The CO2 Monitoring Mission - An approach for the CO2 Anthrogenic sources monitoring

Valerie Fernandez
European Space Agency – CO2M Project Manager

Connect University, 01/07/2021

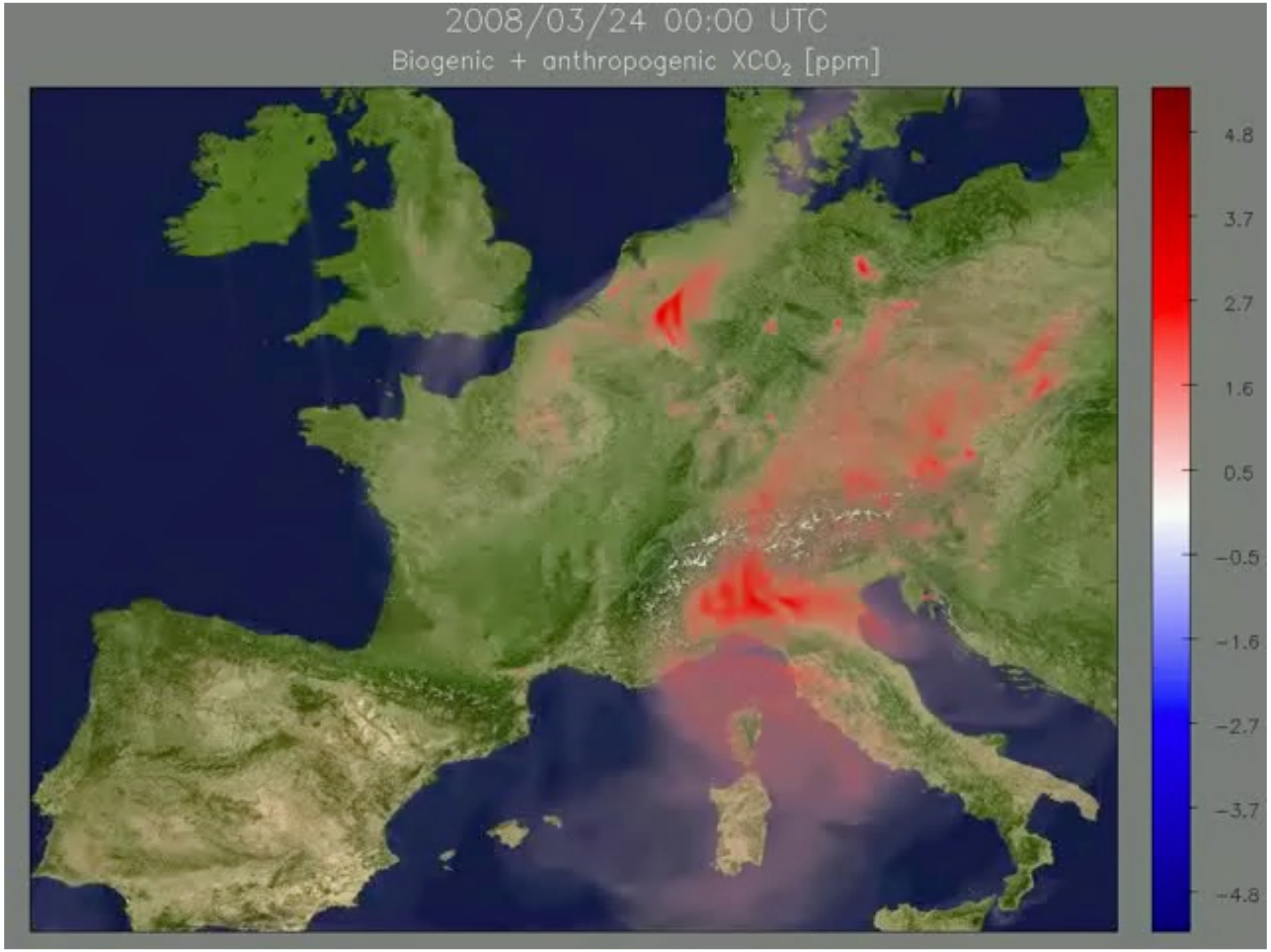
Outlines

- CO_2 location and anthropogenic sources
- From observables to requirements
- Detection from Space – Anthropogenic CO_2 Monitoring mission

CO2M

Copernicus Anthropogenic Carbon Dioxide Monitoring

Plumes of CO2 Mix with regional Patterns



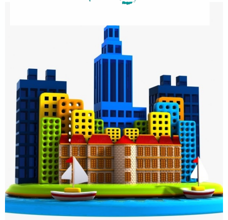
Biogenic sources, during daytime, CO2 is taken up by plants through photosynthesis (blue).
At night the biosphere respires CO2 back to the atmosphere (red).

Anthropogenic sources (red) are concentrated on daypart

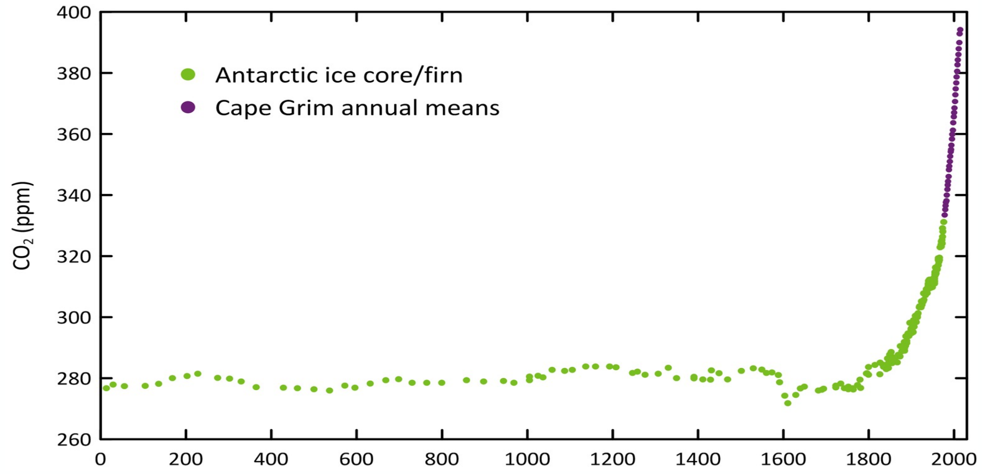
Carbon Cycle at Various Scales

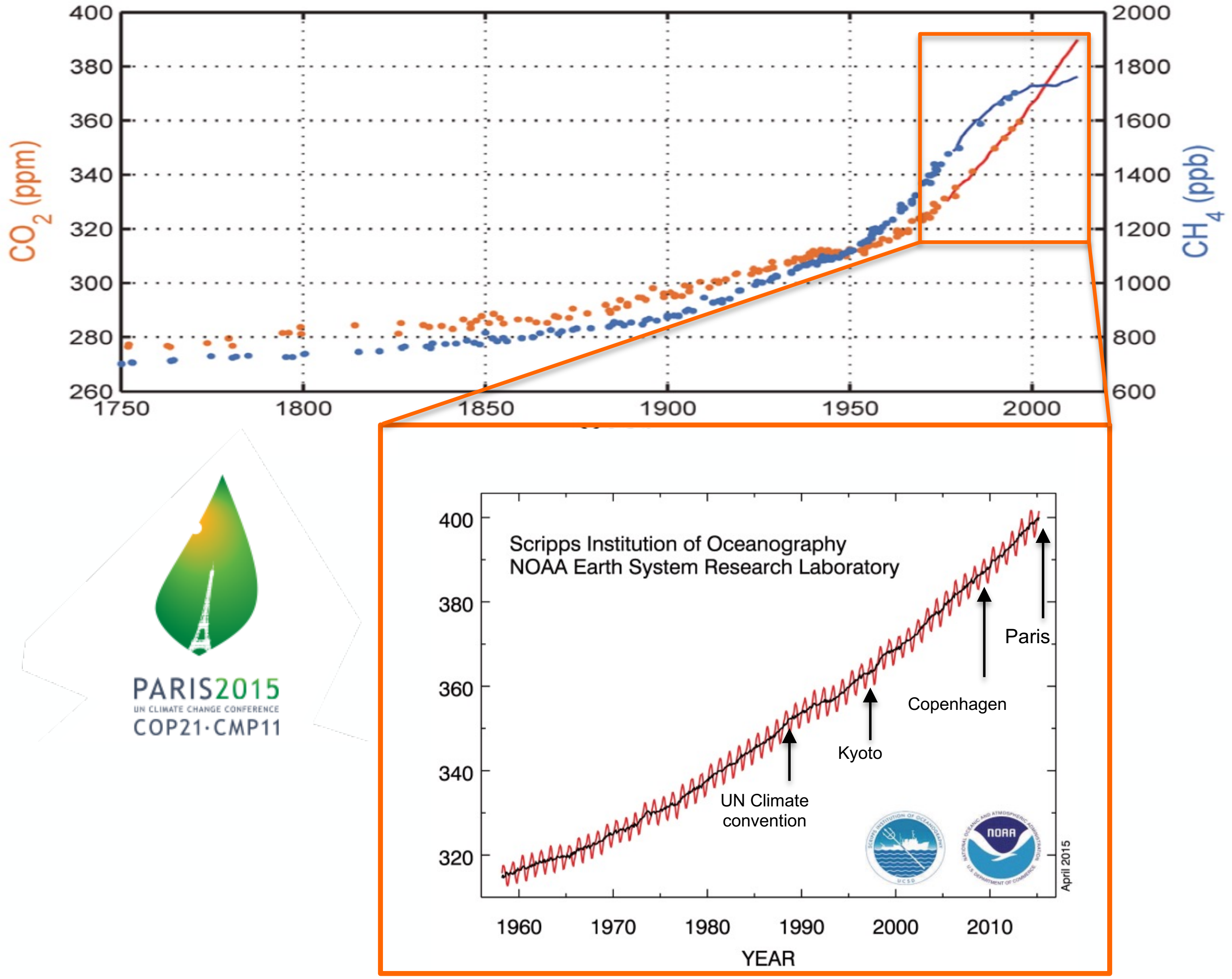
Regional ⟷ Country ⟷ Local

- Atmospheric CO_2 and CH_4 fluxes at weekly intervals to monitor trends at regional scale
- Separation of biogenic and anthropogenic fluxes at the scale of medium-sized countries
- Image plumes from point sources and large cities with sufficient accuracy to estimate their emissions



CO2 and CH4 concentrations increased since 1750





PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

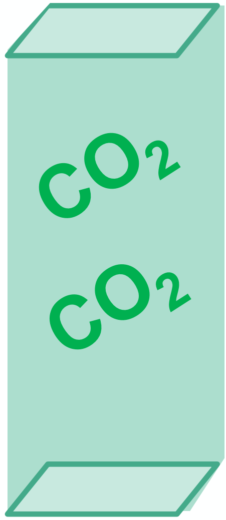
- Increasing CO_2 & CH_4 levels, two powerful greenhouse gases, account for most of the radiative forcing of climate change
- In the Paris Agreement, the signatories agreed to limit global warming to well below 2.0, preferably to 1.5 degrees Celsius, compared to pre-industrial levels (IPCC)

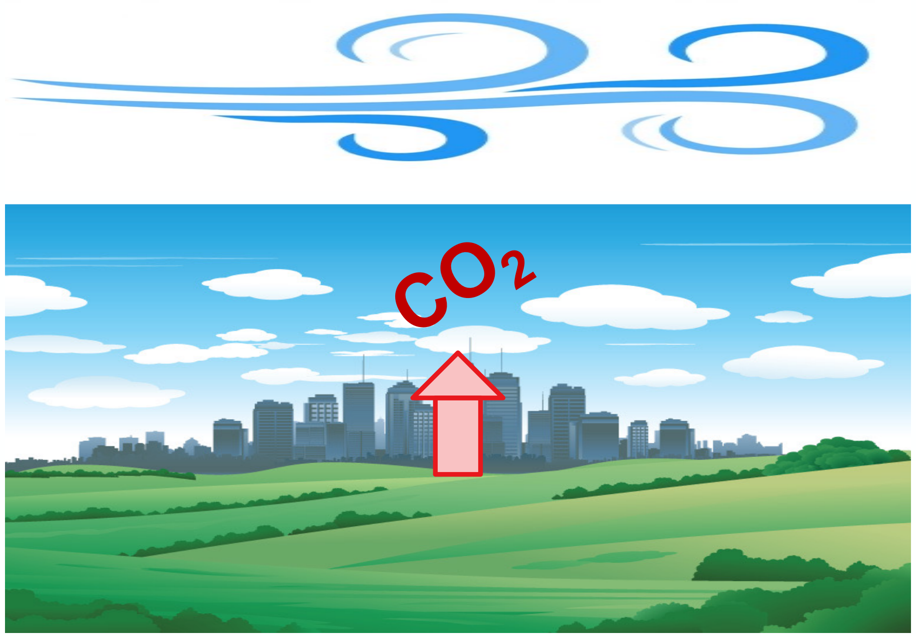
Background CO_2 Mixing with Emissions

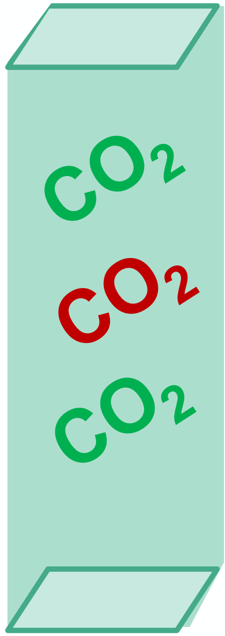
Background

Emissions

Background +
Δ emissions





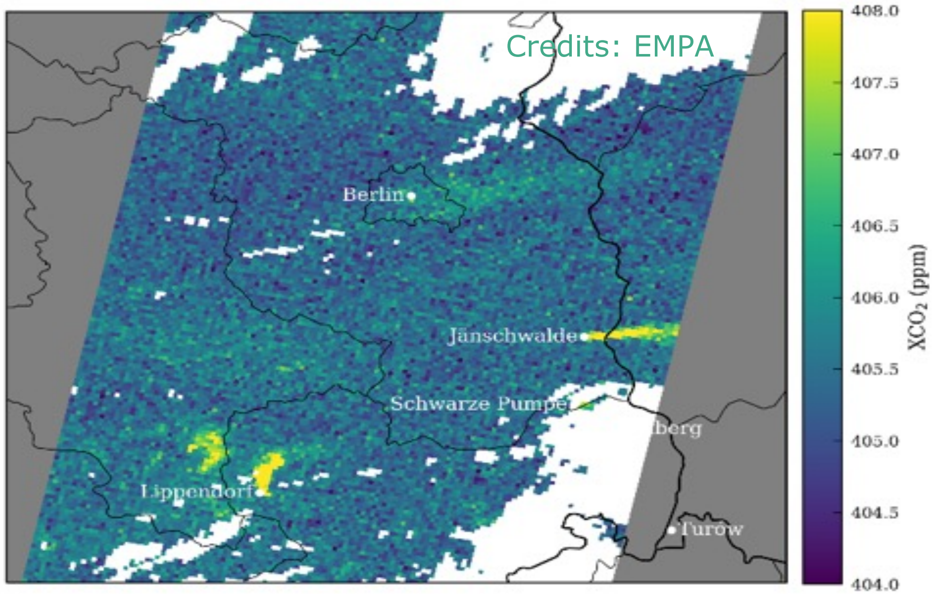


Parameters playing a role

- Source strength
- Area of source (point or city or ….)
- Wind speed/direction
- Turbulence

Measuring CO_2 in the atmosphere

CO_2 is a long-lived trace gas at ~400 parts per million in air
Influence from Biogenic fluctuations
Aim is to measure it at ~0.5 ppm (0.125% !!!)



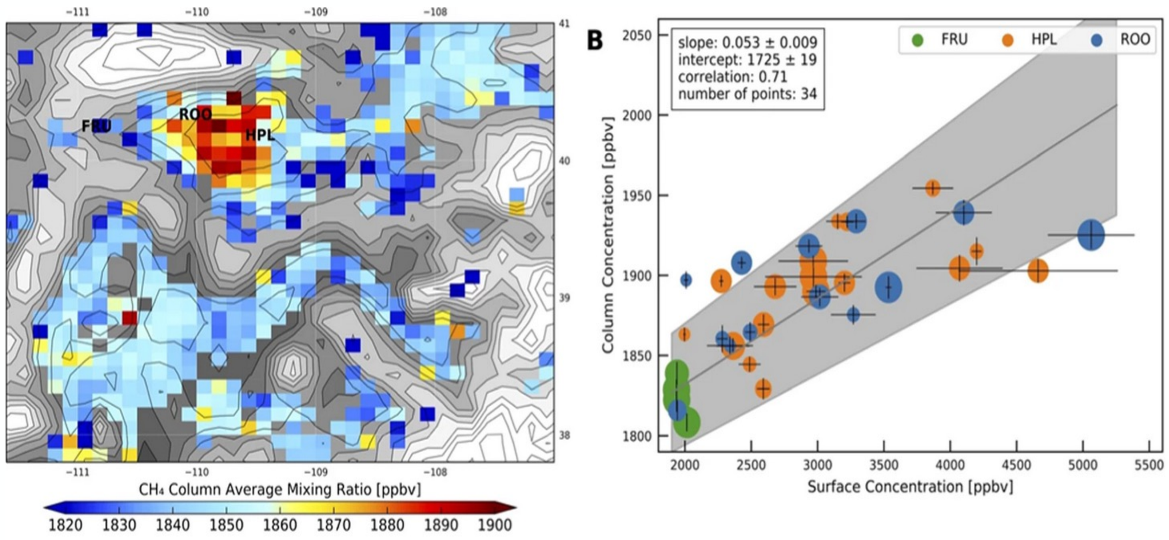
Simulated CO_2 plumes of Berlin and East German power plants
- City anomaly 1 ppm (0.25%)
- Power plant anomaly 2 ppm (0.5%)

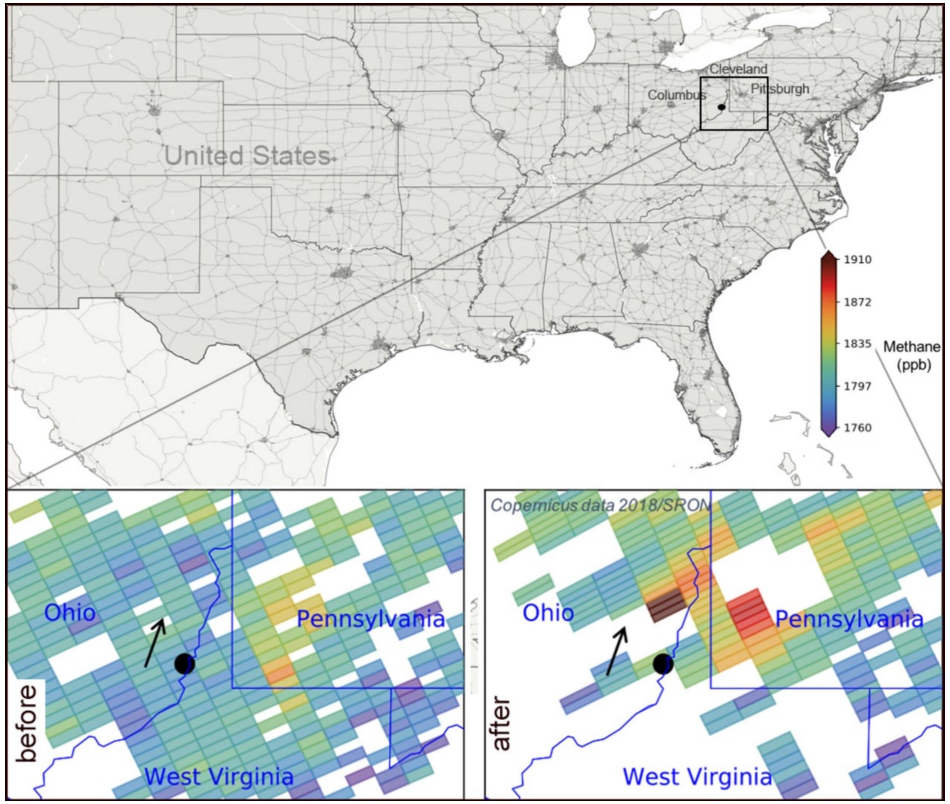
We are looking for ripples (emissions) in an ocean with large waves.
→ Observing the ocean is the easy part.
→ Detecting the ripples is a challenge, but characterizing them allowing emission quantification is the **major** challenge

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 <u>stable background</u>.

Aim is to measure it at ~10 ppb (0.5%)

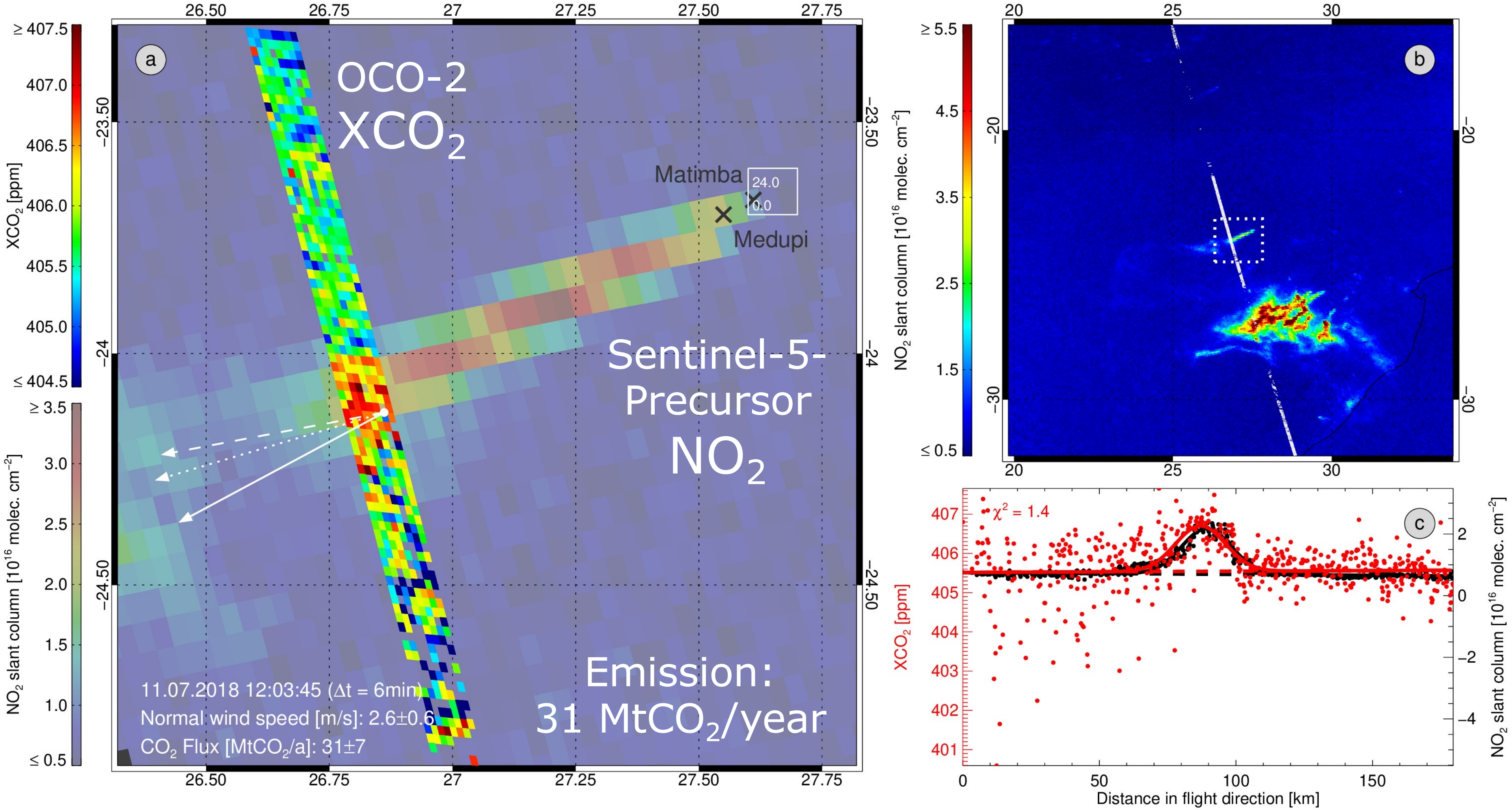




Methane leaks by Sentinel-5p, in footprints of 40 km^2 the anomaly is up to ~90 ppb (5%)
-> smaller footprints will show more anomalies, increasing its accuracy

Localized CO_2 & NO_2 sources – influence of wind

South African power plants, on 11 July 2018



Reuter et al., ACP, 2019
https://acp.copernicus.org/articles/19/9371/2019/

Outlines

- CO2 location and anthropogenic sources
- From observables to requirements
- Detection from Space – Anthropogenic CO2 Monitoring mission

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

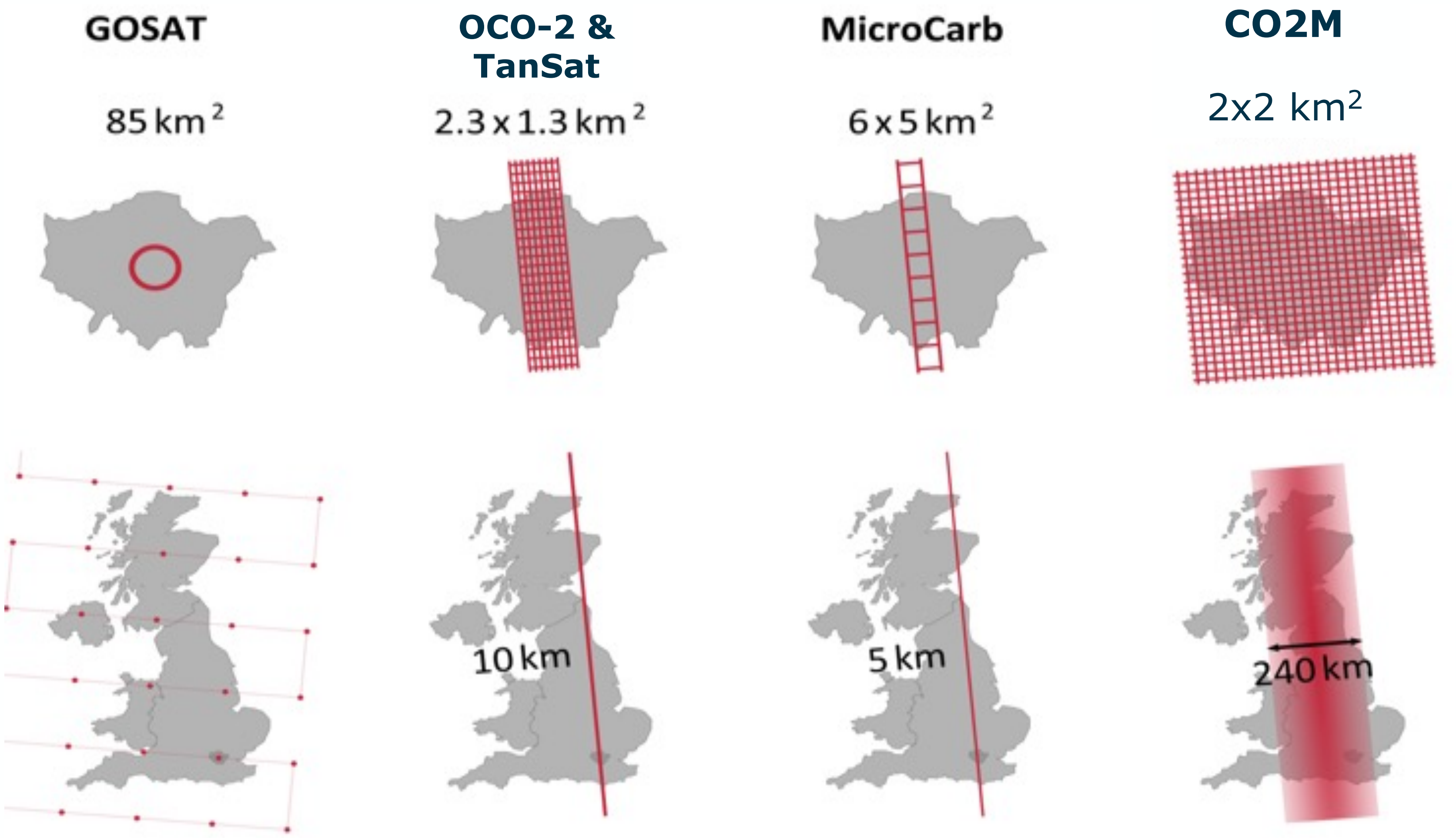
3. **Assessing emission changes against local reduction targets**
   to monitor impacts of the NDCs
   → no regional biases, separate biogenic from anthropogenic fluxes

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

CO2 Monitoring – A contributing mission

For large-scale fluxes, sampling is sufficient

For local scale fluxes, a dense mesh is required → given a certain detector format, then there is a trade-off between high resolution and swath width



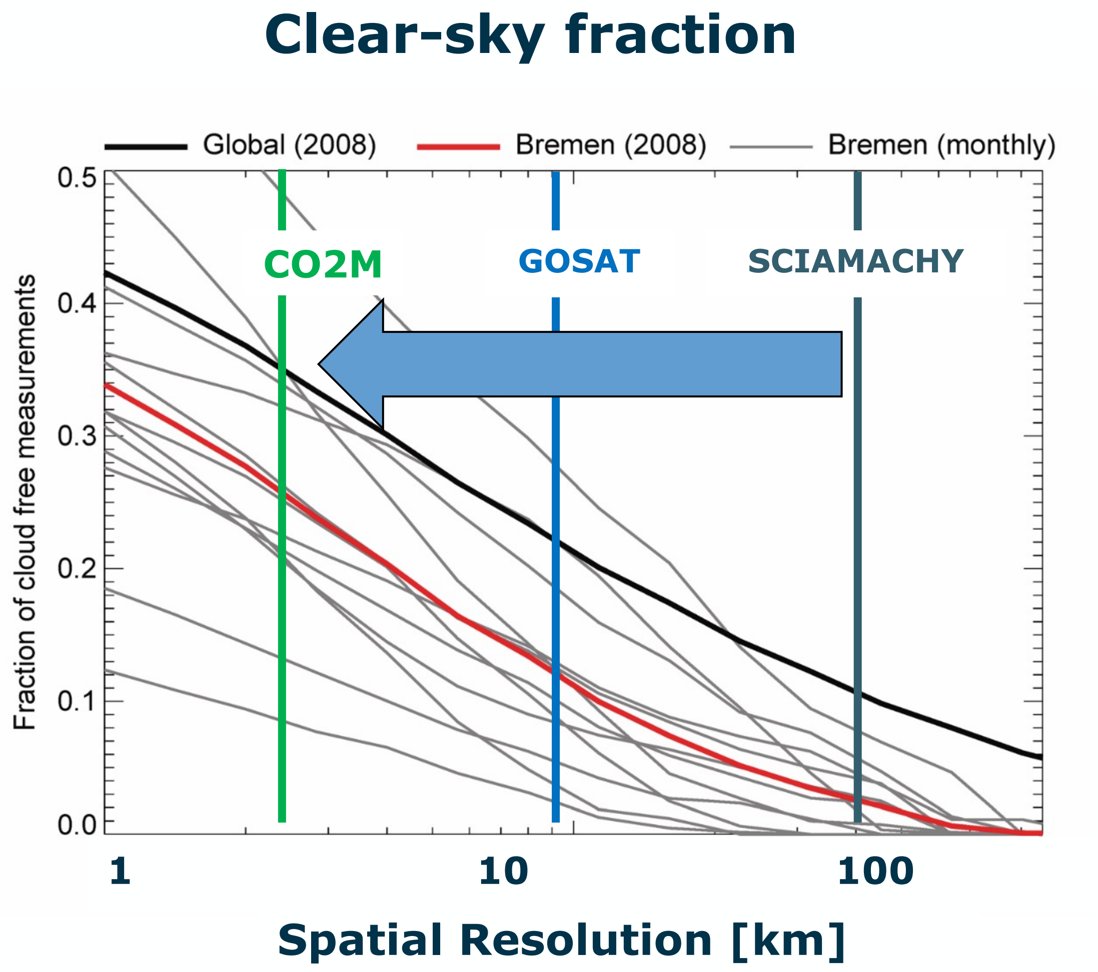
Parameters playing a role
- Precision per spatial sample
- Coverage and revisit time
- Cloud coverage contamination
- Sample homogeneity
- Resolving the structures to be observed, i.e. effective signal

Credits: IUP, Bremen

CO2M – impact of spatial requirement (1/2)

Regional and country scale objectives require adequately sampled **cloud-free** data, even in cloudy areas like Amazonia or higher northern latitudes ➔

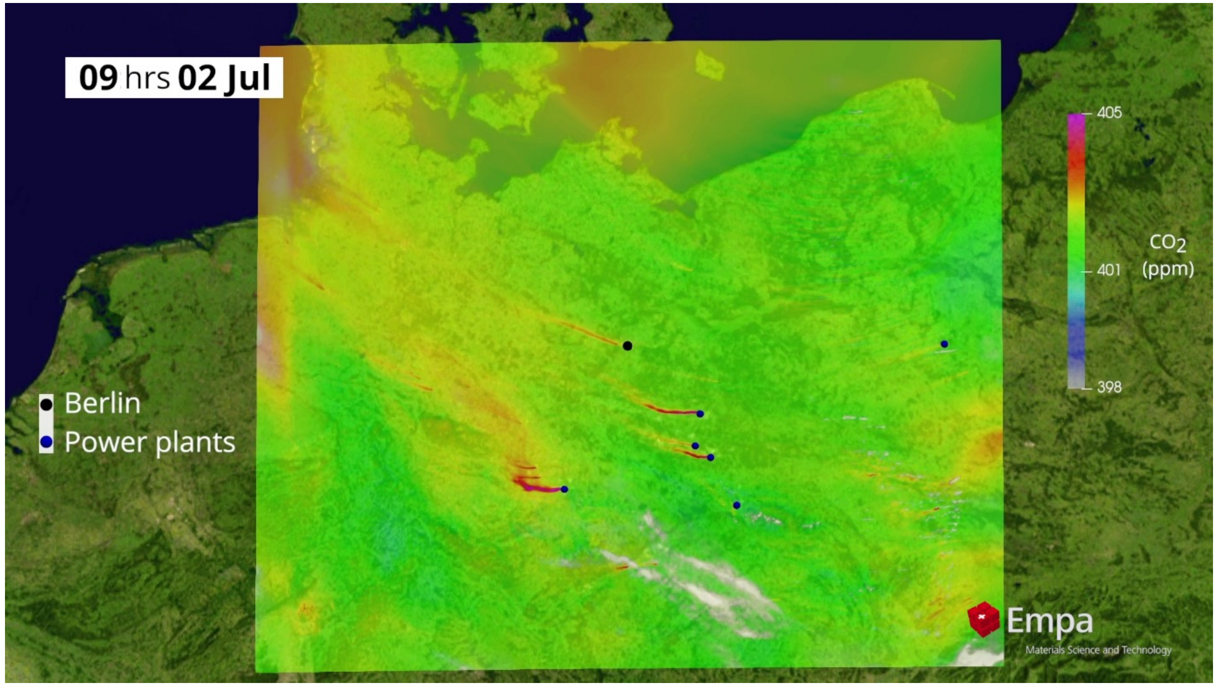
- small pixel (2–4 km) for large number of cloud free observations
- LARGE swath (250km) imaging to resolve the synoptic context and have effective monthly coverage



CO2M – impact of spatial requirement (2/2)

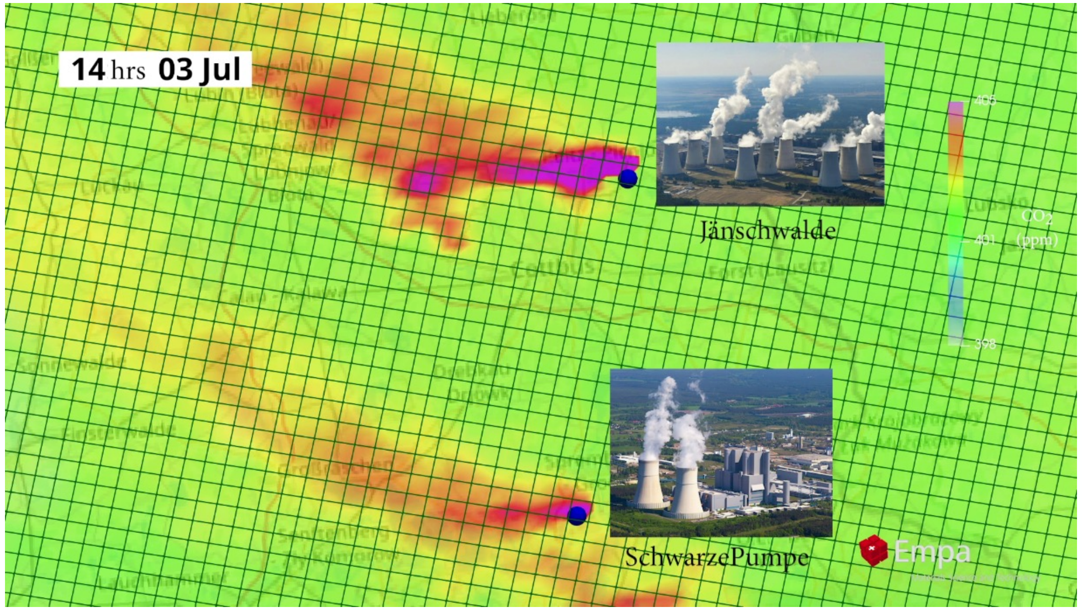
Local scale objectives require high resolution data and imaging to resolve structures:

- high spatial resolution (~2 × 2 km²) needed to image source regions
- adequate coverage 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

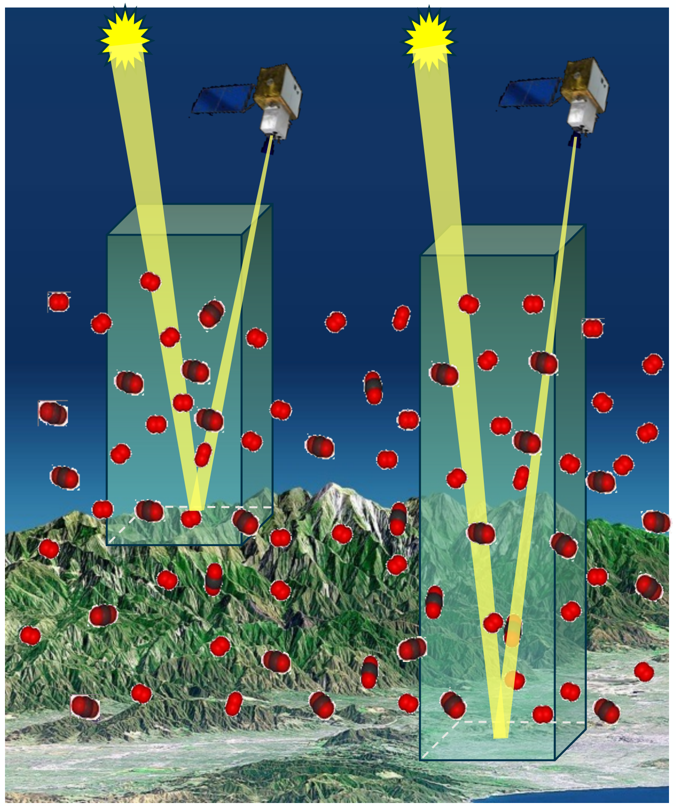
Quantifying XCO2

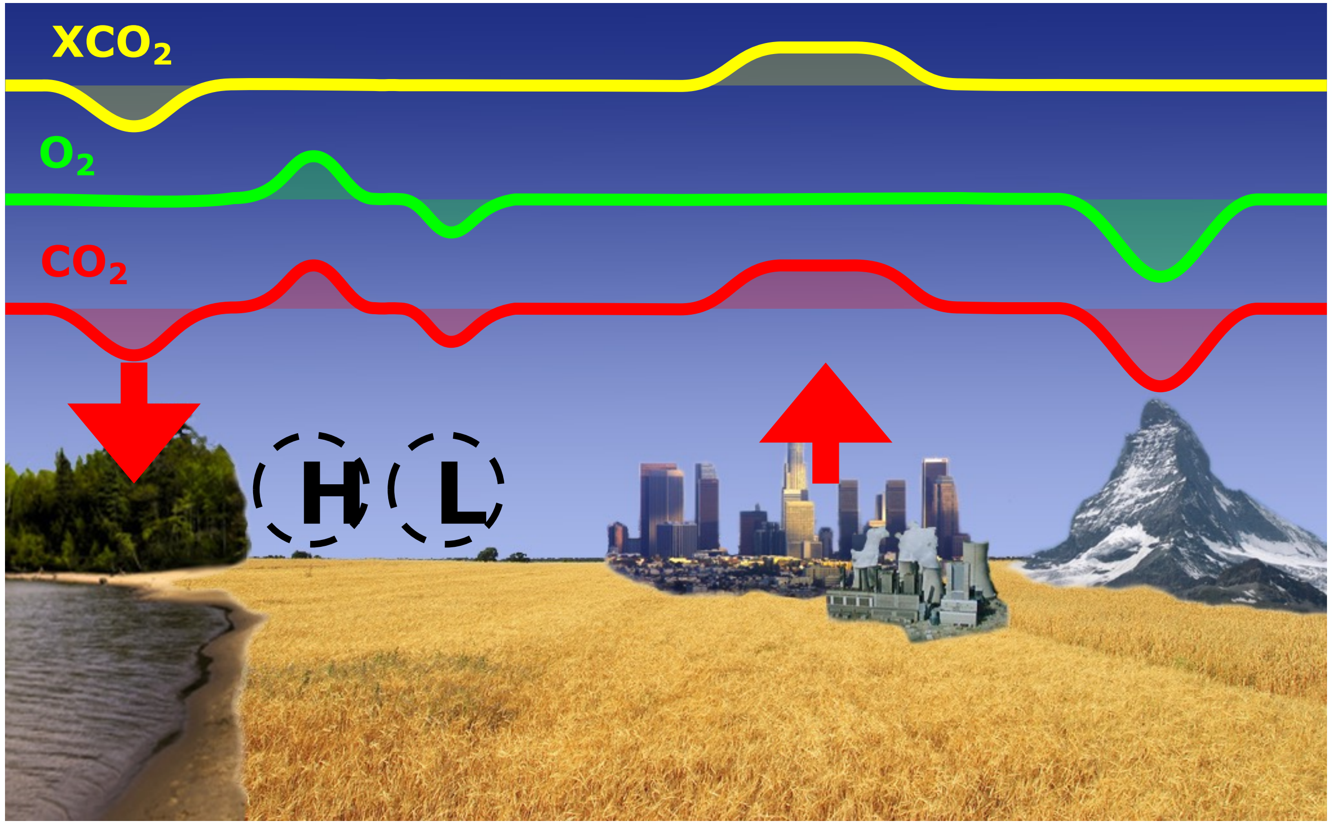
= Column-averaged dry-air mole fraction (mixing ratio) of CO_2, named XCO2

= Vertical CO_2 column / Vertical of dry-air column (via O_2)

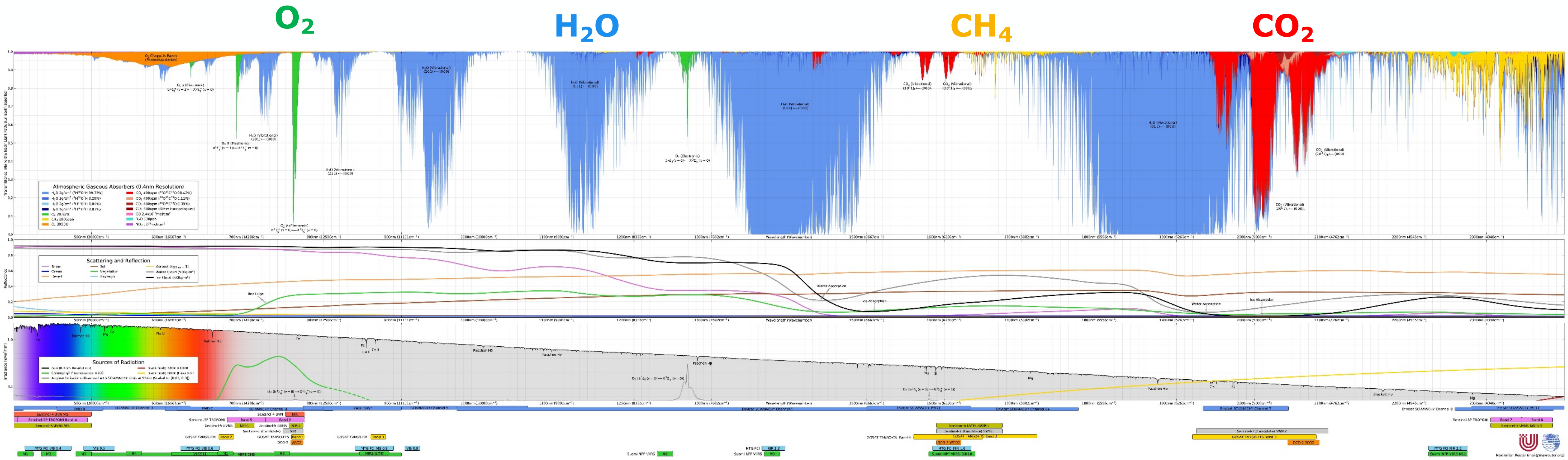
Same for XCH_4

Using absorption spectroscopy to determine vertical columns
[number of molecules/area]





Measuring CO_2 & CH_4 from Space



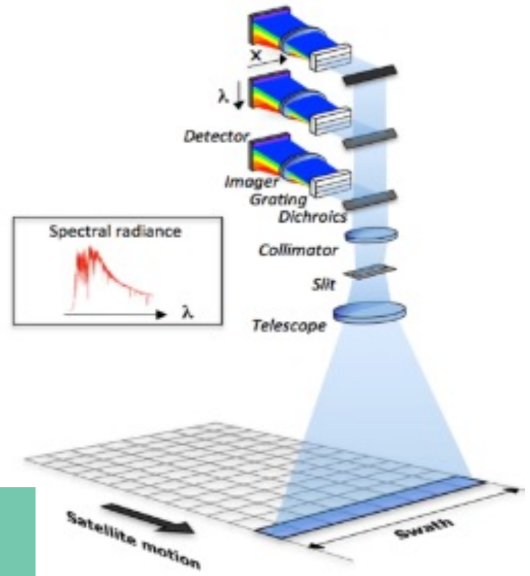
Atmospheric CO_2 has 400 ppm (parts per million) molecules in air or 0.04% → Measuring it is relatively easy.
Atmospheric CH_4 has 1800 ppb or 1.8 ppm (parts per million) molecules in air (0.00018%) → Measuring it is still easy.

Measuring anthropogenic CO_2 emissions is the <u>very hard</u> part, as it requires to measure it with 0.125% for local sources
Measuring anthropogenic CH_4 emissions is the <u>hard</u> part, as it requires to measure it with 5% for local sources

CO2 Monitoring – Spectral Requirements

Parameters playing a role

- Absolute radiometric accuracy: 3%
- Effective radiometric error: 0.1%
- ISRF shape knowledge: 2%
- Zero-level offset: 0.15%
- Spatial co-registration: 95% overlap between bands



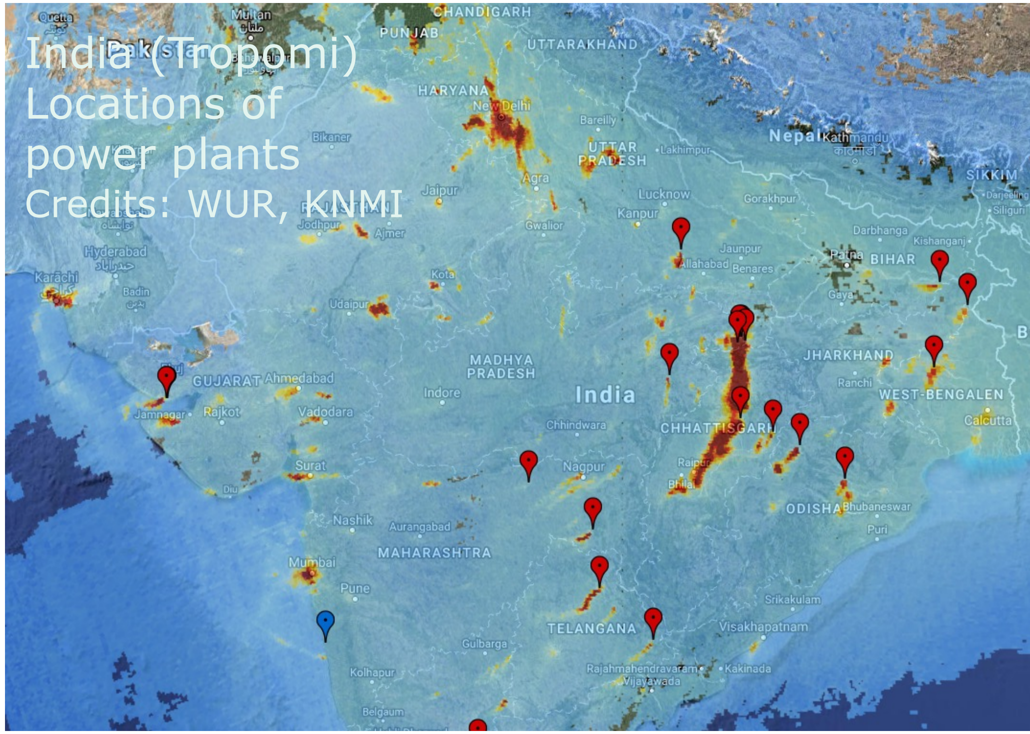
Band	Spectral range	Spectral resolution	Spectral sampling ratio	SNR_{ref} @ L_{ref} (photons/s/nm/cm^2/sr)
VIS (NO_2)	405–490 nm	0.6 nm	3	750 @ 1.35×10^{13}
NIR	747–773 nm	0.12 nm	3	330 @ 6.4×10^{12}
SWIR-1	1590–1675 nm	0.3 nm	3	400 @ 2.1×10^{12}
SWIR-2	1990–2095 nm	0.35 nm	3	400 @ 1.8×10^{12}

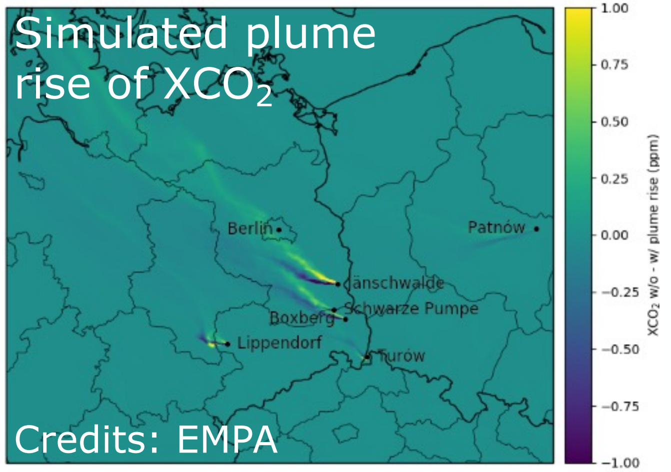
Reference scene is vegetated scene with 50º SZA

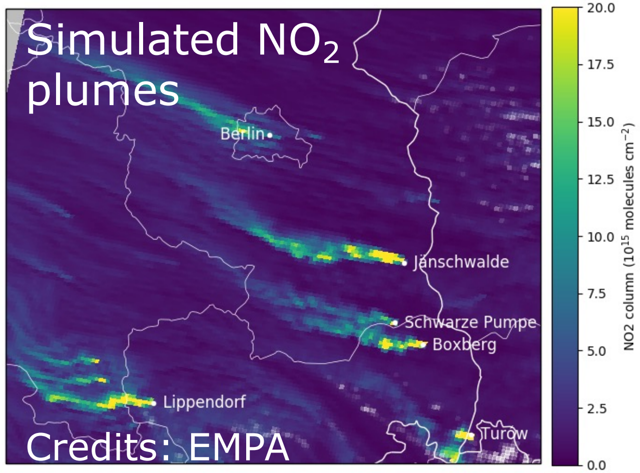
CO_2 Monitoring – NO2 and Cloud Requirements

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 **2x2 km^2 (as for CO_2)**
- NO_2 precision: **$1.5 \cdot 10^{15}$ molec/cm^2**

Cloud imager:
- 3 bands (670 (low water clouds), 753 (low clouds & spatial co-registration), 1378 nm (cirrus))
- Cloud cover of 1–5% → **sampling <<400 m**







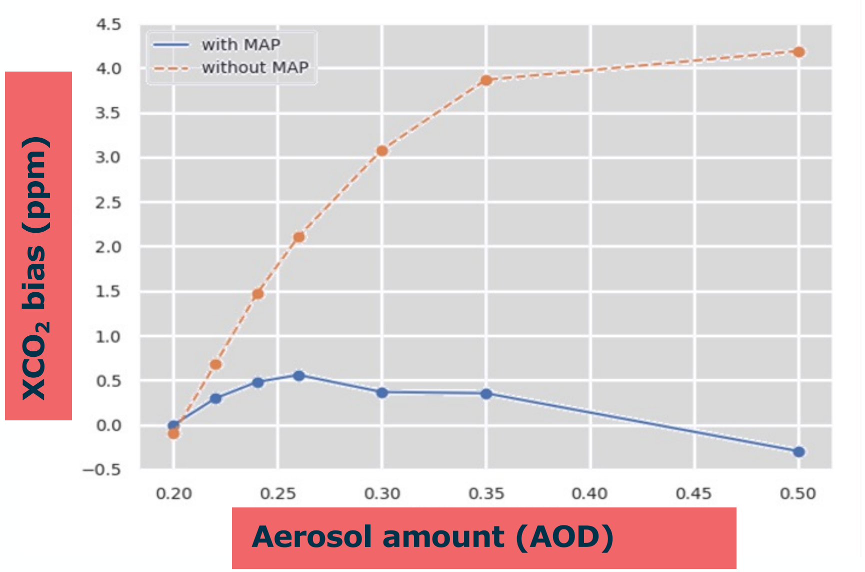
CO_2 Monitoring – Aerosols Requirements

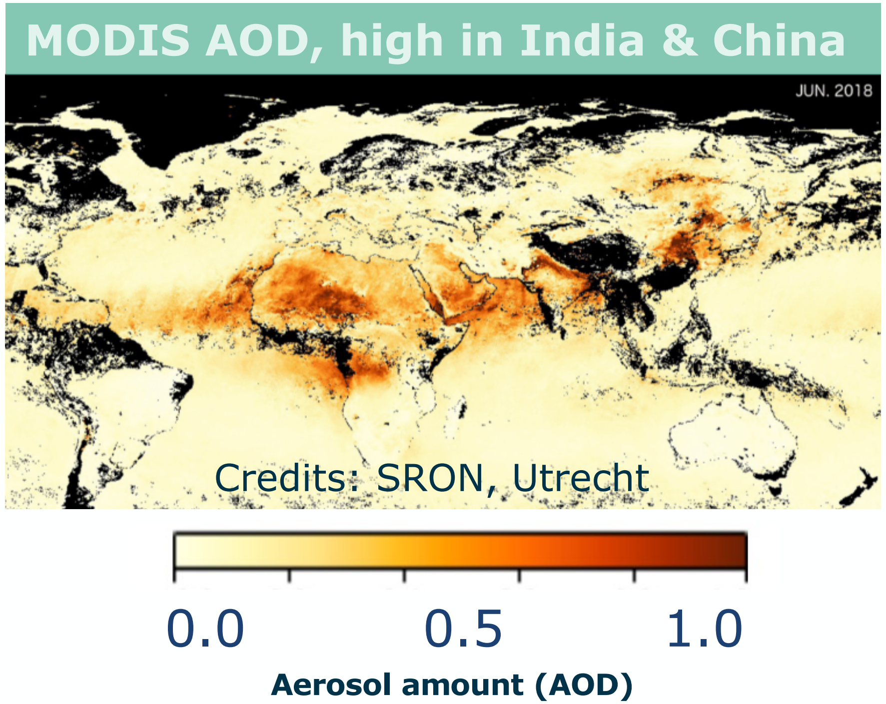
Light path correction by measuring effective aerosol

→ **Higher accuracy CO_2 data (less dependence on bias correction)**

→ **More data and also at higher aerosol loading;** up to 0.5 AOD

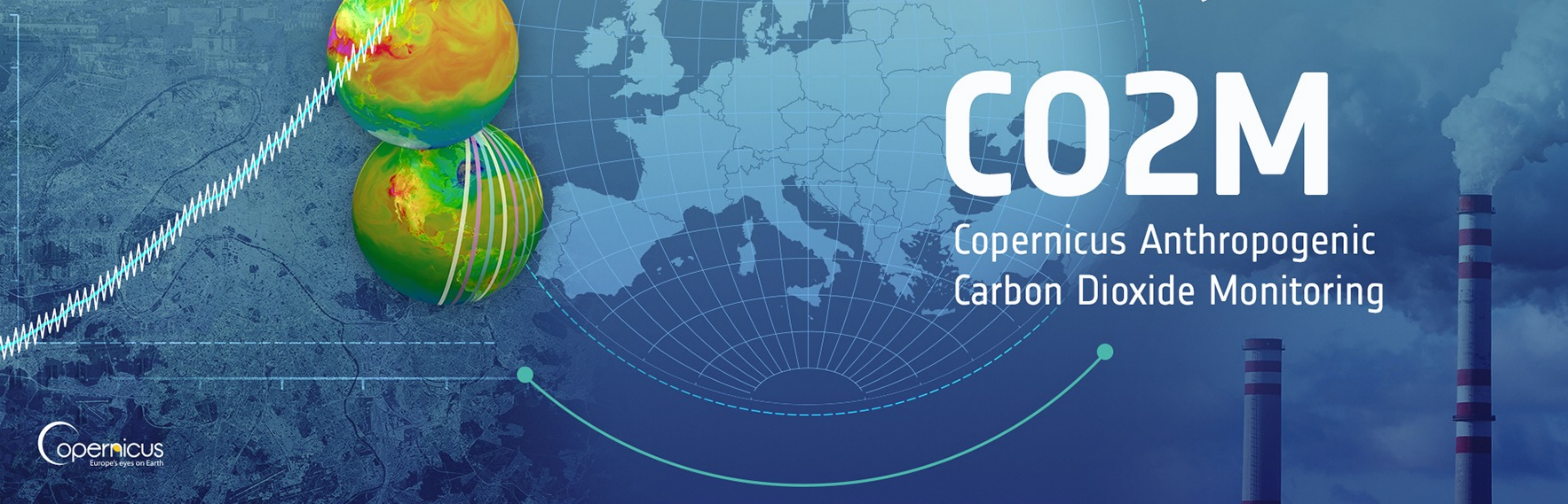
- Spatial resolution **4x4 km²** and **sampling @1x1 km²**
- Heritage missions without polarimeter require bias correction and strict quality filtering for AOD<0.3
- Anthropogenic areas in India and China on average AOD>0.3





Outlines

- CO2 location and anthropogenic sources
- From observables to requirements
- Detection from Space – Anthropogenic CO2 Monitoring mission



CO_2 Monitoring – Measurement principles (1/2)

Spectrometric measurements for CO2 and NO2

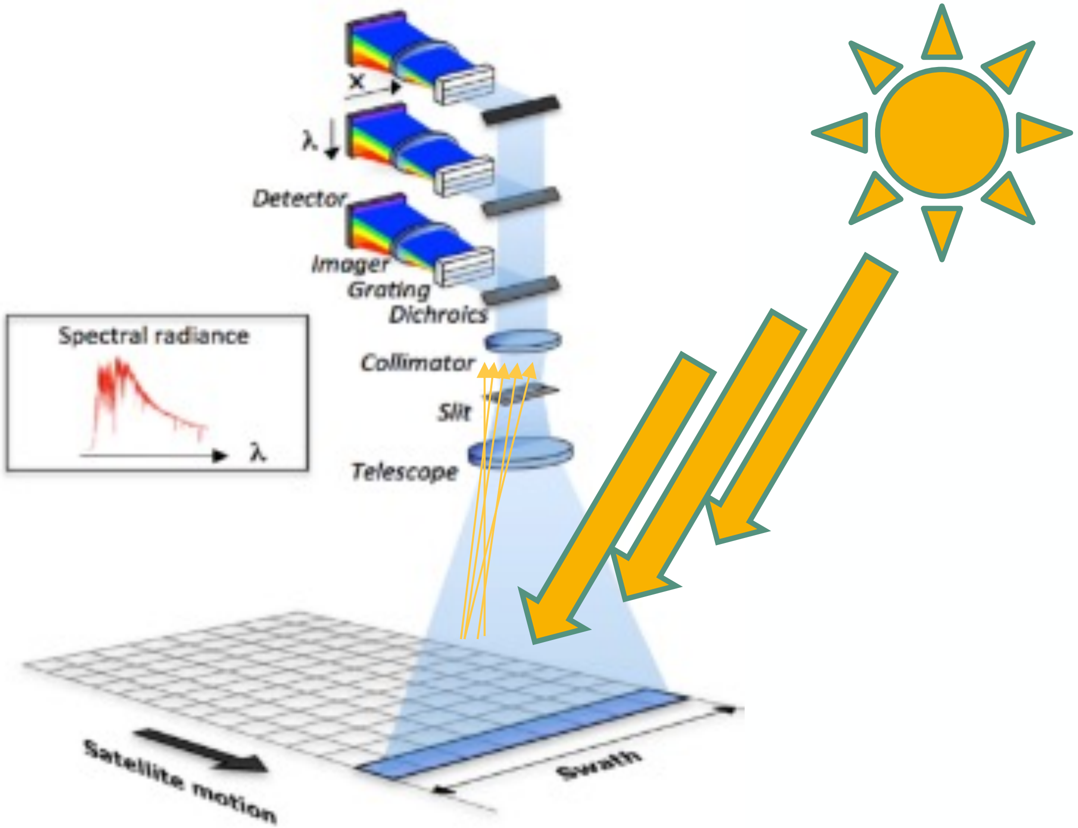
- Very thin scanning of the spectral domain (with grating) from Visible to Short-Infrared
- Very high sensitivity of the detectors over small spatial sampling
- Very low noise in the detection chain to get adequarte SNR

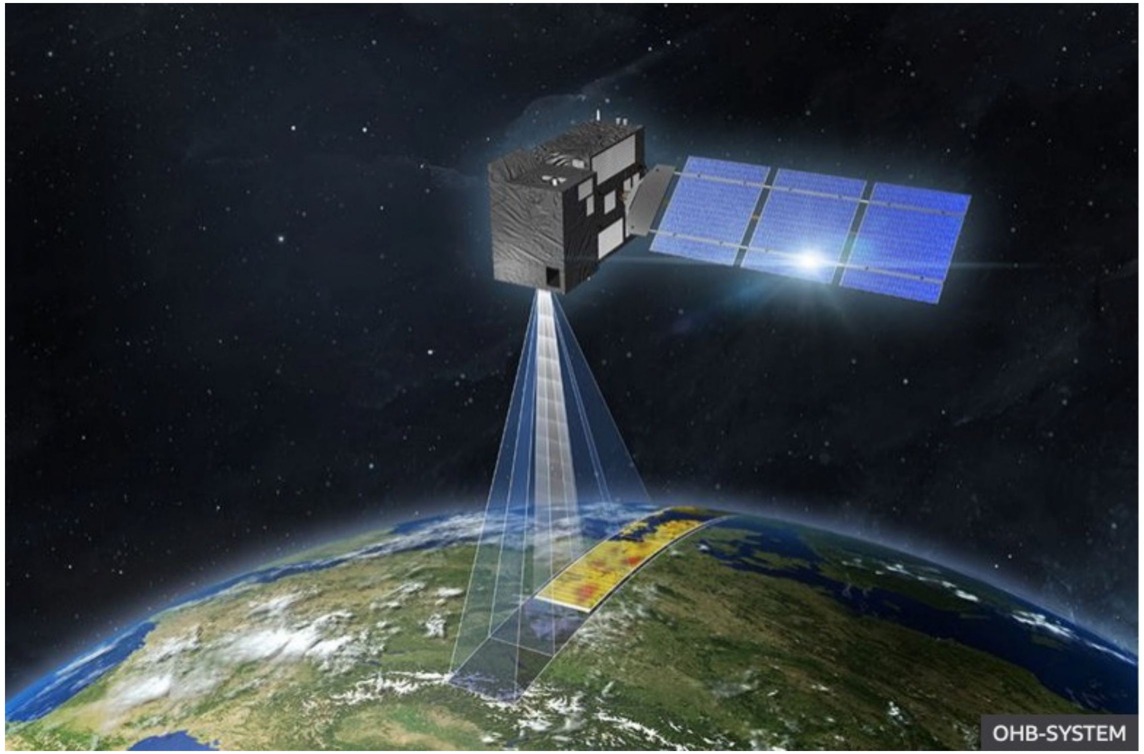
→ To determine continuum of absorption bands with fine spectral information

Mutli-spectral Measurements for cloud detection

- Larger spectral band (stripe filters)
- High Sensitivity of the detector on very small spatial sampling
- Very low noise of the detection chain to meet the performance a sample level

→ coarser spectral resolution to cover the large H2O absorption bands



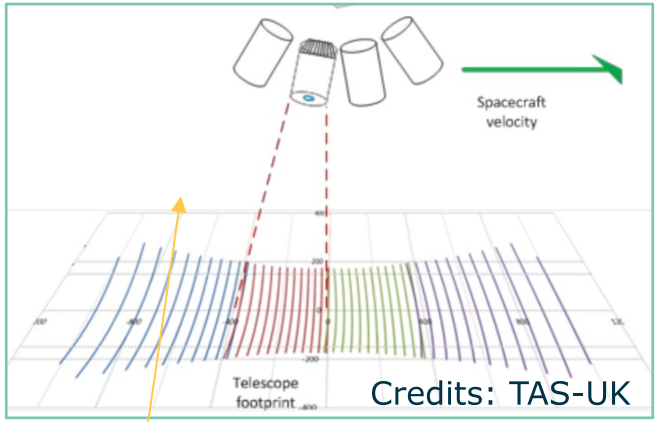


CO_2 Monitoring – Measurement principles (2/2)

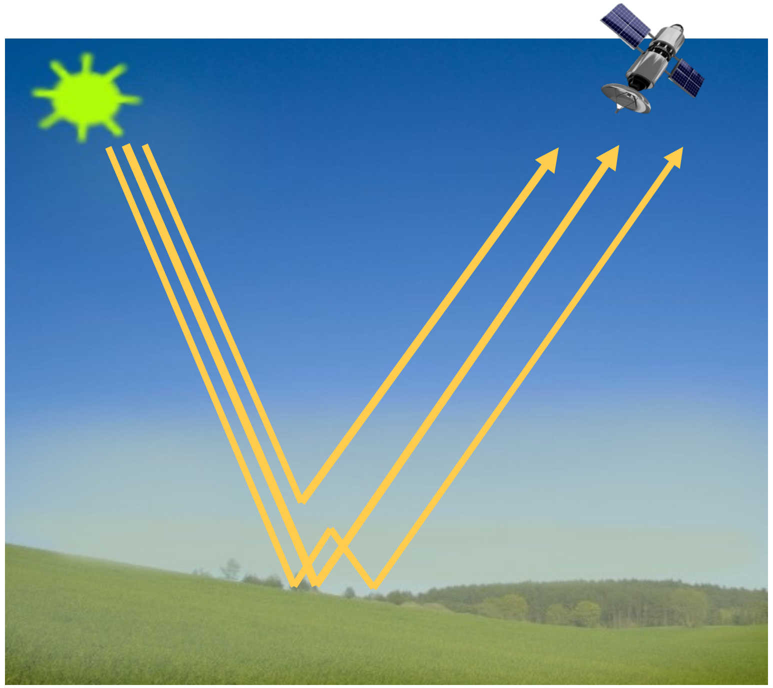
Light path correction by measuring effective aerosol with a multi-angular observable

- **Multi-angular view covering 120 degree**
- **covering VIS to NIR spectral domain by filters**
- **High detector sensitivity with miniaturized polariser to detect small variation**

Measurement principle for multi angular polarimeter

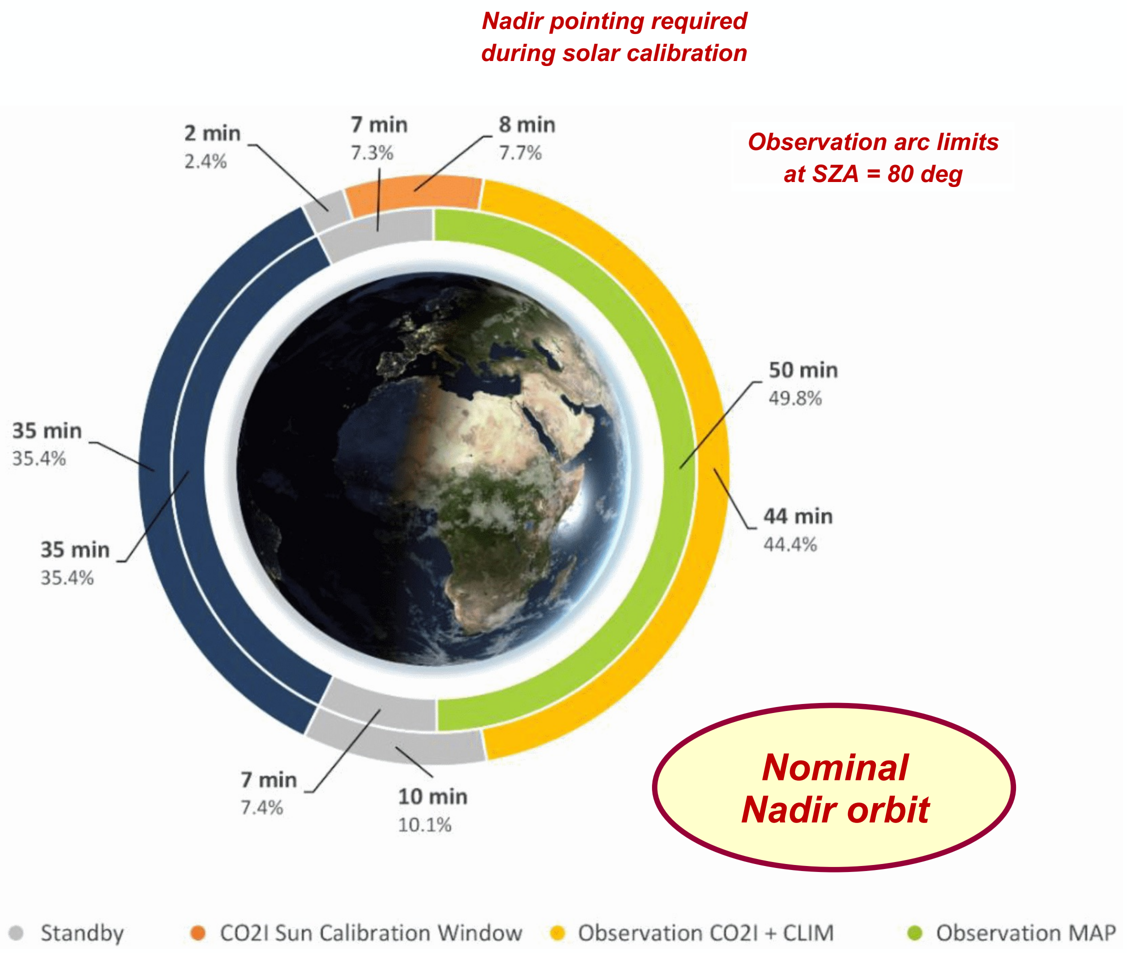


Multi-angle polarimeter
>40 views, 1+6 (pol) bands



Aerosol shorten or enhance light path due to light diffraction or multi-reflections

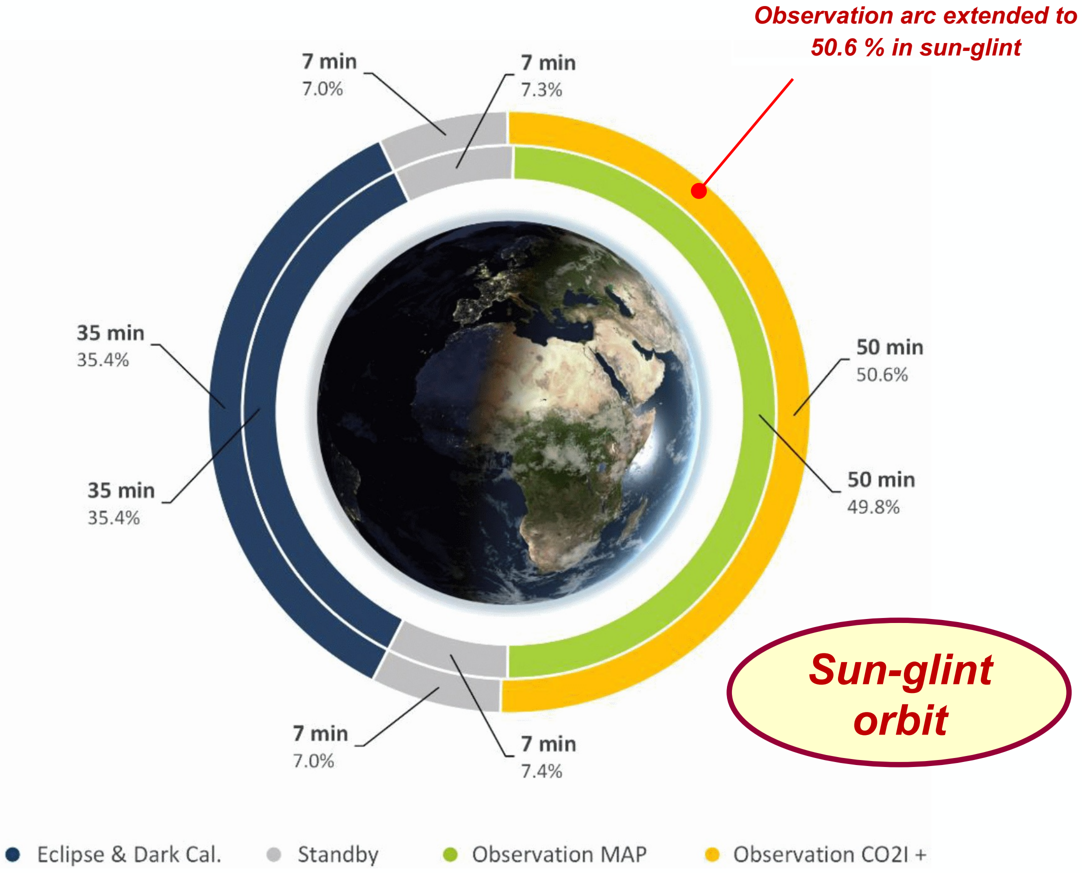
CO2M Space Segment - Key mission features



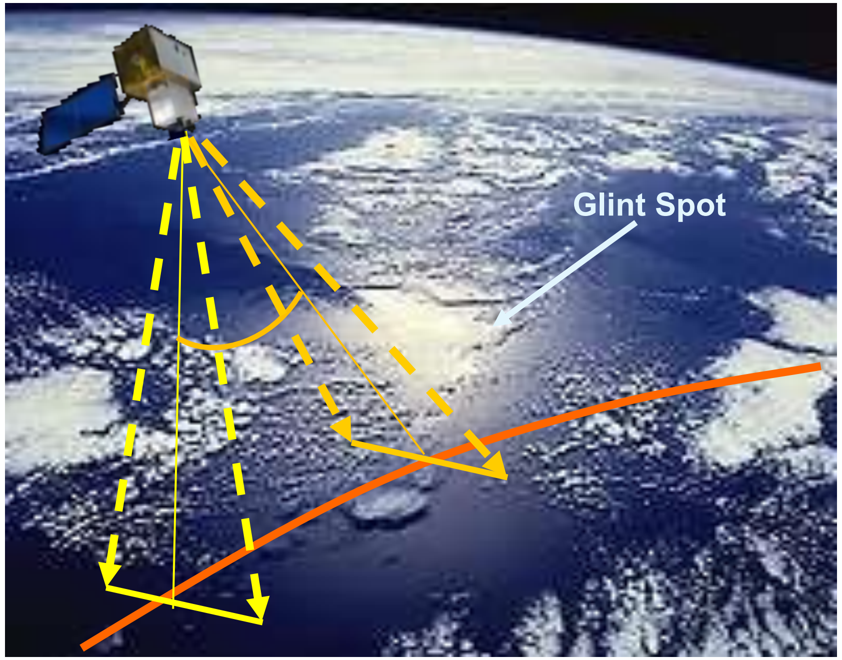
Mission architecture	
Reference Orbit	Reference altitude: 735 km LTDN: 11:30
Repeat cycle	Full coverage at eq., after 11 days with 1 satellite improved to 5 days with 2 satellites
Science data latency	Max. latency : 3.3h, based on 1 Ground station
Lifetime	7.5 years Extendable to 12 years (consumable sized accordingly)
Satellite Mass	1674 Kg
Launcher	Baseline: Vega-C Back-up: Ariane 6.

- CO2M developed in the baseline with 2 satellites with a third one to enhance to less than 3d over European latitude
- Independent launches to be planned for 2 satellites ready by end of 2025 to cope with the CO2 data stock of 2028

CO2M Space Segment - Key mission features

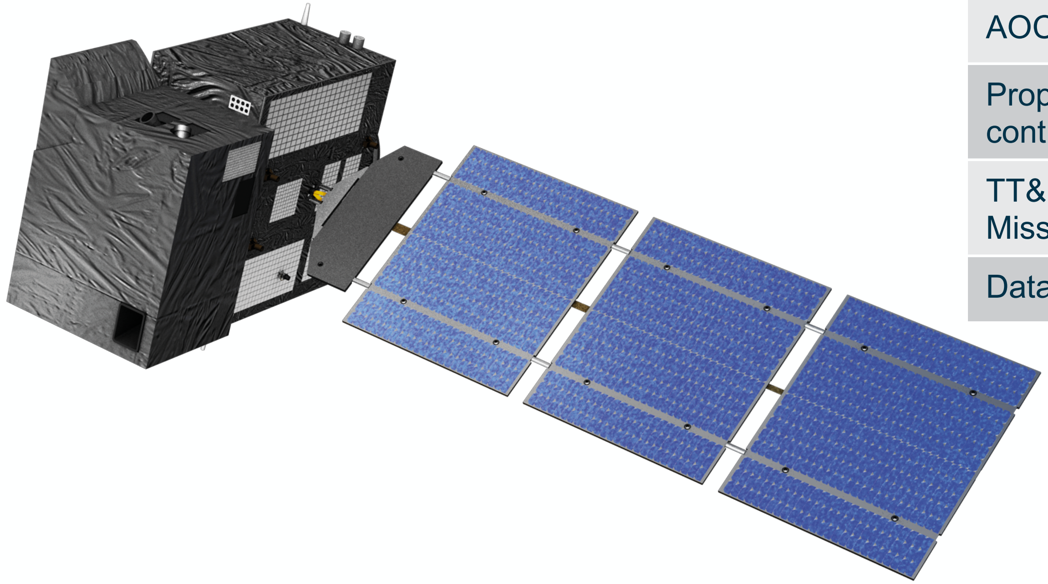


Ocean coverage is important for determining background levels and to measure local source emission outflow in coastal areas downwind, such as megacities and power plants (often using seawater for cooling)



- Ocean surface = low reflectivity (low signal) in nadir view
- Measurements over ocean must be performed in a special mode viewing **sunglint** reflections
- Glint mode allows & improves observations over snow!

CO2M Space Segment - Key technical features

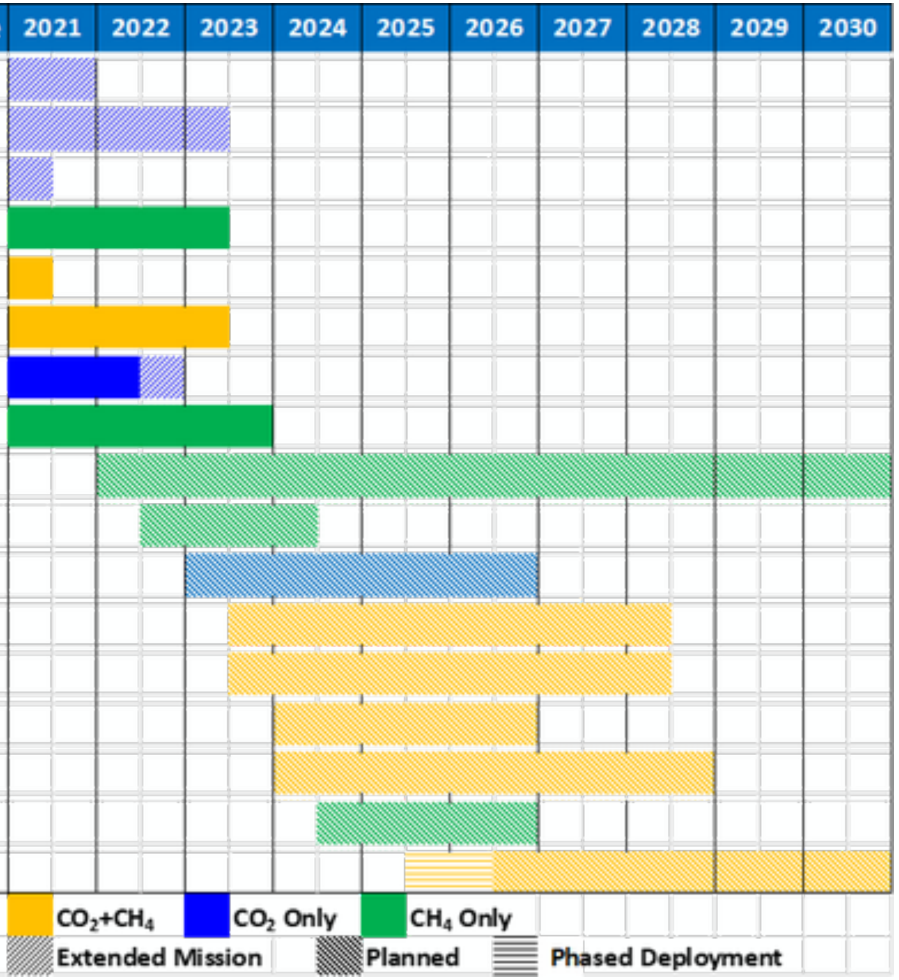


Platform subsystems	All subsystems from well known technology with performance (power, memory, etc..) in the range of existing Copernicus missions
Electrical Power (EPS)	Solar Array: 3 panel wing steered by SADM
AOCS	Gyroless architecture, 3-axis stabilised
Propulsion and Reaction control (RCS)	Mono-propellant, with 8 Thrusters (20N) 2 Tanks sized for controlled re-entry
TT&C Mission Data	S-band TM/TC and ranging Ka-Band single channel (1.8 Gbits)
Data Storage	Mass Memory > 3Tbits (EoL)

Modular PF architecture with functionalities per panels to reduce inter-dependency of disciplines during integration phase

Current and Upcoming GHG Missions

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	●	●	●	



CO_2 & CH_4 are used very generically, i.e. with all capabilities (local, regional, revisit, etc..) mixed
But all contribute to better control and regulate in the future, with synergies and complementarities

Assessing a Mission Capability

The following parameters are of consideration when assessing a greenhouse gas satellite mission

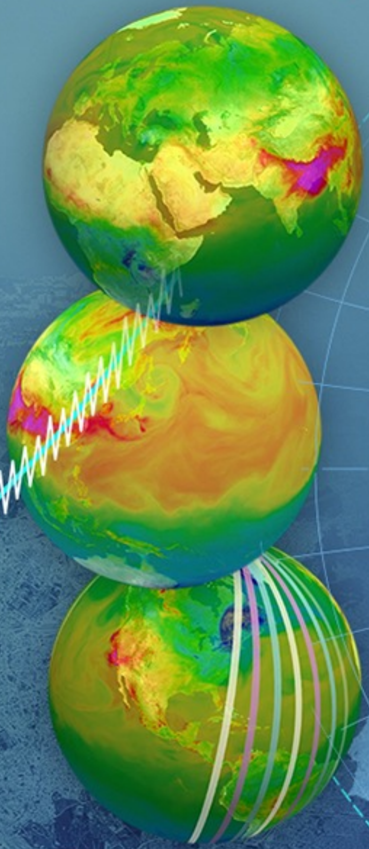
1. Geometric: spatial resolution, spatial sampling, swath width, geolocation knowledge
2. Spectral: resolution, sampling, bandwidth, ISRF knowledge
3. Radiometric: SNR, reference scenario, absolute radiometric accuracy
4. Product requirements: (targeted) precision, systematic bias, CO_2 and/or CH_4, proxy, need for bias correction
5. Coverage: LEO or GEO, continuous/target, ocean/land, number of obs. per orbit, timeliness
6. Mission objective: biogenic and/or anthropogenic, operational/exploratory,
7. Support observations: aerosol, clouds, NO_2, H_2O, solar-induced fluorescence

✓ CO2M Mission defined with such goals

To meet them, on top of the CO2, N02, CH4 observable quality, instrument features need:

- ✓ Treatment of polarization → to remove inaccuracy in the light path
- ✓ Treatment of heterogeneous scenes → small pixel with high sensitivity to discriminate thresholds
- ✓ Straylight and possibly required corrections → to reach the radiometric accuracy and XCO2 precision
- ✓ Radiometric calibration → to remove temporal bias and increase stable accuracy over time

Thank you for your attention



CO2M

Copernicus Anthropogenic Carbon Dioxide Monitoring

@ESA_EO

Europeanspaceagency esa_earth

https://www.esa.int/Applications/Observing_the_Earth/Copernicus