International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

ICSO 2022
International Conference on Space Optics
3 – 7 October 2022 | Dubrovnik | Croatia
esa

Copernicus CO2M: status of the mission for monitoring anthropogenic carbon dioxide from space

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127774I · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2690839

Copernicus CO2M: status of the mission for monitoring anthropogenic carbon dioxide from space

Y. Durand[a], G. Bazalgette Courrèges-Lacoste*[a], C. Pachot[a], A. Pasquet[a], M. Martinez Fernandez[a], D. Sanchez Cabezudo[a], V. Fernandez[a], S. Lesschaeve[b], D. Spilling[c], A. Dussaux[d], D. Serre[d], J. Komadina [e] and F. te Hennepe[e]
[a] European Space Agency, Keplerlaan 1, 2200 AG Noordwijk ZH, The Netherlands; [b] 3 OIP Sensor Systems, Westerring 21, 9700 Oudenaarde, Belgium; [c] Thales Alenia Space, #660, Bristol Business Park, Coldharbour Lane, Bristol BS16 1EJ, UK; [d] Thales Alenia Space, 100 Boulevard du Midi, 06156 Cannes, France; [e] OHB System, Manfred-Fuchs-Platz 2-4, 28359 Bremen, Germany

ABSTRACT

The European Space Agency (ESA), in collaboration with the European Commission (EC) and EUMETSAT, is developing as part of the EC's Copernicus programme, a space-borne observing system for quantification of anthropogenic carbon dioxide (CO_2) emissions. The anthropogenic CO_2 monitoring (CO2M) mission will be implemented as a constellation of identical Low Earth Orbit satellites, to be operated over a nominal period of more than 7 years. Each satellite will continuously measure CO_2 concentration in terms of column-averaged dry air mole fraction (denoted 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 < 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 demanding requirements necessitate a payload composed of three instruments, which simultaneously perform co-located measurements: a push-broom imaging spectrometer in the Near Infrared (NIR) and Short-Wave Infrared (SWIR) for retrieving XCO2 and in the Visible spectral range (VIS) for nitrogen dioxide (NO_2), a Multi Angle Polarimeter (MAP) and a three-band Cloud Imager (CLIM).

Following the kick-off Mid 2020, the industrial activities have now passed the Satellite PDR allowing to enter in phase C/D. The paper will provide an overview of the space segment development achieved during the phase B2, including the platform, the payload activities as well as the end-to-end simulator. The preliminary design of the instruments on board the CO2M mission, the progress of the critical technological activities and the first results of the development models will be highlighted.

Keywords: Copernicus programme, imaging spectrometers, anthropogenic carbon dioxide, greenhouse gas emissions, CO2M

1. INTRODUCTION

1.1 International context

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 [1]. While the targeted emission reductions are based on voluntary Nationally Determined Contributions (NDCs), there is a need for actionable information on the effectiveness of implemented measures and regulations. In this context, the European Commission has formulated a system architecture with Monitoring and Verification Support capacity [2]. The high-level observation requirements call for a multi-satellite constellation with imaging capability at high spatial resolution, global coverage and frequent re-visit. While spaceborne measurements of greenhouse gas concentrations have been on-going since the SCIAMACHY instrument on board ESA's Envisat satellite [3] several missions have now confirmed the feasibility to detect CO_2 point-source from space [4] and new missions will target those high spatial resolution mode measurements: MicroCarb (led by CNES) [5] and the geostationary GeoCarb (University of Oklahoma) [6]. Based on the results of on-going missions and previous instrument studies, there is now considerable heritage of space-borne greenhouse gas observations to design a system dedicated to anthropogenic CO_2 monitoring. The main objectives are to detect CO_2 emission hotspots, monitor their emission variation over time so to assess local and national emission changes in 5-year time steps to estimate CO_2 global stock take. The overall mission schedule targets the second global stock take in 2028 based on inventories of 2026/2027.

1.2 CO2M mission concept

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. Following phase A/B1 and supported by scientific studies with the objective of identifying the observation requirements for a constellation of satellites equipped with a suite of instruments optimized for anthropogenic CO_2 and CH_4 monitoring [7], ESA released an ITT for the preparation of six high-priority Copernicus missions, and in April 2020 selected an industrial consortium led by OHB to implement the CO2M mission with TASiF as prime of the payload.

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. The concentration of these two key greenhouse gases is measured in terms of their column-averaged dry air mole fractions, denoted as XCO2 and XCH4, respectively. CO_2 drives the mission requirements as a well-mixed natural constituent of the atmosphere with relatively small regional variation, the largest part of which is caused by biogenic, natural sources and sinks. Significantly elevated values for XCO2 in excess of a few percent of the background value can be detected within down-wind plumes of coal-fired power plants, and potentially large cities. Since the CO_2 quickly dilutes after emission, the expected signal of enhanced XCO2 depends on the size of the observed spatial samples (spatial resolution) and the wind speed. This drives the observation requirements of the space segment regarding retrieval precision and accuracy, as well as spatial sampling, resolution and global coverage. In particular high single-sounding precision is essential for identifying plumes of elevated CO_2 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 coregistration 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 [8] and is discussed in [9].

1.3 CO2M mission key data

The CO2M mission key data products are as follows:

Level 0 satellite raw data products:
Satellite raw data plus calibration measurements needed to derive level 1 products

Level 1 optical measurement products:
Geo-located, spectral and radiometrically calibrated measurement data for all instruments
Top of the atmosphere (TOA) spectral radiance and reflectance at high spectral resolution suitable for the XCO2, XCH4, NO_2 and SIF retrievals.
Multi-viewing and polarised radiance information for aerosol and cloud retrievals.
Cloud imager radiance information for cloud detection.

Level 2 products after ground processing:
Dry-air column weighted total column CO_2 (XCO2)
Dry-air column weighted total column CH_4 (XCH4)
NO_2 tropospheric column
Aerosol and cloud information
Solar Induced Fluorescence (SIF) of vegetation

The CO2M System will make available the L1 and L2 products to the users within 24 hours from sensing.

2. SATELLITE ARCHITECTURE

2.1 Concept

OHB System is the prime of the CO2M space segment. The stringent radiometric requirements have been translated into a mission concept based on a constellation of identical satellites in sun-synchronous orbit. The reference orbit is a 14 +5/11 Sun Synchronous Orbit with the following characteristics: a repeat cycle of 159 orbit in 11 days; a geodetic altitude varying between 740 and 767 km, with an MLST at descending node 11:30 LTDN. The nadir pointing Field-of-Views (FoV) of the instruments of the payload will be aligned such as to maximise the combined swath width and coverage.
The CO2M constellation consists of 2 satellites with a third one to be decided. Full global coverage of 6 days is provided with 2 satellites. In case of three satellites the coverage is reached in 5 days at equator, and in 3 days at 40 degrees latitude.

The satellite is designed such that the Payload is mechanically and thermally isolated from the Platform. This leads to a clearly defined interface and simplifies many aspects like the Assembly and Integration phase for example. The payload contains 6 titanium interface brackets which are then mounted to the Payload interface ring on the Central Structure of the Platform. The Central Structure is the backbone of the CO2M structure, providing the primary load path of the satellite under all load conditions during its operational life. It is manufactured in aluminum to lower the cost and simplify the design.

The CO2M platform is based on the OHB standard EO platform based on 6 radiator panels, a stacked propulsion tank configuration, decentralized Data Handling System architecture, a separate power conditioning & distribution unit (PCDU) and payload power distribution unit (PPDU) and one wing solar array configuration.

2.2 Operation modes

During the operational phase, the spacecraft will acquire continuously data in the sun-light part of the orbit and download the mission data to ground every orbit (every 100 mins). Nominal spacecraft operations support two main Earth observation modes for CO2M:

- Nadir mode: this mode is intended to be the default one over land. In Figure 1 the observation time are given along the orbit.
- Sun-Glint Mode: this mode is intended to be used over ocean/water surfaces to maximise the radiance on the CO2I/NO2I, with an adapted pitch law changing from 55° to -55° over the sunlit part of the orbit being the observation part, with the driving constraint that the satellite should be pitching when the constraint of SZA < 80 degrees is met. Sun-Glint mode allows as well to extend the coverage poleward as similar benefit are expected for snow-covered regions.

The transitions between Sun-Glint Mode and Nadir Mode are possible at any orbit position to allow mixed sun-glint / nadir orbits with a maximum of one transition per orbit foreseen.

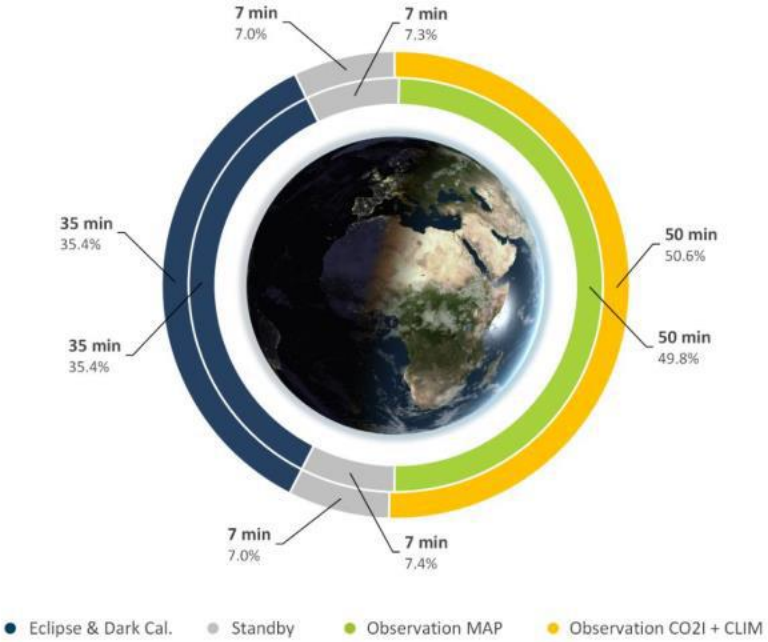

Figure 1: Typical share of the orbit time between the observation time and calibration time for the three instruments

Several calibration modes are provided by the platform:

- For radiometric calibration, a solar and a moon observation modes are planned. Solar calibration is needed for CO2I and MAP. In order not to impact the availability it has to occur with SZA higher than 80°. For CO2I it is baselined on the North Pole as the satellite leaves the eclipse during a time window of about 5 minutes. For MAP the solar calibration can performed in the Sun-Glint mode. Moon calibration is needed for the CLIM instrument which, unlike the CO2I and MAP, does not embark a calibration unit. Due to the full Moon constraint and the LTDN 11:30 orbit, the location of the Moon will always appear behind the spacecraft when in eclipse. This means that an almost full rotation, starting from nadir, will be required to allow to sweep the moon with parts of each detector.
- Dark calibrations are performed for CO2I and MAP using their shutter during the eclipse period.
- Finally a goniometry mode is implemented to simulate the seasonal variation of the Sun position through satellite manoeuvres.

2.3 Budgets

Following the preliminary design review, the overall satellite mass is below 2000 kg and has a volume of 3.8 m x 2.8 m x 1.6 m fitting the Vega C launcher baseline. The storage capacity is 3.8 Tbit and the data is downloaded in a K-band link at every orbit . The satellite command and telemetry link is foreseen via the Kiruna ground station (S band) once a day. Mission planning is covers 14 days of Nominal Operations.

A File Based Operation system has been introduced for CO2M. The satellite will be able to implement the CFDP protocol (CCSDS File Delivery Protocol) in both Class 1 and Class 2, offering a more reliable transmission of TM and Mission data to ground.

The AOCS architecture follows a simple but robust architecture with a clear separation of AOCS units between nominal and safe modes following a control concept based on 3-axes stabilized attitude in nominal operation, spin-stabilized target axis for safe mode and a Gyro-less architecture with accurate pointing performances and stability.

2.4 Development status

A Satellite Structural Model (Figure 2) has been successfully completed in October 2021 allowing to assess the primary load path, identify the critical interface between platform and payload and verify the validity of the finite element model.

Figure 2: The Satellite Structural Model on the shaker at ESTEC/ESA

An Satellite Engineering Model program for early validation of SCSW with hardware in-the-loop, subsystem, FDIR and mission simulation tests is running; the interface to all instruments will be tested with the Instrument Test Bench and will be based on flight representative data handling interfaces allowing a good consolidation of the overall functional design that will be evaluated during next year Satellite CDR.

Figure 3: The Satellite Engineering Model with the first electrical units of the platform integrated

The On-Board Computer Next Generation, the RTU, Magnetometer, Magnetorquer and the Coarse Sun Sensor have been electrically integrated allowing the completion of the AOCS safe mode closed loop test (Figure 3)

3. END-TO-END SIMULATOR

3.1 Concept

The End Simulator (E2ES) is a software tool in place to generate reference data for functional and performance assessment and to support performance calibration and validation on-ground and in-flight. It simulates the complete process and dataflow from a simulated scene before launch, and from a real observation scene during the commissioning, and it generates L1 and simplified L2 data products The E2ES design and implementation is led by TASiF with contributions from ESA and OHB.
The E2ES comprises:
Scene Generator Module (SGM): provides radiance spectra stimuli for all instruments
Geometry module (GM): True & estimated acquisition geometry
Observation Performance Simulator (OPSI): Implements Instruments forward model to translate photons to digital count
L1 Ground Processing Prototype (L1GPP): includes simplified L0 generator, ground processing up to L1c
Simplified L2 generator (SL2P): supports L1 performance evaluation
Performance Evaluation Module (PEM): provide inputs and metrics for analysis

The first version of the simulator with representative interfaces is progressing following the instruments and system PDR.

4. PAYLOAD ARCHITECTURE

4.1 Concept

The payload comprises four instruments:

- The CO2I, which is the instrument dedicated to measuring atmospheric CO_2. Designed for high spatial resolution, high spectral resolution, and high thermal and mechanical stabilities, this instrument will image the spectral flux in the NIR, SWIR-1 and SWIR-2 bands as input to the inverse models for determining column-averaged dry air mole fraction of CO_2 and CH_4.
- The CO2 instrument embeds an imaging spectrometer in the VIS band dedicated to measuring atmospheric NO_2 content, permitting native nominal co-registration and relative radiometric performances with the CO_2 bands, thus the accurate tracing of anthropogenic CO_2 plumes from power plants and cities while limiting the additional hardware and qualification procedures.
- A multi-angle polarimeter (MAP) dedicated to aerosols measurement to better account for cloud and aerosols scattering effects in the retrievals.
- A cloud imager (CLIM) with high spatial resolution to accurately filter the data for cloud-contaminated cases.

The payload also includes the star trackers to ensure the instruments lines of sight registration.

The compact payload architecture relies on a triple bench concept as depicted in Figure 4. 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 bench (SOB) inserted inside a Thermal Guard Assembly (TGA) which provide a stable and constant thermal environment. The CO2/NO2 telescope, the MAP Optical Unit, the CLIM Optical Unit are all sharing the same Ultra Stable Interface Bench (USIB) in CFRP to provide the best co-registration between instruments. 4 star trackers are also installed on USIB, to improve further the geometrical requirements by reducing the sensitivity to the thermo-elastic environment. With respect to the thermal architecture, the CO2I/NO2I, the MAP and the USIB are thermally stabilised and the SWIR channels are passively cooled using a cryo-radiator with sun shield (ECRS).

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 as well as the CO2I/NO2I calibration 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.

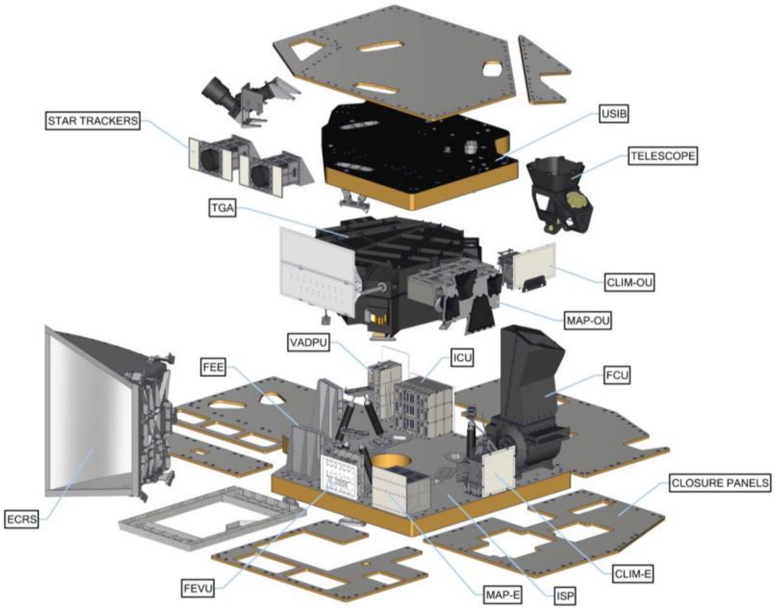

Figure 4: Overview of the three instruments parts, the star trackers and the panels making the payload

4.2 Budgets

The overall payload is fitting in a volume of 2 m x 1.6 m x 1.5 m. Though compact, the mass of the payload during the design phase evolution has exceeded its allocation resulting in a mass optimisation exercise. The main change of design is the use of CFRP panels instead of the aluminum panels initially envisaged, resulting in a mass of 620 kg.

The power is provided by the platform except for the Flight Calibration Unit which is powered by the ICU. The payload power consumption is limited below 350 W.

Data handling between the payload and the platform is running through Wizard link for the CO2I/NO2I spectrometer and through Spacewire link for the MAP & CLIM instruments. In nominal operation a maximum peak data rate per link is expected to be below 60 Mbps. In total, the data volume generated per orbit amounts from 100 GBit for CLIM, 200 GBit for MAP and 400 GBit for the CO2I/NO2I spectrometer.

4.3 The combined Carbon Dioxide and Nitrogen Dioxide Imager (CO2I and NO2I)

Carbon dioxide concentration in terms of column-averaged mole fraction (XCO2) is retrieved from measurements in three spectral bands in the near- and shortwave infrared regions (NIR and SWIR respectively). The CO2M mission will embark a single-band (VIS) NO_2 imager (NO2I) for simultaneous and co-located measurements with the three-band CO_2 imager (CO2I).The main requirements driving the CO2I and NO2I spectrometers are summarized hereafter:

Three spectral channels: NIR (747-773nm), SWIR-1 (1590-1675nm) and SWIR-2 (1990-2095nm).
Very high spectral resolution: ≤ 0.12 to 0.35 nm as a function of the bands;
High spatial resolution: 4 km² pixel on ground;
Swath ≥ 250km
Driving requirements: SNR, radiometric dynamic range, spatial coregistration, ISRF knowledge, and relative spectral radiometric accuracy including in particular the impacts of straylight and sensitivity to polarization.

For NO2 band, embedded in the CO2 instrument:
1 VIS (405-490nm) spectral band;
≤ 0.6 nm spectral resolution;
Driving requirement: SNR & radiometric dynamic range.

The CO2I & NO2I is a push-broom multi-band imaging spectrometer as defined by TAS-F which is the prime of the instrument. It is described in detail in the following papers [10,13].

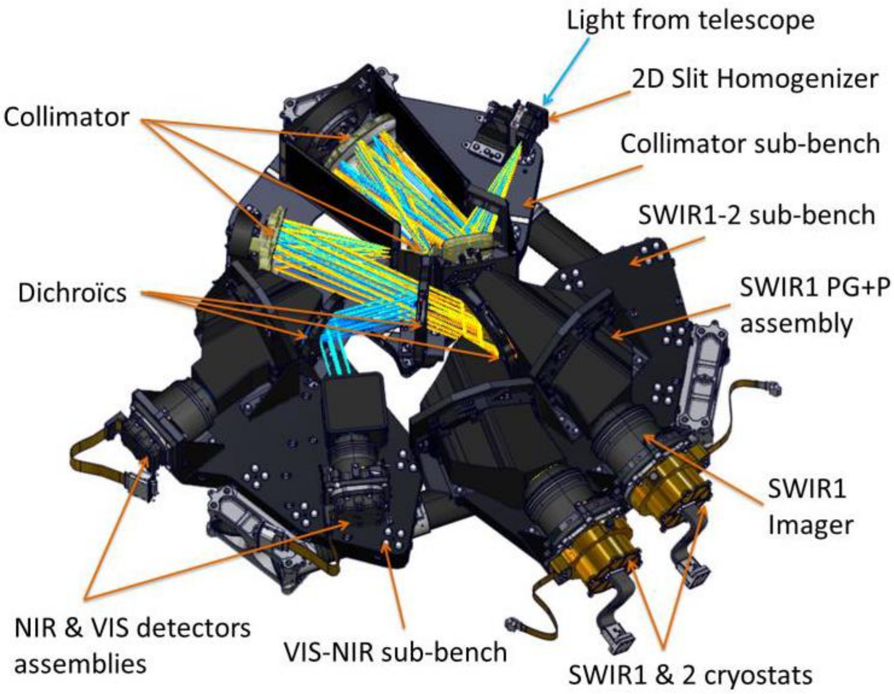

Figure 5: the CO2I/NO2I spectrometer showing the optical path from the 2D slit homogenizer up to the detector of each spectral band

Several critical components went through pre-development activities in order to ensure their sufficient maturity at the time of the flight manufacturing:

The 2D slit homogeniser based on 120 rectangular fibers stacked along the telescope image plane in the ACT direction in order to obtain a stable, scene independent Instrument Spectral Response Function.

The diffraction grating based on a combination of prism-grating-prism in order to reach both spectral performance (sampling, dispersion law…) and enhanced transmission.

The detectors based on a large back-side illuminated CIS-120 CMOS detector for VIS/NIR and on MCT for SWIR bands. Radiometric performance have been measured in comprehensive test campaigns leading to several adaptations for both detectors in order to achieve the demanding requirements.

4.4 The Multi-Angle Polarimeter (MAP)

Heritage from missions which do not measure aerosols show that the efficiency of the bias correction stops when the Aerosol Optical Depth (AOD) is higher than 0.3. However many populated areas have in average larger AOD than 0.3. Simulations show that with a simultaneous aerosol measurement the accuracy of the CO_2 data is improved and more measurements can be used even with AOD up to 0.5. The concept of the aerosol measurement relies on measuring radiance and degrees of polarisation for various angles and spectral bands similar to Polder [11].

The main requirements driving the polarimeter are:
Multi spectral (7 bands), multi-directional: 40 ALT directions, 3 polarisations to measure, with data co-registered with the CO2 instrument;
Driving requirements: DOLP accuracy performance of 0.0035, +/-60° ALT coverage in nadir mode

The aerosols measurement will be performed by the Multi-Angle Polarimeter, MAP built by TAS-UK. The MAP instrument is implemented as a compact pushbroom imager with 4 identical cameras providing a continuous along track coverage over +-60 deg with 40 viewing angles (Figure 6) over a swath of about 300 km. The spatial resolution is about 16 km^2 and 6 spectral bands are used for the aerosols and an additional one for the co-registration with CO2I.

The specificity of the MAP instrument comes from the focal plane assembly which allows to combine both the polarising and spectral filtering functions. This is possible thanks to the use of a large focal plane array composed of: an array of wire grid micropolarisers which offers the 3 needed polarisation with a pitch of the same dimension as the detector pitch and a multispectral filter array which provides one spectral band at the pitch of the triplets of polarizer [12]. A dedicated technology demonstration activity has been put in place to demonstrate the stability of the assembly of the filter, micro-polarisers and detectors through environmental loads. The same detector CIS-120 is used as for CO2I. To keep the instrument compact and minimise stray light a 2 mirrors off-axis telescope is used. Each camera is equipped with its own on-board flight calibration unit providing shutter position & radiometric calibration via sun diffuser. A separate Electronics Unit optimized for thermal rejection, is providing control and delivering binned and oversampled detector data to the mass memory.

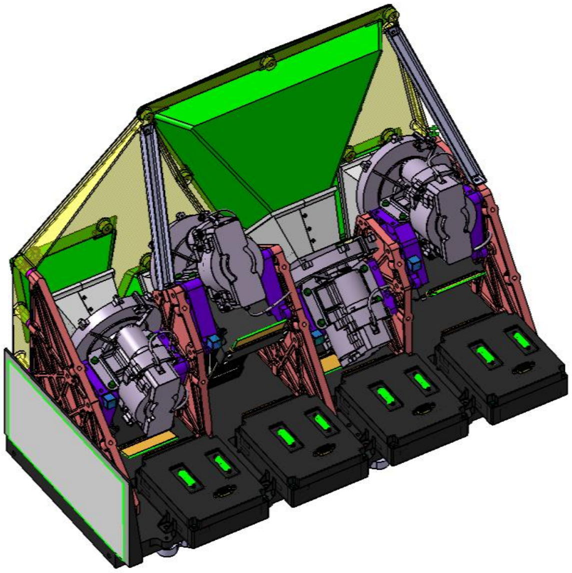

Figure 6: MAP optical unit with the four cameras having each a different along track orientation to cover the +-60 degrees field of view

4.5 The CLoud IMager (CLIM)

A cloud imager is necessary as even a small fraction of cloud cover of the order of 1 to 5 % of the spatial sample prevents from a good retrieval of CO_2. The cloud imager is therefore operating at a much higher spatial resolution than the spectrometer of the order of 100 m.

The main requirements of the CLIM are to provide oversampled pixels, co-located with CO2 in 3 spectral channels: VIS (670 & 753nm) & SWIR (1.37 µm) with limited bandwidths (resp. 20, 9 and 15 nm). SNR and co-registration with CO2I are the driving requirements.

The cloud imager on-board which is developed by OIP in Belgium is based on the Proba V heritage. It uses the same three mirror telescope (TMA) with aluminium mirrors polished by diamond turning. The optical layout is very similar to the one of Proba V with the main adaptation in the baffling, the thermal management and the spectral filters to adapt to the three spectral bands required for CLIM (Figure 7). The one at 1.37 um is to detect high altitude cirrus. Detectors will be the same as the ones used for Proba V, namely the quadrilinear CCD detector from Teledyne E2V and a triple linear InGaAs detector from Xenics for the IR band enabling in particular adequate spatial resolution and SNR.

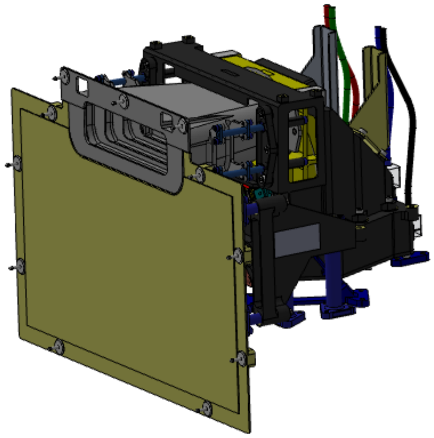

Figure 7: CLIM optical unit with entrance baffle and radiator facing the Earth

CLIM has passed its PDR and both STM and EM are being manufactured to support the coming CDR. Given the ProbaV heritage no specific pre-development activities have been carried out.

5. DEVELOPMENT MODELS RESULTS

The rapid development required to meet the next global carbon stock take imposes to advance the development of the different instruments/units before the PDR system consolidation. It creates risks that have been mitigated by performing several hardware activities for key sub-systems or assemblies. On the way toward system CDR, all the instruments and units CDRs are planned to be completed and based on consolidated information from their specific development models.

5.1 OBSM

One of the driving optical performance of the spectrometer is the stability of the ISRF. In order to achieve it, the stability of the optical bench which supports the collimator of the spectrometer has been improved by the use of a ceramic material SI3N4. Demonstration of the manufacturing capability and stability has been obtained on a fully representative Optical Bench Structural Model (figure 8) validating the modal behaviour. The bench has been successfully proof tested and will be consequently used in the first flight model.

Figure 8: Optical Bench Structural Model in SI3N4

5.2 VIS/NIR and SWIR Detection Chain Models

In order to validate the detection functions, the internal interfaces and the performance of the detection chains, two representative breadboard models have been assembled, one for the VIS/NIR and one for the SWIR bands. The capability to operate the detectors in their flight modes has been demonstrated as well as first tests under illumination and in darkness condition. While in the first measurements, custom video electronics have been used, they will be replaced by representative breadboards of the front-end electronics.

For the SWIR detection chain, a dedicated test bench has been built in order to measure the fine radiometric performance as well as to characterise the residual lag and ROIC effects still present in the detectors. Details of the results of the lag characterisation can be found in [14].

5.3 CO2I Elegant Bread Board

The validation of the optical performance of the SWIR1 band on a fully representative optical design was one of the key objectives of the payload PDR in order to support the progress of the manufacturing of many parts for which CDR has been already achieved (Figure 9). After the manufacturing of all the optical parts, the integration has allowed to optimise the shimming process and the first results have been obtained on three fibers for the key performance, namely ISRF (Figure 10), IEDF and SPSF. Correlation with the models gives a good confidence in the maturity of the optical design, manufacturing process and AIT alignment procedures.

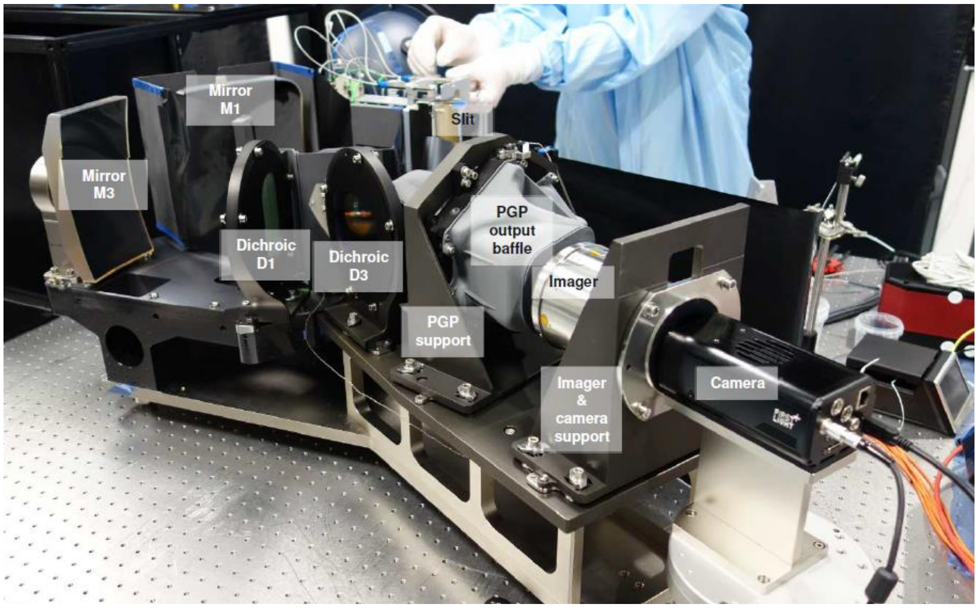

Figure 9: Elegant BreadBoard model with representative SWIR1 optical path (excepted the detector)

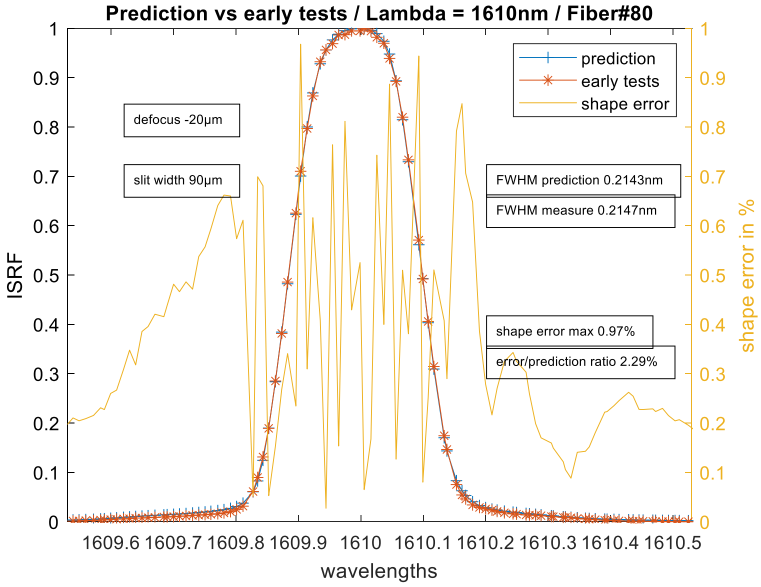

Figure 10: ISRF for SWIR1 from a single fiber illuminated with a homogenous scene measured (orange) and compared with prediction (blue) after recentring and correction of the signal variation

5.4 Instrument Test Bench

The validation of the instrument functional chain includes the engineering models of the ICU, the front end electronics, the Flight Calibration Unit, the MAP and the CLIM. The ITB addresses the validation of the external and internal electrical interfaces and the hardware/software validation. The bench derisk the AIT functional tests as well. For the payload PDR, the coupling of the On-Board Computer (OBC) and a payload simulator has allowed to validate the preliminary ICU On-Board Software including the first TM/TC interface function at the platform level. Once integrated with the Satellite EM it will serve the Mission Simulation testing.

5.5 MAP Elegant Breadboard Model

The validation of the optical performance of one camera has been demonstrated on a dedicated MAP breadboard model, including the complete camera, with the exception of the baffles. The focal plane assembly (FPA) does not cover all spectral bands, thus not fully flight representative. Nevertheless Figure 11 evidences one of the first end-to-end polarisation measurement demonstrating contrast ratio higher than 2 as expected for this blue spectral band which is the worst case of all the bands. The results have been a key input for the successful completion of the MAP PDR and allow a progress toward overall MAP design consolidation. Meanwhile tests on the Elegant Bread-Board continue by increasing the MAP spectral coverage, to get a complete assessment of all end-to-end key performance for its CDR.

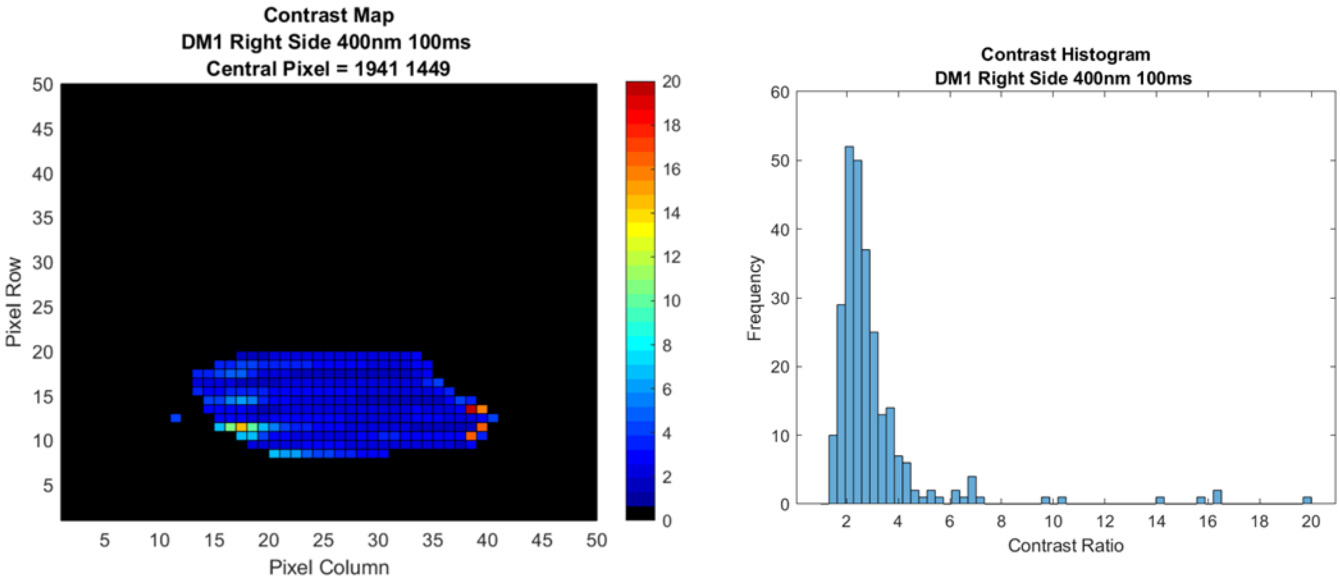

Figure 11: Measured end-to-end polarisation performance (contrast ratio) on MAP breadboard camera in line with expectations

6. SUMMARY AND CONCLUSIONS

The paper has presented an overview of the status of the Copernicus CO2M mission development. The two instruments MAP and CLIM, the payload as well as the System have passed their PDR, allowing the program to enter in phase C/D. The manufacturing of some PFM units has already started both at Satellite and Payload levels in order to achieve the targeted launch dates. In order to mitigate the risks associated to this development approach, early development models have been put in place and results from hardware are already available to correlate the different models and consolidate the design until the CDR, secure the AIT procedures and the processing aspects.

The Satellite SM mechanical tests have been completed and the Satellite EM program is progressing. The design of the three instruments is optimised to maximise the precision and accuracy of single-sounding of column-averaged carbon dioxide concentration as required to identify anthropogenic sources, as well as methane and nitrogen dioxide. This unique data set will serve the need for providing reliable information to evaluate the effectiveness of the efforts in reducing greenhouses gas emissions.

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 Veefkind, 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] Buchwitz, M., R. de Beek, J. P. Burrows, H. Bovensmann, T. Warneke, J. Notholt, J. F. Meirink, A. P. H. Goede, P. Bergamaschi, S. Korner, M. Heimann, and A. Schulz, "Atmospheric methane and carbon dioxide from SCIAMACHY satellite data: Initial comparison with chemistry and transport models", Atmos. Chem. Phys., 5, 941-962, 2005
[4] Taylor, T. et al.: "OCO-3 early mission operations and initial (vEarly) XCO2 and SIF retrievals", Remote Sensing of Environment, Volume 251, 15 December 2020, 112032, https://doi.org/10.1016/j.rse.2020.112032
[5] Pascal, V., Buil, C., Cansot, E., Loesel, J., Tauziede, L., Pierangelo, C., Bermudo, F., "A new space instrumental concept based on dispersive components for the measurement of CO2 concentration in the atmosphere", Proc. SPIE 10564, International Conference on Space Optics ICSO (2012), 105641R (2017)
[6] Crowell, S. and Moore, B., "The GeoCarb Mission", EGU General Assembly 2020, Online, 4-8 May 2020, EGU2020-20213, https://doi.org/10.5194/egusphere-egu2020-20213, 2020
[7] Kuhlmann, G., Broquet, G., Marshall, J., Clement, V., Loescher, A., Meijer, Y. and Brunner, D., "Detectability of CO2 emission plumes of cities and power plants with the Copernicus Anthropogenic CO2 Monitoring (CO2M) mission", Atmos. Meas. Tech., Vol 12 (12), 6695-6719, 2019
[8] 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
[9] Sierk, B., Bezy, J.-L., Loescher, 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
[10] Sierk, B., Fernandez, V., Bezy, J.L., Meijer, Y., Durand Y.,Bazalgette Courrèges Lacoste, G., Pachot, C., Loescher, A. Nett, H., Minoglou, K., Boucher, L., Windpassinger, R., Pasquet, A., Serre D., and te Hennepe, F., "The Copernicus CO2 Mission for monitoring anthropogenic carbon dioxide emissions from space, Proc. SPIE 11852, International Conference on Space Optics - ICSO (2020), 118523M (2021)
[11] Leroy M., Deuze J.L., Bréon F.M., Hautecoeur O., Herman M., Buriez J.C., Tanre D., Bouffies S., Chazette P., and Roujean J.L., "Retrieval of atmospheric properties and surface bidirectional reflectances over the land from POLDER". Journal of Geophycal Research., vol 102, #D14, pp17023-17037, 1997
[12] Spilling, D., Walker, A., "The Multi Angle Polarimeter (MAP) on board ESA's Copernicus Carbon Dioxide Monitoring mission (CO2M)", Proc. SPIE 11852, International Conference on Space Optics - ICSO (2020), 118520R (2021)
[13] Serre, D., Dussaux, A., Bazalgette Courrèges Lacoste, G., Durand, Y., Pasquet, A., Chanumolu, A., Pachot, C., and te Hennepe, F., "The Copernicus CO2M payload for monitoring anthropogenic carbon dioxide emissions", Proc. SPIE , International Conference on Space Optics - ICSO (2022)
[14] Lefebure, A. and al. "Remanence characterization of NGP Lag Free detector in SWIR band", Proc. SPIE , International Conference on Space Optics - ICSO (2022)