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MICROCARB INSTRUMENT, OVERVIEW AND FIRST RESULTS

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ABSTRACT

MicroCarb is a space mission designed to monitor the CO2 fluxes at the earth surface in order to better understand exchanges between atmosphere, oceans and vegetation. The specificity of Microcarb is its capacity 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~25000), Instrument Spectral Response Function (ISRF) knowledge (<1%), radiometry and polarization's sensitivity (~ 0.3%). To achieve such high performances, on ground and in flight spectrometer calibration is a key point for the success of the mission.

The payload is developed by Airbus Defence and Space (ADS) France and the assembly phase is now almost complete. First performance results in ambient conditions were obtained with a calibration detector and were in line with the expected values. The instrument activities will continue with the mechanical qualification and Thermal VACuum (TVAC) tests during which all the instrument performances will be measured. Delivery of the instrument is scheduled today at autumn 2022 for further integration on platform.

This paper will focus on the technical overview of the instrument and on its critical performances. Then we will present the calibration philosophy and the first tests results.

Keywords: Carbon dioxyde, Spectrometer, ISRF, echelle grating

1. INTRODUCTION

Several reports[1,2] have pointed out the necessary contribution of space systems for the monitoring and understanding of the carbon cycle. A better understanding is essential in the context of the present climate change, which impacts the carbon cycle. The recent increase of the level of the emissions due to human activities (and in particular combustion of fossil energy) has broken up the existing natural balance. The community now calls for an operational system with the ability to combine inventories, in situ measurements, and space based observations, with ambitious requirements put on the space system, regarding accuracy, spatial resolution coverage and revisit time. In the context of the COP-21, held in December 2015 in Paris, the French government announced its decision to carry out the development of the MicroCarb program and asked CNES (Centre National d'Etudes Spatiales) to conduct the work, jointly with the national scientific community. This project finds its place between the ongoing pioneering mission OCO-2 (USA) and GoSat (Japan) and a future operational system such as Copernicus CO2M.

MicroCarb will be a compact and relatively low cost space instrument for the monitoring of CO2 column concentrations, to be carried on-board a micro satellite of total mass about 180 kg. Airbus Defense and Space is in charge of the development, integration and characterization of the payload. The Microcarb payload is composed of a visible imager used for the clouds detection and a Short Wave InfraRed Spectrometer which acquires four spectral bands on a single detector. The B1 band, including numerous rays of O2, around 0.76 µm, provides information on the surface pressure, and the vertical distribution of atmospheric aerosols. A second band (B4) that also presents numerous rays of O2, around 1.27 µm, has the advantage of being closer in wavelength to the CO2 bands, which reduces the uncertainty due to the spectral signature of aerosol optical depths, in the context of correction of the atmospheric scattering effects. A B2 band with numerous rays of CO2 around 1,6 µm, is sensitive to the number CO2 molecules in the atmospheric column. A second CO2 band (B3) around 2 µm, with stronger absorption lines, is also sensitive to the concentration of CO2 (the information of both bands is combined to reduce the uncertainties) and gives information about water vapor and aerosols. The spectra of these 4 bands provide the necessary information to retrieve a column concentration of CO2 with some vertical weighting.

Several acquisition modes[3] are identified for MicroCarb, either for scientific measurements collection, or for calibration purposes. The two basic modes for the acquisition of scientific data are Nadir Mode and Glint Mode. The Nadir Mode consists in performing the measurement straight down from the satellite (close to the geocentric direction): used over ground. The Glint Mode performs the measurement in the sun specular direction. This mode is essential to get measurements above oceans, because water acts as a mirror concentrating the whole reflectance in the specular direction, more or less according to its surface roughness, and so to the wind strength.

2. INSTRUMENT OVERVIEW

The payload is composed of a Pointing and Calibration Subsystem (PCS), a common telescope for the imager and the spectrometer, a single grating spectrometer for the 4 spectral bands and a unique detector array. The detectors are managed by video electronics and an Instrument Control Box (BIC) is in charge of the proximity electronics operations, the thermal control, the scan mirror operation and the data exchange with the platform (both science and the TM/TC).

The main characteristics of the instrument are summarized in Table 1:

Table 1 : Instrument Main Characteristics

	Spectrometer				Imager
	B1	B2	B3	B4	
Geometric Performances					
Field Of View (FOV)	4.5km x 9 km (ACT x ALT) 3 FOVs simultaneous				27 km x18 km
Interband registration	3% objective & 10% threshold of non-common area				NA
Radiometric Performances					
SNR per FWHM	420	600	230	450	130
Polarization	< 0.3% Glint mode < 1% Nadir mode				< 3%
Absolute calibration	4%				7%
Intraband Calibration	~ 0.3%				0.5%

Spectral Performances					
Central Wavelength nm	764	1608	2037	1273	625
Bandwith nm	10	22	28	17	150
Spectral oversampling (FWHM)	>2.6				NA
Resolving power	> 24 000				NA
Spectral Shape of ISRF	< 20% (relative to a gaussian shape)				NA
ISRF Knowledge	<1%				NA
Physical characteristics					
Mass	80kg				
Power	< 60 W				
Data Rate	500Gbits/day				
Volume	110 cm x 60 cm x 45 cm				

To be more compact and compatible with the satellite constraints (size and power), and to respect the high level of performances, the concept of the spectrometer, covered by ADS patent, is based on a split pupil telescope[4,5] coupled with a grating for spectral multiplexing[4,5].

2.1 Instrument concept

The acquisition of four spectra on a same detector array is performed by a separation of the different spectra in the spatial direction (Across track) thanks to the use of four slits in the telescope focal plane. As the mission requires a good registration between the four spectral bands, it is necessary to align the 4 slits on the same location on ground, which is made at telescope's pupil level with independent sub pupil per focal plane and introducing dedicated prism in each sub pupil (Pupil Separation Prisms PSP) in the telescope. Figure 1 illustrates the telescope optical design and the PSP principle. An other sub pupil is integrated for the imager.

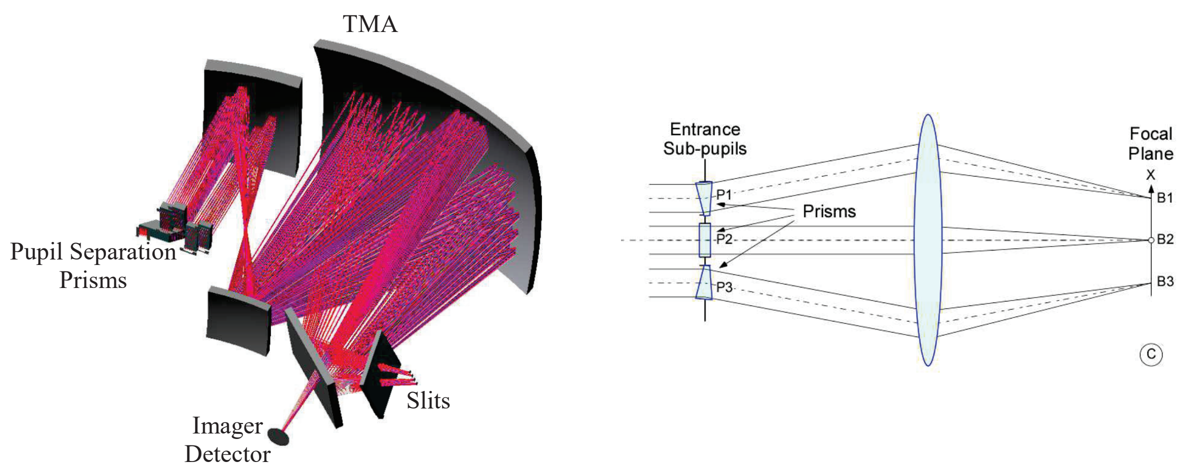

Figure 1. Telescope optical layout and Principle of the split pupil telescope concept

The spectrometer uses an echelle grating with high interference orders. This solution offers a potential high spectral resolution and a high degree of spectral multiplexing because the grating diffracts a wide spectral domain in the same direction. For compacity reason, a double-pass Three Mirror Anastigmat is used for both collimation function and camera lens function that images the slits on the detector and we introduce Pupil Alignment Prisms (PAP) to superimpose the four telescope sub-pupils on the grating, as shown on Figure 2. Doing so, the sizes of the grating and of the spectrometer are limited and are imposed by the largest band sub-pupil (B3 for radiometric requirements).

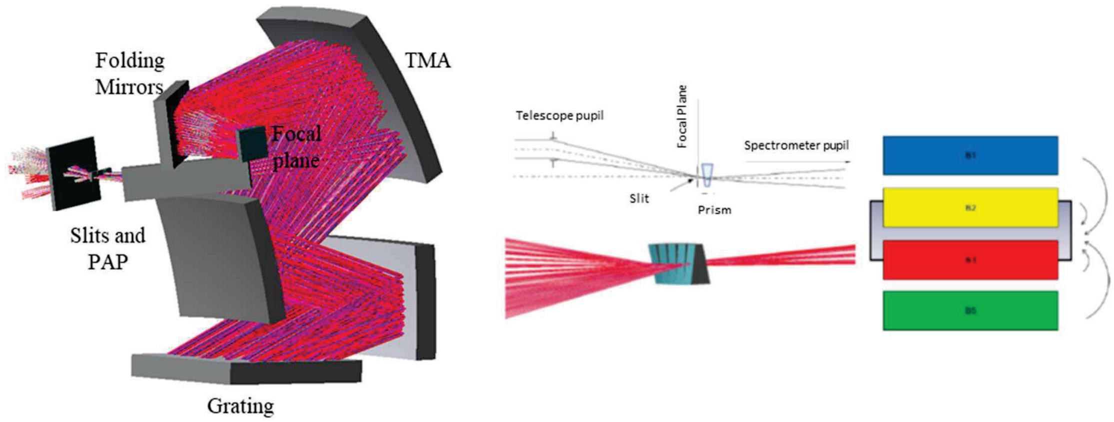

Figure 2. Spectrometer optical layout & Principle of pupils images re alignment on the grating plane.

Four narrow band pass filters are placed in front of the detector to select the useful diffraction order. The detector lines correspond to the spectral direction and the columns correspond to the spatial direction for each band (see Figure 3). Each band columns are divided into 3 so as to obtain 3 FOVs.

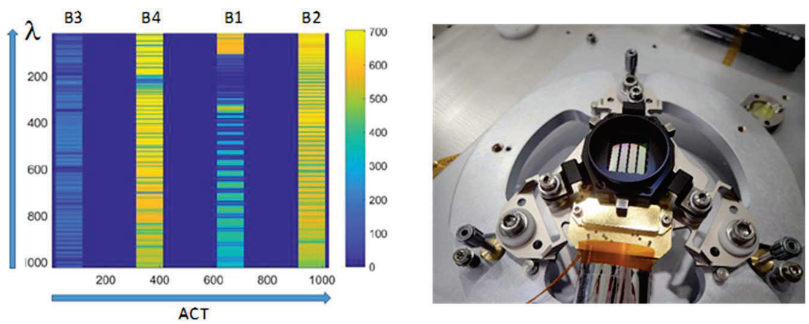

Figure 3. Distribution of spectral bands over the detector (left) and spectrometer focal plane (right) ©ADS

2.2 Instrument Description

The pointing and calibration subsystem is composed of a scan mirror which allows to point the instrument Line of Sight (LOS) across track (Glint & Nadir Modes) and towards internal calibrations sources (White Light Sources (WLS) and diffuser in transmission on the sun port) and a closed position. The WLS acquisitions are used to calibrate the Pixel Response Non Uniformity (PRNU) and the sun acquisitions for absolute radiometric characterization and spectral dispersive law characterization.

After the PCS, the incoming light goes through a polarization scrambler[5] to minimize the instrument polarization sensitivity. As the scan mirror is located before the scrambler, the polarization performance depends on the mirror angle and the choice was made to optimize the polarization at Glint (angle of -25°) by using a folding mirror that compensates the scan mirror polarization for Glint angle. As the polarization is a key performance of the mission, some modelizations have been developed by CNES[6] & ADS, measurements were performed on breadboard and on the telescope during the assembly.

After the scrambler, the light reaches the entrance pupil of the telescope where each prism (PSP) has its own coating dedicated to one spectral band, the size of each sub-pupil is driven by radiometric requirements. Then, the beam is imaged on the slits by a Three- Mirror Anastigmat (TMA) and the separation between the spectrometer and the imager is made by a beam splitter located at the telescope's exit pupil. During the integration of the telescope, a lot of radiometric and geometric measurements were led to verify the performances.

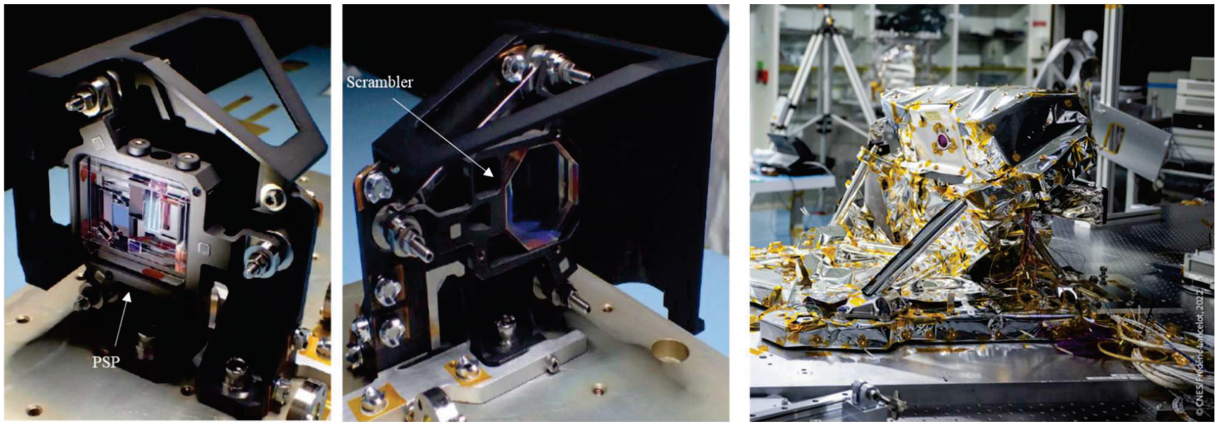

Figure 4. PSP and scrambler before the integration on the telescope ©ADS and Telescope (right)

Then, as the four channels are spatially separated at telescope focal plane, they all have their own slit at the entrance of the spectrometer. The slits are immediately followed by the PAP.

The beam is diffracted in the same direction but at different diffraction orders (between 15 and 40) thanks to the echelle grating[5]. To be more compact, the grating is placed in a Littrow configuration and after a double pass TMA, the four channels are focused on the spectrometer focal plane. Thus ACT magnification is 1 and the spacing of the imaged spectral bands is identical to the slits spacing. The size of the slits, the optical performances and the parameters of the grating have directly an impact on the spectral performances[7], especially on the ISRF shape. A lot of spectral characterizations were made during the integration of the spectrometer to achieve the high performances.

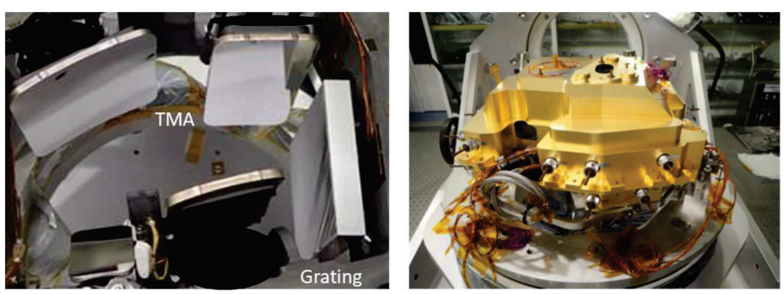

Figure 5. The double pass TMA & the grating during the alignment phase ©ADS (right) and the spectrometer part ©ADS (left)

The 1024 x 1024 detector array is a NGP developed by Lynred. It is cooled down to 150K thanks to a passive cryogenic system relying on a radiator pointing to cold space (at 2.7 K) and protected by a baffle from any illumination caused by the Sun or the Earth, whatever the satellite operational attitude. The cooling system allows also to obtain a temperature of 250K at the spectrometer level, so that it cancels the background signal and improves the radiometric performances. The spectral dimension uses all available pixels (1024) and the pixels associated with each band are binned into three subsets to produce the three simultaneous sounding points. All the pixels, integrated over 1.3 s in nominal modes, are downloaded without any on board processing. The array is operated in Integrate While Read (IWR) mode and non-destructive reading allows to have intermediate measurements inside the integration slot. These data are used to correct ISRFs on ground according to radiometry variations which may occur in the along track direction over the integration period. This processing is necessary to be compliant with the ISRF knowledge requirement.

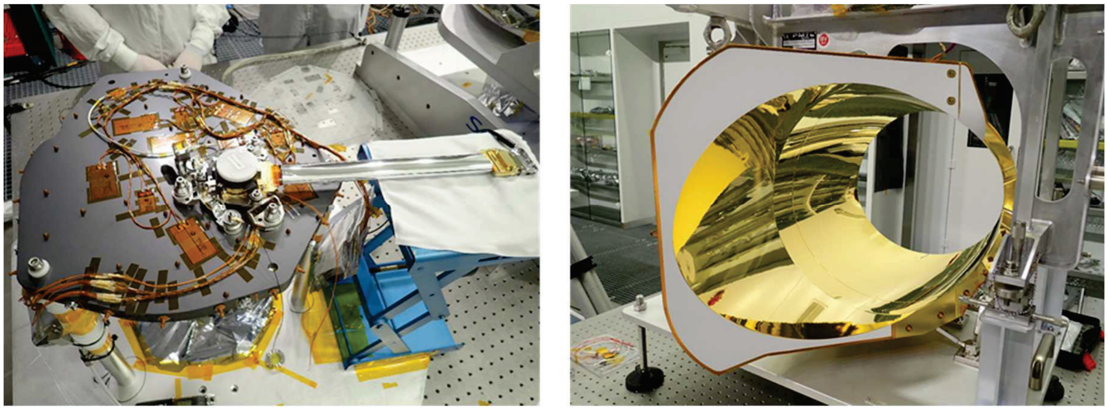

Figure 6. The radiator & the NGP detector ©ADS (left) and the baffle (incoming illumination protection from Earth and Sun) ©ADS

2.3 Final configuration

After completion of individual telescope and spectrometer alignments, a coupling phase was led in which some first performances results were obtained with a Short Wavelength InfraRed (SWIR) camera instead of the flight detector. This camera operates at ambient temperature so that it was possible to measure the instrument before thermal vacuum in three bands (B1, B2 & B4).

This phase was very important to verify the performances and to define the position of the flight detector. Following pictures depict instrument integration stages.

Figure 7. The PCS with the telescope (left) and the spectrometer (right) before the coupling

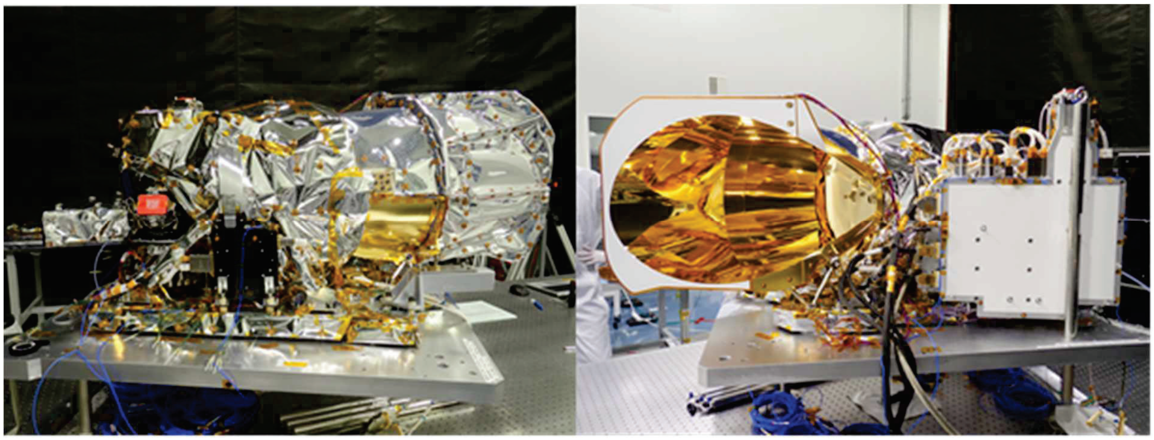

Figure 8. Microcarb Instrument ©ADS (left : sun view with the PCS sun port, right : antinadir view)

3. FIRST MEASURED PERFORMANCES

As the detector has limited performances at ambient temperature and the cooling system is based on passive solution, all the performances of the spectrometer will be measured during the TVAC phase. Waiting for this step was a big risk for the performances assessment, so, measurements were performed at telescope and spectrometer levels and during the coupling. A dedicated Optical Ground System Equipment (OGSE) developed for the TVAC campaign was available during these phases and allowed to perform performances characterization, prepare procedures and anticipate some anomalies.

3.1 Optical Ground System Equipment

National Physical Laboratory from UK (NPL) developed the OGSE in accordance with Airbus requirements and leases it during instrument integration and verification phases. The STAR OGSE is composed of two setups. The setup 1 is a collimator used for spectral and geometric performances and the setup 2 is an integrating sphere used for radiometric performances.

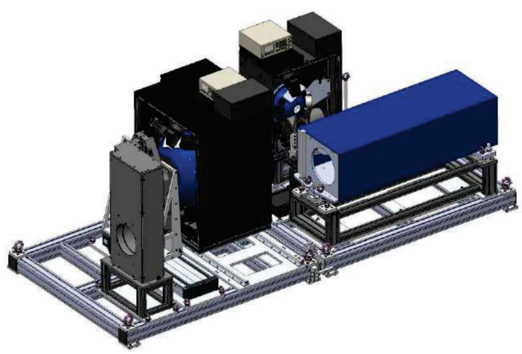

Figure 9. Microcarb STAR OGSE

Both setups are equipped with a broadband source and a common tunable laser source module (M-Squared SolsTiS laser). In addition, a polarizer can be inserted in the light path for polarization measurements.
A set of field masks is available at collimator focal plane for non-uniform illumination purpose, that will be used to characterize ISRF in case of non-uniform scenes and for registration measurements.

3.2 Polarization measurement

During integration of Microcarb instrument, a first set of performances was acquired at telescope level. At this stage, it was possible to rotate the instrument as only the telescope part was assembled. This was the opportunity to measure a critical performance like the polarization sensitivity as it varies with the scan mirror orientation. The strategy was to rotate the instrument in front of the OGSE (setup 2 with the polarizer) of which position was fixed due to its size. This way, for each tested scan mirror orientation, the instrument line of sight was aligned with the OGSE.

This measure was very complex as Microcarb instrument was designed to minimize polarization sensitivity: this means that very small amplitude variations were expected and that any bias would affect the measurement. Indeed, for instance, polarizer transmission showed small spatial variations that required to be taken into account to reveal the sinus expected curve. Also, crosstalk in between spectral bands was an issue, as at telescope level several masking and filtering elements were not yet integrated. This was mitigated adding a mask close to the sub-pupils.

Hereunder is an example of result for band B2 for -12.5° scan mirror orientation.

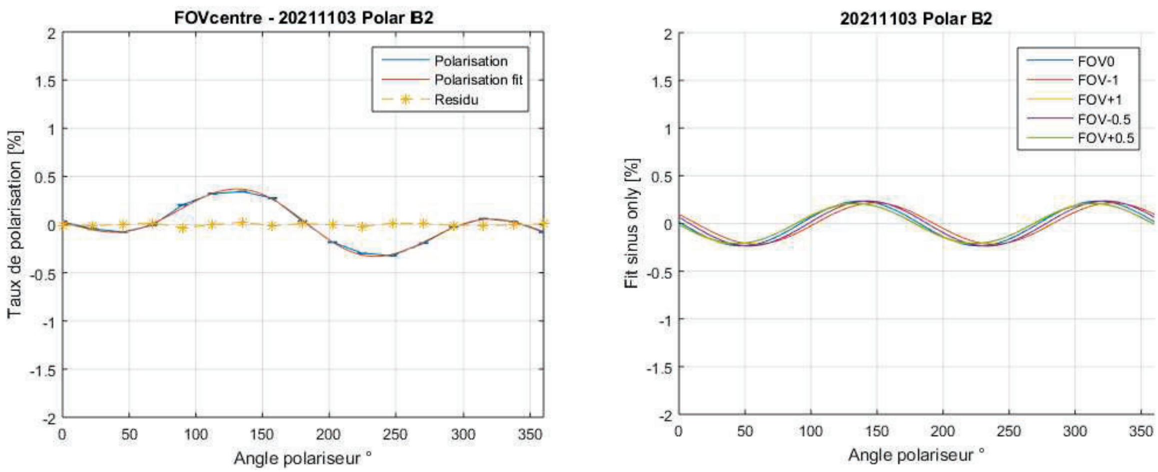

Figure 10. Data before (left) and after (right) polarizer transmission spatial variations correction

The polarization sensitivity is specified to be less than 0.25% in Glint mode which corresponds to an angle of -24° for the scan mirror and 5% in other modes. This is a very challenging requirement and Airbus performed some modelizations to assess this performance. Modelizations showed polarization will be better than 0.25% at Glint for bands B2 and B4, 0.3% at Glint for bands B1 and B3 and 1% otherwise. The results showed that Microcarb instrument is compliant for the measured bands B1, B2 and B4 with a maximum measured value respectively of 0.25%, 0.16% and 0.16% at Glint. The results were also compared to the theoretical model established by Airbus.

Polarization sensitivity for band B2 is in line with the model whereas band B1 results do not show the same evolution with scan mirror orientation as does the model. This can be explained by the high uncertainty due to low signal level in band B1. Concerning band B4, the very small measured values make difficult to reveal the evolution with scan mirror.

Same measurement was repeated after telescope and spectrometer coupling, but only for Glint scan mirror position. The values obtained are very close to the ones measured at telescope level, which means that spectrometer integration did not generate any evolution on polarization sensitivity. A new measurement will be held during the TVAC campaign and B3 polarization performance will be estimated.

3.3 Instrument transmission

After telescope and spectrometer coupling, the instrument transmission was measured with the OGSE setup 1 (broadband source) and the SWIR camera operating at ambient temperature before integrating the flight detector.

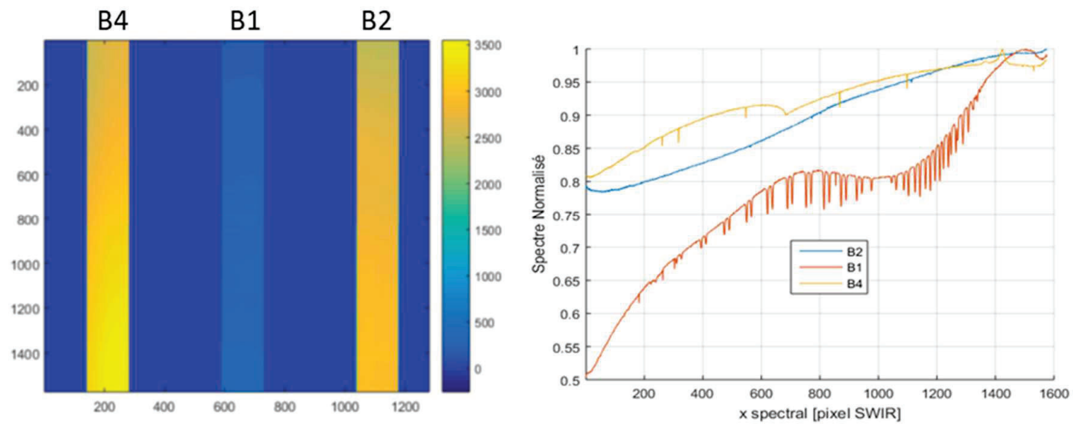

Figure 11. SWIR image (left) & Microcarb telescope and spectrometer measured transmission along one column (right)

These are the first spectra measured with the flight instrument. A non-expected bounce was observed on band B4 (close to the pixel 700) and later explained by the grating manufacturer. Indeed, this is due to the extinction of a tangent order and distribution of its energy in the other orders. In B4, we also detect a ghost at pixel 1400 due to interband straylight, that will be canceled with the detector filters. We note also that in B1 band, we see the atmosphere absorption lines thanks to the high spectral resolution.

We also compared the measurement with our instrument simulator that includes the as-built parameters. This was especially useful for band B1 to understand the shape of the curve that is due to the B1 PSP transmission.

3.4 Instrument Spectral response Function

One of the main performances for this high resolution spectrometer is the ISRF. That is why as soon as the telescope and spectrometer were coupled, this performance was assessed. ISRF first measurement used the SWIR camera, as it was under ambient conditions. It is supposed that detector impact is small on ISRF but this measurement will also be performed at operating cold temperature with the flight detector. Bands B1 and B2 were measured with limited number of laser source wavelengths (setup 1 with tunable lasers).

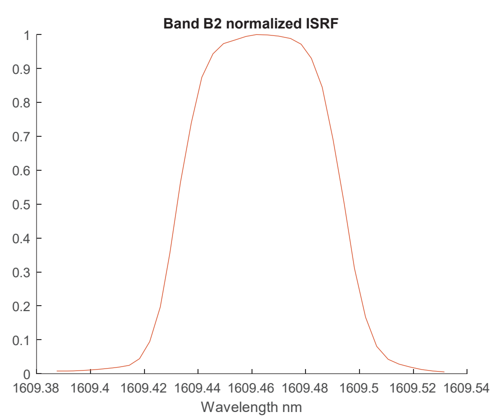

Figure 12. B2 ISRF measurement

Again, the results were compared to our instrument simulator that modelizes the ISRF[7], especially the Full Width at Half Maximum (FWHM) that is related to spectral resolution power $R=\lambda/\Delta\lambda$ is verified. Table 2 summarizes the comparison.

Table 2. Simulated ISRF FWHM vs measured ISRF FWHM for 5 wavelengths of band B2

	Wavelength 1	**Wavelength 2**	**Wavelength 3**	**Wavelength 4**	**Wavelength 5**
Simulated ISRF FWHM (pm)	60,53	61,86	61,65	61,93	61,08
Measured ISRF FWHM (pm)	61,54	61,85	61,64	61,93	61,07
R	26170	26040	26130	26000	26340

The measured FWHM are in line with the simulations so we are confident in Microcarb ability to reach the targeted high spectral resolution.

During thermal vacuum performances measurement, the ISRF will be characterized for +/-10 FWHM range with a wavelength step of FWHM/15.

3.5 Spectral coverage

The last step of the instrument assembly was to align the detector with the telescope and spectrometer. This alignment was driven by the B1 mandatory spectral band that is imaged on 1014 pixels of the detector out of 1024 so with small margin.

Laser illumination at 3 different wavelengths per band was used to define the best detector position taking into account the grating contraction that will occur at operating cold temperature and other ground to flight evolutions.

To be able to predict the cold effect on grating, the diffraction angle as a function of temperature was previously measured on a breadboard[5]. Also the theoretical spectral dispersion was used after adjustment with the laser illumination measurements. Spectral coverage will be confirmed during thermal vacuum testing.

After the integration of the NGP, spectral measurements were performed by a laser, at 3 positions across track in 3 of the 4 instrument spectral bands (as shown Figure 13).The positions of the spots are in line with the expected values.

Figure 13. Instrument First Light

4. CALIBRATION PHILOSOPHY

The majority of the instrument calibration will be done during the thermal vacuum campaign, in the GAIA chamber, at ADS Toulouse.

The OGSE (setup 1 & 2) will be outside the chamber and an custom window tape was developed to see the OGSE signals. Some optics will be in the chamber: a TVAC sensor allowing the absolute monitoring of the broadband and monochromatic incident radiances, a sun simulator to verify the sun port radiometric fluxes and optical fibers connected to the Msquared laser for light tightness verifications.

Thanks to these on ground equipment units, all the performances characterizations (ISRF, absolute calibration, polarization, non linearity, interband & intraband registrations…) will be performed. All optics and structural elements are in silicon carbide (SiC). This technology provides highly stable instruments and guaranties the non-evolution and the good knowledge of the ISRF in flight.

In addition to these measurements, two overall tests with respectively a CO2 gas cell provided by CNES and an end to end direct atmospheric test will be led. This latter will use a heliostat on clean room roof to feed via optical fibers the instrument with sunlight having crossed the local atmosphere. These acquisitions will allow to check the behavior of the instrument on absorption spectra, to carry out processing on physical data and validate the processing chain. The Level 0 corresponds to the raw data. The level 1 gives for each FOV and each band a spectra calibrated in radiance and in wavelength. For Level-2, the radiance spectra shall be converted into column-integrated CO2 concentrations on the basis of full-physics radiative transfer computations.

In flight, for instrument calibration purpose, the scan mirror will be periodically put either in closed position to acquire the dark signal, either pointing at the internal white lamp sources for PRNU response or looking directly at the sun through the diffuser to update the dispersive spectral law and for absolute radiometry.

5. CONCLUSION

The integration of the instrument is now completed. The mechanical and EMC tests have been completed. The major of next activities will be the preparation and the thermal vacuum campaign. This step is crucial for the instrument because it will be the first time that we will measure all the performances at instrument level with the flight detector at operational cold temperature.

Instrument delivery to satellite AIT is now scheduled for November 2022 and the satellite and the system will be ready for a launch from end 2023.

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