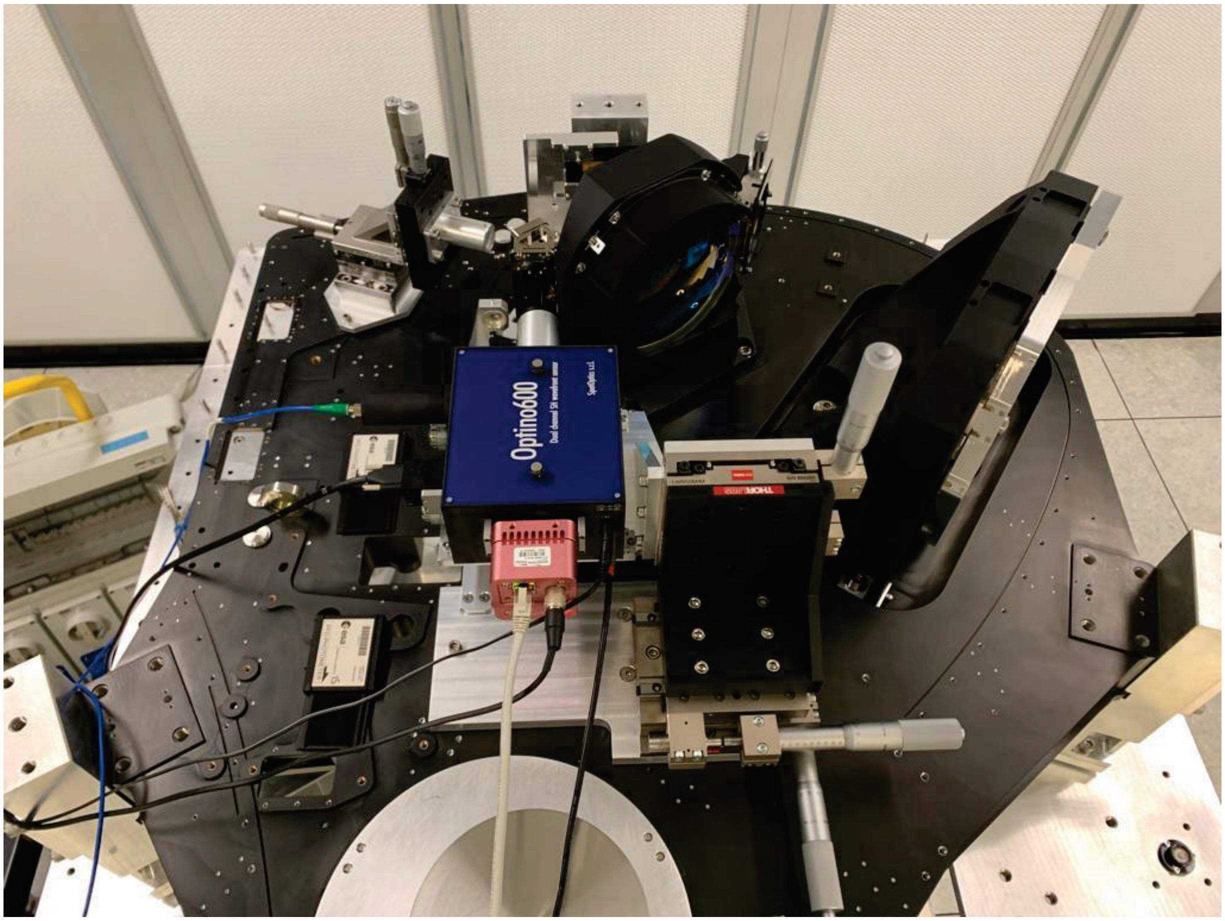


Figure 13. FLORIS flight instrument partially integrated.

4. LESSONS LEARNT

4.1 Disclaimer

The beauty of developing cutting-edge technology for space missions is that every day there is the opportunity to learn something new. This section will address only three lessons learnt. This selection is both subjective and extremely reductive. In contrast with many papers that highlight the excellent performances and the positive results of the mission this section deals with problems and critical areas. The main lessons do not come from celebrating successes but from solving failures.

4.2 The importance of instrument operation on ground

From the start of the mission life and including all the feasibility studies and pre-development activities most of the effort is devoted to design the instrument in order to maximize the performances and science return of the mission in flight. This is understandable and logical but it can impact the design of long lead items components that need to be frozen in an early stage of the project. A typical example is the definition of the focal plane architecture in particular if the procurement of a new image sensor is needed.

This was the case for FLEX. The focal planes of FLORIS are based on a custom CCD design. The detector geometry and the pixel size are specifically designed for the FLEX application. The pixel has a very large full well capacity (2.1 Me-)

that is crucial to operate the instrument without saturation over a large dynamic range from very low signal in the oxygen absorption bands to very bright clouds.

Since the detector will never experience in flight a strong saturation and in order to maximize the full well capacity the CCD architecture doesn't include any mechanism to reduce or control blooming.

Unfortunately the condition of no saturation is not met during on ground testing and in particular for straylight characterization. The very challenging FLEX straylight requirement requires the correction of straylight on ground and this is achieved only if the instrument straylight is very well characterized.

This is achieved by illuminating the instrument with a bright laser source for very long integration times (several seconds compared to 42 msec of nominal integration). In this specific test condition the detector is strongly saturated and there is a quite significant blooming signal that is very difficult to disentangle from the instrument straylight.

The lesson learnt is that the importance of on ground test conditions should be carefully analyzed from the very beginning of a mission in particular when there is the need to anticipate the design and procurement of specific long lead items.

4.3 The pitfalls of bonding optical elements

The bonding of optical elements is a very common and powerful technique. For FLORIS it is used on many optical elements bonded by different companies and with different design solutions. It is a complex domain because it requires a deep knowledge of several engineering fields ranging from optical engineering, to material/mechanical engineering, to chemistry and physics. It also requires very skilled operators and specific preparation of the surfaces to be bonded both in terms of cleanliness and surface geometry and roughness. Some of the recurrent problems are related with workmanship and process control, adhesive properties (e.g. thickness, viscosity) and their characterization, compression creep, pre-tension loss, etc.

Despite usual precautions, the complexity of the bonding process is sometimes underestimated. Unfortunately for FLEX we had few examples.

One example is the use of elastomeric mounting. Yoder (Ref. 5) describe the method of elastomeric mounting (see figure 14) as "*a deceivingly simple technique for mounting lenses, windows, filters, and mirrors*".

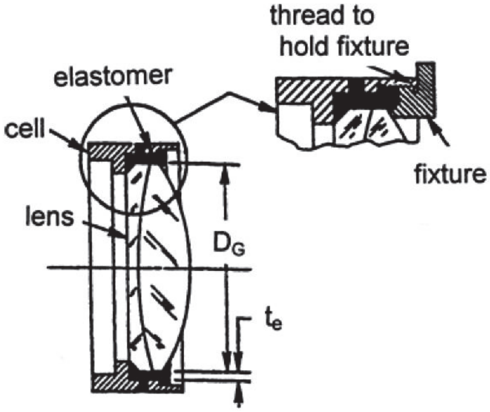


Figure 14. Typical design for a lens constrained by an annular ring of a resilient elastomeric material within a cell. From Yoder. (Ref. 5)

No better definition than deceivingly simple could be given as a warning for the pitfalls of this mounting concept.

It can work properly and it was applied successfully in several instruments but it requires a very good knowledge of the adhesive properties that are often only partially known or based on Technical Data Sheet and/or literature information that unfortunately sometimes deviate from reality. Typical examples are the glue mechanical properties (e.g. Young modulus, Poisson ratio and related temperature dependency). A consequence of a wrong assumption of these parameters can lead to an underestimation of tension forces at the bonding interfaces that actually might generate unexpected de-bonding. This effect is more critical for this kind of mounting solution because the bonded surface and glue quantity are relatively large compared to other designs.

Another common pitfall for all mounting concepts that involve the bonding of optical components is the wrong belief that the process is scale invariant. If for instance a bonding was successfully applied with prisms of a given size it doesn't mean that if the size is doubled the process will still work.

The main lesson learnt is that all bonding processes require very special attention. Either the process is fully mastered because already applied by the same company with the same materials, similar geometries and similar conditions (e.g. thermal ranges of the optical system) or a complete and fully representative model is needed. In addition, the following aspects need always to be considered:

- Understand the true function of the adhesive and all the constrains imposed on the joints.
- Assure that behavior of the materials (adherents as well as adhesives) are known and predictable, including continuity in raw material performances such as their stiffness, CTE, polymerisation shrinkage, etc. This is essential to support credible modeling of the joint behavior in mechanical and thermal environment.
- Deploy correct level of verification in process control (e.g. thickness, cracks, delaminations, chipping, cleanliness & contamination).
- Put in place verification methods of the final product to assure quality of the joint (e.g. visual inspection, pull test, in process hardness samples, single lap shear samples).
- Use right level of confidence in design (statistics), right methodology for training of the users of adhesives (bonders) as well as the guidelines and design rules for the joints. (Ref. 7 and Ref. 8)

ESA-ESTEC has specific laboratory that can help with this characterization.

4.4 The problem of straylight

Not many decades ago the main straylight activity for the optical engineer was limited to the design of external baffles with rudimentary tools. Today the complexity of space missions is strongly increased with objectives to measure signals that are extremely faint and close to the instrument noise floor. This make straylight a very critical instrument requirement. The tools available now to model, measure and correct straylight are also becoming more sophisticated but this improvement is probably not proceeding with the speed required by the mission complexity.

In the specific case of FLEX the radiance associated to Sun induced vegetation fluorescence is a very low signal and as consequence the maximum straylight after on ground correction (L1 straylight residual) shall be even lower (less than 0.04 mW/m2/sr/nm). This requirement drives the instrument design (e.g. low number of optical elements, use of filters in front of the focal plane to block straylight) and manufacturing (very low surface roughness, specific developments of diffraction gratings, very black coatings). Also the level of particle contamination need to be extremely well controlled to limit scattering.

The final instrument straylight is measured during the calibration campaign and the measurement used for straylight correction. Let’s assume just for simplicity that the instrument straylight is perfectly characterized and that the straylight correction is also perfect. After calibration the instrument is delivered to the satellite prime for further platform integration, testing and launch. A very good care is taken to limit and also experimentally measure the expected contamination during all the post instrument delivery phases but this contribution cannot be corrected at L1 because it occurs after instrument straylight measurement. Even if the instrument is very well protected from the external environment, as it is the case for FLORIS, it is not possible to exclude that a particle contamination of few additional ppm is accumulated by the optical elements. The impact of this potential delta contamination is addressed by analysis but considering the uncertainty of the straylight model linked to particle contamination it is very close to the L1 requirement. As a conclusion, with the uncertainties linked to the way we build cleanliness and straylight budgets, it is very difficult to prove compliance with requirements as challenging as the ones of FLEX.

The problem is not specific to FLEX and it will certainly impact many future optical missions. The main lesson here is that there is a strong need to advance in all aspects connected to straylight from the modelling, to metrology (both on ground but also in flight) and post processing correction.

5. CONCLUSIONS

A very synthetic but hopefully also comprehensive summary of the instrument status including the mission objectives and a recall of the instrument design was provided. This is just a ‘picture’ of FLORIS at a specific moment in time since the project is now in a quite dynamic phase with flight hardware integration proceeding at full steam.

This paper is also the opportunity to present few lessons learnt with the hope that they might be useful to the readers or stimulate constructive discussions.

Integration of the FLORIS instrument is expected to be completed by Leonardo in 2023, to be followed by the instrument testing and calibration campaign in 2024 at CSL (B), with the FLEX mission launch planned for mid 2025.

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