

On-Ground Calibration and Performance Characterization of ELOIS, a Compact Hyperspectral Imager for Small Satellite Earth Observation

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ABSTRACT

ELOIS (Enhanced Light Offner Imaging Spectrometer) is a compact, high-performance VNIR/SWIR push-broom hyperspectral imager developed by AMOS under an ESA GSTP In-Orbit Demonstration (IOD) programme. Combined with the flight-proven InnoSat platform from OHB Sweden, the mission targets a broad range of Earth observation applications, from agriculture monitoring and vegetation mapping to land cover classification and water management, delivering hyperspectral data from a small satellite platform. ELOIS covers the 400-2450 nm spectral range at 10 nm resolution with a 35 m GSD and 70 km swath using two co-aligned VNIR and SWIR detectors. The payload targets a 630 km LEO Sun-synchronous orbit with a five-year lifetime. Its high radiometric and SNR performance results from the combination of freeform optics, a high-precision slit, and a multi-blazed diffraction grating, unified through a patented optical design into a compact, all-aluminium instrument. This paper presents the on-ground calibration and performance characterization of the ELOIS instrument, conducted at the Centre Spatial de Liège (CSL) TVAC facility by the AMOS team, using a dedicated collimation OGSE provided by CSL. The characterization followed a two-phase approach. First, an ambient test campaign covered image quality and spectral performance, serving as the reference baseline. Second, tests were performed in a thermal vacuum chamber under conditions representative of in-flight operations, repeated across multiple operational thermal cases. Radiometric calibration was also performed, addressing bad pixels, dark current and its non-uniformity, photo-response non-uniformity (PRNU), and flat-field correction. Spectral calibration demonstrated stability across thermal plateaus, confirming the robustness of the optical design under operational conditions. The resulting pre-flight performance characterization and on-ground calibration confirm that the ELOIS payload is ready to realize its Earth observation mission from orbit.

Keywords: hyperspectral imaging, push-broom spectrometer, VNIR/SWIR, on-ground calibration, thermal vacuum testing, Earth observation, small satellite, MTF

1. INTRODUCTION

Hyperspectral Earth observation from small satellite platforms is expanding rapidly, driven by demand for frequent, high-quality spectral data in agriculture monitoring, vegetation mapping, land cover classification, and water management. ELOIS (Enhanced Light Offner Imaging Spectrometer) is a compact, high-performance VNIR/SWIR push-broom hyperspectral imager developed by AMOS under an ESA GSTP In-Orbit Demonstration (IOD) programme. Combined with the flight-proven InnoSat platform from OHB Sweden, the ELOIS mission targets a Sun-synchronous low Earth orbit at 630 km altitude, with a five-year operational lifetime.

ELOIS covers the 400-2450 nm spectral range at a 10 nm spectral resolution, using two co-aligned VNIR and SWIR detectors. The VNIR channel provides a 35 m ground sampling distance (GSD) with a 15.5 μm pixel size, while the SWIR channel provides a 70 m GSD with a 30 μm pixel size. Both channels share a common 70 km swath.

The VNIR detector natively samples the spectrum at 2.5 nm per spectral pixel (unbinned mode). In nominal flight operation, every four consecutive spectral pixels are binned together on-chip to increase the signal-to-noise ratio, giving an effective spectral sampling of 10 nm (binned mode).

The instrument follows a push-broom configuration built around a modified Offner-Chrisp spectrometer design. It consists of three main subsystems: a front-end three-mirror anastigmat (TMA) telescope, whose focal plane contains the input slit of the spectrometer; an imaging spectrometer based on an advanced Offner layout incorporating a multi-blazed, freeform diffraction grating; and a focal plane assembly combining a dichroic beam splitter with separate VNIR and SWIR detectors. The telescope operates at $f/3.6$, and an intrinsic demagnification of $M = 0.6$ within the spectrometer relaxes the telescope design constraints while allowing the spectrometer to operate at $f/2.1$, one of the fastest of its type. To achieve high diffraction efficiency across the full 400-2450 nm range, the grating uses a dual-blaze profile, with light diffracted into order $m = -2$ used for the VNIR channel and order $m = -1$ for the SWIR channel. All optical components, with the exception of the beam-splitter plates, are made of aluminium, giving the instrument an all-aluminium, intrinsically athermal optical design.

The main driving payload requirements are summarized in Table 1.

Table 1. Main ELOIS payload key performance requirements at reference altitude.

Parameter	HS VNIR	HS SWIR
Spectral range	400-900 nm	970-2450 nm
Ground sampling distance	35 m	70 m
Swath width	70 km	70 km
Spectral sampling	10 nm (2.5 nm asynchronous mode)	10 nm
Spectral FWHM	< 12 nm (< 3 nm asynchronous mode)	< 12 nm
Spectral co-registration (smile)	1 nm	1 nm
Inter-band co-registration (keystone)	0.49 SSD	0.43 SSD
MTF at Nyquist	> 0.3	> 0.3

This paper presents the on-ground calibration and performance characterization of the ELOIS instrument, conducted at the Centre Spatial de Liège (CSL) thermal-vacuum facility by the AMOS team, using a dedicated collimation optical ground support equipment (OGSE) provided by CSL. The characterization followed a two-phase approach: an ambient test campaign, covering image quality, and spectral performance served as the reference baseline; a subsequent thermal-vacuum campaign, conducted under conditions representative of in-flight operation and repeated across multiple thermal plateaus, addressed image quality and spectral performance under operational conditions. Section 2 describes the test setup and methodology. Section 3 reports the measured image quality, spectral registration, and spectral response function of the VNIR and SWIR channels. Section 4 concludes on the overall pre-flight characterization status of the ELOIS payload.

2. TEST SETUP AND METHODOLOGY

The on-ground calibration and performance characterization of the ELOIS instrument was carried out at the Centre Spatial de Liège (CSL), using the FOCAL2 thermal-vacuum facility and a dedicated collimation optical ground support equipment (OGSE) supplied by CSL.

2.1 CSL collimation OGSE

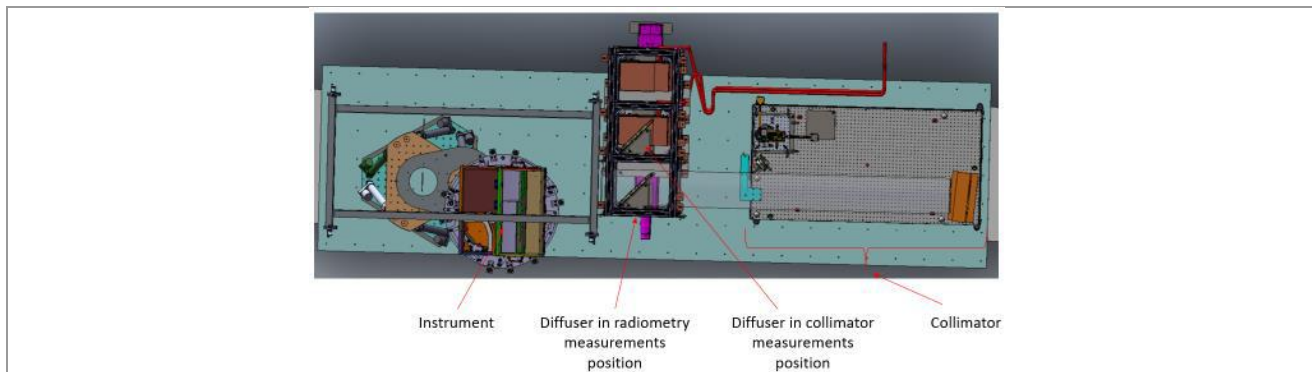


Figure 1. Schematic view from top of the OGSE (right) in front of ELOIS instrument (left) inside the vacuum chamber.

The OGSE comprises two main assemblies: a collimator and a diffuser.

The collimator consists of interchangeable light sources feeding a monochromator for wavelength selection, a rotating linear polarizer, a movable pattern plate carrying the test targets at the collimator focal plane, a fold mirror, and an off-axis parabolic mirror collimating the beam towards the ELOIS entrance pupil. It is used to generate a collimated image of the test patterns for image quality (MTF, keystone), spectral registration, spectral response function, and polarization sensitivity measurements. The pattern plate carries several target patterns, including horizontal and vertical slits for image quality and line-of-sight measurements, a keystone slit pattern, and dedicated straylight targets, mounted on two translation stages for precise positioning in the collimator focal plane.

The diffuser consists of a diffuser plate illuminated by an array of halogen lamps, mounted on a translation stage that moves it between a position in front of the instrument, providing uniform extended-source illumination for radiometric and flat-field calibration, and a retracted position, allowing the collimated beam from the collimator to reach the instrument unobstructed for the other tests.

The ELOIS instrument is mounted on a hexapod whose center of rotation is located at the instrument entrance pupil, allowing the field of view to be scanned by small rotations of the instrument with respect to the fixed collimated beam.

2.2 Two-phase test approach

The characterization campaign followed a two-phase approach. An ambient test campaign was first conducted at CSL, covering image quality, spectral performance, and polarization sensitivity; these ambient results served as the reference baseline for the instrument's on-ground performance. A subsequent thermal-vacuum campaign was then performed in the FOCAL2 chamber, under pressure levels below 10^{-5} mbar, reproducing conditions representative of in-flight operation. Image quality and spectral performance were characterized at several thermal calibration plateaus spanning the expected operational temperature range of the instrument, in addition to dedicated operational thermal plateaus used for functional and thermal-cycling verification.

2.3 Measurement principle

Image quality (MTF and keystone). A narrow slit target, oriented orthogonal to the spectrometer entrance slit, is placed at the OGSE collimator focal plane and illuminated with a polychromatic white-light source. The collimator projects the target onto the ELOIS entrance slit; the grating disperses the polychromatic light across wavelength, so the target's image is spread over the full spectral direction on the detector, while its orthogonal orientation confines it spatially, along the across-track direction. Using the hexapod, the instrument is moved to bring the target image successively to several positions along the across-track (ACT) field of view.

For the MTF, the target is scanned in small sub-pixel steps across the ACT direction at each field-of-view position. The resulting spatial PSF, built from the detector irradiance as a function of scan position, is used to compute the MTF, corrected for the finite width of the scanning slit and the detector pixel size. The OGSE collimator's own MTF contribution, measured separately, can be subtracted from this result to isolate the MTF of the instrument alone.

For the keystone, the spatial (across-track) centroid position of the target's image is extracted from the same acquisitions, grouping successive blocks of detector spectral lines, and tracked as a function of wavelength at each field-of-view position. The keystone is the maximum deviation of this centroid position from its median value, across all wavelengths, expressed as a fraction of a pixel (SSD).

Spectral characterization (registration, spectral response function, smile). A slit target is placed at the OGSE collimator focal plane and illuminated in turn by a series of near-monochromatic wavelengths generated by a monochromator, stepped across the spectral range of interest, at several field-of-view positions. This yields a three-dimensional spectral response matrix, indexed by detector line, detector row, and illumination wavelength.

For each detector pixel, the central wavelength is derived from a Gaussian fit of its response across the wavelength scan, giving the wavelength registration matrix. The spectral dispersion (in nm/pixel) and its linearity follow from a linear regression of central wavelength against detector row; the spectral smile is the deviation of the central wavelength of a

given spectral line across field-of-view positions. The spectral response function itself is obtained from the FWHM of each pixel's response across the wavelength scan, corrected for the finite bandwidth of the monochromator, the width of the input slit image, and the detector pixel size, to isolate the spectral response of the instrument alone.

Full details of each test setup, acquisition parameters, and success criteria are given together with the corresponding results in Section 3.

3. RESULTS

3.1 Image quality (MTF)

The modulation transfer function (MTF) was measured under vacuum using the method described in Section 2.3: a narrow slit target is scanned across the field of view, and the resulting line spread function is used to compute the MTF at the detector Nyquist frequency (32 lines/mm for VNIR, 17 lines/mm for SWIR), after correction for the scanning slit width and the detector pixel size.

VNIR channel. MTF was characterized at several instrument temperature plateaus under vacuum. Results are reported here at two of these plateaus: a temperature of -1°C and a temperature of 21°C. Table 2 summarizes the minimum and maximum MTF values measured across the field of view at each plateau, together with the corresponding instrument-only MTF obtained after subtracting the collimator's own MTF contribution (estimated between its lowest value, at 900 nm, and its highest value, at 400 nm).

Table 2. VNIR MTF results at two instrument temperature plateaus under vacuum.

Parameter	-1°C (as-built)	21°C (as-built)
FoV positions characterized	5	5
Min. instrument MTF	0.271	0.320
Max. instrument MTF	0.468	0.494

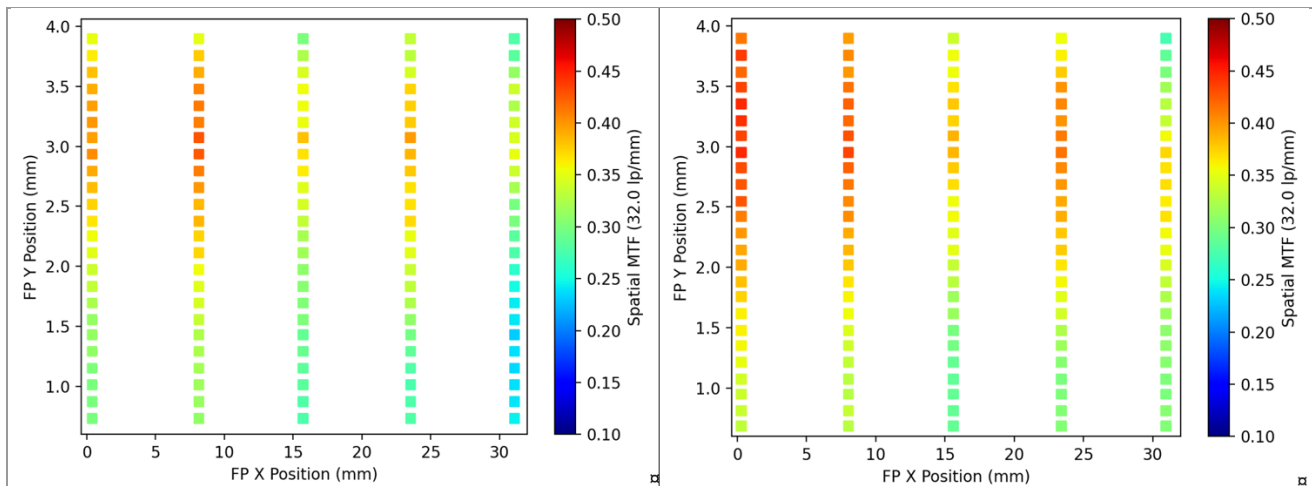


Figure 2. MTF results for ELOIS instrument including the MTF contribution of the collimator, -1°C (left) and +21°C (right) temperature plateaus.

The measured MTF at both plateaus is globally in line with the > 0.3 requirement. In operational conditions, the instrument temperature is expected to remain above +5°C, ensuring optimal VNIR image quality.

SWIR channel. The SWIR MTF was measured at the -1°C plateau, at 5 positions along the field of view. The resulting MTF distribution has a minimum value of 0.19 and a maximum value of 0.42.

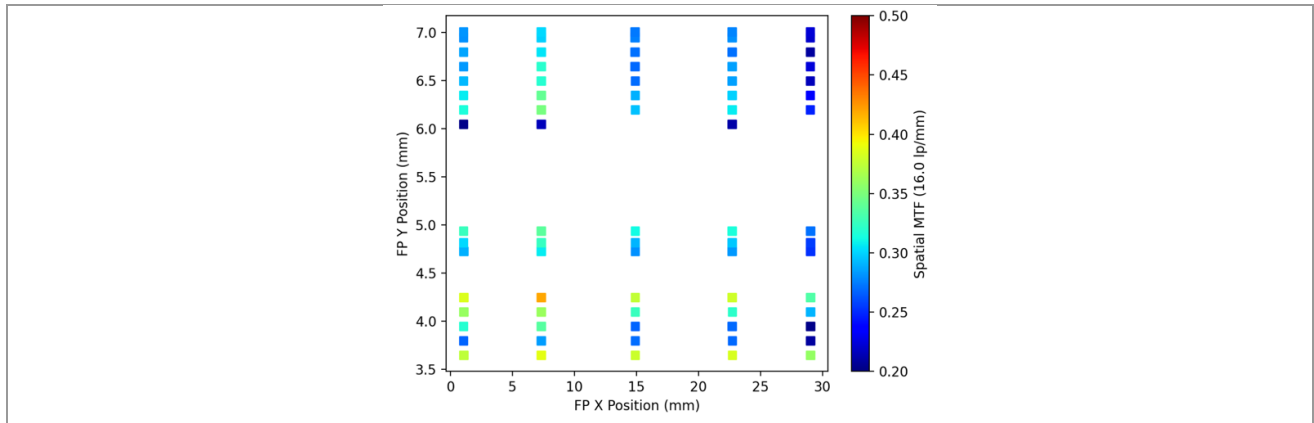


Figure 3. Distribution of the spatial MTF as a function of the pixel position on SWIR detector, including the MTF contribution of the collimator, for an as-built instrument temperature of -1°C .

3.2 Keystone

Keystone quantifies the spatial misregistration between corresponding spectral pixels across the spectral range, i.e. the shift, on the detector, of the image of a fixed scene point as a function of wavelength. It was derived from the same slit-scan acquisitions used for the MTF measurements (Section 3.1), and expressed as a fraction of the spatial sampling distance (SSD).

In nominal imaging mode, the applicable specification requires the spatial misregistration between all corresponding spectral pixels to be smaller than 0.49 SSD for the VNIR channel and 0.43 SSD for the SWIR channel, when calibration is performed over the complete spectral band. If calibration is instead performed independently on sub-sets of spectral bands, the same specification allows the spectral range to be split into up to 4 sub-sets (or up to 3 for the SWIR channel, since the VNIR and SWIR sensors use different calibration files), each of which must individually meet a tighter keystone requirement, down to 0.2 SSD per sub-set at Level 0. This sub-banding approach is expected to be used to improve the spatial co-registration of the hyperspectral images.

VNIR channel. Across both plateaus, the VNIR keystone reaches up to about 0.9 SSD at the extreme field-of-view positions. Table 3 summarizes the resulting keystone range at each plateau.

Table 3. VNIR keystone results at two instrument temperature plateaus under vacuum.

Parameter	-1°C	21°C
FoV positions characterized	5	5
Min. keystone	0.29 SSD	0.07 SSD
Max. keystone	0.91 SSD	0.95 SSD

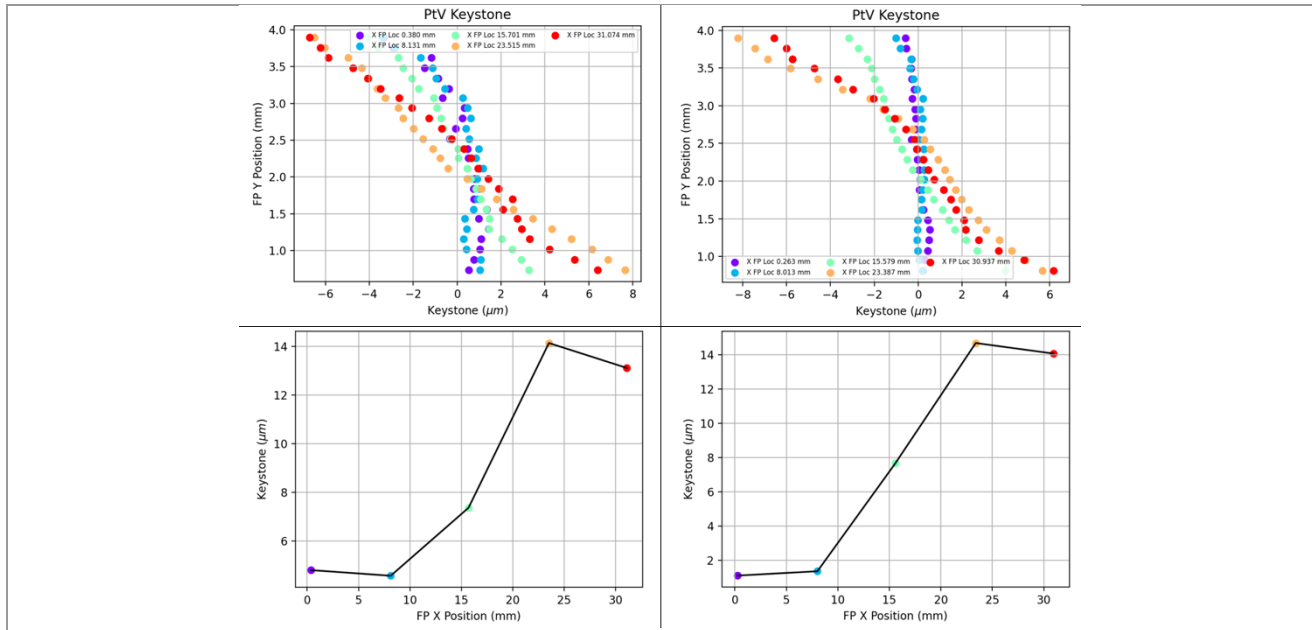


Figure 4. VNIR keystone results for 2 as-built temperature plateaus, -1°C (left) and +21°C (right). Top panels represent the spectral dimension (FP Y position in mm) as a function of the keystone in μm . Ideally, each series of points should be vertical and centered on a keystone of 0. Bottom panels represent the keystone as a function of the spatial dimension (FP X position in mm).

SWIR channel. Keystone was also characterized for the SWIR channel, at the -1°C plateau, at 5 positions along the field of view. Table 4 summarizes the resulting keystone range.

Table 4. SWIR keystone results at the -1°C plateau, at best focus.

Parameter	-1°C (as-built), best focus
FoV positions characterized	5
Min. keystone	0.17 SSD
Max. keystone	0.65 SSD

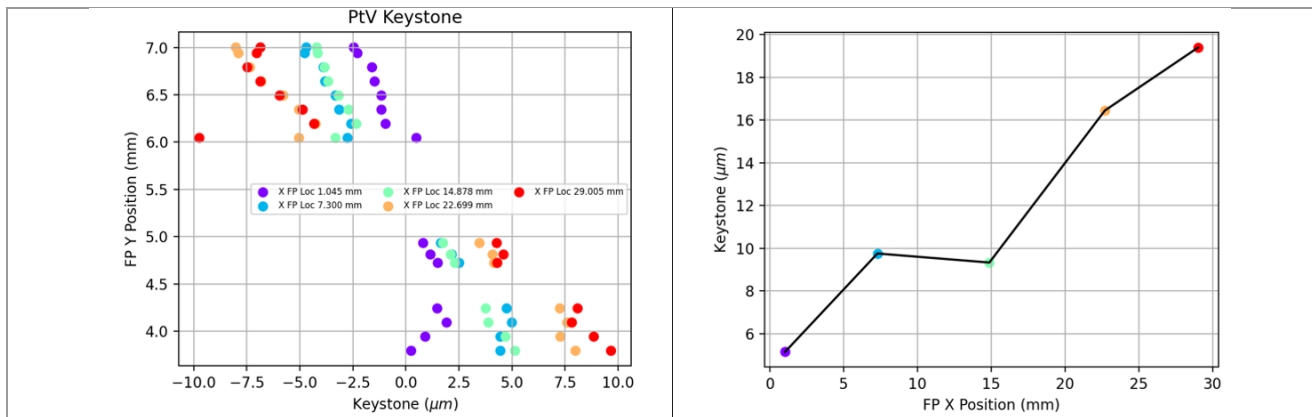


Figure 5. SWIR keystone, at -1°C temperature plateau. Left panel: Spectral dimension (FP Y position in mm) as a function of the keystone in μm . Right panel: Keystone in μm as a function of spatial dimension of the FoV.

The measured SWIR keystone ranges from 0.17 to 0.65 SSD across the field of view, against a requirement of 0.43 SSD; 3 of the 5 tested field-of-view positions are compliant with this requirement.

3.3 Spectral registration (VNIR)

Spectral registration was characterized under vacuum at two instrument temperature plateaus, with as-built temperatures of -1°C and $+8^{\circ}\text{C}$. At each plateau, a three-dimensional spectral response matrix was acquired using a monochromator scanning the VNIR spectral range, from which the central wavelength registered by each detector pixel, the spectral sampling interval (SSI), and the spectral smile were derived, following the method described in Section 2.3.

Unbinned mode. Results are available at both the -1°C and $+8^{\circ}\text{C}$ plateaus. The deviation from linearity of the wavelength registration is below ± 0.4 nm at both plateaus. The spectral dispersion is uniform across the field of view, with a variation between field-of-view positions smaller than one tenth of a spectral pixel, and an average SSI of 2.5 nm/pixel is reached at both plateaus. The spectral smile is below 1.5 nm over 80% of the VNIR spectral range at both plateaus, showing no significant dependence on instrument temperature.

Binned mode. Results are only available at the $+8^{\circ}\text{C}$ plateau. The deviation from linearity of the wavelength registration is below ± 0.5 nm. The spectral dispersion remains uniform across the field of view, with an average SSI of 2.5 nm/pixel. The spectral smile is below 1.5 nm over 90% of the VNIR spectral range.

Table 5. VNIR spectral registration results at the -1°C and $+8^{\circ}\text{C}$ as-built temperature plateaus.

Parameter	Unbinned, -1°C	Unbinned, $+8^{\circ}\text{C}$	Binned, $+8^{\circ}\text{C}$
Registration linearity deviation	$< \pm 0.4$ nm	$< \pm 0.4$ nm	$< \pm 0.5$ nm
Spectral sampling interval (SSI)	2.5 nm/pixel	2.5 nm/pixel	10 nm/pixel
Spectral smile	< 1.5 nm over 80% of VNIR range	< 1.5 nm over 80% of VNIR range	< 1.5 nm over 90% of VNIR range

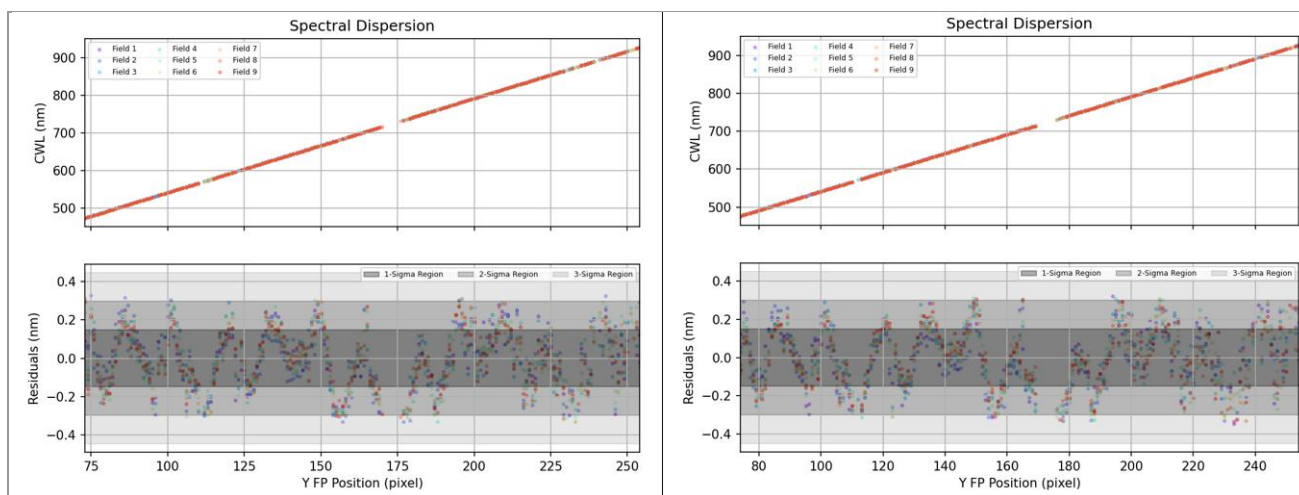


Figure 6. VNIR unbinned mode. Top panels: Central wavelength as a function of the Y position of the detector (spectral dimension). Colors stand for the different points of the FoV. All these points are superimposed on one another, so that the main colors come from the last field traced (#9 for both temperature plateaus at -1°C on left panel and $+8^{\circ}\text{C}$ on right panel). At first glance, the linearity between the central wavelength is good. This is confirmed by the residuals plotted in the bottom panel. The holes in the CWL lines come from bad raw data (pixels saturation) Bottom panel: Residuals showing the difference between observed data and linearly regular predicted data showing a deviation from linearity smaller than ± 0.4 nm.

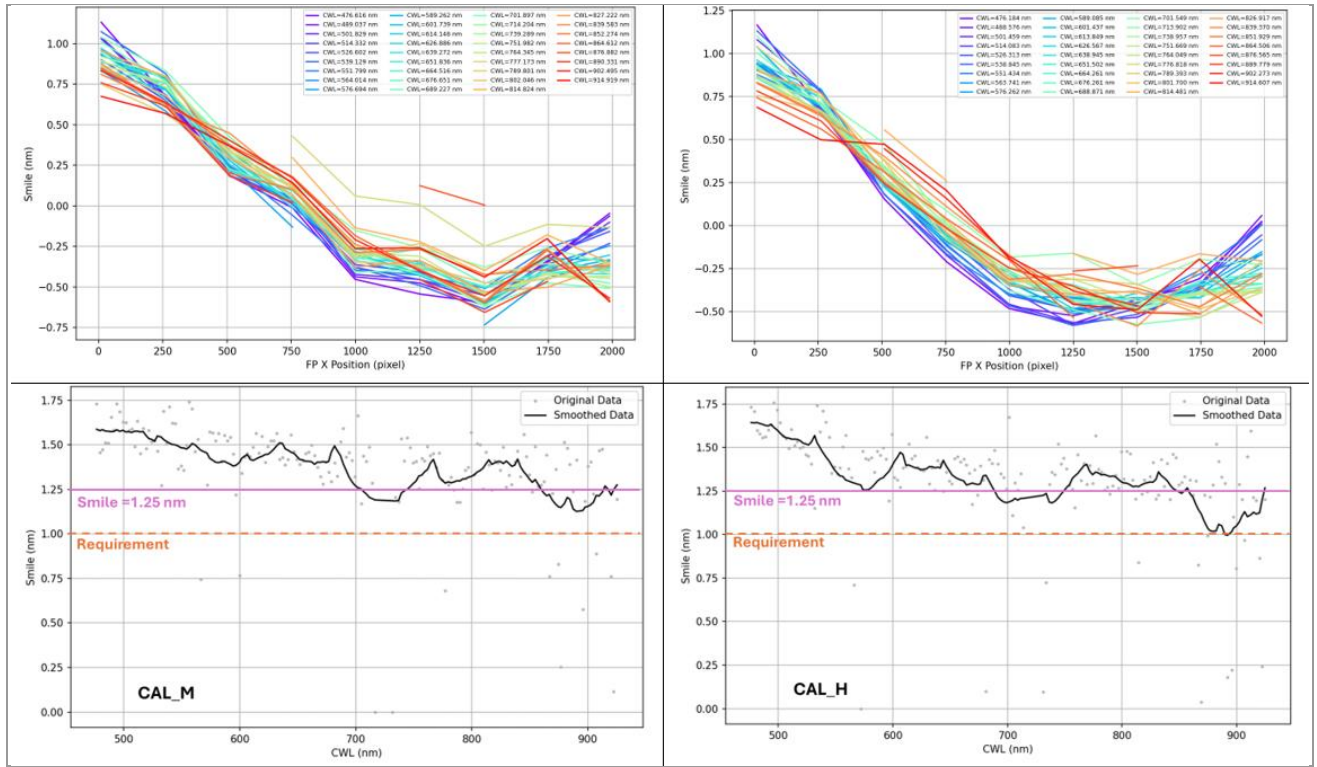


Figure 7. Spectral Smile for the VNIR FP in unbinned mode at the 2 temperature plateaus (-1°C and $+8^{\circ}\text{C}$). Top panels: Values of the smile as a function of the FoV position for selected VNIR sensor lines spanning the 450 – 940 nm spectral range. Bottom panels: Value of Smile (in nm) measured as a function of the central wavelength (spectral position of the sensor)

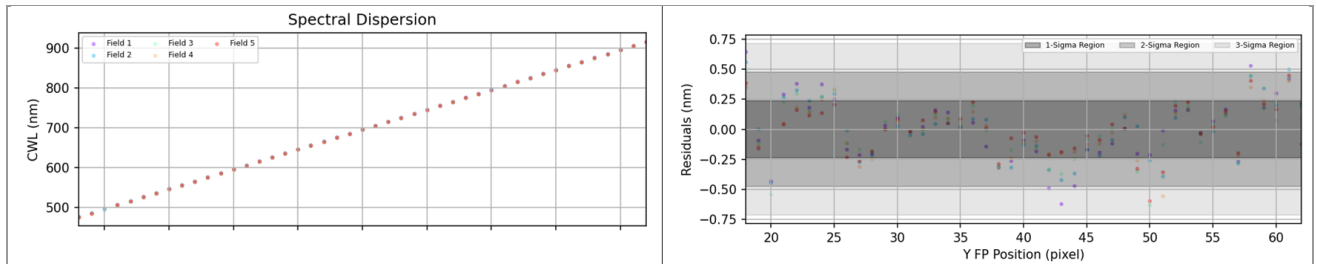


Figure 8. VNIR binned mode, at $+8^{\circ}\text{C}$. Left panel: Central wavelength as a function of the Y position of the detector (spectral dimension). Colors stand for the different points of the FoV. All these points are superimposed on one another, so that the main colors come from the last field traced (field #5). At first glance, the linearity between the central wavelength is good. This is confirmed by the residuals plotted in the bottom panel. Right panel: Residuals showing the difference between observed data and linearly regular predicted data showing a deviation from linearity smaller than ± 0.5 nm. Central wavelength, spectral dispersion, and spectral smile.

3.4 Spectral response function (VNIR)

The spectral response function (SRF) was characterized at the -1°C as-built temperature plateau, in both unbinned and binned detector modes. The ELOIS VNIR channel operates nominally in binned mode in flight; the unbinned mode is used for calibration purposes only.

For each mode, the local SRF was reconstructed at several field-of-view positions and several wavelengths spanning the VNIR spectral range, by scanning a monochromatic source around each selected wavelength and recording the response of individual detector pixels. For each measurement, a raw SRF FWHM is derived directly from the acquired data, and a corrected SRF FWHM is obtained by removing the contribution of the finite bandwidth of the monochromator, the width of the input slit image, and the detector pixel size, to isolate the SRF of the instrument itself.

In unbinned mode, the SRF was measured at 5 field-of-view positions and 5 wavelengths (480, 532, 652, 782, and 907 nm). The corrected, instrument-only SRF FWHM ranges from 2.95 to 3.69 nm, against a requirement of ≤ 3 nm. Most measured points exceed this requirement.

In binned mode, the SRF was measured at 5 field-of-view positions, at the same 5 wavelengths. The overall SRF FWHM ranges from 8.1 to 10.4 nm across these measurements (raw and corrected values are not distinguished in this range), against a requirement of ≤ 12 nm. All measured points are compliant with this requirement.

Since binned mode is the instrument's nominal operating configuration in flight, the SRF compliance obtained in binned mode is the result that determines the in-flight spectral response performance of the VNIR channel. The unbinned-mode results, obtained for calibration purposes only, are reported here for completeness.

Table 6. VNIR spectral response function (SRF) FWHM at the -1°C as-built temperature plateau.

Parameter	Unbinned mode	Binned mode
Requirement	≤ 3 nm	≤ 12 nm
Wavelengths tested	480, 532, 652, 782, 907 nm	480, 532, 652, 782, 907 nm
FoV positions tested	5	5
Corrected (instrument-only) SRF FWHM (range)	2.95 - 3.69 nm	8.1 - 10.4 nm
Compliant	No (most points > 3 nm)	Yes

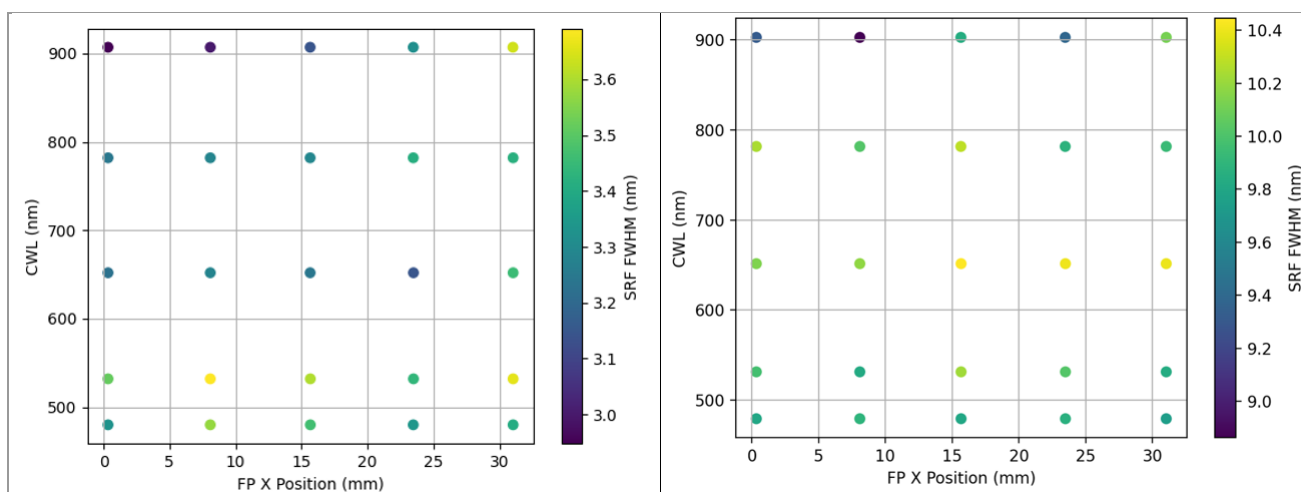


Figure 9. VNIR in unbinned mode (left) and in binned mode (right), -1°C plateau. Distribution of the Spectral Response Function (SRF) as a function of the pixel position on the detector. Each point on the grid corresponds to an individual pixel, with the X and Y axes indicating spatial and spectral position on the detector respectively. The color of each point indicates the SRF value measured at that specific location, according to the color scale on the right of both graphs.

4. CONCLUSIONS

The on-ground calibration and performance characterization of the ELOIS instrument has been presented, based on an ambient test campaign and a subsequent thermal-vacuum test campaign conducted at the CSL facility. Both the VNIR and SWIR channels were tested, and the results were reported against the corresponding success criteria. Image quality, spectral registration and spectral response function were characterized for the VNIR channel, while image quality and keystone were characterized for the SWIR channel. The VNIR MTF is compliant with its requirement at the minimum operational temperature of +5°C, and the spectral registration and spectral response function are compliant, or close to compliant, over most of the tested configurations.

This pre-flight characterization confirms that the ELOIS payload is on track to deliver its Earth observation mission from orbit. Both the VNIR and SWIR channels will be submitted to an in-flight calibration campaign following the instrument's commissioning in orbit.

ACKNOWLEDGMENTS

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