

MICROCARB INSTRUMENT IN-FLIGHT COMMISSIONING: TECHNICAL CHALLENGES AND INITIAL PERFORMANCES RESULTS

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ABSTRACT

MicroCarb is an exploratory space mission designed to monitor the CO₂ fluxes at the Earth surface in order to better understand exchanges between atmosphere, oceans and vegetation. The goal of MicroCarb is to measure very precisely the CO₂ atmospheric concentration (better than 1ppm) using a microsatellite (180kg). The MicroCarb mission is developed by the French Space Agency (CNES) through a funding from French Research Agency (ANR) and with participations from European Union and UK Space Agency.

The MicroCarb payload is composed of a passive Short Wave Infrared spectrometer and a visible imager. The innovative concept of the spectrometer allows to acquire 4 narrow bands (0.76μm, 1.27μm, 1.61μm, 2.04μm) on a same detector thanks to the use of an echelle grating and a split-pupil telescope. The performances required for the instrument are very stringent in terms of spectral resolution ($R \sim 25000$), Instrument Spectral Response Function (ISRF) knowledge ($< 1\%$), radiometry sensitivity ($\sim 0.3\%$) and Signal-to-Noise-Ratio (> 200 per Full Width at Half Maximum). Achieving these performances presents a significant challenge and requires a long and complex in-flight calibration validation campaign.

The payload developed by Airbus Defence and Space (France) was delivered in December 2022. The integration and the qualification of the satellite were performed by Thales Alenia Space UK.

MicroCarb was launched successfully in July 2025 from Kourou (French Guiana) aboard a Vega-C rocket as a co-passenger with the CO₃D satellites from Airbus Defence and Space.

This paper presents the main outcomes of the instrument in-flight commissioning. First, it will address the choice of the optimal instrument operating point. Then, it will focus on the icing contamination and its impact on performances. Finally, some instrument performances in-flight verifications will be presented.

Keywords: Spectrometer, high spectral resolution, contamination

1. INTRODUCTION

1.1 Mission Overview

The goal of MicroCarb^[1] is to perform global measurements of atmospheric carbon dioxide (CO₂) concentrations with sufficient precision to enhance scientific understanding of the exchange mechanisms between emission sources and absorption sinks. It also seeks to investigate the evolution of these mechanisms on a seasonal scale and over the long term in response to climate change.

MicroCarb's orbit is a 22:40 (LTAN) sun-synchronous orbit at 649 km. This is a phased orbit with a 25-day cycle (and a 7-day sub-cycle).

The mission has lots of acquisition modes, either for scientific measurements collection, or for calibration purposes. The two nominal modes for the acquisition of scientific data are Nadir Mode and Glint Mode. The Nadir Mode, used over lands, points straight down from the satellite (close to the geocentric direction). The Glint Mode, used over oceans, points at the sun specular direction. There are some variants like the Scan mode which allows acquiring uncorrelated data by performing soundings over areas far from each other. The instrument's internal mechanism (Pointing and Calibration System) allows for a scan on either side of the track with an amplitude of ± 200 km.

For calibration, Target and CalOffNadir modes are intended for data validation. Its purpose is to compare the CO₂ concentration values derived from satellite measurements with a reference obtained from ground stations. The Target imaging mode corresponds to a stop-over, for instance above a TCCON station of the global atmospheric CO₂ measurement network, and the CalOffNadir mode allows to point TCCON station or EM27 spectrometers thanks to the instrument scan mirror whilst the satellite remains pointed at the nadir.

Additional modes are used for calibration towards the sun, moon, limb, or darkness to meet various calibration needs.

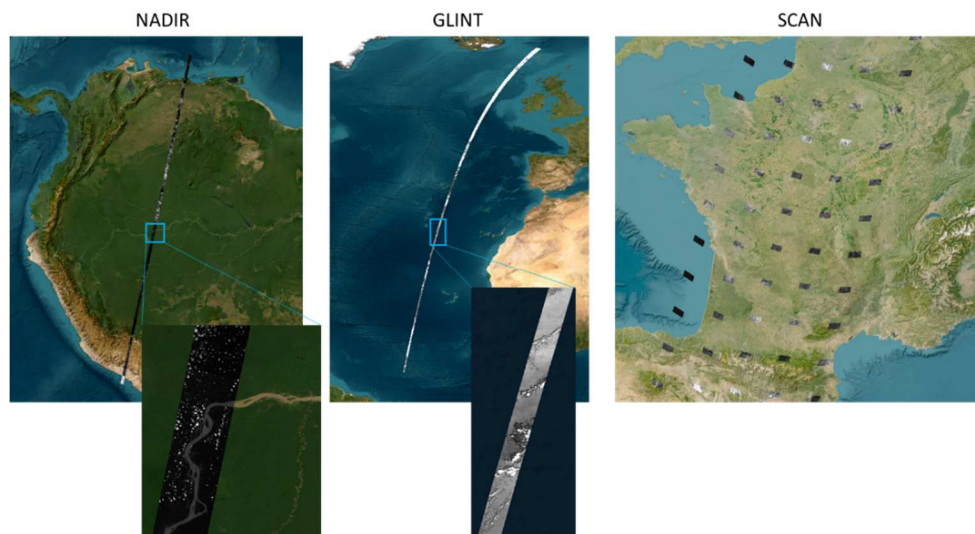


Figure 1. MicroCarb scientific acquisition modes

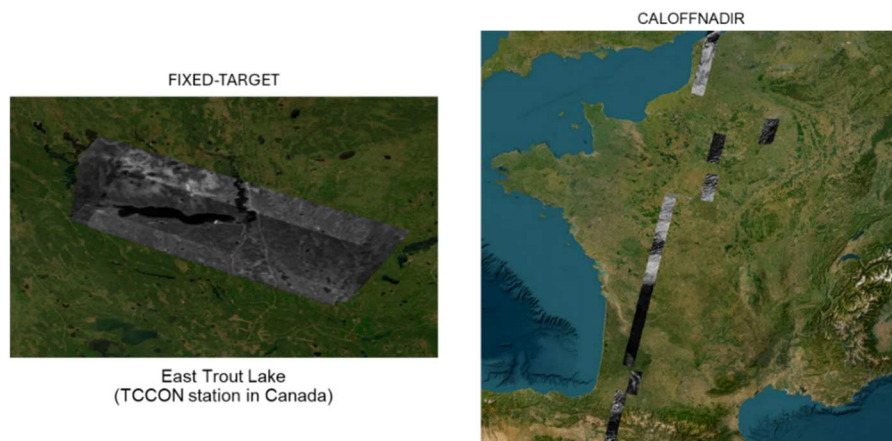


Figure 2. MicroCarb calibration modes

All these modes were validated during the in-flight commissioning.

1.2 Satellite

Using a small satellite for this mission was challenging. The generic Myriade platform^[1] was upgraded for MicroCarb to manage obsolescence of certain equipment, adapt to mission-specific requirements, and comply with the French law on space operations. Notable upgrades include:

- Increased dimensions of the platform structure, inherited from TARANIS
- Replacement of star tracker and RF equipment (SBand and XBand) with more performant models
- On-Board Computer (OBC) with upgraded electronic boards
- Optimization of the 4 reaction wheels geometry and flight software update for guidance and AOCS to meet the mission's high agility requirements
- Power supply disconnection system added to prevent satellite restart after deorbiting

The mass of the satellite is 180Kg, the dimensions are 80 x 100 x 110 cm and the available mean electrical power is lower than 120 Watts. The power budget is an issue on MicroCarb and many optimizations must be done when programming the mission.

1.3 Instrument

The MicroCarb payload^{[2][4]} is made of a visible imager used for the cloud detection and the acquisitions geolocation, and a Short Wave InfraRed (SWIR) Spectrometer. The spectrometer analyses the Sun irradiance reflected by the Earth in four spectral bands. Two spectral bands around 1.61 μm (B2) and 2.04 μm (B3) exhibits numerous absorption lines of CO₂ and are therefore sensitive to the number of CO₂ molecules in the atmospheric column. Two other spectral bands around 0.76 μm (B1) and 1.27 μm (B4) exhibits numerous absorption lines of O₂, which provides information on the dry air amount, mostly related to surface pressure and the vertical distribution of atmospheric aerosols. The information of both bands of O₂ on one side, and both bands of CO₂ on the other side, is combined to reduce the uncertainties and provides information about water vapor and aerosols. The spectra of these four bands are combined to retrieve a column-integrated vertical concentration of CO₂.

At the entrance of the instrument, a Pointing and Calibration Subsystem (PCS) enables to point the instrument Line of Sight (LOS) at several across track directions (to change the acquisition mode), towards internal calibration sources: White Light Sources (WLS) and diffuser in transmission on the sun port, and to a closed position (hereafter named shutter). The WLS acquisitions are used to calibrate the Pixel Response Non Uniformity (PRNU) and the sun acquisitions are used for absolute radiometric characterization and spectral dispersive law estimation. These calibration sources are very useful to follow the evolution of the radiometric response of the spectrometer and the imager.

Then, a telescope images the Earth both on an imager visible detector (COBRA2M) and the spectrometer slits. The telescope section and the calibration pointing system are maintained at 17 °C. The spectrometer is directly attached to the telescope to fulfill the stability requirement of the alignment. The spectrometer uses an echelle grating with high interference orders, offering a potential high spectral resolution and a high degree of spectral multiplexing. Thanks to a double-pass Three Mirror Anastigmat (TMA) used for both collimation and camera lens functions, the spectrometer images the slit on the detector.

The spectrometer area should be maintained at a temperature of -27 °C for spectral and radiometric performances. Finally, the cryostat section composed of SWIR detector array (Next Generation Panchromatic (NGP) 1024 x 1024 pixels) and narrow band-pass filters is maintained at a temperature of approximately -113 °C thanks to a passive cooling system.

By design (small pupils and high spectral resolution), the signals level on the NGP detector is low compared to the well capacity, making the instrument sensitive to remanence effect. An additional permanent illumination of the detector with a LED at 602nm (hereafter named Fond Optique Diffus FOD) has been implemented in order to add a fat zero to the detector and reduce the lag effect. The level of this background signal can be configured in flight and some activities involved finding the optimal value.

In addition, an Instrument Control Box (BIC) is in charge of the proximity electronics operations (Module Video Proximity (MVP) and the Module de Proximité Imageur (MPI), the thermal control, the scan mirror operation and the data exchange with the platform (both science and the TM/TC).

The science data transmission is flexible. For the spectrometer and imager there is no on-board processing except compression. All the matrix pixels can be transmitted, and for the spectrometer some sub acquisitions during the integration time can be transmitted. The configuration of intermediary acquisitions and the matrix windowing is adjustable and can change for calibration and investigation purposes.

Figure 3 presents the spectrometer image acquisition and the L0 data. The detector rows correspond to the spectral direction (1024 pixels), while the columns correspond to the ACross Track direction (each band contains 87 pixels). The matrix-windowing can be configured either as a full matrix or as the useful columns per spectral band, depending on whether the complete 2-D detector image or only the spectral columns that contain the relevant information are required. Each band columns are binned so as to obtain 3 Field Of Views (FOV). The along-track FOV is obtained by the integration time (1.28s). The spectrometer total FOV (13.5 km x 9 km) is the half of the imager one.,

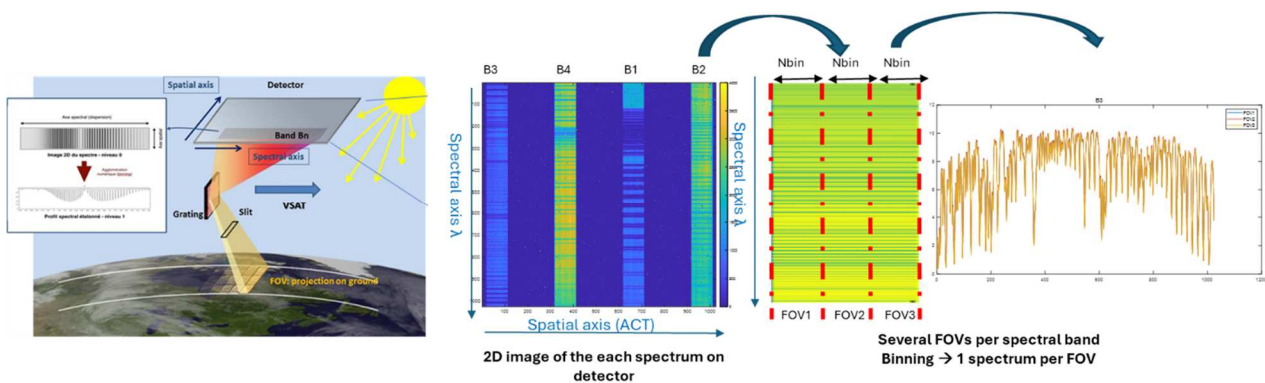


Figure 3. MicroCarb spectrometer principle and illustration of the L0 (raw) and L1 (calibrated and corrected spectrum) data

1.4 System

The MicroCarb mission uses the CNES control ground segment inherited from the Myriade family, located in CNES Toulouse center (France), which includes:

- The multi-mission command and control center
- The S-band and X-band stations of the CNES multi-mission ground station network
- Other miscellaneous multi-mission services as collision risk monitoring.

The mission center is specific to MicroCarb program. It is located also in CNES Toulouse center and in EUMETSAT center (Darmstadt, Germany). Its main functions are:

- Mission programming and payload monitoring
- Payload expertise and calibration
- Processing of measurement data and production of Level 1, 2, and 3 products (L1, L2, L3)
- Reprocessing of data with improved algorithms or updated parameters
- Expertise on product quality
- Archiving scientific data

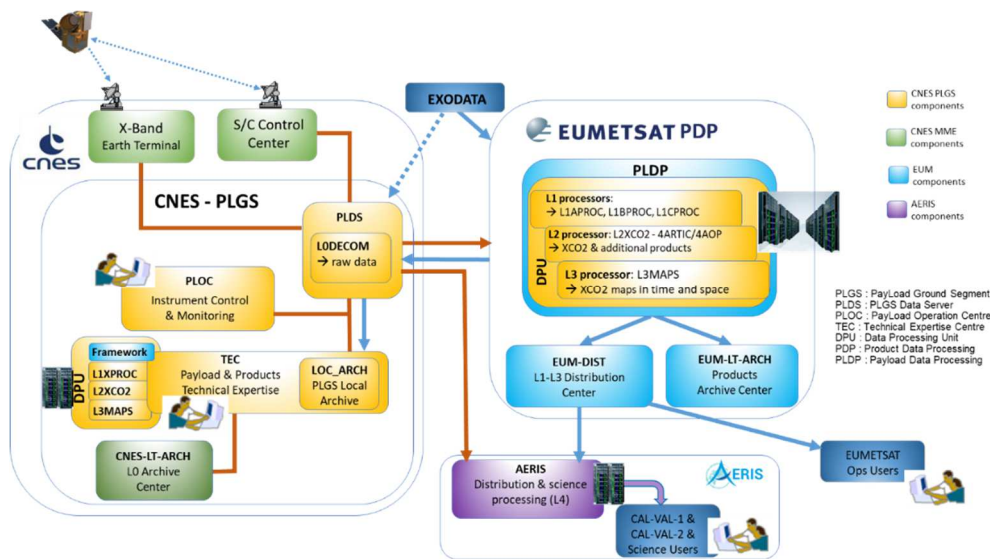


Figure 4. System Architecture

Products dissemination is managed by:

- AERIS atmospheric pole (ICARE center in Lille, France) for distribution to worldwide scientific community
- EUMETSAT for distribution to operational agencies or services like ECMWF, CAMS-COPERNICUS.

Once the satellite finished the LEOP phase, satellite commissioning started. The objectives were:

- Commissioning of the various equipment confirming their good health
- Performing a (very) small maneuver to commission the propulsion system and demonstrate the satellite's maneuverability (in case a debris avoidance maneuver was needed)
- Validating the different pointing and imaging modes of the platform and instrument
- Decontaminating the instrument optics, through 3 weeks of instrument heating

After this phase, the instrument underwent all required verifications and calibrations to verify the good health of the components and to assess its performance. The processing of measurement data is done at CNES Technical Expertise Center that allows analyzing the dependance of instruments performances to different parameters, configurations and optimizing the processing.

This paper describes the instrument activities during the first year. It will address the instrument configuration optimization, it points the unexpected evolution of the radiometric response and presents the effects of the various decontaminations. Finally, the paper presents the status of the current performances.

2. DEFINITION OF THE OPTIMAL INSTRUMENT CONFIGURATION

2.1 Context

The command-control system allows in-flight adjustments of the sounder focal plane and spectrometer temperature setpoints; the FOD level, unfixed before launch, can be tuned in flight via the LED current.

Regarding temperature, the NGP detector uses MCT technology, consequently, its operating temperature affects both the signal- to-noise ratio (SNR) and the occurrence of the Random Telegraphic Signal. Maintaining

good thermal stability is also essential to reduce calibration frequencies and to improve the radiometric accuracy.

During the instrument Thermal-Vacuum campaign (TVAC)^[4], the expected temperature of 150K was not reached, a temperature exceeding 158K was obtained. To take an in-flight evolution into account, most of the measurements were performed at several detector temperatures (between 159K and 165K). One objective of the commissioning phase was therefore to test the detector at different temperatures.

Regarding FOD level, during the TVAC campaign, a series of remanence performance measurements based on dark to light transitions with fast shutter were carried out to analyze the sensitivity to the FOD level. The FOD level influences both the Signal to Noise Ratio and the remanence performance.

Consequently, a tradeoff between the NGP operating temperature and the FOD level was performed during the commissioning phase. Two NGP operating temperatures were tested: 165K (the temperature used in the TVAC campaign) and 159K (the lowest temperature at which the system can be regulated). Three FOD illumination levels were also evaluated: 0mA (no FOD), 1mA and 1.8 mA; the latter two correspond to the TVAC campaign settings. Performances metrics were assessed for different instrument configurations and the results are presented in the following paragraphs.

2.2 Thermal Configurations

In-orbit, the temperature stability of the optical subsystems is a key factor for both radiometric and spectral performances.

The passive cryogenic system, based on a radiator pointing to cold space (at 2.7 K) protected by a baffle from any illumination caused by the Sun or the Earth, and the linear thermal regulation must ensure high thermal stability for both the spectrometer optics and focal plane array. Thus, temperature variations were estimated for the Glint and Nadir observations under the two instrument thermal configurations. The set point of the telescope and spectrometer are adjusted in the 159K configuration to obtain the lowest NGP temperature.

Table 1 shows the mean measured temperature and its peak-to-peak variation for the Glint and Nadir modes.

Table 1. Temperature stability of the optical sub systems in Nadir & Glint acquisitions.

	TVAC campaign temperature "165K configuration"	Lowest temperature at which the system is regulated "159K Configuration "
Telescope	18.02°C (+/-0.02°C) NADIR 18.02°C (+/-0.02°C) GLINT	17.09°C (+/-0.02°C) NADIR 17.09°C (+/-0.02°C) GLINT
Spectrometer	-27.93°C (+/-0.06°C) NADIR -27.93°C (+/-0.06°C) GLINT	-34.91°C (+/- 0.06°C) NADIR -34.91°C (+/- 0.06°C) GLINT
NGP	164.38K (+/-0.03K) NADIR 164.38K (+/-0.28K) GLINT	159.22K (+/-0.02K) NADIR 159.37K (+/-0.36K) GLINT

The spectrometer and the telescope exhibit very high thermal stability with peak-to-peak variation of 0.02°C and 0.06°C, respectively, in Nadir and Glint Modes. In Glint mode, however, the NGP is more temperature sensitive because the satellite performs a large pitch rotation and the baffle is partially illuminated by the Earth. The NGP is equipped with two high accuracy sensors (1mK) that provide a very precise temperature for each acquisition, consequently, a model describing the temperature dependance of the NGP dark signal was developed to improve radiometric precision. Consequently, both thermal configurations satisfy the mission's performance requirements.

2.3 Dark Signal

The dark signal of the Microcarb instrument is the sum of the detector's dark current and the FOD signal which can be considered as a background signal. It corresponds to the complete absence of any signal at the instrument's input.

The dark current is temperature-dependent, whereas the FOD signal is related to the LED current. The FOD signal on the detector is not uniform because the illumination is diffuse, and its level depends on the out-of-band rejection performance of each spectral filter.

Table 2 shows the amplitude of the dark current and the FOD for several operating configurations at the nominal integration time of 1.28s.

Table 2. Dark current and FOD signal in LSB

LSB	B1	B2	B3	B4
DARK CURRENT 165K	3630	3470	3510	3465
DARK CURRENT 159K	1890	1800	1790	1795
FOD 1.8mA 159K	2625	4606	3409	5625
FOD 1mA 159K	1290	2345	1675	2820

The dark current doubles with a 5 K increase in temperature. The FOD level is lowest in B1 band and highest in the B2 and B4 bands. At 159K, the FOD signal exceeds the dark current in the B2 and B4 bands.

Reducing both the dark current and the FOD signal improves the signal-to-noise ratio and, consequently, the mission performance.

2.4 Random telegraph Signal

During the TVAC campaign^[4] we observed dark-signal discontinuities on several pixels that are characteristic of Random Telegraph Signals (RTS) in pixel arrays. The number of RTS-affected pixels was found to increase with the temperature of the NGP.

Because RTS disturbs both calibration and science data, one of the primary objectives of the in-flight activities was to characterize the RTS-affected pixels and to validate a dedicated correction algorithm. Dedicated orbits were scheduled for dark-signal acquisition. During those periods the satellite operated in Nadir mode to guarantee good thermal stability, the PCS was set to the shutter position and the FOD illumination was switched off, thereby maximizing the signal-to-noise ratio.

Figure 5 illustrates the evolution of the dark signal for three representative pixels over 1880 frames (around 45min). The vertical jumps correspond to RTS events; the number and duration of the jumps differ from pixel to pixel.

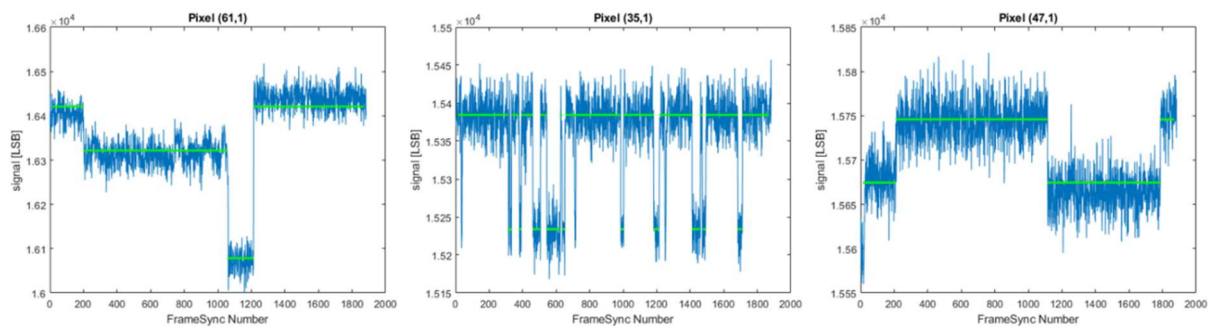


Figure 5 : Dark signal acquisitions during 1880 frames for 3 pixels of the matrix; The jumps correspond to the RTS, 2 and 3-level RTS are observed

The RTS pixels detection algorithm derives from the RTSATP algorithm developed by ISAE Supaero^[4]. It works by convolving a step function with each time series in order to identify RTS jumps emerging from the noise, and to record, in particular, the jump locations and amplitudes. For the present study, the detection threshold was fixed (32 LSB) to evaluate the influence of temperature on the RTS behavior.

The number of RTS-affected pixels, their median maximum amplitudes and their time constants were estimated at two temperatures (159K and 165K) using the 1880 frames data set. Table 3 summarizes these results.

Table 3 : Statistical synthesis of RTS (Number of pixels, median maximum amplitude, duration) at two NGP temperatures

RTS	Temperature	B1	B2	B3	B4
Pixels Number	165K	25%	22%	22%	24%
	159K	9%	9%	8%	8%
Median Maximum Amplitude (LSB)	165K	137	139	151	141
	159K	129	129	138	134
Time constant (FS Number)	165K	260	249	255	264
	159K	232	232	225	229

The RTS pixel count decreases when the temperature is lowered, the reduction between 165K and 159K exceeds a factor of 2 whereas the time constants and the maximal amplitude remain essentially temperature-independent. These results, and their order of magnitude, are consistent with the analysis performed during the TVAC campaign. Consequently, operating the instrument at the lower temperature (159 K) is advantageous for minimizing the number of RTS-affected pixels and for preserving the mission performance. Moreover, this algorithm has also been validated when the FOD is activated. In parallel, an RTS-correction algorithm was incorporated into the L0 processing chain to remove RTS artefacts from both calibration and science data.

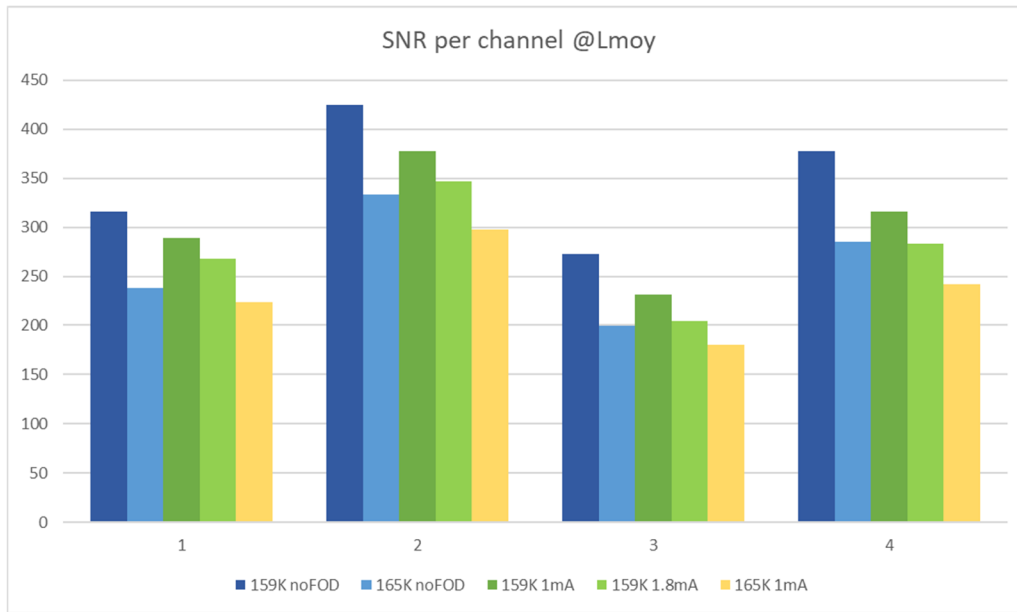
2.5 Signal to Noise Ratio

We estimated the in-flight Signal-To-Noise ratio (SNR) for lamp and Sun acquisitions and compared the results obtained for several operating configurations (temperature and FOD level). Each data set comprises 300 frames and they are corrected for RTS.

For each pixel, the signal is calculated by averaging the 300 frames and then subtracting the dark signal. The noise is the standard deviation of the same 300 frames. The SNR for each spectral channel is obtained by binning the 29 pixels that constitute the elementary FOV; bad pixels are excluded from the binning. Finally, the SNR at the “Lmoy” radiance is defined as the mean SNR across all spectral channels.

As expected, the SNR is higher when the FOD illumination is disabled and the NGP temperature is low. The SNR improves by approximately 30 % when comparing the two extreme operating points :159K with no FOD illumination versus 165K with a 1mA FOD current. Overall, a lower temperature provides a greater SNR benefit than reducing the FOD level; for instance, the SNR measured at 159 K with a 1 mA (or 1.8 mA) FOD current exceeds the SNR obtained at 165 K with the FOD off.

Table 4. Signal to Noise Ratio at Lmoy (1660 LSB, 2320 LSB, 890LSB and 1880 LSB respectively for B1/B2/B3/B4) for several operating configurations



The SNR differences between the various operating points do not agree with the theoretical calculations. This discrepancy arises because the in-orbit SNR estimations are very sensitive to bad pixels management as they result from pixels averaging over one FOV, one has to notice that some flight acquisitions were performed over South Atlantic Anomaly and for these computations transient spikes were not detected. At the end, we obtained SNR very close to ground estimations for the B2 and B4 bands and lower by 10% in B1 and 30% in B3.

In conclusion, operating the NGP at a lower temperature with a 1.8 mA FOD current yields a higher SNR than the configuration at 165 K with a 1 mA FOD current.

2.6 Remanence

The efficiency of the LED (FOD) to reduce remanence was proven during the TVAC tests^[4]. To assess in-flight remanence non-regression, dark to light and light to dark transitions were generated with the scan mirror, which moves from the white lamp source to the shutter position. During each transition, signal was acquired using the multi-reading mode, producing an image every 90ms throughout the integration time. The difference between two consecutive sub-images provides an estimate of the remanence. Accuracy was increased by averaging the differences of several pixels and repeating the transition cycle multiple times. These measurements were carried out for three LED current levels (0mA, 1mA, 1.8mA), and for two NGP temperatures (159K and 165K).

Figure 6 and Figure 7 present the signal evolution during dark to light and light to dark transitions for different operational temperatures and for several FOD signals set by LED current. The signal transition does not occur simultaneously across the spectral bands because the sub-pupil associated with each band is located at a different position in the telescope, and the scanning mirror sequentially samples those distinct pupils.

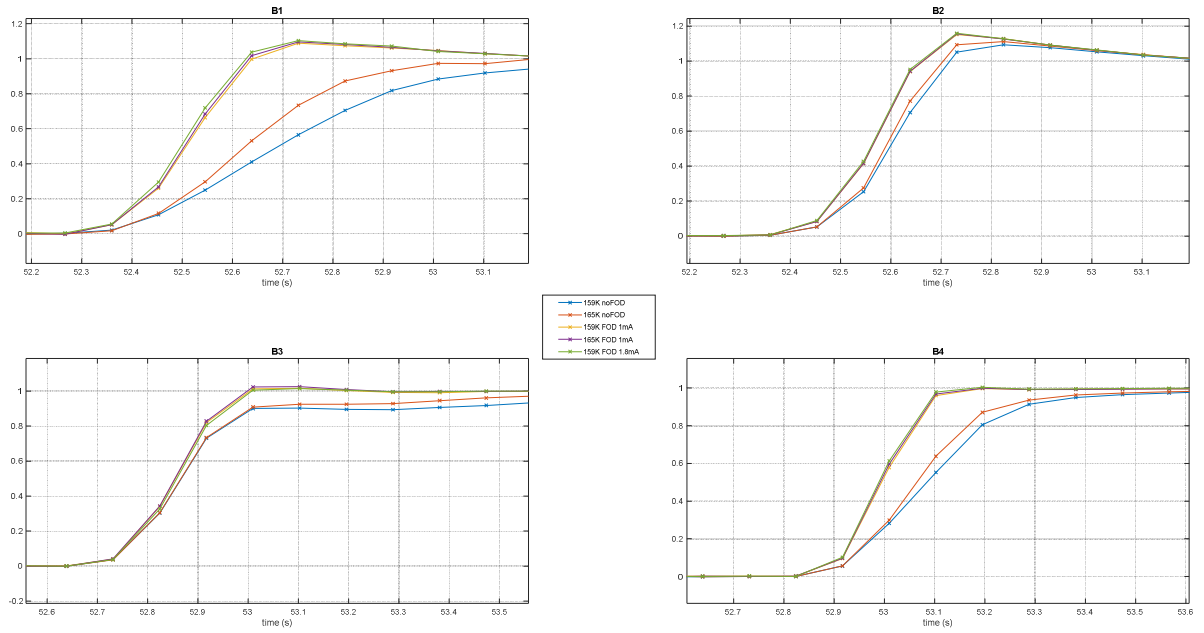


Figure 6. Remanence measurements (Detector signal during a transition dark to light in different conditions (FOD current and NGP temperature))

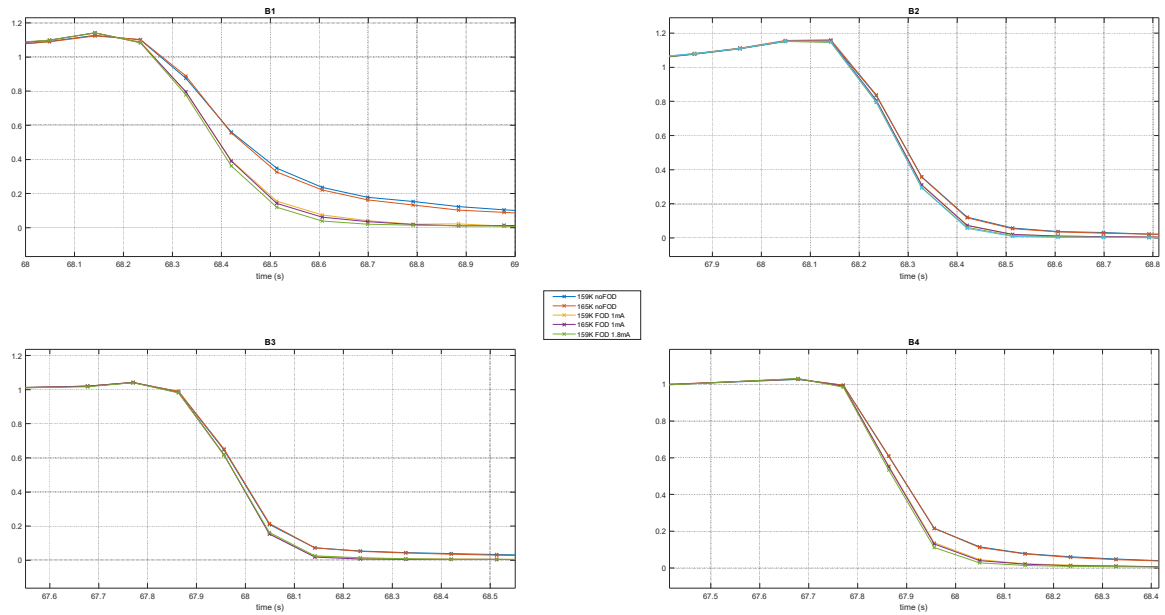


Figure 7. Remanence measurements (Detector signal during a transition light to dark in different conditions (LED current and NGP temperature))

These curves demonstrate the rise time and the fall time are inversely proportional to the LED current amplitude. The temperature has a weak impact on the remanence performance in this range.

Moreover, the rise time depends on the wavelength, the short wavelengths are more sensitive to the remanence. The in-orbit results are similar to those of the TVAC campaign^[4], no evolution of the remanence was observed. Consequently, a 1mA FOD current is sufficient to reduce the remanence.

2.7 Selection of the operating point

For radiometric purposes, operating at a low temperature and using a low FOD are highly advantageous: the RTS and the dark signal are reduced, which in turn raises the signal-to-noise ratio. The remanence is unaffected by temperature, and the FOD values of 1 mA and 1.8 mA give nearly the same results. Consequently, a 1 mA FOD was chosen for the upcoming in-flight activities. To keep the detector regulated throughout the mission, a temperature margin was built in; a set point of 160 K on the NGP was found to be optimal.

3. ICING CONTAMINATION

3.1 Detection of contamination in MICROCARB

Following a three-week decontamination period at a temperature of -1°C for the optics sub systems, the instrument was switched on and the FOD was not applied. During the first month in-flight acceptance testing and the initial calibration and validation phases, the instrument observed regularly two calibrations sources, the internal white lamp source (WLS) and the sun through a diffuser.

These measurements revealed a rapid, non-monotonic evolution of the radiometric response. The evolution of the response is estimated by correcting the lamp and Sun data relative to the dark signal. The signal is then averaged across rows and columns and normalized relative to the first in-flight acquisition, which was obtained a few days after the instrument was switched on.

In B1 band, during the first acquisition month, the signal increases and then decreases; the variation is on the order of 15 %. In B2 and B3 bands, the signal decreases; the drops are 11 % and 8 %, respectively. In B4 band, the signal decreases and then increases; the variation is on the order of 11 %.

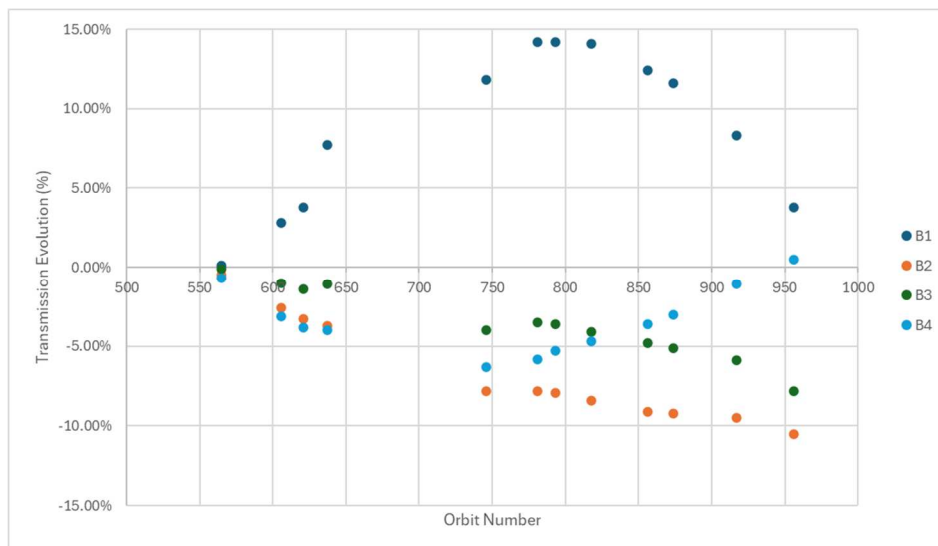


Figure 8. Spectrometer response curve (lamp measurement) averaged across the band and ACT direction

Moreover, a thorough analysis of the full NGP detector images reveals straylight outside the spectral bands. It was first identified after the TVAC campaign, but on-ground characterization was limited because the majority of the TVAC acquisitions were performed on the detector's operational spectral bands (i.e., not the full matrix). Consequently, the phenomenon could not be fully quantified. In flight, the data are displayed with a dynamic-range enhancement to improve contrast, straylight becomes apparent at the short wavelength and it appears correlated with contamination.

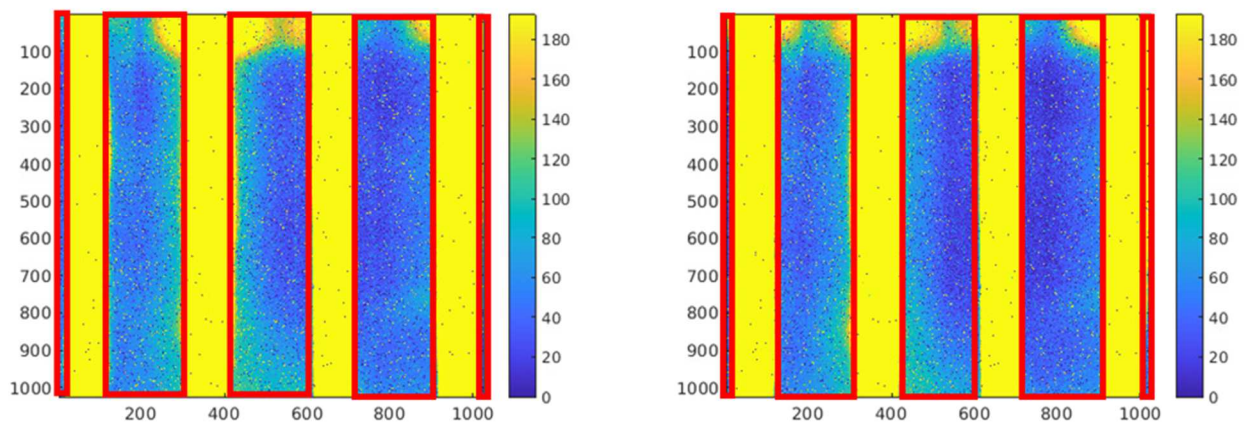


Figure 9. Trend of the parasitic signal (adaptive scaling to enhance contrast) for orbit n°556 (a) and orbit n° 956 (b)

Because these behaviors are seen in both Lamp and Sun measurements, icing contamination of the cold subsystem is the most likely cause.

During the calibration-validation phase, several de-icing scenarios were tested in parallel with the selection of the optimal instrument configuration and complementary optical analyses^[6] were performed to explain this phenomenon.

3.2 De-icing

Descriptions of the different de-icing

The first decontamination phase consists of a three-week period during which the optical sub systems are held at -1°C . During this period, the instrument must be turned off for power budget reasons and the platform provides the required heating. The return to operational temperatures (165K configuration) is carried out in three steps:

- While the detector remains at -1°C , the spectrometer is cooled down.
- Once the spectrometer temperature stabilizes at approximately -25°C , the detector is then cooled down to its operational temperature.
- Once the NGP temperature is reached, the instrument switches on

The subsequent measurements are referred to as “Cycle 1” and were performed without FOD.

The second de-icing, carried out in October, is similar to the first, but lasted only 3 days. The cycle 2 response acquisitions began immediately after the decontamination to obtain a reference as quickly as possible. During the cycle 2, the various instrument configurations (FOD and NGP Temperature) were tested, and they affected the evolution of the radiometric response.

De-icing at -1°C reduces the mission availability, because the spectrometer and NGP cooling phases last 20 hours and 14 hours respectively and the instrument must be turned off. Consequently, a decision was made to assess a de-icing strategy that involved the application of heat exclusively to the detector. In this instance, the instrument remains switched on (detector off). The decontamination was conducted on January 2026: the detector temperature setpoint has been adjusted to -73°C . It took 40 minutes for the detector to reach this temperature. The process of de-icing was conducted for a period of 24 hours. The cycle 3 acquisition began with an instrument configuration similar to that at end of cycle 2.

The two most recent de-icing were performed in March and May 2026. Both were performed at -1°C , i.e. under the same conditions as the second de-icing; the only difference was that the FOD illumination was applied when

the instrument was switched on, and the nominal instrument configuration was used. These two runs are referred to as Cycle 4 and Cycle 5.

To monitor the radiometric evolution across the different cycles, the calibration frequency for the internal calibration lamp (WLS) and Sun sources was increased to several calibrations per week.

Radiometric response evolution per cycle

Figure 10. illustrates the evolution of the radiometric response throughout the successive cycles for each spectral band. Contamination affects all bands, producing variations of up to 20 %–25 %. Moreover, the rate of contamination differs among the bands, with the sequence of speeds observed in B1, B4, B2 and B3 respectively so from shorter to longer wavelength. Note, that the discontinuities visible across the four bands (e.g. November and January) are related to changes in the instrument's configuration (FOD level and NGP temperature). The FOD modifies the detector response and requires time for the response to stabilize.

The analysis of the different cycles shows:

- The second decontamination had the expected effect on the signal: an increase across all spectral bands. Cycle 2 began with a signal gain of 10 % in B1 band, 16 % in B2 band, 9 % in B3 band, 14 % in B4 band. However, the signal changed very rapidly, the loss in B1 and B4 reached 15 % within three weeks and non-monotonic variations were also observed in B1, B2 and B4 during the 100 days cycle 2. Optical analyses^[6] revealed that ice deposition on the interferential filters and detector drives the temporal drift of the signal, modifying the spectral transmission as the ice layer thickens.
- The decontamination at -73°C had an unanticipated effect on the signal. At the beginning of cycle 3, the signal revealed an increase of 7 % in B1 band, a decrease of 5 % in B2 band, a 2 % increase in B3 band, and a 10 % decrease in B4 band. Thereafter, slow variations were again observed in all spectral bands. We conclude that the de-icing at -73°C is not sufficient to return to a neutral state, we suspected that the contamination state was the same as it was one month earlier. Consequently, this de-icing method has been rejected.
- The optimal instrument configuration, identified at the end of Cycle 3, was implemented for Cycles 4 and 5. Consequently, the signal evolution of these two final cycles is almost identical and differs from cycle 2. While the de-icing step restores signal, it is followed by a rapid loss of signal during the first few days; this initial degradation is attributable to the FOD application and ice contamination. After 4 days, the trend correlates with ice contamination, which appears to progress more slowly than in cycle 2. Even though the cycle 5 starts with a lower signal which could be explained by the lamp ageing, the radiometric response evolves more slowly highlighting the benefit of the de-icing.

Before the launch, the required stabilization time of the NGP response to the FOD was uncertain because the TVAC test campaign could not characterize it. The campaign's short duration and the numerous changes to the test setup and instrument configuration hindered a reliable estimate of that time. In flight, the different FOD activations and the repeated calibration measurements allow us to conclude that four days are required for the NGP response to stabilize.

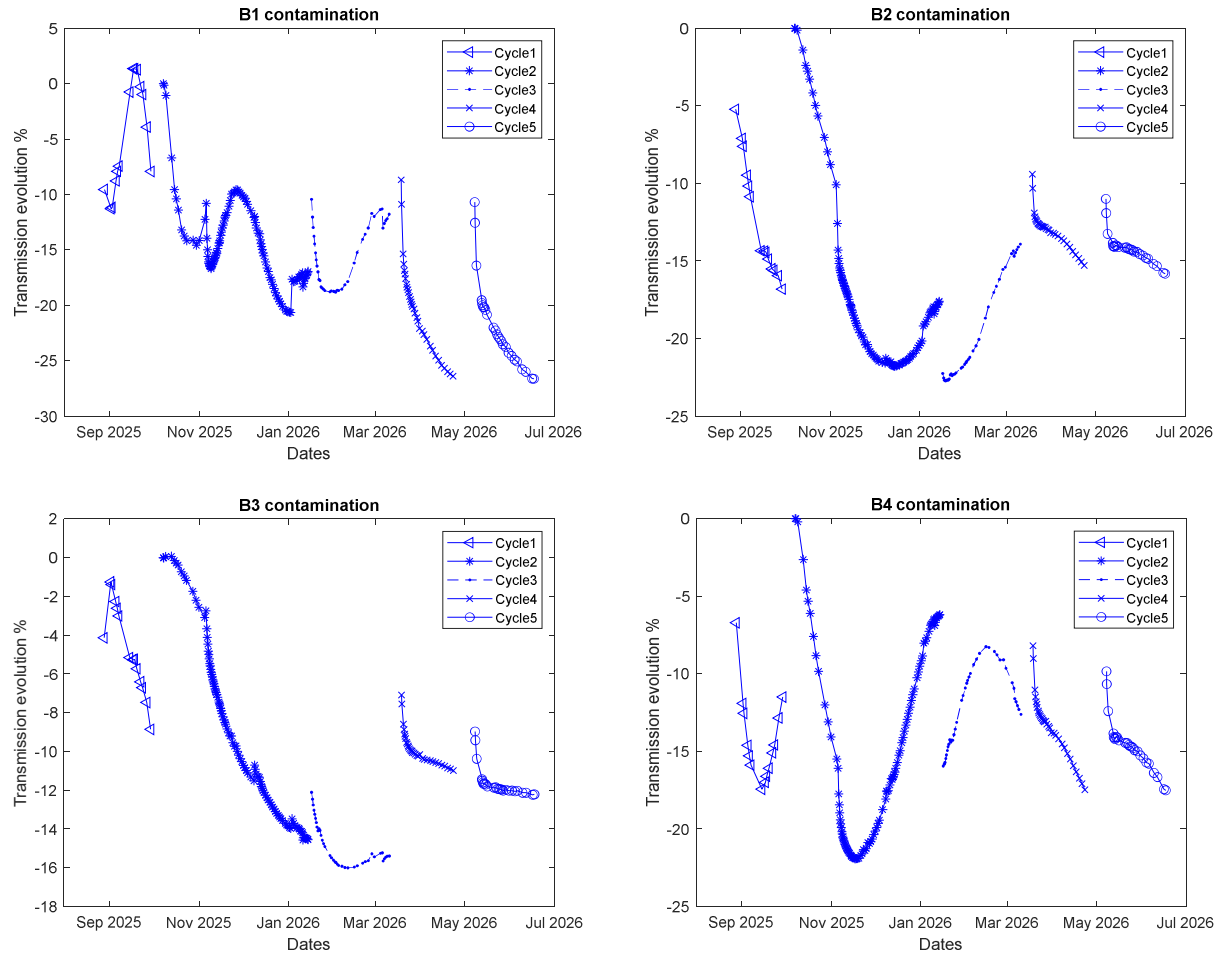


Figure 10. Evolution of the instrument transmission per band during the first year (the different cycles are separated by de-icing), the signal is averaged across rows and columns and normalized relative to the first acquisition of cycle 2.

Straylight evolution per cycle

A temporal analysis of the full detector images acquired with the WLS on the sounder reveals a clear evolution of straylight. In the upper part of the matrix (the first 120 rows), the parasitic signal extends along the columns. Around B4 band, the signal is more distributed. De-icing phases reduce this straylight (see Figure 11), but it reappears with each cycle and the progression appears to be correlated with the level of contamination. This phenomenon is observed in both lamp and solar measurements.

This straylight originates from reflections between the detector and the filters and from scattering; both mechanisms are amplified with contamination (up to some percents). Moreover, a parasitic signal was identified in the upper left corner of the B1 band, this signal is present just after the de-icing and seems to be decorrelated from the contamination. This parasitic signal had already been observed during the TVAC while performing the CO₂ gas-cell measurement, leading to the conclusion that the signal originates from B2.

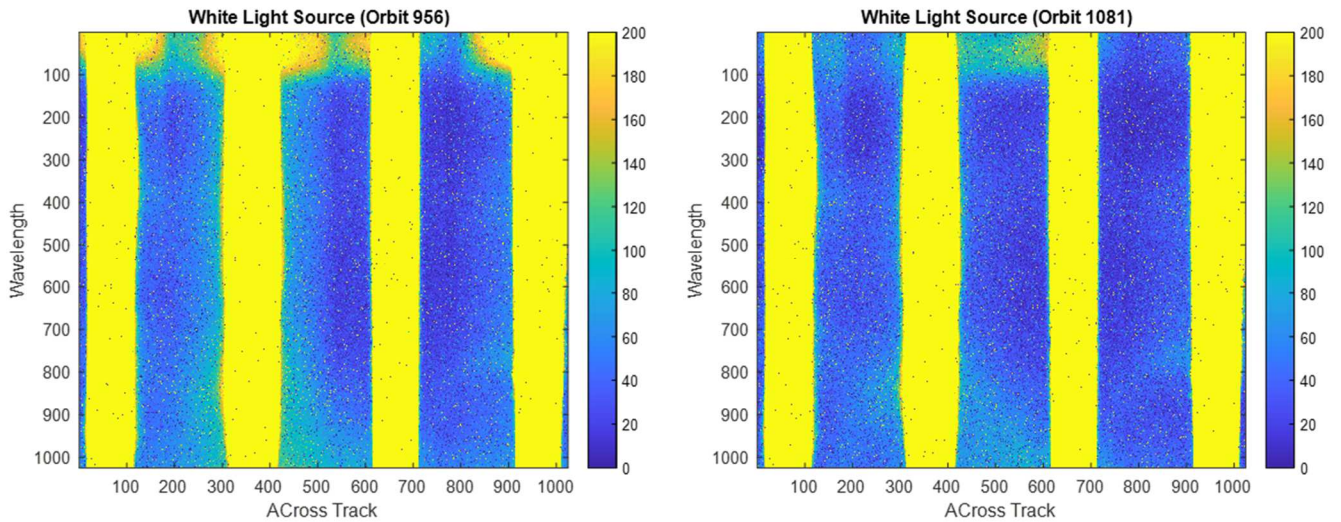


Figure 11. Changes in stray light: measurement before (left) and after (right) the second de-icing, (165K and no FOD configuration, only dark correction processing, average of 300 frames on WLS source)

In addition, the application of the FOD impacts the crosstalk: when the FOD is ON, the edges of the spectral bands become noticeably sharper. Moreover, the FOD effect on crosstalk is not instantaneous; its latency is of the same order as the stabilization time of the NGP response. Figure 12 and Figure 13 illustrate how the edges of the B4 spectral band evolve (Full detector image or ACT profiles).

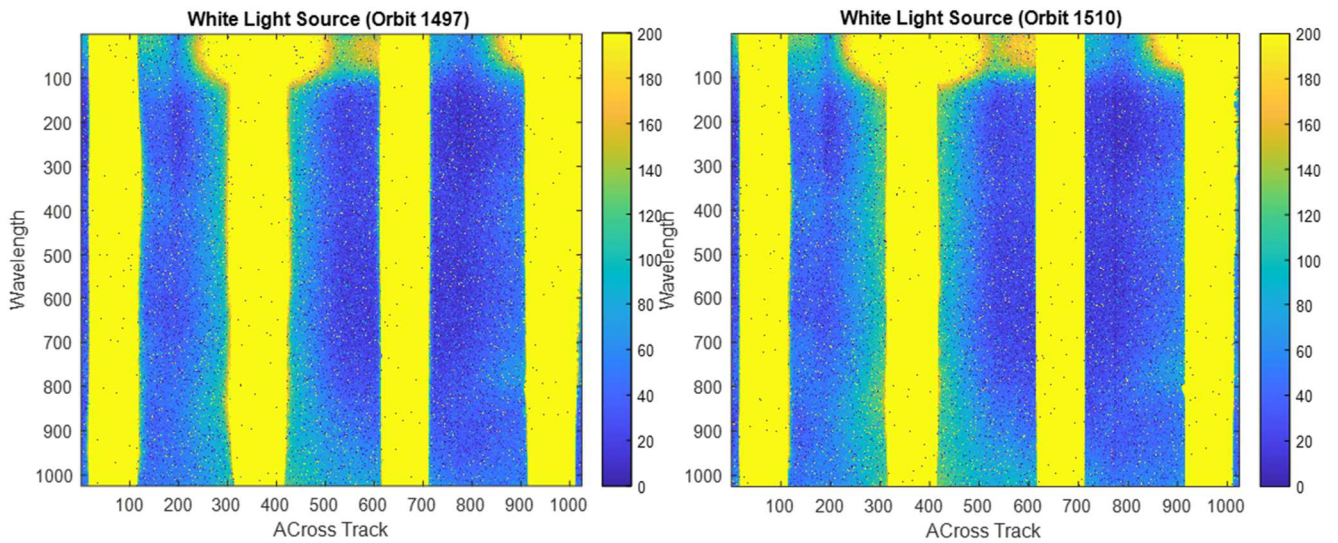


Figure 12. Effect of FOD on Crosstalk : Measurement before (left) and after (right) the FOD application (the FOD modifies the edges of the spectral bands, especially in B4 band)

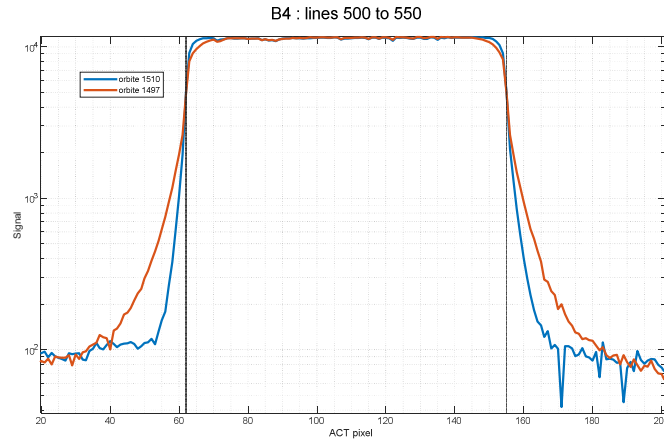


Figure 13. Effect of FOD on the B4 signal: ACT profiles obtained by averaging the signal from channels 500 to 550 (red no FOD, blue 1mA FOD)

The pattern of the straylight evolves during each cycle in the upper part of the matrix. First, the signal appears around the B4 and B1 spectral bands as shown Figure 14. In these images, the straylight around B3 & B2 is barely visible because cycle 4 is too short and icing contamination is slower than cycles 1 & 2. Afterwards, the straylight appears then in the left part of B2 and finally in the right part of B3 (Figure 11 illustrates the final state of straylight (orbit 956)). Moreover, the scattering around B4 seems to slow down, the evolution is slower during the cycle 4.

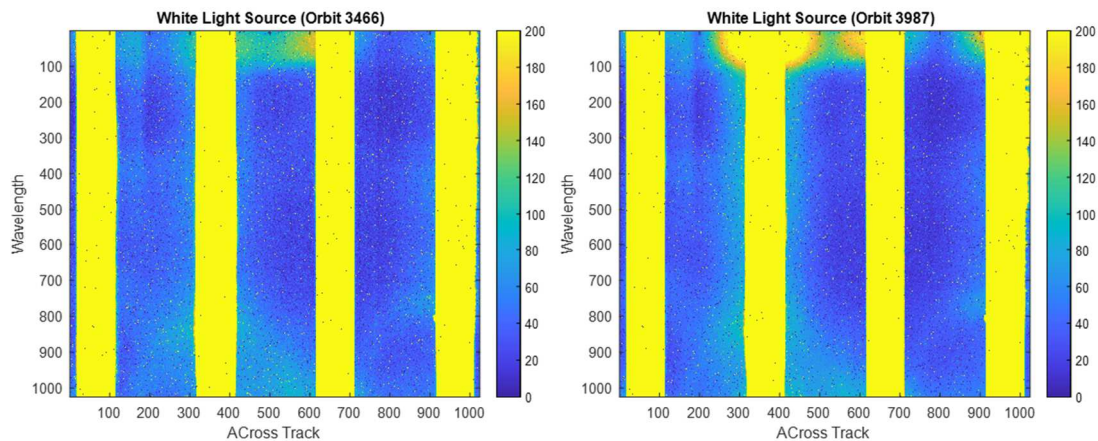


Figure 14. Changes in stray light during the cycle 4: measurement at the beginning (left) and at the end (right) of the cycle 4, (160K and FOD 1 mA configuration, only dark correction processing, average of 300 frames)

The straylight phenomenon is complex; ongoing analysis aims to better understand its evolution and how it influences the signal inside the spectral bands.

Conclusion

The spectrometer is affected by an unexpected water-ice contamination that degrades its radiometric performances. This contamination impacts both the signal and the straylight level. The amplitude of the signal variations is linked to the optical design based on interferential filters coupled to a multilayer coating on the detector^[6] whereas the straylight fluctuations are driven by the ice which modifies the surface reflection and scattering properties. Although several decontamination cycles have been performed, the icing anomaly persists. The root cause lies in the confinement of multiple components inside the cryostat cavity together with internally multilayer insulations (MLI) that have direct view factors to critical optical surfaces. Moreover, during

the de-icing phase the ice sublimates but the resulting water vapor cannot be efficiently evacuated because the vacuum pipe aperture is too small.

The impact of icing is not acceptable for the mission performances. Consequently, different strategies are being pursued : frequent radiometric calibration to enhance the radiometric accuracy, regular de-icing phases to slow the ice build-up, and accumulation of flight data to validate and refine the radiometric processing chain. These activities address a major challenge for the in-flight validation campaign. Nevertheless, the latest results are promising: the progression of the ice slows down.

4. IN-FLIGHT INSTRUMENT PERFORMANCES

Once the optimal instrument configuration has been chosen, the estimation of the instrument's performance has begun.

Power consumption is estimated by accounting for the various acquisition modes during the daylight portion of the orbit and by performing a dark-calibration for each nighttime orbit. The payload mean power is approximately 38W. During the first six months, the data-rate changes because the spectrometer detector's window size was increased to track the stray-light pattern. Currently, the data rate is about 675 Gbits per day.

Table 5. Main characteristics of the Microcarb Instrument

Instrument	Physical Characteristics
Mass	80Kg
Power	38W (mean power including 5.7 W for thermal regulation)
Data Rate	675 Gbits/day
Volume	460 mm x 780 mm x 1310 mm

Regarding geometry, the information from the Attitude and Orbit Control System (AOCS) together with a temperature and date correction model (CorLoc) is used to evaluate the a posteriori geolocation performance. The resulting Mean Knowledge Error is below 120 m. The geolocation stability performance (Relative Pointing Error) is estimated by absolute correlation. It depends on the observation mode; in nadir mode, the line of sight is very stable (<0.2 pixel) whereas in scan or fixed target modes the fluctuations can reach 0.5 pixel. The interband registration is performed using Sentinel-2 and moon observation; the bands B1 and B2 have a good registration while bands B2 and B3 present the worst registration.

Table 6. First geometric performances results

Geometry Performances		Comment
Field Of View (km)	Imager 27 x 18 (ACT x ALT) Spectrometer 13.5 x 9 (ACT x ALT)	Imager FOV = 2 x Spectrometer FOV 3 FOVs simultaneous obtained by binning
A Posteriori Geo-Location MKE	< 120m at Nadir	Requirement 450 m
Geolocation stability RPE	< 25m (Peak To Peak) Nadir mode < 62m (Peak To Peak) Fixed Target and Scan modes	Requirement 220 m
Interband registration	< 420m (ALT direction, worst case) < 99m (ACT direction, worst case)	Requirement 450 m

Regarding the spectral performances, the spectral dispersive law is estimated from solar observations. The thermal stability of the spectrometer and the focal plane ensure the validity of this spectral law for atmospheric acquisitions. The bandwidth, spectral sampling, and smile all meet the required specifications. Regarding resolution and the shape and stability of the Instrument Spectral Response Function, the analyses are ongoing.

Table 7. First spectral performances results

Spectral Performances				
	B1	B2	B3	B4
Wavelength range μm	[0.7583 - 0.7688]	[1.5968 - 1.6189]	[2.0231 - 2.0510]	[1.2646 - 1.2821]
Spectral Sampling pm at λ_{moy}	10.24	21.6	27.2	17.1
Smile	< 0.2 pixel			

Regarding radiometry, the mission requirements are very challenging (< 4 % for absolute calibration and < 0.3 % for intraband calibration). The RTS, dark-signal stability, and contamination all affect calibration accuracy. The high signal to noise ratio allows us to assess the instrument's characteristics and to define new correction procedures. Processing of the L0 and L1 data is currently being updated, and the first results of the implemented correction algorithms are promising.

CONCLUSION

This paper presents an overview of the MicroCarb in-flight commissioning. The validation of all acquisition modes was carried out concurrently with the optimization of the instrument's operating point and with the investigations of the unexpected icing contamination. A detector temperature of 160K together with a FOD current of 1mA provides the best overall performance for the mission. A large set of analyses has been performed to characterize the ice-induced contamination and to quantify its impact on both the radiometric response and the stray-light level.

The availability of multiple calibration sources (internal white-lamp and solar diffuser, moon), the flexibility of the instrument configuration (size matrix, FOD current, temperature) and the ability to adapt the mission plan and the data processing chain of the data were a big advantage to face to the unforeseen issues.

The next phase of the mission will focus on:

- Characterizing stray-light – quantifying its evolution across the detector, understanding how ice deposition scatters and reflects, and developing mitigation and correction strategies
- Refining the radiometric response – continuously monitoring the lamp and Sun signals and updating the calibration coefficients to maintain radiometric accuracy.
- Enhancing data processing – optimising the L0-to-L1 pipeline to deliver reliably calibrated spectra for atmospheric CO₂ retrievals.
- Implementing regular de-icing phases or long de-icing to slow the build-up of ice contamination

These activities are essential to achieve the required radiometric accuracy for the MicroCarb scientific objectives.

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