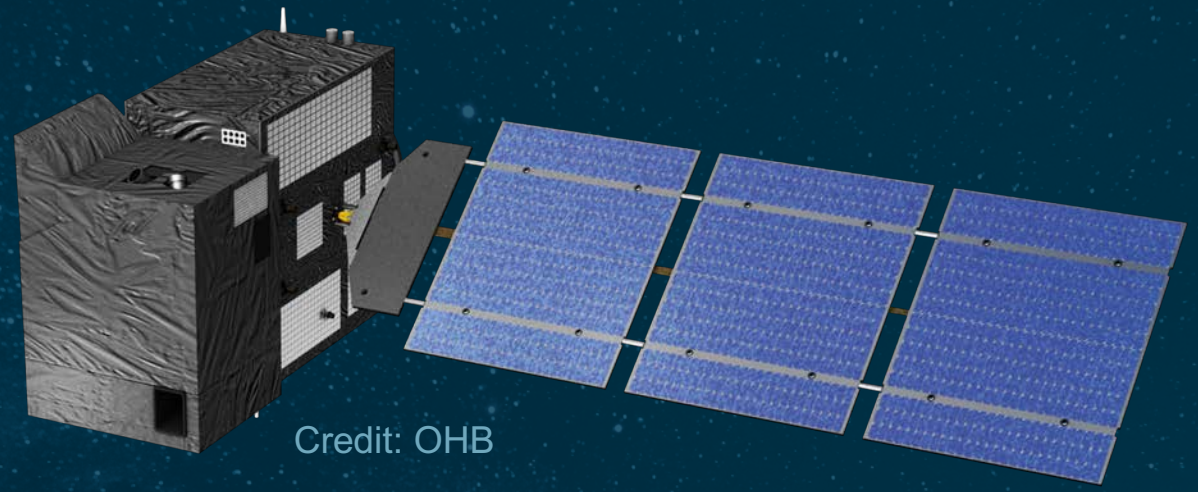
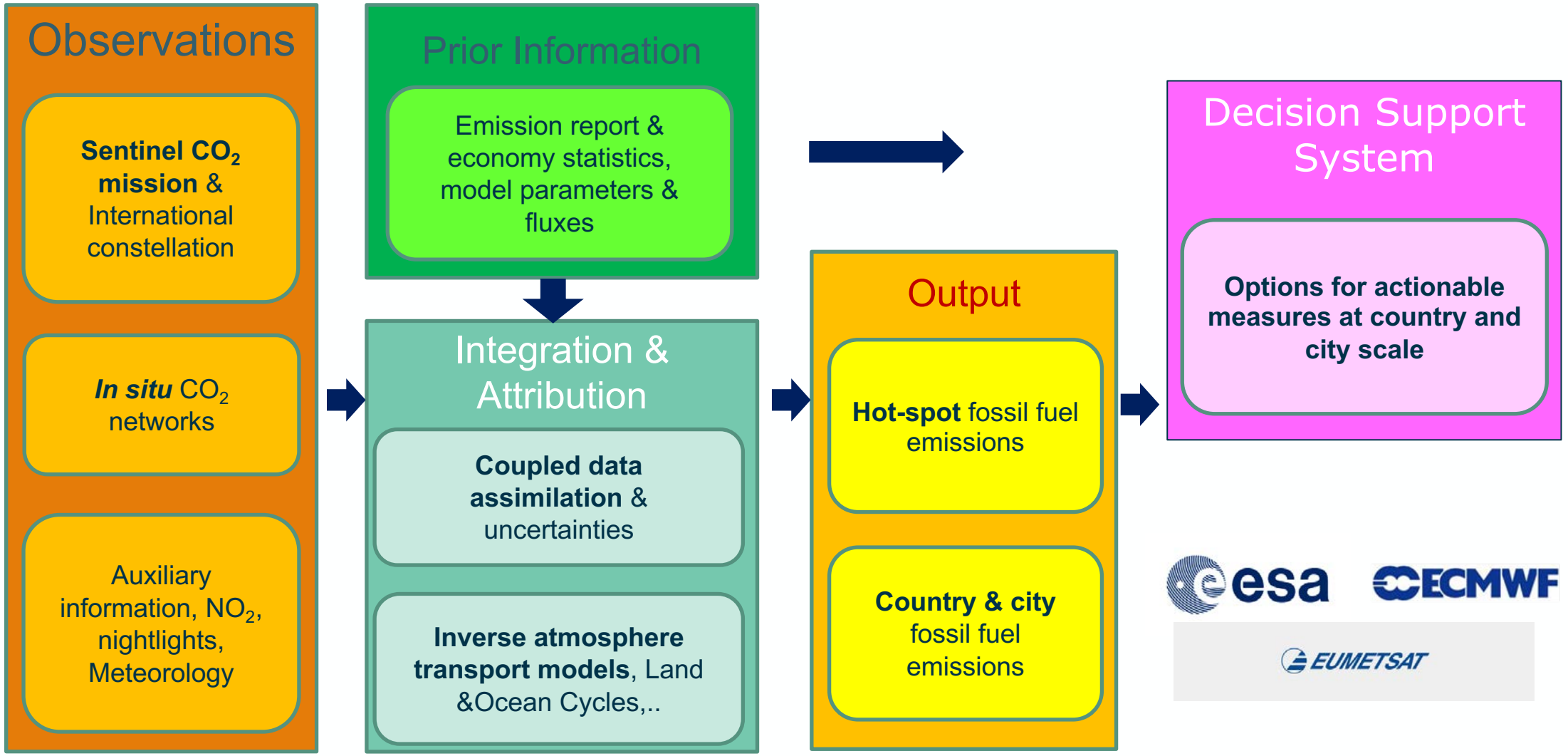


Credit: OHB

Anthropogenic CO2 Monitoring with the Copernicus CO2M Mission

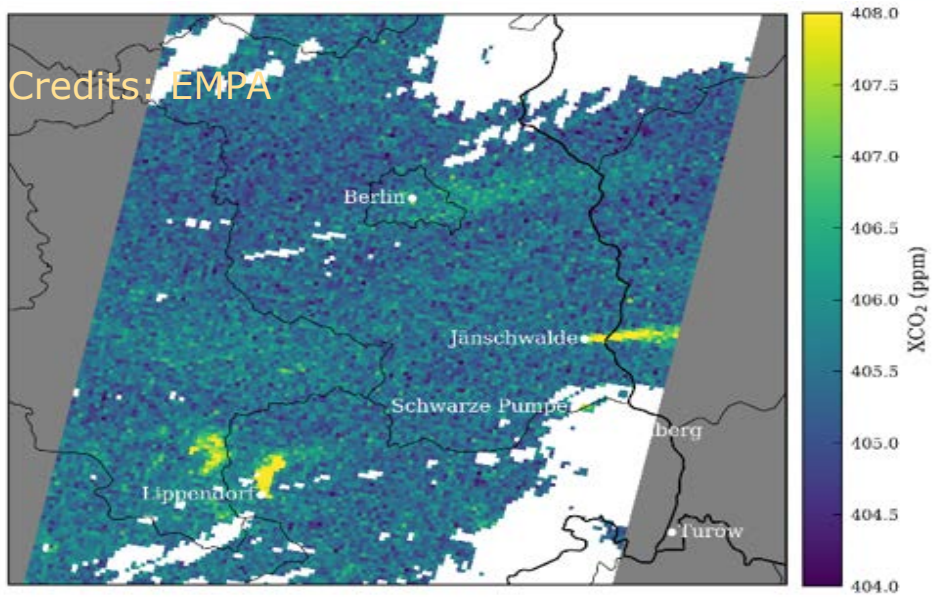
Dr. Yasjka Meijer
CO2M Mission Scientist
24-10-2022
Contact: Yasjka.Meijer@esa.int

An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support Capacity



Measuring CO_2 in the atmosphere

CO_2 is a long-lived trace gas at ~400 parts per million in air
Biogenic fluctuations are large
Aim is to measure it at 0.7 ppm precision

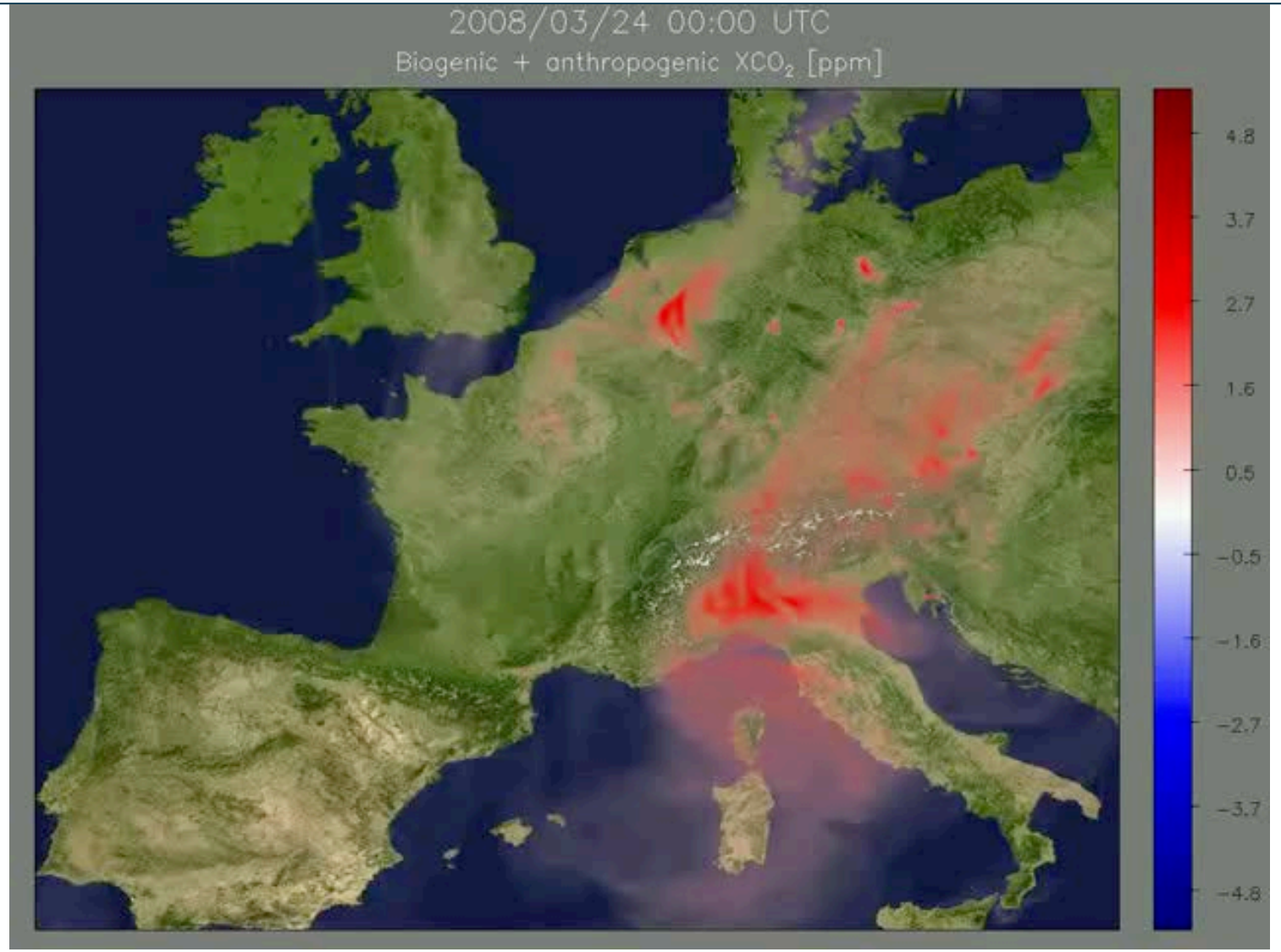


Simulated CO_2 plumes of Berlin and East German power plants.

- City anomaly 1 ppm (0.25%)
- Power plant anomaly 2 ppm (0.5%)

We are looking for ripples (emissions) in an ocean with large waves. Observing the ocean is the easy part! Detecting the ripples is a challenge, but characterizing them allowing emission quantification is THE major challenge

Plumes of CO2 Mix with Large-Scale Patterns

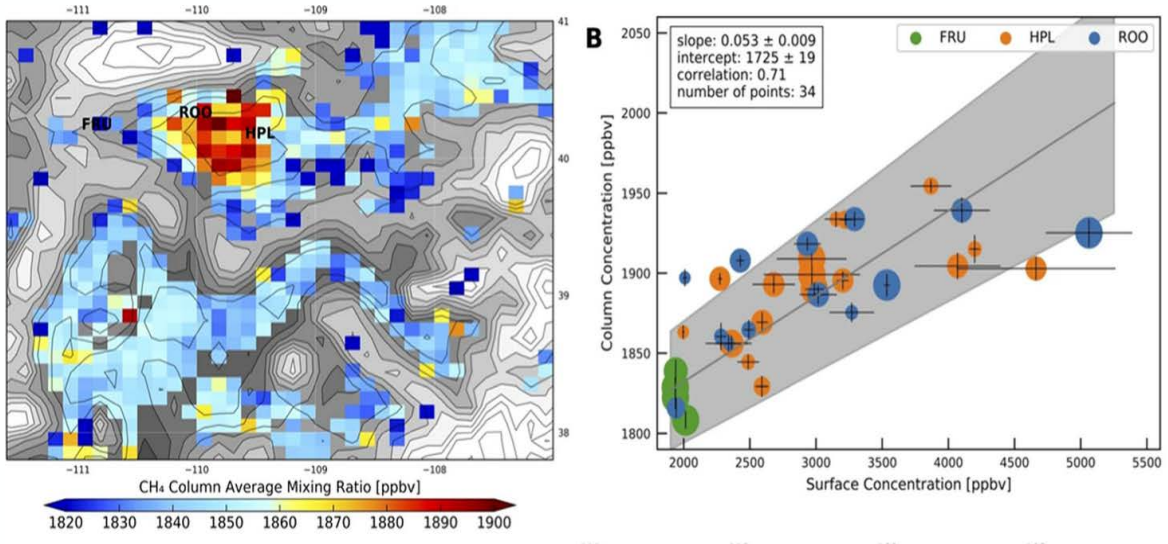


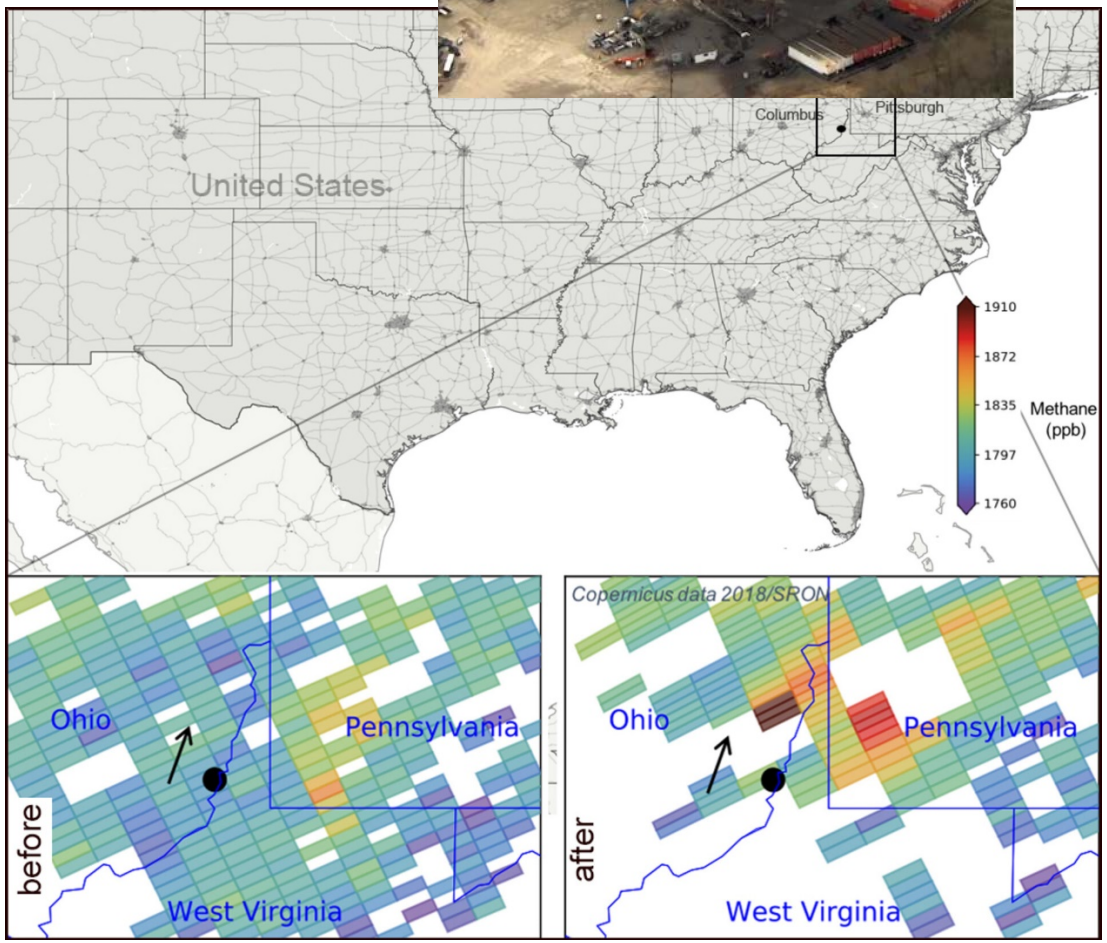
Credits: EMPA

Measuring CH_4 in the atmosphere

CH_4 has ~1800 parts per billion in air. Its atmospheric lifetime — around 12 years — is much shorter than that of carbon dioxide. No significant biogenic fluxes leading to a stable background.

Methane leaks by S-5p, in footprints of 40 km^2
the anomaly is up to ~90 ppb (5%)





CO2M precision of CH_4 is ~10 ppb (0.5%) at 4 km^2
NB smaller footprints will give higher anomalies

Monitoring & Verification Support (MVS) Capacity
End-to-end System requirements to monitor CO_2

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

Monitoring & Verification Support (MVS) Capacity

End-to-end System requirements to monitor CO_2

1. **Detection of emitting hot spots** such as megacities or power plants
   → **high precision CO_2 data, high spatial resolution, no local biases**

2. **Monitoring the hot spot emissions**
   to assess emission reductions/increase of the activities
   → **quantify emissions (plume info), frequent revisit**

3. **Assessing emission changes against local reduction targets**
   to monitor impacts of the NDCs
   → **no regional biases, separate biogenic from anthropogenic fluxes**

4. **Assessing the national emissions and changes**
   in 5-year time steps to estimate the global stock take
   → **no long-term drifts, high accuracy data, inter-calibrated**

MVS Capacity Overarching Objectives

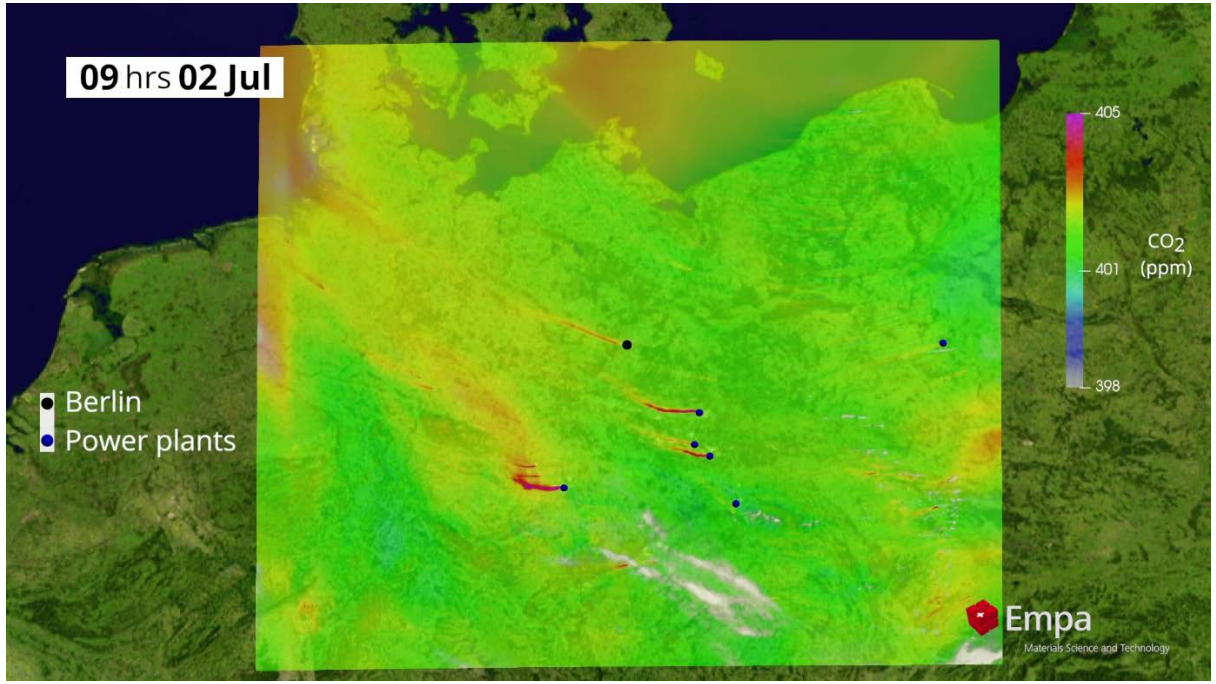
Overarching system level objectives:

1. Provide input to meet all 4 objectives simultaneously
   → focus on anthropogenic component but with contrasting instrument requirements
2. Independent / self-standing system
   → rely as little as possible on external information, self-calibrated
3. Robust /mature
   → rely on mature concepts & allow to have observations under various conditions
4. Operational / systematic
   → no exploratory modes and build a very systematic data flow for all 4 objectives
5. Global coverage
   → no selection of targets and provision of systematic coverage everywhere

CO2M – impact of spatial requirement

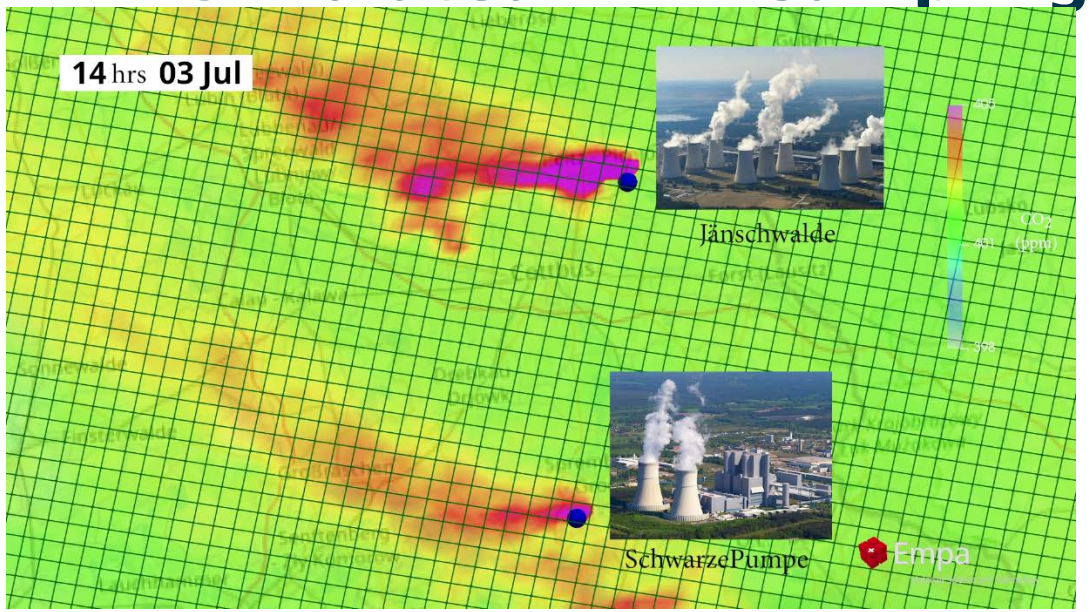
Local scale objectives require high resolution cloud free data and imaging to resolve structures:

- high spatial resolution (~2 × 2 km^2) needed to image source regions
- adequate coverage (~ 250 km swath) to cover power plants & cities incl. surrounding background



NB color scale is from 398–405 ppm,
i.e., 1.75% of the column

Simulated 2 km sampling

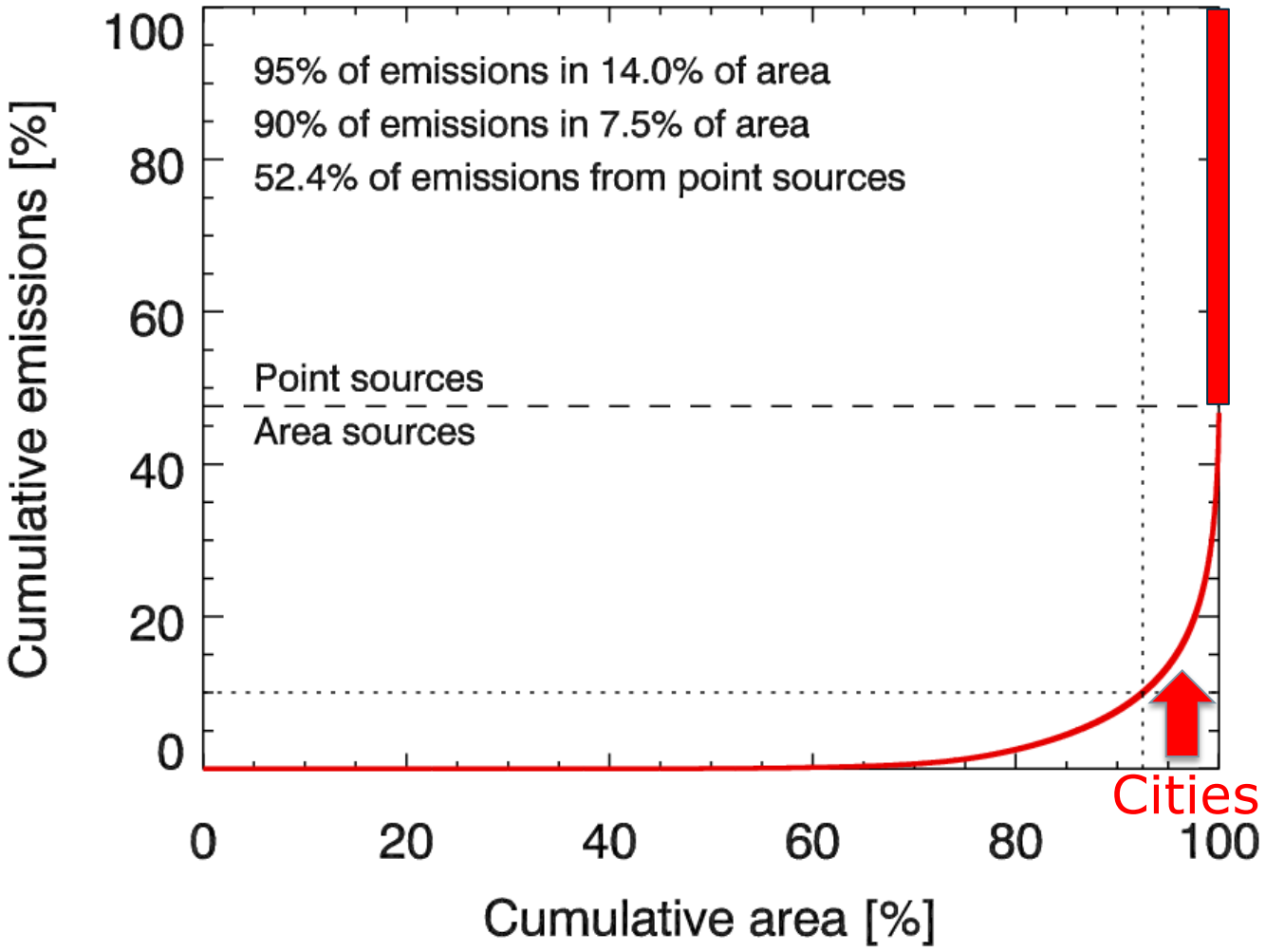


~ 100 km

Credits: EMPA

Why interest in CO_2 emissions from cities?

Cities account for ~70% of global CO_2 emissions ..... and have large reduction potential

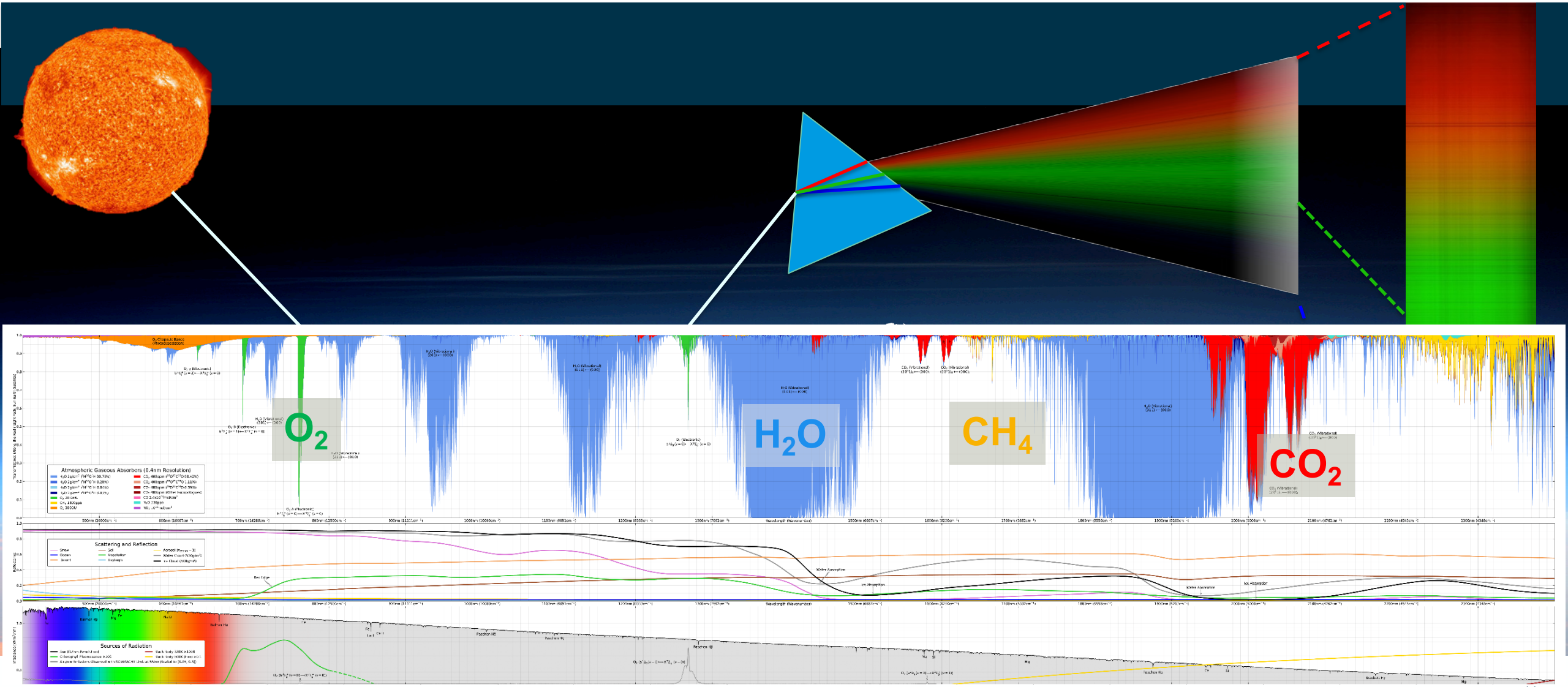


CO_2 emissions are concentrated:

- 90% emitted over less than 8% of area of Europe
- 52% from point sources, primarily power plants

Credits: EMPA, based on TNO-MACC

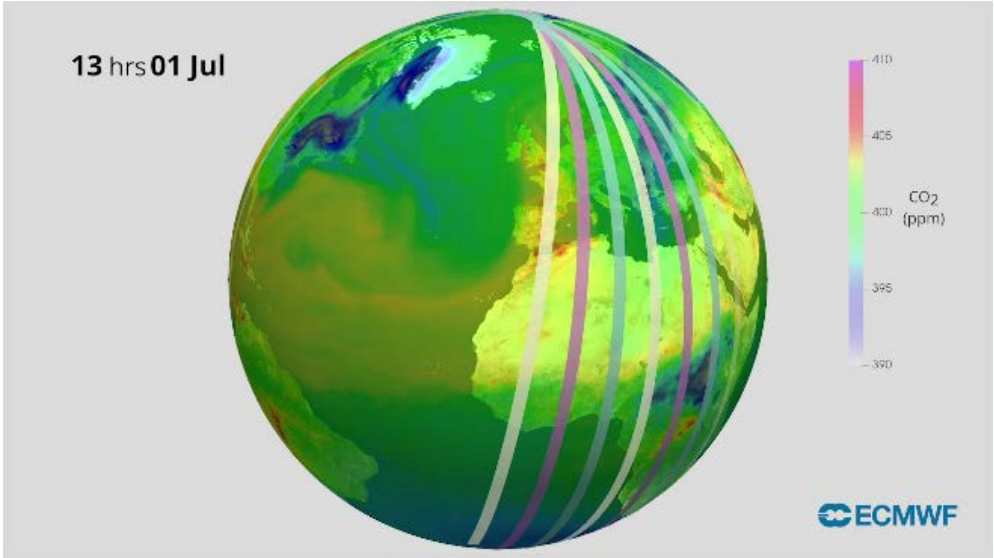
How do satellites measure these gasses?

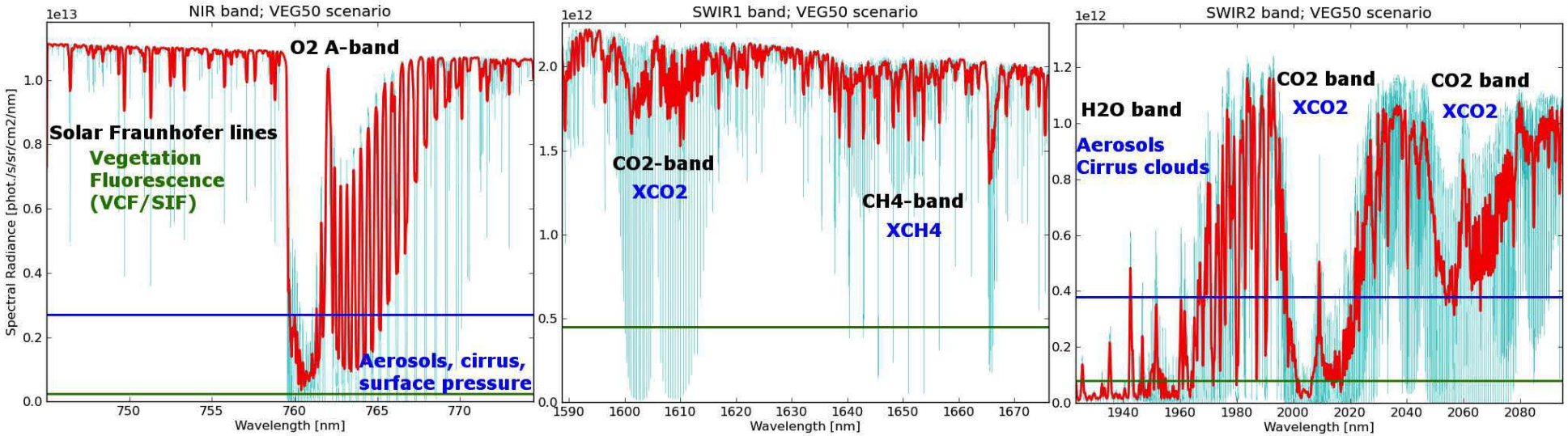


CO_2 Monitoring – Mission Requirements

Mission requirements for XCO_2:

- Precision for XCO2 **0.7 ppm**
- Spatial co-registration: **95% overlap**
- Absolute radiometric accuracy: **3%**
- **Reference scene is vegetated (dark) scene**





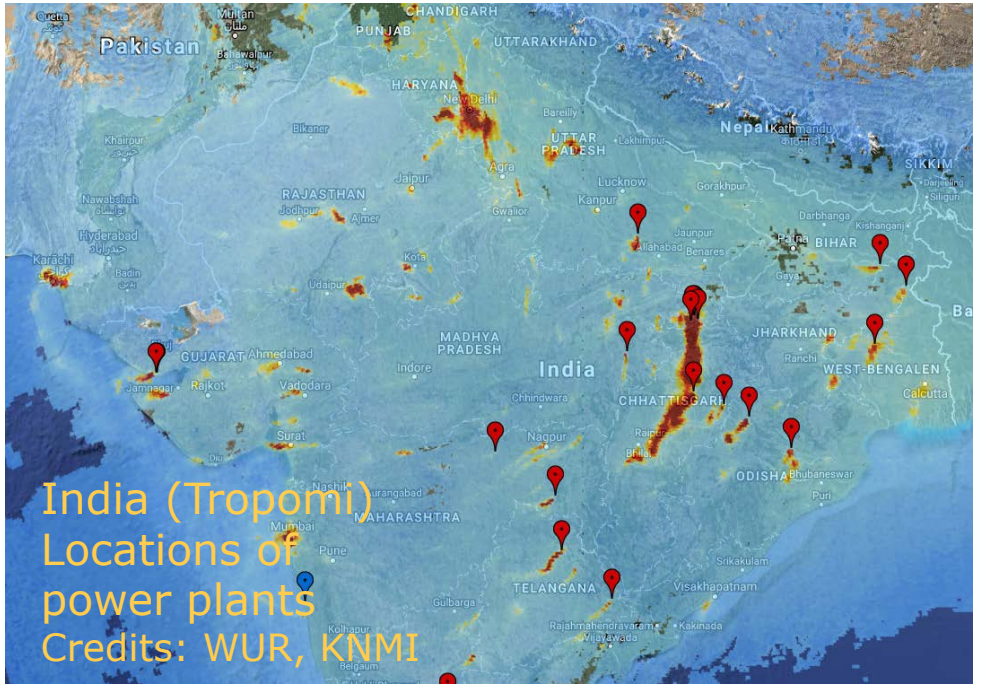
CO_2 Monitoring – Mission Requirements

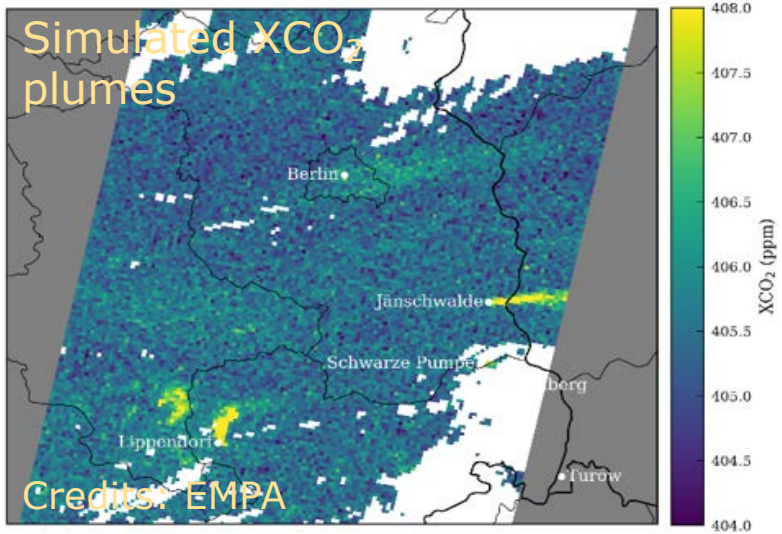
Tracer NO_2 data:

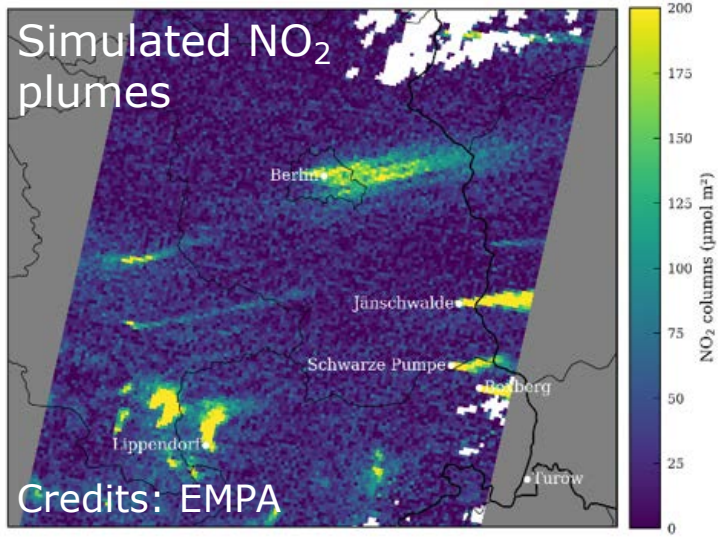
NO_2 plumes for CO_2 plume location, height, and to select best wind field for inversion

→ **more & better CO_2 emission estimates**

- Spatial resolution **4 km² (as for CO_2)**
- NO_2 precision: **$1.5 \cdot 10^{15}$ molec/cm²**
- VIS band: **405 – 490 nm**





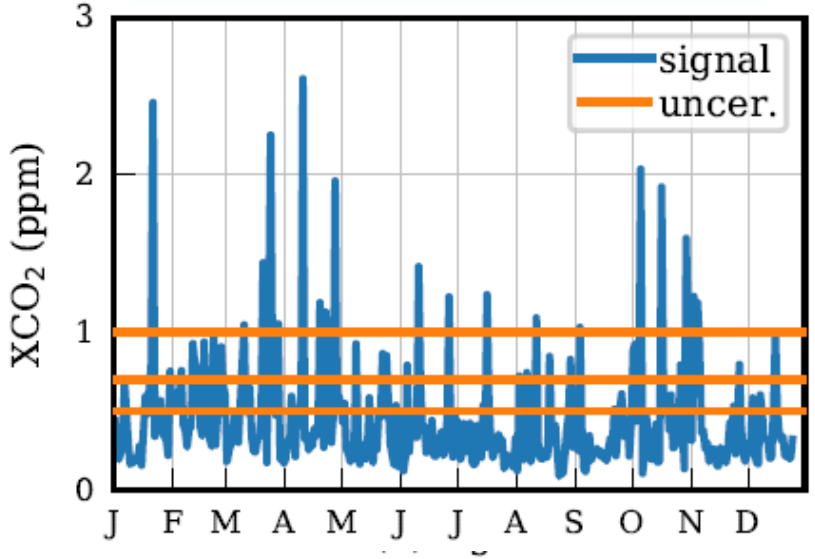


Plume detection: noise & background variability

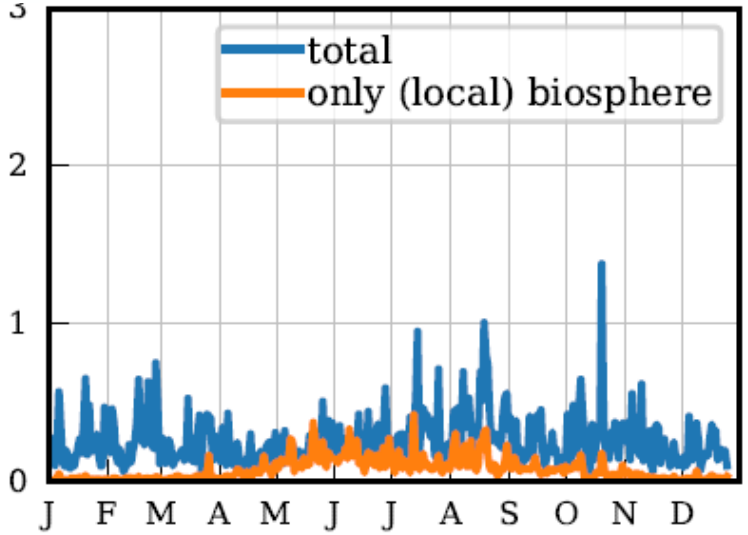
Berlin plume peak signal

Spatial variability of background

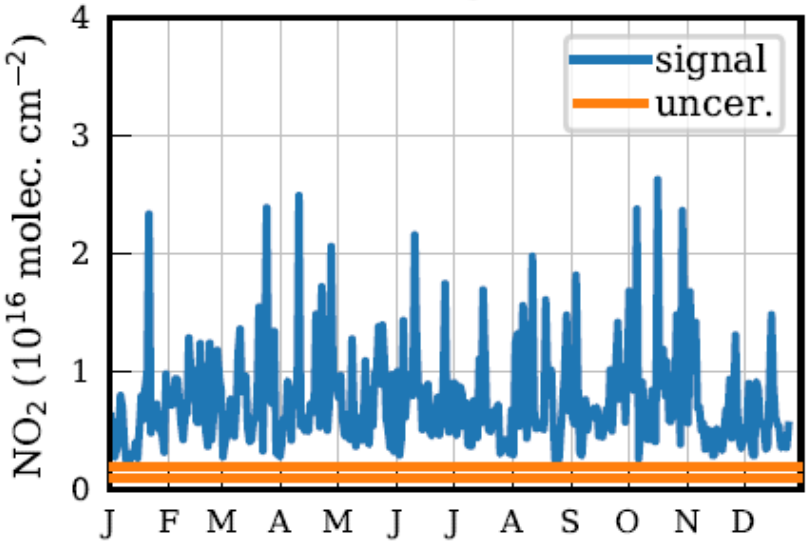
CO_2



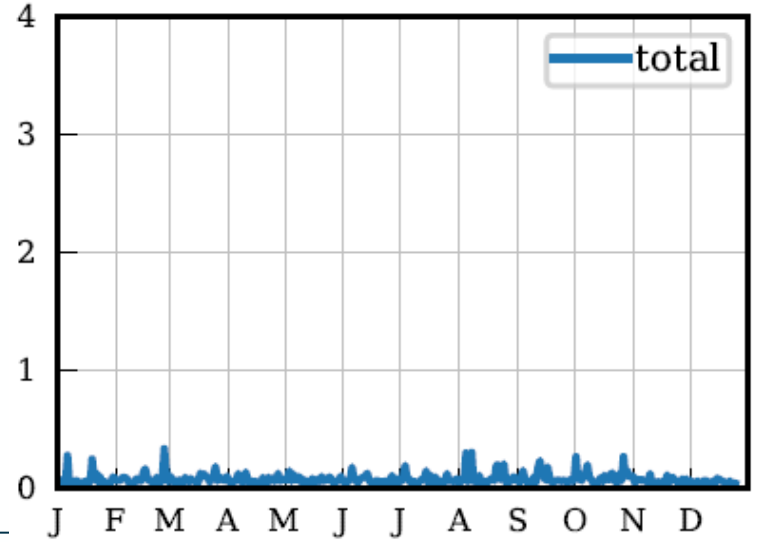
High noise
Medium noise
Low noise



NO_2



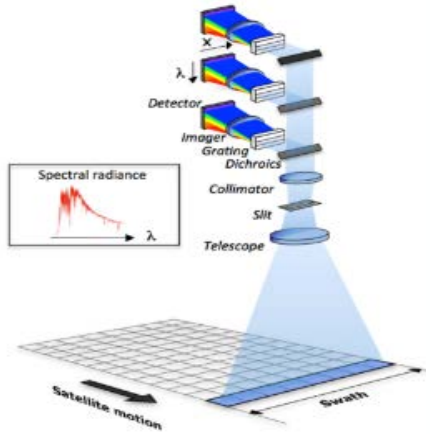
Credits: EMPA

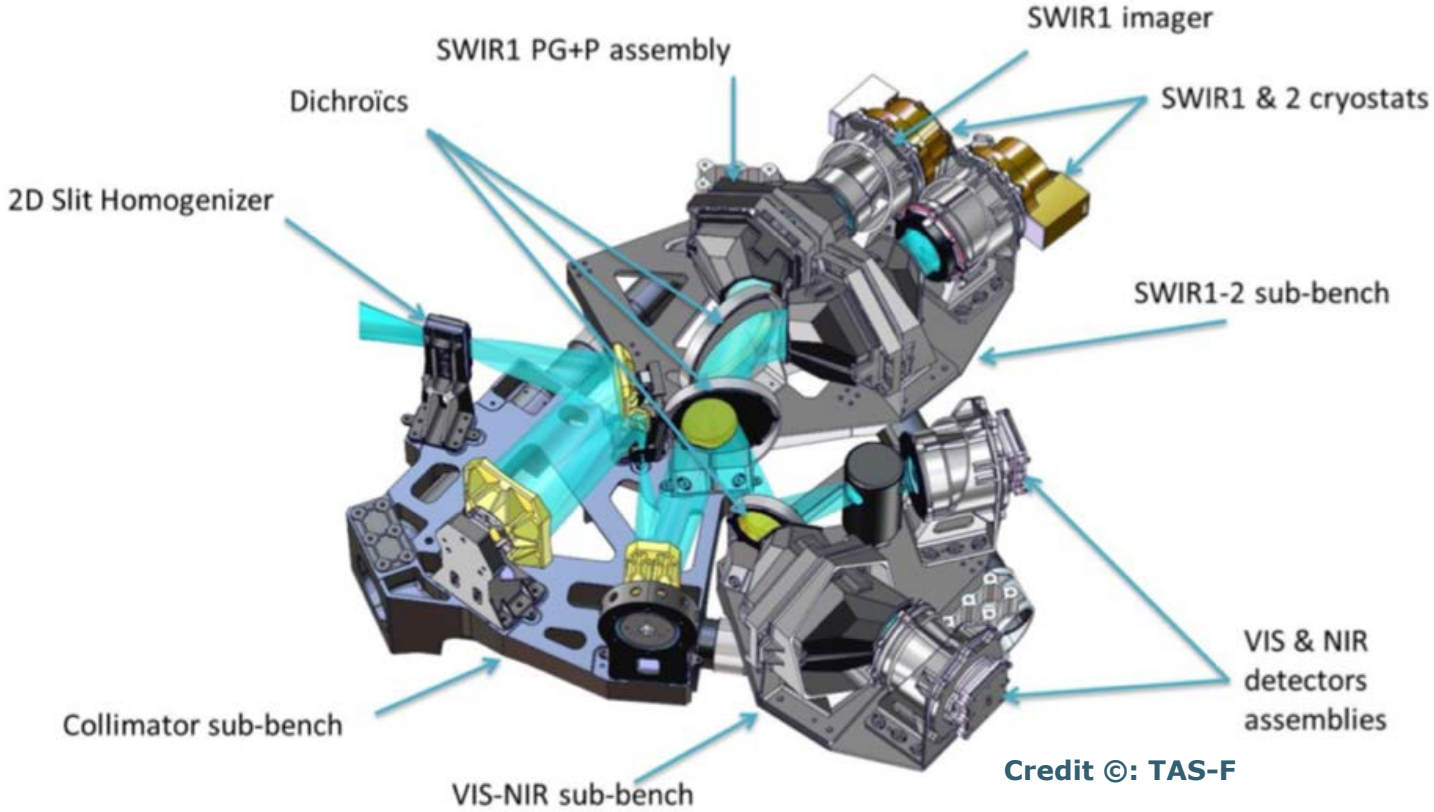


CO_2 (CH_4) and NO_2 Imaging Spectrometers

Push-broom imaging spectrometer with four bands and >250 km swath width

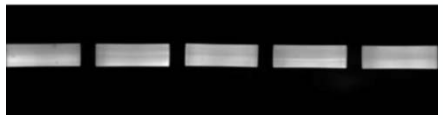
Band	Spectral range
VIS	405–490 nm
NIR	747–773 nm
SWIR-1	1590–1675 nm
SWIR-2	1990–2095 nm



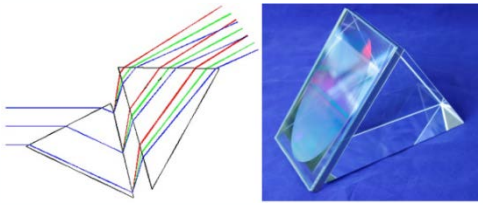


Credit ©: TAS-F

Telescope	Common telescope with polarisation scrambler and 2D slit homogeniser
Collimator	One reflective collimator, common for all bands
Band separation	Dichroic split of 1st VIS-NIR & SWIR, then VIS & NIR and SWIR-1 & SWIR-2
Dispersers	Prism-Grating-Prism
Detectors	NGP in SWIR & Te2v CIS-120 in VIS & NIR



Credit © Optec



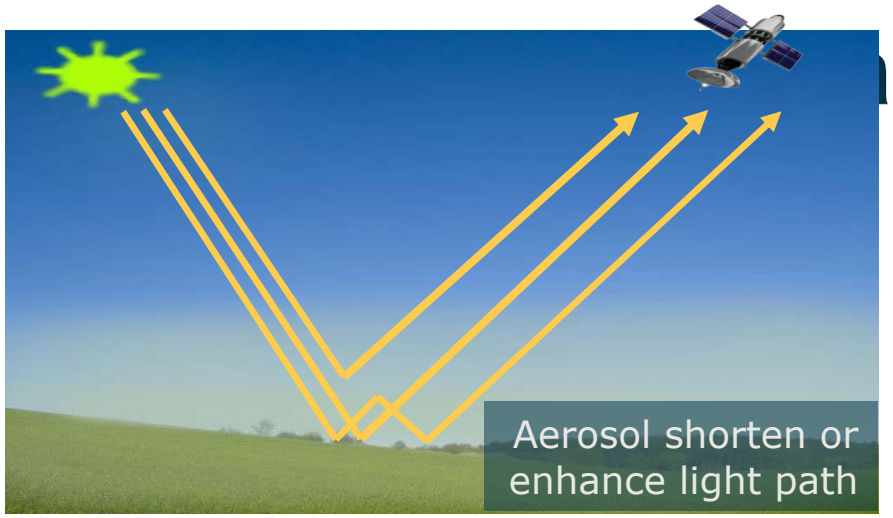
Credit © IOF

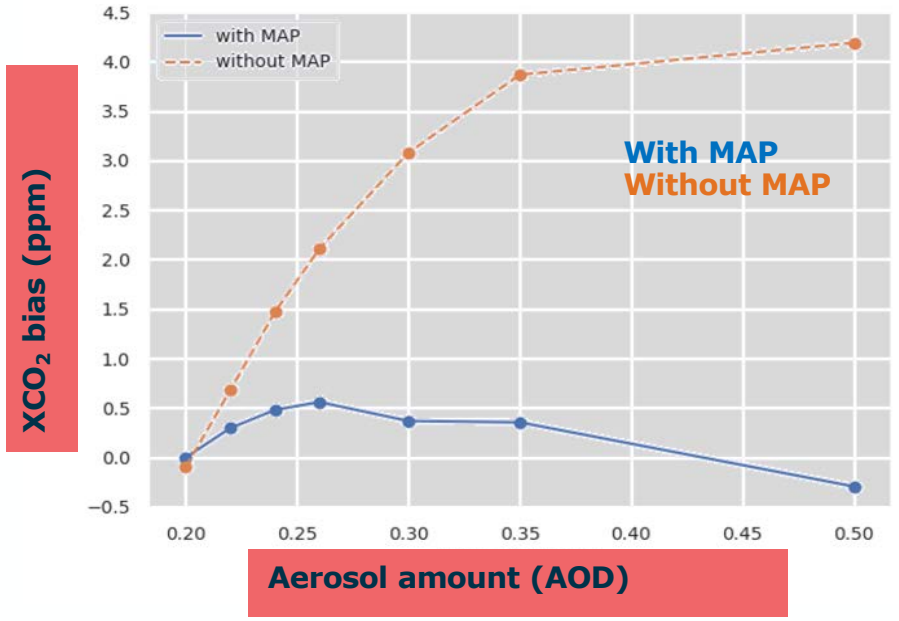
CO_2 Monitoring – Mission Requirements

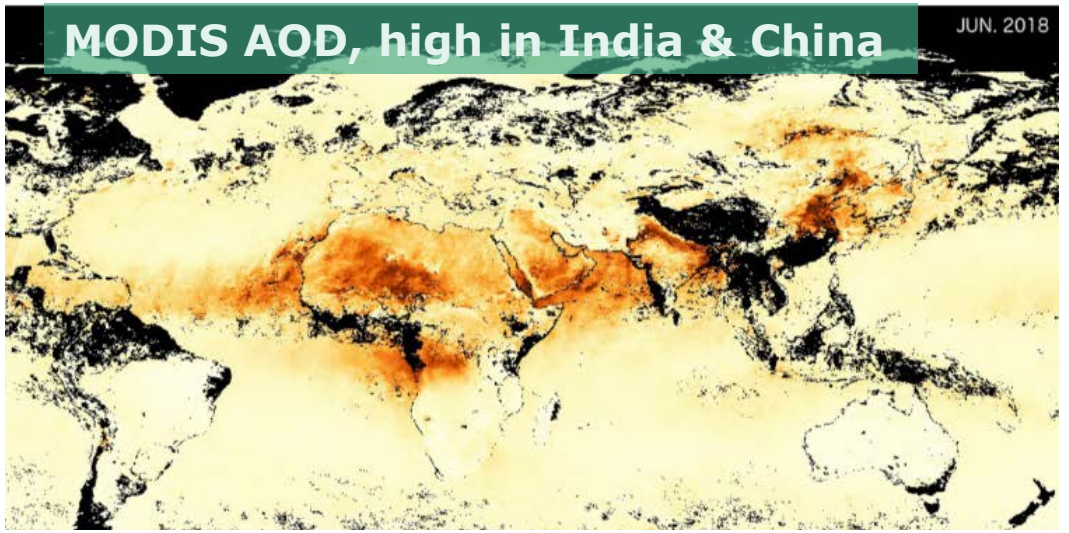
Aerosol data:
Light path correction by measuring effective aerosol parameters with a multi-angle polarimeter (**MAP**)

→ **Higher accuracy CO_2 data (less dependence on bias correction)**
→ **More data and also at higher aerosol loading;** up to 0.5 AOD

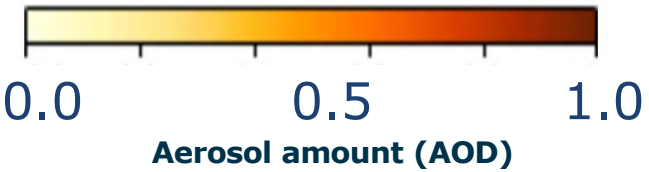
- Heritage missions without MAP require bias correction and strict quality filtering for AOD<0.3
- Anthropogenic areas in India and China on average AOD>0.3







Credits: SRON, Utrecht



CO2M – Multiple Angle Polarimeter

Light path correction for **accurate CO_2 observations** measuring effective aerosol parameters with **Multi-angle polarimeter (MAP):**

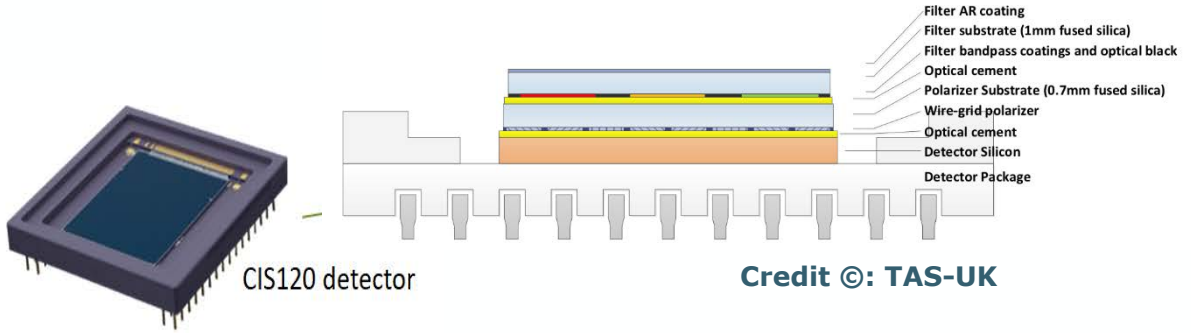
- 6 spectral bands with polarisation at 0º, 60º, 120º
- 1 NIR band for spatial co-registration
- DoLP error <0.0035
- 4 cameras with 12 views per camera

→ along track coverage, >40 viewing angles (+/- 60º)

Spatial resolution 4x4 km² and sampling ~1x1 km²

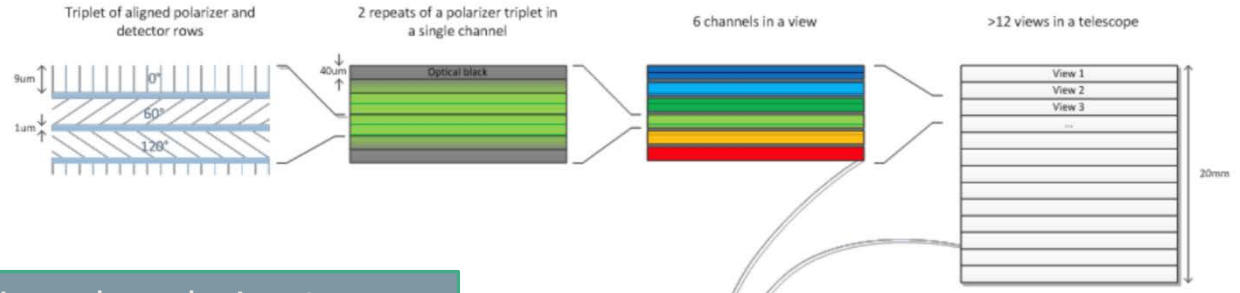
MAP Channel	Central wavelength	Spectral width
VNIR-1	410 nm	20 nm
VNIR-2	443 nm	20 nm
VNIR-3	490 nm	20 nm
VNIR-4	555 nm	20 nm
VNIR-5	670 nm	20 nm
VNIR-6*	753 nm	9 nm
VNIR-7	865 nm	40 nm

* Only for co-registration purpose and no polarization



Credit© T-E2V

Credit ©: TAS-UK



Multi-angle polarimeter
>40 views, 1+6 (pol) bands

Credit ©: TAS-UK

CO2M – Cloud Imager (CLIM)

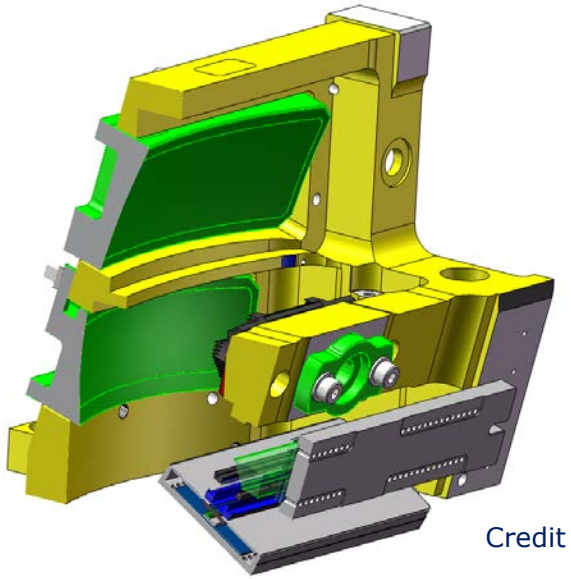
Objective:

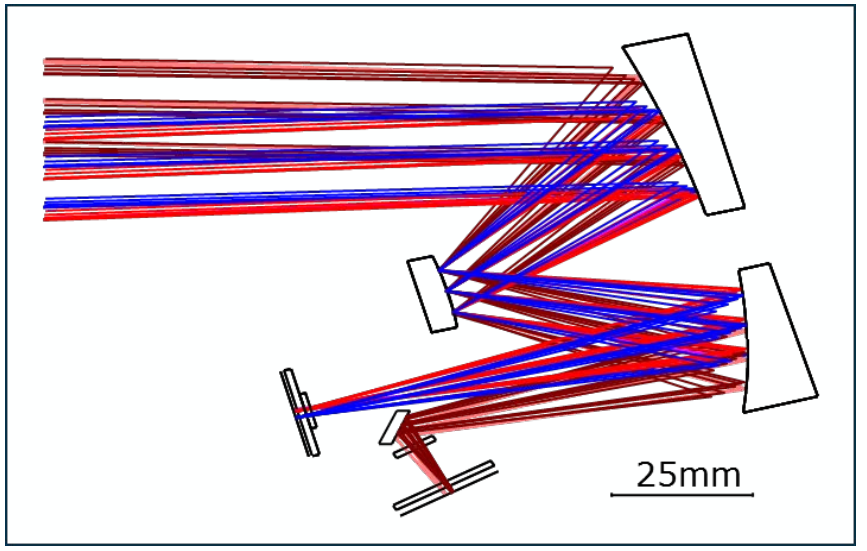
- Detect cloud cover of <1–5%
- Detect (thin) cirrus clouds

Specs:

Sampling @400m

CLIM swath >>CO2I swath





Credit © IOP Sensors

Band	Band center
CLIM-1	670 nm
CLIM-2	753 nm
CLIM-3	1378 nm

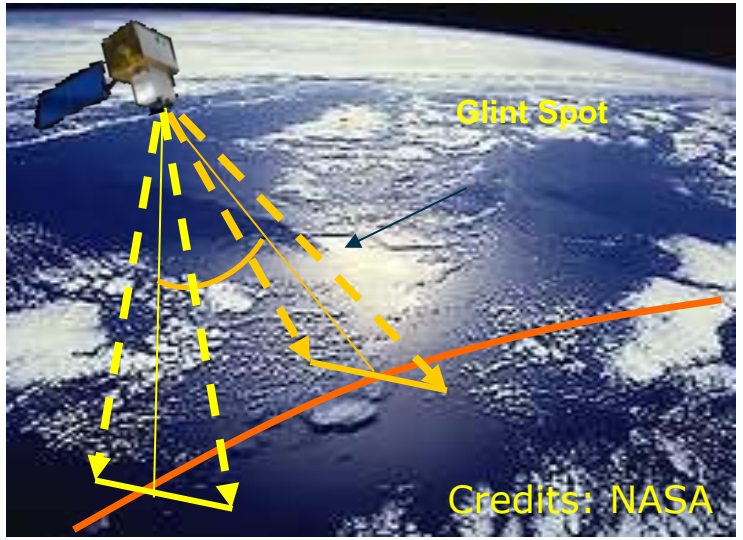
→ For low altitude water clouds

→ For co-registration and calibration among instruments

→ for high altitude cirrus cloud detection

Requirement for glint mode observations (ocean / snow)

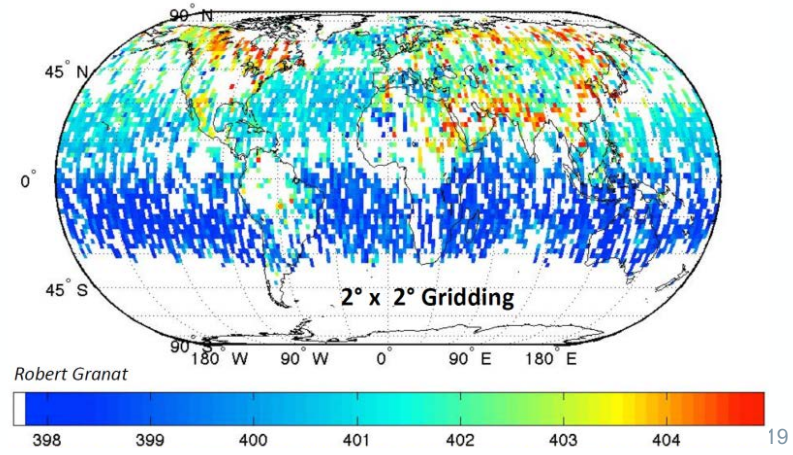
- Ocean surface has low reflectivity in nadir observations
- Measurements over ocean in a special mode viewing **sunglint/glitter** reflections
- Pointing along track towards glint spot
- Sunglint observations have been proven to be valuable for GOSAT and OCO-2



Ocean coverage important for:

- determining background levels
- measure outflow of emissions in coastal areas
  NB power plants often use seawater for cooling

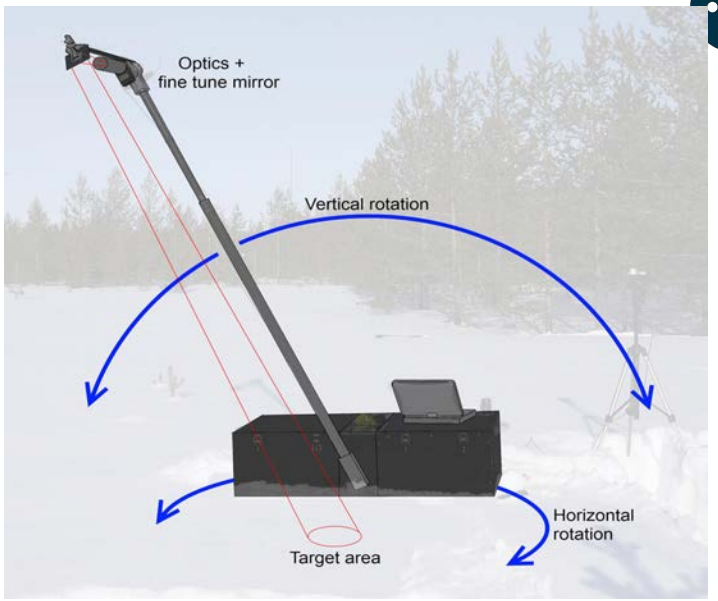
NASA OCO-2: Sunglint + Nadir Observations



ESA SNOWITE study on glint (led by FMI)

Preliminary conclusions:

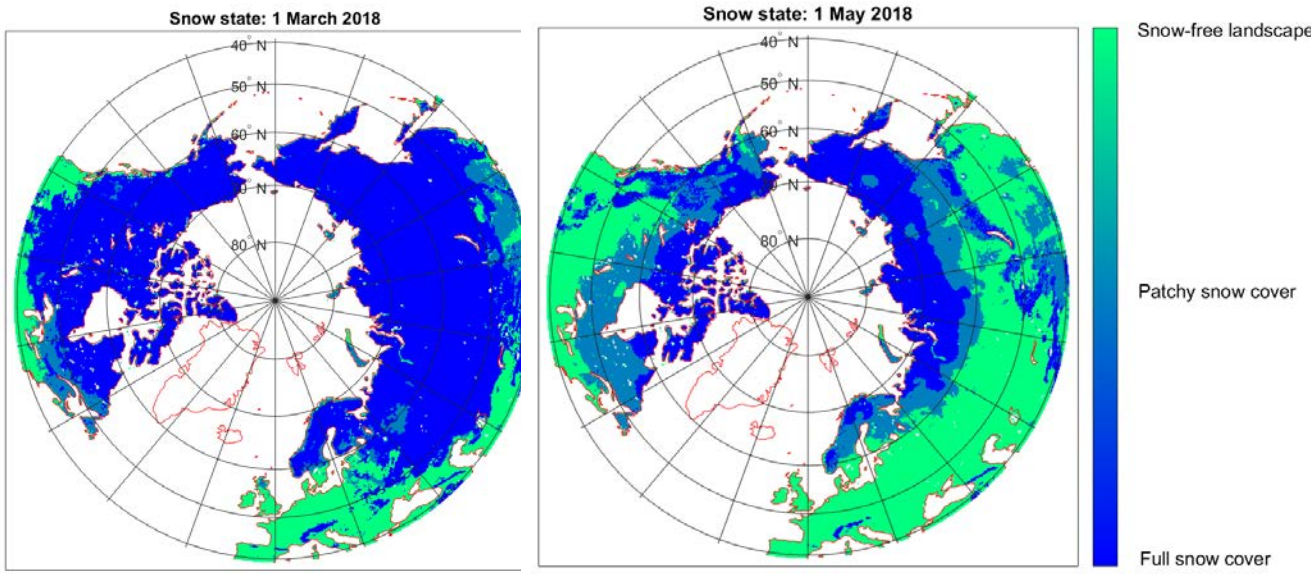
- Over snow-covered surfaces, SNR in glint mode is higher than in nadir in all three bands, which supports preferring glint-mode observations over snow-covered surfaces.
- We will derive a BRDF model for CO_2 retrieval



Credits: FMI

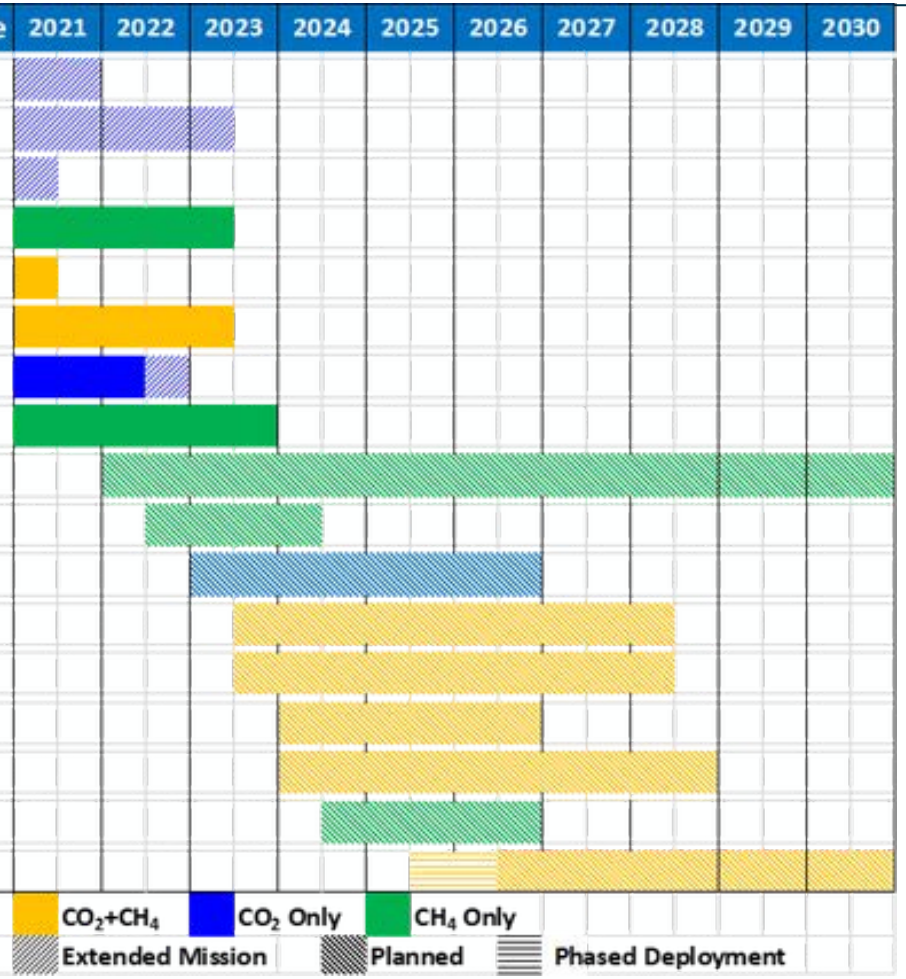
OCO-2 data (B10) has been co-located with snow and ice information

Over ocean	Over land	Over ocean ice cover	Over land snow cover
6 995 639	14 951 207	2 192 702	7 001 679
22,5%	48%	7%	22,5%



Current and Upcoming GHG Missions – Generic

Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan	●	●	●	
OCO-2	NASA/USA	●		●	
GHGSat-D - Claire	GHGSat/Canada		●		●
Sentinel 5P TROPOMI	ESA/Europe		●	●	
GaoFen-5 GMI	CHEOS/China	●	●	●	
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan	●	●	●	
OCO-3	NASA/USA	●			
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada		●		●
MetOp Sentinel-5 series	EC Copernicus/Europe		●	●	
MethaneSAT	EDF/USA		●		●
MicroCarb	CNES/France	●		●	
Feng Yun 3G (CMA)	CMA-NMSC/China	●	●	●	
Carbon Mapper[1]	Carbon Mapper LLC/USA	●	●	●	●
GeoCarb	NASA/USA	●	●	●	
GOSAT-GW	JAXA-NIES-MOE/Japan	●	●	●	
MERLIN	DLR/Germany-CNES/France		●	●	
CO2M	EC Copernicus/Europe	●	●	●	

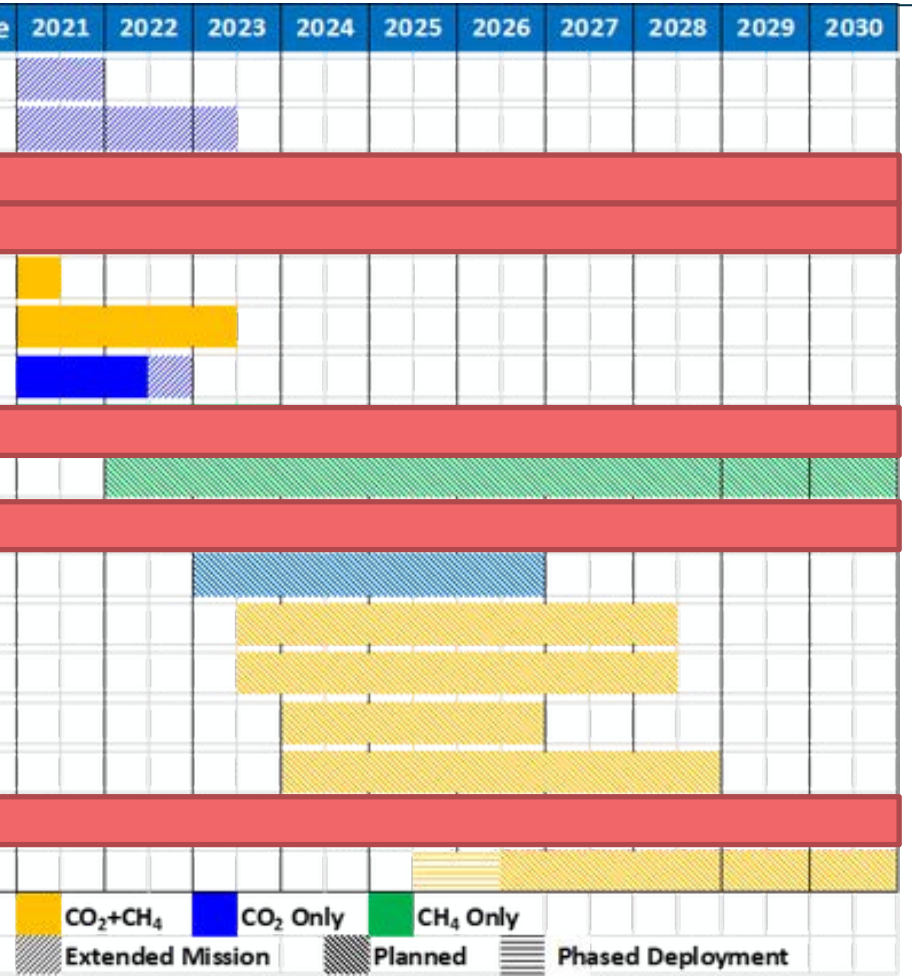


Source: CEOS GHG White paper, 2018

NB terms CO_2 & CH_4 are used very generically, i.e. all in one basket

CO_2 Missions – Detection of Local Scale Emissions

Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan	●	●	●	
OCO-2	NASA/USA	●		●	
GHGSat-D - Claire	GHGSat/Canada				
Sentinel 5P TROPOMI	ESA/Europe				
GaoFen-5 GMI	CHEOS/China	●	●	●	
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan	●	●	●	
OCO-3	NASA/USA	●			
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada				
MetOp Sentinel-5 series	EC Copernicus/Europe		●	●	
MethaneSAT	EDF/USA				
MicroCarb	CNES/France	●		●	
Feng Yun 3G (CMA)	CMA-NMSC/China	●	●	●	
Carbon Mapper[1]	Carbon Mapper LLC/USA	●	●	●	●
GeoCarb	NASA/USA	●	●	●	
GOSAT-GW	JAXA-NIES-MOE/Japan	●	●	●	
MERLIN	DLR/Germany-CNES/France				
CO2M	EC Copernicus/Europe	●	●	●	



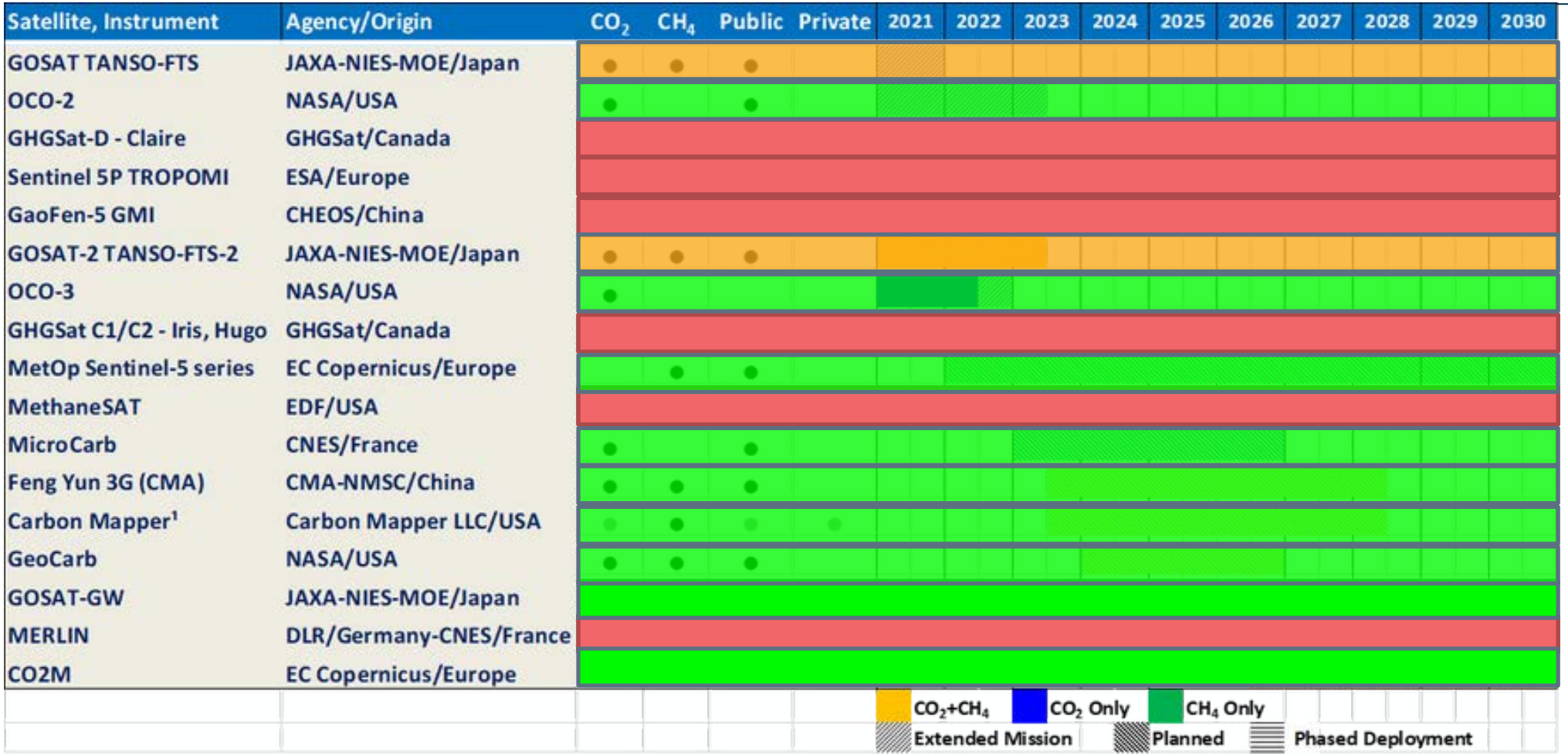
At least some background compared to an enhancement should be detectable by these missions.

Not addressing frequency of observations or coverage.

Not capable

Capability unknown

CO_2 Missions – Quantification of Power Plant Emissions



At least some observations lead to quantification of (strong) source for these missions.

Not addressing frequency of observations or coverage.

Not capable Capable Capability unknown

CO_2 Missions – Quantification of City Emissions

Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan														
OCO-2	NASA/USA														
GHGSat-D - Claire	GHGSat/Canada														
Sentinel 5P TROPOMI	ESA/Europe														
GaoFen-5 GMI	CHEOS/China														
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan														
OCO-3	NASA/USA														
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada														
MetOp Sentinel-5 series	EC Copernicus/Europe														
MethaneSAT	EDF/USA														
MicroCarb	CNES/France														
Feng Yun 3G (CMA)	CMA-NMSC/China														
Carbon Mapper[1]	Carbon Mapper LLC/USA														
GeoCarb	NASA/USA														
GOSAT-GW	JAXA-NIES-MOE/Japan														
MERLIN	DLR/Germany-CNES/France														
CO2M	EC Copernicus/Europe														

CO_2+CH_4 CO_2 Only CH_4 Only

Extended Mission Planned Phased Deployment

At least some observations lead to quantification of megacities for these missions.

Not addressing frequency of observations or coverage.

Not capable Capable Capability unknown

CO_2 Missions – Monitoring of Anthropogenic Emissions

Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan														
OCO-2	NASA/USA														
GHGSat-D - Claire	GHGSat/Canada														
Sentinel 5P TROPOMI	ESA/Europe														
GaoFen-5 GMI	CHEOS/China														
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan														
OCO-3	NASA/USA														
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada														
MetOp Sentinel-5 series	EC Copernicus/Europe														
MethaneSAT	EDF/USA														
MicroCarb	CNES/France														
Feng Yun 3G (CMA)	CMA-NMSC/China														
Carbon Mapper[1]	Carbon Mapper LLC/USA														
GeoCarb	NASA/USA														
GOSAT-GW	JAXA-NIES-MOE/Japan														
MERLIN	DLR/Germany-CNES/France														
CO2M	EC Copernicus/Europe														

CO_2+CH_4 | CO_2 Only | CH_4 Only

Extended Mission | Planned | Phased Deployment

Frequent revisit and global coverage of major sources

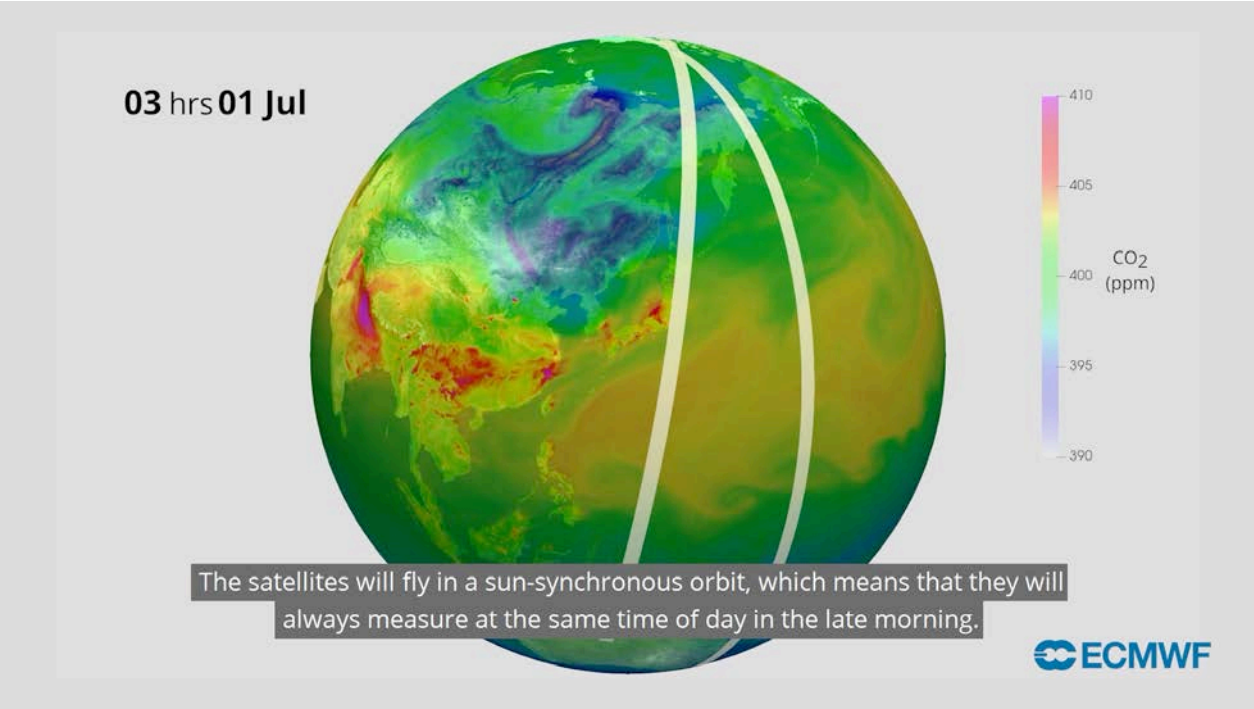
→ GEO orbit

Not capable | Capable | Capability unknown

Copernicus CO2M Mission – Status

Project status:

- Implementation phase started in **July 2020**
- Implementation with CDR forecasted **in 2023**
- **Constellation** of satellites
- Each satellite **>250 km swath**
- First and second satellite to be delivered in **January 2026**
- First launch forecasted by **early 2026**



Credit: EMPA

Main Products	Spatial	Precision
CO_2	4 km^2	0.7 ppm
CH_4	4 km^2	10 ppb
NO_2	4 km^2	1.5 10^{15} molecules cm^{-2}
Veg. SIF*	4 km^2	0.7 mW m^{-2} sr^{-1} nm^{-1}

*Vegetation Solar Induced Fluorescence → indicator of biogenic activity

Mission Requirements Document, see https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf

Copernicus
Europe's eyes on Earth

European Commission

EUMETSAT

ECMWF

esa
European Space Agency

What can YOU do?

Use the bike

Eat less meat
(e.g. once a week not)

Green energy

Healthier and better for the climate