

Performance and Calibration of the FLORIS Payload for the ESA FLEX Mission

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ABSTRACT

The Fluorescence Explorer (FLEX) is a pioneering European Space Agency (ESA) Earth Explorer mission designed to provide global maps of vegetation fluorescence, offering unprecedented insights into plant photosynthetic activity. At the heart of this mission is the Fluorescence Imaging Spectrometer (FLORIS), an innovative optical payload developed to detect the faint solar-induced chlorophyll fluorescence (SIF) signal. Because the SIF signal is remarkably weak compared to the reflected solar background, FLORIS demands radiometric accuracy, high spectral resolution within the 500–780 nm range, and strict control of straylight.

This paper presents the performance results and calibration status of the FLORIS instrument following its comprehensive calibration campaign at the Centre Spatial de Liège (CSL). FLORIS underwent a rigorous suite of thermo-vacuum environmental tests and optical calibrations designed to simulate flight conditions while precisely quantifying the instrument behaviour. Our presentation details the calibration methodology, custom Optical Ground Support Equipment (OGSE), and measurement results. We report on the absolute and relative radiometric accuracy achieved across the instrument's spectral channels, as well as the precise determination of the Instrument Spectral Response Function (ISRF) and spectral stability over varying operational thermal gradients. Special attention is given to spatial and spectral co-registration metrics, Signal-to-Noise Ratio (SNR), and stray light characterization—fundamental challenges for the mission's success.

Ultimately, the CSL calibration campaign confirmed the robust optical performance of FLORIS, demonstrating the sensitivity and precision necessary to capture the SIF signature from space. Following the calibration campaign, the instrument was integrated onto the satellite platform at Thales Alenia Space in July 2025. The fully assembled 400 kg spacecraft subsequently completed its environmental test campaign in April 2026, including acoustic, sine, TVAC and EMC tests at TASF site, confirming its launch readiness.

FLEX is now scheduled for launch on 14 September 2026 from Kourou, French Guiana, on a Vega-C rocket as a secondary payload beneath Sentinel-3C. After deployment, the satellite will execute a critical orbital drift manoeuvre to fly in tandem with Sentinel-3A. During its initial three-month commissioning phase, FLEX will perform specialised calibration manoeuvres targeting the Sun, Moon, and dark ocean. This presentation outlines the final steps of the mission leading to the In-Orbit Commissioning Review in early 2027, paving the way for a new era of global vegetation monitoring.

Keywords: Imaging spectrometer, ESA Earth Explorer, Fluorescence retrieval

1. INTRODUCTION

Mission background and scientific objectives

Global monitoring of terrestrial vegetation dynamics and photosynthetic capacity is essential for understanding the terrestrial carbon cycle, assessing agricultural yield, and evaluating ecosystem responses to climate change. Traditional optical remote sensing metrics, such as the Normalized Difference Vegetation Index (NDVI), quantify canopy structural properties and greenness; however, they do not directly measure instantaneous photosynthetic activity or early physiological stress (e.g., heat or drought-induced down-regulation).

The Fluorescence Explorer (FLEX), selected as the 8th Earth Explorer mission of the European Space Agency (ESA), introduces a paradigm shift in Earth observation by directly measuring Solar-Induced Chlorophyll Fluorescence (SIF).

Emitted by plants during photosynthesis in the 650–780 nm spectral window, SIF provides an un-mixing probe for physiological state prior to visible chlorosis or structural degradation. As highlighted during the recent FLEX Fluorescence 2026 Workshop in Bonn [1], global high-resolution SIF operational products are poised to bridge the critical gap between plant-level photosynthesis models and global carbon flux estimations.

The Measurement Challenge & The FLORIS Instrument

Retrieving SIF from satellite altitudes presents an extraordinary optical and radiometric challenge. The emitted fluorescence signal constitutes only a small fraction (typically 1–5%) of the reflected solar radiance background in the red and far-red spectral regions. To decouple SIF from the dominant surface reflectance and atmospheric scattering backscatter, the measurement strategy relies on the high-resolution retrieval of signal infilling within narrow solar Fraunhofer lines and atmospheric absorption bands—specifically the oxygen absorption features O2-B (~687 nm) and O2-A (~760 nm).

To fulfill these extreme science requirements, the core payload of the FLEX mission is the Fluorescence Imaging Spectrometer (FLORIS). FLORIS is a push-broom grating spectrometer operating across the 500–780 nm spectral range. The payload incorporates two main optical channels:

- **High-Resolution (HR) Channel:** Operating over the O2-B and O2-A bands with fine spectral resolution (~0.3 nm) to disentangle the faint SIF signal from overlapping reflectance features.
- **Low-Resolution (LR) Channel:** Covering the broader 500–780 nm interval with moderate spectral resolution (~2.0 nm) to capture the full fluorescence emission envelope and essential baseline reflectance properties.

Meeting these objectives requires unprecedented optical performance: strict Signal-to-Noise Ratios (SNR > 115 in absorption troughs), absolute radiometric calibration uncertainties below 5%, ultra-precise spatial/spectral co-registration between HR and LR channels, and rigorous stray-light suppression.

Baseline Configuration and Tandem Mission Architecture

Because SIF retrieval demands accurate atmospheric correction (characterizing aerosol optical depth, surface pressure, and column water vapor), FLEX operates within a dedicated tandem mission architecture. Flying in close formation with ESA’s Sentinel-3 spacecraft, FLEX leverages the simultaneous observations of the Ocean and Land Colour Instrument (OLCI) and the Sea and Land Surface Temperature Radiometer (SLSTR). This synergistic observation concept allows FLEX to dedicate its payload optimization entirely to high-resolution SIF extraction while utilizing Sentinel-3 data for broad atmospheric and thermal surface characterization.

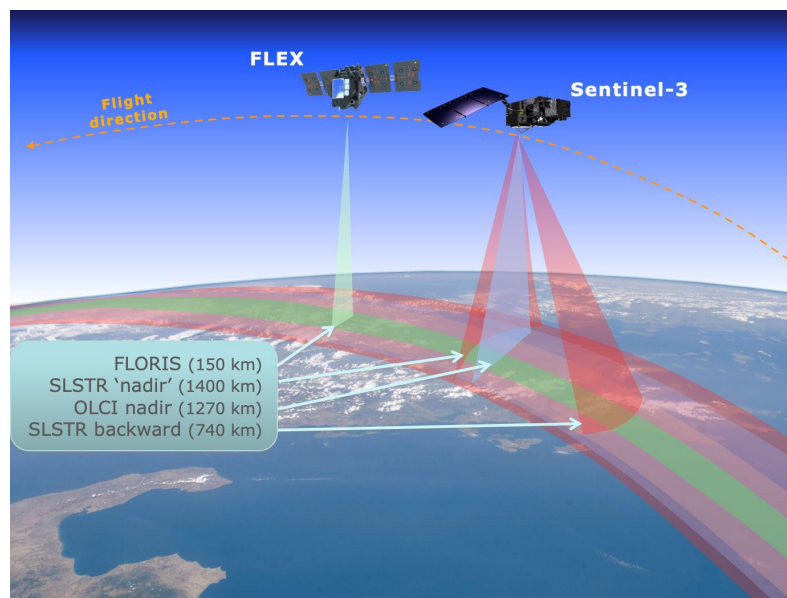


Figure 1. FLEX and Sentinel-3 tandem observation architecture.

Calibration Campaign

To verify that FLORIS meets its stringent pre-flight performance requirements under representative operational conditions, a comprehensive ground testing and calibration campaign was performed at the Centre Spatial de Liège (CSL). The campaign was designed to generate the calibration key data products required for Level-1 processing and to validate the optical performance of the proto-flight payload, including radiometric, spectral, geometric, polarimetric, straylight, detector, and Sun-port characterization.

This paper focuses on the calibration approach, the main optical ground support equipment, and the key performance results obtained during the CSL campaign. It also discusses the principal lessons learnt from the ground verification activities and outlines the transition from pre-flight calibration to the forthcoming in-orbit commissioning phase.

2. INSTRUMENT ARCHITECTURE

FLORIS Instrument Concept & Optical Design

The Fluorescence Imaging Spectrometer (FLORIS) is a compact, high-precision push-broom imaging spectrometer designed to observe a 150 km swath at a Ground Sampling Distance (GSD) of $300 \text{ m} \times 300 \text{ m}$ from an altitude of $\sim 815 \text{ km}$. To achieve high spectral resolution across specific target absorption bands without compromising the SNR over the broader spectral range, FLORIS employs a shared common fore-optics telescope feeding two optical channels through a double-slit assembly in the focal plane:

- **High-Resolution (HR) Spectrometer:** Dedicated to resolving narrow atmospheric absorption bands (O2-B at 686–697 nm and O2-A at 759–769 nm) with a fine spectral sampling ($\Delta\lambda < 0.1 \text{ nm}$) and resolving power required to extract SIF via Fraunhofer line infilling.
- **Low-Resolution (LR) Spectrometer:** Covering the continuous 500–780 nm spectral baseline at moderate resolution (0.5–2.0 nm) for broad surface reflectance characterization, Photochemical Reflectance Index (PRI) measurements, and atmospheric aerosol correction.

The telescope is a dioptric Petzval design with 5 lenses and both spectrometers are based on Offner design architecture with holographic diffraction gratings.

A dual Babinet scrambler is placed at entrance pupil position to reduce the polarization sensitivity of the instrument that is mainly driven by the two diffraction gratings.

The first optical element is a bandpass filter designed to allow only the nominal spectral range to enter the system and limit potential spectral straylight.

The optical layout is shown in Figure 2 and the instrument architecture with the different subsystems mounted on the optical bench are shown in Figure 3.

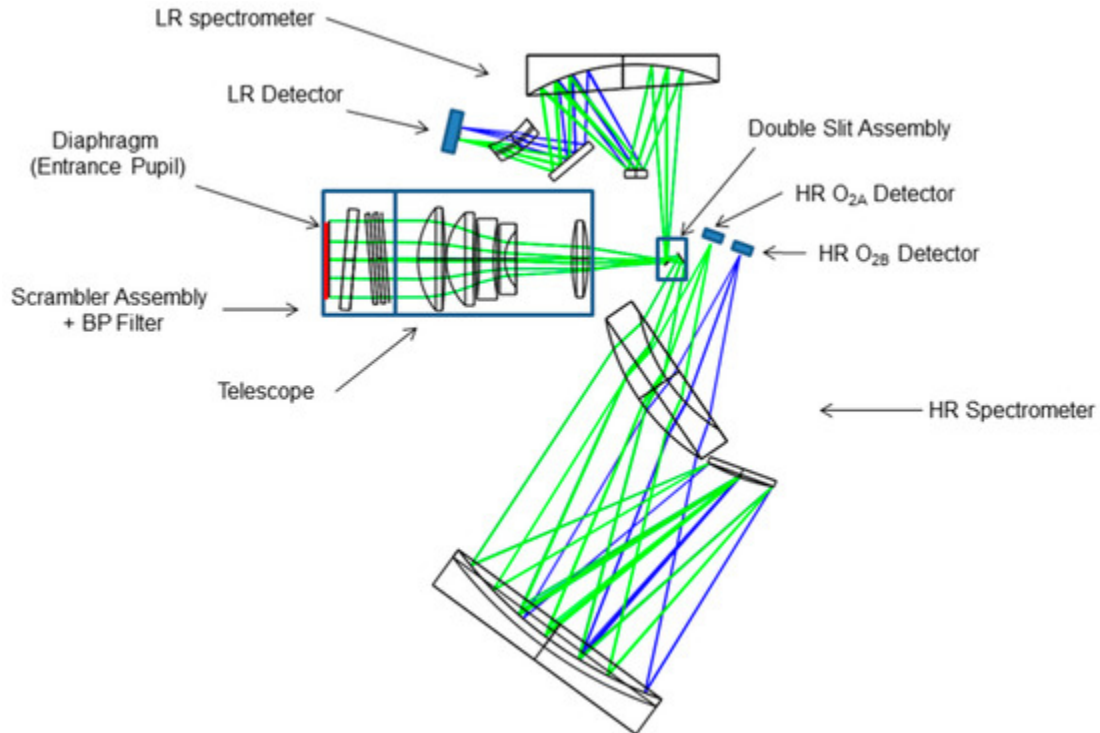


Figure 2. Optical layout showing in field separation between LR and HR spectrometers.

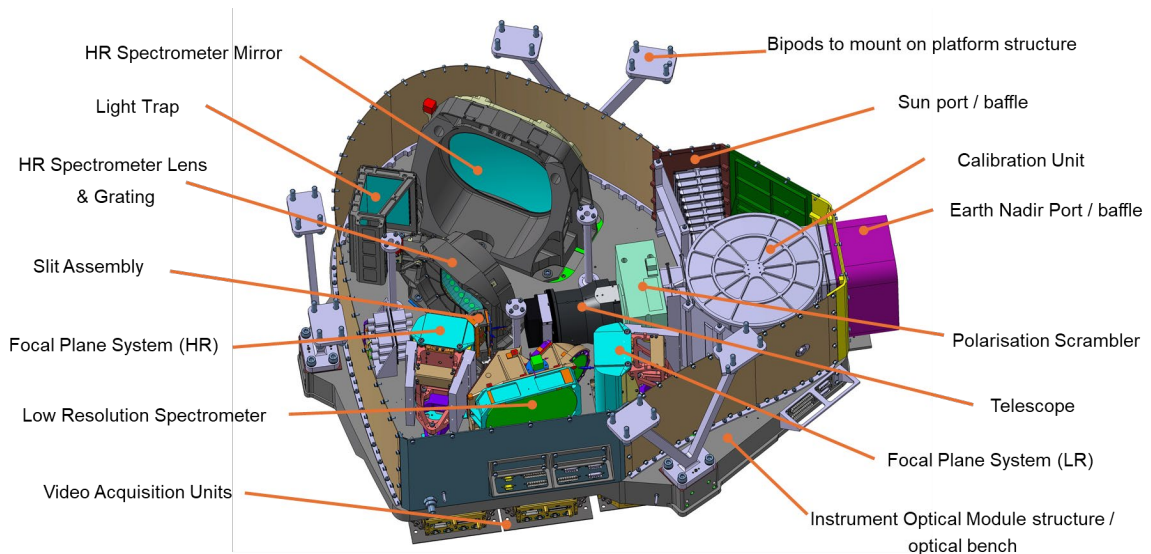


Figure 3. Instrument architecture and different subsystems.

The payload integrates an internal On-Board Calibration Unit (CU) equipped with a rotating carousel mechanism. The CU places a sun-illuminated Lambertian diffuser into the entrance beam for in-flight absolute radiometric drift tracking, alongside a dark cavity target for zero-level bias calibration.

The FLORIS payload was integrated by LDO (Italy) with contributions from 15 different European countries.

A detailed description of the instrument design can be found in [2,3].

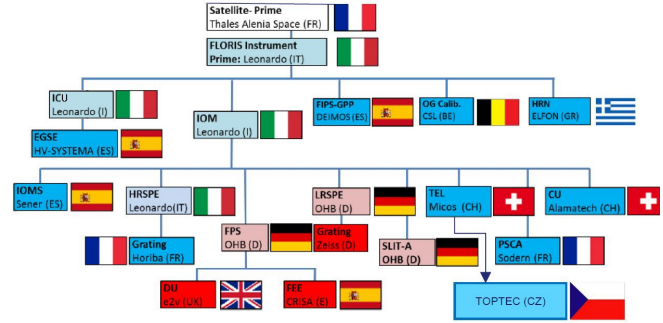
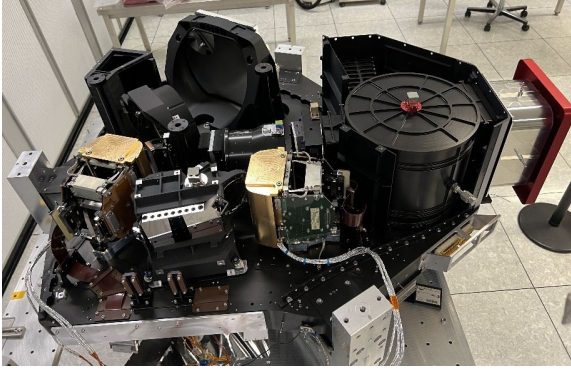


Figure 4. Instrument integrated before mounting the cover (left) and contribution from different European industries and institutes (right).

3. CALIBRATION AND TEST SETUP

TVAC facility at CSL

The FLORIS instrument underwent a comprehensive on-ground calibration campaign at the Centre Spatial de Liège (CSL) between January 2025 and June 2025. The objectives of the campaign were:

- to determine the calibration key data products (KDPs) required for in-flight processing and performance characterisation, including radiometric, spectral, geometric, straylight, detector, polarimetric and Sun-port calibrations
- to validate instrument performances already measured at subsystem level and partially measured by the instrument prime (OMR model).
- to complete the Instrument performances characterization, partially measured at subsystems and instrument prime levels due to test set-up limitations

Ground testing and optical characterization of the FLORIS Proto-Flight Model (PFM) were performed in the Focal-3 thermal-vacuum (TVAC) chamber. The chamber maintained a vacuum level $< 10^{-6}$ mbar with strict thermal boundary control, simulating orbital operational thermal ranges and operational gradient limits (+15°C to +25°C on the primary optical bench).

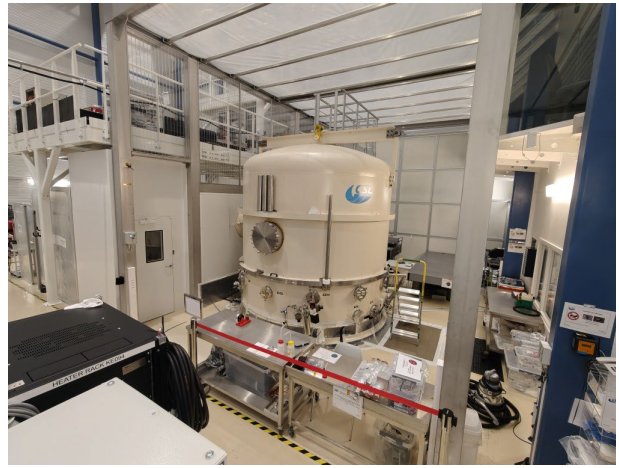


Figure 5. Focal-3 TVAC chamber at CSL. The left image shows an earlier TVAC configuration, but clearly showing the appendix used for the geometric collimator. The right image shows the current TVAC setup.



Figure 5. FLORIS instrument during the CSL calibration campaign.

Calibration setup

Two major facility configurations were used for calibration:

- CAL#1 for geometric, radiometric, spectral, detector and Sun-port measurements.
- CAL#2 for straylight calibration and characterisation using a dedicated low-straylight configuration and black tent environment.

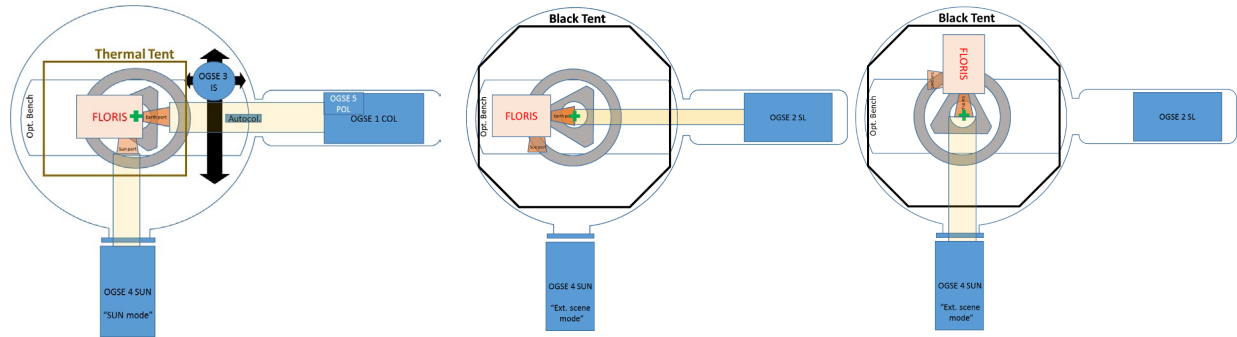


Figure 6. CAL#1 (left) and CAL#2 (center and right) layout schemes.

Several custom optical ground support equipments (OGSEs) were developed and fully validated before the calibration campaign.

During radiometric and spectral calibration in CAL#1 the instrument was mounted inside a thermal tent and a dedicated mechanical ground support equipment (MGSE) comprising a hexapod and a rotation stage was used to collect optical stimuli from a 300 mm diameter integrating sphere (IS) or a Sun simulator.

The integrating sphere was coupled to an external quartz-tungsten-halogen (QTH) source and high finesse tunable lasers to deliver narrow spectral lines across the instrument spectral range for precise mapping of the Instrument Spectral Response Function (ISRF).

During geometric calibration, the integrating sphere was moved outside the instrument field of view, and a geometric collimator based on a long-focal-length off-axis parabolic mirror was used to project slit patterns and pinholes to characterise spatial distortion (keystone), spectral distortion (smile), point spread functions (PSF), and channel co-registration. This setup was also used to measure the instrument polarisation sensitivity by means of a polariser in the focal plane of the geometric collimator.

The straylight OGSE consists of a straylight collimator, a set of vanes coated with Acktar, and a black tent. The design of this OGSE benefits from CSL heritage from several space missions, including Proba-V, SoloHI, and SCOPE [4,5]. The collimator is coupled to a high-power tunable laser to measure the straylight response at a given wavelength.

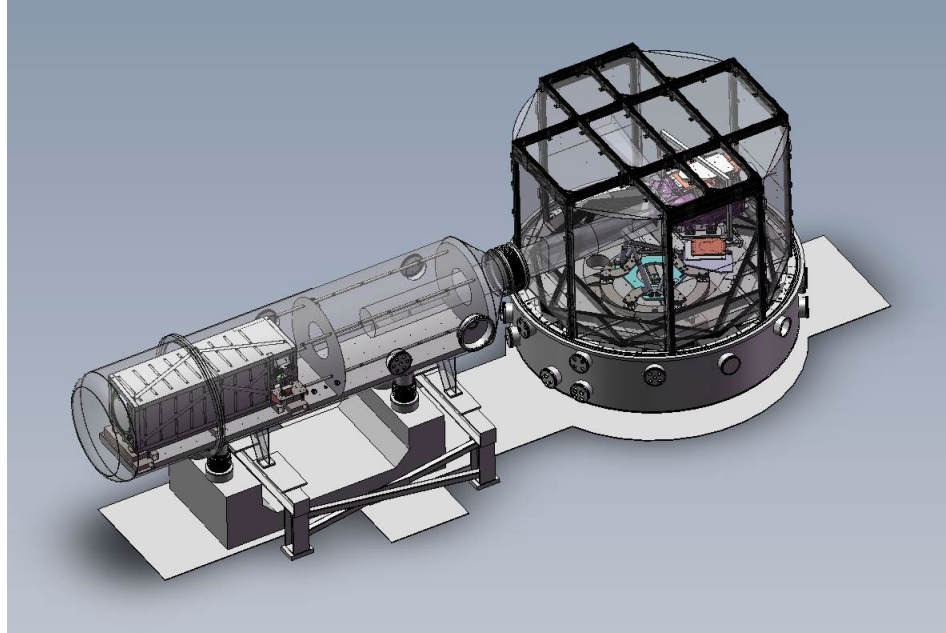


Figure 7. Straylight OGSE.

A typical challenge in straylight testing is to quantify and, if necessary, decouple the straylight introduced by the test setup. A dedicated time-of-flight (ToF) campaign was performed by CSL to quantify the straylight contribution of the calibration facility. The details of this method are reported in [6]. An analyser was placed on the hexapod instead of the FLORIS instrument, using a narrow-field lens with a temporally resolved detector, specifically a SPAD. The technique separated facility straylight from analyser artefacts, air scattering, and detector signatures through optical path discrimination. The results demonstrated that the residual facility straylight is much smaller than the instrument straylight and can therefore be considered negligible for FLEX straylight calibration.

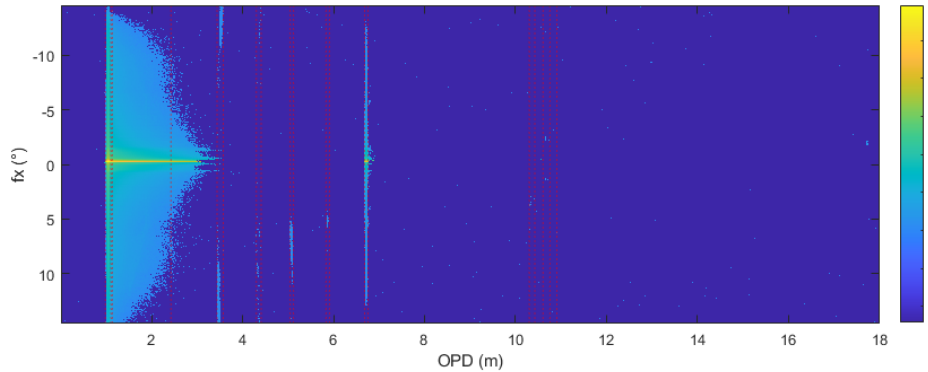


Figure 8. Results of ToF measurements. The bright line at around 7 meters from the sensor indicated a direct reflection from a vane that was not in the nominal position. This measurement helped to improve the setup.

3. GEOMETRIC, RADIOMETRIC & SPECTRAL CALIBRATION RESULTS

Geometric Calibration

Dedicated geometric collimators and autocollimators were used to characterise instrument line-of-sight, reference frames, field geometry and image location performance. Reference frame measurements were generated to support geolocation processing.

Radiometric Calibration

Measurements were performed using a calibrated integrating sphere, spectroradiometer monitoring system and dedicated irradiance and radiance references. The calibration produced:

- Absolute gain coefficients (ARG)
- Flat-field correction maps
- Detector non-linearity correction coefficients
- Polarisation sensitivity

Specialised monitoring enabled correction of the source stability, wavelength shifts and spectral response effects.

Absolute Radiometric Calibration (ARC) matrices were established by recording detector response over varying integration times across the operational dynamic range.

Dark signal non-uniformity (DSNU) and photo-response non-uniformity (PRNU) were extracted and decoupled.

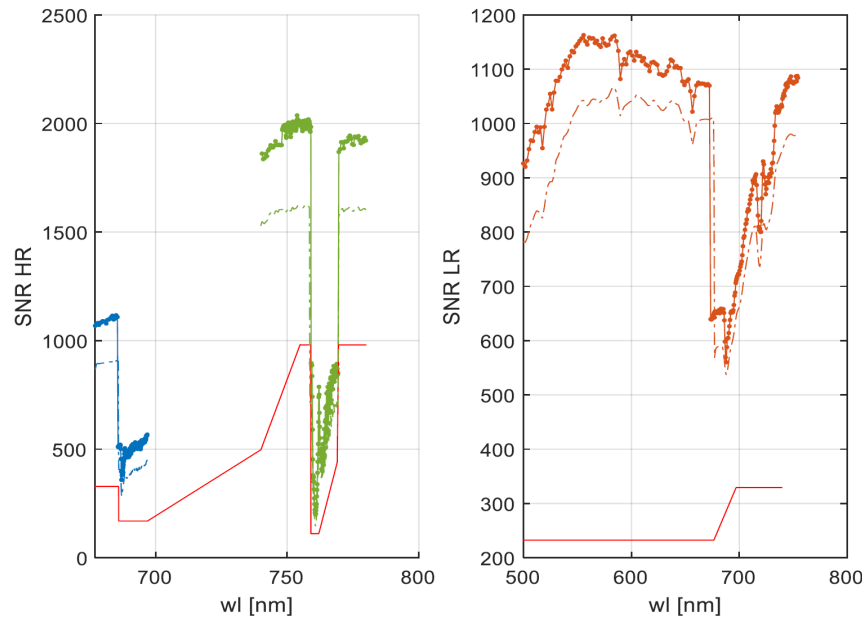


Figure 10. SNR results (bold point-dash curves) compared with SNR predictions (light point-dash curves) and requirements (continuous red templates).

The measurements confirmed that the SNR performance exceeds the baseline requirement of > 115 within the O2-A band absorption feature at 760 nm under reference nominal illumination. In these deep absorption troughs, detector gain settings and low read noise (< 15 e-) preserve the dynamic sensitivity required for SIF infilling extraction.

Regarding radiometric accuracy, uncalibrated residual errors were constrained to $< 2.1\%$ for absolute radiance measurements across both HR and LR channels, and relative pixel-to-pixel radiometric errors were reduced to $< 0.4\%$ after applying PRNU corrections. Although the radiometric calibration results through the nadir port were satisfactory, issues encountered with the SUN port measurements prevented the derivation of a reliable relationship between the nadir measurements and those obtained through the diffuser. Additional Sun observations through the SUN port will therefore be carried out during in-orbit commissioning to establish this link. This is captured among the lessons learned presented in the Conclusions section.

The instrument shows very good linearity overall; however, at very low signal levels, the residual non-linearity approaches 2%. A correction is therefore required to meet the post-calibration requirement of less than 1% residual non-linearity. One lesson learned from the FLEX calibration campaign is that the originally planned low-order polynomial correction is not always adequate.

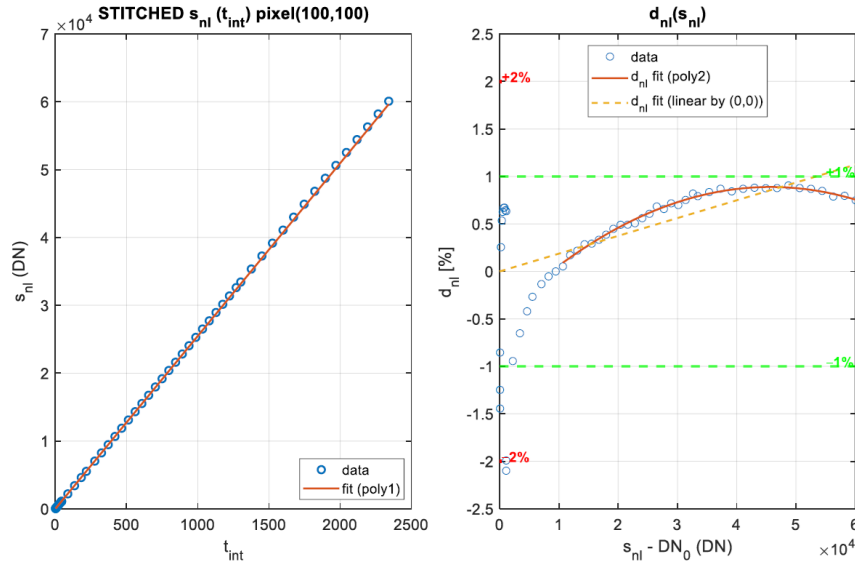


Figure 11. Linearity measurement (left) and non-linearity residual (right).

The measured instrument polarisation sensitivity is below 2% for the HR channels and 4% for the LR channel, in line with the performance expected from analysis.

Spectral Calibration

The extraction of SIF using solar line infilling relies on absolute spectral accuracy ($\Delta\lambda \leq 0.01$ nm) and precise characterization of the Instrument Spectral Response Function (ISRF) for all spectral samples.

Tunable laser scans at 0.005 nm steps resolved the core and wings of the ISRF. The spectral resolution was derived as full width at half maximum (FWHM) of the ISRF profile. The measured values of ~ 0.3 nm for O2-A and O2-B bands match the design values.

Thermal spectral stability was evaluated by introducing operational temperature fluctuations ($\pm 2^\circ\text{C}$ gradient shifts on the optical bench). The observed spectral drift was < 0.003 nm/ $^\circ\text{C}$, confirming high passive optomechanical stability in line with mission needs.

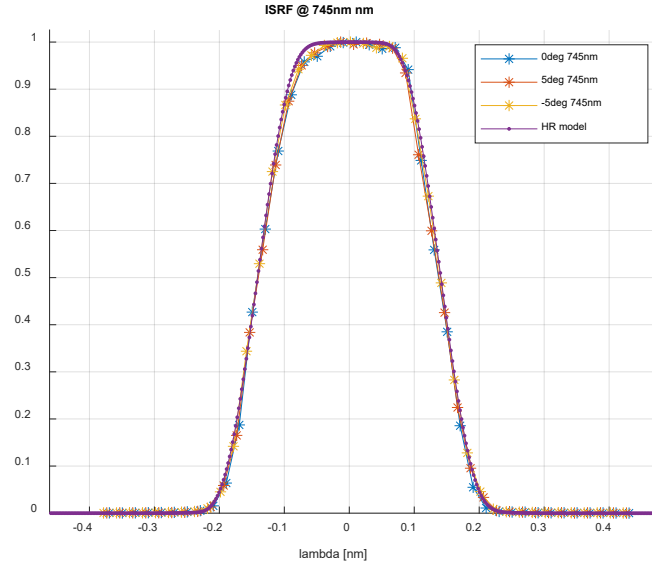


Figure 9. ISRF profile derived from laser monochromatic scans (dotted lines) compared with analytical model (continuous line).

Spatial and spectral co-registration

FLORIS was designed to minimize smile and keystone distortion. This low-distortion performance was preserved at instrument level through careful manufacturing and alignment of all subsystems.

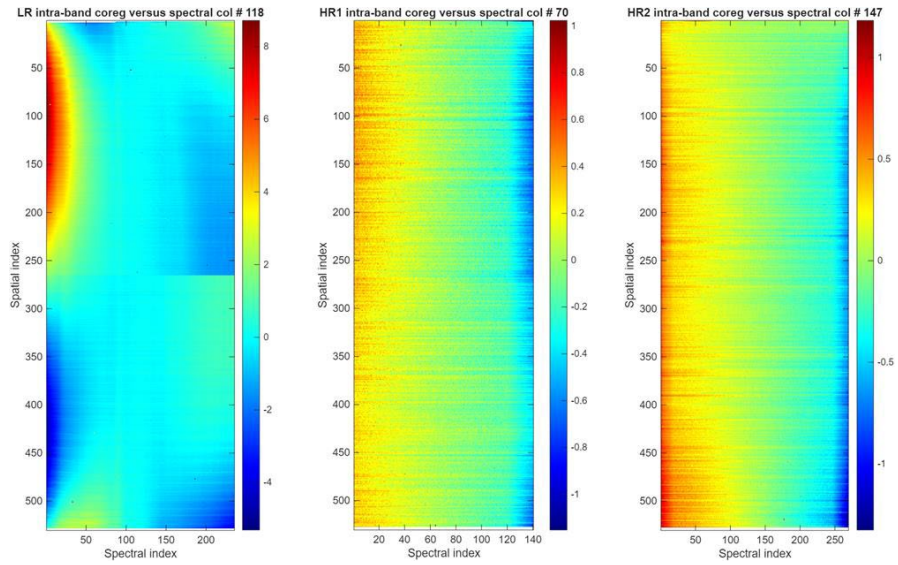


Figure 13. Spatial co-registration (keystone) for the LR and HR channels. The maximum co-registration error is 8 arcsec for LR and 1 arcsec for HR, compared with an angular sampling distance of 74 arcsec.

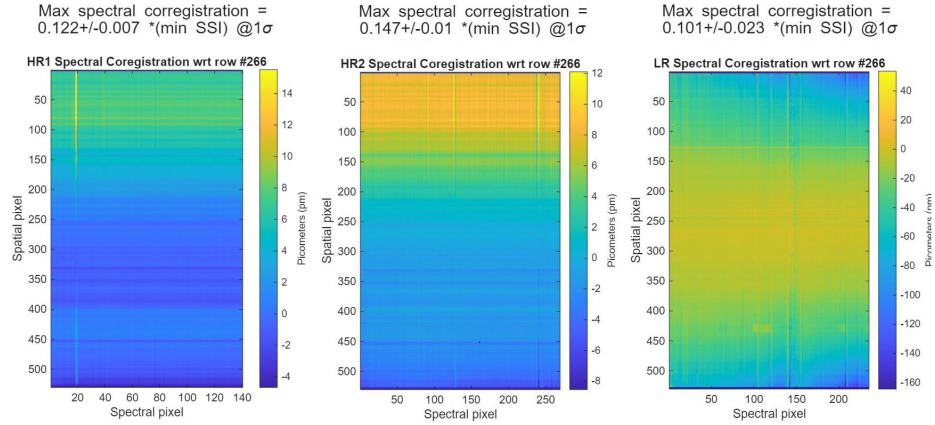


Figure 14. Spectral co-registration (smile) for the LR and HR channels. The measured values are in line with expectations and more than ten times better than the requirement.

Image quality

Instrument image quality was assessed using System Integrated Energy (SIE), which quantifies the fraction of energy contained within a specified focal-plane region while accounting for all image-quality degradations. The measurements confirmed compliance with the SIE requirements: greater than 0.7 within $1.2 \text{ SSD} \times 1.1 \text{ SSD}$ and greater than 0.9 within $1.6 \text{ SSD} \times 1.5 \text{ SSD}$. These results confirm the good optical quality of the instrument, consistent with earlier measurements at telescope and spectrometer level.

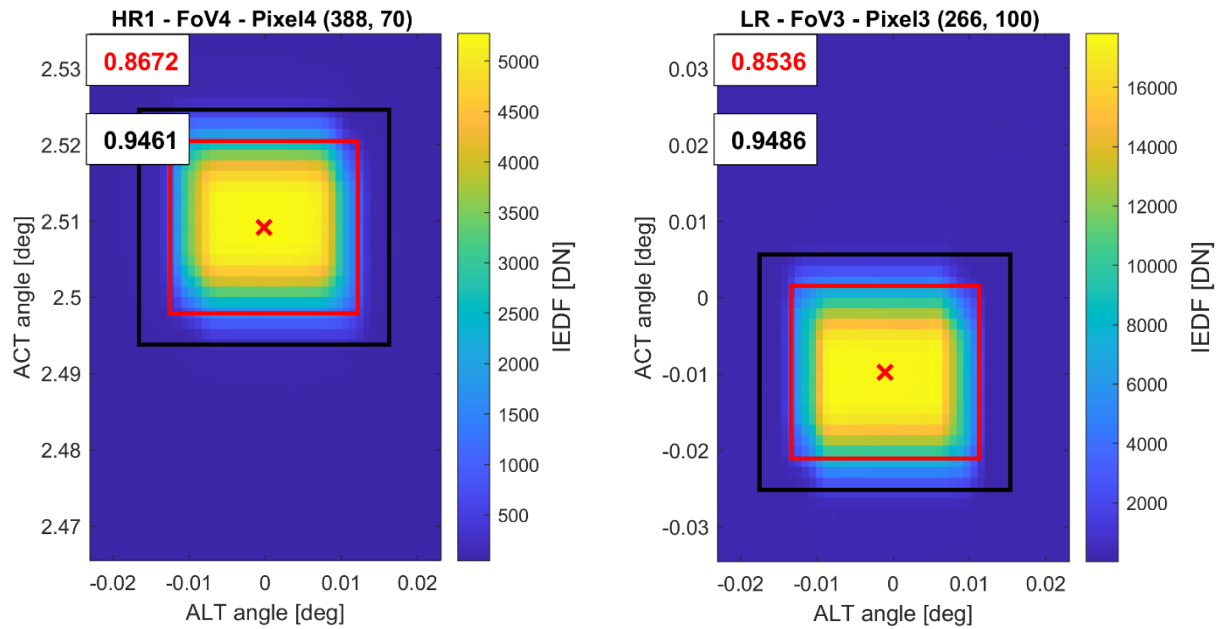


Figure 15. Two examples of SIE for HR (left) and LR (right).

Straylight results

A dedicated straylight campaign was conducted using monochromatic collimated sources in a specially optimised low-straylight environment. Measurements generated instrument straylight maps and correction data products for Level-1 processing.

Point-response straylight kernels were measured at several field positions and wavelengths, both inside and outside the nominal field of view and spectral range. These measurements were used to correlate the optical straylight model, which was then applied to generate straylight maps representative of extended scenes.

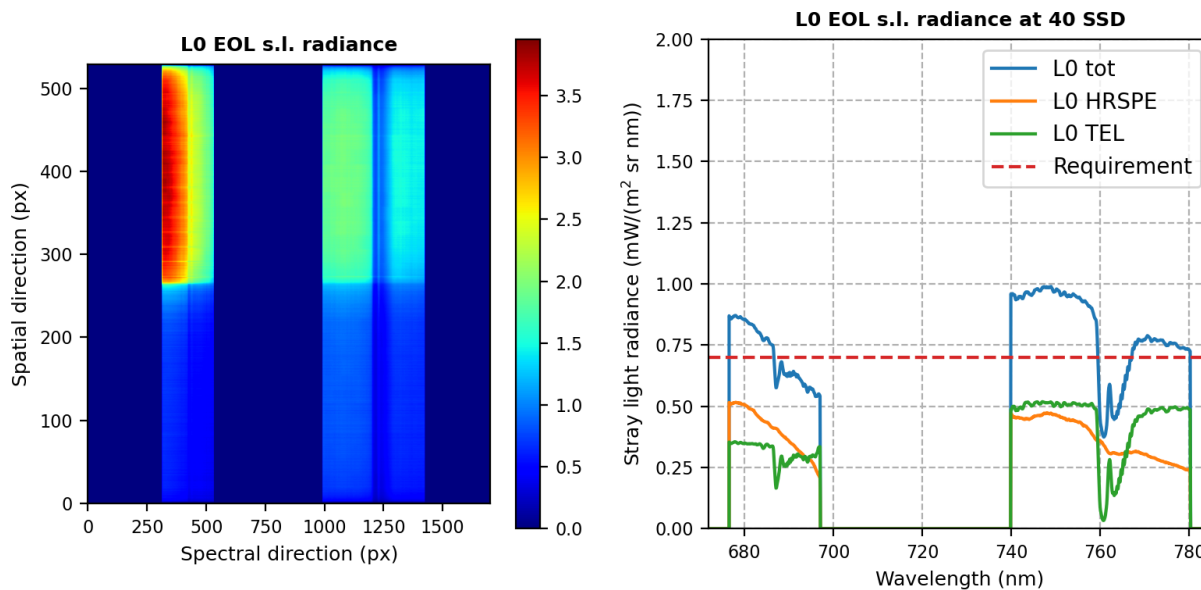


Figure 16. Level-0 straylight map for the high-contrast requirement scene (left). Straylight profile at 40 SSD from the transition zone (right).

Significant effort was devoted to minimising instrument straylight through dedicated hardware measures, including ultra-black coatings, super-polished optical surfaces, and carefully designed internal and external baffles. Despite these mitigations, the measured straylight exceeds the very stringent Level 0 requirement. The overall straylight level is moderately above the expected performance assessed with previous measurements on the engineering model and at subsystem level, because the straylight characterisation campaign at CSL identified new straylight paths that had not been found at Instrument Prime level (OMR), thereby improving the representativeness of the straylight model. A dedicated correction method based on a classical matrix deconvolution approach has therefore been implemented in the Level 1 processor to reduce the straylight contribution in the calibrated data products.

Although the correction method is highly effective, some straylight contributions cannot be fully isolated and corrected. Examples include potential changes due to additional contamination during satellite-level testing and the launch campaign, as well as straylight generated by bright clouds located outside the instrument field of view. As a result, the estimated residual straylight at Level 1 remains approximately a factor of two above the requirement.

The residual corrected straylight is expected to reduce the precision of the SIF retrieval, but it does not fundamentally compromise the quality or usability of the Level 2 fluorescence products.

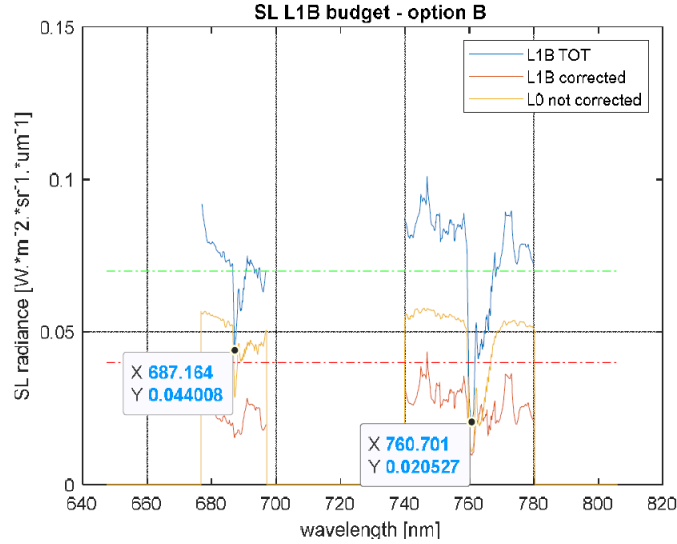


Figure 17. Straylight profile at 40 SSD from the transition zone after correction. The overall straylight level (blue curve) is the sum of the corrected straylight (red curve) and the straylight contributions that cannot be corrected, such as delta contamination and out-of-field straylight.

5. CONCLUSIONS, LESSONS LEARNT AND OUTLOOK

Summary of Ground Performance Verification

The comprehensive ground calibration campaign of the FLORIS instrument, performed at the Centre Spatial de Liège (CSL) and complemented by extensive data analysis, confirms that the optical payload satisfies the principal performance requirements for the ESA FLEX mission.

The measured straylight level is approximately a factor of two higher than the Level 0 specification and remains non-compliant at Level 1 after correction; however, the impact on fluorescence retrieval is limited. The increase is attributed to several effects, including improved measurement and processing, separation of blooming from straylight, additional straylight paths involving the slit assembly, inclusion of the polarisation scrambler, and better representativity of the flight configuration compared with the OMR model.

Lessons Learnt

The non-linearity error at Level 0 exceeds 1% for very small signals, and the planned low-order polynomial correction is not sufficient. A Ground Processing Prototype update is therefore required to implement the measured non-linearity correction without relying on an inadequate fit.

The SUN-port calibration sequence was affected by OGSE-related limitations. The illumination setup did not behave as expected, the radiometric computation of the output radiance required modification of the setup while the calibration campaign was already ongoing, and the high-power lamp used during the calibration failed during the measurement. Moreover, spectral characterization of the illumination was not available during the test itself, and the lamp-to-lamp spectral dispersion measured afterwards was not negligible. As a result, the SUN-port measurements require further consolidation before they can be used as a robust absolute reference for in-orbit calibration continuity. The main lesson learnt is that modifications to the test setup during an active calibration campaign should be avoided wherever possible. Under the strong schedule pressure typical of such campaigns, late changes increase the risk of implementation errors, incomplete verification, and insufficient time for proper validation. It is also risky to assume that any missing characterization of the test setup can be completed after the test campaign, since unexpected events, such as source degradation or lamp failure, may prevent the required measurements from being repeated under representative conditions.

Despite the extensive test campaign on the instrument engineering model (OMR), the straylight calibration campaign carried out at CSL revealed additional straylight contributions at a very late stage of the programme. This late

identification can be attributed to two main factors. First, due to programmatic constraints, including overall cost limitations and the late availability of some subsystems, the OMR was not fully representative of the flight instrument. Second, the CSL straylight test setup was specifically designed to measure very low straylight levels, with higher sensitivity than the earlier test configurations. The main lesson learnt is that a greater investment in the engineering-model representativeness and in the accuracy of the associated straylight test facility could have enabled an earlier and more reliable quantification of the actual straylight performance.

Assembly Status and Launch Preparation

Following the CSL campaign, satellite activities progressed seamlessly. Payload integration onto the spacecraft bus was completed at Thales Alenia Space in July 2025. The fully assembled 400 kg spacecraft subsequently completed its environmental test campaign in April 2026, including acoustic, sine, TVAC, and EMC tests at the TASF site, confirming its launch readiness.

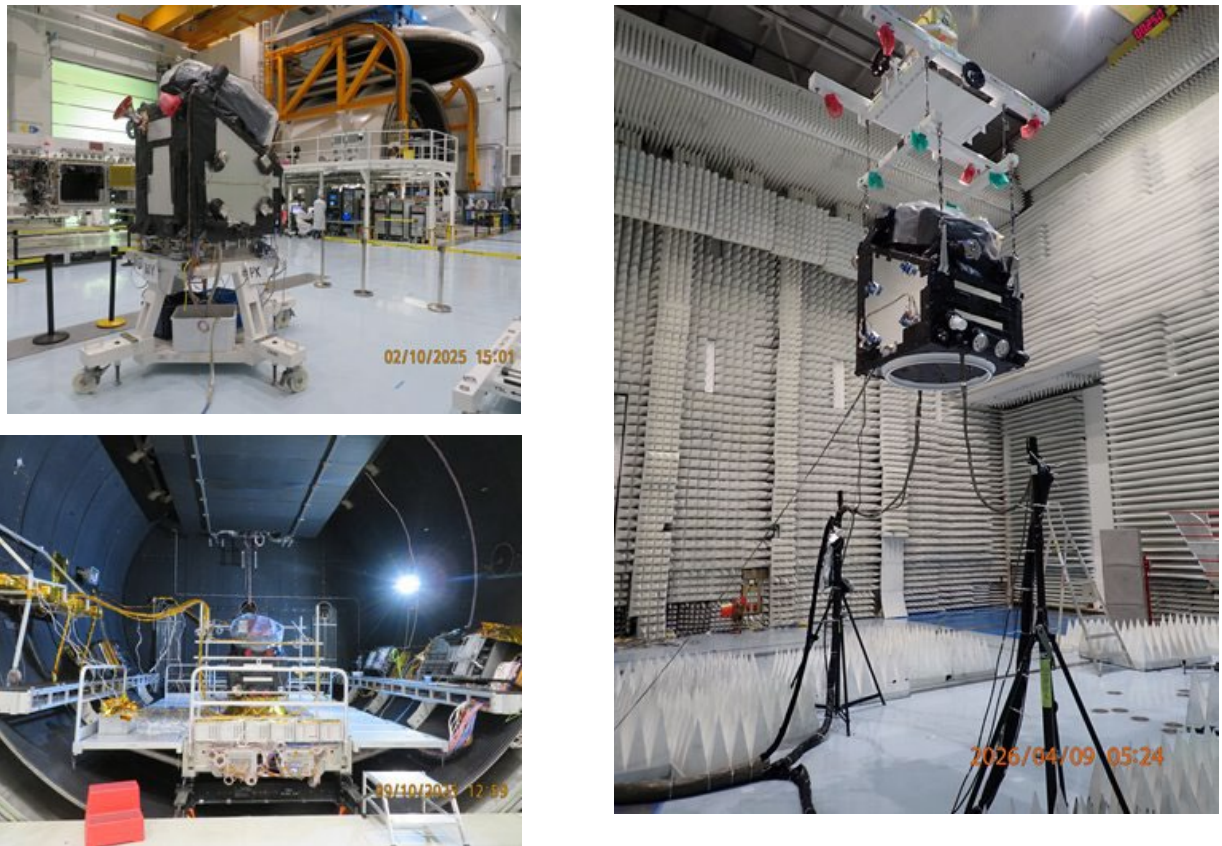


Figure 18. Satellite integration and tests.



Figure 19. A new Odyssey: from the cold of the Belgian winter calibration campaign to French Guiana, with FLORIS arriving in Kourou in July 2026.

Orbital Operations and In-Orbit Commissioning Plan

FLEX is scheduled for launch in September 2026 from Kourou, French Guiana, as a secondary payload on a Vega launcher. Following orbital injection, the spacecraft will execute a sequence of orbital manoeuvres to enter its designated sun-synchronous tandem orbit, maintaining a tight along-track formation with Sentinel-3A to ensure near-simultaneous surface observations.

During the initial 3-month commissioning phase, FLORIS will execute dedicated in-orbit calibration sequences targeting:

1. Solar Calibration: Using the onboard solar diffuser assembly to track absolute radiometric drift and gain stability.
2. Lunar radiometric assessment: Executing pitch maneuvers to acquire spatial and radiometric reference profiles of the moon.
3. Deep Convective Cloud acquisitions: using a reduced integration time to avoid saturation and perform a radiometric assessment.
4. Deep Space and Dark Ocean Operations: Establishing zero-level offset baselines and straylight residual background levels.
5. Spectral characterisation using solar and telluric absorption lines observed through the Sun diffuser and during nominal Earth-observation acquisitions.
6. Geometric calibration using ground control points.

These activities lead directly to the In-Orbit Commissioning Review (IOCR), planned for early 2027. Once operational, the FLEX/FLORIS mission will deliver global, high-precision SIF datasets, marking a significant advance in optical remote sensing of ecosystem productivity and global carbon-cycle dynamics.

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