Operational monitoring of anthropogenic CO$_2$ with the European Copernicus mission

Valerie Fernandez, ESA, Noordwijk, the Netherlands & CO$_2$M Phase A/B1 Study team
The Challenges

- UNFCCC Parties agreed for "enhanced transparency framework" (bottom-up) through national inventory reports (Paris Agreement, 2015) & complemented by global CO$_2$ Monitoring and verification support capacity
- Global CO$_2$ budget to provide input to 5-yearly global stocktake (from 2023)
- Analysis at local/regional level may support countries in evaluating the effectiveness of their CO$_2$ emission reduction strategies and possibly in defining revised Nationally Determined Contributions of the UNFCCC Parties
- Need to provide independent evidence on and verification of nationally reported anthropogenic CO$_2$ emissions and support assessing the uncertainties and gaps associated with the emission inventories
An Operational Anthropogenic CO\textsubscript{2} Emissions Monitoring & Verification Support Capacity

**Observations**
- **Sentinel CO\textsubscript{2} mission** & International constellation
- **In situ** CO\textsubscript{2} networks
- Auxiliary information, NO\textsubscript{2}, nightlights, Meteorology

**Prior Information**
- Emission report & economy statistics, model parameters & fluxes

**Integration & Attribution**
- Coupled data assimilation & uncertainties
- **Inverse atmosphere transport models**, Land & Ocean Cycles, ...

**Output**
- **Hot-spot** fossil fuel emissions
- **Country & city** fossil fuel emissions

**Decision Support System**
- Options for actionable measures at country and city scale
Why interest in CO$_2$ emissions from cities?

CO$_2$ emissions are mainly:
- 90% emitted over less than 8% of area of Europe
- 52% from point sources, primarily power plants

Cities account for ~70% of global CO$_2$ emissions
..... and have large reduction potential

Credits: EMPA, based on TNO-MACC
1. Detection of emitting hot spots such as megacities or power plants.

2. Monitoring the hot spot emissions to assess emission reductions/increase of the activities.

3. Assessing emission changes against local reduction targets to monitor impacts of the NDCs.

4. Assessing the national emissions and changes in 5-year time steps to estimate the global stock take.
CO$_2$ Monitoring Mission as Expansion
Imaging capabilities for CO₂ & NO₂ sources

South African power plants, on 11 July 2018

CO₂

NO₂

Sentinel-5 Precursor

Matimba

Medupi

Emission: 31 MtCO₂/year

Reuter et al., ACP (submitted)
## Sentinel CO2M – Products

<table>
<thead>
<tr>
<th>Product</th>
<th>Spatial Resolution</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>4 km$^2$</td>
<td>0.5–0.7 ppm</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>4 km$^2$</td>
<td>10 ppb</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>4 km$^2$</td>
<td>$1.5 \times 10^{15}$ molecules cm$^{-2}$</td>
</tr>
<tr>
<td>Vegetation SIF</td>
<td>4 km$^2$</td>
<td>0.7 mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$</td>
</tr>
<tr>
<td>Aerosol params</td>
<td>16 km$^2$</td>
<td>0.05 AOD, 500 m LH</td>
</tr>
<tr>
<td>Cloud params</td>
<td>5%</td>
<td>Water clouds &amp; cirrus</td>
</tr>
</tbody>
</table>

VIS band also covers CHO-CHO (glyoxal)
VIS & SWIR bands also cover H$_2$O vapour
Mission requirements for XCO$_2$ & NO$_2$:

- Spatial resolution **4 km$^2$**
- Revisit **3 days (at ~40 deg) / 5 day global**
- XCO$_2$ precision: **0.5 – 0.7 ppm**
- XCO$_2$ systematic bias: **< 0.5 ppm**
- NO$_2$ precision: **1.5·10$^{15}$ molec/cm$^2$**
- Imaging swath: **> 250 km**
- Equator crossing: **11:30 hrs**
CO₂ Monitoring – Space Segment Requirements 2/4

Mission requirements for XCO₂ & NO₂:
• Spatial co-registration: 95% overlap
• Absolute radiometric accuracy: 3%
• Effective radiometric error: 0.1%
• ISRF shape knowledge: 2%
• Viewing modes: nadir (land) & sun-glint (water)

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral range</th>
<th>Spectral resolution</th>
<th>Spectral sampling ratio</th>
<th>SNR_{ref} @ L_{ref} (photons/s/nm/cm^2/sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS</td>
<td>405–490 nm</td>
<td>0.6 nm</td>
<td>3</td>
<td>750 @ 1.35 x 10^{13}</td>
</tr>
<tr>
<td>NIR</td>
<td>747–773 nm</td>
<td>0.12 nm</td>
<td>3</td>
<td>330 @ 6.4 x 10^{12}</td>
</tr>
<tr>
<td>SWIR-1</td>
<td>1590–1675 nm</td>
<td>0.3 nm</td>
<td>3</td>
<td>400 @ 2.1 x 10^{12}</td>
</tr>
<tr>
<td>SWIR-2</td>
<td>1990–2095 nm</td>
<td>0.55 nm</td>
<td>3</td>
<td>400 @ 1.8 x 10^{12}</td>
</tr>
</tbody>
</table>
Tropomi zoom mode during Phase E1

Sampling 2.4 x 1.8 km²

Credits: KNMI & B. Leune TU-Delft

Belchatow, Poland
Aerosol & cloud scattering:
Light path correction is very important. Heritage missions without MAP require bias correction and strict quality filtering for AOD<0.3. Thin cirrus & small cloud fractions also impact the retrieval beyond the required XCO₂ error budget.

For CO₂M, Light path correction by measuring effective aerosol & clouds:
→ Higher accuracy CO₂ data (less posterior bias correction)
→ More data and also at higher aerosol loading; up to 0.5 AOD
→ Cloud cover of CO₂ pixel 1 – 5%

Credits: SRON, Utrecht
CO₂ Monitoring – Space Segment Requirements 4/4

**Aerosol data:**
- **Multi-angle polarimeter (MAP)** for light path correction
- Either 5 views continuous band **or** 40 views multi-channel
- Observation zenith angle **± 60 degrees**
- Spatial resolution **4x4 km² @ 4x oversampling**
- Degree of linear polarisation (DoLP) total error **<0.0035**

<table>
<thead>
<tr>
<th>MAP Band</th>
<th>Spectral range [nm]</th>
<th>L_TOA Spectral resolution</th>
<th>DoLP spectral resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVN</td>
<td>385–770</td>
<td>5 nm</td>
<td>15–40 nm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAP Channel</th>
<th>Central wavelength</th>
<th>Spectral width</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIR-1</td>
<td>410 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>VNIR-2</td>
<td>443 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>VNIR-3</td>
<td>490 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>VNIR-4</td>
<td>555 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>VNIR-5</td>
<td>670 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>VNIR-6</td>
<td>753 nm</td>
<td>9 nm</td>
</tr>
<tr>
<td>VNIR-7</td>
<td>865 nm</td>
<td>40 nm</td>
</tr>
</tbody>
</table>

**Cloud Imaging (CIM)**
- Multi channels imager (VIS/SWIR)
- Spatial sampling **400 m**

<table>
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<tr>
<th>CIM Channel</th>
<th>Central wavelength</th>
<th>Spectral width</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIM-1</td>
<td>670 nm</td>
<td>20 nm</td>
<td>200</td>
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<tr>
<td>CIM-2</td>
<td>753 nm</td>
<td>9 nm</td>
<td>200</td>
</tr>
<tr>
<td>CIM-3</td>
<td>1370 nm</td>
<td>15 nm</td>
<td>200</td>
</tr>
</tbody>
</table>
Towards an anthropogenic CO₂ Monitoring & Verification Support Capacity

Paris Agreement

CO₂ Mission advisory group

Global Stock

Take 1

Global Stock

Take 2

using 2026 inventories

CO₂ Monitoring Task Force

Capacity built up period

Capacity operational

Launch of Copernicus CO₂ Monitoring Constellation

2020 projects

CHE & VERIFY

ESA support studies

MRD v1 v2

CEO S White paper

2015 2017 2019 2021 2023 2026 2028

Towards an anthropogenic CO₂ Monitoring & Verification Support Capacity

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Towards an anthropogenic CO$_2$ Monitoring CO2M Space segment development

- **Paris Agreement**
  - 2015
- **EU users req.**
  - 2017
- **CO2M B2 KO**
  - 2019
- **Global Stock Take 1**
  - 2021
- **Global Stock Take 2**
  - 2023
- **CO2M#1 FAR**
  - 2026
- **CO2M#2 FAR**
  - 2028
- **CO2M#3 FAR**
  - 2036

**Phase A/B1**
- C02M Feasibility phase
- Competitive phase with 2 parallel contracts
- Evaluation of the B2/C/D/E1 proposals

**Phase B2/C/D**
- Proto-flight and recurrent Sat. development, qual., acceptance
- Awarded consortium lead by a prime contractor

**E1**
- Data collection initiated during com.

**E2 Phase: CO2 Operational Monitoring With CO2M**
- Sat. Deployment in 2026

**Space Segment Development with staggered launches**

- **2015**
- **2017**
- **2019**
- **2021**
- **2023**
- **2026**
- **2028**
- **2036**
Thank you

ESA, Noordwijk, The Netherlands

B. Pinty, H. Zunker
EC, DG-GROW, Brussels, Belgium

CO₂ Monitoring Mission Advisory Group, Major international institutions

C. Retscher, C. Zehner
ESA, Frascati, Italy
Plume detection: noise & background variability

Berlin plume peak signal

CO₂

Spatial variability of background

NO₂

High noise
Medium noise
Low noise
CO$_2$ monitoring mission status & planning

- Users requirements: CO$_2$ red report (Nov. 2017)
- Objectives and requirements for space component: Mission Requirements Document (MRD)
  - Version 1 finalized by Q4 2017
  - Version 2 by mid 2019
- Phase A/B1 space system activities until mid 2019
- Implementation phase targeted to start early 2020 (a.o. depending on ESA ministerial conference end 2019)
- Support the 2028 global stocktake
Sentinel GHG & CEOS collaboration

CEOS Virtual Constellation collaboration options with CO2M:

- Add CO$_2$ imagers in constellation → Increase coverage
- Add CO$_2$ lidar in constellation → calibrate imagers
- Contribute with in-situ
- Contribute with radiometric calibration
- Exploit data

Animation of constellation with 3 satellites each 250 km swath