Europe‘s plans and activities w.r.t. GHG satellite remote sensing – Sentinel 5 P and 5, CarbonSat, MERLIN

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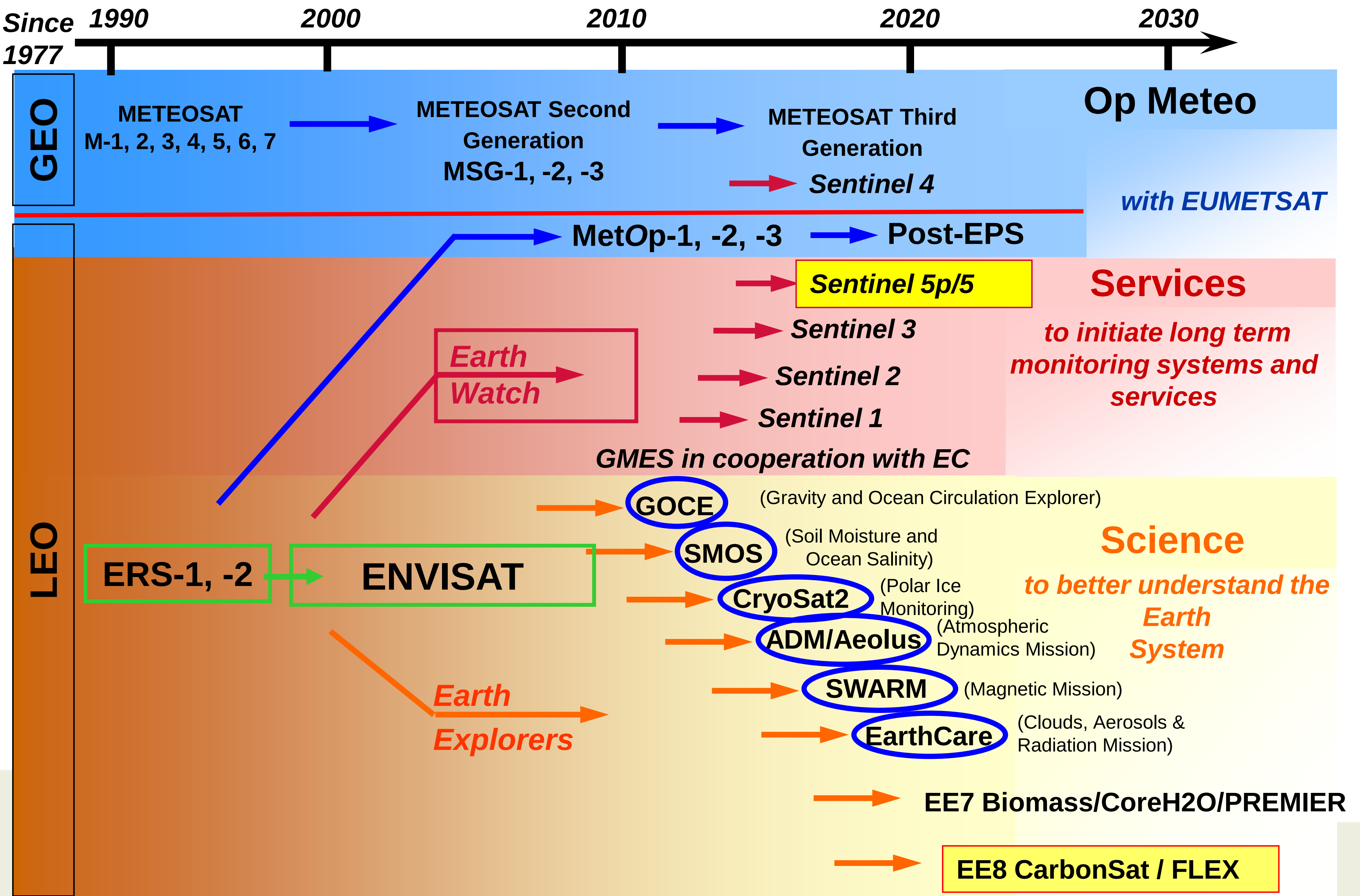
EUMETSAT

Europes Earth Observation Missions



Global Monitoring for Environment and Security (GMES)

The European contribution to GEOSS

Services Component – led by EC

- **Produces information services in response to European policy priorities in environment and security**
- Relies on data from in-situ and space component

In-situ component – led by EEA

- Observations mostly within national responsibility, with coordination at European level

Space Component – led by ESA

- Sentinels - EO missions developed specifically for GMES
- Contributing Missions - EO missions built for purposes other than GMES but offering part of their capacity to GMES

GMES Atmosphere Space Component

- Atmospheric composition requirements for an operational mission have been defined based on in-depth analysis (CAPACITY, CAMELOT etc.)
- Two complementary implementation components have been identified, namely
  - Sentinel-4, i.e. the **GEO related component**, will get implemented as a UVN instrument added to the MTG sounder satellites alsoe making use of the IR sounder and MTG imager capabilities
  - Sentinel-5, i.e. the **LEO related component**, will get implemented as a UVNS instrument added to the Post-EPS satellites making use of the combined meteorology-chemistry IR sounder, the multi-spectral imager and the polarisation imager if implemented to meet the S-5 requirements

➔ To avoid a data gap a Sentinel-5 Precursor will get implemented on a dedicated platform making use of NPP/VIIRS

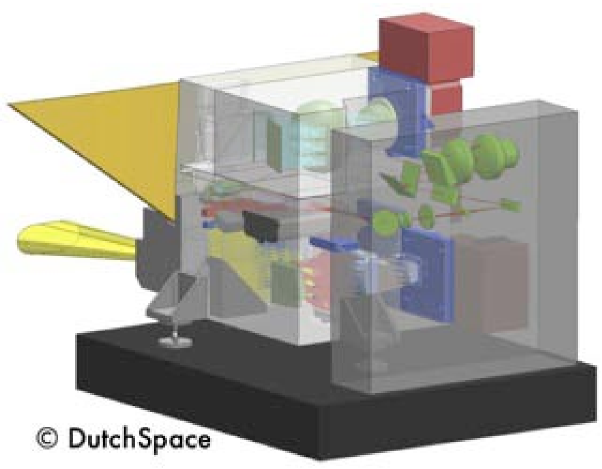
Sentinel-5 Precursor

GMES ATMOSPHERE MISSION IN POLAR ORBIT

- The ESA Sentinel-5 Precursor (S-5P) is a pre-operational mission focussing on global observations of the atmospheric composition for air quality and climate.
- The TROPOspheric Monitoring Instrument (TROPOMI) is the payload of the S-5P mission and is jointly developed by The Netherlands and ESA.
- The planned launch date for S-5P is late 2014 with a 7 year design lifetime.

Sentinel 5 Precursor

- UV-VIS-NIR-SWIR nadir view grating spectrometer.
- Spectral range: 270-500, 675-775, 2305-2385 nm
- Spectral Resolution: 0.25-1.1 nm
- Spatial Resolution: 7x7km^2
- Global daily coverage at 13:30 local solar time.



CONTRIBUTION TO GMES

- Total column O_3, NO_2, CO, SO_2, **CH_4**, CH_2O, H_2O, BrO
- Tropospheric column O_3, NO_2
- O_3 profile
- Aerosol absorbing index, type, optical depth

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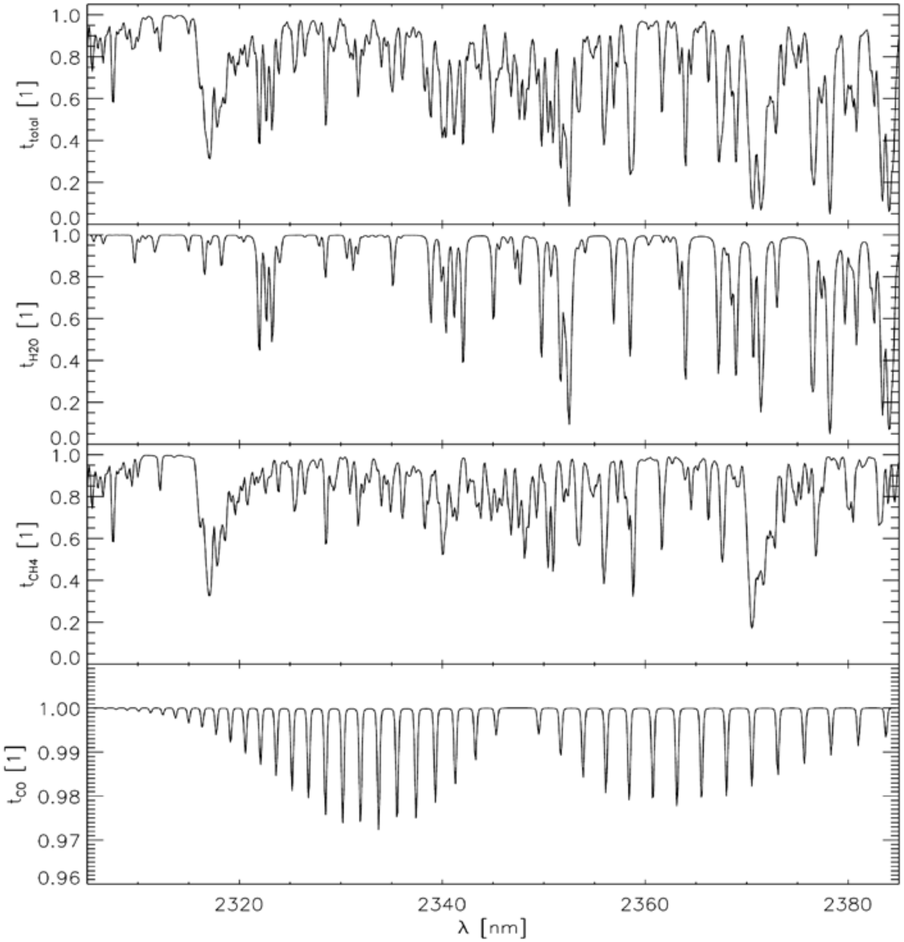
Netherlands Space Office

S5P SWIR 2.3 µm band



Total transmittance

H2O transmittance

CH4 transmittance

CO transmittance

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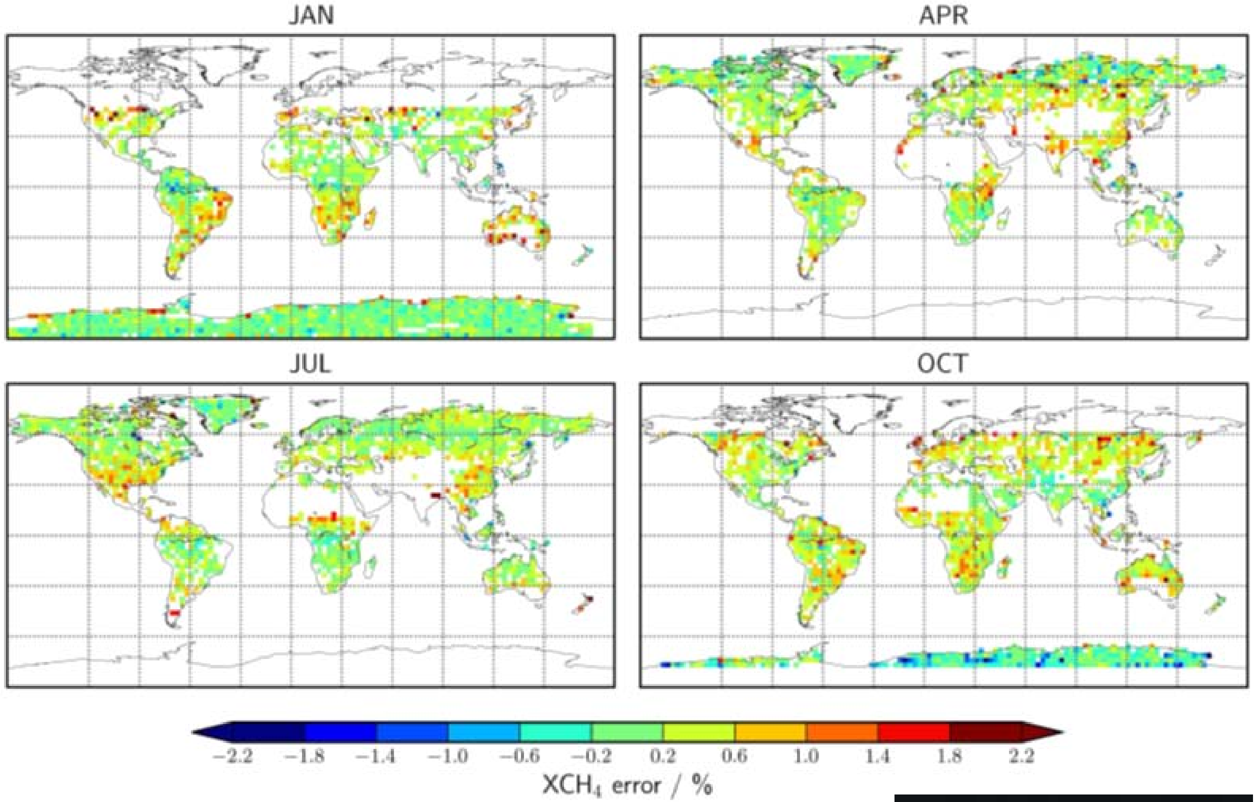
Expected Performance of S5-P for CH4

Method: retrieve aerosol/cirrus amount, size, and height together with CH4 (and CO, H2O and surface albedo)

• use VIIRS to select scenes that are free of thick clouds.

- Retrieval employs measurements at the O2 A and and the SWIR 2.3 µm band.
- Goal: 1% error



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Butz et al. RSE, 2011, accepted

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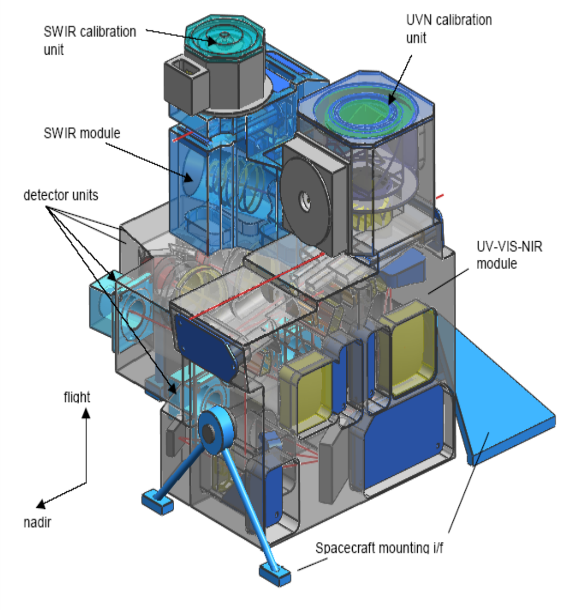
Sentinel–5: LEO atmospheric mission

Applications:

- air quality, climate forcing and stratospheric ozone

Instrumentation:

- UV-VIS-NIR-SWIR spectrometer (UVNS)
- UV-Visible (270-500nm), NIR (685-775nm) and SWIR (1590–1675nm; 2305-2385nm)
- push-broom grating spectrometer with spectral resolution between 0.4 nm and 1.0 nm

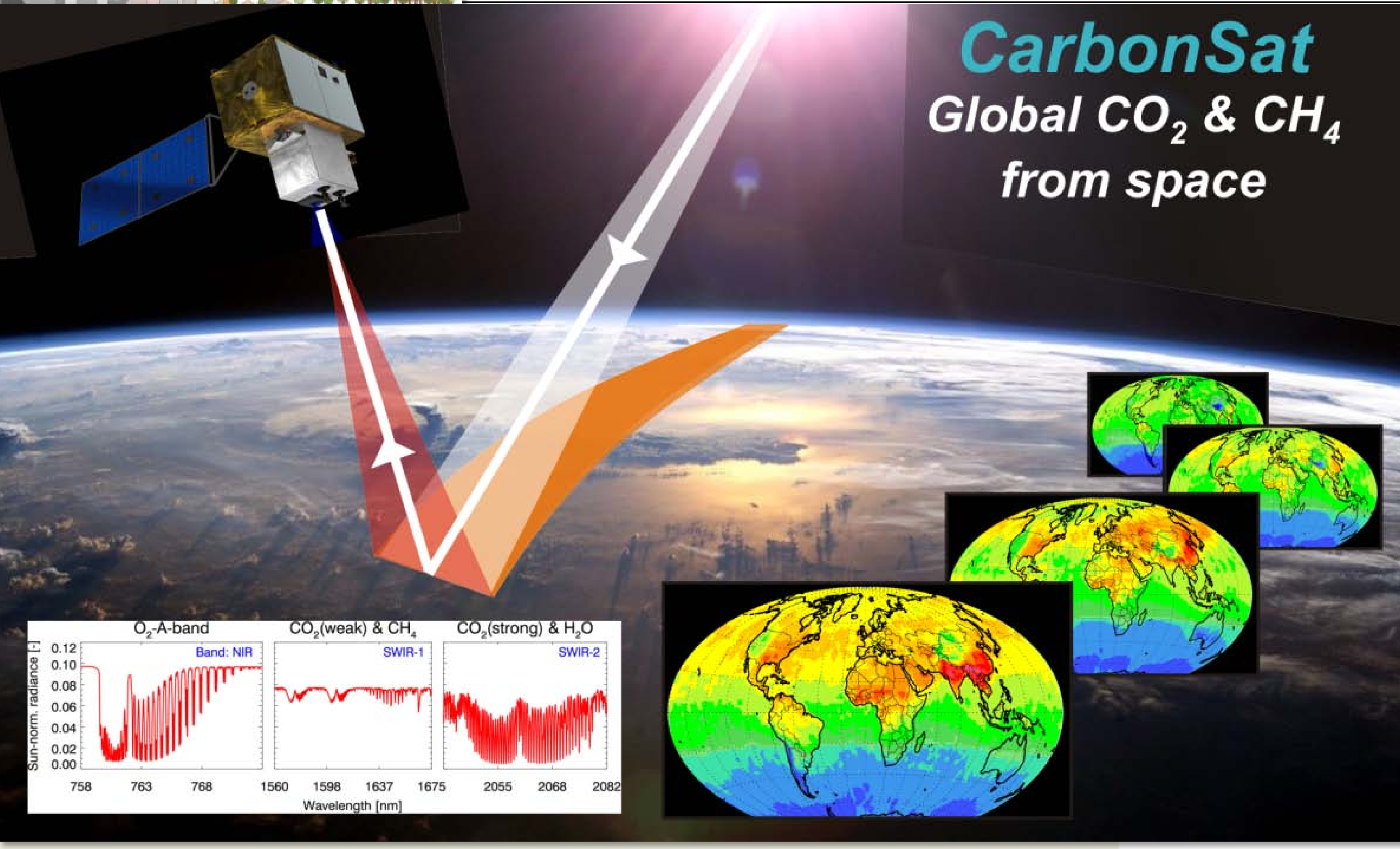


- Spatial sampling with 50 (T)/15 (G) km < 300nm and 15 (T)/5(G) km > 300 nm
- Global daily coverage
- sun-synchronous Low Earth Orbit at 824 km mean altitude
- Sentinel-5 embarked on post-EPS, operated by EUMETSAT
- Use of PostEPS thermal IR sounder and imager
- **Launch > 2018**

Sentinel 5 Precursor and Sentinel 5

		Sentinel 5P	Sentinel 5
CH_4	Spectral range [nm]	2305-2385	1590–1675 (2305-2385)
	spectral resolution [nm]	0.25	0.25
	XCH4 precision & accuracy	1% :: 2%	< 1%
CO_2	Spectral range [nm]	-	1590–1675 1940–2030 (lower priority)
	spectral resolution [nm]	-	0.25
	XCO2 precision & accuracy [ppm]	-	tbd
CO	Spectral range [nm]	2305-2385	2305-2385
	spectral resolution [nm]	0.25	0.25
	CO precision :: accuracy	10% : : 15%	10% : : 15%
Spatial Resolution	[km] x [km]	7 x 7	15 (T)/5(G)
Swath	[km]	2600	~2600
Local Time		13:30	Morning orbit

ESA Earth Explorer 8 Candidate Mission



CarbonSat Proposal Team

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Technical support from OHB-System AG for defining the overall Satellite System and Spacecraft bus, and Kayer-Threde for defining the Satellite Payload is kindly acknowledged.

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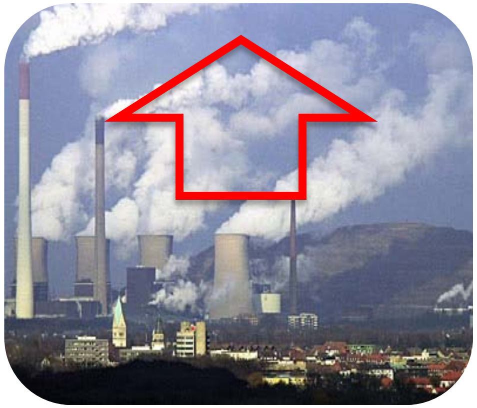
CO_2 and CH_4 are driving global warming

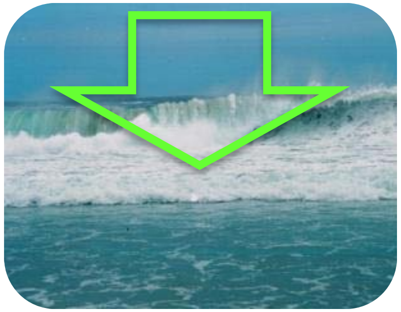
Radiative forcing: CO_2 accounts for ~ 60%
CH_4 accounts for ~ 20%

How much is emitted where, when and by what?



Are the reported Emissions correct?

How much CO_2 is absorbed by forests and oceans? (Sinks)

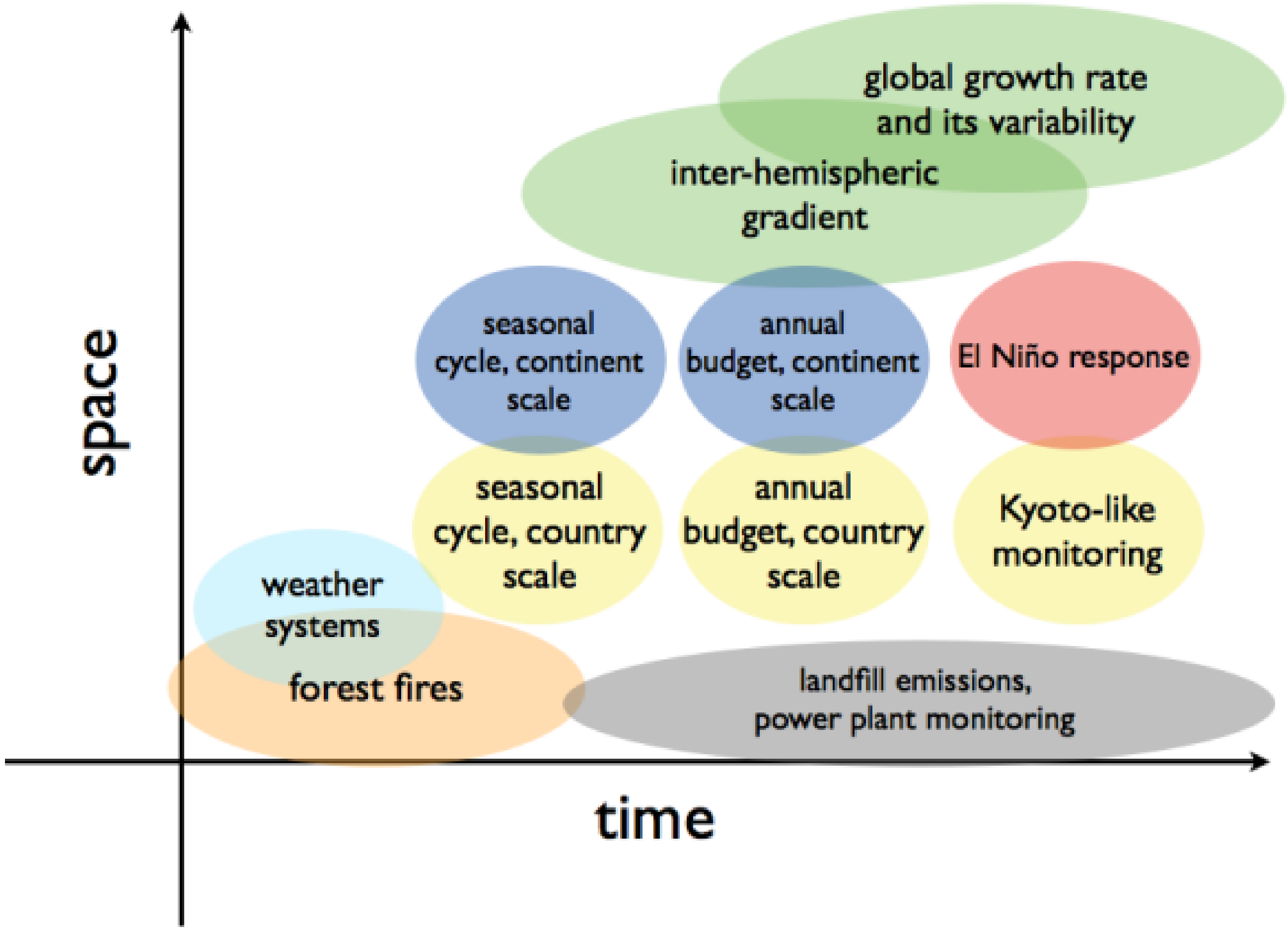


Are the reported sinks correct?

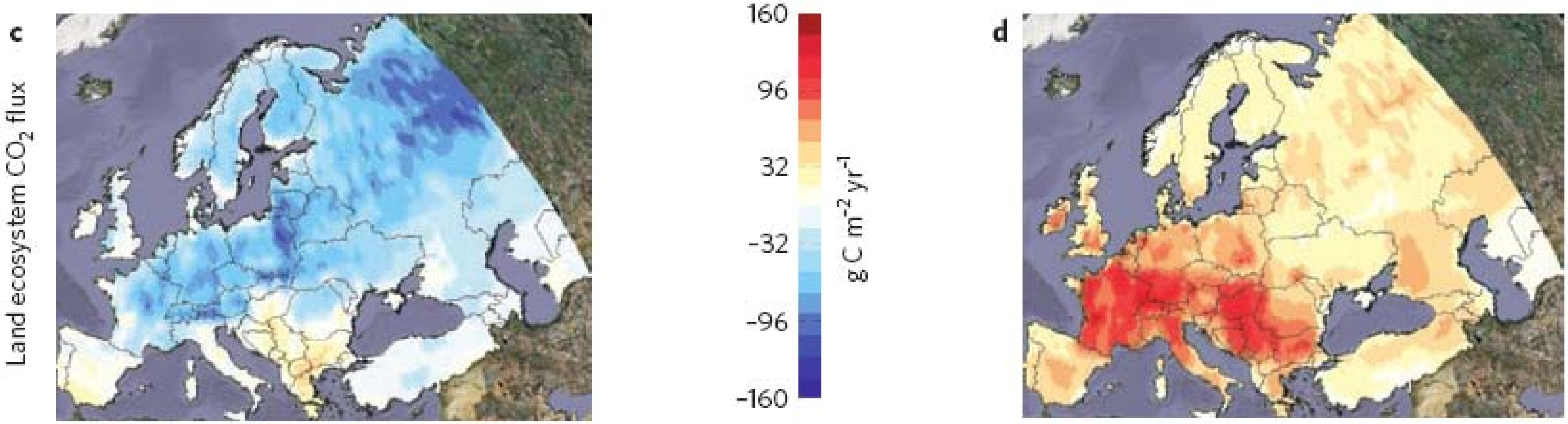
How today's CO_2 sinks will behave in a changing climate? Will they turn into sources?

How todays sources and sinks will behave in a changing climate?

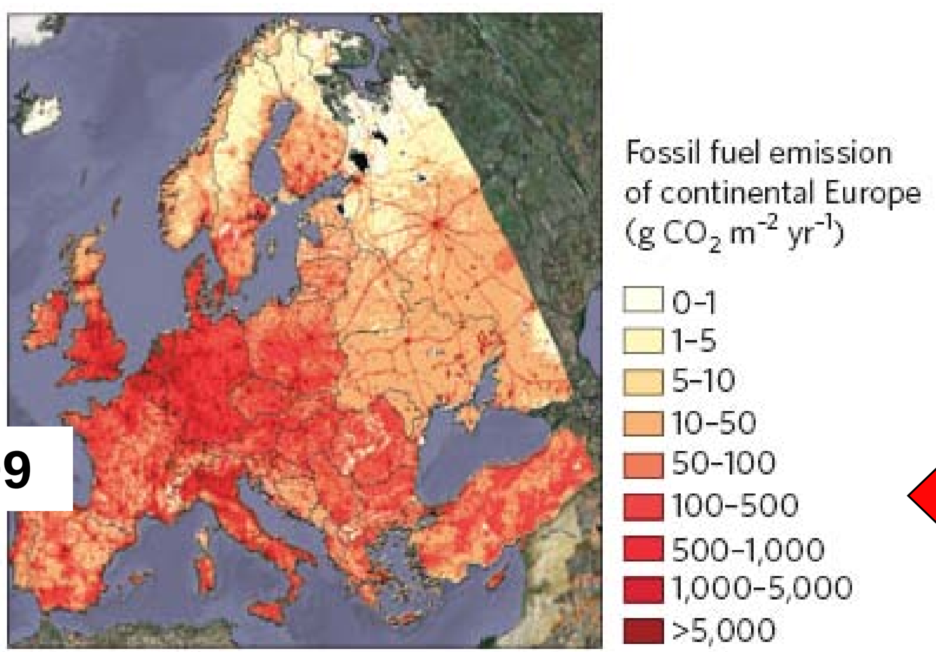
Relevant Scales



Carbon Balance of Europe

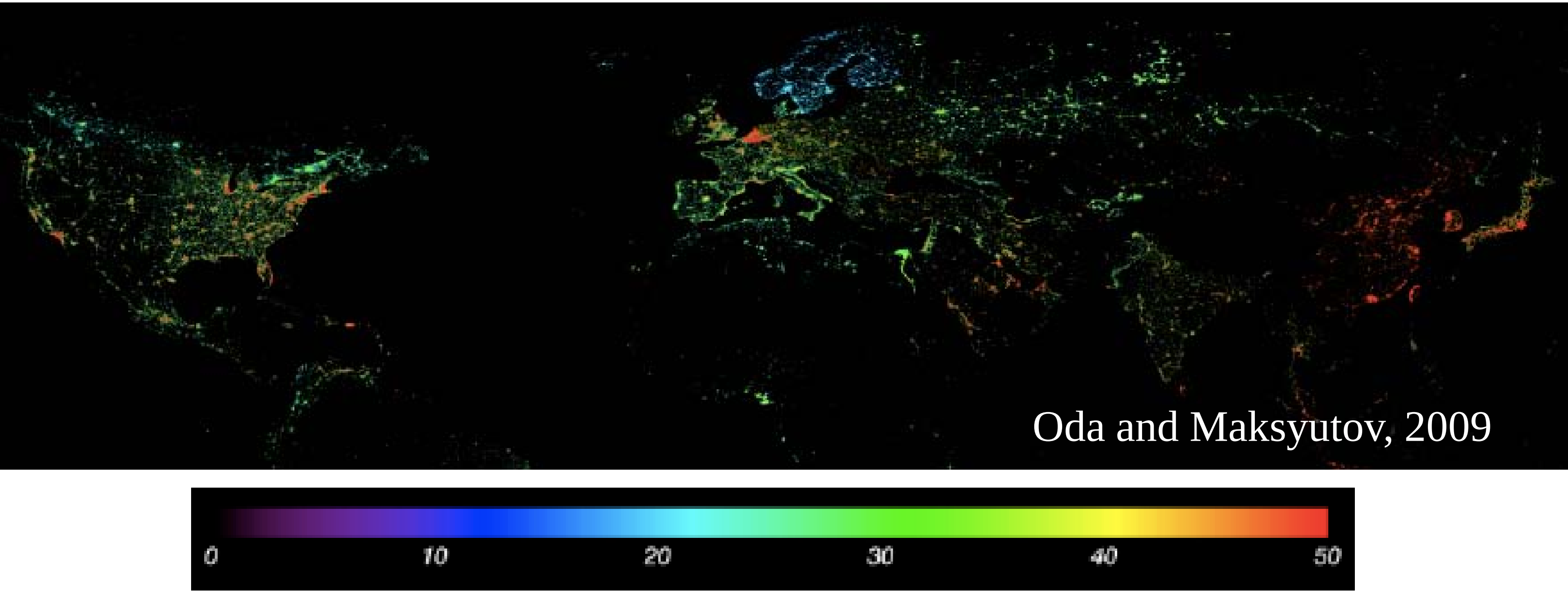


ecosystem CO_2 flux 2000-2004 av. sd. **Error on ecosystem CO_2 flux**



E. D. Schulze, NGEO, 2009

Anthropogenic CO_2 emissions



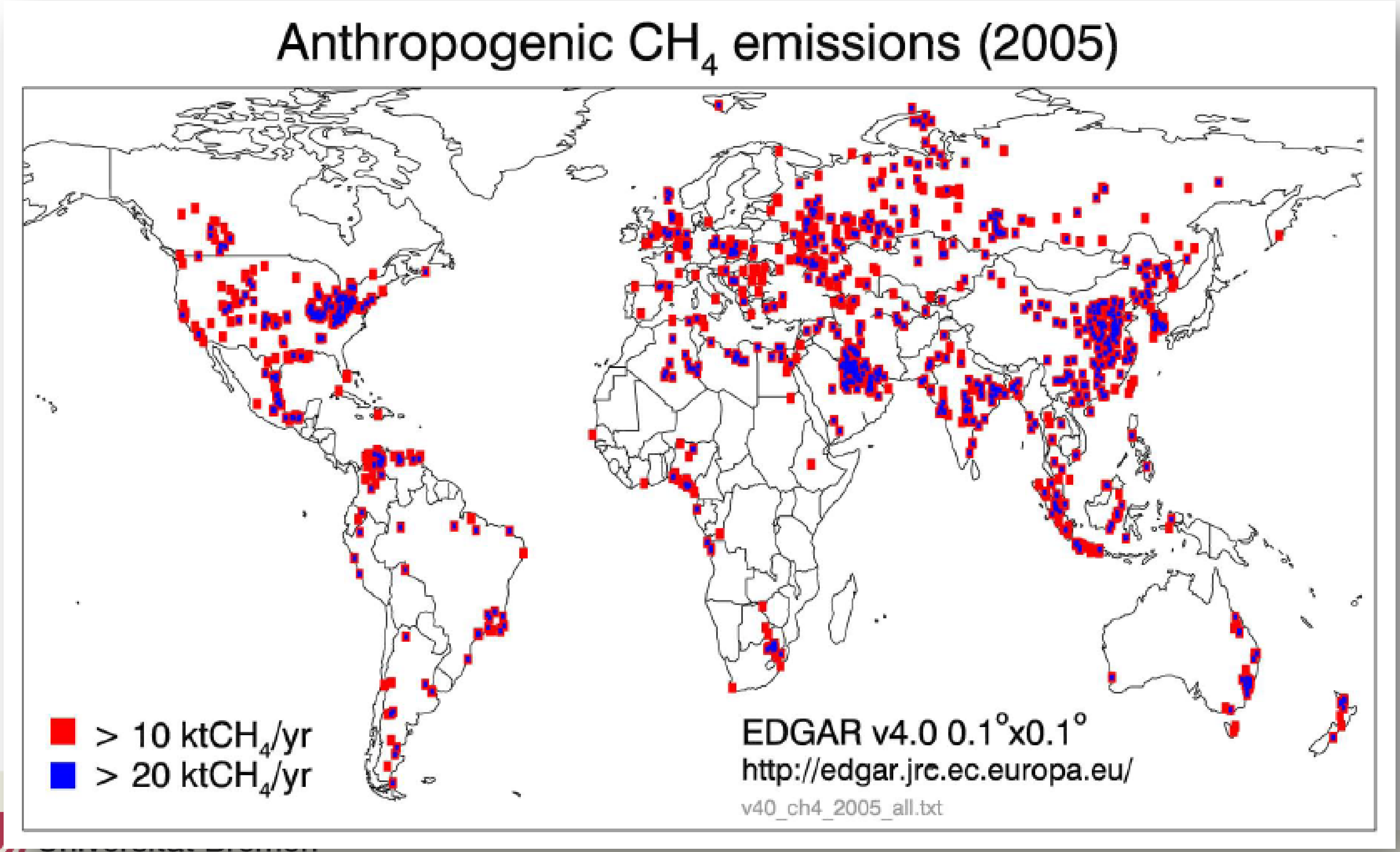
$MtCO_2$/year

CarbonSat single overpass detection limit 4 $MtCO_2$/year (u = 4 m/s)

CarbonSat single overpass detection limit 1 $MtCO_2$/year (u = 1 m/s)

Methane Hot Spots

XCH_4 retrieval precision = 8 ppb (0.5%):
CH_4 emission statistical error (1-sigma): 3-8 ktCH_4/yr (u=2-6 m/s)



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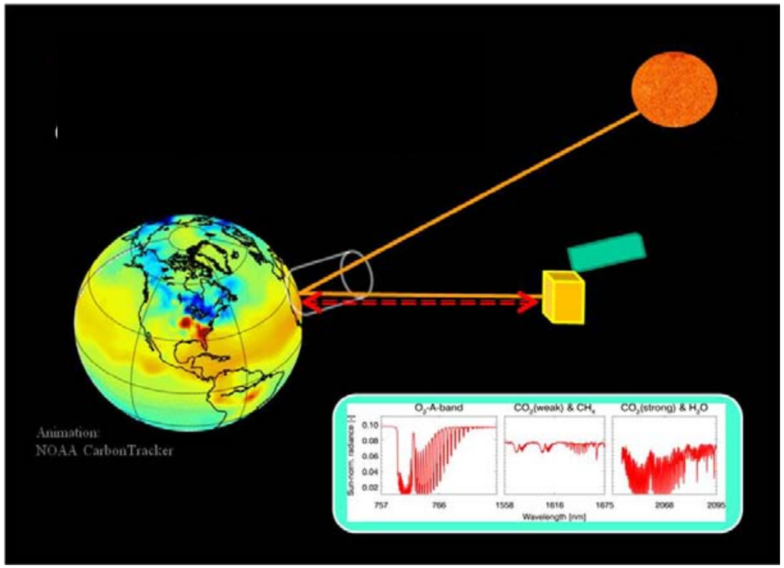
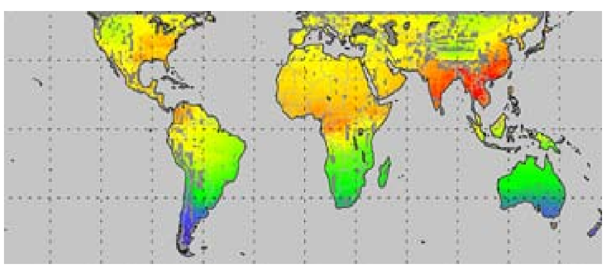
Bovensmann et al. AMT, 2010

Overarching Goal: Determine GHG Fluxes by atmospheric measurements (ground based and satellite) & Inverse Modelling



Global distribution of GHG, here CH_4

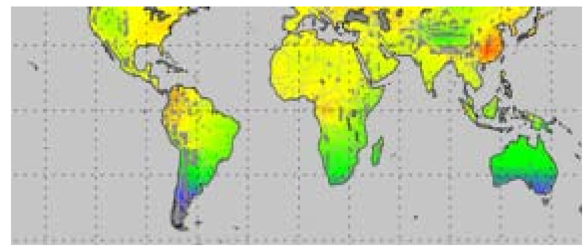


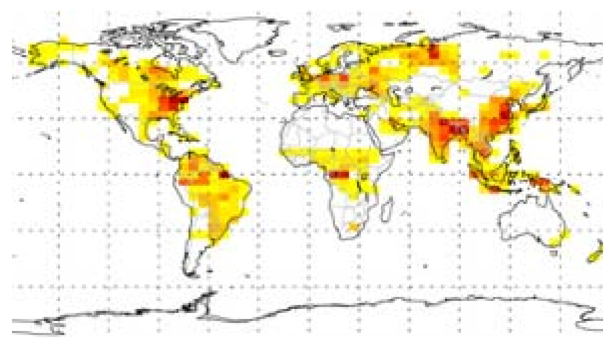
comparison between measurement and model

Simulated concentrations using a priori GHG fluxes

Forward simulation

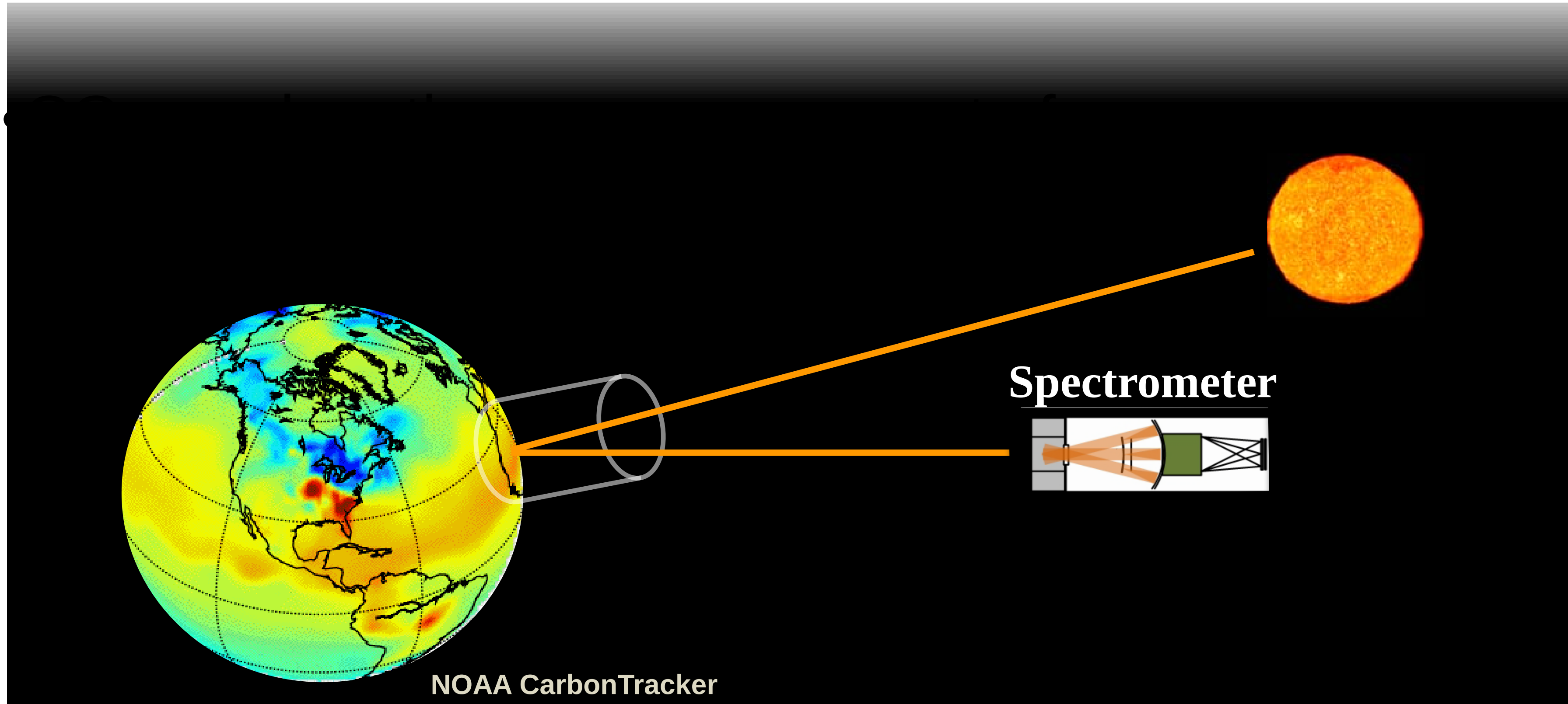
Inverse modelling

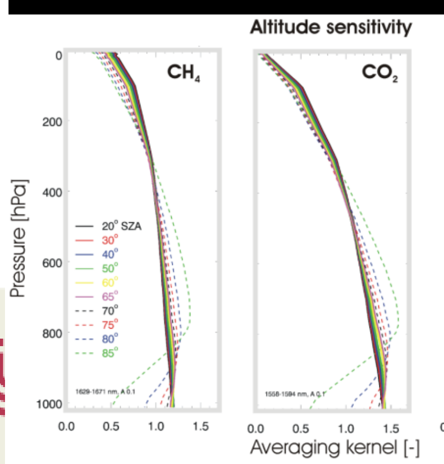


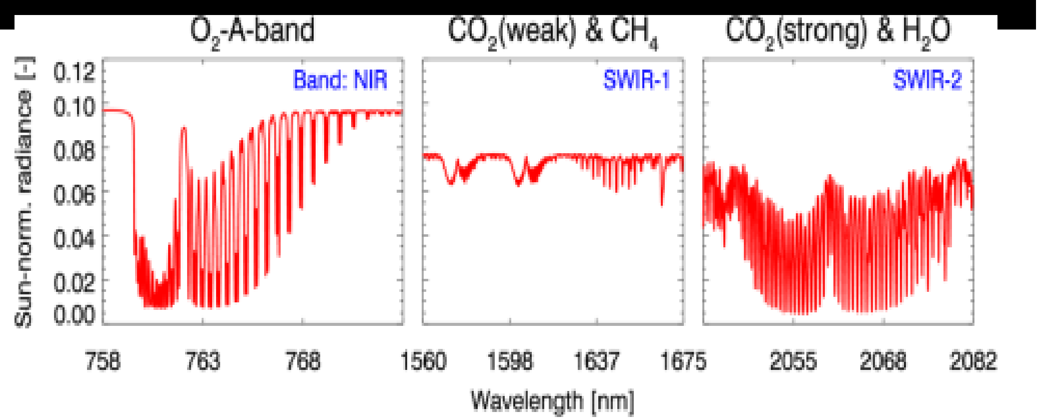


Result: True regional GHG fluxes (here CH4) through minimizing the distance between measurement and simulation

Measurement Concept Passive: Absorption Spectroscopy (basic concept proven by SCIAMACHY)







CarbonSat EE8 scientific (& societal) objectives

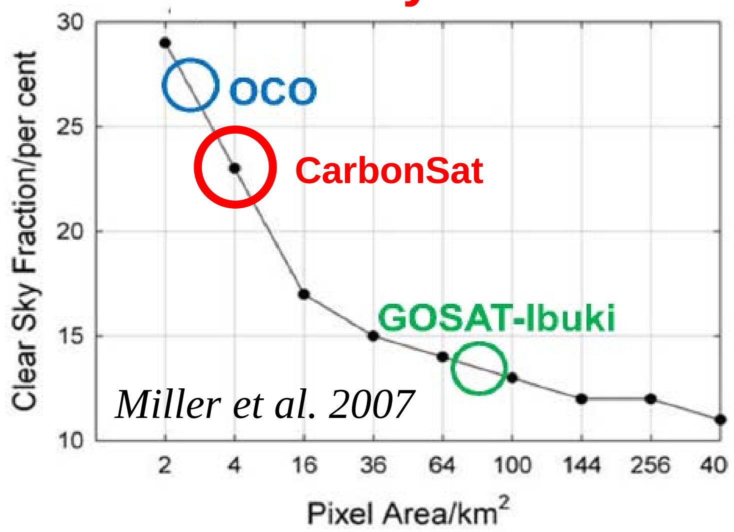
- To quantify magnitudes and spatial and temporal distributions of CO_2 and CH_4 sources and sinks from regional to suburban scales.
- To identify the CO_2 uptake mechanisms of the terrestrial biosphere and oceans.
- To determine the response of CO_2 and CH_4 sources and sinks to a changing climate.
- To assess potential contributions to treaty verification of UNFCCC and post-Copenhagen agreements
- **CarbonSat aims to better separate biogenic and atnhropogenic fluxes by “imaging” strong localised CO_2 and CH_4 emissions.**

CarbonSat Mission Requirements Overview	
Parameter	**Description**
Main geophysical data products	**Level 2:** Column-averaged mixing ratios of carbon dioxide (CO_2) and methane (CH_4) at ground-pixel resolution: XCO_2: Precision: < 1 ppm (threshold < 3 ppm = 0.8%) XCH_4: Precision: < 10 ppb (threshold < 18 ppb =1%) **Level 3:** XCO_2 maps (e.g., monthly at 0.5°x0.5°) XCH_4 maps (e.g., monthly at 0.5°x0.5°) The required **relative accuracy** for monthly averages at 500 x 500 km^2 resolution is: XCO_2: < 1 ppm (threshold < 2 ppm = 0.5%) XCH_4: < 10 ppb (threshold < 18 ppb = 1%) **Level 4:** • Regional CO_2 surface fluxes: Precision weekly fluxes @ 500 x 500 km^2 in $gC/m^2/day$: < 1 (goal), < 2 (threshold) • Regional CH_4 surface fluxes: Precision weekly fluxes @ 500 x 500 km^2 in $mgCH_4/m^2/day$: < 10 (goal), < 20 (threshold) • CO_2 hotspot emissions (e.g., power plant emissions): Precision single overpass ($MtCO_2/yr$): < 4 (goal), < 8 (threshold) • CH_4 hotspot emissions (e.g., geological sources): Precision single overpass ($ktCH_4/yr$): < 4 (goal), < 8 (threshold)

CarbonSat mission requirements

- Based on lessons learned from SCIA, OCO, GOSAT
- Single measurement error
  - XCO_2 < 1-3 ppm
  - XCH_4: < 8-18 ppb
- Orbit: LEO polar-sun-sync, early afternoon, with NPOESS
- High spatial resolution and coverage:
  - **2×2 km² ground pixel**
  - **500 km swath width**
- Spectrometer for **O_2, CO_2 and CH_4** absorption bands around **765 nm, 1.6 µm, and 2.0 µm**
- cloud/aerosol imager
- nadir imaging (main mode), glint mode, calibration modes
- 5-7 years mission lifetime

Clear Sky Fraction

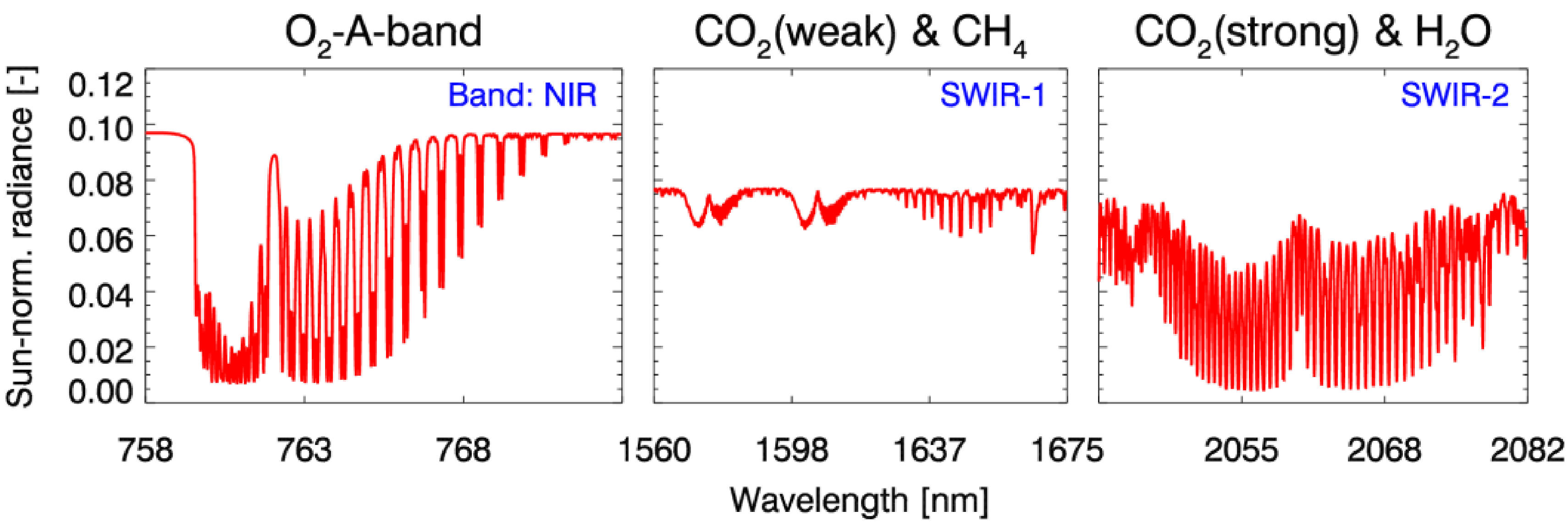


CarbonSat Number of Clear-Sky Observations				
Instrument	Spatial resolution [km²]	Total number observations per day	Clear-sky frequency	Total number clear-sky observations per day
CarbonSat	4	28,000,000	23%	6,440,000
OCO	3	1,680,000	27%	453,600
GOSAT	85	10,000	13%	1,300
SCIAMACHY	1800	70,000	5%	3,500

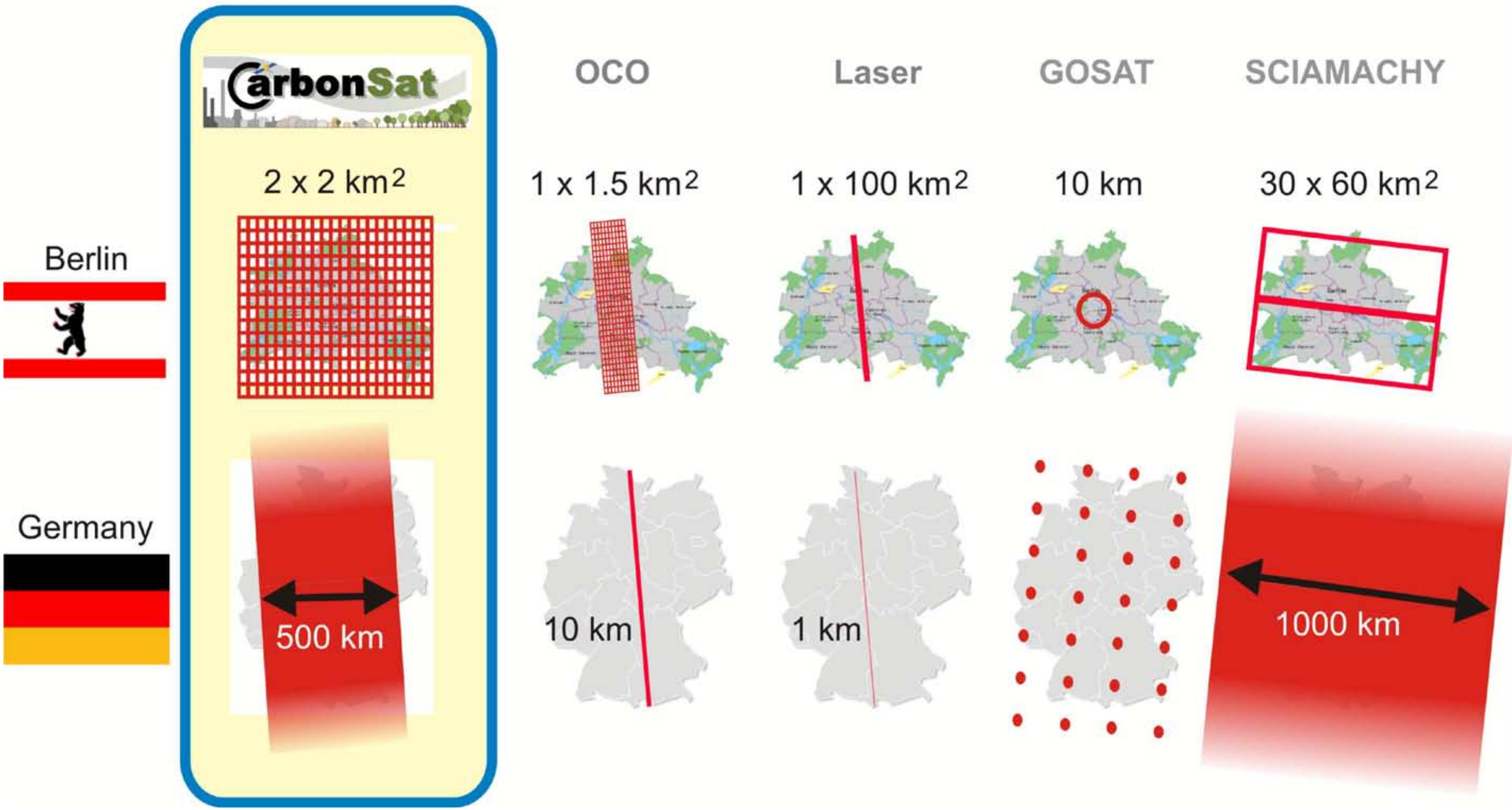
***Table 1:** Estimate of CarbonSat's number of total and clear-sky observations per day compared to other missions.*

Req.: Spectral bands, resolution & sampling

CarbonSat Imaging Spectrometer			
Band	**Spectral range [nm]**	**Resolution [nm]**	**SNR [-]** (A=0.1, SZA=50^{o}, t_{int}=0.3s)
NIR	757 - 775	< 0.03 (< 0.045)	> 500 (> 250)
SWIR-1	1559 - 1675	< 0.15 (<0.35)	> 600 (> 300)
SWIR-2	2043 - 2095	< 0.1 (< 0.125)	> 300 (> 120)

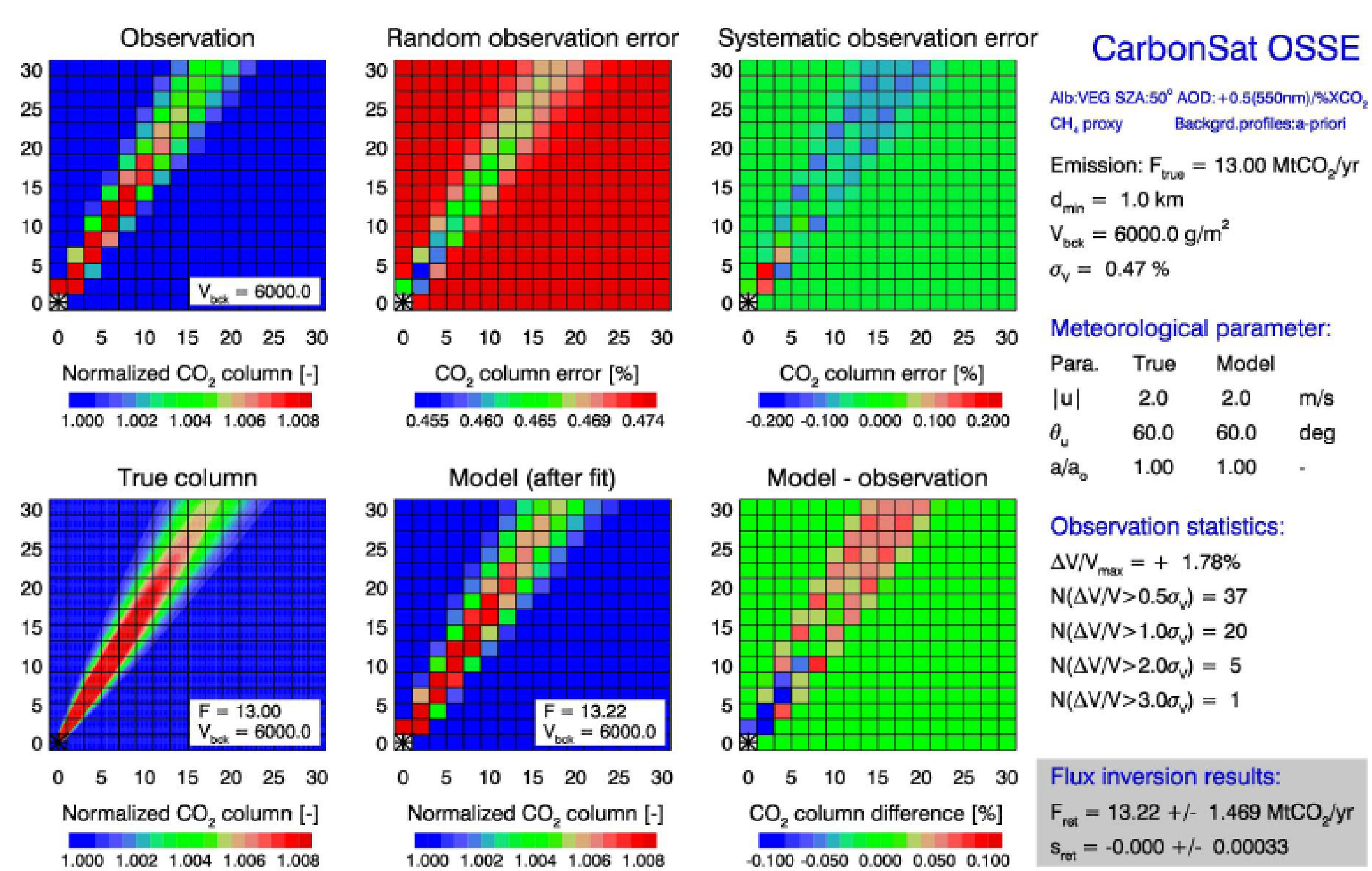


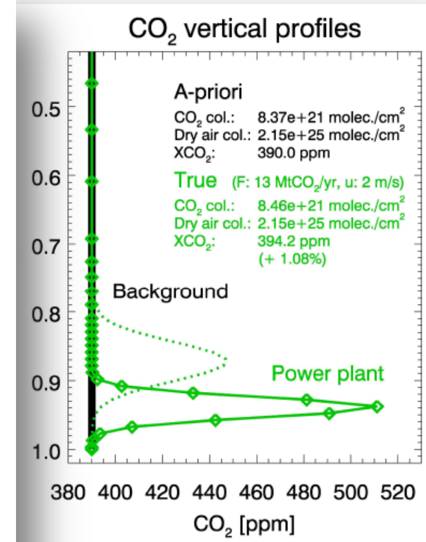
CarbonSat - Spatial resolution & coverage



CarbonSat spatial resolution and coverage enables new important application areas: CO_2 and CH_4 emission „hot spot“ detection/monitoring

Power Plant CO_2 Emission Uncertainties





SZA: 50º
Albedo: Vegetation

Aerosols:
ΔAOD +0.5 (550 nm) per % ΔXCO_2

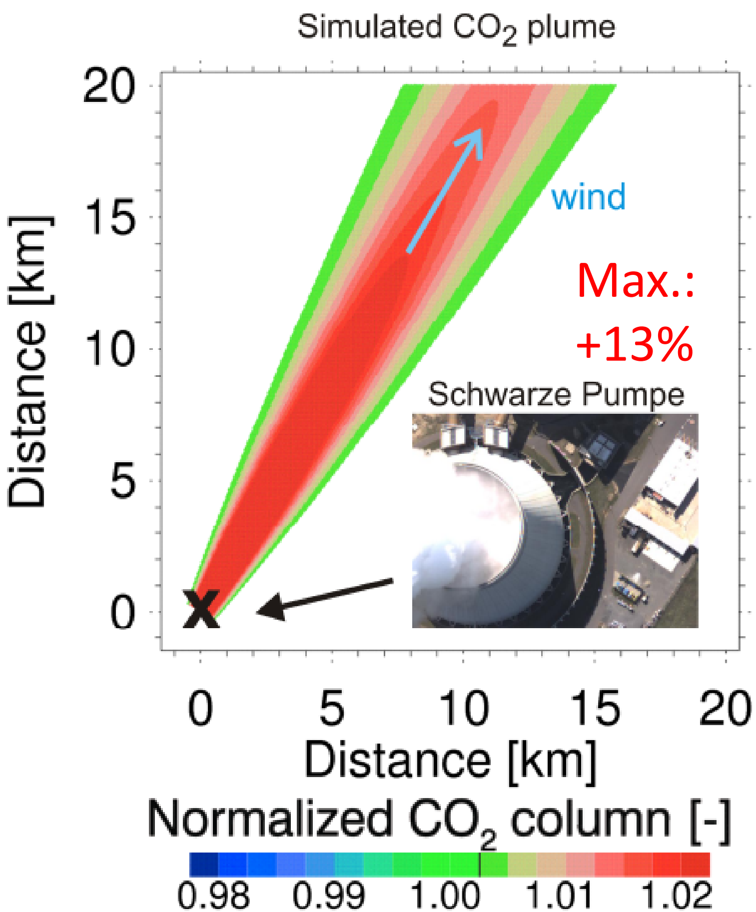
Random error:
1.47 $MtCO_2$/yr

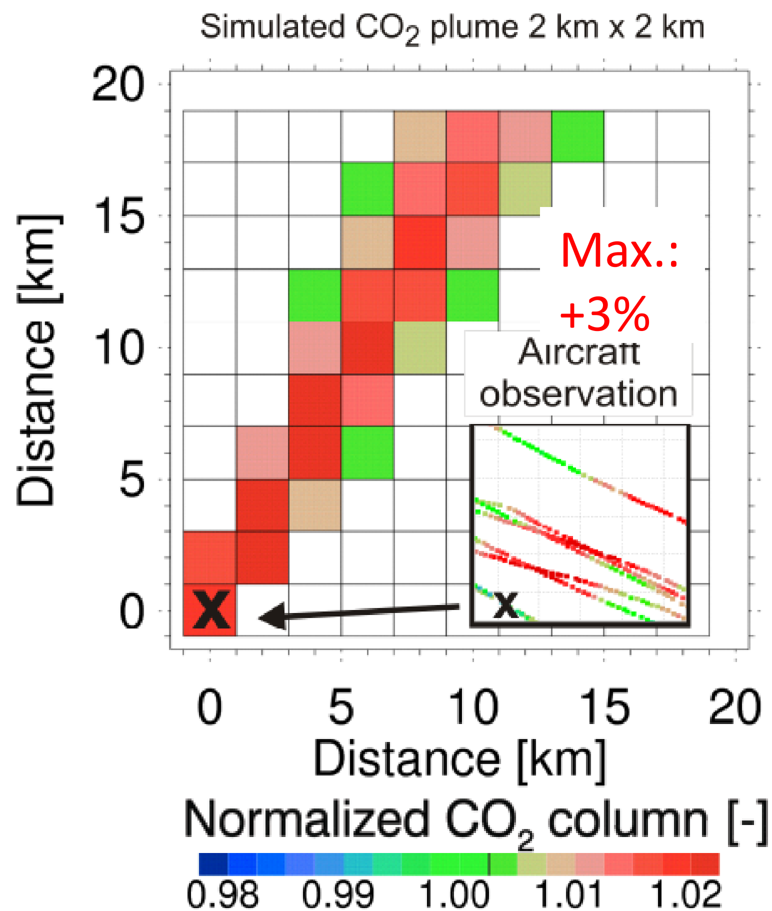
Systematic error:
0.22 $MtCO_2$/yr

Inverse plume modelling using airborne data shows that power plant emissions can be derived with an error < 5%,
Krings et al in preparation

Bovensmann et al. AMT, 2010

Example: CO_2 from a power plant (coal): Airborne vs. CarbonSat





Emission: **13 MtCO2/year**

(„moderate“; many power plants emit 20-35 $MtCO_2$/year)

Airborne: Gerlowski et al. AMTD, 2010

Emission uncertainty single overpass (2 ppm XCO_2 error, $u = 1$ m/s): **+/- 1 MtCO2/year** (1-sigma)

approx. proportional to wind speed u & statistical meas. error

Global Methane Budget

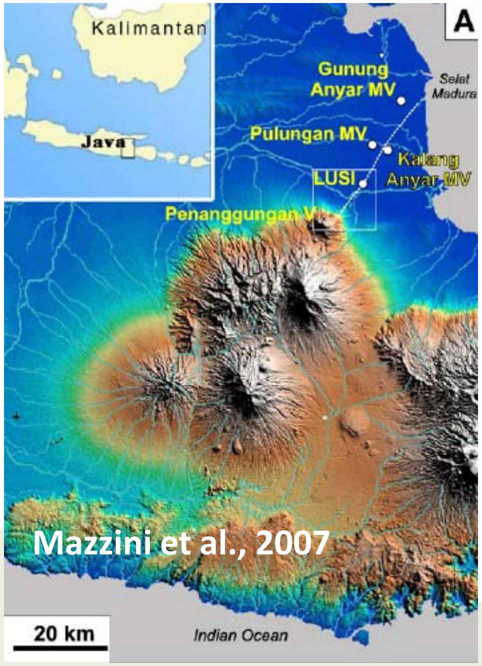
Identified Methane Source	**estimate Mt CH4/yr**	**Range of estimates Mt CH4/yr**	**IPCC 2007 Mt CH4/yr**	**source characteristic**	**r**
total wetlands	145	92 - 237		mainly natural, extended sources	
rice agriculture	60	40 - 100		anthropogenic, extended sources	
ruminant animals	93	80 - 115		anthropogenic, extended sources	
termites	20	20 - 20		natural extended source	
biomass burning	52	23 - 55		mainly anthropogenic, extended source	
energy generation (coal, gas, oil)	95	75 - 110		anthropogenic, localised source	
landfills	50	35 - 73		anthropogenic, localised source	
Ocean	10	5 - 15		natural extended source	
Hydrates (marine & terrestiral)	5	5 - 10		natural, partly localised source	
geological (Etopie et al. 2008)	*53*	*42 - 64*		natural, partly localised source	
Total identified sources	**583**	**500 - 600**	**582**		
identified methane sinks					
tropospheric oxidation	507	450 - 510			
stratopsheric loss	40	40 - 46			
soils	30	10 - 44			
total identified sinks	**577**	**460 - 580**	**581**		
Love et al 2006, updated w.r.t. IPCC 2007 and Etopie et al. 2008					
Total sources-sinks	**-47**	**-80 to + 140**	**1**		

CarbonSat: CH_4 emission hot spot targets

Oil and gas fields

Pipelines incl. compressor stations

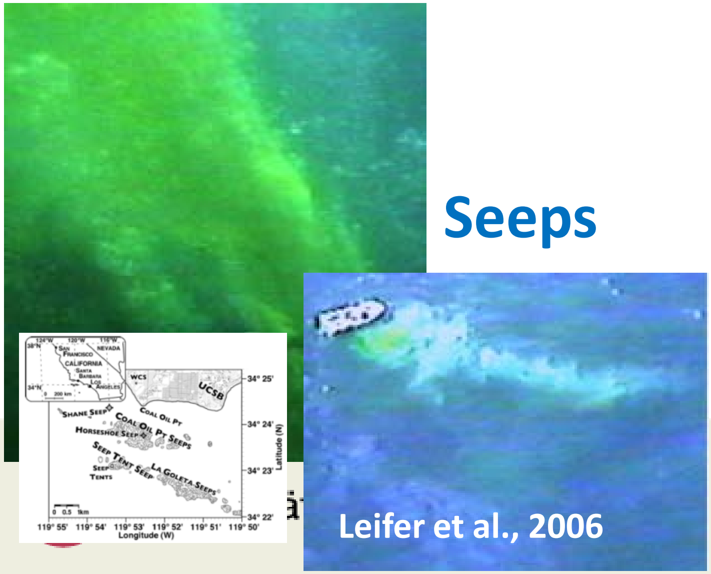
Mud volcanoes



Mazzini et al., 2007

Landfills / Waste

Seeps



Leifer et al., 2006

CarbonSat: Methane hot spot emission targets

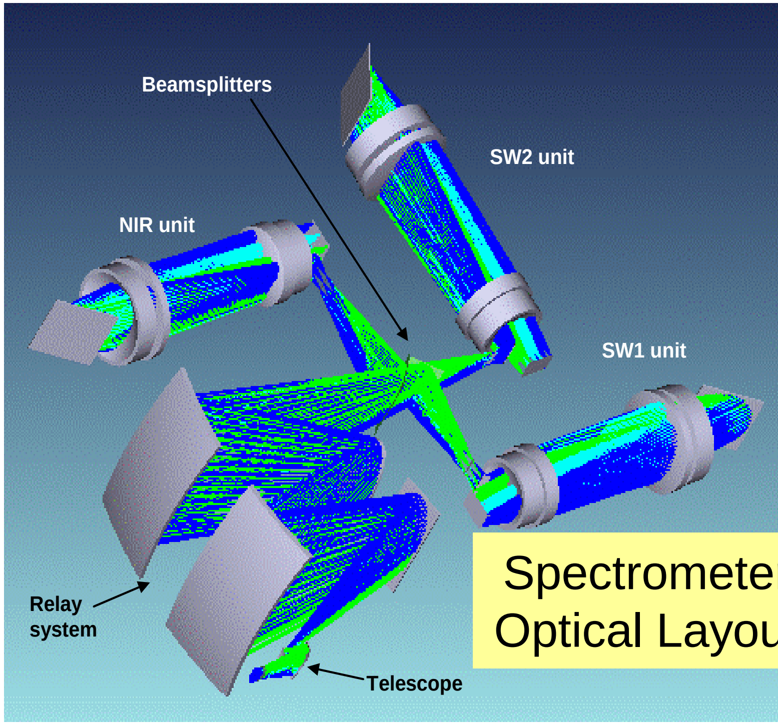
Target must produce a detectable methane column enhancement at 2x2 km^2 resolution:
=> Single overpass detection limit is **4 - 8 ktCH4/year** (u = 2 - 6 m/s, precision 8 ppb)

Methane hot spot targets	Comparison with CarbonSat detection limit
Pipelines incl. compressor stations	Under certain conditions detection may be possible even at GOSAT resolution of 10 km (estimated GOSAT detection limit 11 ktCH4/year (u = 1 m/s, 4 ppb) (Inoue et al., 2009); leaks in eastern Europe found to be up to **29 ktCH4/year**
Oil and gas fields	E.g. western siberian gas fields (Yamal, south of Kara sea) Jagovkina et al., 2000 (500 ppb above background below 500 m = approx. **2%** column enhancement) or Prudhoe Bay, northern Alaska (unpublished ARCTAS DC-8 March 2008 results: CH_4 columns enhanced by about **5%** along several km)
Landfills	Many landfills emit more than **10 ktCH4/year** (e.g., European Pollutant Release and Transfer Register)
Mud volcanoes	Under certain conditions (e.g., eruption) detection may be possible even at SCIAMACHY resolution of 30x60 km^2 (Kourtidis et al., 2006)
Seeps	Several, e.g. Coal Oil Point (COP) marine seeps, Santa Barbara, California (Leifer et al, 2006): about **25 ktCH4/year** (1.15 m^3/s) or Georgia Black Sea seeps (Judd et al., 2004): about **40 ktCH4/year**
Other	Potentially many other more or less localized targets such East Siberian Arctic Shelf (ESAS): up to +8 ppm over Laptev Sea along > 100 km (Shakhova et al., 2010)

See: Bovensmann et al., AMT, 2010

CarbonSat spectrometer (Kayser Threde)

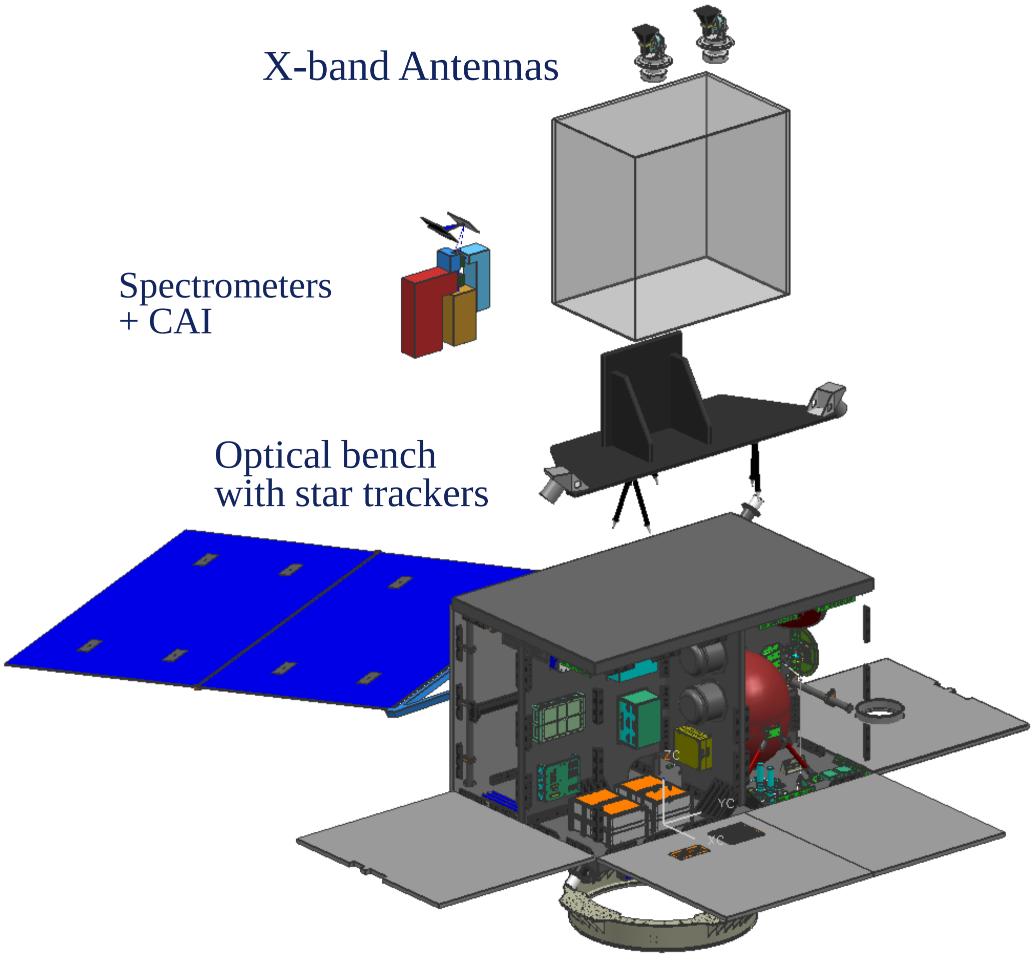
Parameter	Value / Description
Orbit height	828km
Field of view	35°
Swath	500km
SSD	2km x 2km (at nadir)
Polarisation handling	Polarisation scrambler
Spectrometer slit size	54 µm x 13.5 mm
Spectral bands: NIR SW1 SW2	[nm] 757-775 1,559-1,675 2,043-2,095
Spectral resolution NIR SW1 SW2	0.045 nm, 3 pixels 0.35 nm, 3 pixels 0.125nm, 3 pixels
Calibration accuracy	< 1.5 %
Polarisation sensitivity	< 0.01
Detector technology	substrate-removed MCT
Pixel size	18µm x 18µm
Spectral pixels	~ 1000
Spatial pixels	~ 250 (after binning)
Detector temperature	150K

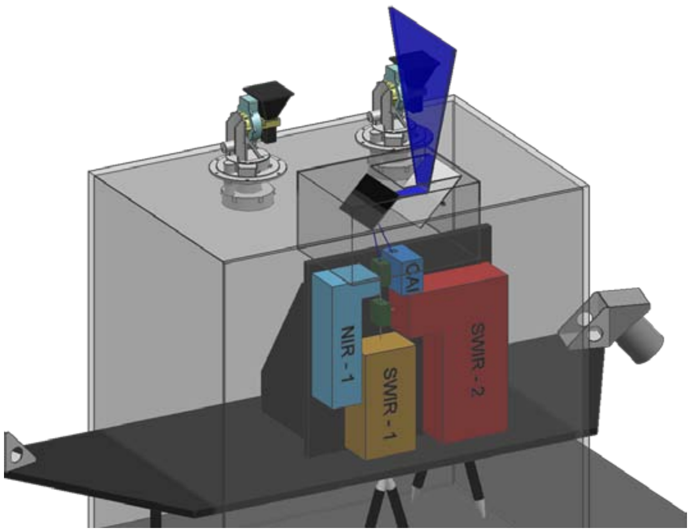


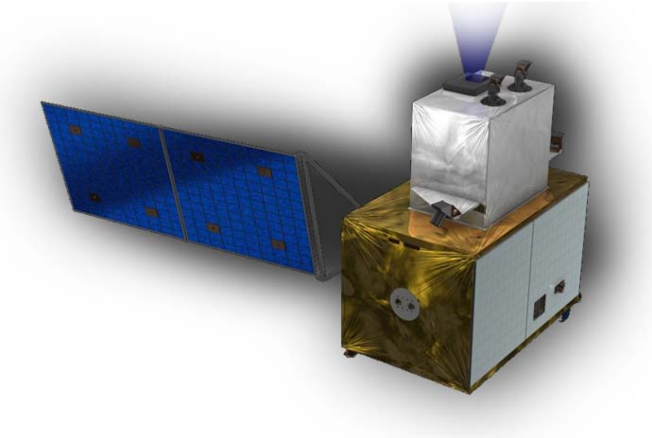
Spectrometer Optical Layout

- Push broom grating imaging spectrometer
- High spectral resolution, high SNR, high accuracy
- Nadir and sun glint tracking observation modes
- Sun diffuser and on-board light sources for regular calibration and stability monitoring
- Mass (including CAI) ~ 90kg
- Power (including CAI) ~ 150W

Configuration of CarbonSat Platform (OHB)



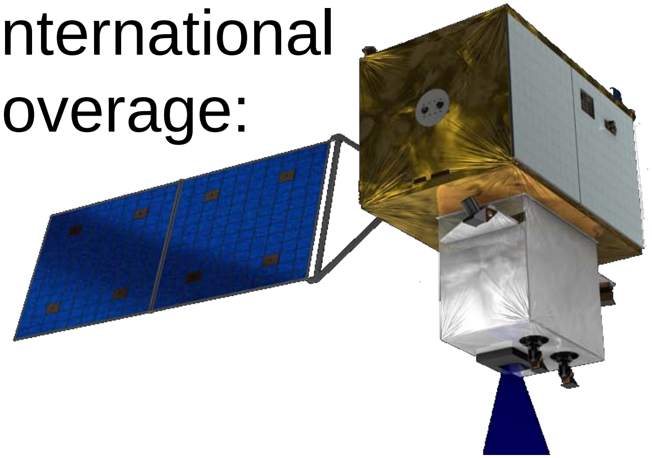




Summary & Conclusions

- Due to the highest sensitivity of solar backscatter NIR/SWIR absorption spectroscopy to concentration changes in the lowest atmosphere (PBL), this method has higher relevance for source/sink determination then thermal IR
- CarbonSat mission concept is designed to provide for the first time data with local spatial resolution (2 x 2 km2) and good global coverage (500 km swath), to „image“ **CO_2 and CH_4** hot spots and allow hot spot source estimates
  - selected by ESA for Phase A/B1 as Earth Explorer #8 (opportunity class), launch 2018 earliest
  - Mission & instrument studies, incl. inverse modelling ongoing
  - Investigation of other (fast-track) mission implementation options ongoing
- Vision: international constellation of CarbonSat's

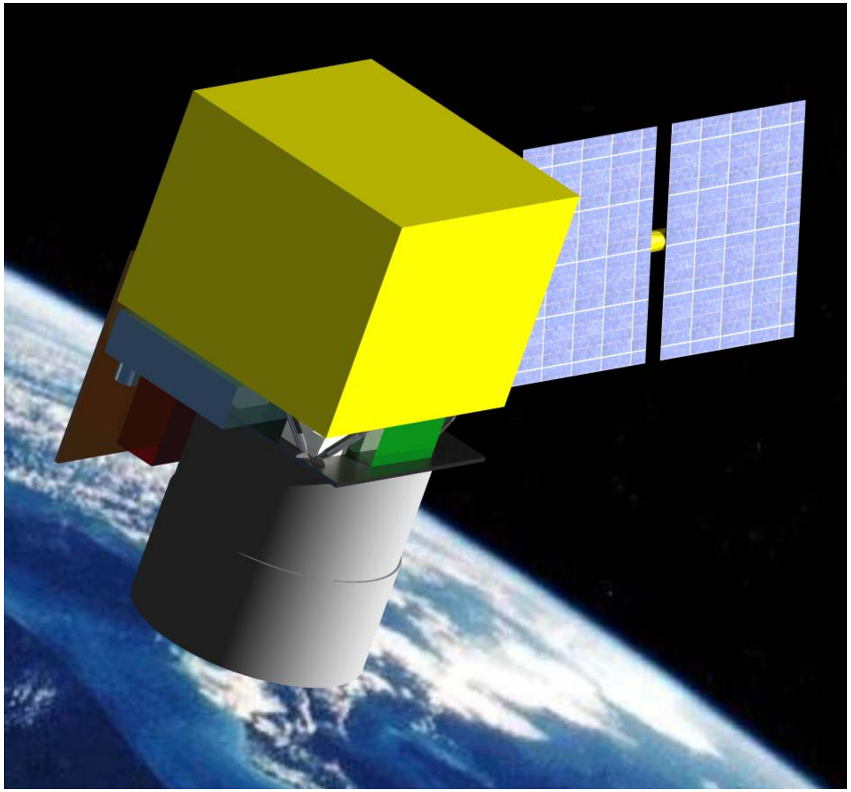
CarbonSat Constellation



- Five CarbonSat-type satellites in an international constellation to provide global daily coverage:
  - Timely detection of changes
  - Higher accuracy achieved through averaging more measurements
  - Globally compareable data
  - Reliable and timely services
- Establish an international common understanding about the magnitude of greenhouse gas fluxes in a changing climate
- Provide an independent and transparent global system to support verification of **international agreements on CO_2 and CH_4 emission reduction**

The French-German Climate Mission MERLIN

- Measurement of the column-integrated dry-air volume mixing ratio of methane, called XCH_4 using the DIAL technique with following features:
  - random error: ≤ 36 ppb
  - systematic error: 3 ppb
  - horizontal resolution: 50 km
  - individual measurement: 100 m
  - global coverage (high latitudes in winter time)
  - no bias from aerosol and cloud scattering due to range-gated instrument operation
- Estimation of methane sources in key observational regions with the help of inverse modelling
- Estimation of vegetation height from individual off-line measurement
- Measurement of cloud boundaries and elevated aerosol layers



Artist view of the spacecraft MYRIADE from CNES carrying the CH4 IPDA lidar instrument from DLR

The End

Further Reading …

Atmos. Meas. Tech., 3, 781–811, 2010
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doi:10.5194/amt-3-781-2010

Atmospheric Measurement Techniques

A remote sensing technique for global monitoring of power plant CO_2 emissions from space and related applications

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Abstract. Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas (GHG) causing global warming. The atmospheric CO_2 concentration increased by more than 30% since pre-industrial times – primarily due to burning of fossil fuels – and still continues to increase. Reporting of PP CO_2 emission due to instrument noise is in the range 1.6–4.8 $MtCO_2$/yr for single overpasses. This corresponds to 12–36% of the emission of a mid-size PP (13 $MtCO_2$/yr). We have also determined the sensitivity to parameters which may result in systematic errors such as atmospheric transport