Operational products and Cal/Val for the Copernicus anthropogenic CO2 Monitoring (CO2M) mission

CEOS AC-VC 19
17 October 2023

The CO2M greenhouse-gas monitoring constellation

Up to three satellite missions each with >250 km swath:

- Providing greenhouse-gas data for the UNFCCC 2nd global stocktake (GST) in 2028

Three instruments per platform:
- CO2/NO2 push-broom grating spectrometer (CO2I/NO2I)
- Multi-Angle Polarimeter (MAP)
- Cloud Imager (CLIM)

Orbit:
- Sun-synchronous orbit 14 5/11
- 159 orbits repeat cycle (~11 days)
- 735 km altitude
- 11:30 LT
- Platforms in same orbital plane

<table>
<thead>
<tr>
<th>Product</th>
<th>Spatial resolution</th>
<th>Precision</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>4 km²</td>
<td>0.7 ppm</td>
<td>&lt;0.5 ppm</td>
</tr>
<tr>
<td>CH₄</td>
<td>4 km²</td>
<td>10 ppb</td>
<td>&lt;5 ppb</td>
</tr>
<tr>
<td>NO₂</td>
<td>4 km²</td>
<td>1.5x10⁻¹⁵ molec/cm²</td>
<td>&lt;3.5x10⁻¹⁵ molec/cm²</td>
</tr>
<tr>
<td>SIF*</td>
<td>4 km²</td>
<td>0.7 mW m⁻² sr⁻¹ nm⁻¹</td>
<td>&lt;0.2 mW m⁻² sr⁻¹ nm⁻¹</td>
</tr>
<tr>
<td>Aerosols</td>
<td>6 km²</td>
<td>0.05 AOD, 500 m LH</td>
<td>&lt;0.05 AOD, 500 m LH</td>
</tr>
<tr>
<td>Clouds</td>
<td>4 km²</td>
<td>&lt;1% of FOV</td>
<td></td>
</tr>
</tbody>
</table>
Copernicus CO2M System Development

**ESA is responsible** of the Space Segment development and its commissioning.

**EUMETSAT is responsible** of the development of the operational ground segment (with contributions from ESA) and the CO2M system operations in system commissioning and routine phase.

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For payload data (PDGS):
- **MDPS** (Mission Data Processing Sub-Segments, including: L0/L/L2 Operational Processors; Archival Dissemination) provided by EUMETSAT;
- **MDAS** (Mission Data Acquisition Sub-Segment) provided by ESA as a service.

For Flight Operations (FOS):
- **MCOS** (Mission Control and Operations sub-segment, including Mission Planning Facility) provided by EUMETSAT;
- **TT&C** (Telemetry, Tracking and Command) provided by ESA as a service.
EUMETSAT CO2M MDPS scientific processing tasks

CO2M Mission Data Processing System

Make one “hyper-GHG/NO2-instrument” out of three!

Below this level: everything is co-registered or provided at the CO2I/NO2I spectrometer footprint
## CO2I/NO2I observation statistics

### Estimated amount of data (per dayside orbit, per satellite):
- Number of measurements (CO2I/NO2I): ~1.1 million
- Number of clear sky GHG retrievals: ~200,000
- Level-1 / Level-2 GHG/NO2 product sizes: ~35 / 5 GB
- All CO2M products: ~280 GB

### Estimated number of possible XCO2/XCH4 L2 retrievals:

#### Worst case (max land) Scenario

<table>
<thead>
<tr>
<th>Orbit type</th>
<th>Worst case (max land) Scenario</th>
<th>Number of observations with surface albedo &gt; 0.03</th>
<th>20 % of total (land/water) used for GHG retrieval due to cloud (&lt;1%) and AOD&lt;0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nadir</td>
<td>Land</td>
<td>630105</td>
<td>131215</td>
</tr>
<tr>
<td></td>
<td>Water (glint&gt;0.03 albedo)</td>
<td>25971</td>
<td></td>
</tr>
<tr>
<td>Pitched</td>
<td>Land</td>
<td>722035</td>
<td>201586</td>
</tr>
<tr>
<td></td>
<td>Water (glint&gt;0.03 albedo)</td>
<td>285895</td>
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</tbody>
</table>

#### Average (full day) Scenario

<table>
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<tr>
<th>Orbit type</th>
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<tr>
<td>Nadir</td>
<td>Land</td>
<td>250530</td>
<td>98065</td>
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<tr>
<td></td>
<td>Water (glint&gt;0.03 albedo)</td>
<td>249827</td>
<td></td>
</tr>
<tr>
<td>Pitched</td>
<td>Land</td>
<td>239793</td>
<td>200222</td>
</tr>
<tr>
<td></td>
<td>Water (glint&gt;0.03 albedo)</td>
<td>720592</td>
<td></td>
</tr>
</tbody>
</table>

*These figures are per Satellite per orbit.

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## “Nadir orbit” configuration

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## “Pitched orbit” configuration
Multiple GHG algorithm approach – FOCAL, RemoTAP, FUSIONAL-P

Complementarity, resilience and performance:

- Different physical retrieval approaches - Full-physics (RemoTAP/FUSIONAL-P), scattering approximation (FOCAL);
- Different heritage lines (SCIAMACHY, OCO-2, GOSAT, Sentinel5p/5, 3MI, SPEXOne, POLDER);
- Complementary exploitation of information content of CO2M payload information (CO2I/MAP/CLIM);
- Complementary processing cost (cheap, medium, heavy).

<table>
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<th>CO2M platform information content usage:</th>
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<tbody>
<tr>
<td>Processing step</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>RemoTAP UoL-FP-FUSIONAL-P FOCAL</td>
</tr>
<tr>
<td>Pre</td>
</tr>
<tr>
<td>Main</td>
</tr>
<tr>
<td>Post</td>
</tr>
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</table>

Prelim. processing cost estimates:
GHG L2:
(3 algorithms)
< 3700 cpus / platform

Full system processing:
(including all instruments level-1 and 2)
< 4300 cpus / platform

\(^1\) Multiple platforms will require less per platform on average because of cpu re-use
Early results from synthetic data (GHG level-2 XCO2)

EUMETSAT CO2M GHG science study:

Three GHG algorithms for CO2M
“Four+-pillar” CO2M validation

On-board Cal:

<table>
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<tr>
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<th>CO2I</th>
<th>MAP</th>
<th>CLIM</th>
<th>Frequency</th>
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<tr>
<td>SUN</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>daily</td>
</tr>
<tr>
<td>Moon</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Irreg.</td>
</tr>
<tr>
<td>WLS</td>
<td>X</td>
<td></td>
<td></td>
<td>weekly</td>
</tr>
<tr>
<td>Tuneable LED</td>
<td>X (ISRF)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>orbit</td>
</tr>
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Vicarious Cal “as needed”

- SNOs
- Ref. Targets
- etc.

Microwave, OCO-x, GOSAT-x, S5, etc.

~0.05 nm (@1.6 μm)

“Four-pillar” CO2M operational product validation and monitoring space-to-ground and space-to-space approach

+ NDACC/Aeronet for NO₂ and AOD
"Four+-pillar" CO2M validation

**On-board Cal:**

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**Vicarious Cal**

- SNOs
- Ref. Targets
- etc.

"as needed"

**CO2M Ground-based network products central processing hub (ITT: Q 2024)**

Scientific support study on ground-based product requirements (LMU)
Scientific support study on ground-based network product processing (KIT)

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**MicroCarb, OCO-x, GOSAT-x, S5, etc.**

~0.05 nm (@1.6 μm)

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**CO2M 0.3 nm (@1.6 μm)**

**Product Cal/Val**

- Cross-Cal

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**PANDONIA**

5 nm (@1.6 μm)

**Product Cal/Val**

- Cross-Cal

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**COCCON**

0.14 nm (@1.6 μm)

**Product Cal/Val**

- Cross-Cal

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**TCCON**

0.001 nm (@1.6 μm)

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**Product Cal/Val**

- Cross-Cal

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Scientific feasibility study for PaNIR

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"Four-pillar" CO2M operational product validation and monitoring space-to-ground and space-to-space approach

+ NDACC/Aeronet for NO₂ and AOD

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Spectrally oversampled reference

Similar spectral resolution

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GSICS

GSICS

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EUMETSAT CO2M Cal/Val study:

Started 1st July 2021

Support definition and metric of product validation (in particular the use of ground-based network product data TCCON, COCCON, NDACC, PaNIR, AirCore, …) for CO2M operational monitoring of anthropogenic emissions.

- Operational provision of network data (timeliness and availability!)
- Overpass statistics, station environment and co-location criteria for use of ground-based total column measurements of XCO2, XCH4, NO2 and aerosol close to the sources
- Contributing requirements to ground based network products defined for CO2M

Database: http://co2m.aeronomie.be
EUMETSAT CO2M ground-based network product study:

Started: 1st August 2023 (Karlsruhe Institute for Technology)

Support definition of ground-based network data product processing dedicated to the need of operational CO2M continuous validation and monitoring

- Define ground-based network product (GBP) processing for CO2M: complement existing network products (level-2) with CO2M tailored network products (CO2M-GBP L2)
  - Processing of CO2M tailored products (CO2M-GBP L2) (e.g. from TCCON, COCON, ...)
  - Reduced spectral resolution (increase SNR), use of common auxiliary information (a priori model data, cross-sections, etc.) as used by CO2M GHG processors, etc.
  - Evaluate/monitor/trace network to network and station to station biases (TBC)
  - Compare performance of CO2M-GBP L2 to network standard products (NS-GBP L2)
  - Make network provided and CO2M tailored products available to CO2M validation and continuous monitoring
  - Make input (auxiliary data, cross sections etc) fused in CO2M tailored products available to ground-based network product producers

- Support engineering of operational ground-based network data processing system
Grating technology based measurement system for ground-based GHG

- **Modified Pandora-2S** with NIR & Visible channel for columnar measurements of CO₂, CH₄ and H₂O

- **Wider resolution (compared to FTIR)** allows:
  - High frequency **direct sun** measurements
  - **Sky observations** to retrieve information on the spatial inhomogeneity and vertical distribution of the GHG

- **Developed for producing real time data**

- **Low acquisition and operation costs**
  - No problems during unattended operations at Innsbruck (Nov 2022 to Mar 2023) and Izaña (Mar 2023 to present)

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EUM CO2M study with:

**Sun & Sky Viewing**

![Graph showing TYPICAL OPTICAL DEPTHS FOR 2.50nm RESOLUTION](image)

- **CO₂ [ppm]**
- **CH₄ [ppb]**
- **H₂O [mol/m²]**

**Scientific feasibility study for PaNIR**
CO2M product Cal/Val preparation

- **CO2M Cal/Val plan version** available (version 2 due by System CDR);
- **EUMETSAT** is developing a dedicated document for ground-based (network) product requirements for future CO2M product validation and continuous monitoring;
- **EUMETSAT** is developing a dedicated facility for provision and central processing of ground-based network data for CO2M product validation and monitoring;
- **EUMETSAT** is working with the ground-based networks (TCCON, COCCON, NDACC, Pandonia, Aeronet) on the central routine provision of level-1 data for CO2M operations.
Thank you!

Questions welcome.
CO2M INSTRUMENTS

CO2I/NO2I push-broom grating spectrometer
- Target species: CO2, CH4 & NO2
- Spatial resolution: 4 km²

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral range</th>
<th>Spectral resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS</td>
<td>405–490 nm</td>
<td>0.3 nm</td>
</tr>
<tr>
<td>NIR</td>
<td>747–773 nm</td>
<td>0.2 nm</td>
</tr>
<tr>
<td>SWIR-1</td>
<td>1590–1675 nm</td>
<td>0.3 nm</td>
</tr>
<tr>
<td>SWIR-2</td>
<td>1990–2095 nm</td>
<td>0.35 nm</td>
</tr>
</tbody>
</table>

Multi-angle polarimeter
- Target species: Aerosol
- Spatial resolution (native): 1 km²
- 43 views (0 > OZA < 60°) (out of 48 native)
- Spatial resolution (aerosol product): 4 km²

Cloud imager
- Target species: Clouds
- Spatial resolution: 100 / 200 m

MAP Band  | Wavelength
----------|----------------|
VNIR-1    | 410 nm         |
VNIR-2    | 443 nm         |
VNIR-3    | 490 nm         |
VNIR-4    | 555 nm         |
VNIR-5    | 670 nm         |
VNIR-6*   | 753 nm         |
VNIR-7    | 865 nm         |

* Channel used for cross calibration purposes with less views

CLIM Band  | Wavelength
-----------|----------------|
CLIM-1     | 670 nm         |
CLIM-2     | 753 nm         |
CLIM-3     | 1370 nm        |

See presentation by Gregory Bazalgette Courreges-Lacoste
CO2M CO2I spectrometer false colour radiance image (VIS/NIR/SWIR)

CO2M 6-orbits test-data set of top-of-atmosphere radiances for a constellation of 3 platforms

“West” platform continuously pointing towards the sun-glint spot

3rd July 2025 (205)
1. EU west (pitch on)
2. EU cent (pitch: off)
3. EU east (pitch: off)

9th Sep 2025 (205)
1. Asia cent (pitch: off)
2. Asia west (pitch: on)
3. Asia east (pitch: off)