THE IPERLITE HYPERSPECTRAL MISSION: IN-ORBIT CALIBRATION AND VALIDATION RESULTS

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ABSTRACT

IPERLITE is a new hyperspectral Earth observation mission led by VITO Remote Sensing. It is designed to demonstrate compact, high-performance imaging from a small satellite platform. Built on Aerospacelab's VSP-150 platform, the mission carries the CSIMBA (Compact Smartspectral Imager for Monitoring Bio-agricultural Areas) instrument, an innovative hyperspectral sensor based on thin-film interference filters directly deposited on a CMOS detector. The instrument acquires up to 154 spectral bands spanning the 465–900 nm visible and near-infrared (VNIR) spectral range with a 20 m ground sampling distance over an 80 km swath, supported by digital Time Delay Integration (TDI) to enhance radiometric performance. This paper presents the first in-orbit calibration and validation results obtained during the commissioning phase, including the geometric, radiometric and spectral performance of the mission and the validation of the operational Level-1C processing chain. The results demonstrate the maturity of the IPERLITE processing chain and confirm the readiness of the mission to provide calibrated hyperspectral data products for scientific exploitation. With the successful completion of the commissioning phase beginning of July 2026, the IPERLITE mission is now entering its operational phase, and the scientific community is invited to apply for access to its hyperspectral data.

Index Terms— Hyperspectral, Cal/Val, Commissioning

1. INTRODUCTION

Recent years have seen a rapid expansion of spaceborne hyperspectral missions, providing unprecedented opportunities for quantitative Earth observation. The combination of high spectral resolution and increasing revisit frequency enables improved retrieval of vegetation properties, water quality, soil characteristics, and other environmental variables. Alongside large flagship missions, compact satellite platforms are emerging as a cost-effective solution to increase hyperspectral observation capacity.

Following its launch end of November 2025, the Belgium IPERLITE mission entered an extensive in-orbit commissioning phase aimed at validating the instrument performance and establishing the operational processing chain. The commissioning covered the complete calibration and validation workflows, including geometric, radiometric and spectral calibration, together with the verification of the operational Payload Data Ground Segment (PDGS).

This paper presents the first in-orbit calibration and validation results of the IPERLITE mission. It summarizes the adopted calibration methodologies, evaluates the geometric and radiometric performance using both dedicated calibration campaigns and independent reference datasets, and presents the status of the operational processing chain. With the successful completion of the commissioning phase, the mission is now transitioning towards routine operations and scientific exploitation

2. IMAGING CONCEPT

The IPERLITE payload is the CSIMBA (Compact Smartspectral Imager for Monitoring Bio-agricultural Areas) instrument, a compact hyperspectral pushframe imager. Unlike conventional pushbroom systems, CSIMBA uses a two-dimensional CMOS detector (CMV12000) on which narrow-band spectral filters are arranged line-wise across the focal plane, with 12 detector rows per spectral band. As the satellite moves along its orbit, successive image frames are acquired and combined to reconstruct the hyperspectral image cube, resulting in an acquisition principle analogous to a pushbroom sensor while preserving the advantages of frame-based imaging. The pushframe concept provides improved light collection efficiency and enables precise geometric co-registration within each acquired frame.

The instrument supports three acquisition modes: TDI12, TDI6 combined with panchromatic (PAN) regions, and TDI0 (without Time Delay Integration). Digital Time Delay Integration (TDI) increases the signal-to-noise ratio by summing successive detector rows observing the same ground target. In the nominal TDI12 mode, twelve detector rows are combined on-board before read-out, whereas TDI0

acquires every detector row independently and is mainly used for instrument characterization and calibration activities.

The focal plane consists of hyperspectral detector rows covering the 465–900 nm visible and near-infrared spectral range, complemented by panchromatic regions located at the top and bottom of the detector. Because the spectral bands are distributed along the along-track direction, a given ground target is observed sequentially at different wavelengths as the satellite advances. Consequently, each spectral band is acquired with a small temporal offset, making accurate geometric co-registration and attitude correction essential for the generation of high-quality hyperspectral image cubes.

3. RADIOMETRIC CALIBRATION

The objective of the radiometric calibration is to convert the detector digital numbers (DN) into accurate Top-of-Atmosphere (TOA) radiance and reflectance products. The in-flight calibration consisted of four main components: (i) offset and dark current correction, (ii) Pixel Response Non-Uniformity (PRNU) correction, (iii) spectral calibration verification, and (iv) absolute radiometric calibration. The resulting calibration coefficients are implemented in the operational Level-1 processing chain.

During commissioning, several detector and sensor characteristics were identified that required dedicated investigation before the operational calibration could be established. These included a strong variation in detector sensitivity across the spectral range, temperature-dependent offset and dark current, detector read-out artefacts, and saturation of the most sensitive spectral bands when using the pre-flight acquisition settings. Following optimization of the acquisition strategy and calibration methodology, the operational radiometric calibration was established for the nominal TDI12 acquisition mode with an integration time of 800 µs.

3.1 Offset, dark current and PRNU calibration

Detector offset and dark current were characterized using dedicated nighttime acquisitions over ocean targets acquired over a wide range of detector temperatures. Since the detector background exhibits an approximately linear dependence on detector temperature, a pixel-wise linear regression model was derived to estimate the offset and dark current for each detector pixel as a function of temperature. This model allows accurate correction over the complete range of operating conditions encountered during routine acquisitions.

The detector relative response was calibrated using dedicated 90° yaw maneuvers, during which the same ground target is successively observed by different detector pixels. These acquisitions provide an accurate estimate of the relative sensitivity of every detector element. The yaw maneuvers were acquired in TDI0 mode to avoid artefacts introduced by the on-board TDI summation and subsequently converted to TDI12 calibration coefficients by averaging twelve consecutive detector lines.

Application of the offset, dark current and PRNU corrections substantially improves the radiometric quality of the imagery. Figure 1 illustrates the effect of the corrections on two representative spectral bands. The detector-induced striping and across-track response variations visible in the raw imagery are effectively removed, resulting in a homogeneous radiometric response across the full field of view.

3.2 Radiometric Calibration Results

The absolute calibration coefficients were derived using acquisitions over the pseudo-invariant calibration sites (PICS) Libya-4 and Niger-2. Top-of-Atmosphere reflectance was simulated using the OSCAR desert model [1] and compared with the measured IPERLITE observations to derive band-specific calibration coefficients. For a few highly sensitive spectral bands affected by saturation over the bright desert sites, the calibration coefficients were instead derived from observations over the La Crau RadCalNet site.

Further validation was performed using cloud-free Sentinel-2 Simultaneous Nadir Observation (SNO) acquisitions. Figure 2 presents the comparison between IPERLITE and Sentinel-2 TOA reflectance for all Sentinel-2 spectral bands. The measurements are closely distributed around the 1:1 agreement line, demonstrating good radiometric consistency without significant systematic bias. A slightly larger spread is visible for Band 4 (664 nm), where several observations indicate higher reflectance values for IPERLITE than for Sentinel-2. However, this behaviour is not systematic across all match-ups and is therefore not considered indicative of a consistent calibration bias.

A complementary qualitative comparison was carried out EnMAP Level-1C acquisitions over the Libya-4 pseudo-invariant calibration site. The mean TOA reflectance spectra of both sensors exhibit very similar spectral shapes, with matching oxygen and water vapour absorption features. The slightly larger variability observed for IPERLITE is attributed to the larger range of acquisition viewing geometries, with off-nadir angles reaching up to 30°.

As part of the commissioning activities, monthly lunar acquisitions have also been initiated to support the verification of the absolute radiometric calibration and the long-term monitoring of radiometric stability. The current lunar dataset is still under evaluation, and commissioning of the lunar calibration methodology is ongoing before it can

be incorporated into the operational calibration and validation framework.

Overall, the agreement with independent reference datasets confirms the validity of the operational radiometric calibration and demonstrates that the IPERLITE Level-1C products provide radiometrically consistent hyperspectral observations suitable for quantitative Earth observation applications

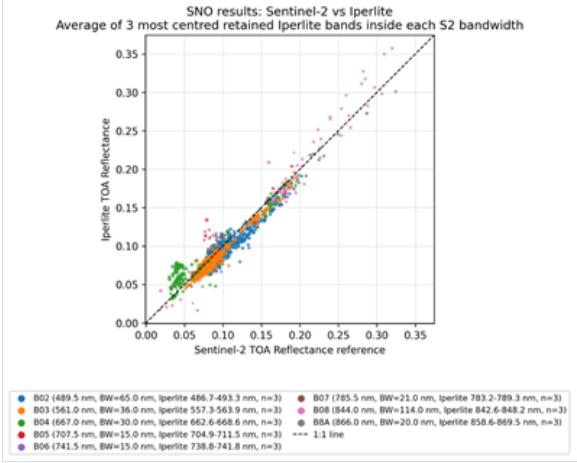


Figure 2 Scatter plot comparing IPERLITE and Sentinel-2 Top-of-Atmosphere (TOA) reflectance for the five cloud-free Simultaneous Nadir Observation (SNO) acquisitions. All Sentinel-2 bands are displayed in a single plot and are distinguished by different colours.

4. GEOMETRIC CALIBRATION

The primary objective of the geometric calibration is to accurately geolocate every detector pixel on the Earth's surface while ensuring precise co-registration between the 154 hyperspectral bands. Due to the pushframe acquisition concept and the sequential acquisition of the spectral bands on the focal plane, each band observes the same ground target at a slightly different time (max time separation of 5s is observed between first and last band in the focal plane layout). Consequently, variations in satellite attitude and platform jitter can introduce both absolute geolocation errors and spectral band misregistration, making dedicated in-flight geometric calibration essential.

4.1. Geometric calibration methodology

The IPERLITE systematic geometric correction combines physics-based direct georeferencing, image simulation, Normalized Cross Correlation (NCC) image matching, and joint bundle adjustment to produce hyperspectral imagery that is both accurately georeferenced and co-registered across all spectral bands. The methodology exploits a single accurately corrected reference band (i.e. Band 77 in the center of the frame) to estimate systematic geometric errors and compensate for the inter-band misalignment introduced by the temporal separation between detector acquisitions.

The reference band is first absolutely corrected using direct georeferencing based on the sensor model, precise orbit and attitude information, and a digital elevation model. Ground Control Points (GCPs) extracted from a global cloud-free Sentinel-2 reference database are used to refine the line-of-sight model and generate an accurately georeferenced reference image.

For every remaining spectral band, direct georeferencing is used to project the orthorectified reference image into the viewing geometry of the corresponding band, thereby generating a simulated image. Normalized Cross Correlation chip matching between the simulated and observed images provides a dense set of tie points, which are subsequently introduced into a joint bundle adjustment. In this adjustment, satellite attitude corrections are estimated globally, while the interior orientation parameters are estimated independently for each spectral band. Finally, the estimated correction parameters are incorporated into a second direct georeferencing step to generate the final orthorectified and geometrically consistent hyperspectral products.

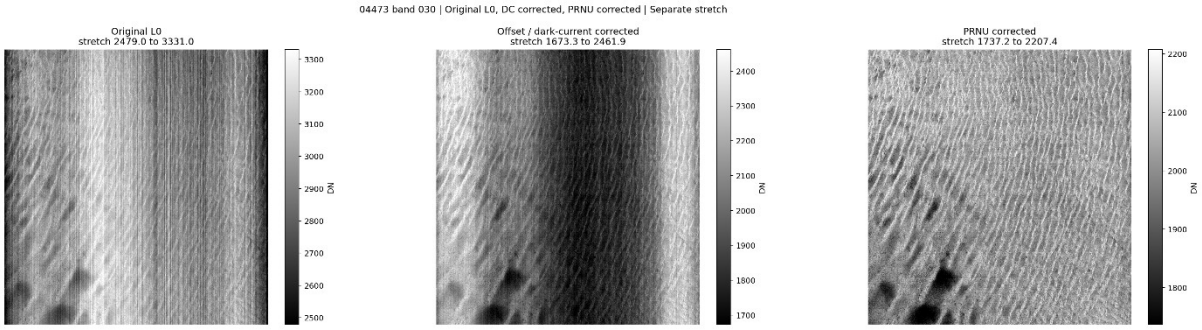


Figure 1. Effect of the radiometric corrections on Band 30. From left to right: raw image, image after offset and dark current correction, and image after subsequent PRNU correction. The radiometric corrections substantially improve image uniformity by removing detector-induced spatial non-uniformities across the field of view.

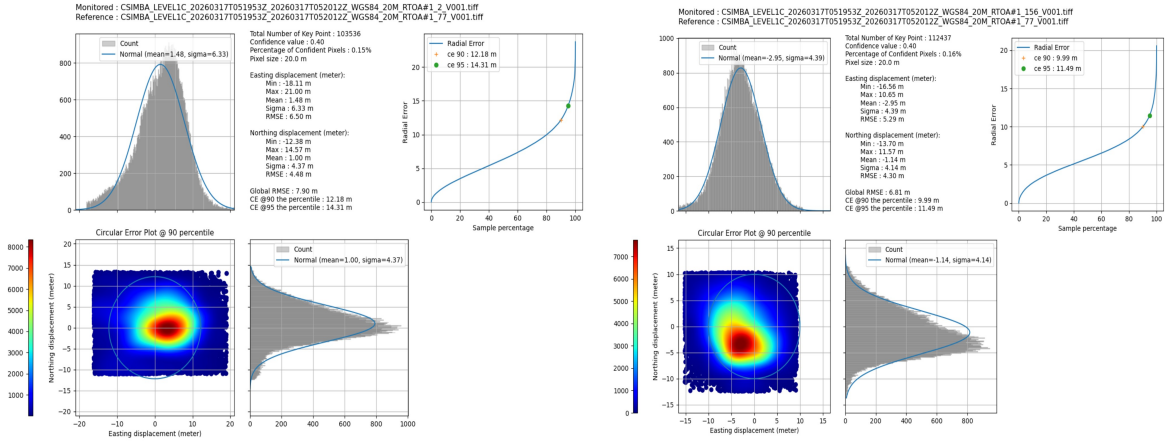


Figure 3. Band Co-registration accuracy (left: reference band 77 vs band 2, right: reference band vs band 156)

4.2. Geometric calibration results

4.2.1. Absolute geolocation accuracy

Following launch, the initial satellite geo-pointing exhibited a significant systematic bias, with the line of sight deviating by approximately 2.8 km towards the north-east. Such a large offset would require excessively large search windows during Ground Control Point matching. Therefore, a preliminary coarse boresight refinement was introduced to estimate and remove the dominant pointing bias, reducing the residual absolute geolocation error to approximately 100 m before applying the operational geometric correction.

Following coarse boresight correction, bundle adjustment is systematically applied to every acquisition. Ground Control Points are matched on the reference band and the resulting image displacements are introduced into the bundle adjustment to estimate residual corrections to the line-of-sight model and the satellite roll, pitch and yaw angles. The quality of the correction depends on the number and spatial distribution of the available GCPs. Cloud cover may significantly reduce the number of valid matches, in which case a fallback line-of-sight model is applied and the resulting products are flagged as having degraded geometric quality.

The geometric performance was evaluated through comparison with Sentinel-2 reference imagery using the ESA KARIOS image registration tool. For the example scene presented in the commissioning report, more than 30,000 automatically extracted Ground Control Points were used to assess the geometric accuracy. After applying the geometric correction, the Circular Error at the 95th percentile (CE95) is approximately 40 m, corresponding to about two image pixels, demonstrating that the operational geometric correction achieves the expected mission performance.

4.2.2. Interband geolocation accuracy

Once the reference band has been absolutely corrected, it serves as the geometric reference for all remaining spectral bands. Band co-registration is performed using an image-based matching technique in which tie-point templates extracted from the reference band are matched in each target spectral band using Normalized Cross Correlation. The resulting image displacements are incorporated into the bundle adjustment, yielding updated line-of-sight and attitude correction parameters for every spectral band.

The performance was evaluated using Bands 2 and 154, which have the largest temporal separation with respect to the reference Band 77 and therefore represent the most demanding registration cases. The resulting inter-band registration accuracy ranges between 0.5 and 0.67 pixels, demonstrating that the proposed correction methodology successfully compensates for the temporal offsets between detector acquisitions while preserving excellent geometric consistency across the complete hyperspectral cube.

5. PAYLOAD DATA GROUND SEGMENT

A complete Payload Data Ground Segment (PDGS) has been developed and successfully commissioned to process IPERLITE data products from raw satellite telemetry to calibrated hyperspectral products. The PDGS automatically ingests the raw Level-0 (L0) data from the satellite, applies the geometric and radiometric corrections developed during the commissioning phase, performs orthorectification, and generates Level-1C (L1C) Top-of-Atmosphere (TOA) reflectance products.

The processing chain has been validated for the different acquisition configurations supported by the mission, ensuring consistent product generation across the operational imaging modes. The Level-1C products are idistributed in the Cloud Optimized GeoTIFF (COG) format together with standardized XML metadata, allowing direct integration into common GIS and remote sensing software.

Building upon the Level-1C products, a Level-2A (L2A) processing chain based on VITO's iCOR atmospheric correction processor [2] has been implemented to generate surface reflectance products. At the time of writing, the Level-1C processor has been fully commissioned and is operational, whereas the Level-2A processor is still undergoing commissioning and validation.

The IPERLITE products will be disseminated through the Belgian Terrascope Earth Observation platform, providing users with access through services such as the STAC catalogue, TerraViewer, Jupyter Notebook environments and cloud processing infrastructure.

The data access policy is currently being finalized and will be announced before the conference, marking the start of the operational scientific exploitation of the IPERLITE mission.

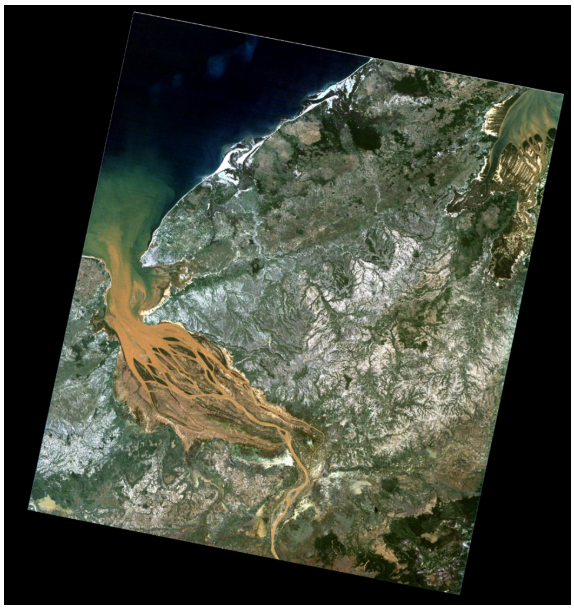


Figure 4. Iperlite Ture RGB image acquired above Mahajanga (Madagascar) at 20260317T070809Z (UTC).

6. REFERENCES

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