

PERFORMANCE VERIFICATION AND CALIBRATION OF THE CO₂I/NO₂I INSTRUMENT OF THE CO₂M MISSION: CO₂I/NO₂I SPECTROMETER TVAC CHARACTERIZATION

G. Bazalgette Courrèges-Lacoste (2), *S. Ballion* (1), *J-M Gaucel* (1), *A. Liotard* (1), *A. Dussaux* (1), *A. H. Ouslimani* (2), *A. Pasquet* (2), *Y. Durand* (2), *A. Chanumolu* (4), *M. Casti* (4), *S. Strauss* (3), *G. Huber* (3), *J. Habets* (3)

(1) *Thales Alenia Space, 100 Boulevard du Midi, 06156 Cannes, France;* (2) *European Space Agency, Keplerlaan 1, 2200 AG Noordwijk ZH, The Netherlands;* (3) *OHB System, Manfred-Fuchs-Platz 2-4, 28359 Bremen, Germany,* (4) *SSC Space Netherlands for European Space Agency, Zwarteweg 39, 2201 AA Noordwijk, The Netherlands*

The European Space Agency (ESA), in collaboration with the European Commission (EC) and EUMETSAT, is developing as part of the EC's Copernicus Sentinel expansion programme, a space-borne observing system for quantification of the emissions of the main greenhouse gases: anthropogenic carbon dioxide (CO₂) and methane (CH₄). The anthropogenic CO₂ monitoring (CO₂M) mission will be implemented as a constellation of three identical LEO satellites, to be operated over a period of at least 7 years and measuring CO₂ concentration in terms of column-averaged dry air mole fraction (denoted as XCO₂). Each satellite will continuously image XCO₂ along the satellite track on the sun-illuminated part of the orbit, with a swath width of 250 km. Observations will be provided at a spatial resolution better than 2 x 2 km², with high precision (<0.7 ppm) and accuracy (bias <0.5 ppm), which are required to resolve the small atmospheric gradients in XCO₂ originating from anthropogenic activities.

The industrial consortium in charge of CO₂M is led by OHB, with Thales Alenia Space Cannes in charge of the Payload. CO₂M is now in phase D, with manufacturing, integration and testing of the first two flight models (PFM and FM2).

This paper presents the challenging verification and calibration approach of the CO₂M Payload. After an overview of the design of the CO₂I/NO₂I instrument, it presents the main results obtained after validation at sub-equipment level, and at an optically representative breadboard level used for the definition of calibration procedure and for the validation of the flight OGSEs. Then the first results of the characterization of the CO₂I/NO₂I PFM spectrometer in thermo-vacuum conditions at the Thales Alenia Space facility in Cannes are presented. Finally, an overview of the foreseen on-ground spatial, spectral and radiometric calibration activities necessary to fulfil the demanding mission requirements is presented.

Keywords: CO₂M, hyperspectral imager, calibration and verification, GHG monitoring, Copernicus, Payload, CO₂, CH₄, NO₂

1. INTRODUCTION

To tackle climate change and its negative impacts, world leaders at the UN Climate Change Conference (COP21) in Paris reached a breakthrough on 12 December 2015: the historic Paris Agreement. The Agreement established the goal of significantly reducing anthropogenic emissions of greenhouse gases (GHG) [1]. In this context, the European Commission has formulated a system architecture with Monitoring and Verification Support capacity [2]. The corresponding high-level observation requirements call for a multi-satellite constellation with imaging capability at high spatial resolution, global coverage and frequent re-visit. As one of the six missions of the extension of the Copernicus programme, the EC has selected the anthropogenic CO₂ Monitoring mission for its capability of point-source detection and quantification.

The main objective of the CO₂M observing system is to provide highly accurate global mapping of carbon dioxide and methane concentrations at sufficiently high spatial resolution and revisit frequency. In particular, high single-sounding precision is essential for identifying plumes of elevated CO₂ concentration from instantaneous image acquisitions without regional and temporal averaging. This translates into stringent requirements for signal-to-noise ratio (SNR), as well as spatial co-registration and spectral stability, which drive the instrument design. The

radiometric and spectral sizing requirements for the CO2M mission have been derived from the CO2M Mission Requirement Document [3] and are discussed in [4].

The main instrument of the Payload is the CO2I/NO2I instrument dedicated to measuring atmospheric CO2 and CH4. The instrument measures the spectral radiance in the NIR [747-773nm], SWIR-1 [1590-1675nm] and SWIR-2 [1990-2095nm] bands, used as inputs to the inverse models for determining total column concentrations for atmospheric CO2 and CH4. The instrument is designed for high spatial resolution, high spectral resolution, and requests high thermal and mechanical stabilities. The CO2I/NO2I instrument embeds an imaging spectrometer in the VIS band [405-490nm] dedicated to measuring atmospheric NO2 content. It permits native nominal co-registration and relative radiometric performances with the CO2 bands, thus the accurate tracing of anthropogenic CO2 plumes from power plants and cities while optimizing both design and the industrial process, limiting the additional hardware and qualification activities. This combined CO2 and NO2 instrument is the core of the payload, and two additional instruments of limited mass and volumes are embarked: a multi-angle polarimeter (MAP) dedicated to aerosols measurement to better account for cloud and aerosols scattering effects, and a cloud imager (CLIM) with high spatial resolution to accurately filter the data for cloud-contaminated cases.

2. PAYLOAD ARCHITECTURE

The compact payload architecture relies on a triple bench concept as depicted in Fig 1 and is described in [5]. The instrument support panel (ISP) provides the interface between the payload and the platform. On it all the instrument electronics units are mounted as well as the flight calibration unit (FCU) of the CO2I and NO2I. The CO2/NO2 spectrometer is located on a dedicated optical bench (SOB) inserted inside a Thermal Guard Assembly (TGA) which provide a stable and constant thermal environment. The CO2I/NO2I telescope, the MAP Optical Unit, the CLIM Optical Unit all share the same Ultra Stable Interface Bench (USIB) in CFRP to provide the best co-registration between instruments. Four star-trackers are also installed on the USIB, to improve further the geometrical performances by reducing their sensitivity to the thermo-elastic environment. With respect to the thermal architecture, the CO2I/NO2I NIR/VIS bands, the MAP, the CLIM and the USIB are thermally stabilised, and the SWIR channels are passively cooled using a cryo-radiator with sun shield (ECSR).

In order to ensure flexibility in the payload development, each instrument is developed, tested and qualified in its own facility. The whole CO2I/NO2I integration, payload integration and qualification are performed in a single facility at TASiF in Cannes. The final steps of the MAP, CLIM and star trackers integrations, validations and calibrations are also performed at the same place.

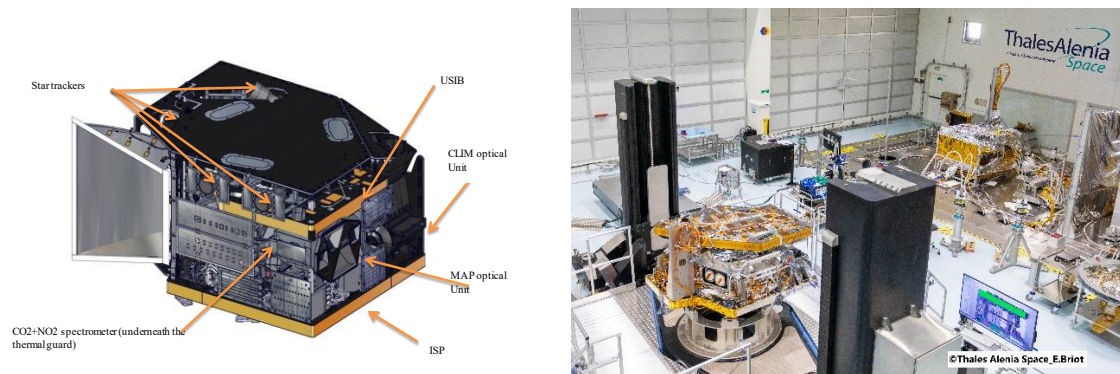


Figure 1: Left: Overview of the CO2M Payload, with the triple bench concept with the three instruments the four star trackers and the panels. Right: CO2M Payload FM2 (front left) under assembly and PFM (back right) under test preparation, at the Thales Alenia Space Facility in Cannes.

After completion of the Assembly and Integration phase, the Payload will experience a series of environment tests (mechanical and thermal) followed by an extensive period of performance verification and calibration in thermo-vacuum conditions in the TASiF facility at Cannes.

The rest of the paper will focus on the CO2I/NO2I Instrument, which is the core instrument of the payload, and specifically on the verification and calibration approach that has been retained to guarantee that the science objectives of the mission are achieved.

The CO2I/NO2I Instrument

The instrument, which is developed by the payload industrial prime, Thales Alenia Space, is built around its CO₂ and NO₂ spectral bands spectrometer. It is assembled onto an optical bench whose rigidity is ensured by Si₃N₄ ceramic tubes, material also used on the collimator bench, that requires the most stringent stabilities between the optical elements. The CO₂ and NO₂ spectrometer is interfaced toward on one side the payload to platform interface bench and on the other side an ultra-stable interface bench, onto which the optical units are mounted. The four spectral bands share the same slit and collimator, and 3 dichroic plates separating the four bands which have their own dedicated disperser, imager and detection focal plane (see Fig 2).

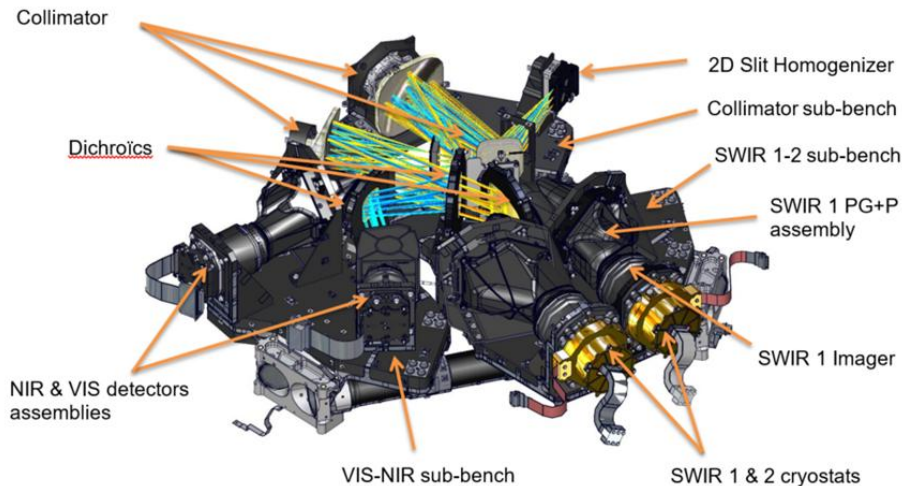


Figure 2. CO₂I/NO₂I spectrometer assembly.

The main design features of the CO₂I/NO₂I are the following:

Fore-optics

Fore-optics telescope, which is procured by TAS-Switzerland, is composed of a TMA (Three-Mirror Anastigmat) with an intermediate image, complemented by 2 folding mirrors. It also includes a polarization scrambler which is located at telescope entrance pupil to minimize the polarization impact on on-ground footprint), and a complex spectral filter implemented in order to limit the out-of-band straylight in the 4 spectral bands.

Before the fore-optics a Flight Calibration Unit (FCU) procured by Centre Spatial de Liège, can insert in the light path a solar diffuser allowing radiometric calibration of the instrument. White light source (WLS) as well as laser diodes can also be activated on ground and in flight to support radiometric/spectral characterization of the instrument.

Slit homogenizer

The spectrometer slit, which is manufactured by OPTEC, is a two-dimensional slit homogenizer (2DSH) based on a hundred of rectangular optical fibers. The fibers permit homogenizing the along-track and across-track input scene contrast, in order to make the Instrument Spectral Response Function (ISRF) more robust to the spatial content of the observed scenes. Fibre core section, together with telescope and scrambler, defines the sample field of view and the spatial sample angle. The spacing between the fiber cores is imaged at the detector focal plane and provides a mean of co-registration between the four instrument bands. Different breadboards and optical models have been tested at unit level and on the instrument optical model at TASiF.

Spectrometer parts

The Spectrometer is composed of a collimator (TMA + 1 folding mirror), 3 dichroic plates for beam splitting according to the 4 spectral ranges, Prism Grating Prism disperser (PGP) and an imager for each of the four bands. A major performance driver is the Instrument Spectral Response Function (ISRF) stability from Ground to End of Life (EoL) that demands very high mechanical stabilities. For this reason, ceramic (Si₃N₄) has been used for collimator bench and a thermal guard has been implemented to enclose the full spectrometer and ensure very high thermal stability. Most of the parts of the spectrometer are fulfilling tight requirements for transmission, roughness, surface cosmetics and contamination to address the demanding performance for radiometry and straylight.

Detection chain

The detection chain dedicated to VIS and NIR channels, including the 2 CMOS digital sensor from Teledyne e2v, CIS120 detector assemblies, is managed by the VNIR Front End Video Unit (FEVU), which constitutes the video electronics in a single module. The SWIR NGP Detector Assembly from Lynred is composed of 4 analogical video outputs. The Analog SWIR Video Unit (VADPU) aims to acquire analog pixels from two NGP-SWIR detectors through deported Front End Electronics. Both Video Units are developed by TAS in Toulouse.

Detectors key performances are driven by mission needs in terms of radiometry (SNR) and radiometric accuracies (detection biases). This includes, in particular, high Spectral Detection Efficiency, controlled remanence and non-linearity, dark current stability.

The two SWIR detectors are passively cooled down to 150 K. A passive Cooling Thermal Model has been used to validate the design and performances of the detector cooling, including radiator, sunshield, thermal control.

3. CO₂I/NO₂I PERFORMANCE VERIFICATION AND CALIBRATION APPROACH

This section focuses on the on-ground activities that have been put in place since the start of the program to allow a step-by-step progressive verification and calibration of the CO₂I/NO₂I instrument. Another critical activity which is the in-flight verification and calibration during commissioning will be subject to a dedicated paper in the future.

Performance validation strategy

As explained above the on-ground verification and calibration is part of the more general performance validation strategy that should be achieved at the end of the commissioning on the payload, roughly 6 months after launch. The strategy is depicted in the Fig 3 below.

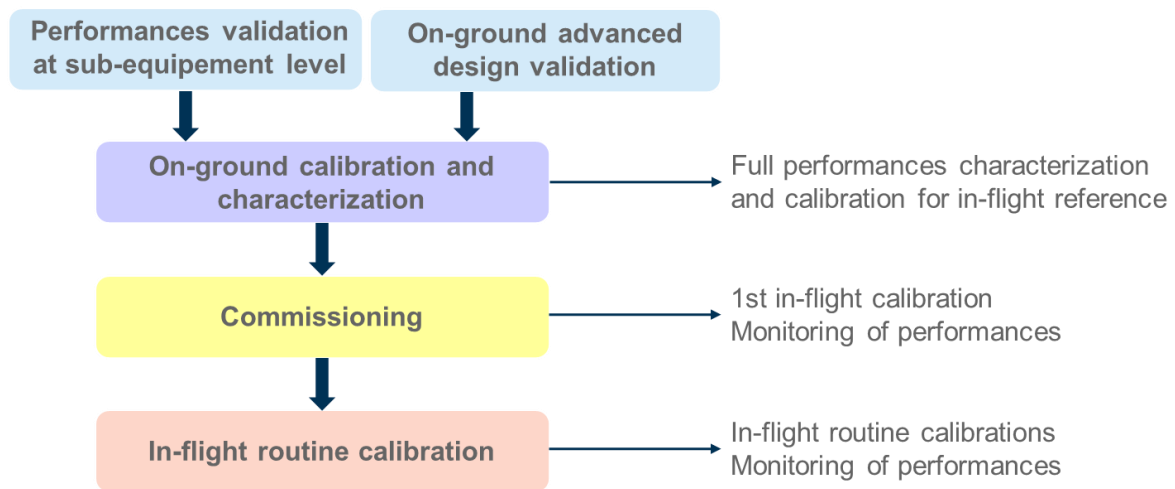


Figure 3. CO₂I/NO₂I performance validation strategy.

Starting at an early stage of the on-ground activities, the performance validation is following an incremental bottom-up approach, with validation at (sub-)equipment level, breadboarding activities and finally with a quasi-representative Optical Model of one the spectral band of the CO₂I/NO₂I instrument.

Validation at sub-equipment level

Essentially three sub-equipment's have been characterized and validated at an early stage of the development (validation completed at Payload CDR), those are:

Performances	Equipment	
VNIR detectors performances	VNIR detectors	Performances characterized by the sub-co (e2V) Non-linearity and remanence performances validated at TAS level during DCBM tests sequence
SWIR detectors performances	SWIR detectors	Performances characterized by the sub-co (LYNRED) Non-linearity and remanence performances validated at TAS level during TB2 tests sequence
Diffuser BRDF	FCU	BRDF characterized by the sub-co (CSL)

Through this early characterization the project gained in very detailed understanding of the sub-equipment's performance, sometimes inducing the need of correction of their slight imperfections (e.g. remanence effect for the SWIR detector, or persistence effect for the VNIR detector [6]), and providing an early set of calibration data before final calibration at instrument level (for instance the diffusers BRDF for a large subset of incidence angles and wavelengths).

In total the following models have participated to this advanced design validation strategy, the first two being focused on performance validation:

VNIR DCBM (Detection Chain Breadboard Model)

SWIR DCBM (Detection Chain Breadboard Model)

PCTM (Passive Cooling Thermal Model)

ITB (Instrument Test Bench)

Validation at instrument breadboard/Optical Model

After completion of this step, the next performance validation step consisted in testing an instrument elegant breadboard (EBB). This elegant breadboard, consisting in the SWIR-1 band of the CO2I spectrometer, was later extended to the full optical chain of the SWIR-1 channel (Telescope +polarization scrambler+ spectrometer) in a so-called CO2I Optical Model (OM). The aims of the CO2I OM were:

- Instrument optical design validation
- OGSE performances validation
- Optical tests procedures validation
- Post-processing validation
- Instrument performances validation

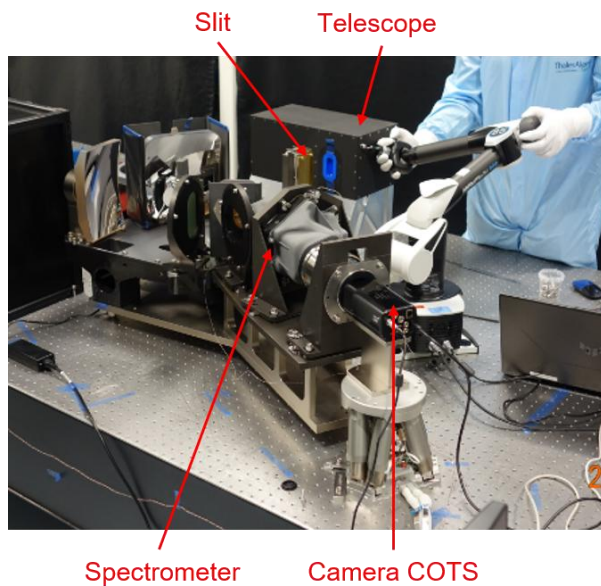


Figure 4: CO2I OM composed of CO2I spectrometer part for the SWIR1 band + telescope + scrambler for the SWIR1 band

An extensive characterization program took place on the EBB/OM as shown in Fig. 5.

	Without PFM OGSE	With PFM OGSE
Performances validations	EBB	OM
Spectral calibration		
ISRF with uniform scene	X	X
ISRF with non uniform scene	X	X
Straylight characterization		
Straylight characterization for kernel computing	X	X
Straylight correction validation	X	X
Spatial characterization		
IEDF FWHM and barycentre characterization	X	X
2D IEDF characterization	--	X
Radiometric characterization		
Polarisation characterization	--	X

Figure 5: overview of the performance validation activities achieved with the EBB and OM of CO2I.

Amongst the most critical results achieved with the CO2I OM, it is worth mentioning the complete mapping of the SWIR-1 channel straylight [7] allowing the correlation of the straylight model. Also an early characterization of the SWIR-1 Instrument Spectral Response Function (ISRF) in uniform as well as non-uniform scenes (i.e. validation of the uniformization capacity of the 2DSH) was performed.

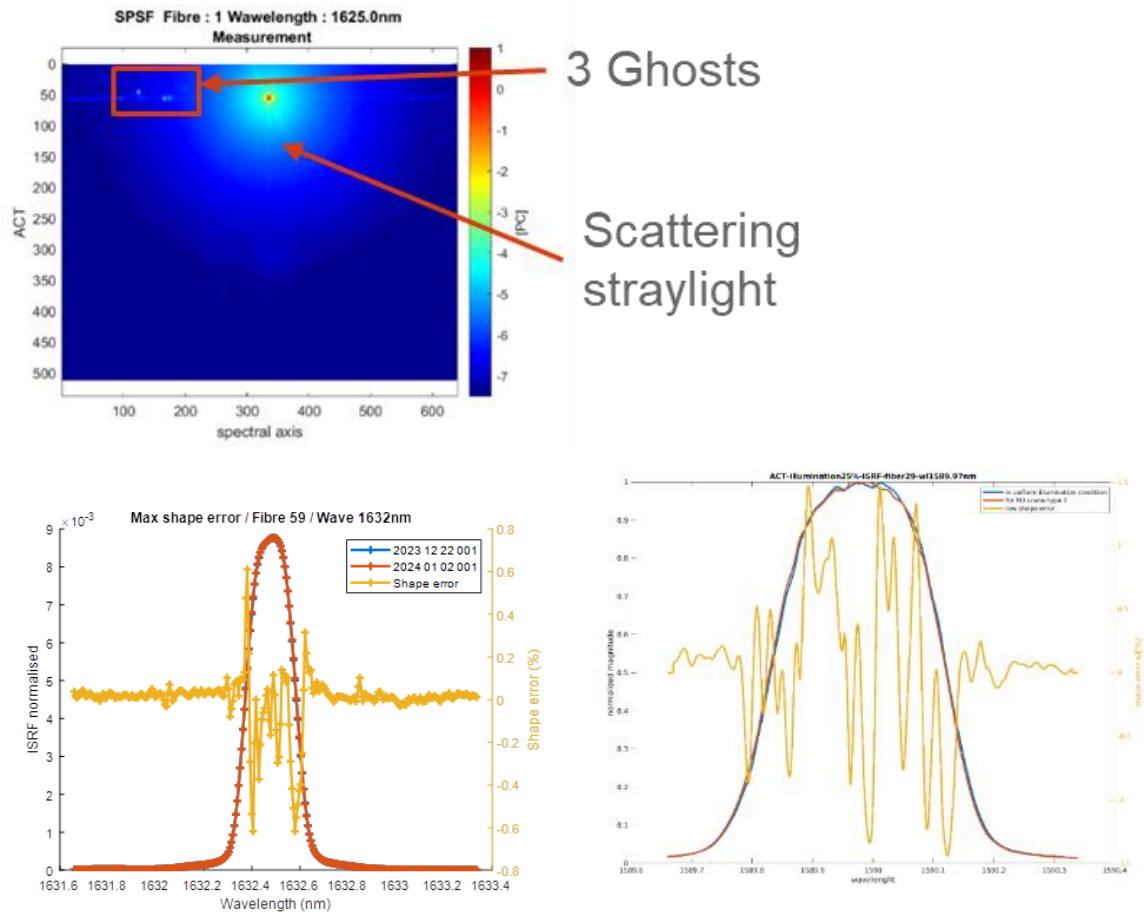


Figure 6: Top - Measurement by illuminating 1 fiber with 1 wavelength at the same time (SPSF). Characterization of all straylight effects with dynamics down to $1e-7$ of the input signal. bottom left: example of ISRF shape reproducibility. bottom right - Comparison of the ISRF shape between uniform and non-uniform scene along ACT direction with 25% illumination.

The EBB and OM of CO2I SWIR-1 channel enabled early performance validation before starting the assembly of the CO2I/NO2I Instrument. This is considered as a fundamental derisking related to the achievement of the performances.

CO2I spectrometer characterization in Thermo-Vacuum conditions

As an intermediate step between the elegant breadboard/OM characterization and the full performance verification and calibration of the flight instrument, the CO2I/NO2I spectrometer (integrated in the payload) went through a series of tests in thermo-vacuum conditions with two principal objectives: on one end the determination of the best focus position of the four focal plane assemblies, and on the other end a thermal balance test aiming at correlating the thermal model of the payload.

However, taking advantage of the two TVAC slots (1- to determine the best focus and manufacture the flight shims, 2- to validate the best focus positions) necessary to achieve the objectives depicted above, a series of performance tests in flight representative conditions have been implemented. Specifically, a subset of ISRFs of the four spectral bands have been measured at different stages of the tests: in ambient conditions with sub-nominal focus, in TVAC conditions with sub-nominal focus, in ambient conditions with best focus, in TVAC conditions with best focus. This provided a very deep understanding of the behavior of the instrument in different environment conditions as well as some key information about the sensitivities of the ISRFs. Regular ISRF measurements will be performed at different stages of the AIT phase up to the start of the calibration campaign to monitor any change of the ISRF. Thanks to its high sensitivity, the ISRF is indeed a very efficient tool to verify the good health of the optical design. Finally, these measurements provided a first set of flight representative ISRF.

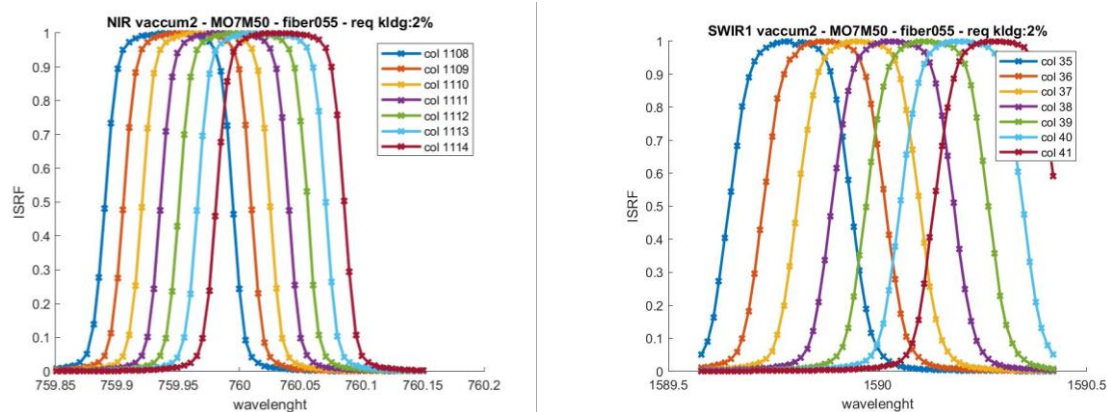


Figure 7: ISRF achieved with Spectrometer in focus in TVAC environmental conditions for the NIR band (left) and SWIR-1 band (right).

During this test series other performance aspects of the CO2I/NO2I spectrometer have also been measured in operational conditions such as straylight detector edge effect, detectors addressing, bad/dead pixels and icing.

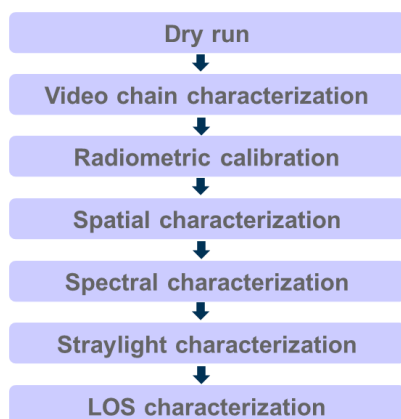
All these measurements offer an early set of characterization data of the instrument well prior to its on-ground verification and calibration enabling an early performance verification of key performances such as spectral and radiometric.

CO2I/NO2I on-ground performance verification and calibration

The final performance verification and calibration step of the CO2I/NO2I instrument will occur in the early 2027 time frame with the on-ground verification and calibration of the instrument, when mounted on the fully assembled Payload. The instrument will follow an extensive program of tests in flight representative conditions at the TASiF facility in Cannes. Key elements of this performance verification program are:

- All performance calibrations and characterizations are realized under vacuum environment.
- At the start of the sequence a « dry run » of the complete sequence is done, ensuring a full end to end functional test of the calibration chain (instrument config, OGSE, ...) and providing a (very) preliminary (but very early) set of key data.
- During the test sequence, a radiometric « good health » test will be realized regularly using the FCU White Light Source (WLS).

The program is constructed as follow:



The aim of this phase is to provide for the CO2I/NO2I instrument, L0 performance verification as well as calibration parameters for geometrical, spectral and radiometric key performances. The next figures provide a detailed overview of the performance verification & calibration activities, which are built in logical measurement blocks. Note that such measurement block approach offers the possibility to switch/re-do measurements until the last moment securing by this the success of the calibration campaign.

Performances	PFM	OGSE	Performances	PFM	OGSE
Spectral calibration			Video chain calibration and characterization		
ISRF with uniform scene	X	COBRA + TLS (laser)	Defective and RTS pixels characterization	X	COBRA
ISRF with non uniform scene	X		Video chain parameters calibration	X	
Straylight characterization			SLO characterization	X	
Straylight characterization for kernel computing (in-band and out-of-band)	X	TLS (laser)	Non-linearity calibration	X	
Straylight correction validation	X		Radiometric calibration		
Out-of-field straylight characterization	X	COBRA	Radiometric calibration through earth port	X	COBRA
Spatial characterization			Polarization sensitivity	X	
IEDF FWHM and barycentre characterization	X	COBRA	Remanence parameters calibration	X	
2D IEDF characterization	X		Dark and gain dependance vs temperature	X	
LOS characterization			Radiometric calibration through sun port	X	ASPIC
CO2I LOS characterization	X	COBRA	Sun diffuser BRDF characterization	X	
Inter-instrument LOS characterization	X	Theodolite			

Figure 8: List of performance verification/calibration measurements with reference to the Optical ground Support Equipment involved. COBRA = OGSE used to illuminate the instrument Earth port; ASPIC= OGSE used to illuminate the instrument Sun port.

Finally, before the instrument final acceptance, another fundamental performance verification step will have been archived through so-called performance close-loop test aiming at verifying some key requirements with the complete L1b processing chain and associated calibration key data (CKD) involved. This would provide the demonstration that the whole instrument plus its processing chain is fit for the mission purpose.

4. CONCLUSIONS

This paper provides an overview of the verification and calibration approach of the CO2M main instrument, the CO2I/NO2I.

At the CO2M start of the AIT phase, the full on-ground instrument calibration and characterization plan is consolidated:

- ❖ **Very good confidence** in the test sequences thanks to advanced validation (EBB, OM, OGSE)
- ❖ **Very good confidence** in the FCU and detectors performances thanks to tests at manufacturer level

Regarding the challenges related to the particularities of the mission/instrument design/Test facility:

- ❖ Risk on the too short campaign duration: largely mitigated by the advanced validation work
- ❖ Limitation inducted by the full configuration under TVAC: mitigated by the calibration configuration fully tested in ambient + health checks done at the start of the campaign.

ACKNOWLEDGEMENTS

This paper presents the work performed by the European Space Industry consortium led by OHB (Satellite prime) and TAS-Cannes (Payload prime) on the CO2M mission. The authors would like to convey their gratitude to their respective colleagues at OHB and TAS, as well as to all the partner companies within the CO2M industrial consortium for their valuable contributions to the continuing success of this very challenging mission.

This paper has been produced under the Copernicus programme co-funded by the EU.

REFERENCES

- [1] Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104 (2015)
- [2] Janssens-Maenhout, G., Pinty, B., Dowell, M., Zunker, H., Andersson, E., Balsamo, G., Bezy, J., Brunhes, T., Bosch, H., Boikov, B., Brunner, D., Buchwitz, M., Crisp, D., Ciais, P., Counet, P., Dee, D., Denier Van Der Gon, H., Dolman, H., Drinkwater, M., Dubovik, O., Engelen, R., Fehr, T., Fernandez, V., Heimann, M., Holmlund, K., Houweling, S., Husband, R., Juvyns, O., Kentarchos, A., Landgraf, J., Lang, R., Loescher, A., Marshall, J., Meijer, Y., Nakajima, M., Palmer, P.I., Peylin, P., Rayner, P., Scholze, M., Sierk, B., Tamminen,

- J. and Veeffkind, P., "Towards an operational anthropogenic CO₂ emissions monitoring and verification support capacity", Bulletin of the American Meteorological Society, ISSN 0003-0007 (online), 101(8), 2020, p. E1439-E1451, JRC119796 (2020)
- [3] Meijer, Y., "ESA Copernicus CO₂ Monitoring Mission Requirements Document (MRD)", Tech. rep. Version 3.0, October 2020, available at https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf
- [4] Sierk, B., Bezy, J.-L., Loesch, A., and Meijer, Y., "The European CO₂ Monitoring Mission: observing anthropogenic greenhouse gas emissions from space", Proc. SPIE 11180, International Conference on Space Optics ICSO 2018, 111800M.
- [5] G. Bazalgette Courrèges-Lacoste, C. Pachot, H. Ouslimani, Y. Durand, A. Chanumolua, M. Martinez Fernandez, M. Caleno, T. Bastirmaci, A. Birtwhistle, Y. Meijer, V. Fernandez, "Progress on the development of the Copernicus CO₂M mission", Proc. of SPIE Vol. 13192 131920S-1, Sensors, Systems, and Next-Generation Satellites XXVIII.
- [6] J-M Gaucel, Bernd Sierk, Matthew Soman, Anantha Chanumolu, Gregory Bazalgette Courrèges-Lacoste, Yajka Meijer, Ruediger Lang, "CHARACTERIZATION AND MITIGATION OF DETECTION CHAIN PERSISTENCE IN THE CO₂M IMAGING SPECTROMETER", Proc. SPIE, International Conference on Space Optics ICSO 2026.
- [7] E. Duquesne, STRAYLIGHT ANALYSIS OF CO₂M SPECTROMETER PART", Proc. of SPIE Vol. 13699 1369925-1, International Conference on Space Optics — ICSO 2024.