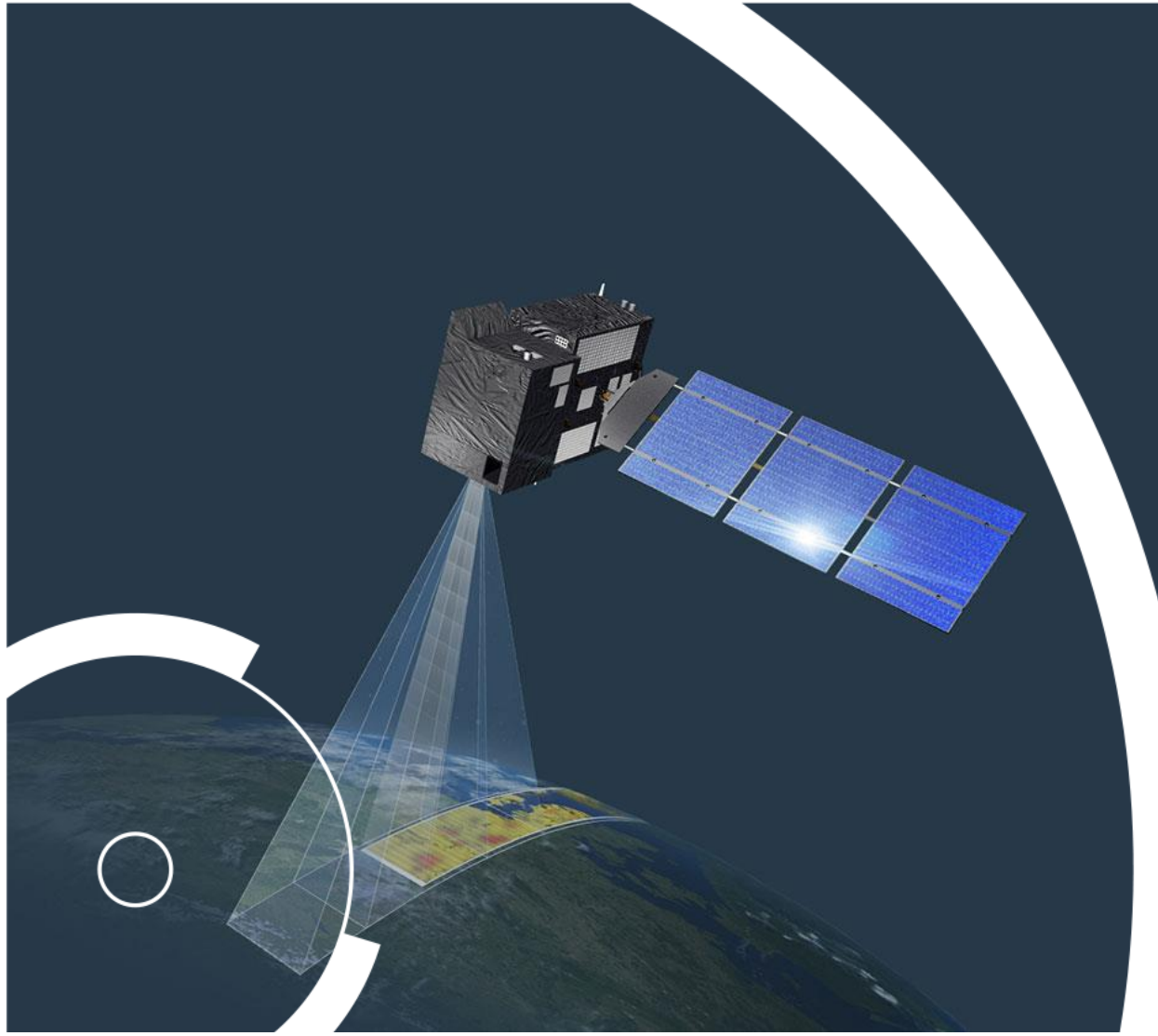
EUMETSAT

PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth



# The CO2I imaging spectrometer of theCO2M mission: Calibration and correction of instrument effect

**Ruediger Lang**[*1], Maurizio De Bartolomei[1], Helmut Bauch[1], Bojan Bojkov[1], Leonid Butenko[1], Hannah Clarke[1], Paola Colagrande[1], Josef Gasteiger[1], Catherine Hayer[1], Bernd Husemann[1], Thomas Honig[1], Antoine Lacan[1], Fabrizio Di Loreto[1], Thierry Marbach[1], Pepe Phillips[1], Cosimo Putignano[1], Vincenzo Santacesaria[1], Sruthy Sasi[1], Bernd Sierk[1], and Eduardo Valido Cabrera[1]

*1) European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)*

*ATMOS-24, 1 July 2024*

# The CO2M greenhouse-gas monitoring constellation

copernicus.eumetsat.int


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

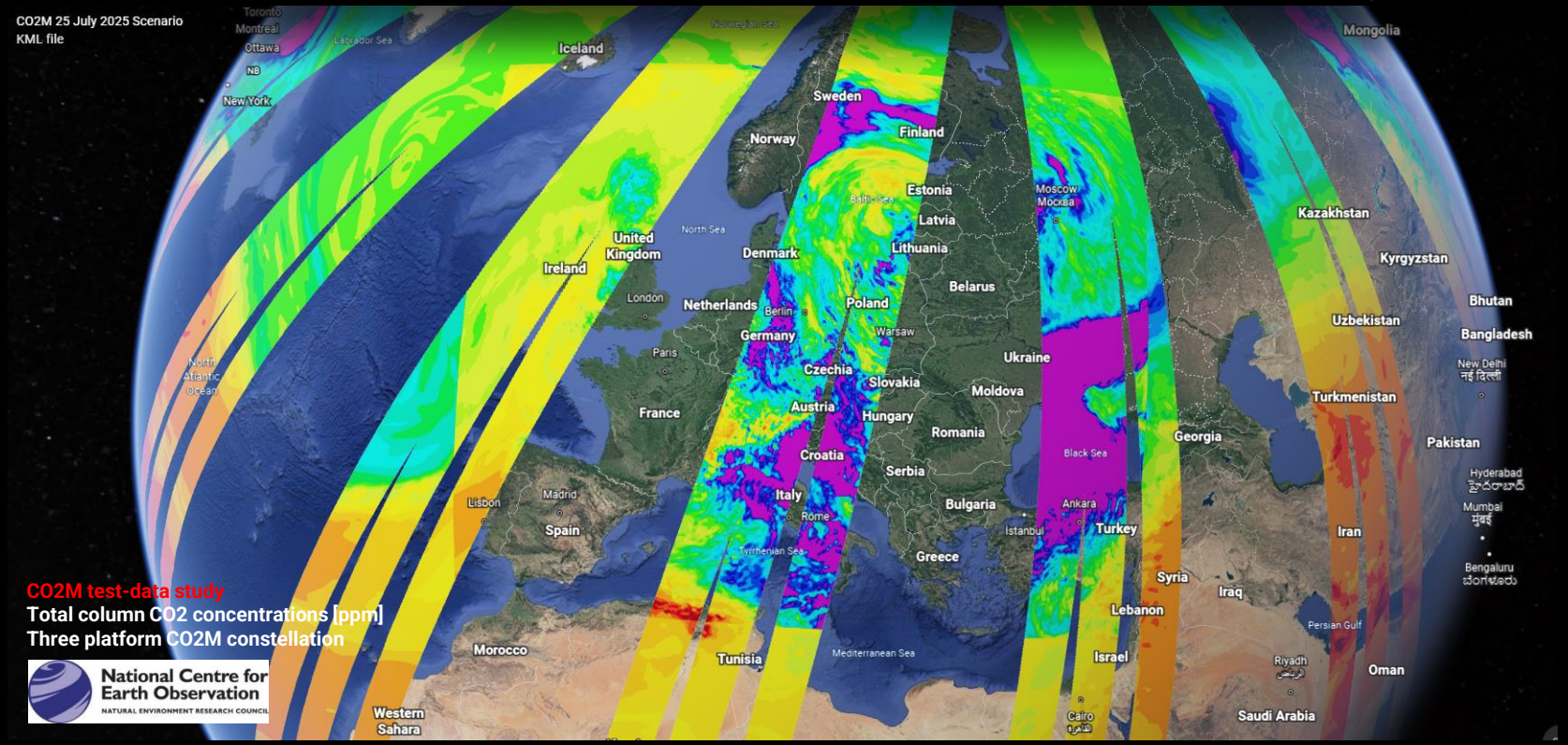
✓ Providing greenhouse-gas data for the UNFCCC 2nd global stocktake (GST) in 2028

**Three instruments per platform:**

- CO2/NO2 push-broom grating spectrometer (CO2I/NO2I)
- Multi-Angle Polarimeter (MAP)
- Cloud Imager (CLIM)

**Orbit:**

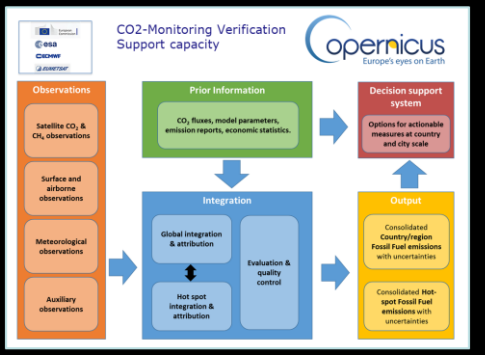
- Sun-synchronous orbit 14 5/11
- 159 orbits repeat cycle (~11 days)
- 735 km altitude
- 11:30 LT
- Platforms in same orbital plane




**End user products:**

| Product | Spatial resolution | Precision | Bias |
|---|---|---|---|
| CO2 | 4 km² | 0.7 ppm | <0.5 ppm |
| CH4 | 4 km² | 10 ppb | <5 ppb |
| NO2 | 4 km² | $1.5 \times 10^{15}$ molec/cm² | $<3.5 \times 10^{15}$ molec/cm² |
| SIF* | 4 km² | 0.7 mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$ | <0.2 mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$ |
| Aerosols | 16 km² | 0.05 AOD, 500 m LH | <0.05 AOD, 500 m LH |
| Clouds | 4 km² | <1% of FOV | |

*Solar Induced Fluorescence

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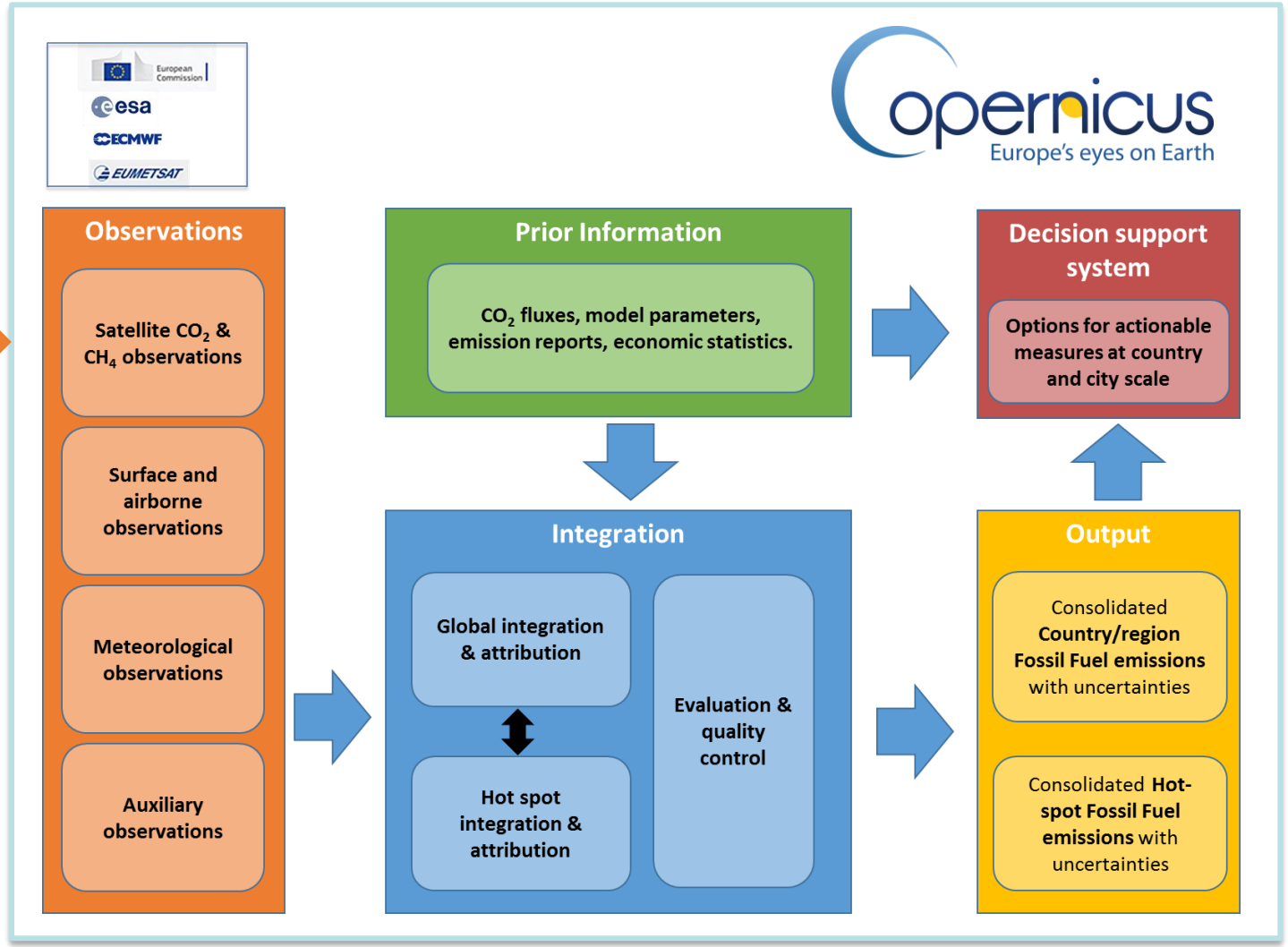
# Anthropogenic CO2 Monitoring and Verification Support (MVS) Capacity

CO2-MVS system overview

CO2M

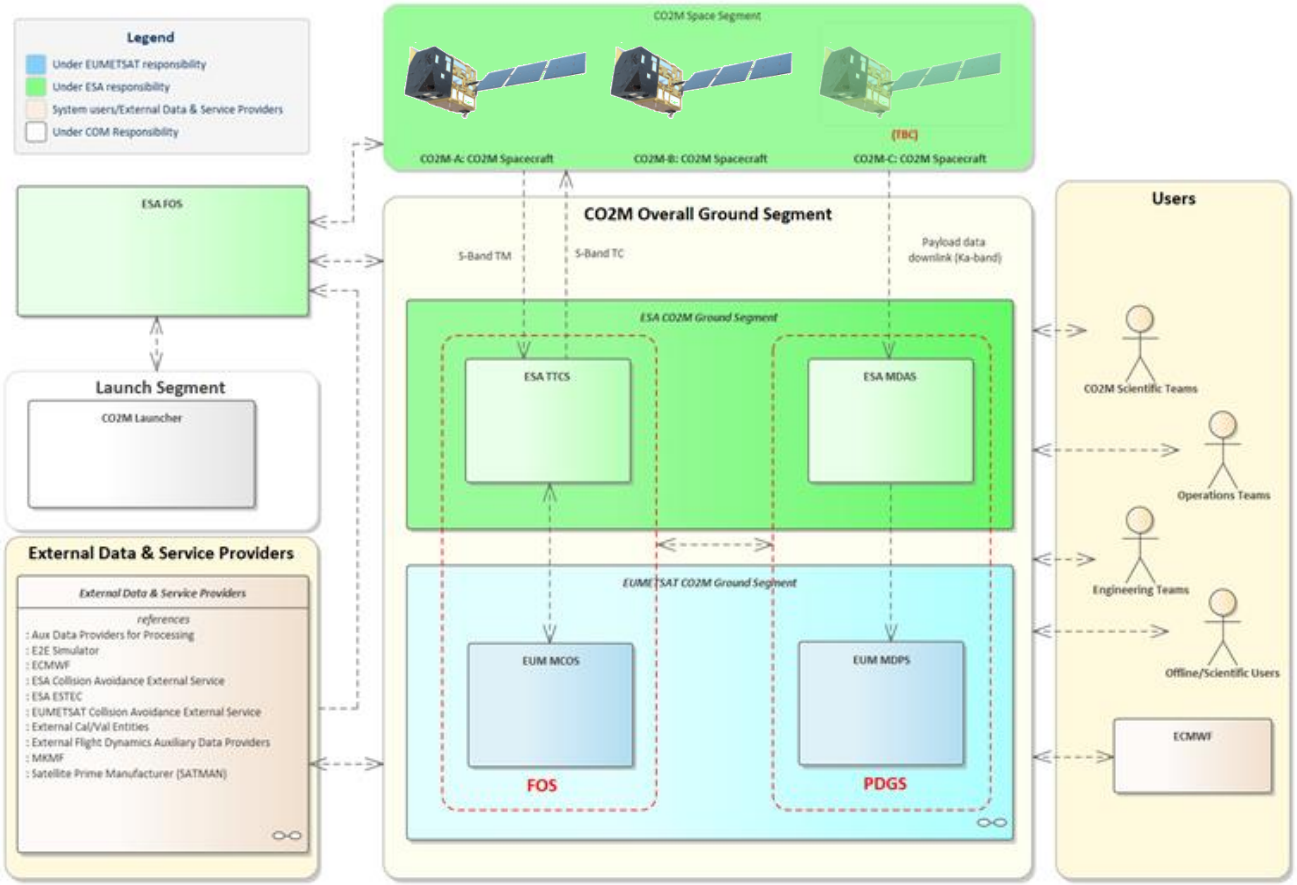


# Copernicus CO2M System Development



- **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.




**For payload data (PDGS):**

- MDPS (Mission Data Processing Sub-Segment, including: L0/L1/L2 Operational Processors; Archival Dissemination) provided by EUMETSAT;
- MDAS (Mission Data Acquisition Sub-Segment) provided by ESA as a service.

**For Flight Operations (FOS):**

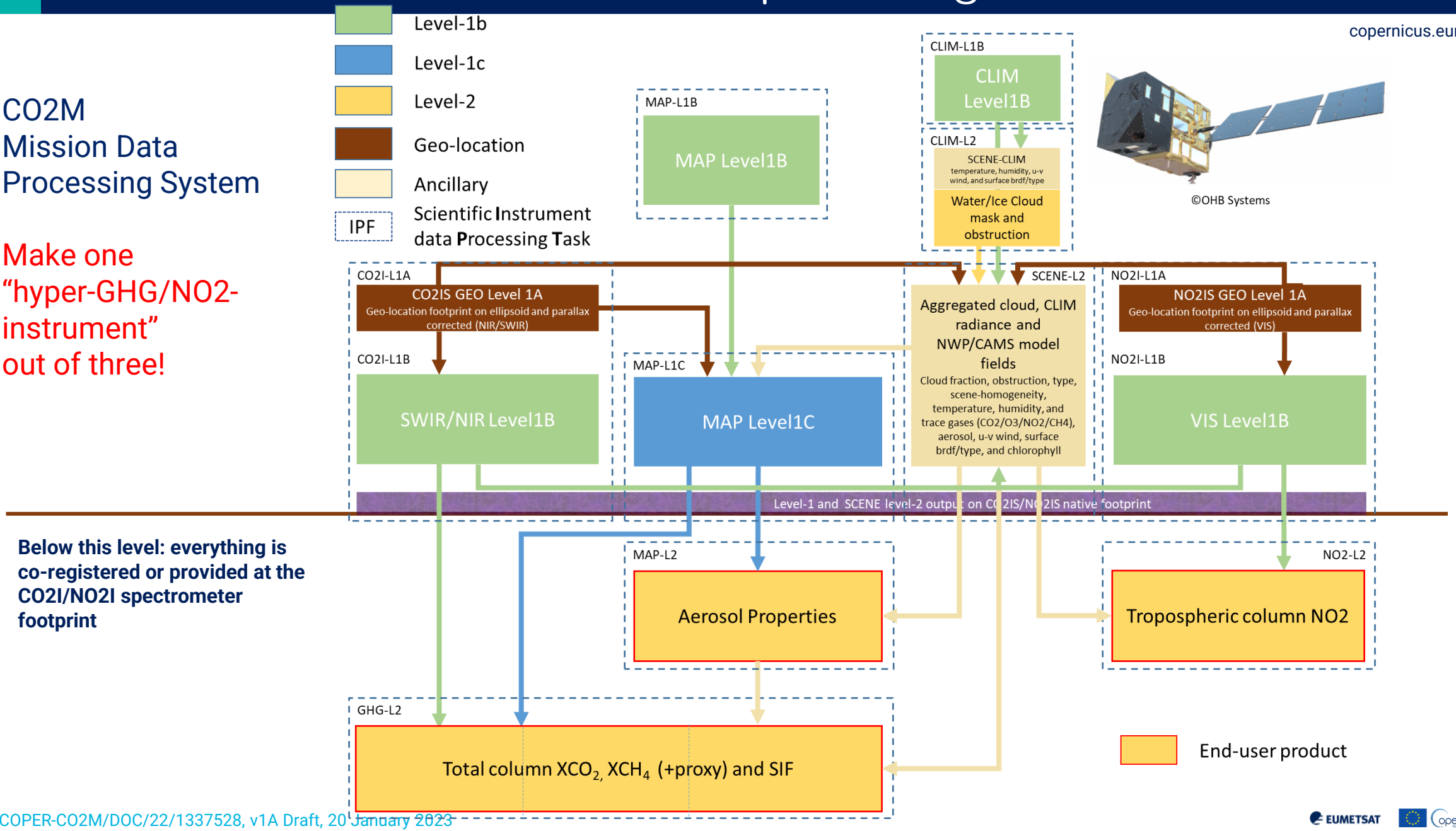
- MCOS (Mission Control and Operations sub-segment, including Mission Planning Facility) provided by EUMETSAT;
- TT&C (Telemetry, Tracking and Command) provided by ESA as a service.

# 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 / 6 GB |
| All CO2M products: | ~280 GB |

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

**Worst case (max land) Scenario**

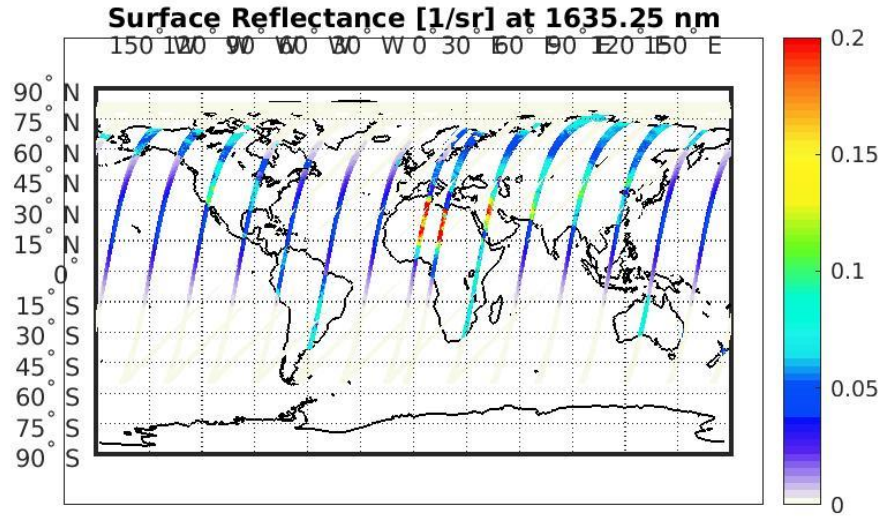
| Orbit type | Worst case (max land) Scenario | Number of observations with surface albedo > 0.03 | 20 % of total (land/water) used for GHG retrieval due to cloud (<1%) and AOD<0.5 |
|---|---|---|---|
| Nadir | Land | 630105 | 131215 |
| | Water (glint>0.03 albedo) | 25971 | |
| Pitched | Land | 722035 | 201586 |
| | Water (glint>0.03 albedo) | 285895 | |

**Average (full day) Scenario**

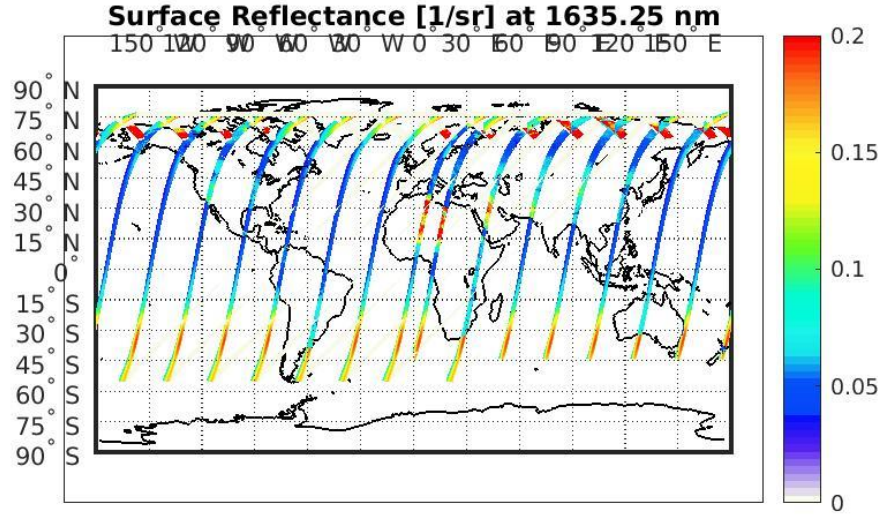
| Orbit type | Average (full day) Scenario *) | Number of observations with surface albedo > 0.03 | 20 % of total (land/water) used for GHG retrieval due to cloud (<1%) and AOD<0.5 |
|---|---|---|---|
| Nadir | Land | 250530 | 98065 |
| | Water (glint>0.03 albedo) | 249827 | |
| Pitched | Land | 239793 | 200222 |
| | Water (glint>0.03 albedo) | 720592 | |

*These figures are per Satellite per orbit.*

"Nadir orbit" configuration




"Pitched orbit" configuration

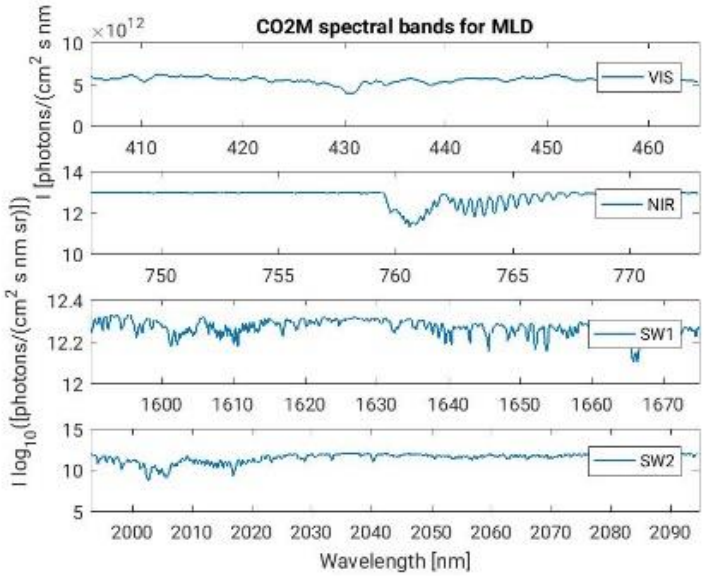


# CO2M level-1 and SCENE-L2 products

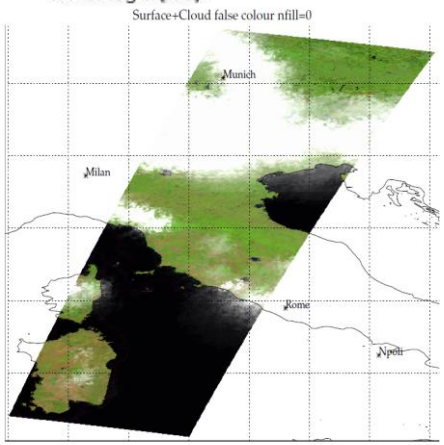


**Level-1b NO2-IS:**
Calibrated radiances
VIS (405 – 490 nm)

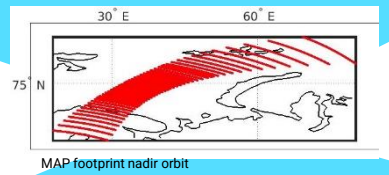
**Level-1b CO2-IS:**
Calibrated radiances
NIR (747 – 773 nm)
SWIR-1 (1590 -1675 nm)
SWIR-2 (1990 -2095 nm)



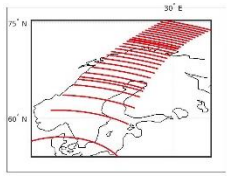

False-color image VIS/NIR/SWIR-1 for modelled CO2M radiances from prelim. EUM test-data-set *(From EUM test-data study)*




**Level-1b MAP:**
Calibrated pol. radiances
(410 443 490 555 670 (753) 865 nm)

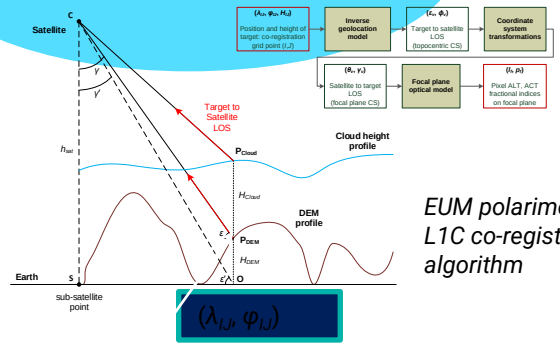



MAP footprint nadir orbit



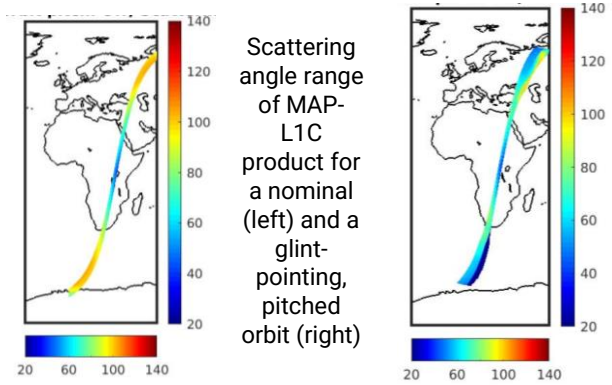
MAP footprint pitched glint orbit

**Level-1c MAP:**
Multi-view I,Q,U radiances
at **CO2-IS** footprint



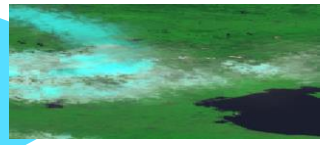

*EUM polarimeter L1C co-registration algorithm*

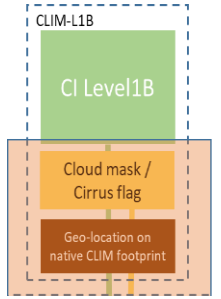
Pointing from *P* at CO2-IS lat/lon footprint point *(I,j)*, from terrain height *H* to MAP instrument detector plane. (Cloud height parallax not considered for CO2M, TBC)



Scattering angle range of MAP-L1C product for a nominal (left) and a glint-pointing, pitched orbit (right)

**Level-1b CLIM:**
Calibrated radiances
(670 753 1320 nm)
Cloud and cirrus flag / cloud and cirrus obstruction at native resolution






*EUM cloud CLIM L2 study (Syn-Cloud): Brockmann Consult*

**Level-2 SCENE:**
Aggregated cloud and cirrus obstruction at CO2-IS resolution:

- Cloud fraction (geometric)
- Cloud distance
- Cloud top height
- Cloud obstruction (radiometric)
- Scene inhomogeneity (std of imager radiances)

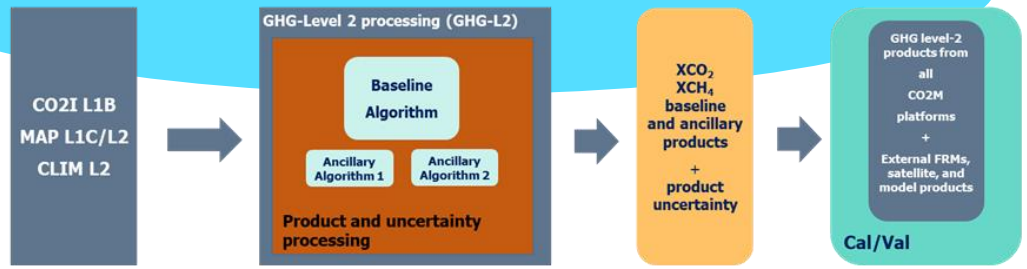
**Additional cloud information:**

- *CO2-IS NIR:* Oxygen A-Band
- *NO2-IS:* $(O_2)_2$ absorption
- *MAP*: I, Q, U (Rainbow, cloud type, …)
- CO2-IS SWIR: cirrus

# CO2M level-2 products



## CO2M GHG level-2 product: XCO2 / XCH4




*CO2M GHG retrieval algorithms: (XCO2, XCH4)*

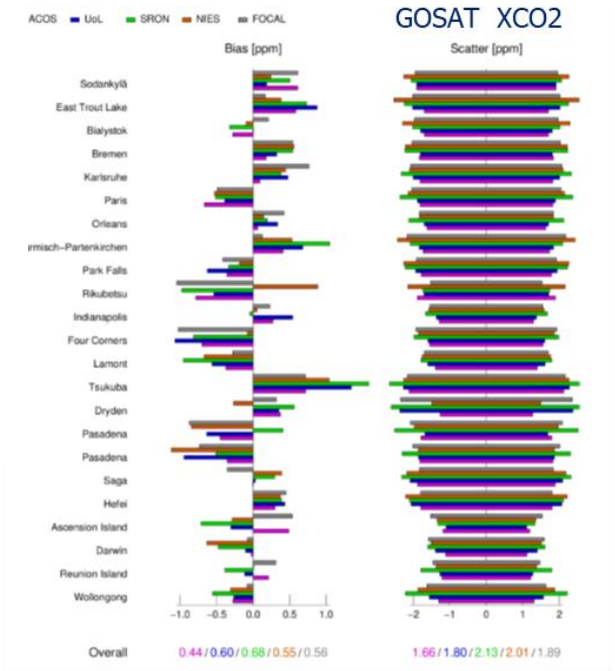
**RemoTAP**
(Hasekamp, Landgraf, Lu et. al.)

**FOCAL**
(Reuter, Buchwitz, Noel, Hilker, et al)

**FUSIONAL-P**
(Boesch, di Noia, et al.)

**CO2M Products requirements:**

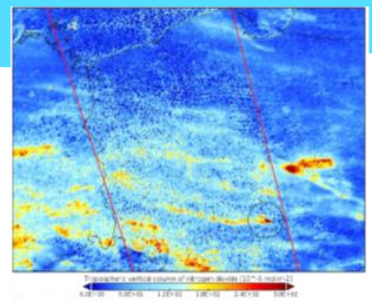
| Product | Spatial resolution | Precision |
|---|---|---|
| CO2 | 4 km² | 0.7 ppm |
| CH4 | 4 km² | 10 ppb (est.) |
| NO2 | 4 km² | 1.5x10¹⁵ molec/cm² |
| SIF* | 4 km² | 0.7 mW m⁻² sr⁻¹ nm⁻¹ |
| Aerosols | 16 km² | 0.05 AOD, 500 m LH |
| Clouds | <5% of FOV | Water & cirrus clouds |




Noel et al., AMT 2021

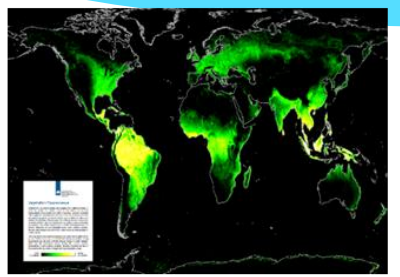
## CO2M NO2 level-2 product (plume mapping)

*EUM NO2 level-2 study algorithm: TriOpSys/KNMI*

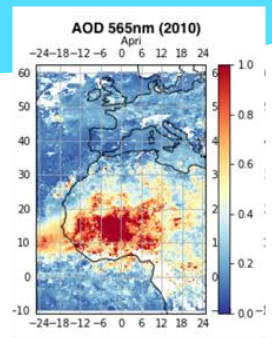


TropOMI/S5p zoom mode at ~2x2 km

## CO2M SIF and Aerosol level-2 product



*EUM SIF level-2 study algorithm: U. Leicester*




*EUM Aerosol level-2 study algorithms: GRASP (GRASP-SAS/U. Lille)*

# 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).

**CO2M platform information content usage:**

| Processing step | GHG L2 Input | | |
|---|---|---|---|
| | RemoTAP | UoL-FP-FUSIONAL-P | FOCAL |
| Pre | SCENE-L2 | SCENE-L2 | SCENE-L2 |
| Main | CO2I L1B+MAP-L1C | CO2I L1B+MAP-L2 | CO2I L1B |
| Post | | | MAP-L1C/L2+CLIM L2 |

SRON Universität Bremen

**Prelim. processing cost estimates:**

*GHG L2 :*
***(3 algorithms)***
**< 3700 cpus / platform*)**

*Full system processing:*
***(including all instruments level-1 and 2)***
**< 4200 cpus / platform*)**

*) **Multiple platforms will require less per platform on average because of cpu re-usage**

# Early results from synthetic data (GHG level-2 XCO2)

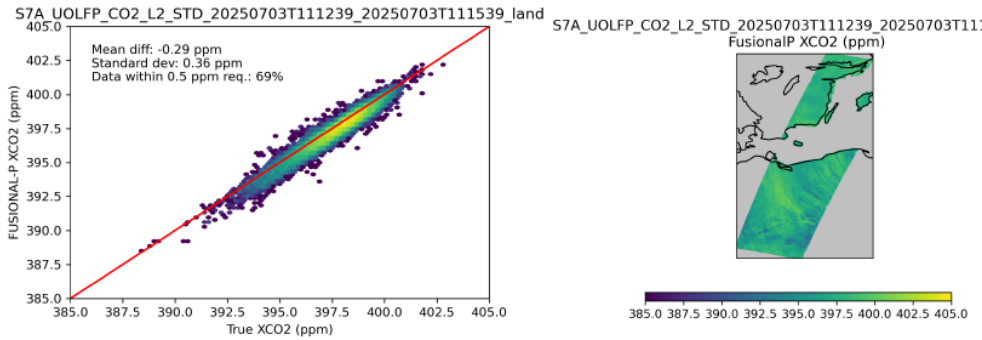
## *Three GHG algorithms for CO2M*

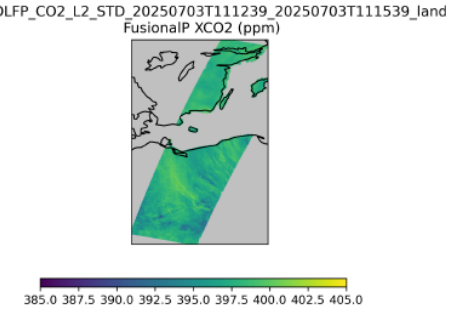
### FOCAL

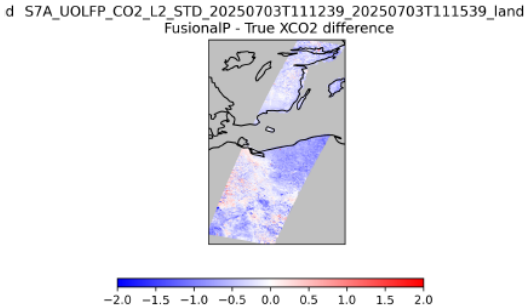
Universität Bremen

| Processing step | GHG L2 Input | | |
|---|---|---|---|
| | RemoTAP | UoL-FP-FUSIONAL-P | FOCAL |
| Pre | SCENE-L2 | SCENE-L2 | SCENE-L2 |
| Main | CO2I L1B+MAP-L1C | CO2I L1B+MAP-L2 | CO2I L1B |
| Post | | | MAP-L1C/L2+CLIM L2 |

*ATBDs v2L, 2024*




### FUSIONAL-P

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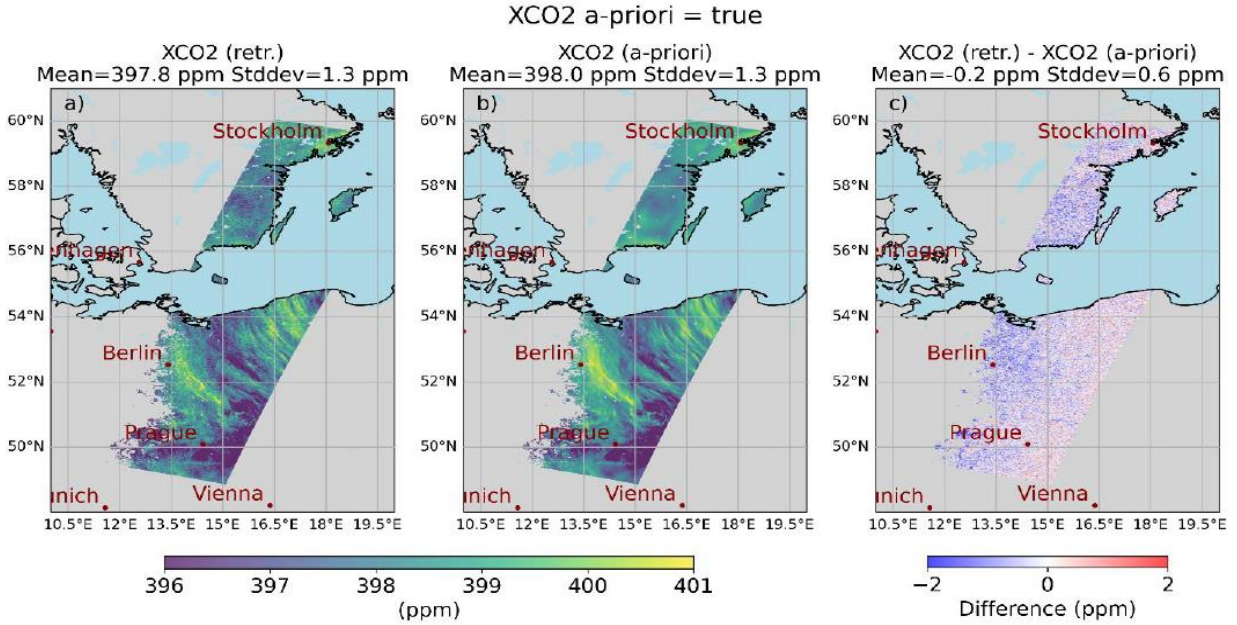
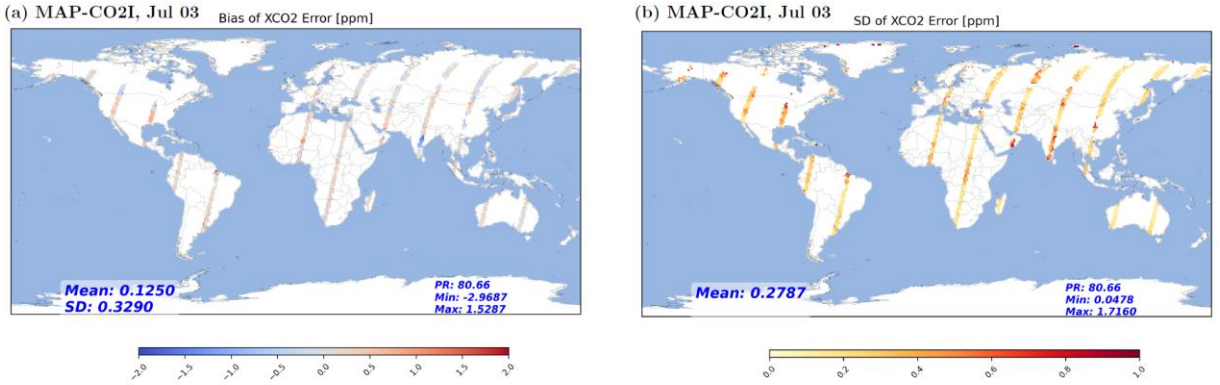



### RemoTAP

SRON



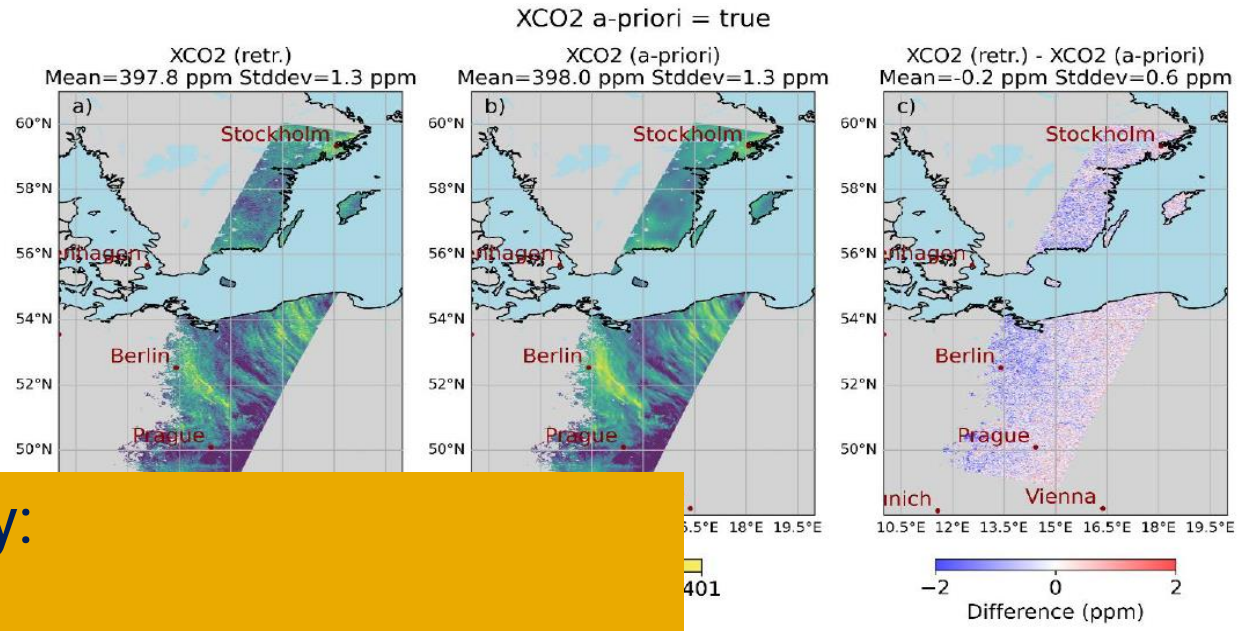
# Early results from synthetic data (GHG level-2 XCO2)

## *Three GHG algorithms for CO2M*

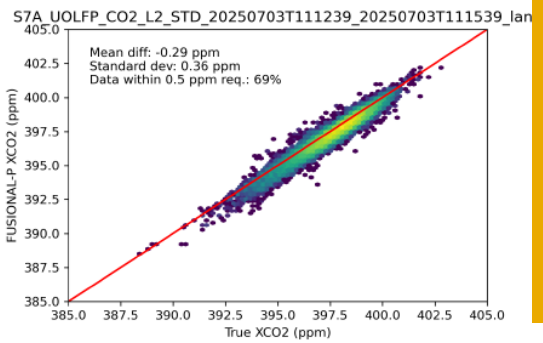
### FOCAL

Universität Bremen

| Processing step | GHG L2 Input | | |
|---|---|---|---|
| | RemoTAP | UoL-FP-FUSIONAL-P | FOCAL |
| Pre | SCENE-L2 | SCENE-L2 | SCENE-L2 |
| Main | CO2I L1B+MAP-L1C | CO2I L1B+MAP-L2 | CO2I L1B |
| Post | | | MAP-L1C/L2+CLIM L2 |




*ATBDs v2L, 2024*

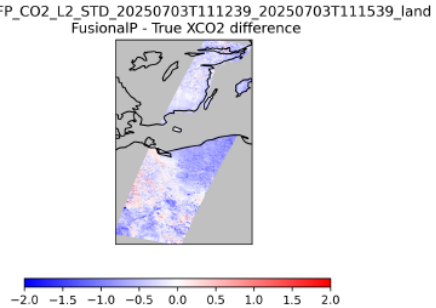


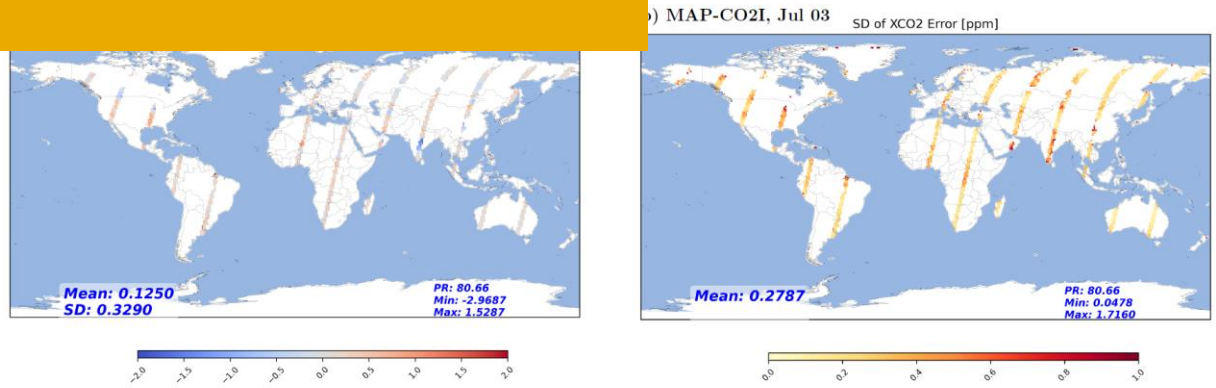

See presentations by:

2.2.3 Stefan Noel, Tue 11:40 FOCAL
2.2.4 Antonio Di Noia, Tue 11:50 Fusional-P

### FUSIONAL-P

Universität Bremen



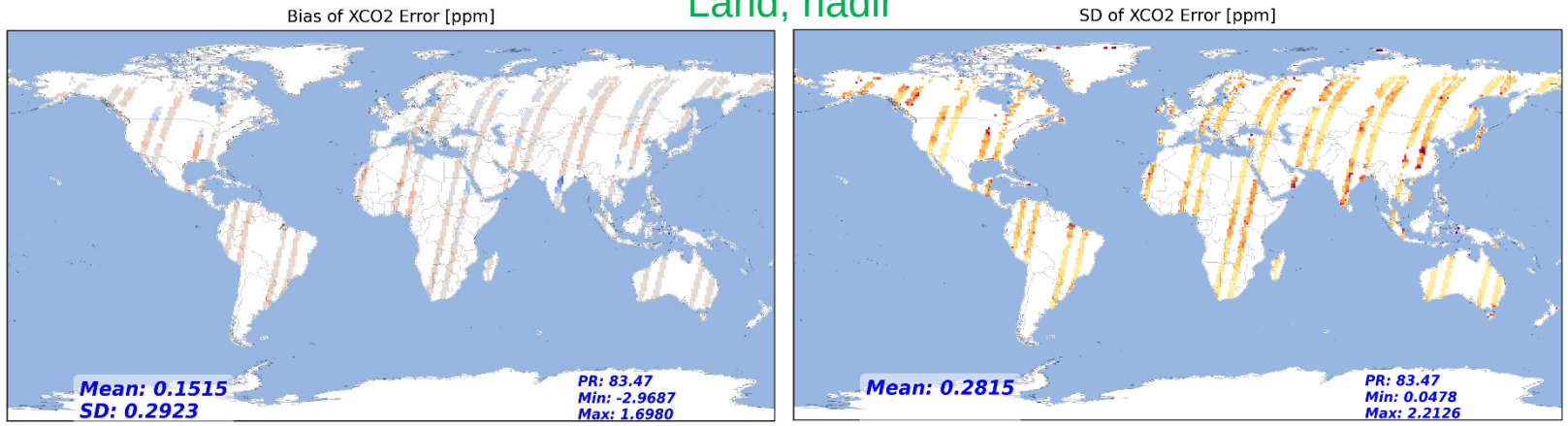



# MAP-CO2I Retrievals of RemoTAP

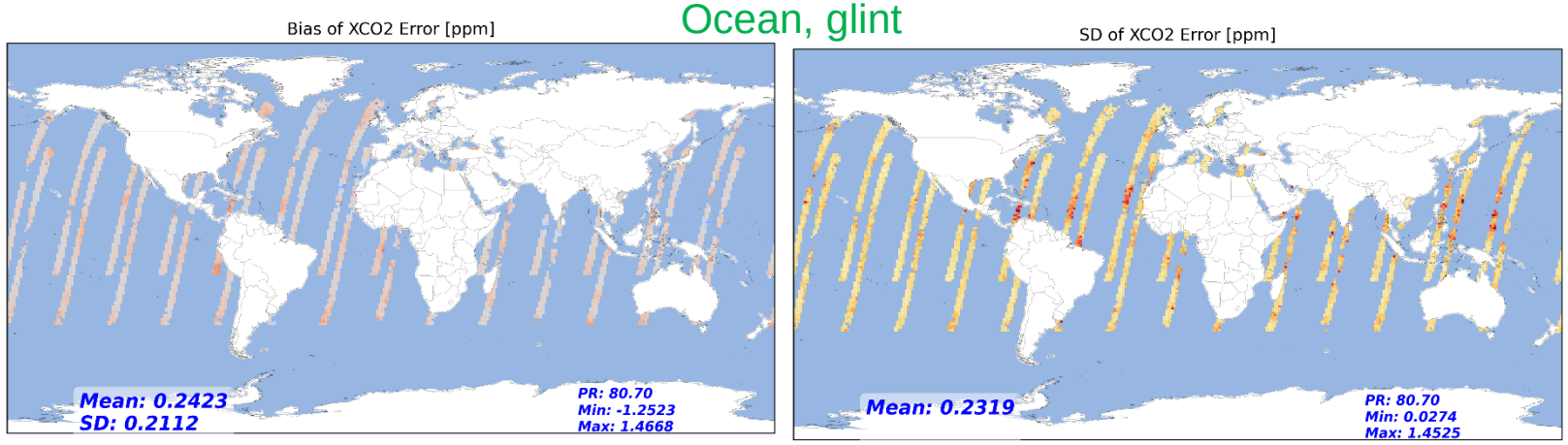


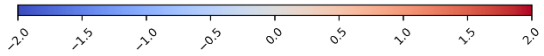
SRON

Land, nadir




Ocean, glint





| case | Accuracy | Precision | Overall RMSE | Overall bias |
|---|---|---|---|---|
| Land, nadir | 0.2923 ppm | 0.2815 ppm | 0.5493 ppm | 0.1593 ppm |
| Ocean, glint | 0.2112 ppm | 0.2319 ppm | 0.4230 ppm | 0.2430 ppm |

# Early results from synthetic data (NO2 level-2)

***NO2 algorithms or CO2M***

***Bełchatów coal power plant***

***Albedo effects, ATBD 2024***

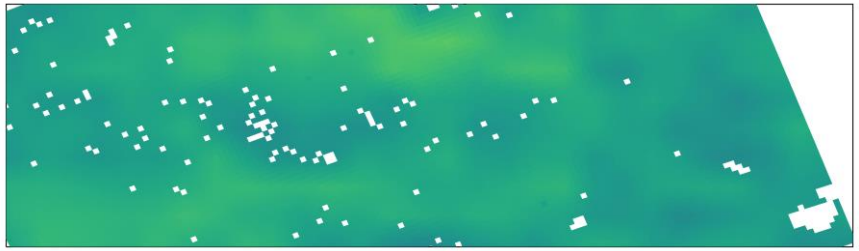
eumetsat.int

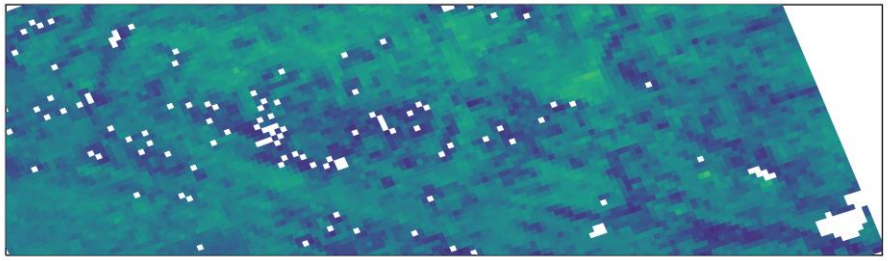
Source: Wikipedia

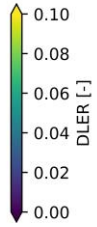
S5P algorithm

CO2M algorithm

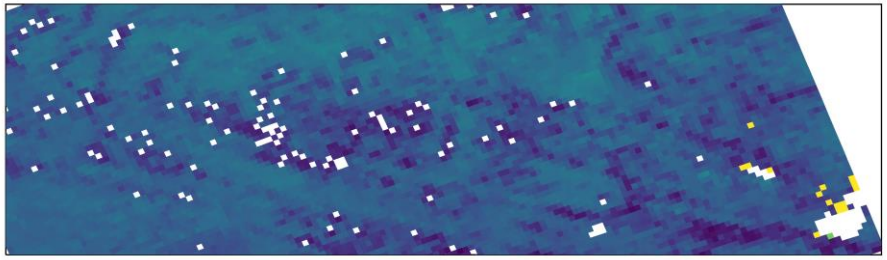
Surface reflectance (DLER)

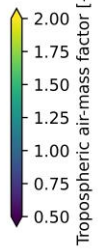




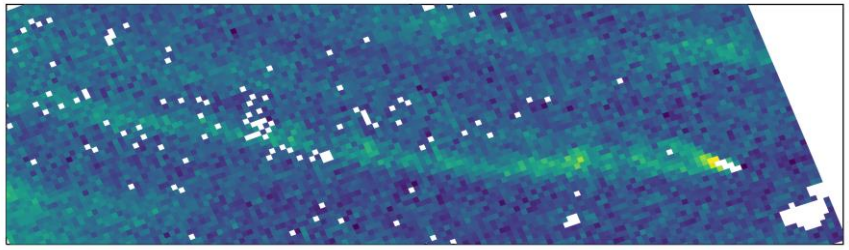


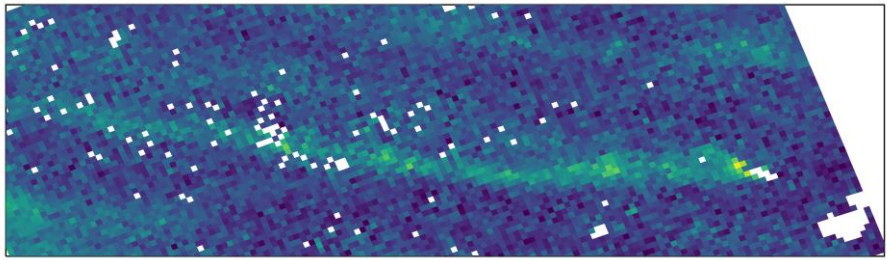

Tropospheric air-mass factor

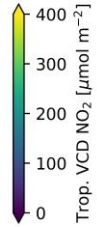




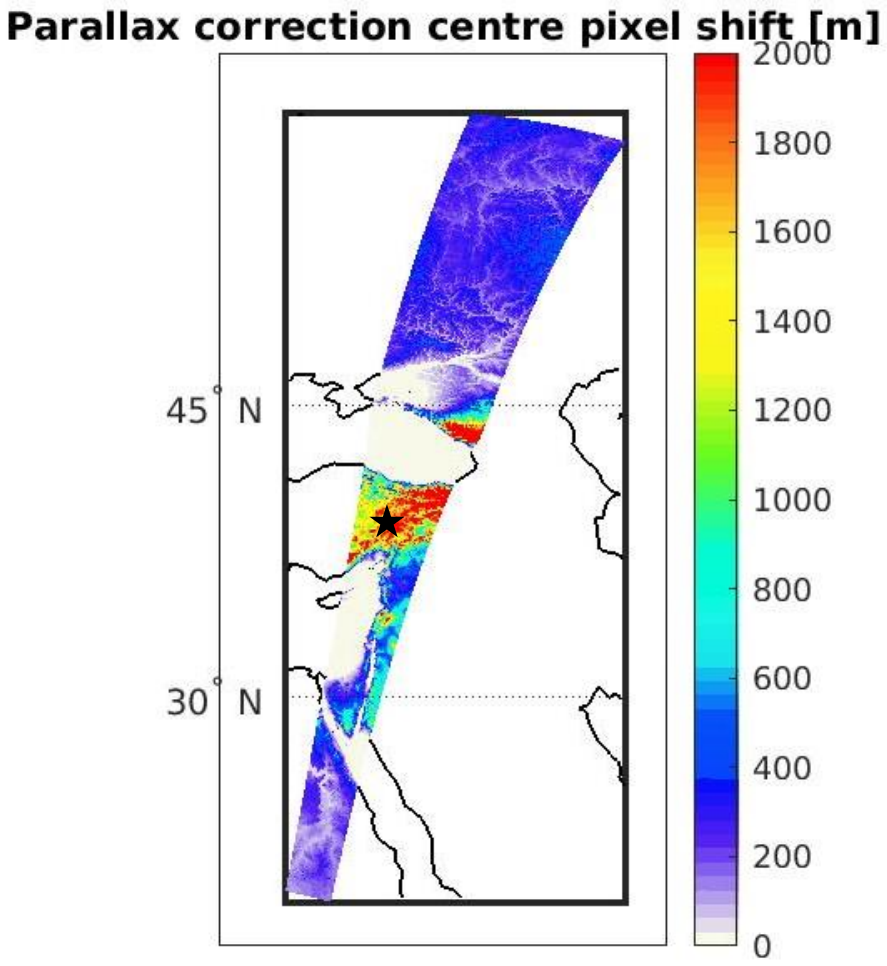

Tropospheric $NO_2$ vertical column





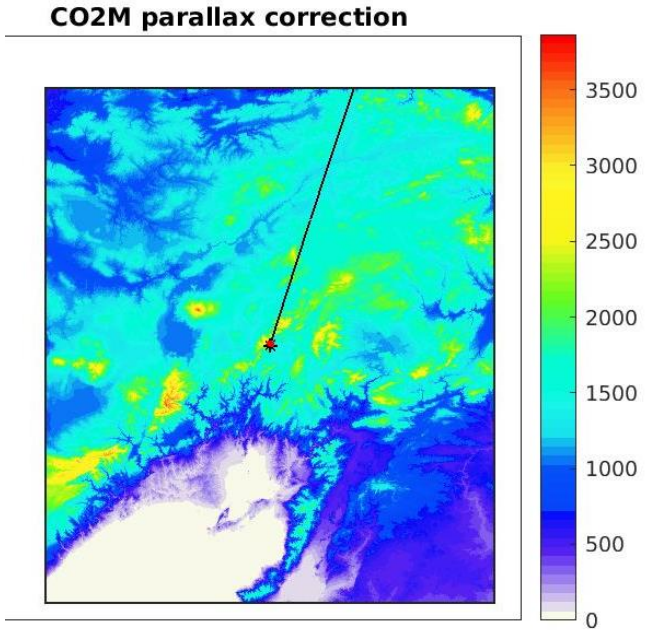


# CO2M CO2I parallax corrected footprints (sun-glint/pitched orbit)

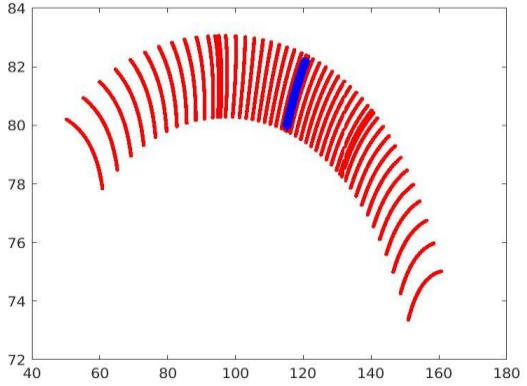



Use of Copernicus GLO-90 DSM (surface model!) optimised at ~230 m resolution

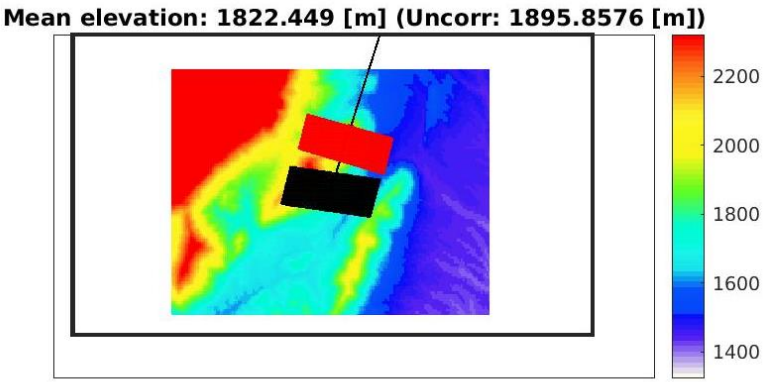
➢ Move to higher resolution (~90 m) possible in the future



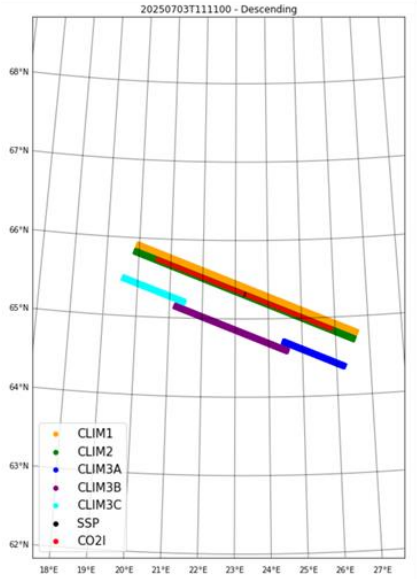

Multi-angle polarimeter footprints…



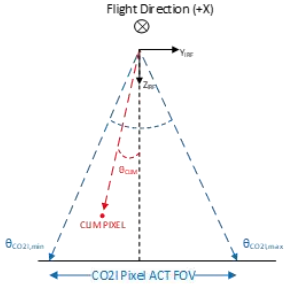

…co-registered on parallax corrected CO2I spectrometer footprint

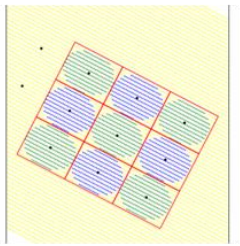



Cloud imager cloud mask (100 m VNIR / 300 m SWIR)



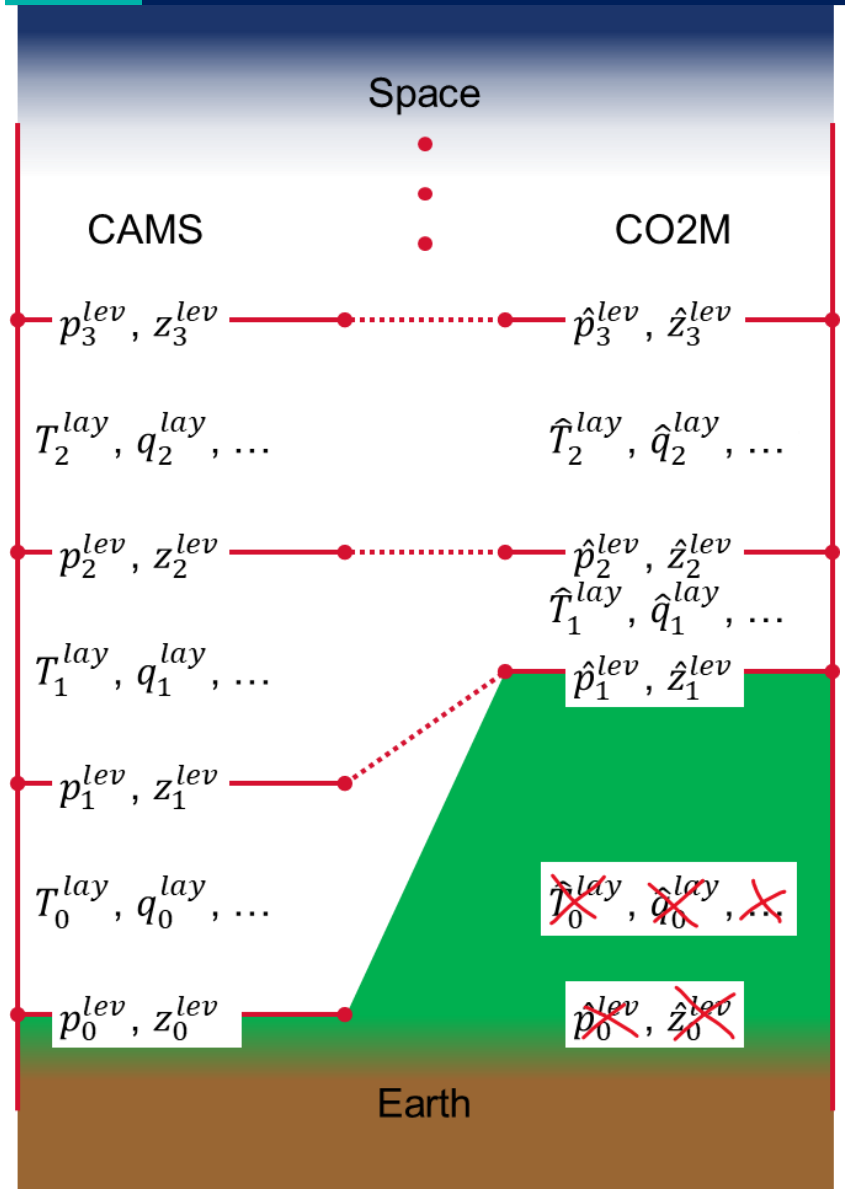

Parallax corrected cloud mask locations aggregated within parallax corrected Spectrometer LOS (SEDF) area



# Central auxiliary data processing (SCENE level-2)

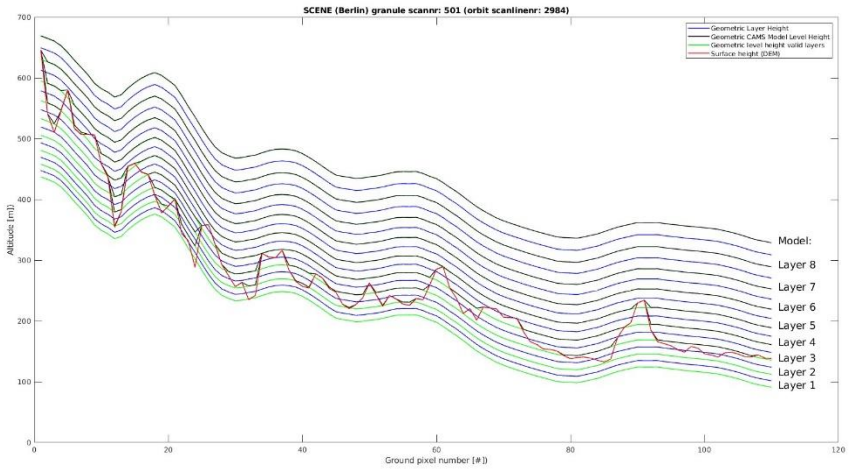





"Air around mountain" approach, M. Reuter et al.

Profile model data (>10x10 km²)

| cams_data/ |
|---|
| hybrid_level_coeff_a |
| hybrid_level_coeff_b |
| cams_aerosol_wavelength |
| surface_pressure_cams |
| surface_pressure |
| surface_altitude_geoid |
| surface_altitude_geoid_cams |
| surface_layer_number |
| pressure |
| temperature |
| specific_humidity |
| co2 |
| co |
| ch4 |
| o3 |
| no2 |
| so2 |
| hcho |
| aerosol_optical_depth |
| aerosol_optical_depth_black_carbon |
| aerosol_optical_depth_organic_matter |
| aerosol_optical_depth_desert_dust |
| aerosol_optical_depth_sea_salt_aerosol |
| aerosol_optical_depth_sulphate |
| hydrophilic_black_carbon |
| hydrophobic_black_carbon |
| hydrophilic_organic_matter |
| hydrophobic_organic_matter |
| sulfate |
| desert_dust |
| sea_salt |
| ammonium |
| nitrate_fine_mode |
| u_wind_speed |
| v_wind_speed |
| snow_depth |
| snow_albedo |
| sea-ice cover |




Derived total column model data

| Derived quantities under scene_data/ |
|---|
| geopotential |
| geometric_layer_height |
| geometric_level_height |
| tropopause_height |
| dry_air_particle_number |
| total_column_water_vapour |
| total_column_o3 |
| total_column_no2 |
| total_column_so2 |
| total_column_hcho |
| total_column_xco |
| total_column_xco2 |
| total_column_xch4 |

(at CO2M centre pixel surface altitude Using Copernicus DSM GLO-90 at ~230 m resolution)

# SCENE cloud information from CLIM data



| clim_data/ | |
|---|---|
| **scene_inhomogeneity** | [scanline×ground_pixel × clim_ch *)] |
| **cloud_fraction** | [scanline×ground_pixel **x cloud_area**] |
| **cloud_distance** | [scanline×ground_pixel **x cloud_area**] |
| **cloud_obstruction** | [scanline×ground_pixel] |
| **cloud_top_height** | [scanline×ground_pixel] |
| **cirrus_fraction** | [scanline×ground_pixel **x cirrus_area**] |
| **cloud_distance** | [scanline×ground_pixel **x cloud_area**] |
| **cirrus_obstruction** | [scanline×ground_pixel] |
| **cloud_optical_thickness** | [scanline×ground_pixel] |
| **cloud_optical_thickness_uncertainty** | [scanline×ground_pixel] |

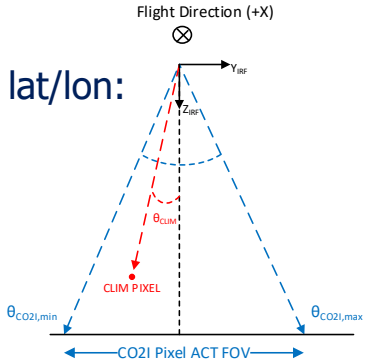
*) clim_ch=CLIM1/2

## cloud_area / cirrus-area

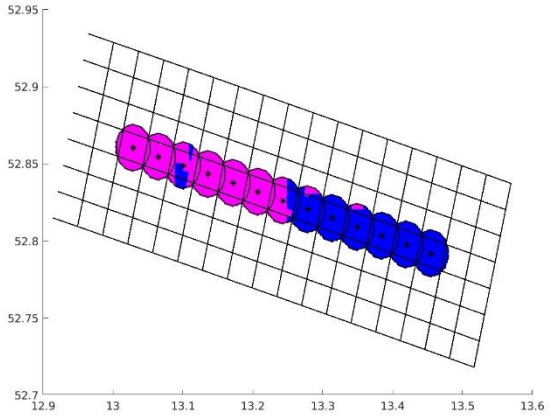
4 areas covered

Area around CO2I/NO2I centre pixel lat/lon:

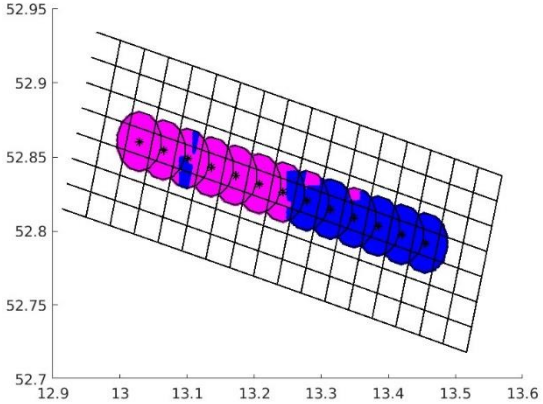
semimajor = [0.02 0.04 0.06 0.08]
semiminor = [0.02 0.04 0.06 0.08]



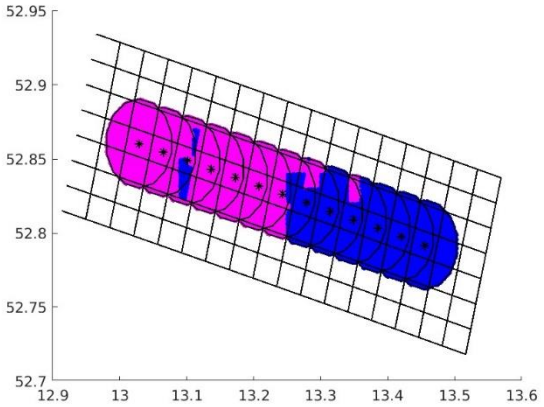

Sub-set of CO2I swath:



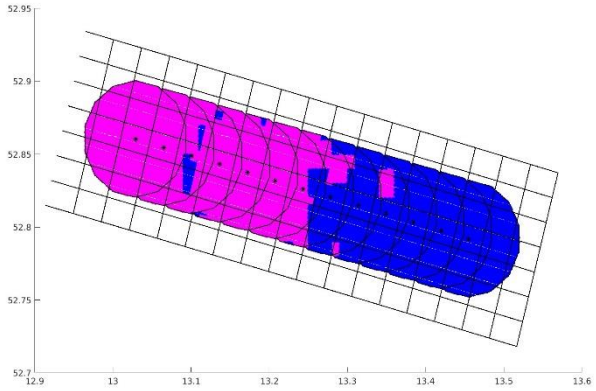

Area 1




Area 2




Area 3




Area 4

# SCENE cloud information from CLIM data



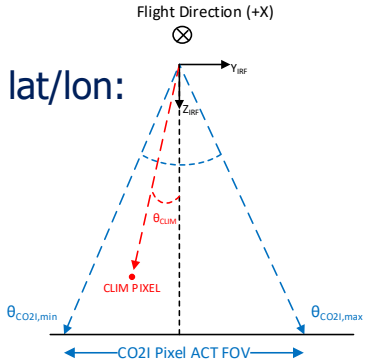
| clim_data/ | |
|---|---|
| **scene_inhomogeneity** | [scanline×ground_pixel × clim_ch *)] |
| **cloud_fraction** | [scanline×ground_pixel **x cloud_area**] |
| **cloud_distance** | [scanline×ground_pixel **x cloud_area**] |
| **cloud_obstruction** | [scanline×ground_pixel] |
| **cloud_top_height** | [scanline×ground_pixel] |
| **cirrus_fraction** | [scanline×ground_pixel **x cirrus_area**] |
| **cloud_distance** | [scanline×ground_pixel **x cloud_area**] |
| **cirrus_obstruction** | [scanline×ground_pixel] |
| **cloud_optical_thickness** | [scanline× |
| **cloud_optical_thickness_uncertainty** | [scanline× |

## cloud_area / cirrus-area

4 areas covered

Area around CO2I/NO2I centre pixel lat/lon:

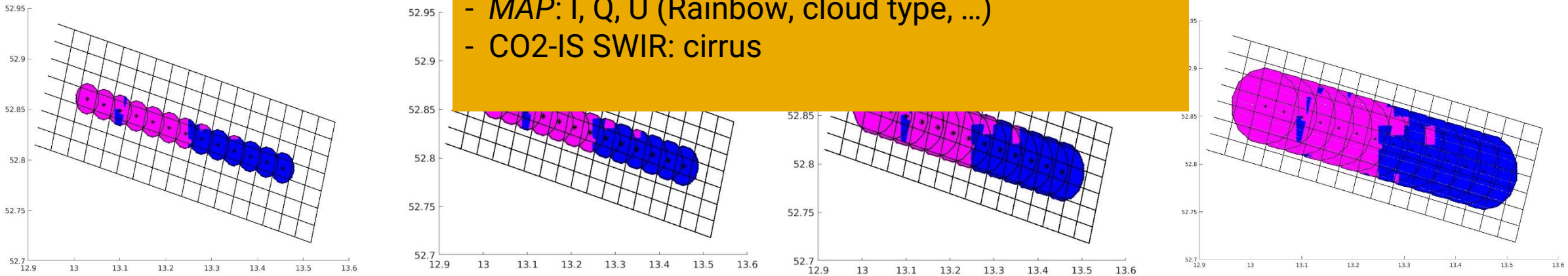
semimajor = [0.02 0.04 0.06 0.08]
semiminor = [0.02 0.04 0.06 0.08]




**Additional cloud information from CO2I / MAP:**

- *CO2-IS NIR:* Oxygen A-Band
- *NO2-IS:* $(O_2)_2$ absorption
- *MAP*: I, Q, U (Rainbow, cloud type, …)
- CO2-IS SWIR: cirrus

Sub-set of CO2I swath:



Area 1 | Area 2 | Area 3 | Area 4

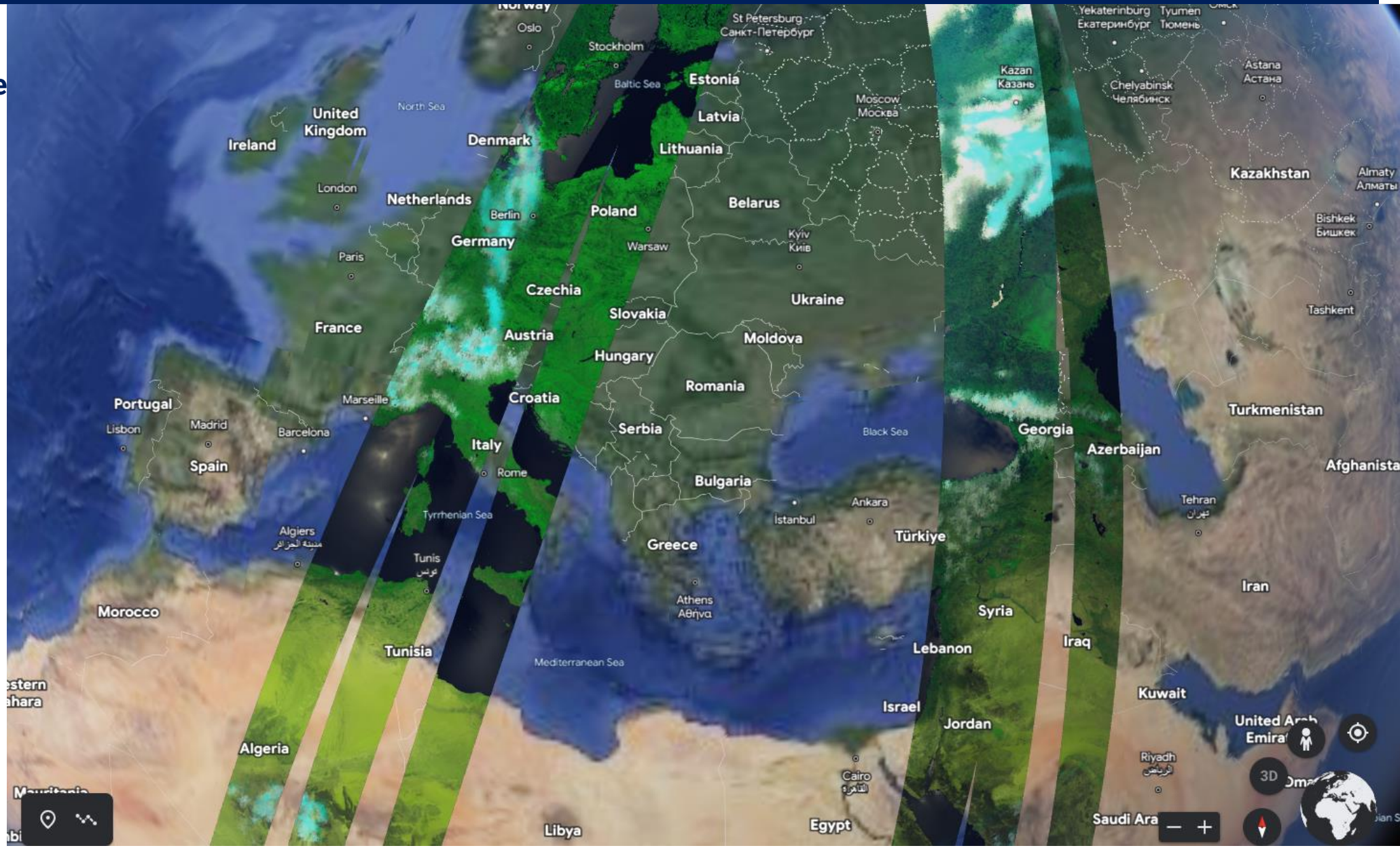
# CO2M CO2I spectrometer false colour radiance image (VIS/NIR/SWIR)

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)




HYGEOS

LILLE Icare AERIS

RAL Space
Remote Sensing Group

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

# Status summary



- Critical Design Reviews for product processing ongoing.
- CDR for the system (satellite and ground segment) expected by Q4 2024.
- First results and test-data for all product levels available.
- CO2M multi-instrument, multi-algorithm approach is expected to maximise usage of full CO2M information content and to increase product accuracy and robustness.

# EUMETSAT CO2M scientific support studies



https://www.eumetsat.int/copernicus-co2m-science-support