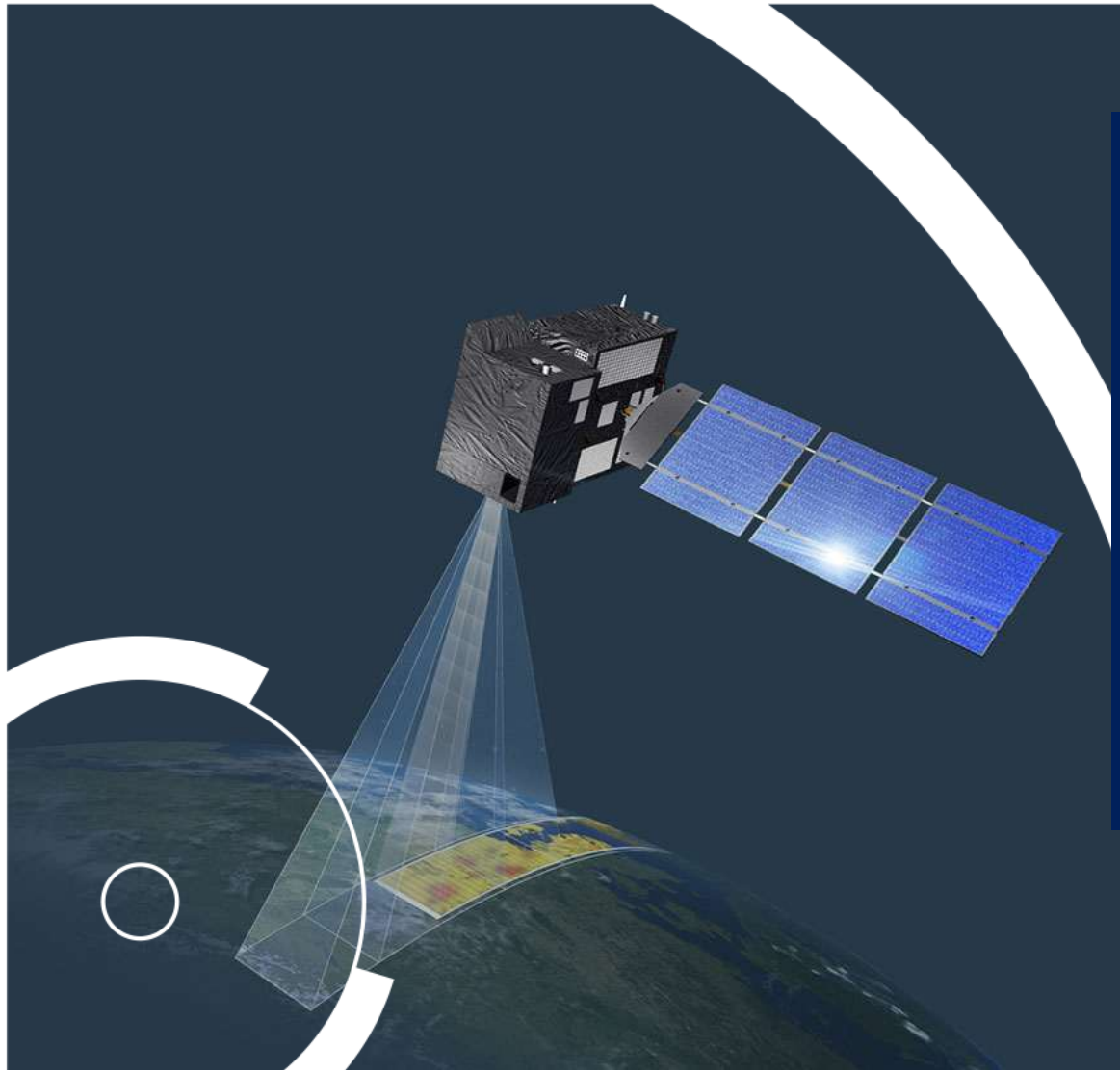


CO2M status and results from developments

IWGGMS-21 2.07

9-12 June 2025

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

The CO2M greenhouse-gas monitoring constellation

copernicus.eumetsat.int

Three satellite missions each with 270 km swath:

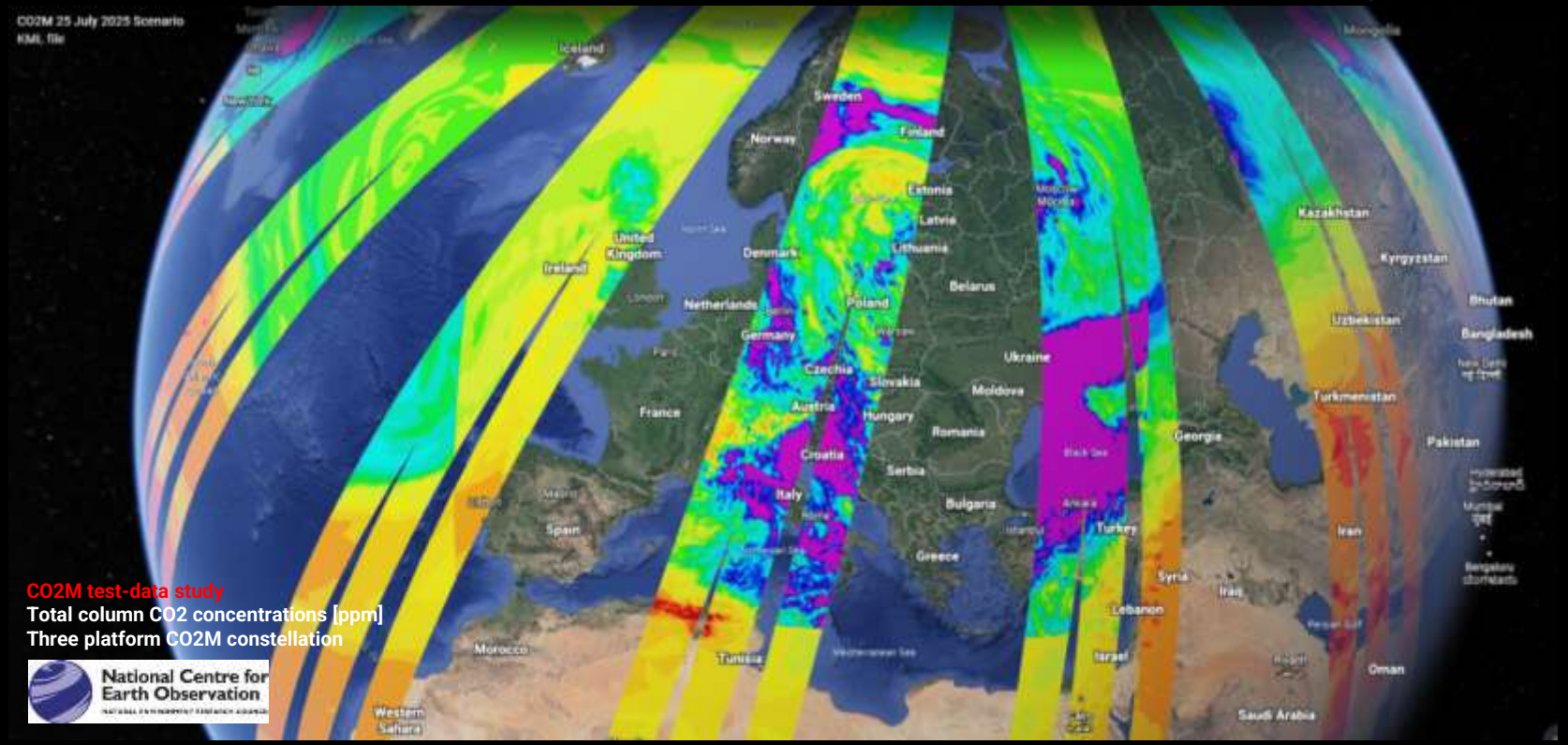
- ✓ Providing greenhouse-gas data for the Copernicus GHG Monitoring and Verification Support capacity

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	1.5x10^{15} molec/cm²	<3.5x10^{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	

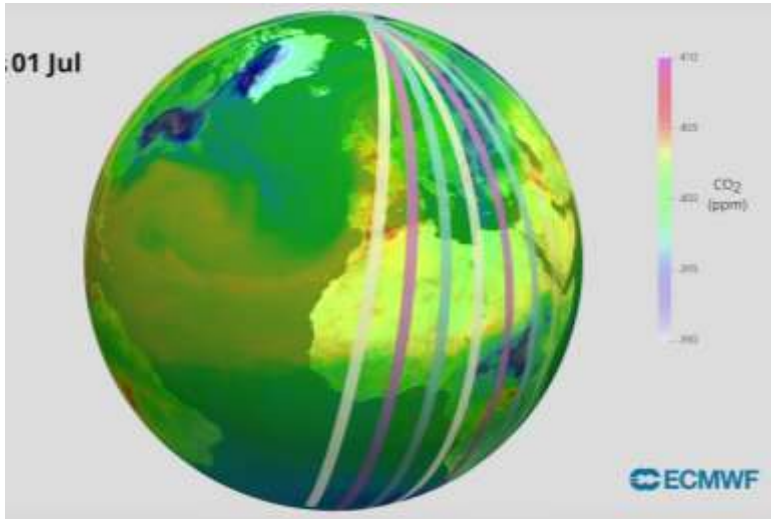
*Solar Induced Fluorescence

EUMETSAT copernicus esa

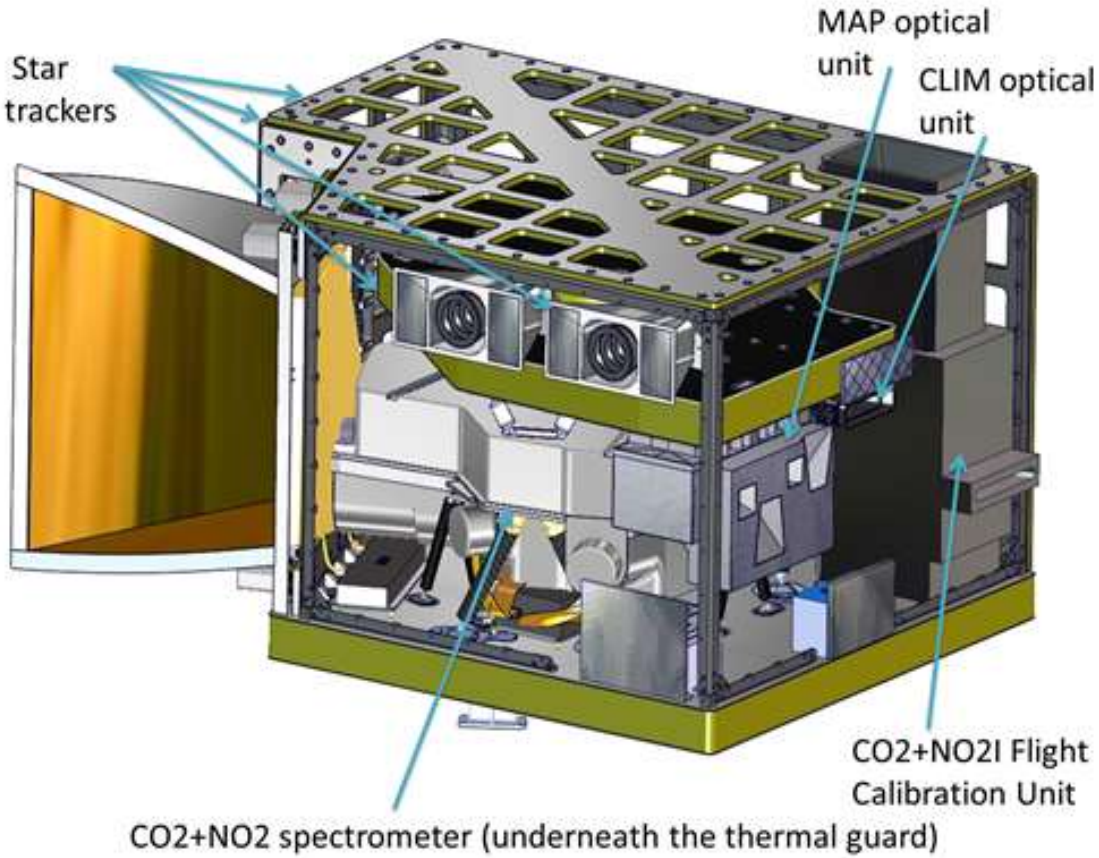
Payload Implementation

Payload Components

- **CO2 I**mager **(CO2I)**: 3 band (1 NIR, 2 SWIR) push-broom imaging spectrometer
- **NO2 I**mager **(NO2I)**: extra band (VIS) in CO2I
- **M**ulti-**A**ngle **P**olarimeter **(MAP)** for aerosol
- **CL**oud **IM**ager **(CLIM)** for low cloud & cirrus

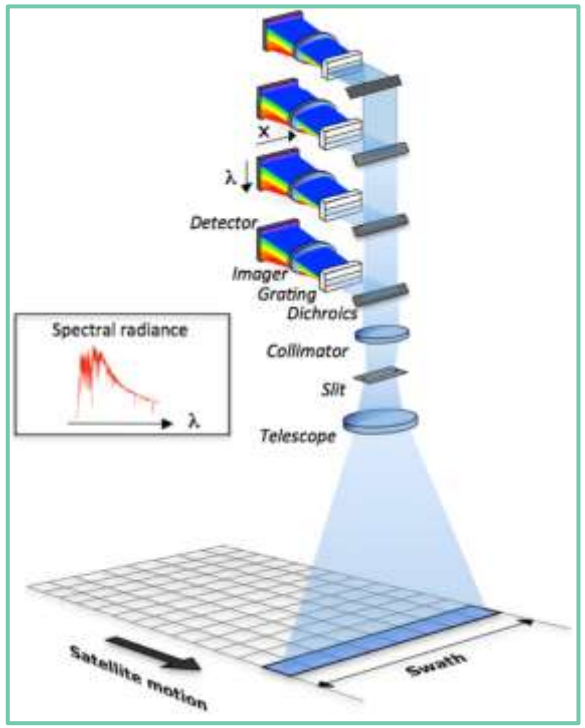


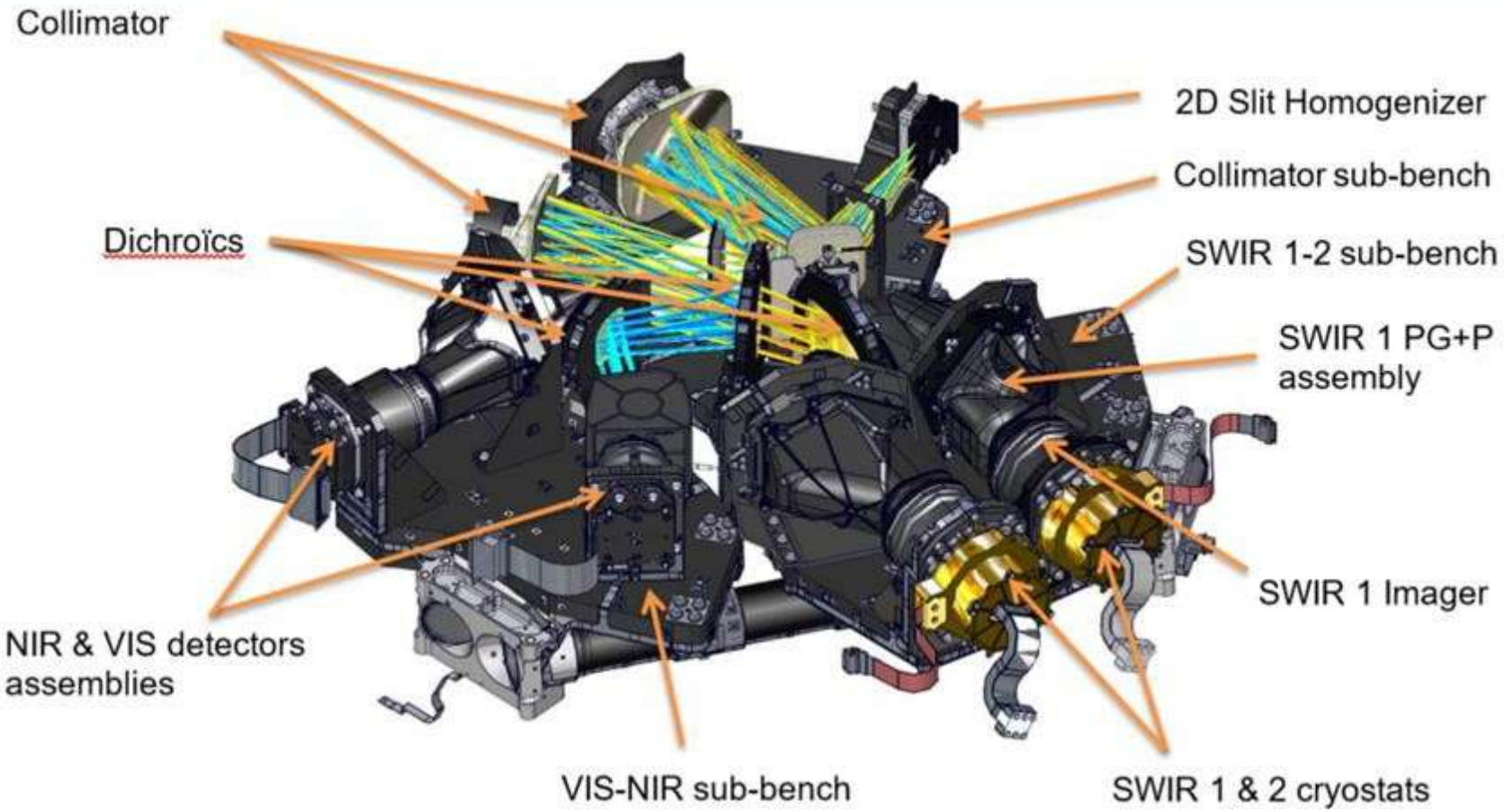
Credits: EMPA



Credits: TASiF

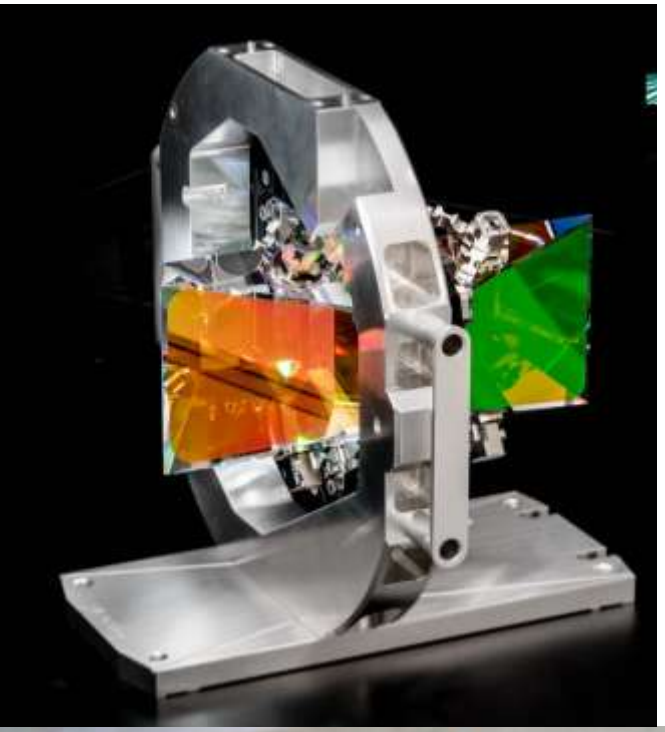
CO_2 & NO_2 Pushbroom Imaging Spectrometer





Credit Thales Alenia Space

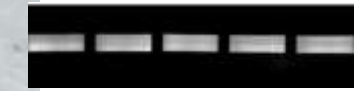
Some other impressions



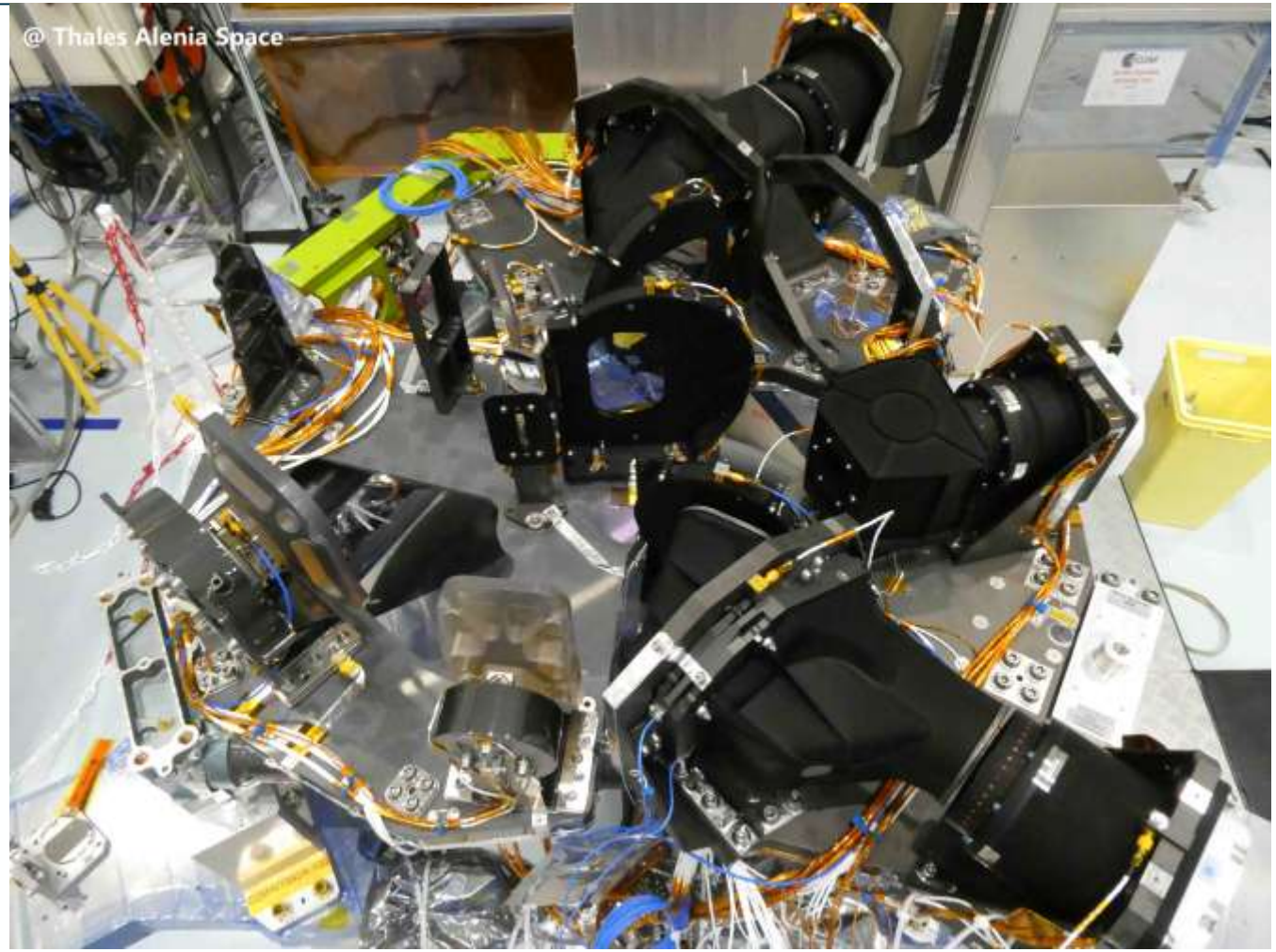
Credit IOF Fraunhofer

Prism +
Grating +
Prism

Entrance slit with 110 fibers



Credit Optec

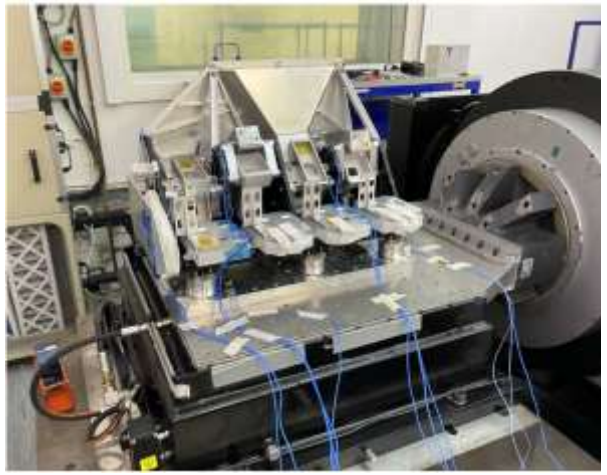


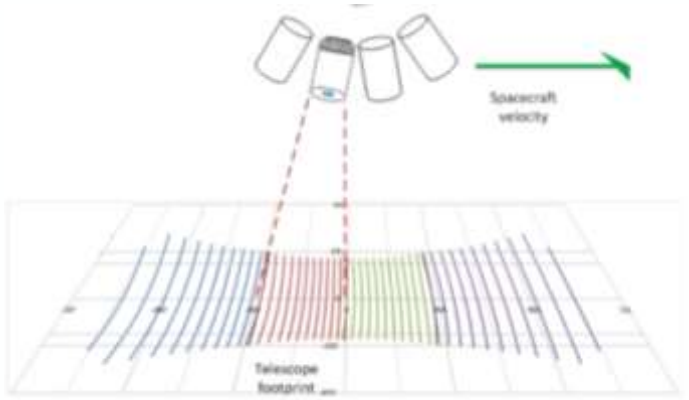
Credit Thales Alenia Space

MAP and CLIM

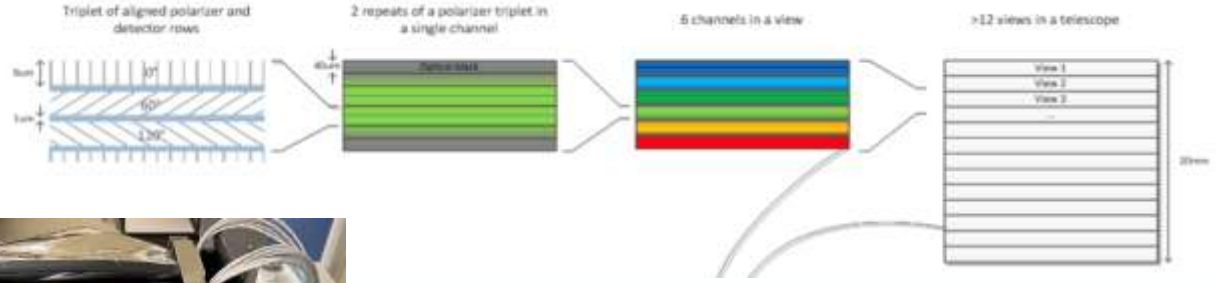
Multi-angle polarimeter (MAP):

- 40 viewing angles (+/- 60º), plus 8 more @larger angles
- Spatial resolution: 4x4 km2 while sampling < 1x1 km2





Credit Thales Alenia Space



Cloud Imager

Binning on-ground, specs @400m

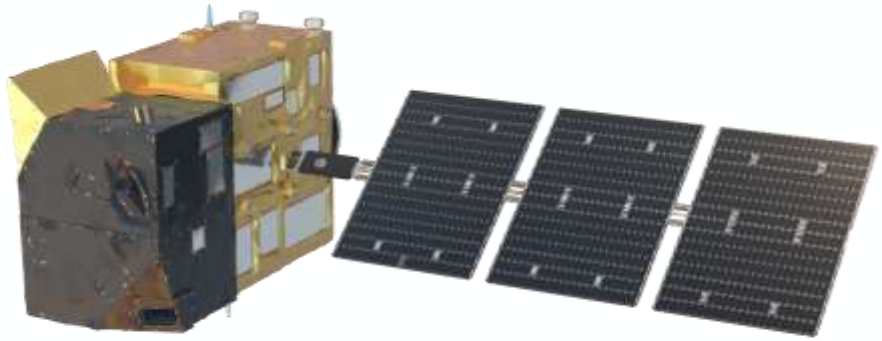
Band	Band center	Band width	Native sampling (ALTxACT)
CLIM-1	670 nm	20 nm	94m x 87m
CLIM-2	753 nm	9 nm	94m x 87m
CLIM-3	1378 nm	15 nm	376m x 163m

Credit OIP Belgium

Copernicus CO2M Mission – Status

Project status:

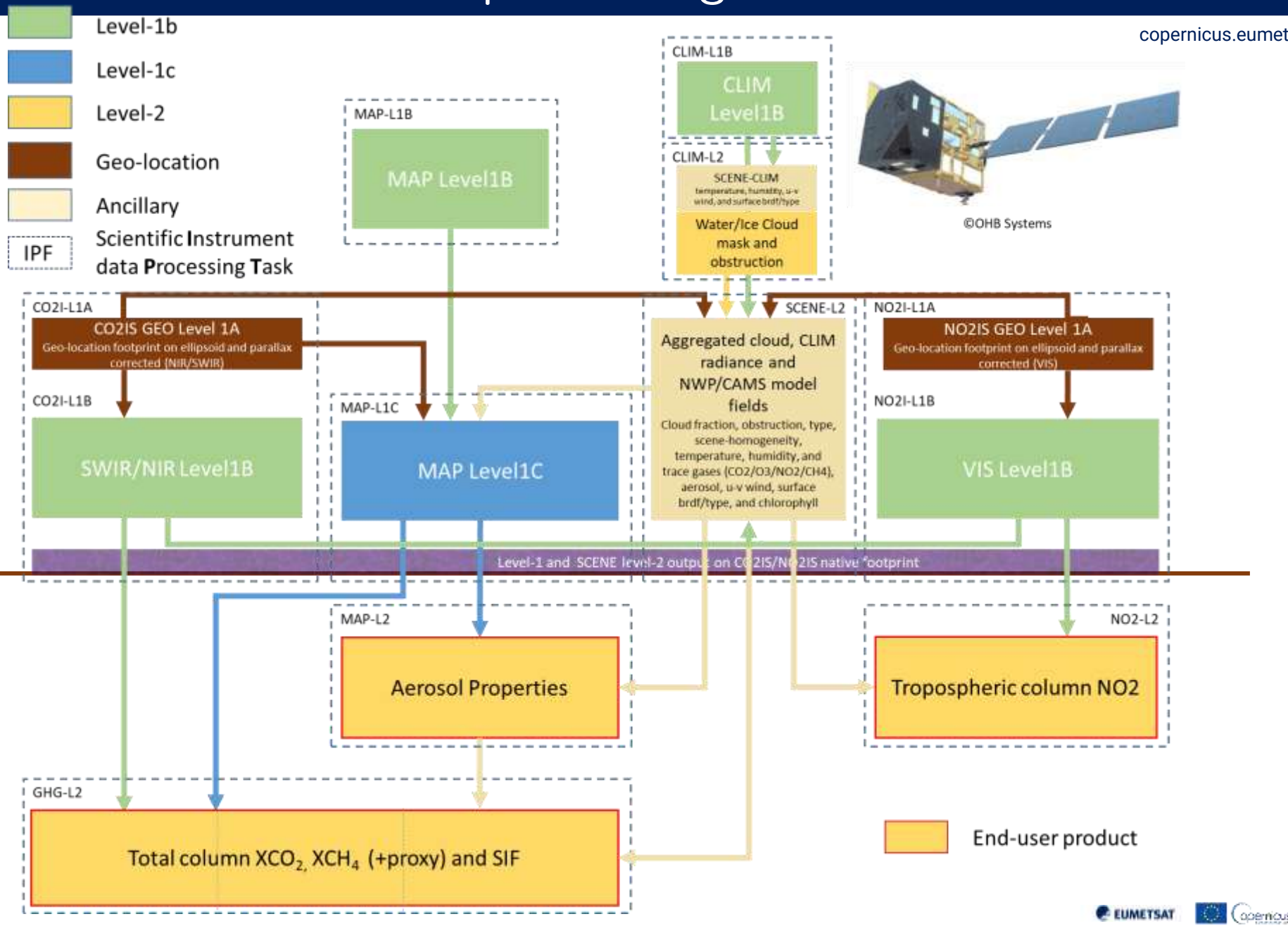
- **Constellation** of 3 satellites
- Each satellite **>270 km swath**
- First satellite Acceptance Review **08-2027**
- Second satellite Acceptance Review **02-2028**
- Third satellite is scheduled in **2029**



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

EUMETSAT CO2M MDPS scientific processing tasks

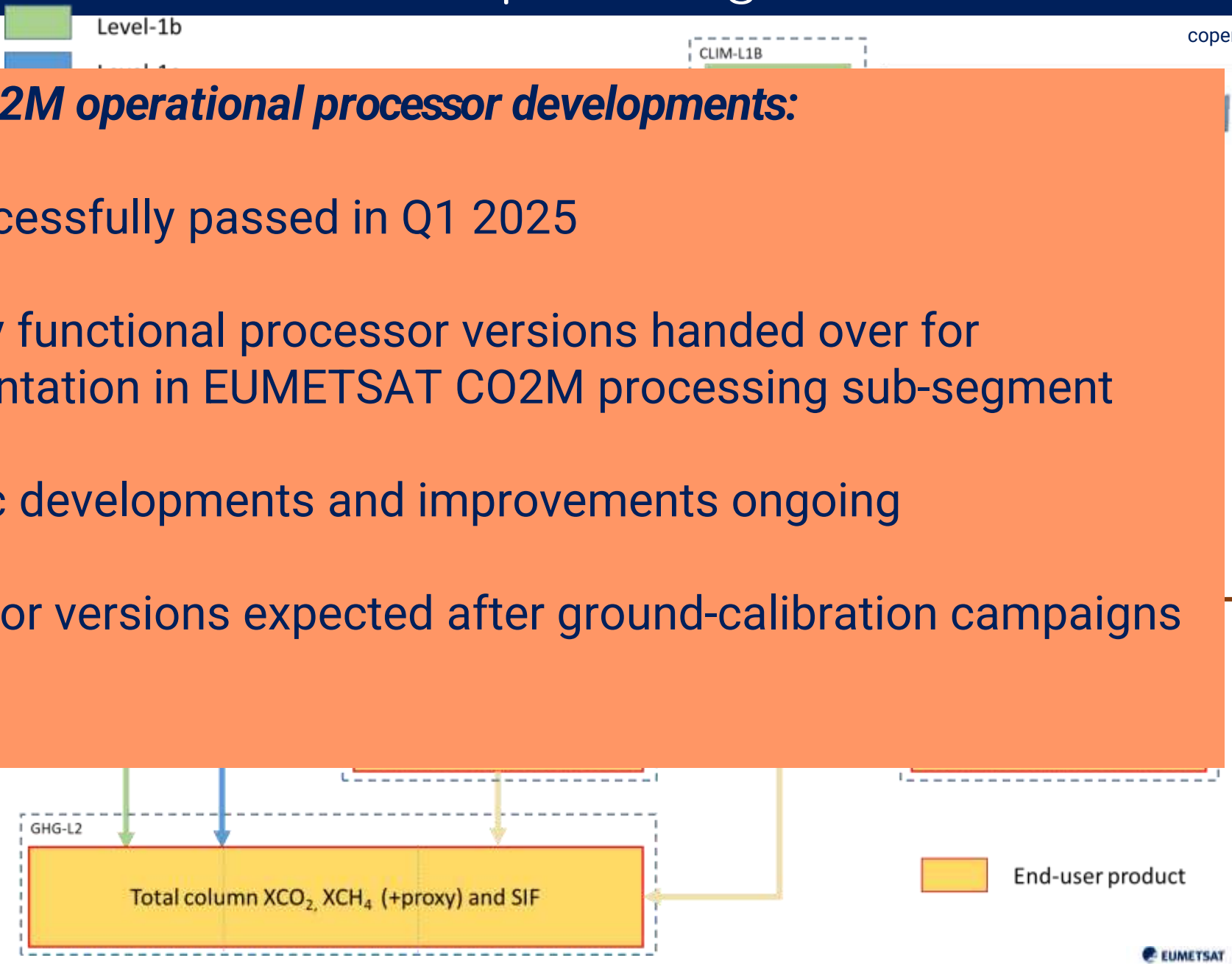
CO2M
Mission
Process

Make or
"hyper-G
instrume
out of th

**Below this l
co-registere
CO2I/NO2I
footprint**

Status of CO2M operational processor developments:

- CDR successfully passed in Q1 2025
- First fully functional processor versions handed over for implementation in EUMETSAT CO2M processing sub-segment
- Scientific developments and improvements ongoing
- Next major versions expected after ground-calibration campaigns in 2026

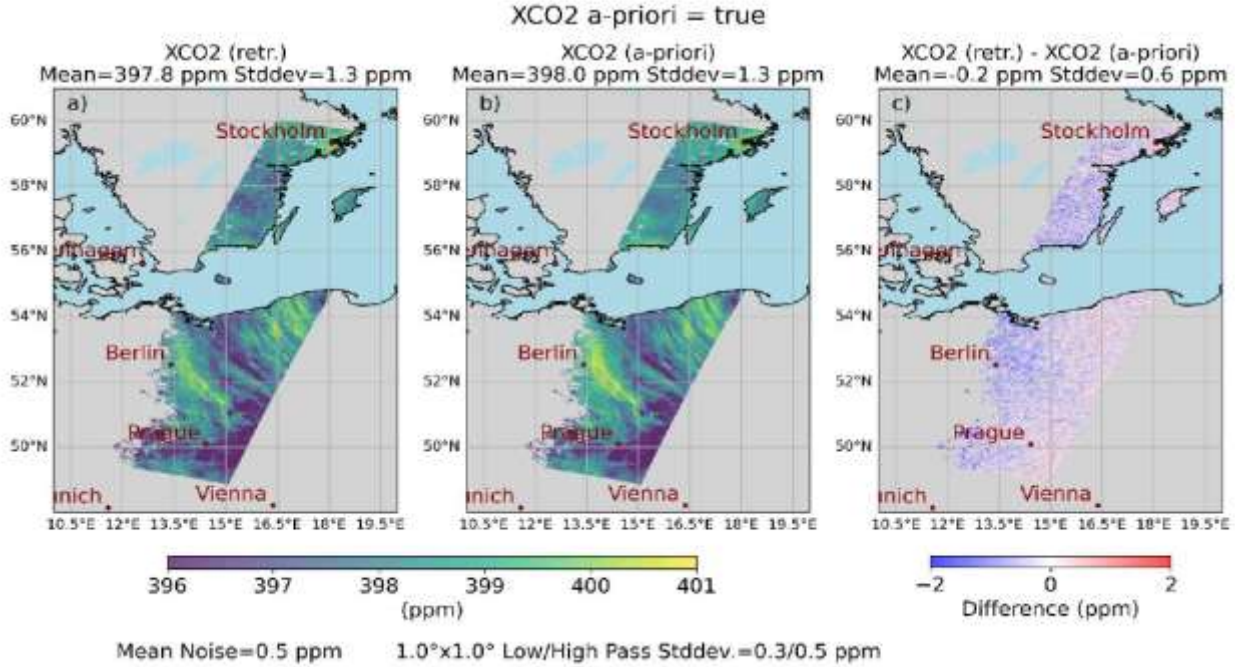


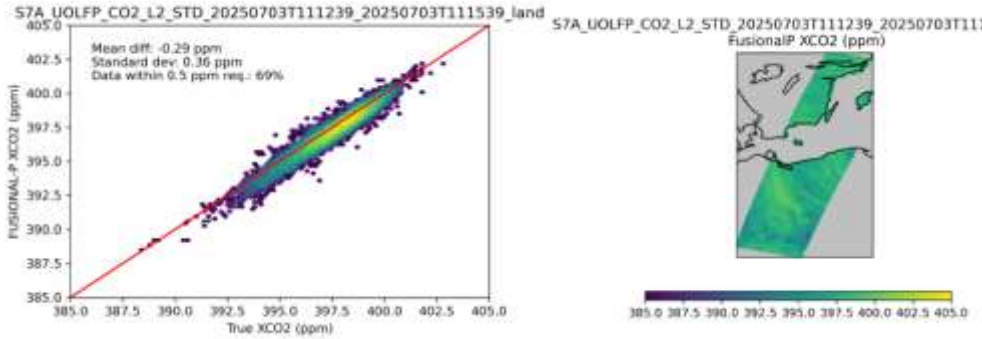
Early results from synthetic data (GHG level-2 XCO2)

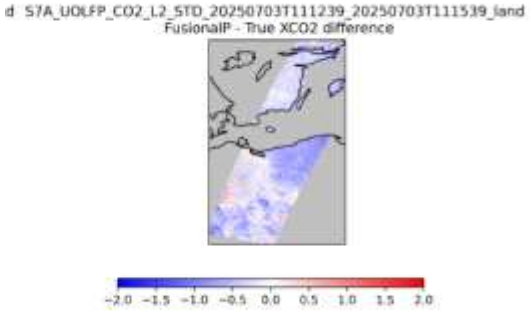
Three GHG algorithms for CO2M

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

FOCAL

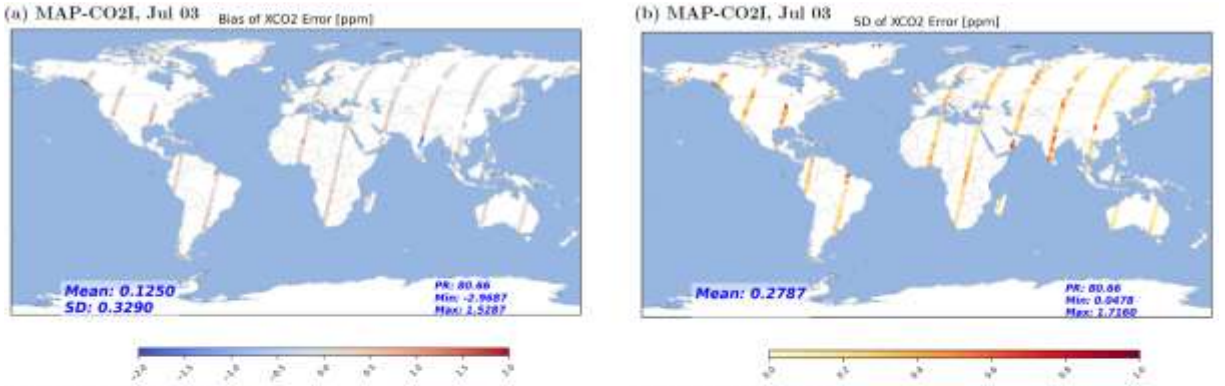






UoLfP

RemoTAP

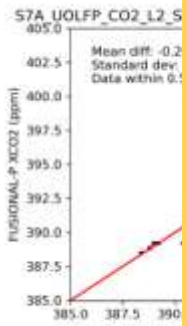


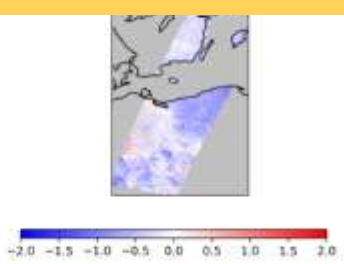
Early results from synthetic data (GHG level-2 XCO2)

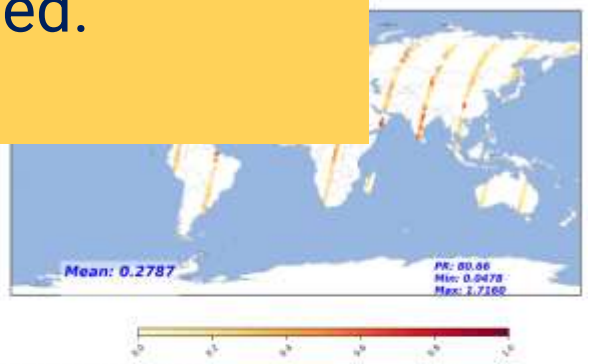
Three GH… for CO2M

Status of CO2M GHG operational processor developments:

- All three GHG processors delivered as fully functional operational software for integration in the operational CO2M MDPS.
- All GHG processors demonstrate compliance to requirements for a platform configuration in nadir over land, either on a sub-set or on a full set of representative test-data.
- GHG product performances over water and for a platform in “sun-glint mode”, both land and ocean are currently evaluated.



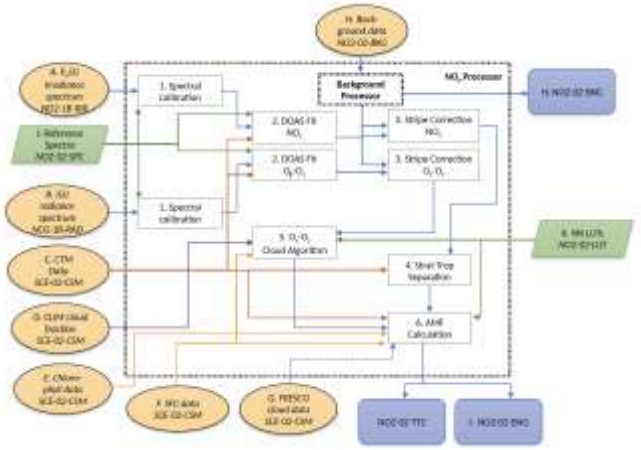


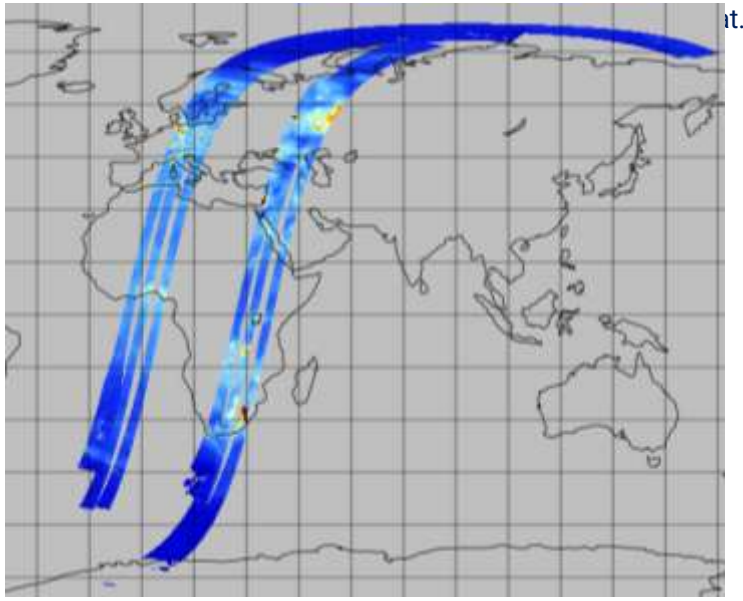


UoLfP

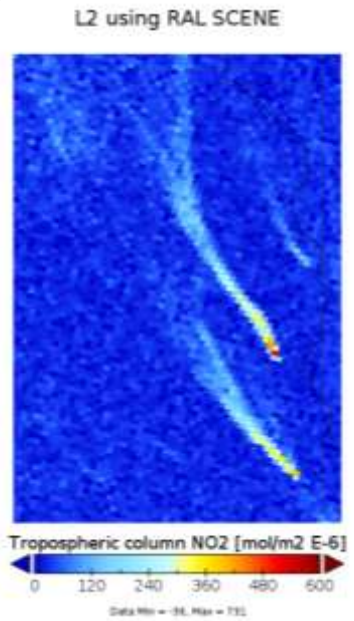
The CO2M NO2 level-2 product

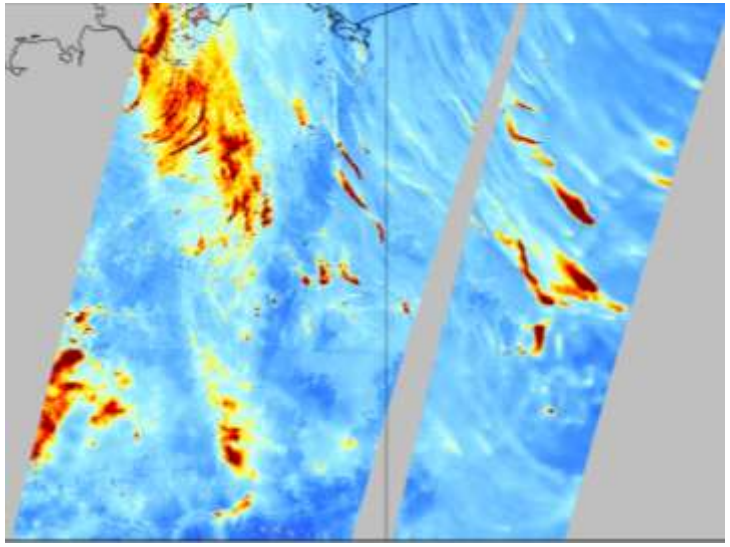
Based on heritage from OMI/TROPOMI NO2 algorithms



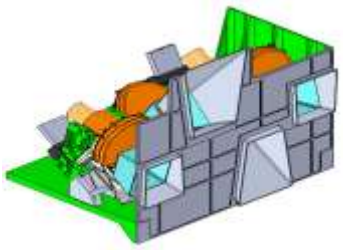


- **DOAS fit left unchanged**
  - CO2M: solar irradiance measurements
- **Troposphere-stratosphere separation:**
  - No assimilation CTM system as in TROPOMI
  - Use of CAMS global model data
  - As of CAMS IFS cycle 48R1: full stratospheric chemistry
- **Cloud correction:**
  - O2-O2 DOAS (VIS) with scattering cloud model
  - O2-A (NIR) as fallback
  - CLIM cloud information
- **Air-mass factors (AMF):**
  - Hi-res surface BRDF/DLER information
  - Scattering cloud model
  - CAMS NO2 a-priori profile shape (~40 x 40 km2)

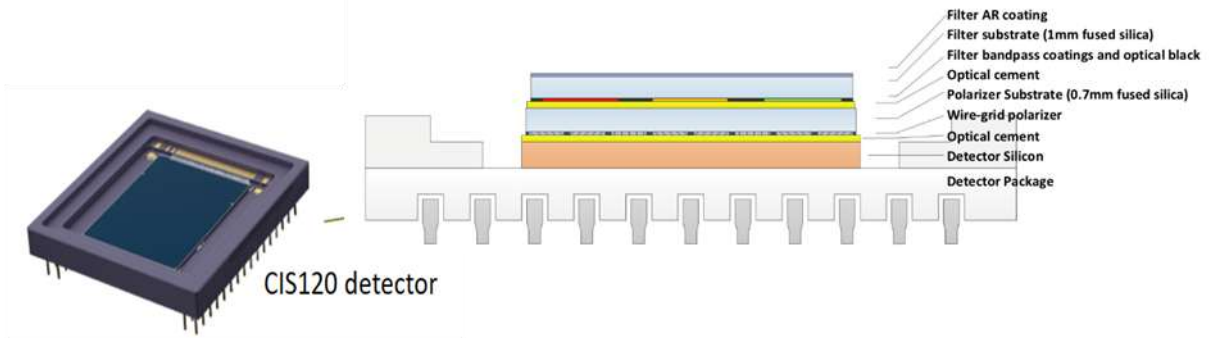


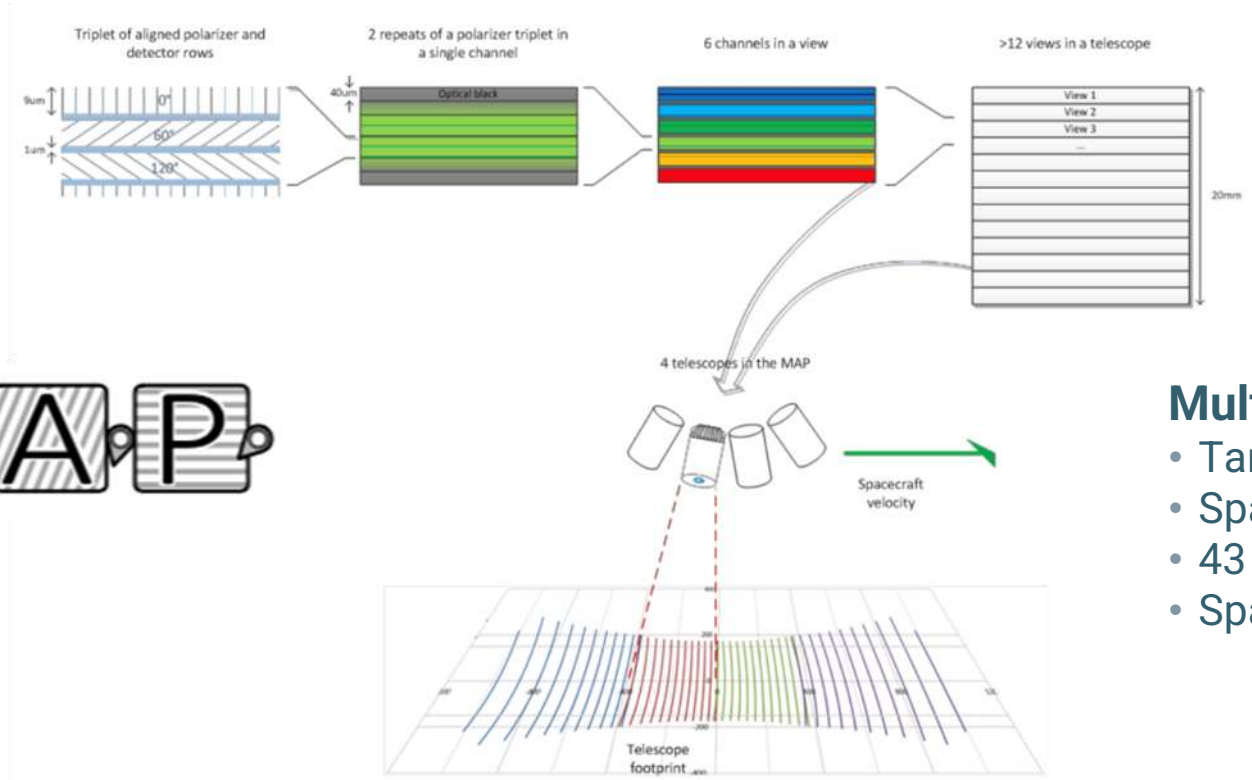


CO2M MAP polarimeter focal plane design



Credit © TAS-UK



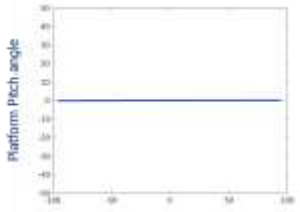


Multi-angle polarimeter

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

Nominal and pitched ("sun-glint"-pointing) platform orbits for CO2M

Nominal Orbit



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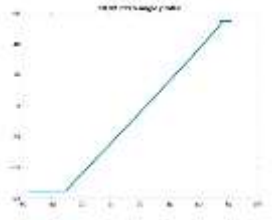
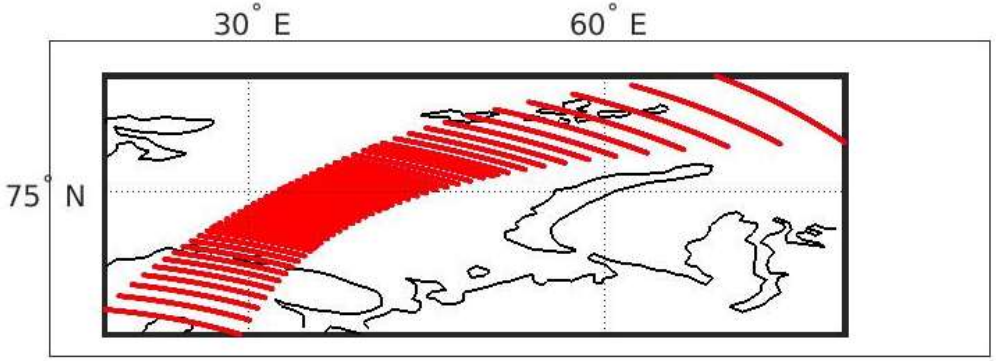
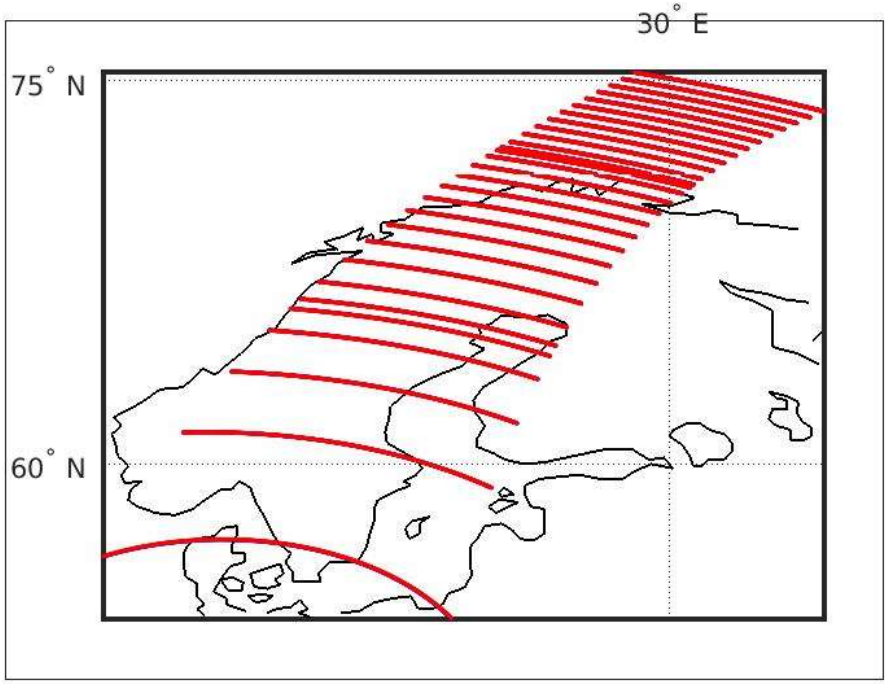




Platform pitch angle at 0 deg
(all 41 views +-60 degrees)

Pitched Platform Orbit

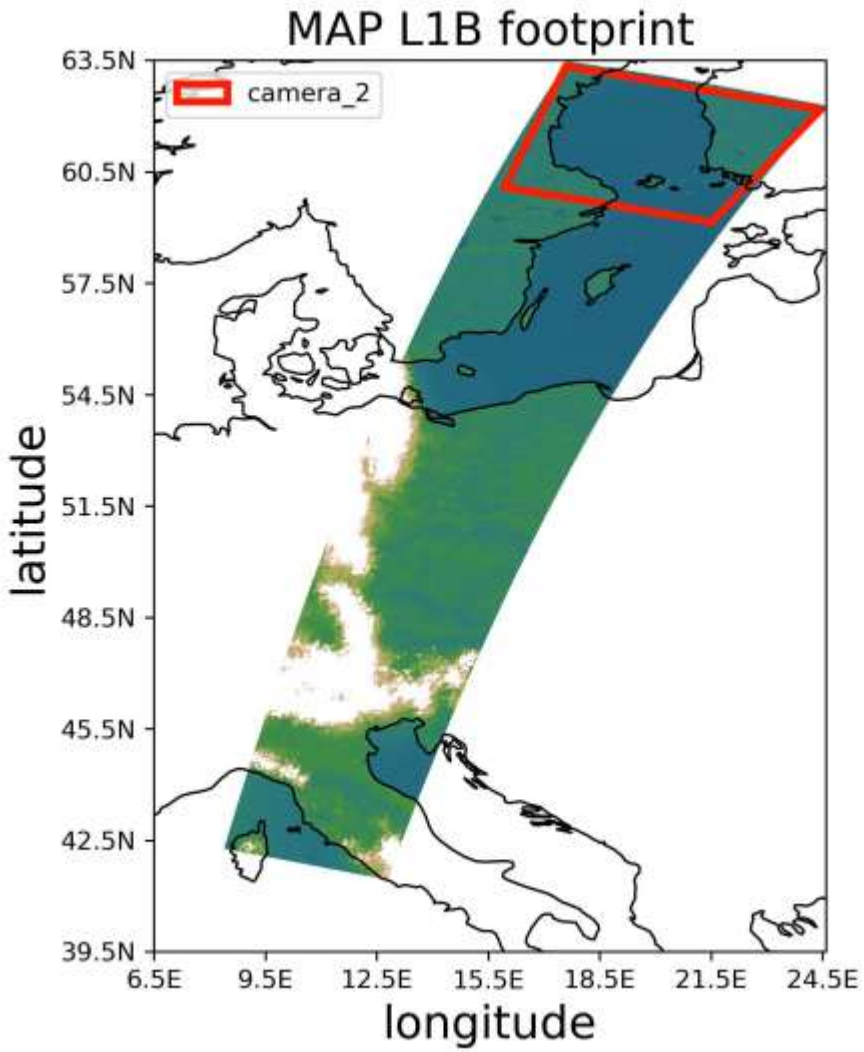
*)

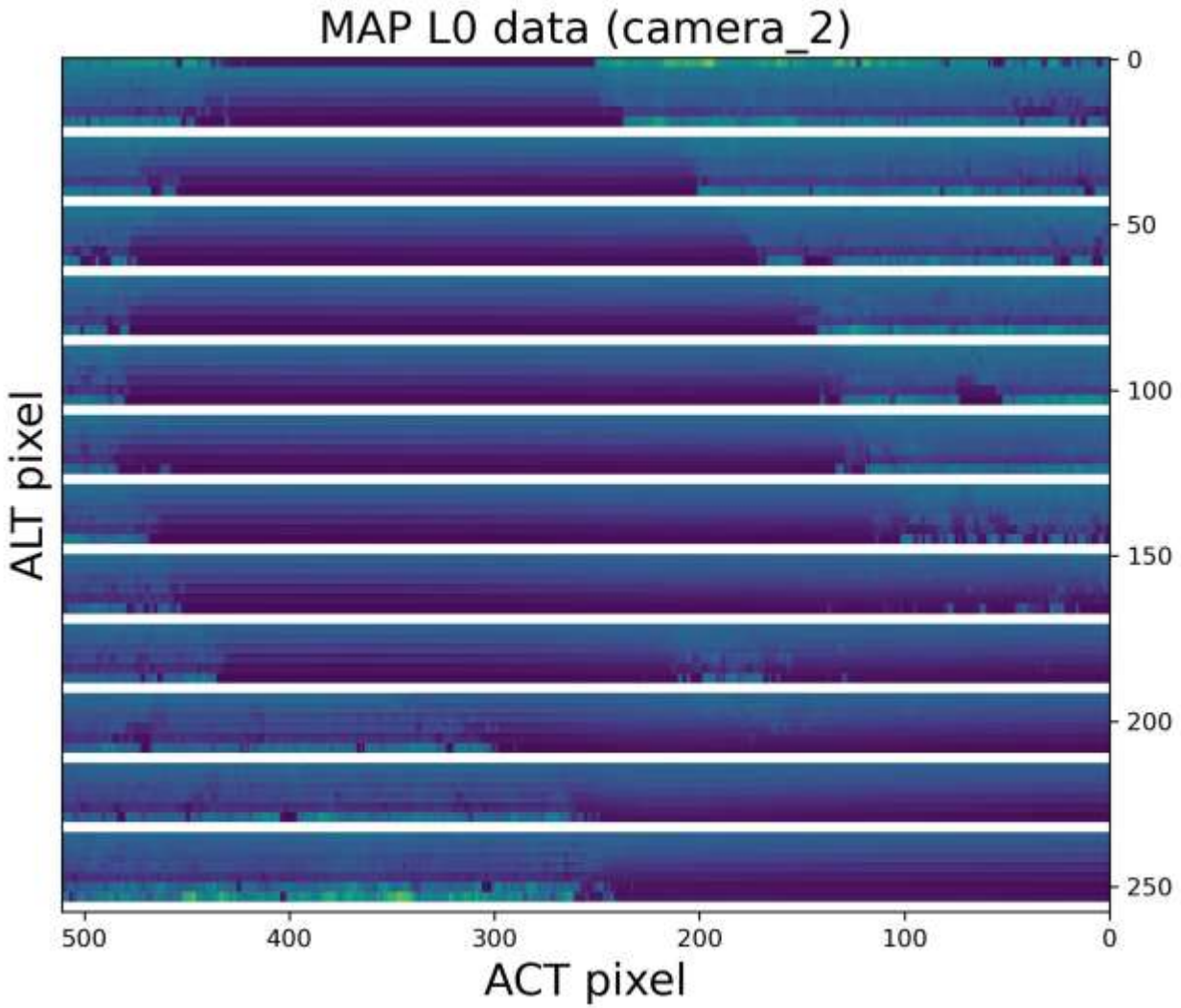


Platform pitch angle at 50 deg forward looking
(all 29 valid views +-60 degrees)

*) Cox-Munk model for water (glint) reflectance at 7 m/s averaged wind-speed.

Simulation of CO2M MAP level-0 data – detector level





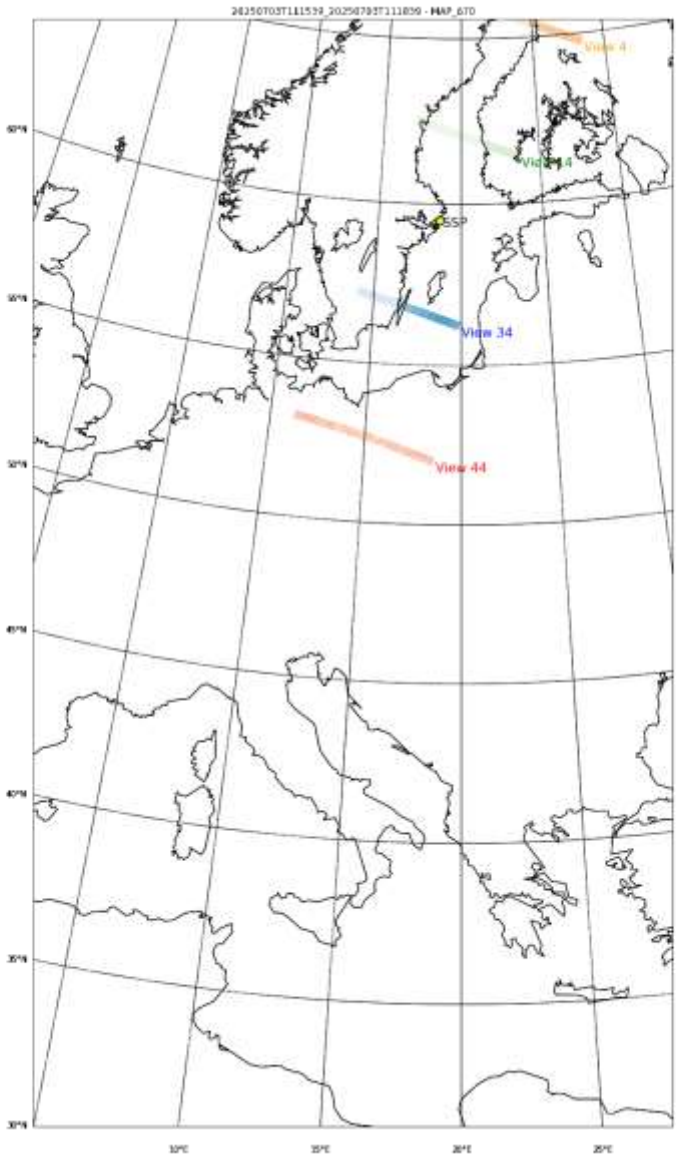
Simulation of CO2M MAP L1 data – L1B to L1C co-registration to CO2I grid

The CO2M MAP L1B

2 granules
(total 6 minutes)

Nadir pointing

4 views out of 48
are shown

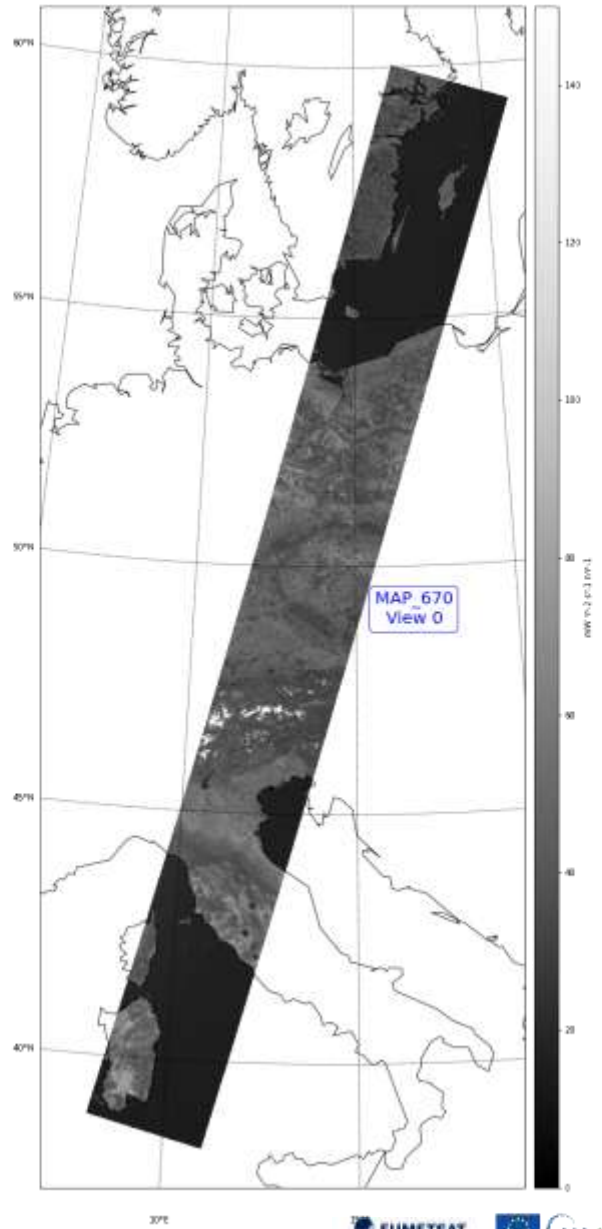


The CO2M MAP L1C

2 granules
(total 6 minutes)

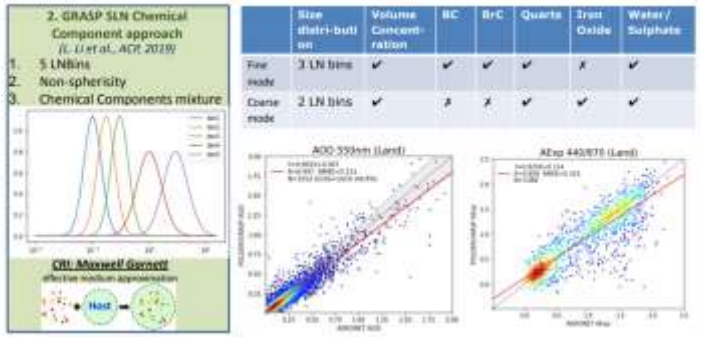
Nadir pointing

45 Co-registered
views



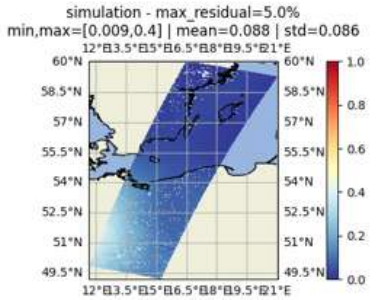
CO2M MAP level-2 aerosol product for pathlength correction

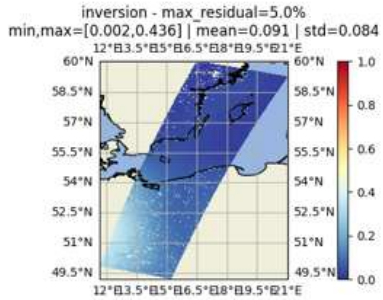
The GRASP/Components aerosol model has been selected for MAP with 3x3 MAP L1C pixels fitted simultaneously.

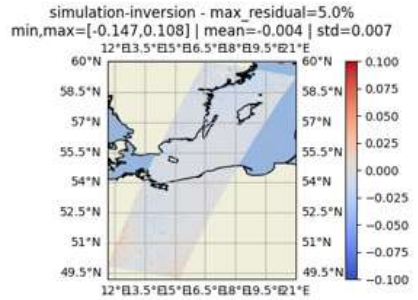


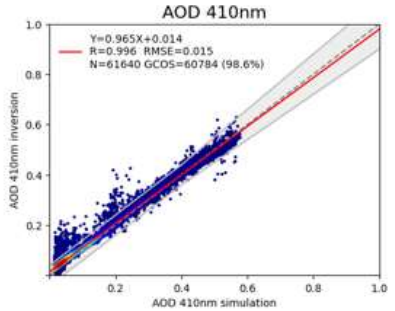
The GRASP (Generalized Retrieval of Aerosol and Surface Properties) is used for the simultaneous retrieval of both aerosol and surface properties.

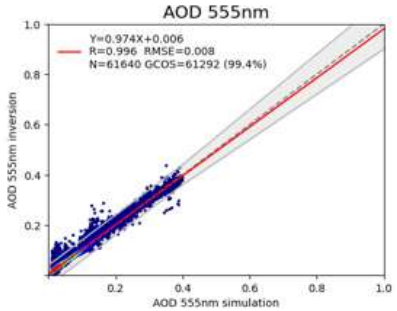
Aerosol retrieval performed in the VNIR, is used for an atmospheric correction in the SWIR for the CO2 retrieval.

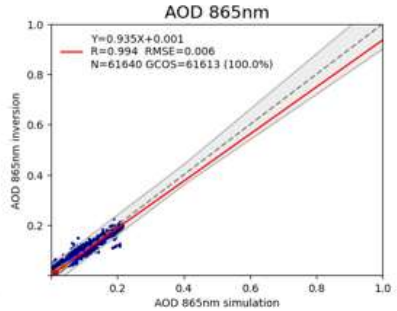


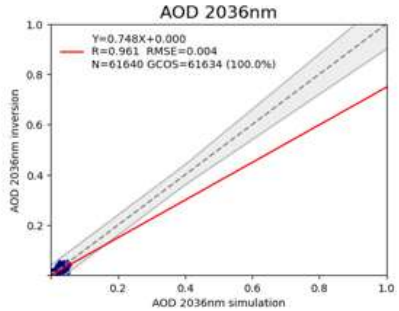




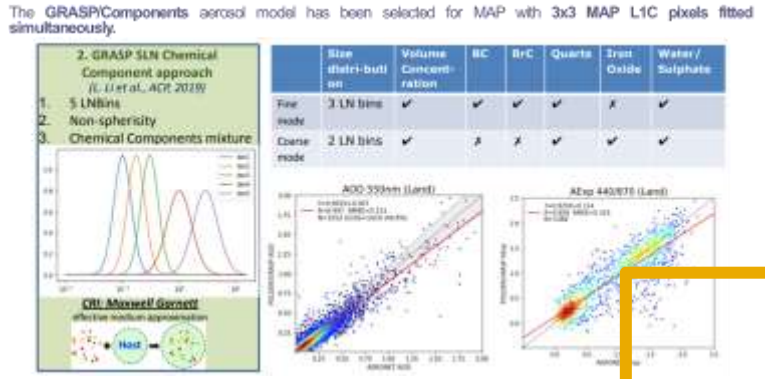








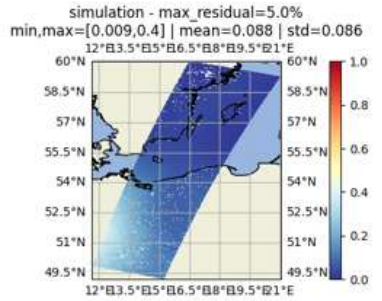
CO2M MAP level-2 aerosol product for pathlength correction

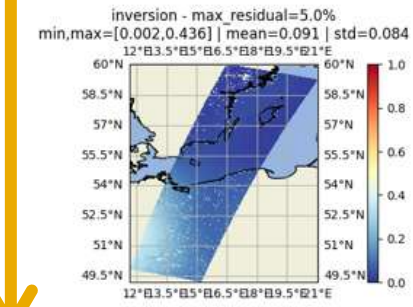


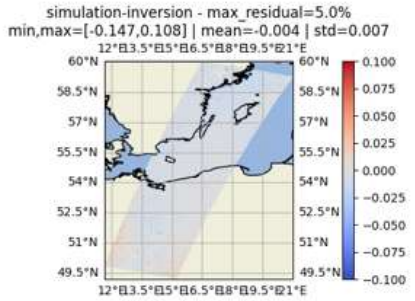
The GRASP (Generalized Retrieval of Aerosol and Surface Properties) is used for the simultaneous retrieval of both aerosol and surface properties.

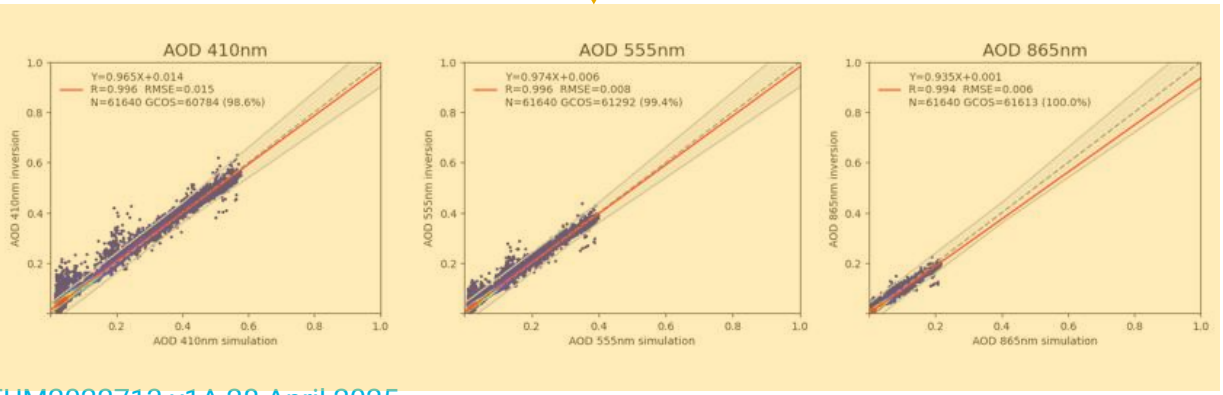
Aerosol retrieval performed in the VNIR, is used for an atmospheric correction in the SWIR for the CO2 retrieval.

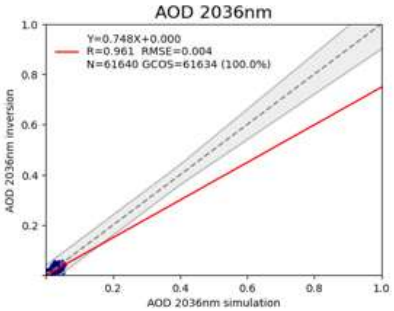
MAP Band	Wavelength
VNIR-1	410 nm
VNIR-2	443 nm
VNIR-3	490 nm
VNIR-4	555 nm
VNIR-5	670 nm
VNIR-6*	753 nm
VNIR-7	865 nm



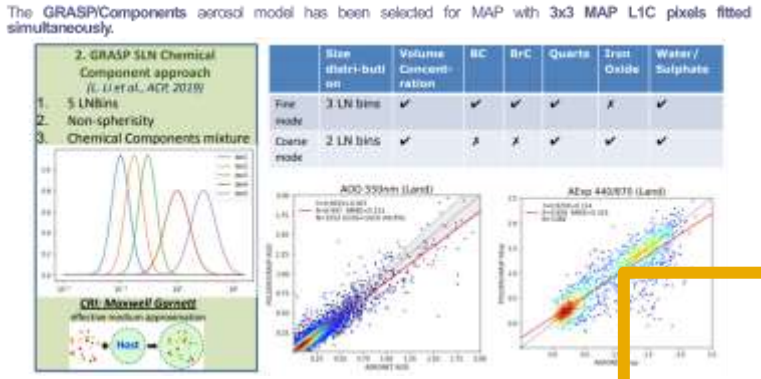








CO2M MAP level-2 aerosol product for pathlength correction

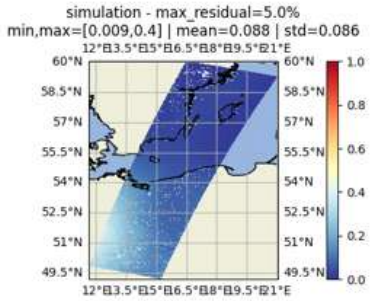


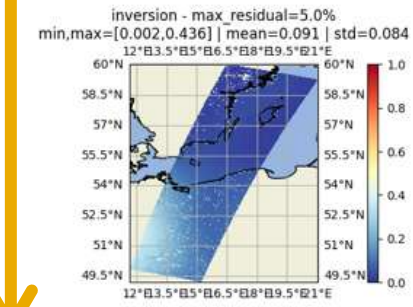
The GRASP (Generalized Retrieval of Aerosol and Surface Properties) is used for the simultaneous retrieval of both aerosol and surface properties.

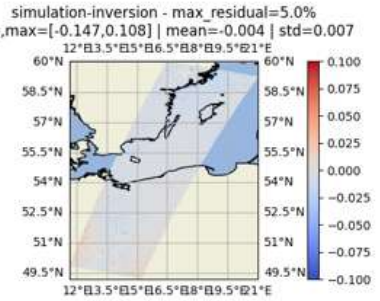
Aerosol retrieval performed in the VNIR, is used for an atmospheric correction in the SWIR for the CO2 retrieval.

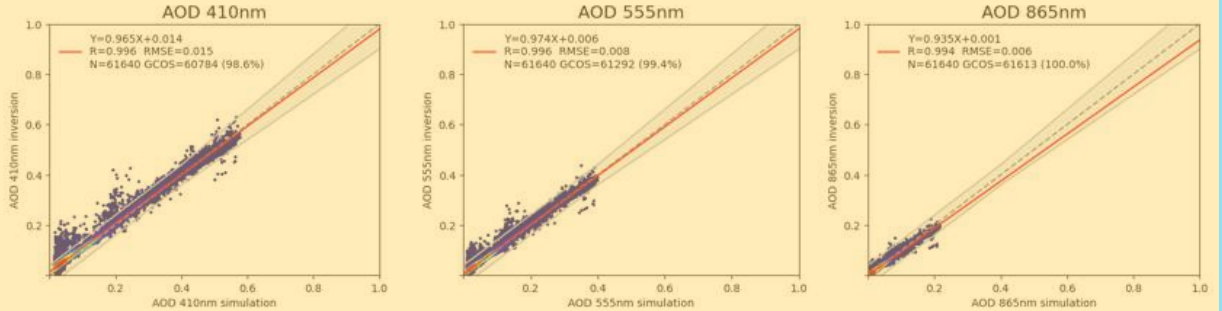
MAP Band	Wavelength
VNIR-1	410 nm
VNIR-2	443 nm
VNIR-3	490 nm
VNIR-4	555 nm
VNIR-5	670 nm
VNIR-6*	753 nm
VNIR-7	865 nm

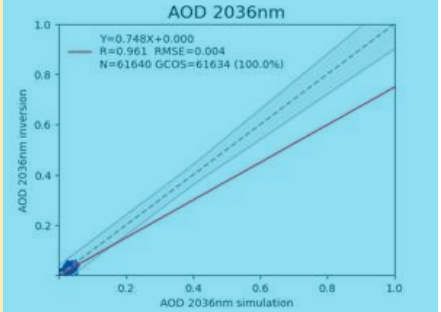
+





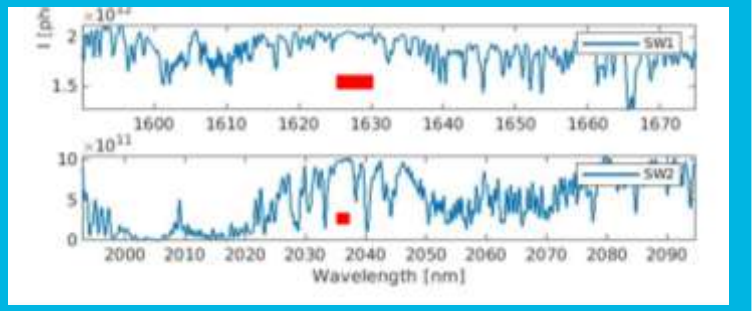






CO2I SWIR1/2 background reflectance

- SWIR 1: *1620-1627.5 nm*
- SWIR 2: *2034.9-2037.5 nm*



CO2M cloud information from CLIM data for GHG/NO2/AOD

clim_data/	
scene_inhomogeneity	[scanline×ground_pixel × clim_ch *)]
cloud_fraction	[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**]
cirrus_obstruction	[scanline×ground_pixel]
cloud_optical_thickness	[scanline×ground_pixel]
cloud_optical_thickness_uncertainty	[scanline×ground_pixel]
cirrus_distance	[scanline×ground_pixel **x cloud_area**]
cloud_distance	[scanline×ground_pixel **x cirrus_area**]

Cloud_shadow_mask *[scanline×ground_pixel]*

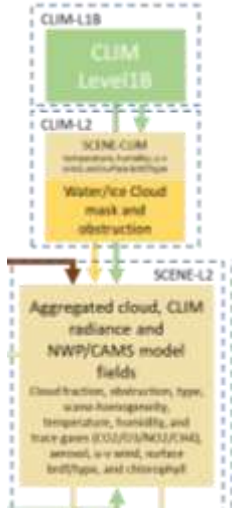
*) clim_ch=CLIM1/2

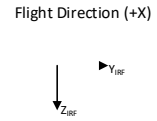
cloud_area / cirrus-area

4 areas covered

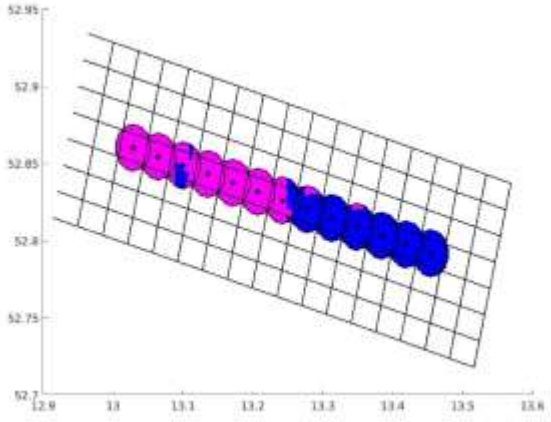
Area around CO2I/NO2I centre pixel lat/lon:

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

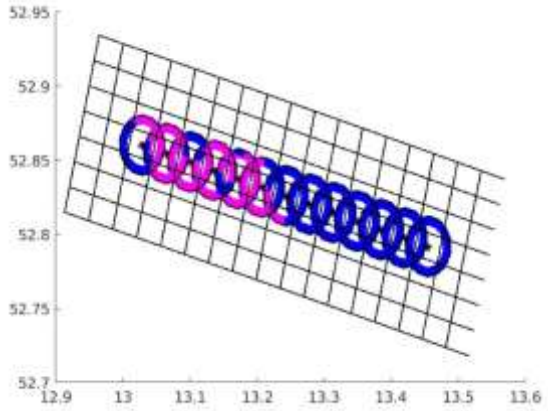




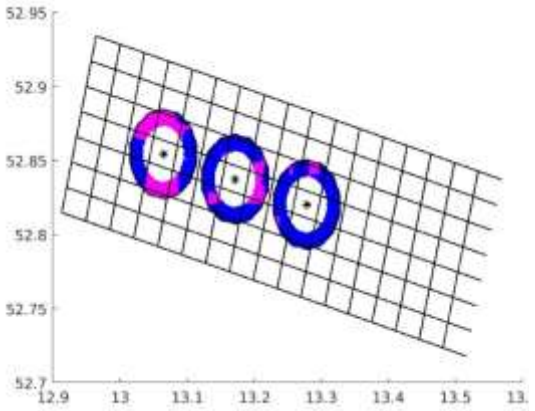
Sub-set of CO2I swath:
Aggregation area / CLIM cloud mask:



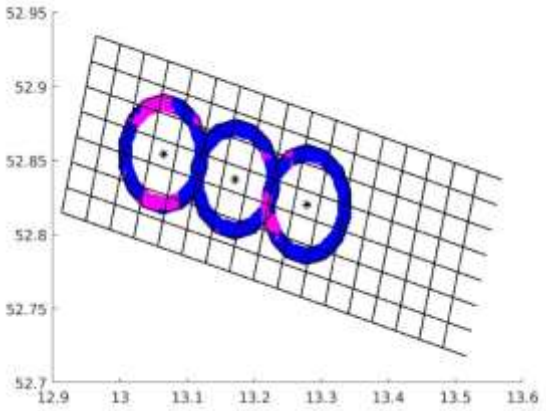
circle 1



circle 2



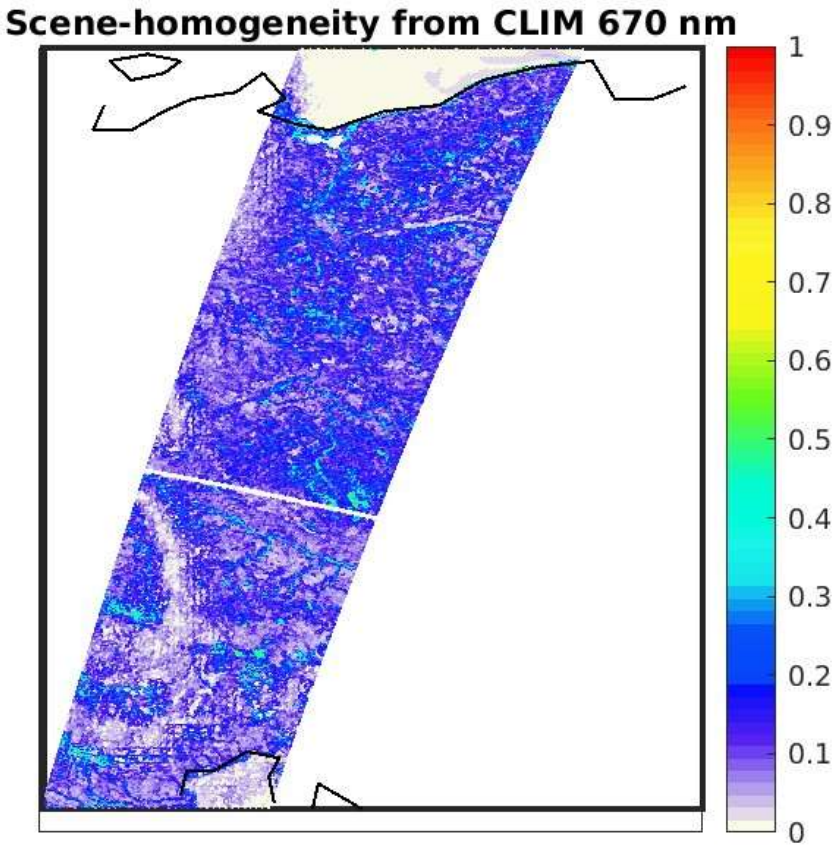
circle 3
(only every 3rd plotted)



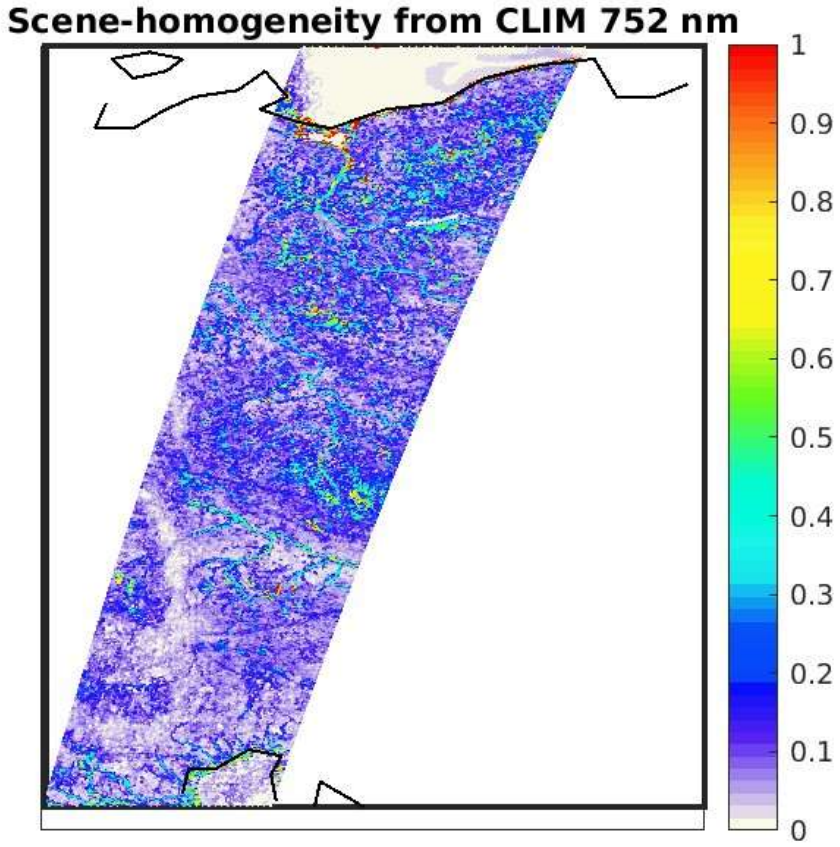
circle 4
(only every 3rd plotted)

CO2M scene-inhomogeneity information from CLIM for MAPI 1C/GHG/AOD/NO2

Scene-inhomogeneity: std($I_{vis/nir}$)/mean($I_{vis/nir}$)

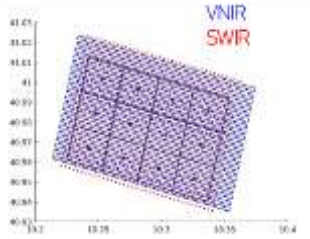


At 670 nm



At 752 nm

~200 CLIM measurements aggregated to CO2I/NO2I footprint:



“Four+-pillar” CO2M validation

GSICS

On-board Cal:

Source	CO2I	MAP	CLIM	Frequency
SUN	X	X		daily
Moon	X	X	X	Irreg.
WLS	X			weekly
Tuneable LED	X (ISRF)			
Dark	X	X	X	orbit

CO2M
0.3 nm (@1.6 µm)

- SNOs
- Ref. Targets
- etc.

Cross-Cal

MicroCarb, OCO-x, GOSAT-x, S5, etc.
~0.05 nm (@1.6 µm)

GSICS

Vicarious Cal
“as needed”

Product VAL

Product Cal/Val

Product Cal/Val

Product Cal/Val

PaNIR
2.5 nm (@1.6 µm)

Cross-Cal

COCCON
0.14 nm (@1.6 µm)

Cross-Cal

TCCON
0.005 nm (@1.6 µm)

Spectrally oversampled reference

Similar spectral resolution

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

+ NDACC- FTIR CH4 + Pandonia/NDACC-NO2 + Aeronet for AOD

“Four+-pillar” CO2M validation

GSICS

On-board Cal:

Source	CO2I	MAP	CLIM	Frequency
SUN	X	X		daily
Moon	X	X	X	Irreg.
WLS	X			weekly
Tuneable LED	X (ISRF)			
Dark	X	X	X	orbit

CO2M

- SNOs
- Ref. Targets
- etc.

Cross-Cal

GSICS

Vica
“as r

See presentation by Cat Hayer

Tuesday: 16:00 JST

4.07: The Copernicus anthropogenic CO2 Monitoring (CO2M) mission – operational product validation and monitoring

ersampled

Similar spectral resolution

PaNIR
2.5 nm (@1.6 µm)

COCCON
0.14 nm (@1.6 µm)

TCCON
0.005 nm (@1.6 µm)

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

+ NDACC- FTIR CH4 + Pandonia/NDACC-NO2 + Aeronet for AOD

CO2M Mission Data Processing Sub-segment developments

Thank you!

Conclusions and discussions

- The CO2M processing system is designed to provided level-1b/c radiance and auxiliary information from three instruments and from all auxiliary data providers as consistent as possible - co-registered and collocated at a common reference grid ("hyper-instrument") and as common input to all CO2M level-2 processors.

- Since different GHG algorithms react differently to the propagation of (complex) information content and deficiencies in instrument performance, robust and reliable results can only be expected from multiple algorithms with significant differences in their exploitation of the overall information content of the overall system (also true for ground-based data retrievals!).

- For CO2M product Cal/Val the accumulation of significant and representative statistics during the course of product commissioning (and to be continued thereafter) is of highest priority in order to discriminate the different bias contributors and to make bias emerge from noise.

- Priority on continuous collection of reference data with high automation, low human resource need and low carbon cost

- Significant use of in-flight accumulated reference data (vicarious statistical and/or from stable well-known targets) for product Cal/Val

- The aim is to re-use existing operational validation and monitoring environments (S4/S5/3MI) in EUMETSAT