

Implementing the future of operational high-resolution thermal infrared radiometry with the Copernicus LSTM mission: Instrument design and development status

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ABSTRACT

The Copernicus Land Surface Temperature Monitoring (LSTM) mission is a cornerstone of the Copernicus Expansion Program, addressing a long-standing gap in the provision of high-resolution thermal infrared observations required for operational land surface temperature (LST) and evapotranspiration monitoring. By combining high spatial resolution, frequent revisit enabled by a satellite pair, and stringent, traceable radiometric performance, LSTM is designed to establish a new operational capability for thermal infrared radiometry in support of key Copernicus services. These services address climate change adaptation, sustainable water management, food security, urban heat monitoring, and a range of complementary environmental applications. This paper presents the current development status of the LSTM thermal infrared instrument, with emphasis on the latest progress achieved during Phase C, up to its critical design review. The instrument provides multi-spectral observations through a set of six bands in the VIS and SWIR and five bands in the thermal infrared, with high spectral stability and tight spectral tolerance to support robust radiometric retrievals and atmospheric correction. Attention is given to the radiometric performance of the instrument, which is a key mission driver. The consolidated architecture implements 5 thermal bands (8 to 12.5 μm) accompanied by 6 VNIR-SWIR spectral bands (0.4 to 1.7 μm). The design achieves an absolute radiometric accuracy at instrument level of better than 0.3 K with an excellent radiometric resolution of better than 0.1K at 300 K, securing an LST measurement of better than 1 K on ground with a native resolution of 37m-50m. The paper reports on extensive breadboarding and validation activities performed to retire critical technical risks, validate key technologies, and demonstrate compliance with radiometric, thermal, and geometric performance envelopes. The paper further describes the ongoing flight model Assembly, Integration and Test (AIT) campaign, outlining the adopted verification logic, calibration strategy, and performance verification approach. The consolidated CDR-level performance estimates, together with early AIT results, confirm the capability of the LSTM instrument to deliver a robust, operational high-resolution thermal infrared radiometry capability in support of long-term Copernicus services.

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Keywords: Copernicus, LSTM, Earth observation, thermal infrared, multi-spectral imager, Land Surface Temperature, Evapotranspiration

1. INTRODUCTION

Freshwater resources are increasingly under pressure from the combined effects of climate change, population growth, changing consumption patterns, and the intensification of agricultural production. Agriculture currently accounts for approximately 70% of global freshwater withdrawals [1] and is expected to face increasing competition for water resources while simultaneously being required to meet growing food demands. Climate-induced changes in precipitation patterns, increased frequency and severity of droughts [2], and rising evapotranspiration rates further exacerbate water stress in many regions of the world. As global food demand expands, particularly in regions already exposed to water stress, the pressure on freshwater availability is expected to increase, creating risks for food security, ecosystem stability, and socio-economic resilience [3]. Therefore, improving agricultural water-use efficiency and enabling sustainable water resource management have become key priorities for international environmental and agricultural policies. Accurate monitoring of evapotranspiration (ET), which represents the largest water flux between land and atmosphere, is widely recognized as a fundamental requirement for quantifying crop water consumption, assessing drought conditions, and supporting irrigation management practices aimed at optimizing agricultural productivity while minimizing water use [4]. Land surface temperature (LST) is a key metric for the derivation of ET rates.

At the same time, thermal infrared observations acquired at high spatial and temporal resolution have emerged as a critical source of information for a wide range of environmental monitoring and climate adaptation applications. Land Surface Temperature (LST), recognized by the Global Climate Observing System as an Essential Climate Variable [5], provides direct insight into land-atmosphere interactions, surface energy exchanges, vegetation stress and ecosystem functioning [6]. High-resolution thermal observations also support the monitoring of urban heat islands and population exposure to extreme temperatures [7][8], contribute to the characterization of droughts and heatwaves, and provide valuable information for natural hazard monitoring. They have demonstrated significant capability for the detection and tracking of wildfires through the observation of thermal anomalies, while also supporting the monitoring of volcanic activity and other geophysical processes. As climate change increases the frequency and severity of many of these phenomena, the availability of systematic, high-quality thermal infrared observations is expected to play an increasingly important role in supporting climate resilience, civil protection, environmental management and public-health strategies.

In response to these emerging societal and environmental needs, the High Spatio-Temporal Resolution Land Surface Temperature Monitoring (LSTM) Mission has been selected as one of the Copernicus Expansion Missions. The mission is designed to complement current Sentinel observation capabilities by providing unprecedented high-revisit thermal infrared (TIR) observations over land and coastal regions [9]. Its primary objective is to support the retrieval of evapotranspiration (ET) at European field scale through accurate measurements of Land Surface Temperature (LST) and Land Surface Emissivity (LSE), thereby enabling more robust estimates of crop water consumption and water productivity. By providing the information required to optimize irrigation practices and improve agricultural water-use efficiency, LSTM will contribute directly to sustainable freshwater resource management under increasing climatic and socio-economic pressures. In addition, the mission's unique thermal observing capability will support a broad range of complementary applications spanning environmental monitoring, climate services, disaster-risk reduction and natural-resource management.

The user-required accuracy of ET retrieval, corresponding to 15% systematic error and 5% random error, translates into a required LST measurement accuracy of approximately 1 K to 1.5 K at ground level [9]. Optimally, the LST observations needed to estimate ET needs to be derived daily but this could be relaxed to 3 days as a minimum threshold. Furthermore, the objective of monitoring agricultural processes at the scale of individual fields imposes a spatial sampling distance of 50 m, corresponding to the characteristic dimension of a 1 ha agricultural parcel. The thermal measurements are then complemented by co-registered observations in the visible (VIS), near-infrared (NIR) and short-wave infrared (SWIR) spectral domains, required for atmospheric correction, cloud screening and accurate geolocation [13]. User requirements for the timely delivery of ET products impose Level-2 land surface temperature product latencies of 6 h to 12 h, enabling Level-3 evapotranspiration products to be delivered within 9 h to 18 h after acquisition. These latency constraints require all Level-1 processing functions, including radiometric calibration, geometric correction, resampling and geolocation, to be completed within a timeframe of 3 h to 6 h.

The development of the LSTM mission has been entrusted by the European Space Agency (ESA) to an industrial consortium led by Airbus Defence and Space Spain (Madrid), with responsibility for payload development assigned to Airbus Defence and Space France (Toulouse). Scheduled for launch in 2029, LSTM is designed to establish a sustained global operational capability for high-quality, high spatio-temporal resolution thermal observations extending well into the next decades. Synergies with other institutional thermal infrared missions also currently under development, including NASA's TIR component of the Explorer for Artemis Geology Lunar and Earth Mission (EAGLE-TIR) as well as the CNES-ISRO TRISHNA mission, are expected to maximize the scientific and socio-economic impact of the LSTM mission.

2. MISSION CONCEPT AND KEY REQUIREMENTS

LSTM Mission Concept

Global coverage requirements are addressed through a constellation of two identical LSTM satellites phased by 180° , providing a global revisit time of two days at the Equator and near-daily observations over Europe. Each satellite (Figure 1) will be operated at an average altitude of 651 km in Sun Synchronous Orbit, allowing for observations over Europe at a Mean Local Solar Time (MLST), descending, of 13:00. Observations in TIR are planned during night and daytime whereas VNIR and SWIR observations are only performed during daytime. Each satellite embarks a single multi-spectral whiskbroom radio-imager covering eleven spectral bands spread within three focal planes. The ground projection of each focal plane and scanning pattern are shown on Figure 2.



Figure 1. General view of the LSTM satellite. The payload composes the lower module on this picture

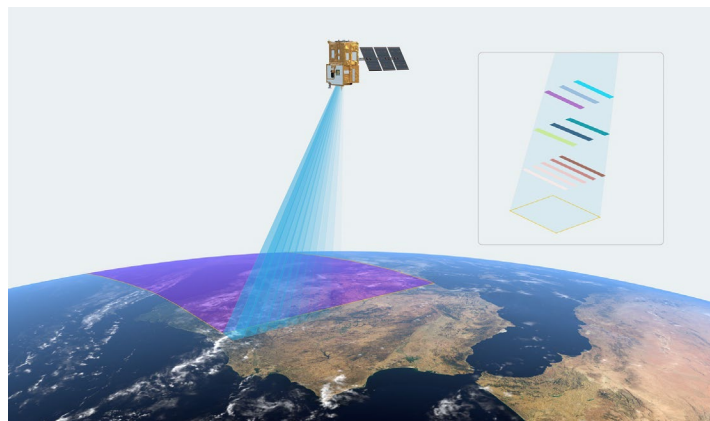


Figure 2. LSTM scanning pattern

Key requirements

The LSTM mission objectives have been translated into a set of key spectral, radiometric, spatial image quality and geometric requirements. Key spectral, radiometric and spatial image quality requirements are presented in Table 1 and Table 2 for the VNIR-SWIR bands (also referred to as solar channels) and TIR bands respectively, while key geometric requirements are summarized in Table 3.

The spectral bands to be acquired are defined by their central wavelength and spectral width, on which stringent tolerance (between 1.5nm and 10nm depending on the bands in VNIR-SWIR, ≤ 20 nm in TIR) and knowledge (0.2nm to 1nm in VNIR-SWIR and ≤ 5 nm in TIR) are demanded. Knowledge is a prime importance as it influences directly the end-product quality. The Instrument Spectral Response Function (ISRF) is indeed used in the LST retrieval algorithms. The shape of the ISRF is strictly controlled in order to guarantee very good rejection ratio of the integrated incoming signal which lies out of the spectral band of interest, compared to the in-band signal.

Table 1. Collection of the LSTM key spectral, radiometric and image quality requirements in the visible and near infrared (VNIR) and short-wave infrared (SWIR) bands. This summary includes spectral performance (central wavelength and full width at half maximum (FWHM)), radiometric performance (minimum, reference and maximum radiances L_{min} , L_{ref} and L_{max} defining the required dynamic range, absolute radiometric accuracy (ARA)) and image quality specified by the modulation transfer function (MTF) of the L1b product at the Nyquist frequency of the Level 1c product, i.e. after re-sampling of the images on a 50 m regular grid.

	Units	VNIR0	VNIR1	VNIR2	VNIR3	SWIR1	SWIR2
Central wavelength	[μ m]	0.490	0.665	0.865	0.945	1.380	1.610
FWHM	[μ m]	0.065	0.030	0.020	0.020	0.030	0.090
L_{min}	[W/m ² /sr/ μ m]	11.70	3.31	0.95	0.51	0.06	0.4
L_{ref}	[W/m ² /sr/ μ m]	128.00	108.00	52.39	8.77	6.00	4.00
L_{max}	[W/m ² /sr/ μ m]	615.48	484.13	307.80	232.91	45.00	69.78
SNR @ L_{ref}	[-]	162	142	100	114	100	133
ARA @ L_{ref}	[%]	3.5	3.5	3.5	3.5	5	5
MTF @ L_{1c} Nyquist	[-]	0.2 - 0.3	0.2 - 0.3	0.2 - 0.3	0.2 - 0.3	0.2 - 0.3	0.2 - 0.3

In the thermal bands, for the sake of simplicity in the interpretation of the requirements, all radiometric performances are expressed in terms of Top of Atmosphere (TOA) brightness temperature, and the dynamic range is defined, in agreement with the mission objectives, between 250 K and 460 K. The LSTM solar channels are harmonized with those of Sentinel-2. The signal-to-noise ratio (SNR) (resp. Noise Equivalent delta Temperature or NEdT) translates the need for radiometric precision, i.e. the dispersion of the recorded radiance (resp. brightness temperature) due to (measurement) noise.

Table 2. Collection of the LSTM key spectral, radiometric and image quality in the thermal infrared (TIR) bands. The set of requirements is identical to the ones of VNIR-SWIR bands presented in Table 1, with an additional requirement about pseudo-noise. All radiometric performance are expressed in [K] in order to relate them directly to the measured brightness temperature. In particular the requirement about radiometric precision is expressed as a noise equivalent delta temperature (NEdT) rather than SNR.

	Units	TIR1	TIR2	TIR3	TIR4	TIR5
Central wavelength	[μ m]	8.600	8.900	9.200	10.900	12.000
FWHM	[μ m]	0.180	0.180	0.180	0.400	0.470
NEdT @ 300 K	[K]	0.1	0.1	0.1	0.1	0.1
ARA @ T_{ref}	[K]	0.3	0.3	0.3	0.3	0.3
MTF @ L_{1c} Nyquist	[-]	0.15 - 0.3	0.15 - 0.3	0.15 - 0.3	0.15 - 0.3	0.15 - 0.3

The Absolute Radiometric Accuracy (ARA) quantifies the systematic measurement deviation from its “true” value while the Relative Spectral (resp. spatial) Radiometric Accuracy, RSRA (resp. RXRA) ensures that the radiometric error remains similar from one spectral band (resp. one spatial sample) to the other. Additionally, a pseudo-noise requirement has been introduced to account for the radiometric error introduced by the instrument PSF, through the unavoidable contribution of optical diffraction or by the Line of Sight (LoS) instabilities [10].

The spatial resolution, i.e. the ability of the instrument to spatially resolve spatial features on ground, is specified through the Modulation Transfer Function (MTF) at Nyquist frequency (a.k.a. the sampling frequency). Because of the Earth ellipsoid shape, the native sampling frequency of LSTM is not constant over the swath inducing an across-swath varying sampling frequency. The MTF is specified on the L1b product, but at a ground-projected frequency equivalent to 50m sampling grid, i.e. the frequency of the L1c product.

Table 3. Collection of the LSTM key geometrical requirements.

	Units	All Bands	Comments
Observational Zenith Angle	[deg]	< 30 [G] / < 35 [T]	
SSD @ L1c	[m]	50	LSTM L1C product
SSD @ L1b	[m]	< 50	Selected concept facilitates native sampling in the range from 37m (nadir) to 50m (swath edge)
Geolocation without GCP	[-]	< 1 SSD	At 95% confidence level
Geolocation with GCP	[-]	< 0.5 SSD	At 95% confidence level
Co-registration with GRI	[-]	< 0.3 SSD	At 95% confidence level with Sentinel-2 Global Reference Image (GRI)
Bands Spatial Co-registration	[-]	< 0.3 SSD	At 95% confidence level

This set of demanding requirements brings several constraints on the design of the satellite, the instrument and of its subsystems. These design drivers are detailed in the subsequent sections. A whiskbroom scanning concept was selected to fulfill the high revisit time, requiring a large nominal swath of 687 km to be fast-scanned in less than 6 seconds, due to technological limitations in the along-track (ALT) dimension of the sensors. The ARA in the TIR bands (0.3K) at the reference temperature (300K) corresponds to 0.4% to 0.6% of the equivalent radiance (to be compared to 3.5% required in the solar bands) and can only be met with the implementation of a high frequency two-point on-board calibration scheme. In both solar and thermal bands, the radiometric accuracy specified requires particular attention to stray light, which is controlled both by a careful optical design for ghost rejection and by the implementation of stray light correction in the data processing chain, as well as characterisation and potential correction of any detector “exotic” effects such as lag, crosstalk or offset, that could increase the radiometric error in highly non uniform scenes. On the other hand, Time Delay Integration (TDI) is implemented on all bands to reach the high SNR (resp. low NEdT) and accommodate large scene signal dynamic. This operation is performed either by the Front-End Electronics (FEE) or on chip at detector level, depending on the bands and combined to pixel selection/deselection in relation with NSWIR and TIR detectors operability being lower than 100%. The spectral filtering and out-of-band rejection functions are ensured by a two-stage stripe filters design while tight spectral tolerancing is met by combination of optical design constraints (high telecentricity) and selection of first-class manufacturers.

Finally, the spatial image quality and demanding geometric performance specifications (MTF, geolocation or spatial co-registration between the bands) demand very stringent pointing requirements on the scanner mechanism, as well as a very good overall mechanical stability. A full-SiC optical telescope, benefiting from Airbus expertise and cumulated heritage on past space programs in combination with careful attention brought to the thermal control design keeps the thermo-elastic deformation induced by the in-orbit environment to a level low enough to secure the right level of pointing stability, while for the MTF the design consideration have to be extended to include, on top of the usual contributions, to TDI de-synchronization control.

3. INSTRUMENT DESIGN

The LSTM instrument design has been presented in the past and reported also here again for completeness [11][12]

Functional diagram

The functional diagram of the instrument is presented in Figure 3. The eleven spectral bands of the LSTM instrument are recorded on three separate focal planes: the visible detector (VIS) dedicated to the VNIR0, VNIR1 and VNIR2 bands, the short-wave infrared (SWIR) is used for VNIR3, SWIR1 and SWIR2, and the TIR detector images the five thermal bands. All three focal planes are accommodated in front of a single telescope. A pendulum scanner mechanism acquires a wide swath in the across-track direction and allows for acquiring an on-board calibration black body source at every scan cycle as well as deep space acquisitions, both used for the calibration of thermal bands. Another calibration and shutter mechanism is used to insert a solar diffuser target in the optical path for the calibration of the solar channels in the exact same way as Sentinel-2 MSI calibration. A first dichroic beam splitter (DBS1, or VTDBS) separates the optical paths of the TIR bands from the path of the solar bands, while a second dichroic assembly (DBS2 or VNDBS), separates the VIS and SWIR path on their respective detectors. Spectral response function of the instrument is shaped via two stages of stripe filters, the first placed at the intermediate focal plane (immediately after the VTDBS) and the second directly in front of the respective detectors. Each focal plane is enclosed in a specific assembly, providing adequate thermal environment, i.e. ambient for VIS, passively cooled to 200 K for SWIR, and actively cooled at cryogenic temperature (65 K) for the TIR detector.

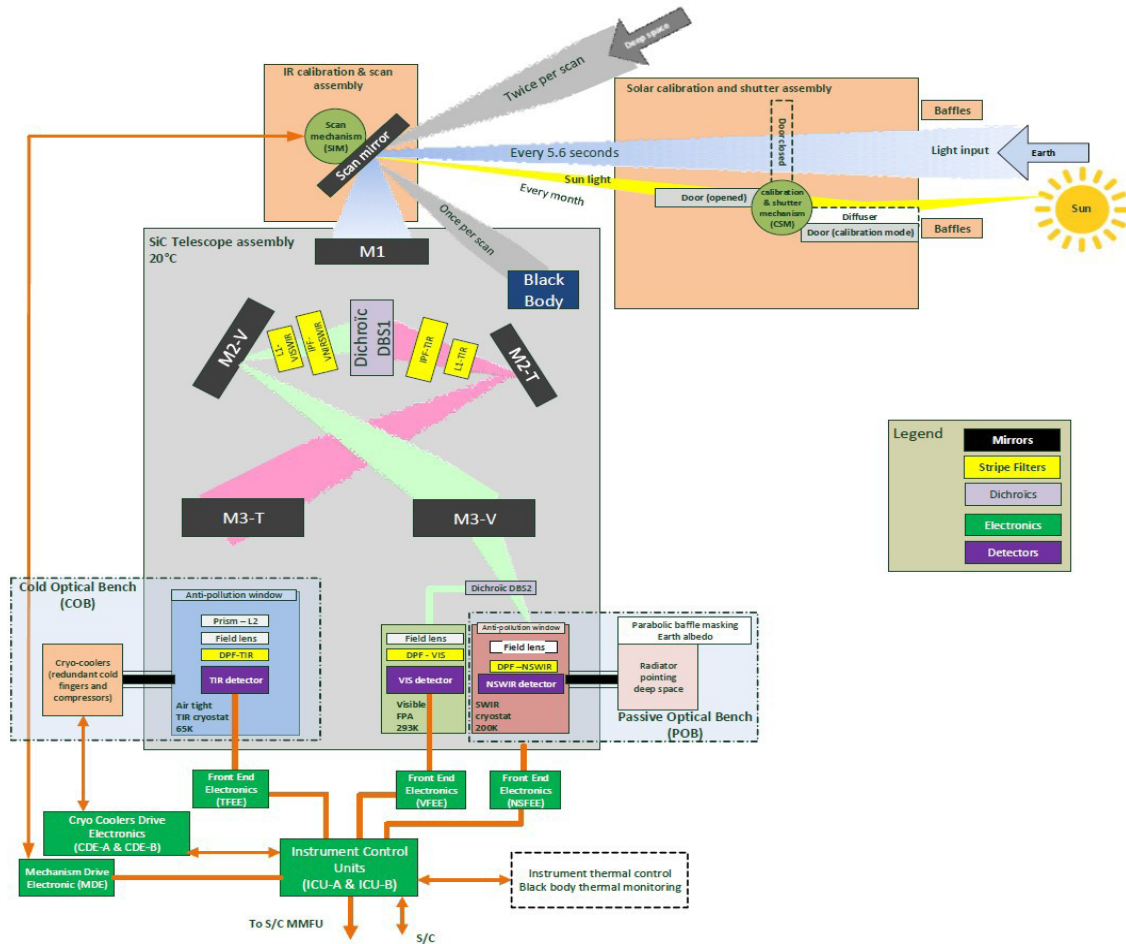


Figure 3. Functional diagram of the LSTM instrument

The Instrument Control Unit (ICU) centralizes and distributes all Telemetry and Tele-commands (TM/TC) to the instrument units, handles the science data from the detector and interfaces with the spacecraft electronics and with the payload electronic modules, such as the Front-End Electronics (FEE) associated to each detector, the Mechanism Drive Electronics (MDE) or the Cryocooler Drive Electronics (CDE). The ICU controls the thermal regulation of the whole instrument via a large set of thermal sensors and heaters.

Optical Design

The accommodation of three detectors dedicated to three spectral ranges in a single instrument relies on the LSTM original patented optical design (cf. Figure 4). The dual TMA is composed of five freeform mirrors in silicon-carbide (SiC) mounted on a single SiC baseplate. The primary mirror M1 is common to all spectral paths, and two sets of secondary and tertiary mirrors M2 and M3 compose the VNIRSWIR path on the one hand and the TIR path on the other hand. The number of refractive components is minimized so as to avoid ghosts and scattering stray light, thus no re-imaging optical systems are implemented. The entrance pupils (equivalent circular diameter >200 mm in TIR and >130 mm in VNIRSWIR) are located at slightly different longitudinal positions to image their respective on-board calibration targets without any vignetting that would be detrimental to the radiometric accuracy. Area and shape of the pupil is optimized independently for TIR and VNIRSWIR optical paths to meet both SNR and MTF requirements. The focal length of each path is designed to provide the same pixel instantaneous field of view. The first stage of spectral filters is in the intermediate focal plane beyond the DBS1. The second set of filters is in front of the photosensitive surface of the detectors (see Figure 5). The accuracy and stability over the field of view of the spectral response is ensured by the very stringent telecentricity in both the intermediate and detector focal planes. This optical design pays particular attention to the control of stray light, and several features are implemented to reduce the number of unwanted rays reaching the detectors. First, the telescope is integrated on a single monolithic baseplate. On one side the scan mirror, the calibration black body and the M1 are integrated. The beam is then directed through an aperture in the baseplate towards its other side, where the rest of the optical path, up to the focal planes, is integrated. This physical separation between a front cavity and a rear cavity reduces the possible parasitic paths coming from direct entrance in the Earth observation view port. The double filtering stage also contributes to the stray light reduction by filtering out the spectral content out of the useful band, upstream of the focal plane assemblies. Several optical components are wedged in such way that most of the main ghost paths are geometrically rejected. The strong astigmatism introduced in the system by the wedged components is compensated by the introduction of a compensating prismatic lens in the Cold Optical Bench (COB).

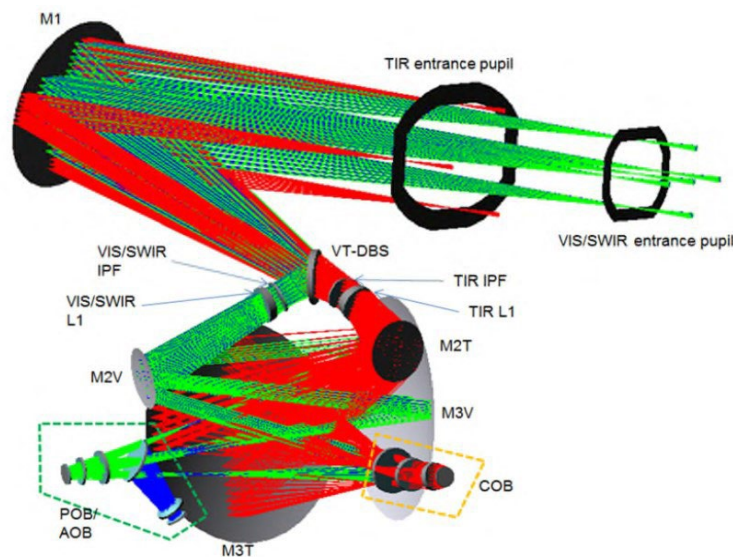


Figure 4. Optical design of the LSTM instrument - Patented* - France, Patent demand 2005561 deposited 26/05/2020



Figure 5. VNIRSWIR stripe filters (left) (courtesy of OBJ) and TIR detector plane filters assembly (right) (courtesy of the University of Oxford)

Scanner mechanism

The LSTM scan mechanism (SCM) enables the instrument to successively observe the earth, the deep space port, and the on-board black body dedicated to the radiometric calibration of the thermal bands. The scan sequence, pictured on Figure 6, consists in the observation of the earth ($\pm 29^\circ$ LoS angles centered on Nadir, corresponding to 687 km of nominal swath on-ground) with a constant velocity, followed by an acceleration to successively acquire the deep space port, stop on the black body, and quickly return to its initial position while acquiring the deep space port a second time. The short repeat cycle duration (5.7s) ensures that successive swaths are acquired without any gap in the data, and with sufficient overlap to allow efficient image reconstruction.

Several key performance of the instrument are directly linked to the scan mechanism performances. For instance, the Spatial Sampling Distance (SSD) in the ACT direction is defined by the LoS angular displacement during the frame time (254 μ s), meaning that the drift of the pointing performance from one frame to the next leads to an instability of the SSD, and a relative pointing error occurring between TDI stages will affect the MTF through the effect of TDI desynchronization. Similarly, the knowledge of the scanner position provided by the mechanism encoder must be very good in order to guarantee the image geolocation with a sufficient accuracy. These requirements demands for a mechanism with very stable motion velocity, low wobbling and high performance encoder. To fulfill these challenging requirements, AIRBUS selected the state-of-the-art DSM (Dual Swing Mechanism) stepper mechanism from IASI-NG that benefits from exhaustive qualification campaigns [14].

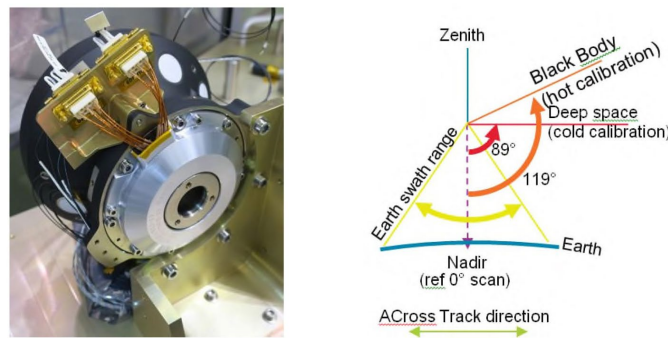


Figure 6. LSTM scan mechanism (left) and scanning sequence (right)

Detection chain

As mentioned above, three separate detectors are used to cover the LSTM spectral range. The VIS detector covers the first half of the solar channels (VNIR0, VNIR1 and VNIR2 from 0.490 μ m to 0.865 μ m), the SWIR detector is dedicated to the second half (VNIR3, SWIR1 and SWIR2 from 0.945 μ m to 1.610 μ m) and the TIR detector to the five thermal bands (TIR1 to TIR5 from 8.6 μ m to 12 μ m). Each detector has its dedicated driving FEE, which are all piloted by the ICU.

The three detectors have many important features in common despite their different suppliers, technologies and implementations. Each spectral band is associated to a CMOS stripe detector, with the long edge oriented along the ALT direction, acquiring one row of the swath at a time, corresponding to a given position of the scan. Their location at the focal planes of a common telescope, and the fact that they image the same ALT swath ensure that the acquired swath of each spectral channel overlaps, which ensures a native very good spatial co-registration between the spectral bands.

The acquisition mode of all bands is based on time delay integration, in order to optimize the SNR, although the number of TDI stages depends on the specific radiometric constraints of each band. The TDI acquisition concept, illustrated on the top part of Figure 7, is based on the fact that the imaged scenes is translated over the detector plane by the scanning motion. Hence, to improve the signal acquired on a given target point on ground, the same point is acquired from several pixels along the scan direction (i.e. the ACT direction) and the signal from all the acquired pixels is added up. This imposes that the frame time (254 μ s) is perfectly synchronized with the time the scanner needs to sweep a distance equal to the pixel pitch. A desynchronized acquisition between TDI stages contributes to the MTF performance, similar to scan motion smearing during integration period.

In the visible chain, detector pixels operability is 100% and all rows are therefore used for TDI. On the SWIR and TIR bands on the other hand, it is expected that a number of pixels are defective (i.e. cannot meet the SNR requirements) and have to be left unused. For this reason, the number of rows of the detector is larger than the number of TDI stages that are actually used. The bottom part of Figure 7 displays an example (illustrative only) where 4 TDI stages are used on 9-pixel wide window. The pixels in green on this figure represent non-defective pixels that are used to integrate the signal, while the orange pixels are deselected and their signal is not considered. A Look Up Table (LUT) is characterized before launch and used for the pixel deselection.

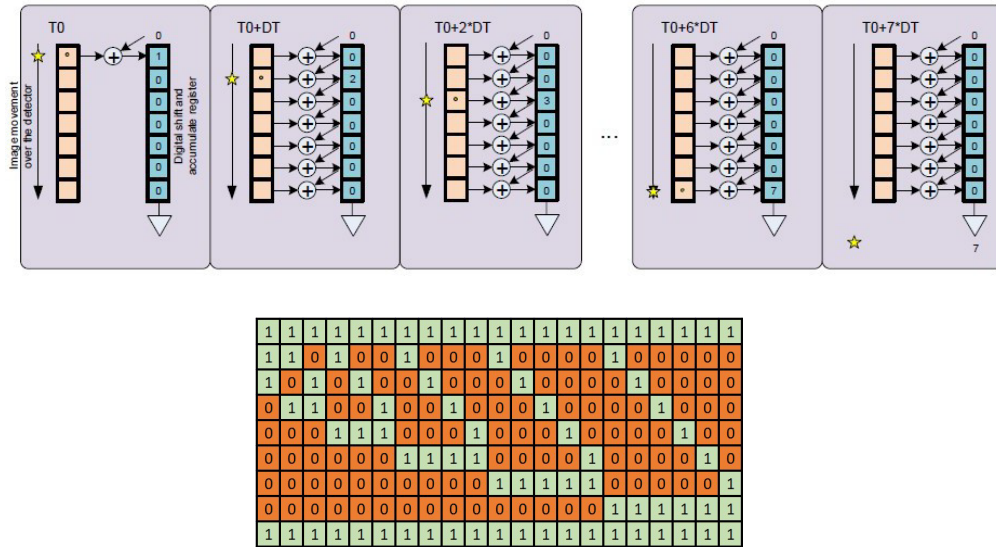


Figure 7. Principle of Time Delay Integration and example of pixels deselection with 4 TDI stages among a window width of 9 pixels

VIS detection chain

The VIS detector is a CMOS image sensor based on front-illuminated Si detection layer, featuring very low dark current when operated at ambient temperature. The VIS detector is integrated in the ambient optical bench (AOB) without any need for cooling. The photosensitive area is composed of two rows of 1200 pixels (15 μ m pixel pitch) in the ALT direction in VNIR0 and VNIR1 and four rows in VNIR2 (cf. Figure 8). The TDI summation is performed at FEE level.

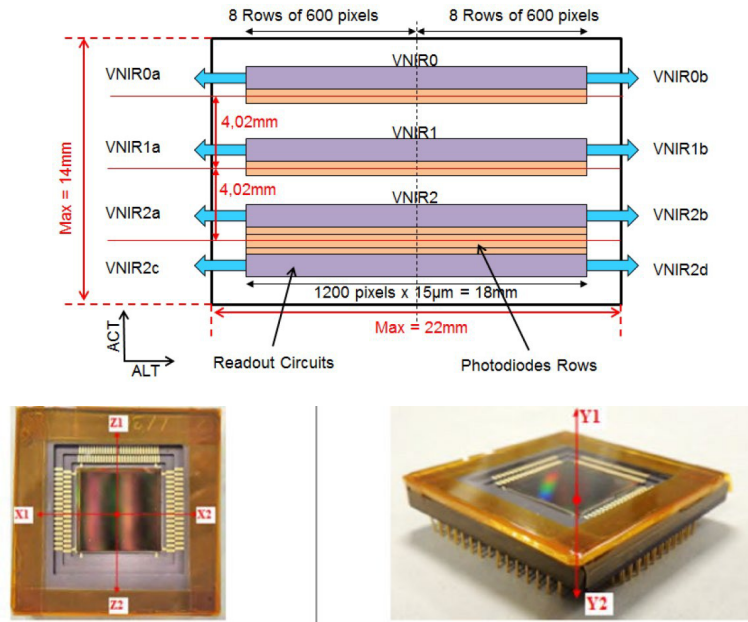


Figure 8. Schematics of the VIS detector (top), picture of the detector package (bottom) (courtesy of ADS - ISAE)

SWIR detection chain

The SWIR detector is composed of a n/p HgCdTe (or MCT) detection layer, hybridized on a Read Out Integration Circuit (ROIC), based on CMOS technology [15]. It features four photodiode sub-arrays, two of them are binned to increase the signal in VNIR3 and the two others are associated to SWIR1 and SWIR2. Each photodiode comprises 12 rows of 1200 pixels (cf. Figure 9). The TDI process can be applied to all 12 rows but a selection/deselection process is implemented to allow discarding defective pixels. Up to 2 pixels per column can be deselected without affecting the SNR performance. Contrary to the other two detectors, the TDI summation is performed on-chip. The SWIR detector is operated at 200 K, and is integrated in the Passive Optical Bench (POB).

TIR detection chain

The TIR detector relies on a new generation of LWIR and VLWIR technology able to provide large ALT dimensions and high data rate. Two low dark current p/n MCT photodiode arrays hybridized on large ROIC based on CMOS process compose the TIR retina, covering the bands TIR1, TIR2, TIR3 (first PV array) and TIR-4 and TIR-5 (second PV array), as illustrated in Figure 10. The coverage of the ALT swath of the instrument is ensured by 1088 pixels. Each PV subarrays has 32 pixels in the ACT direction in which a readout window is selected in which the number of defective pixels is minimized. This, feature, coupled with pixel deselection prior to TDI performed by the FEE, allows maximizing the available SNR while maintaining an operable rate of pixels of 100%. A tradeoff on MCT absorber thickness is necessary to maximize the internal detection efficiency, favored by a thicker absorbing layer, and the detector MTF which benefits from a thinner layer [16]. The TIR detector is operated at 65 K in order to guarantee low dark current performance and is therefore enclosed in an actively cooled cryostat (cold optical bench - COB).

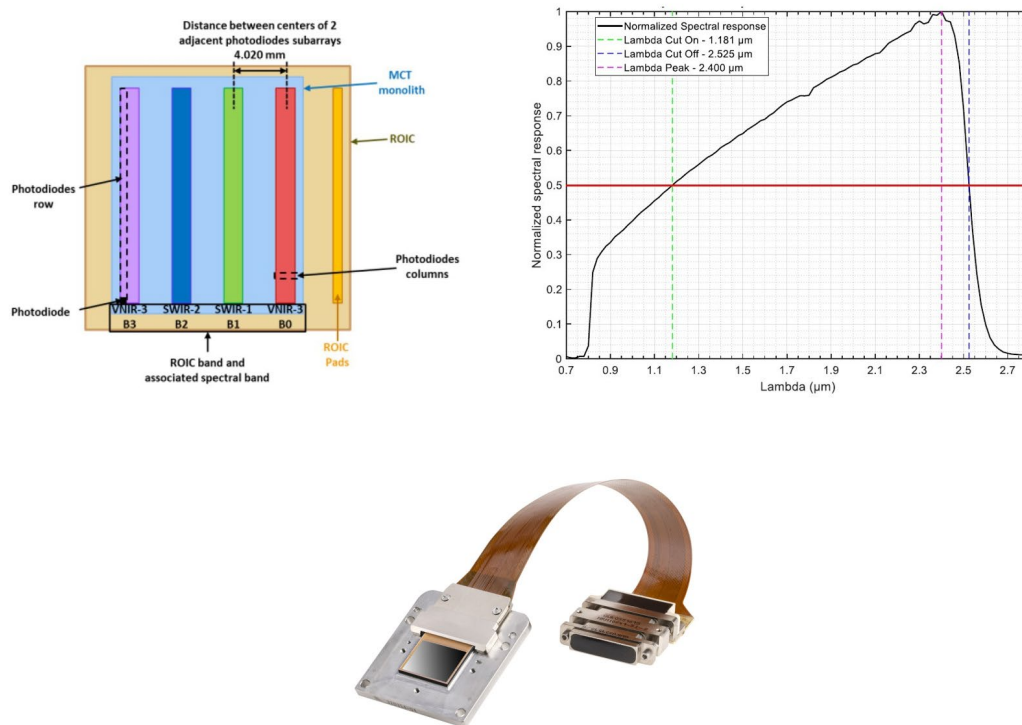


Figure 9. Schematics of the SWIR detector (left), typical spectral response (right), and detector package with flex (bottom) (courtesy of Lynred)

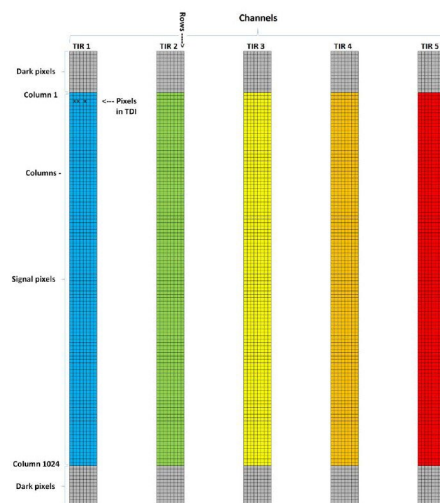


Figure 10. Schematics of the TIR detector layout

On-board radiometric calibration

The thermal infrared on-board calibration source (OBCS) consists of a surface black body with unregulated temperature slowly varying around 290K. Its large emissive surface covers the full pupil, and allows for the simultaneous radiometric

calibration of the complete detector area. An accurate monitoring of the black body temperature at all times, coupled with very good spatial uniformity over the OBCS surface are key to guarantee the quality of the radiometric calibration performed at every scan repeat cycle. The acquisition of the deep space port completes the TIR calibration scheme by providing a reference dark acquisition at every cycle.

The calibration of the solar channels is not sensitive to the variations of the thermal environment and only requires monitoring of long-term drifts. A large solar diffuser is mounted on the instrument aperture door and allows, as the OBCS in the thermal bands, for a full pupil calibration. The calibration of the solar bands is performed monthly by introducing the diffuser in front of the instrument aperture. This operation is identical to the calibration performed on Sentinel-2 MSI [17].

All calibration targets are integrated in positions addressable by the scanning mirror in its nominal operation motion. The optical chain from the calibration target up to the detector is therefore identical to the optical path followed by the Earth radiation minimizing by design calibration errors and avoiding the use of additional dedicated optics and mechanisms.

Mechanical design

The high mechanical stability required to meet the instrument pointing performance and to ensure the optical quality relies on a full SiC telescope assembly relying on AIRBUS heritage on previous programs such as Gaia, MSI, ATLID for ESA and export programs. The double cavity telescope is entirely integrated and aligned on a single SiC baseplate. The scan mechanism and the primary mirror, the two optical elements composing the front cavity, are integrated on one side of the baseplate. The secondary and tertiary mirrors of the solar and thermal bands, the first dichroic assembly (including the first filtering stage), and the three focal plane assemblies are integrated on the other face of the baseplate. The full SiC design guarantees a very high mechanical stability by minimizing the thermo-elastic deformation of the assembly along the orbit. Three optical heads of star tracker units are also mounted on the telescope structure, allowing improved performance of the satellite pointing performance.

The SiC telescope assembly is interfaced on the Instrument External Structure (IES) thanks to four CFRP (Carbon-Fiber-Reinforced Polymers) bipods. This structure accommodates the different electronic units (CDE, MDE and ICU), the Calibration and Shutter Mechanism as well as the calibration blackbody. The IES also supports all thermal radiators and the secondary hardware such as the heat pipes, electrical harness, connectors, optical baffles and MLI (Multi-Layer Insulator). The second important function of the IES is to interface the whole instrument onto the platform. The S- and K- band antennas, as well as the gyros, although platform components, are directly accommodated on the IES.

Thermal design

Control of the thermal environment is of particular importance for an infrared instrument, for two main reasons. First, every surface at a given temperature emits a thermal flux, which depends on its temperature and emissivity. Therefore, each component of the LSTM instrument contributes to the thermal background flux, which is, by nature, in the spectral range detected by the TIR detector. The thermal background must therefore be of limited amplitude, in order to leave sufficient dynamic range to the detector for the detection of the useful flux, and at the same time, remain extremely stable in order to maintain a good correspondence between the measured flux and the Earth brightness temperature, i.e. to maintain a good absolute radiometric accuracy. The stability horizon is reduced by the presence of the on-board calibration source allowing for a radiometric calibration of the TIR band every 5.7 seconds.

The second driving feature for thermal control is the operating temperature of the detectors. The low dark current performance that is necessary to ensure the high SNR (resp. low NEdT) is provided at 200K for the SWIR detector and 65K for the TIR detector.

These constraints translate in the need for a distinct thermal control for the telescope assembly (including scan mechanism and ambient optical bench), the passive optical bench and the cold optical bench.

Heating lines on the telescope baseplate, scan mechanism are dedicated to maintaining these elements around 20°. The high conductive thermal coupling of the mono-material SiC to SiC interfaces between the mirrors and the baseplate ensures that the optical surfaces are kept stable without additional heater control system.

The SWIR detector is enclosed in the Passive Optical Bench (POB) and is passively cooled down to 200 K thanks to a dedicated radiator, left unexposed to any earth or sun exposure over the orbit and combined to a parabolic baffle directing the Earth view out of the baffle surface in order to limit the incident heat flux. The detector package is linked to the radiator thanks to a thermal strap. The optical components inside the POB (cf. Figure 11) are naturally operated at cold temperatures. The stripe filters positioned very close in front of the detector are kept at the same temperature through conductive coupling, and the field lens and window temperature are around 215K and 250K respectively, through radiative transfer mainly.

The cryogenic temperature of the thermal detector (65 K) asks for an active cooling system. The TIR focal plane assembly is enclosed in a cryostat and connected to a pair of cryocoolers accommodated on the instrument external structure through dedicated cold fingers assemblies. The cryostat keeps the TIR optics (stripe filters, field lens and prism) at cold temperature, and a dedicated internal cold optical baffle limits the thermal background close to the detector surface.

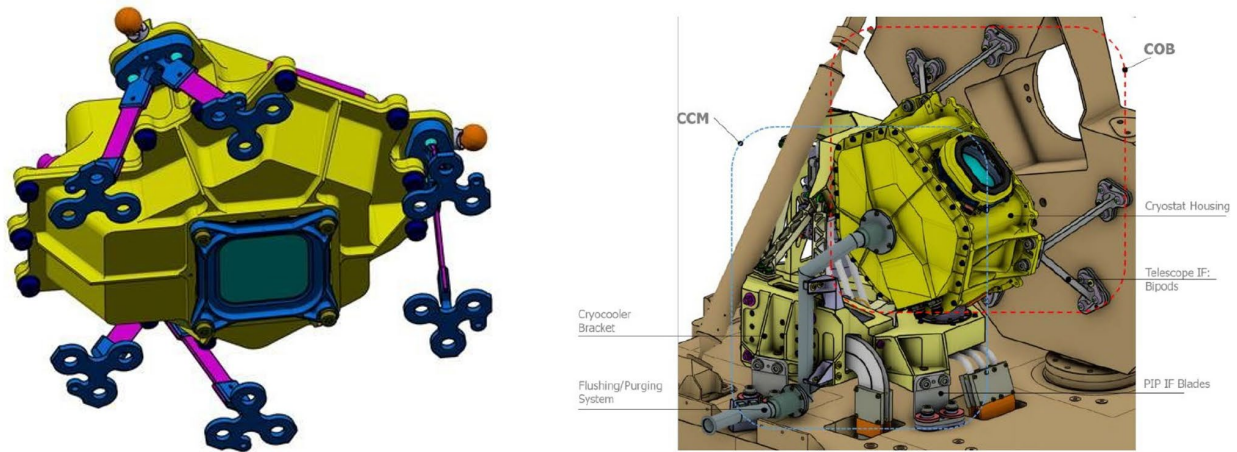


Figure 11. Passive Optical Bench (left) and Cold Optical Bench (COB) overviews

Technical budgets

The LSTM instrument is embarked on a recurring platform, and its overall dimensions, mass power need and data transfer rate are sized to match its capability (cf. Table 4).

Table 4. Instrument budgets

Size	2017 ×1790 ×1500 mm ³
Mass	<550 kg
Power	<500 W
Science data rate	137 Mbps (VIS), 177 Mbps (SWIR), 245 Mbps (TIR)

4. INSTRUMENT DEVELOPMENT PLAN

A large effort has been made since the beginning of the LSTM project to shape and execute an exhaustive and comprehensive development plan to successfully mitigate all the identified technological, technical and programmatic risks, while adhering as much as possible to the programmatic constraints of the project (cost and schedule).

The development plan is consequently mainly driven by the risk mitigation plan, early consolidation of performances and step-by-step verification starting with verification at unit and sub-system level and concluding with verification (and

qualification) at full instrument level. It is split according to the three standard phases B2, C/D & D1 where phase B1 encompasses predevelopment activities. The B2/CD program development is secured thanks to specific key points and supporting BB and EM activities.

The overall development logic is defined in consistency with the instrument requirements needs, the instrument prime know-how, as acquired on former similar programmes, and any specific industrial constraints (linked to the suppliers selected). Specifically for LSTM, the development logic has been tailored both at unit level and sub-system and system level to serve the above needs in the most efficient and effective way possible. Figure 12 shows the overall logic adopted for the LSTM instrument development.

The LSTM model philosophy supports a comprehensive development approach with intermediate model developments (BBM – breadboard model, DM – demonstrator model, EM – engineering model, EQM – engineering/qualification model) and flight models at units, assembly and instrument levels. This allows incremental risk mitigation and performance verification that secure the flight model performance and delivery schedule.

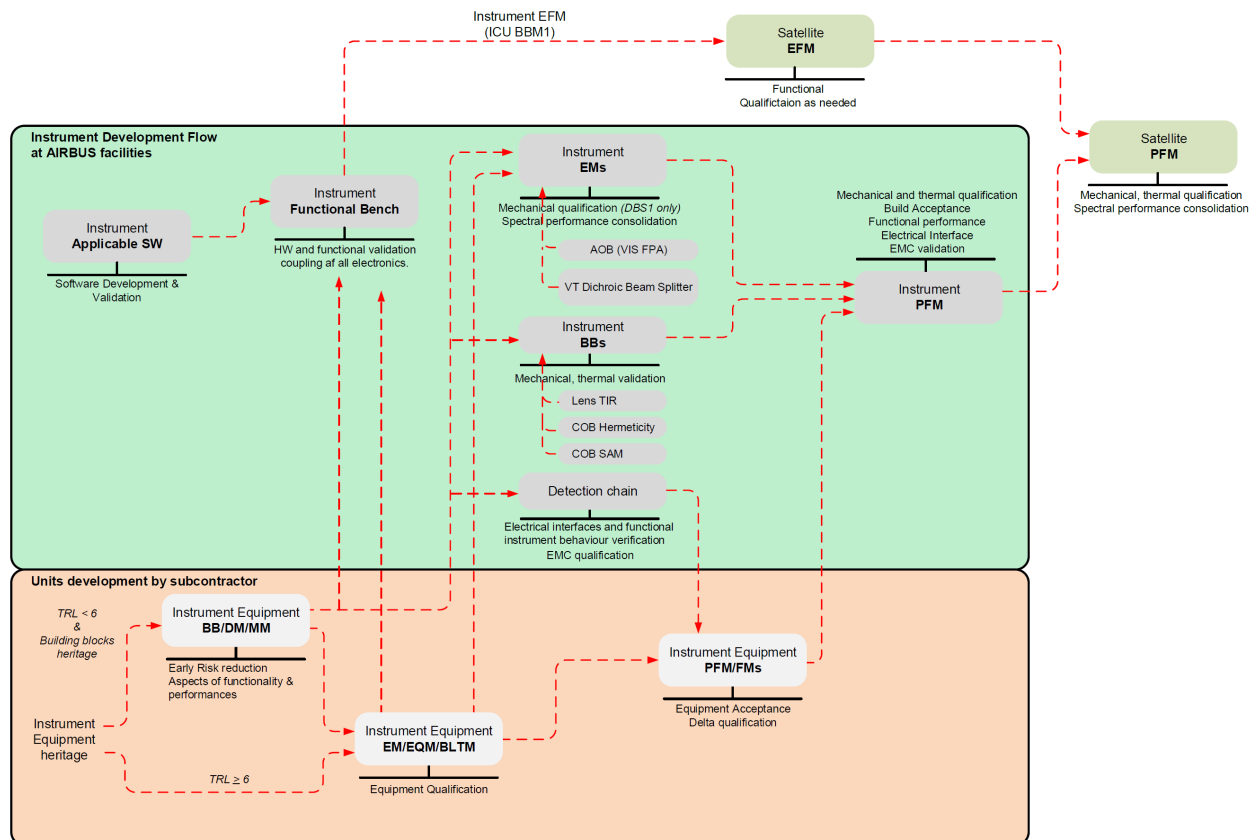


Figure 12. LSTM instrument development logic

In general terms, we can distinguish three separate group of activities during the instrument development: (a) technology maturation activities, or otherwise TRL6 activities, targeting to secure the very early technology demonstration for the most critical and novel elements, (b) BB and EM activities, targeting to consolidate and validate the adopted design prior to the FM unit/system MAIT activity (manufacturing, assembly, integration & test) as well as to consolidate the in-orbit performances in support of the critical design review of the mission, and, naturally, (c) FM manufacturing and qualification activities to support the delivery of a final qualified product.

For each level (unit or system) a dedicated model philosophy has been adopted (on a case per case basis, driven by heritage, technical and technological readiness, design maturity, and AIT complexity) and an associated test matrix derived for each of these models. As shown in the diagram, several of the early unit-level models are also used to “feed” the BB and EM campaigns, the detection chain validation activity, or the functional bench campaigns at instrument level.

TRL6 activities in LSTM

For all Copernicus expansion missions, including LSTM, a strong requirement for the demonstration of a sufficient level of technology readiness in support to the preliminary design phase of the instrument has been imposed on the overall development. The requirement to reach TRL6, the latest, by the Preliminary Design Review (PDR), has meant that an extensive survey of all critical technologies and critical functions of the instrument and the platform has been conducted very early in the program, resulting into a so-called LSTM technology strategy map, where any technological gaps compared to existing heritage or previous pre-development efforts, vis-à-vis the needs of the preliminary design, were identified. Based on these strategy documents, ESA derived a set of a minimum number of tests required to validate the TRL6 of each instrument unit on fully representative models for the corresponding critical function. Subsequently the instrument and platform prime flew down these requirements to tailored test campaigns at unit supplier level for the respective identified critical units. Overall, a set of about forty (40) test campaigns for a similar number of critical functions/demonstrators, have been conducted at supplier level for the most critical units, including the detectors, the filters, and the dichroics for the instrument and the mass memory and gyro units for the platform. The Table 5 below provides an example of the TRL6 campaign of the LSTM TIR detector (cf. Figure 13). The TRL6 campaigns were conducted in support of the successful closure of the instrument and system PDR.

Table 5. TRL6 test campaign for the TIR detector conducted at detector supplier level (AIM - DE). The table defines the critical function to be demonstrated (first column) associated with the various detector configurations (vertical blocks in the first column) vis-à-vis the various hardware models defined to use to demonstrate this critical function (i.e. ROIC, FPA or Full Detector Package model). The various tests on each of the hardware models are shown below the table.

	ROIC	FPA	DP
ROIC			
Performances		X ⁽¹⁾	X ⁽²⁾⁽³⁾
Reliability	X ⁽⁶⁾		
Rad. hardness	X ⁽⁷⁾	X ⁽⁸⁾	
FPA			
Performances		X ⁽¹⁾	X ⁽²⁾
Environmental robustness		X ^{(10)(11-H)}	
Rad. hardness		X ⁽⁸⁾⁽⁹⁾	
DP			
Interfaces		X ⁽⁵⁾	X ⁽³⁾⁽⁴⁾
Performances			X ⁽²⁾
Environmental robustness			X ^{(10-H)(11) (12)(13)}
Construction			X ⁽¹⁴⁾

(1) ESA predevelopment EO tests
(2) BBM EO tests
(3) Settling time/noise
(4) Geometrical tests
(5) Reflectivity test

(6) ESD/HCI
(7) HI
(8) TID
(9) TNID
(10) HTS
(11) Moisture
(12) Shock/Vibrations
(13) Thermal Cycling
(14) CA

(H) TRL6 covered by heritage

EM campaign (unit level)

This campaign encompasses all intermediate models used to validate the design, derisk the MAIT campaign and secure an early demonstration of the performance and it applies equally at unit level and at Instrument system level, as well as the timely delivery of the flight units. Depending on the risk profile of each unit as well as the needs of the EM campaign at instrument level, a set of intermediate models was defined for each LSTM unit. For each of those campaigns, specific objectives are agreed in advance, focusing either on validation and consolidation of performances and/or on design verification against specified environment, and/or on AIT derisking, and/or on verification of interfaces.

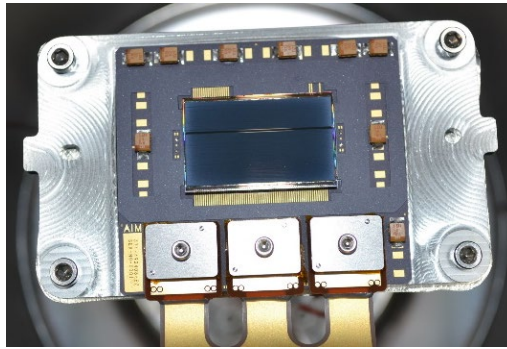


Figure 13. The LSTM detector in open package configuration in one of the models used for the TRL6 demonstration (courtesy of AIM DE).

Table 6 shows, as an example, typical intermediate models adopted for the development of filters and dichroic units of LSTM and their respective objective. Figure 14 below shows the SWIR DPF (detector plane filter) assembly MM model mounted onto the GSE ready for its TVAC testing at unit supplier level.

Table 6. typical model philosophy adopted for the development of the LSTM filters and dichroics

Model	Representativeness	Objective
Development Model (DM)	Coated substrate only	Demonstration TRL6 of coating
Mechanical Model (MM)	Uncoated substrate with representative mechanical mounting	Verify the mechanical mounting concept and its environmental stability / Supports LSTM intermediate-model test campaigns.
	Uncoated substrate	Used for the EM DBS1 assembly model.
Engineering Model and Engineering Qualification Model (EM/EQM)	Fully representative model	Used at instrument level to support integration, verification, and qualification activities.

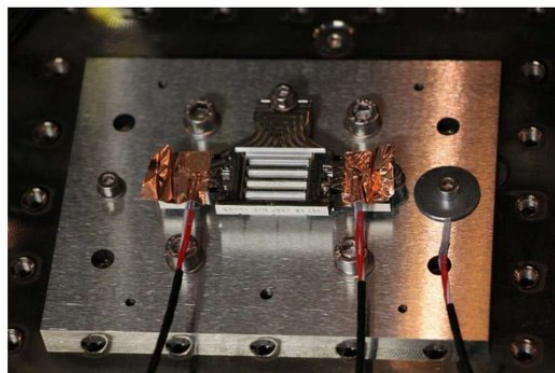


Figure 14. DPF-SWIR-MM fixed onto GSE in TVC-chamber (courtesy of Materion Optic Balzers Jena (OBJ)). Temperature sensors are fixed on the DPF-SWIR-MM via copper tape. As part of this campaign the MM model was cycled 51 times between 168 K and 323 K at a pressure of < 10-5mbar. The dwell time was > 25 min [21].

EM campaign (instrument level)

At instrument level, the EM campaign was designed to secure the design, performance and development of three major sub-systems of the instrument, namely the Cryogenic Optical Bench (COB), the Ambient Optical Bench (AOB) and the VTDBS dichroic assembly and retire their respective AIT activities, before embarking on the PFM/FM2 MAIT. More specifically, the following activities have been designed and implemented as part of the instrument level EM campaign:

The Cryogenic Optical Bench (COB) EM campaign consists of:

- A breadboard model (BB) of the Lens Assembly, aiming to carry out a mechanical and thermal stability derisking of the lens mounts. The test outcomes are used to validate the lens mechanical mounting and the consolidation of the LSTM Instrument CDR and to allow the start of manufacturing of flight mechanical parts (cf. Figure 15).
- A second breadboard model (BB) is foreseen to validate the cryostat hermeticity performance and assess impact of depressurization on alignment during ground tests. This BB contributes (also called BBH) to feed cryostat parts MRR and to secure the on-ground verification activities carried on the COB operated at ambient pressure (cf. Figure 16).
- A third model was developed for COB alignment derisking and dynamic behavior characterisation (Structural Alignment Model - SAM) (cf. Figure 20). The outcome of this campaign is used to inform the alignment procedure in terms of introducing a pre-compensation /de-focus during alignment in ambient of the COB bench in front of the telescope.

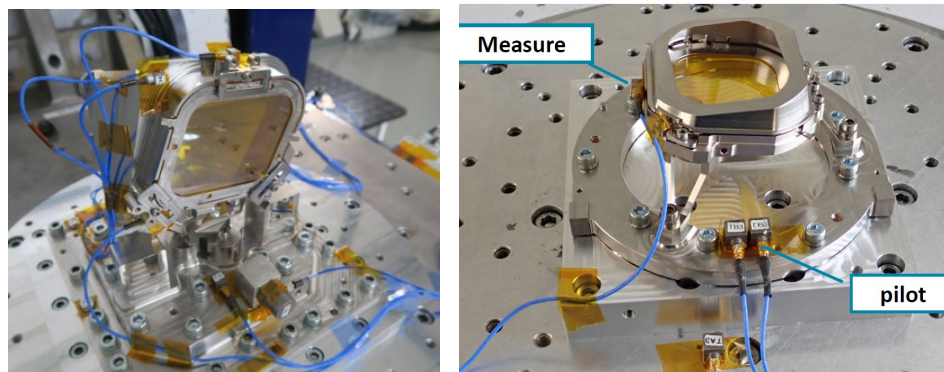


Figure 15. DBS1 MM mechanical test (left) and TIR lens BB mechanical test (right).

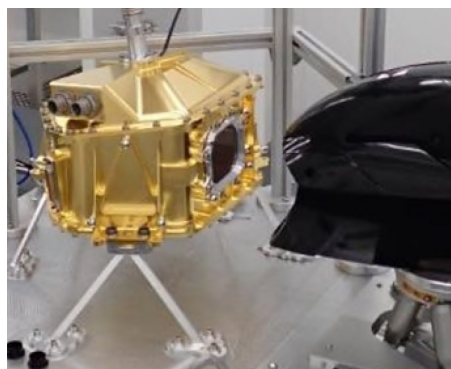


Figure 16. Hermeticity BB under test (WFE measurement of the COB APW- anti pollution window)

Ambient Optical Bench (AOB) EM campaign consists of:

- An Engineering model (EM) is foreseen to Derisk AOB alignment phase (same OGSE used for AOB EM and AOB+POB PFM (cf. Figure 18), &
- A DBS2 assembly EM model to confirm DBS2 mechanical strength and stability in its mount, as well as derisk the AIT phase (cf. Figure 17).
- A Filed Lens (FL EM) model, to validate the lens thermo-mechanical strength and stability (in their mounts) and derisk the AIT phase (cf. Figure 17).

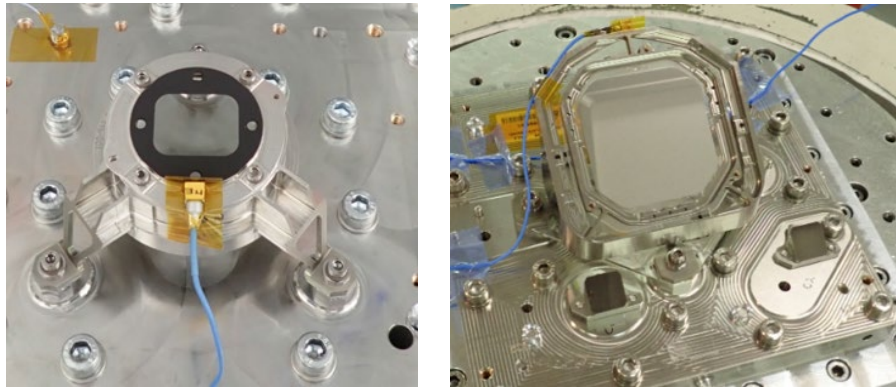


Figure 17. AOB EM FL ready for mechanical test (left) and DBS2 EM ready for dynamic test (right)

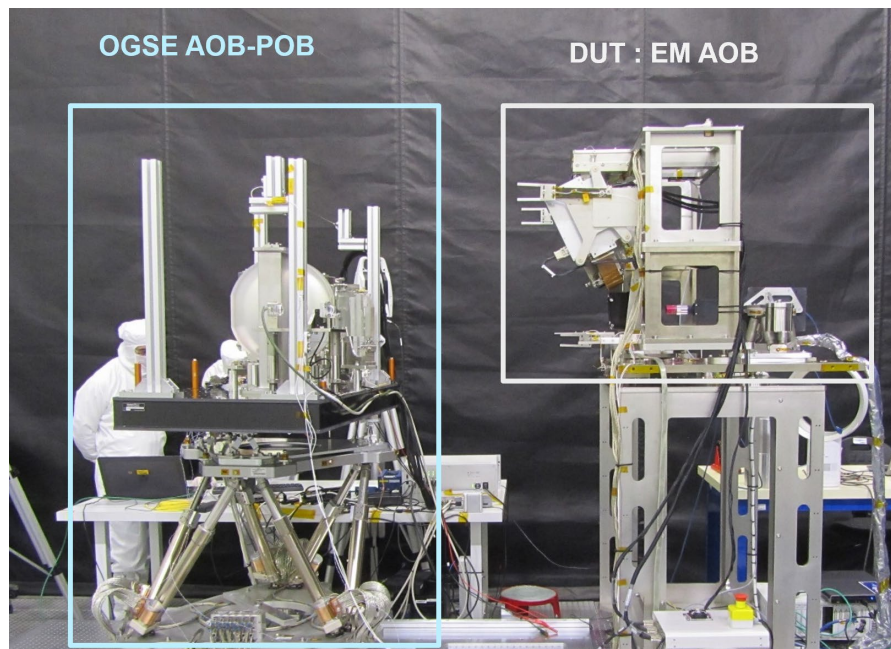


Figure 18. AOB EM campaign. A dedicated OGSE (specific development within the LSTM project) is positioned in front of the EM AOB. A translation rail allows the OGSE to switch between «Remote Configuration» (see picture above) or «Close configuration»

VT Dichroic Beam Splitter (VT-DBS) sub-assembly

- An Engineering model (DBS1 OM – optical model) is foreseen to characterize the spectral performance under FM-like optical illumination and validate the spectral performance prediction model (cf. Figure 19).
- A second Engineering/Mechanical model (EM DBS1 MM) was implemented to qualify thermally and mechanically the VTDBS sub-assembly (cf. Figure 15)

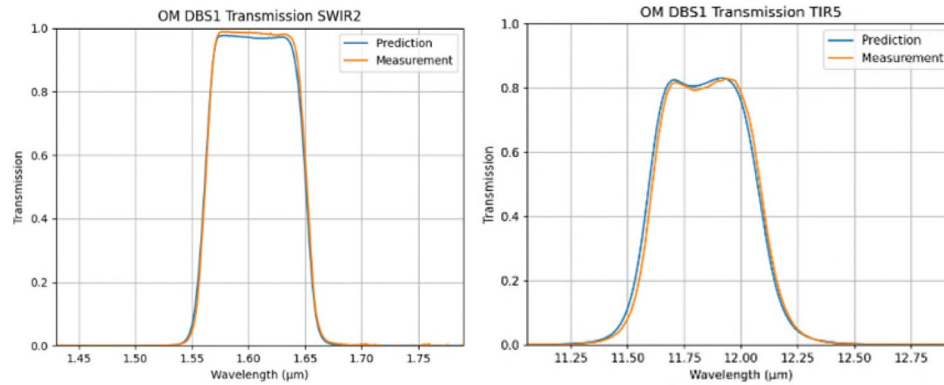


Figure 19. DBS1 OM campaign results. The campaign has confirmed the validity of the spectral model prediction within measurement uncertainty in line with system requirements

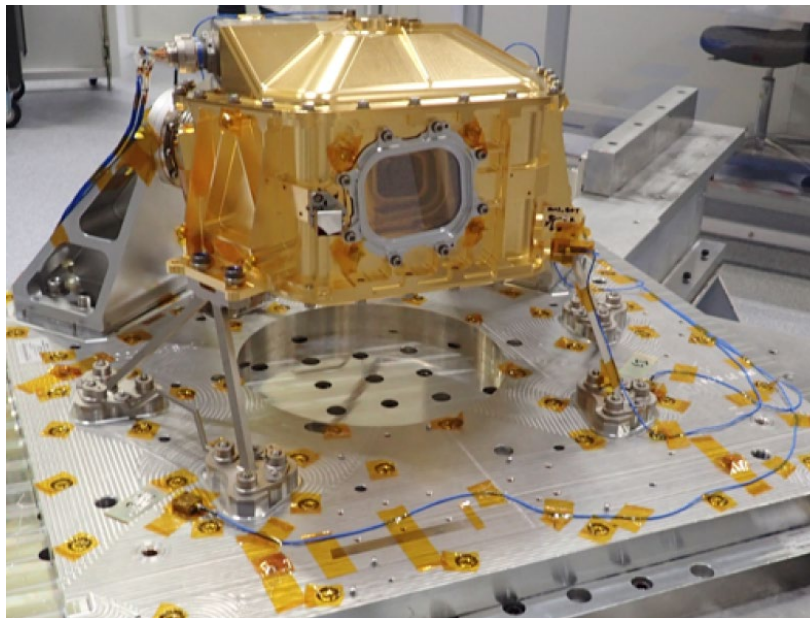


Figure 20. COB SAM during shock test.

All pictures above comes from the EM test campaign at instrument level. The BB/EM campaign of the instrument was completed in support of the instrument CDR.

Instrument electrical and functional bench

The instrument Functional Bench aims to consolidate the electrical architecture of the LSTM instrument. At early phase C stage, Hardware Test Couplings (HTCs) were conducted to test the TM/TC from functional and electrical point of view and to validate the interfaces between the Instrument Control Unit (using the ICU BB model: BB1), the Front-End Electronics Development Models (DM), the Mechanism Drive Electronic Engineering Model (EM), and the CryoCooling System Drive Electronics Engineering Model (EM). For these tests a preliminary software version was used.

After delivery of the software version V1, the Instrument Functional Bench is step by step completed by the electronics, at Engineering Models or Engineering Qualification Models grade, aiming to perform non regression test to verify the hardware and functional implementation (via Functional tests campaigns – FTCs) with incremental versions of the Instrument Application Software (IASW).

Detector chain validation activities

A major element of the LSTM development logic has been the incorporation at system level of a series of coupling tests among the detection chain units (i.e. front-ends and detectors), with incrementally more representative units. This set of activities which has started early and spanned over a long period of time has been essential for the gradual de-risking of the interfaces between all three detectors and their respective front ends, as well as for the step-by-step consolidation of the detection chain performances. As such this activity has been extremely important for validating key radiometric performances to support the proper consolidation and closure of the instrument CDR (see next Section).

The overall logic and associated hardware models (detectors and front-end electronics) that have facilitated the Detector chain activity at instrument prime level, are shown on Figure 21.

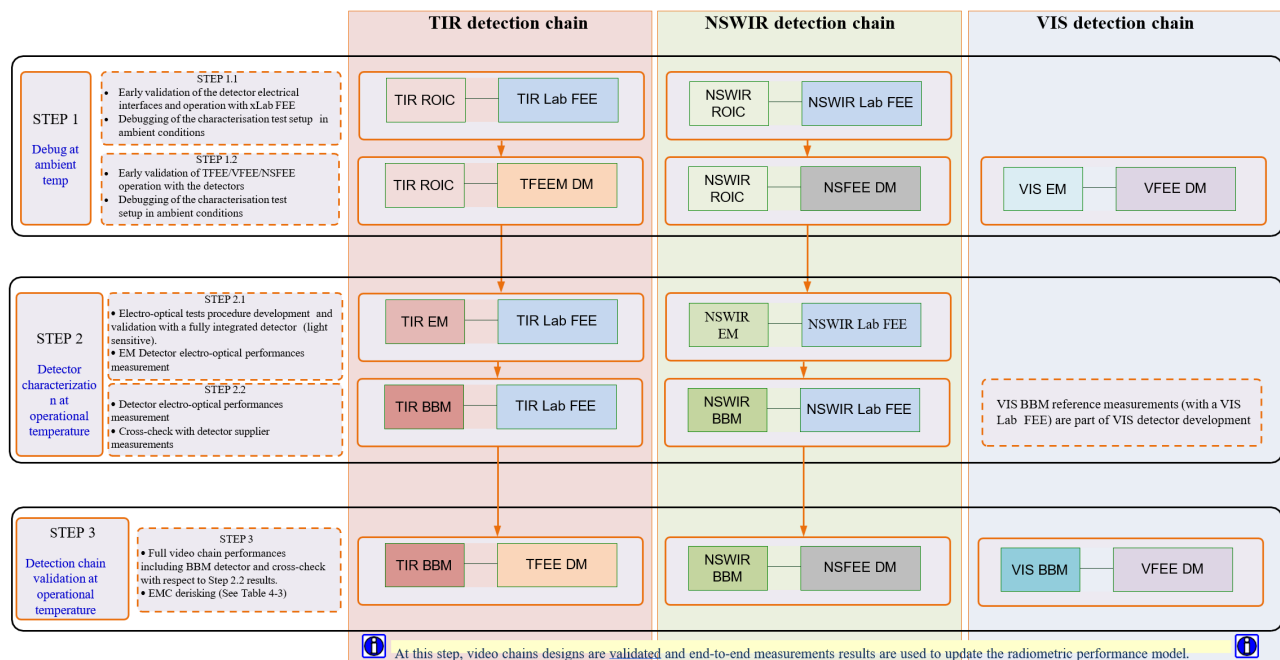


Figure 21. Detection chain validation activities for LSTM in the Airbus Detection Lab. An incremental approach is adopted with early models in the beginning and increasingly more mature/representative models for the last steps to facilitate a step-by-step de-risking, characterisation and validation of the detector chain performances for the three detection chains of the LSTM instrument respectively (TIR, NSWIR and VIS).

5. PREDICTED END-2-END PERFORMANCES

The Instrument CDR (Critical Design Review) took place in Q4/2024 followed by the Satellite CDR in Q1/2025. One of the key objectives of the CDR was to consolidate performances and confirm compliance to key mission requirements for the lifetime of the mission. We are reporting in this section the CDR status of the predicted LSTM performances.

As explained above, the consolidation of the mission performances (mostly driven by the instrument performances) is conducted and updated throughout the system development and in increasing levels of confidence. This is visually shown in Figure 22.

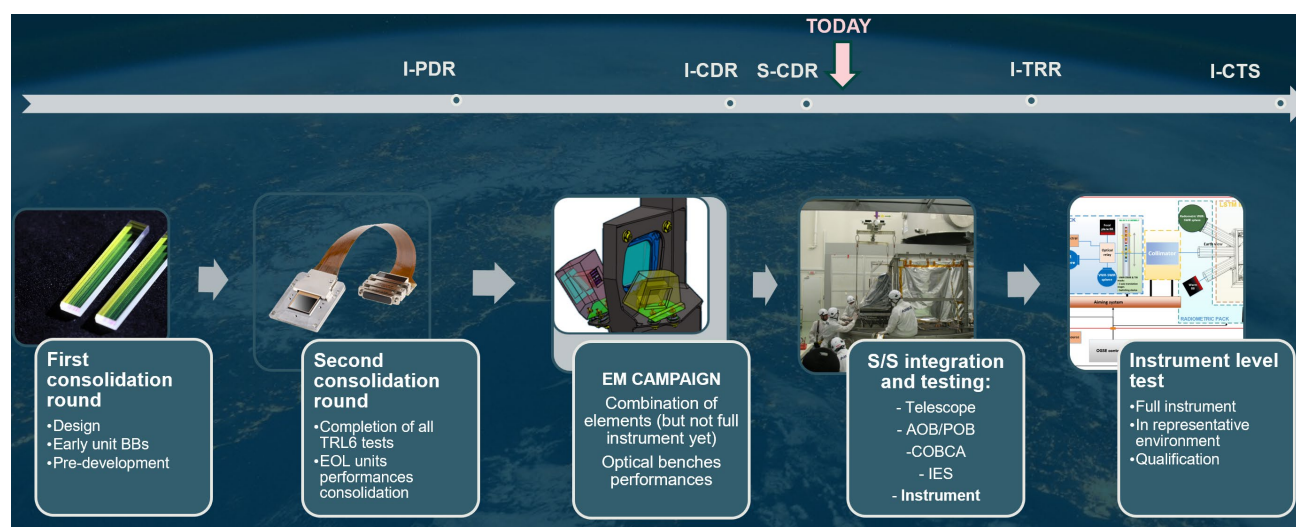


Figure 22. Process of performance consolidation throughout project development

The reported performances in the current section are provided with a high level of confidence, since they are supported by actual hardware measurements either at unit level (from measurements on intermediate models at supplier level) or by hardware measurements on s/s level at Instrument prime level obtained throughout the EM campaign of the instrument as explained in the previous section, as well as the satellite level CDR analysis and contributors. For example, the radiometric performances reported here are in line with the activities described in Figure 23 (first two sections; green and blue).

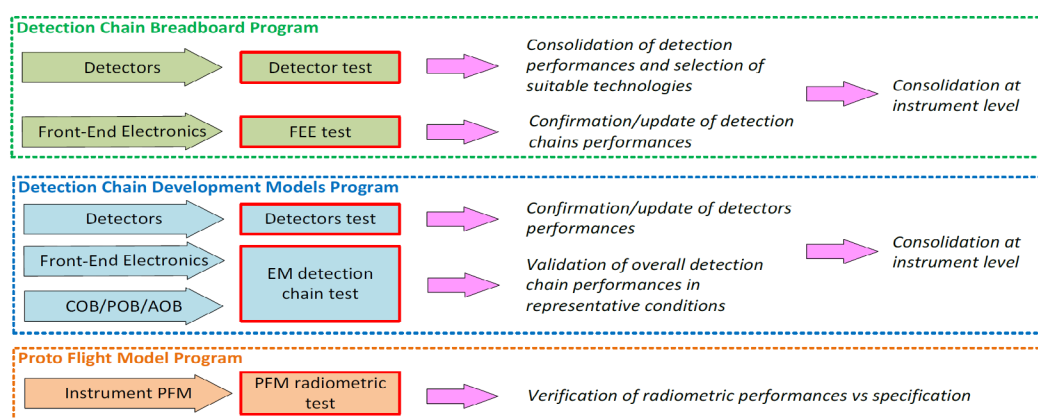


Figure 23. Instrument radiometric performances consolidation and final verification logic. This paper reports on the consolidation of the performances derived from the activities of the first two blocks (green and blue)

Further updates on the performance are expected to come through the PFM/FM2 MAIT campaign (currently ongoing) and of course final updates (and verification) before launch, through the instrument characterisation and calibration campaign. The latter is currently foreseen, for the PFM instrument, in Q1-Q3/2028.

Geometrical performances

Geometrical performances have been consolidated based on gyro performance estimation, TED (thermos-elastic analysis based on predicted thermal maps in orbit), scan mechanism measured performance (using actual measurements on a fully representative model in closed loop control configuration), system level micro-vibration analysis based on measured and/or simulated exported torques and assuming cryocooler frequency tuning, as well as (for performances requiring GCP - Ground Control point refinement) image matching algorithm and a robust per-pixel in-flight characterisation update. All geometrical performances are compliant to the target key specification (see Table 3 in Section 2 above).

Figure 24 shows the predicted evolution of SSD at L1b (native sampling) over the swath, thus securing a higher native sampling everywhere compared to the L1c user product. Geolocation performances across the swath with and without GCP are provided in Figure 25.

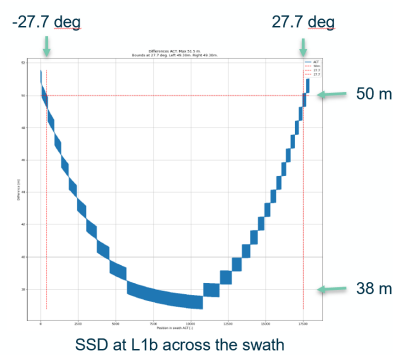


Figure 24. Native spatial sampling distance (L1b) evolution across the swath of the instrument. L1b SSD remains everywhere smaller than 50m and gets down to approximately 38m close to Nadir.

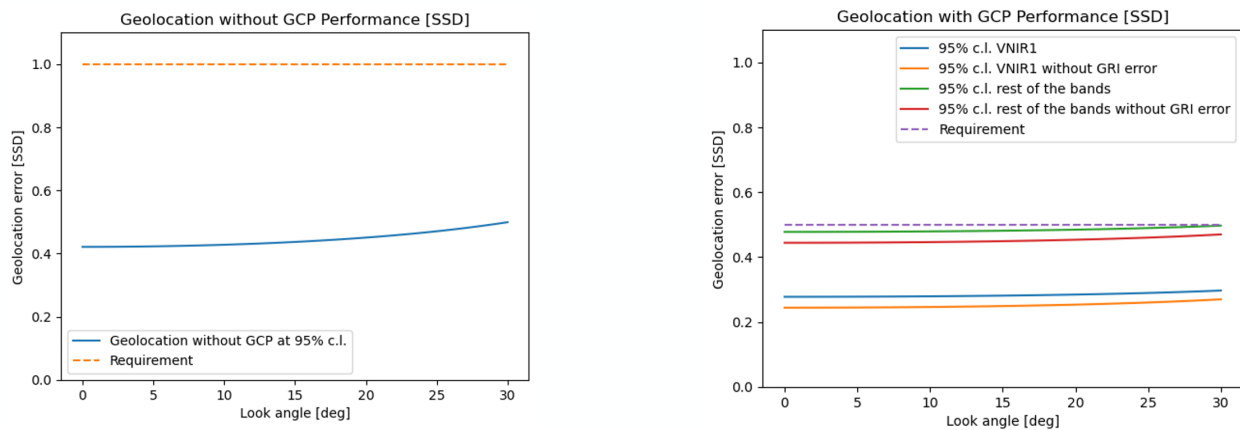


Figure 25. Geolocation performances with (left) and without (right) Ground Control Points across the swath. Full compliance is expected and even with a large margin for the non GCP refined performances.

Co-registration performances are specified against the S2 GRI as well as spatial co-registration knowledge (Beginning of Life – BOL) among the different bands (see Table 3 in Section 2 above for the required performance). In both cases, predicted performances are well compliant over the entire swath of the instrument (see Figure 26). In worst case

assumptions, some degradation could be expected for the End-of-Life (EOL) case of the band co-registration towards the edge of the swath (not reported here), driven by the evolution in time of the pointing performances of the scanner.

It is worth noting that geolocation and co-registration performances drive radiometric error in scenes of spatially non-uniform nature. Details of this impact and how this is handled in LSTM in terms of radiometric error and uncertainty propagation can be found in communications published elsewhere [23].

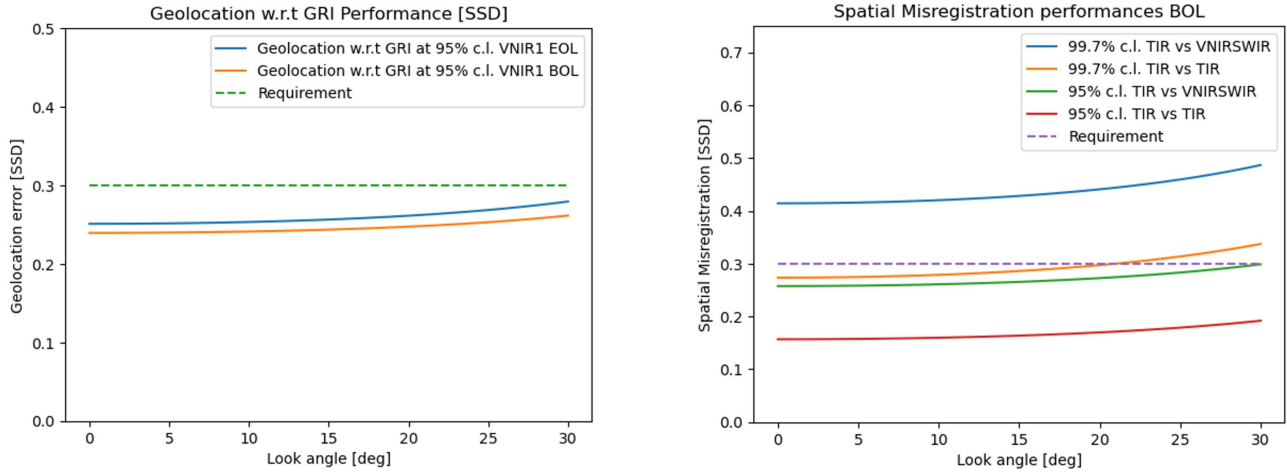


Figure 26. Predicted co-registration performances with the S2 GRI (left) and among different LSTM bands (right) showing compliance with the requirements. Performance at 99% confidence level is shown for information.

Radiometric Resolution Performances

In LSTM, radiometric resolution is specified in terms of SNR for VNIR and SWIR bands, and in terms of NeDT for the TIR bands in units of mK (see Table 1 and Table 2 in Section 2) and at a given reference level of input radiance or equivalent Brightness Temperature (respectively for the TIR bands) at the entrance to the instrument. The below reported predicted performance for the three different detections chains in LSTM is consolidated using tests both at supplier level and at the instrument prime detection Lab level i.e. using the stepwise approach adopted for the detection Lab development program (see Figure 21 above). They are based on end-to-end electro-optical tests using fully representative development models (DMs) for the front-end electronics (FEE) and fully representative detector breadboard models (BBMs) or detector Engineering Models (EMs). Performances are adapted to the latest CDR prediction for the system level fluxes. For the EOL prediction, the impact on the SNR (respectively NEDT) is calculated using test data coming from the environmental campaigns at detector level (e.g. dark current or ROIC noise increase due to radiation) as well as assumptions based on heritage on the loss of throughput through life.

As with all instruments based on focal planes featuring large pixel arrays, there is a natural slight dispersion of performance among the different pixel elements. Detector parameters such as DSNU (Dark Signal Non-uniformity) or PRNU (photo-response non-uniformity) are direct measures of this fact. Such focal plane level dispersion propagates and manifests itself in the system level prediction of the SNR (resp. NEDT) as a slight variation of the system level performance among the different pixel elements (in the case of the LSTM, this means a slight variation of the SNR/NEDT in the ALT direction) (see Figure 27). To secure the compliance of all pixels of the FPA with the mission requirements, a careful trade considering these parameters in combination with the prediction for the BOL and EOL fluxes, leads to the selected operational point of the detector.

In the following tables (Table 7 and Table 8), we report on the SNR/NEDT CDR predicted performance per LSTM band, BOL and EOL. For the sake of simplicity, we report here CDR predictions for minimum guaranteed performance for the “majority” population, this being defined as 86% of the pixel population per LSTM FPA. The figures indicate

comfortable margins with respect to system requirements. Outliers (or “worst case” pixels) are not reported here, as final performances in that respect will depend on yield and the selection of the FM candidates from the FM detector lot (currently under finalization).

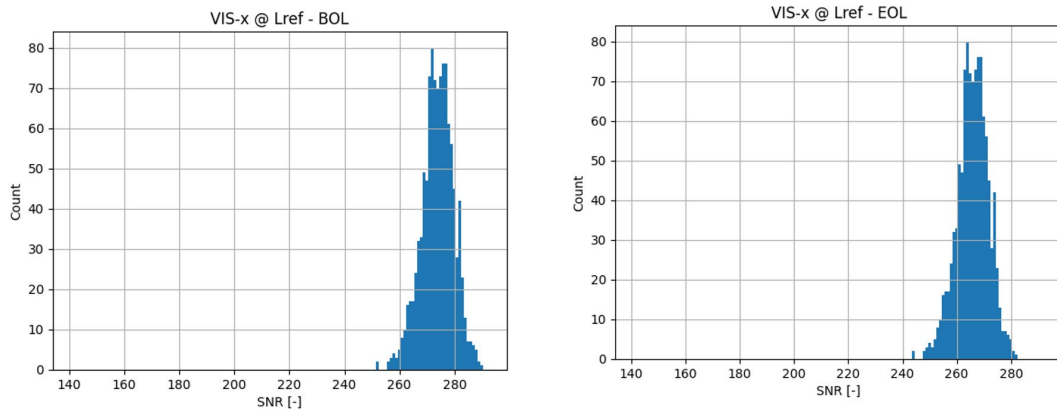


Figure 27. Typical dispersion of system SNR performances BOL (left) and EOL (right) among the pixel population.

Based on CDR predictions, even for the “worst case” pixels good compliance is maintained for most of the bands and even for the EOL predictions. For instances where this is not the case, the deviations are only for a very limited number of pixels (out of the 1000 pixels per FPA) and still well within a few % of the specification. Some information from the FM detector campaigns can already be found in the open literature [22].

Table 7. EOL prediction of NEDT performance for the LSTM TIR bands (CDR status). “Majority” means 84% of the total pixel population ALT. The NEDT performance is provided for the reference brightness temperature as well for a temperature of 270K (threshold lower dynamic range), to illustrate the nominal evolution of the performance as a function of the scene brightness temperature. Naturally, for BTs higher than the reference ones, the radiometric resolution of the instrument will be further improved.

Brightness Temperature	Unit	TIR-1	TIR-2	TIR-3	TIR-4	TIR-5
Specification @ 300K	[mk]	100	100	100	100	100
NEDT @ 300 K (Tref)	[mk]	< 87	< 84	< 83	< 80	< 91
NEDT @ 270 K	[mk]	< 125	< 118	< 115	< 103	< 112

Table 8. BOL and EOL prediction of SNR performance for the LSTM VNIR and SWIR bands (CDR status). “Majority” means 84% of the total pixel population ALT. The SNR performance is provided for the reference radiance input. Naturally the SNR performance (shown for information) will degrade for lower radiance levels and improve for higher radiance levels. Very large margins exist for all the VNIR bands and less so for the SWIR bands, notably for the SWIR-2 band and its EOL performance.

Radiance Level	VNIR-0	VNIR-1	VNIR-2	VNIR-3	SWIR-1	SWIR-2
Specification	162	142	100	114	100	133
SNR BOL @ Lref	> 258	> 268	> 192	> 144	> 123	> 152
SNR EOL @ Lref	> 237	> 260	> 189	> 134	> 114	> 139

Absolute Radiometric Accuracy (ARA) Performances

Absolute radiometric accuracy is a complex system level performance that is driven by several contributors, some of which might be also scene-dependent. The actual performance is also intimately linked to the selected in-orbit calibration concept. The figures below (cf. Figure 28) report on the predicted ARA performance (CDR status) for each of the LSTM bands over the applicable dynamic and for the case of uniform scenes.

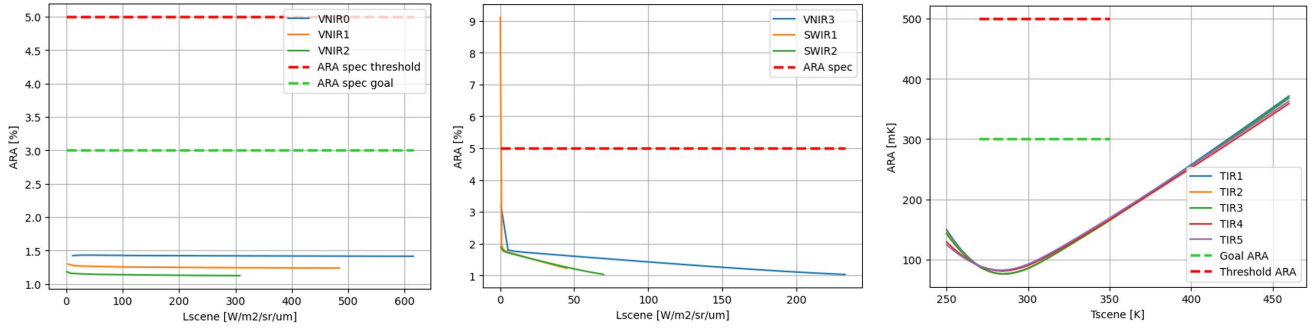


Figure 28. Absolute radiometric accuracy performance for the LSTM bands over uniform scenes (prediction)

The ARA performance for uniform scenes is very good and with comfortable margins against the specification. The only exception is the ARA for the band SWIR1 and for very low radiance levels, however, the reported value (above the 5% specification) is still acceptable for this band primarily being used for Cirrus cloud detection.

In LSTM, a large effort has been made to secure the ARA performances even for non-uniform scenes. As with all instruments, for scenes featuring high contrast features, instrument effects such as straylight (SL), or detector level exotic effects (offset, lag, and/or crosstalk) can lead to degradation of the respective ARA performances. In LSTM, despite very good performances being already achieved in terms of straylight control by optical design, as well as exotic effects of limited amplitude as characterized at detector level dedicated activities, some degradation of ARA is to be expected for scenes of very high spectral or spatial contrast. While we do not report on this here (more details can be found here: [24]), it is mentioned here that the baseline strategy for LSTM (to be confirmed by instrument level tests) is to a-priori correct for SL (even with kernels to be update in orbit) as well as for inter-band crosstalk in the case of TIR and SWIR bands, and temporal lag in the case of SWIR bands. For straylight correction in particular, the correction algorithm is based on the evaluation of the stray light signal from the acquired scene and the instrument PSF calibrated on-ground (and an in-orbit update using the Moon), which is then subtracted from the acquired scene. This type of algorithm is successfully implemented on several other ESA missions [18][19][20]. Such corrections are expected to guarantee excellent robustness of the ARA performance against real or high contrast scenes and will secure the LSTM mission as a golden standard in terms of radiometric accuracy.

Modulation Transfer Function performances

Modulation transfer function (MTF) is a key metric defining the capacity of a measurement to resolve features of a given frequency. Defining a very high sampling frequency alone does not guarantee that the resolution of the system is equally high. Such capability is driven only by the actual MTF performance achieved for these frequencies. Predictions for the MTF performance in the various LSTM bands are shown in Figure 29 below.

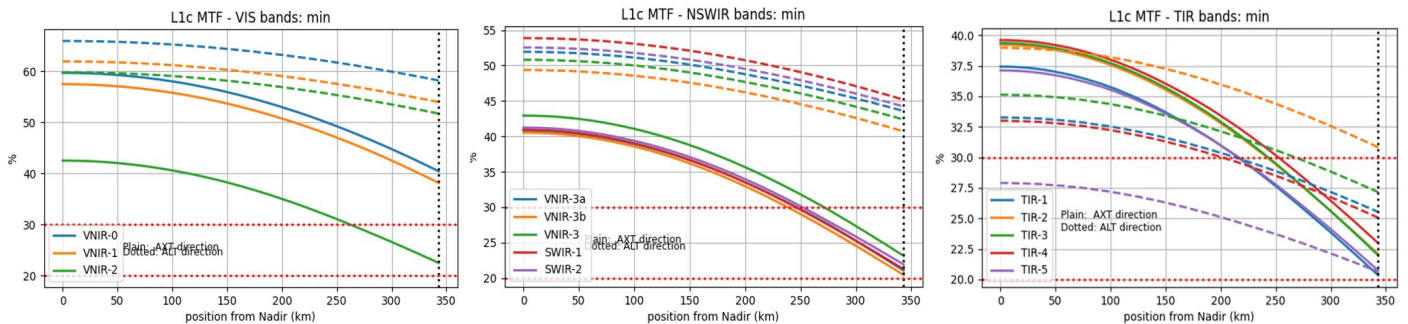


Figure 29. Minimum ACT and ALT MTF performance over the swath for the LSTM VIS (left), SWIR (center) and TIR (right) bands at the L1c Nyquist frequency (prediction). MTF performances are the result of several contributors (detector, electronic, stability, pointing, micro-vibrations, etc.) both at instrument and platform level. Individual contributors are not shown here

The reported MTF performances varies over the swath. This is natural since the reporting is done for the Nyquist frequency of the L1c product (50m), while as described above, the native sampling of the instrument is in fact higher than 50m, the more so the closer we get to the Nadir. Therefore, the very large values displayed at cases does not automatically mean a risk for aliasing since the native sampling is always (for all points of the swath) higher than the L1c final product.

What is not directly shown in the graphs above is that even considering the MTF at the L1b Nyquist frequency in some cases, indeed it might exceed the 0.3 value specified. This in turn could cause indeed a concern for aliasing. This is the case for examples for the three VIS bands (VNIR1-3) for both ALT and ACT, and less so for the SWIR bands and only for the ALT direction. Preliminary analysis done with scenes pertinent to the primary user case of LSTM has nonetheless confirmed that aliasing on those cases won't be an issue.

Spectral performances

CDR predictions on spectral performances have confirmed compliance with the system level requirements, both in terms of bands definitions (central wavelength and bandwidth) but also in terms of tolerances. The following figures (Figure 30 and Figure 31) give the Instrument Spectral Response Function (ISRF) for the various LSTM bands as of the CDR status. IMPORTANT: these are currently predictions fed by lower-level measurements on key optical components at supplier level. Final ISRF performance will be provided at instrument level tests.

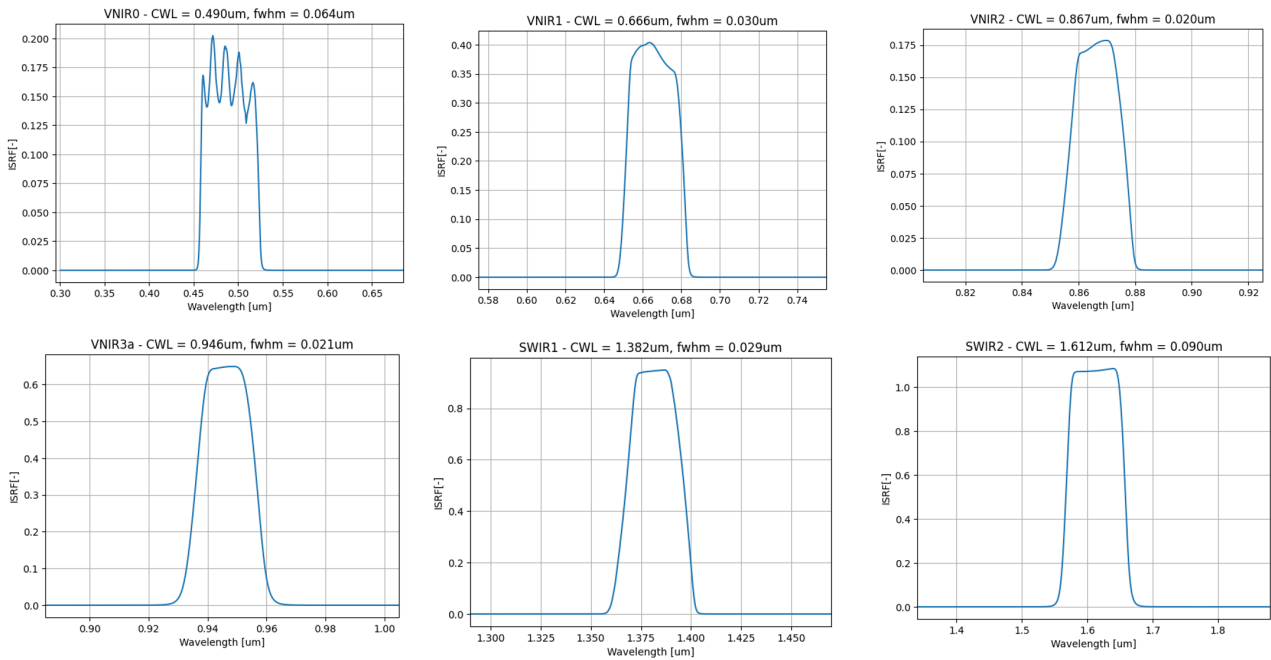


Figure 30. ISRF prediction for the VNIR and SWIR LSTM bands (CDR prediction). The rippling effect shown in VNIR0 is a direct consequence of the lack of antireflection coating in the VIS detector.

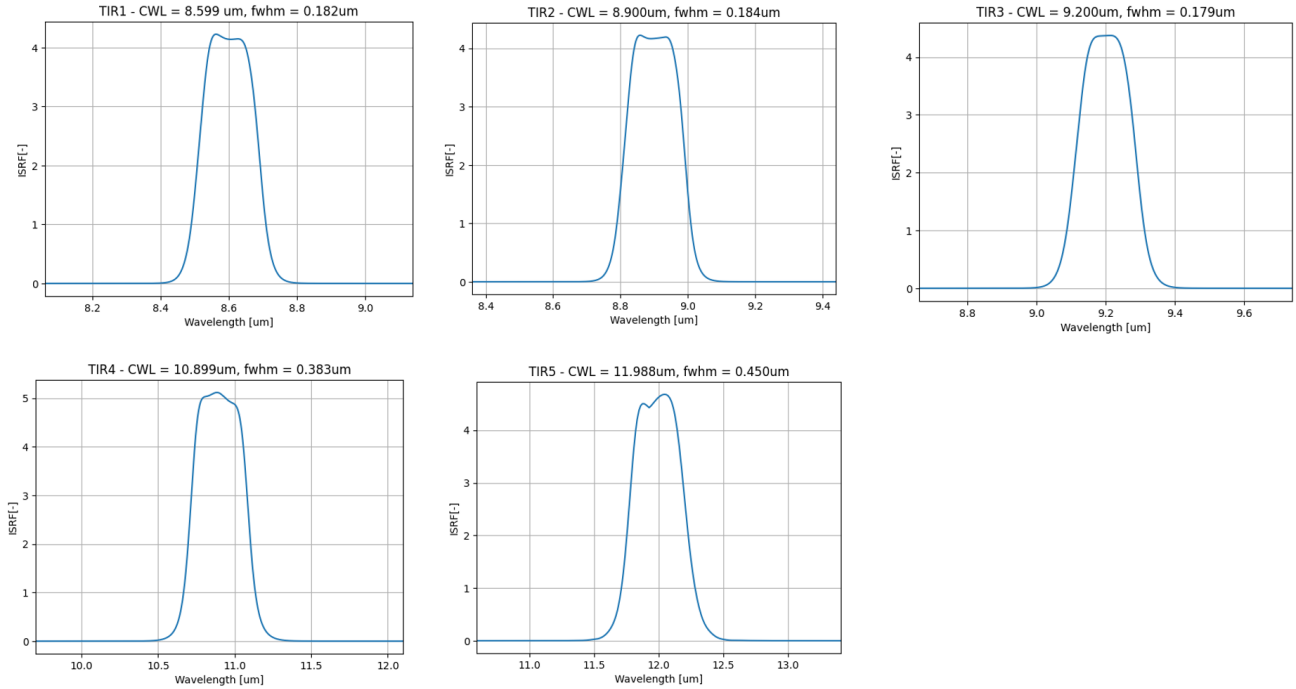


Figure 31. ISRF prediction for the TIR LSTM bands (CDR prediction).

6. INSTRUMENT AIT CAMPAIGN

The modularity of the LSTM Instrument leads to an optimized AIT sequence facilitated through the parallel integration of several sub-assemblies independently, and finally a global integration onto the Telescope and then onto the IES before the Instrument tests campaign. The AIT flow is based on four parallel assembly lines, eventually merging to the upper instrument assembly level for which the end-to-end performance is verified with dedicated environment tests (cf. Figure 32). A fifth line runs in parallel (not shown in the figure), which facilitates the functional verification of the instrument and the software development to support the instrument level tests.

The following teams are dedicated to parallel AIT assembly lines of all the flight models:

- the telescope line,
- the TIR or COB line,
- the NSWIR or POB, and the VIS or AOB line.
- the scan mechanism line

The PFM AIT instrument is currently well underway, with all subsystem AIT activities initiated. Details and status will be provided in future communications. Current planning foresees the completion of all instrument integration activities in Q4/2027 and an Instrument CTS in Q3/2028 for a launch campaign towards the end of 2029.

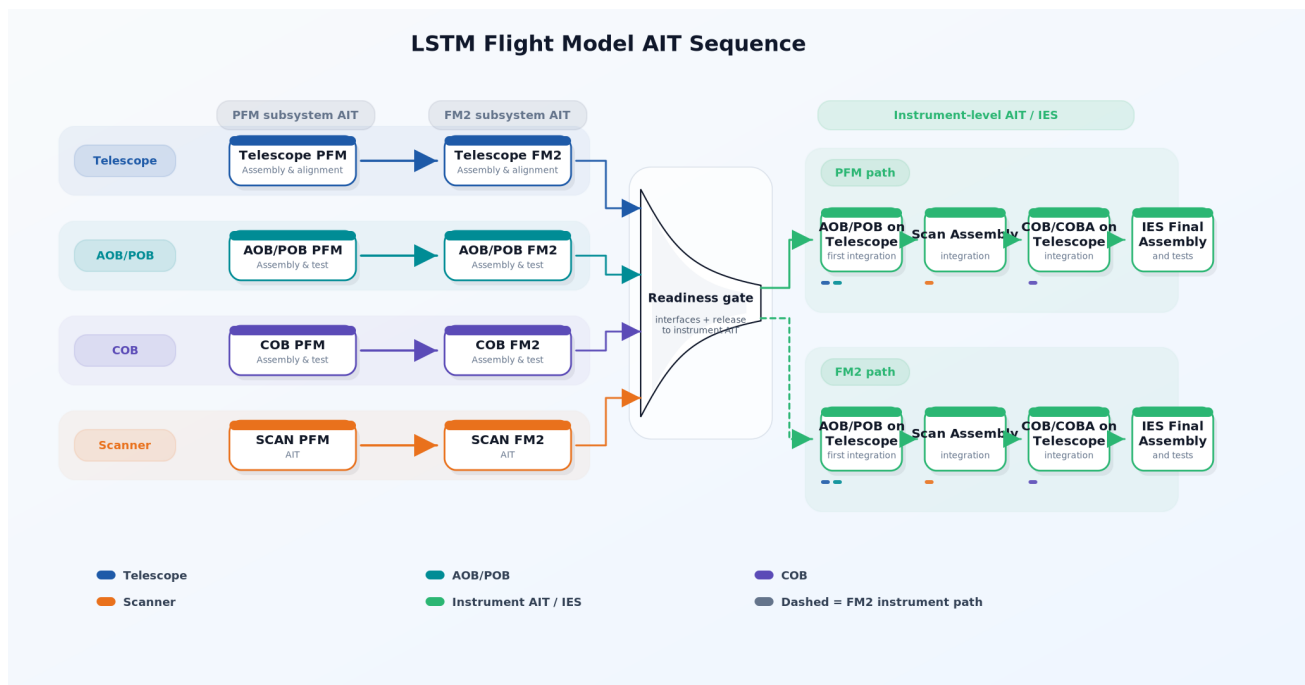


Figure 32. LSTM flight model AIT sequence



Figure 33. AIT activity in the AIRBUS GAIA chamber for the co-alignment of the AOB/DBS2/POB and its verification in TVAC

7. CONCLUSIONS

The LSTM mission is cornerstone mission of the Copernicus program. We have reported on the main objectives of the mission, key requirements and the adopted design with emphasis on the instrument. We reported on the extensive breadboarding and validation activities performed to retire critical technical risks, validate key technologies, and demonstrate compliance with radiometric, thermal, and geometric performance envelopes. The paper further describes the ongoing flight model Assembly, Integration and Test (AIT) campaign, outlining the adopted verification logic and performance verification approach. The consolidated CDR-level performance estimates, together with early AIT results, confirm the capability of the LSTM instrument to deliver a robust, operational high-resolution thermal infrared radiometry capability in support of long-term Copernicus services.

ACKNOWLEDGEMENTS

The authors would like to thank the entire teams in both ESA and Airbus Defence and Space as well as in all the companies which are part of the industrial consortium for their dedication to the successful development of the LSTM mission. The LSTM mission is part of the Copernicus program funded by the EU and ESA.

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