Quantification of natural and man-made greenhouse gas surface fluxes from satellite observations of atmospheric CO_2 and CH_4 column amounts

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on behalf of the CarbonSat Team

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WFB Bremen and DLR Space Agency

http://www.iup.uni-bremen.de/carbonsat/

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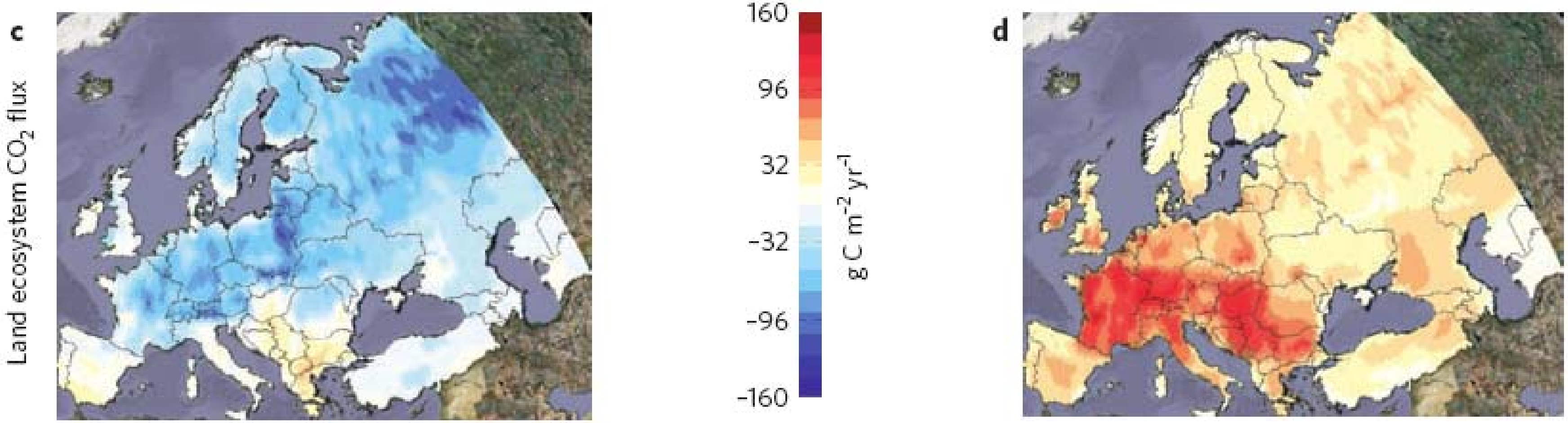
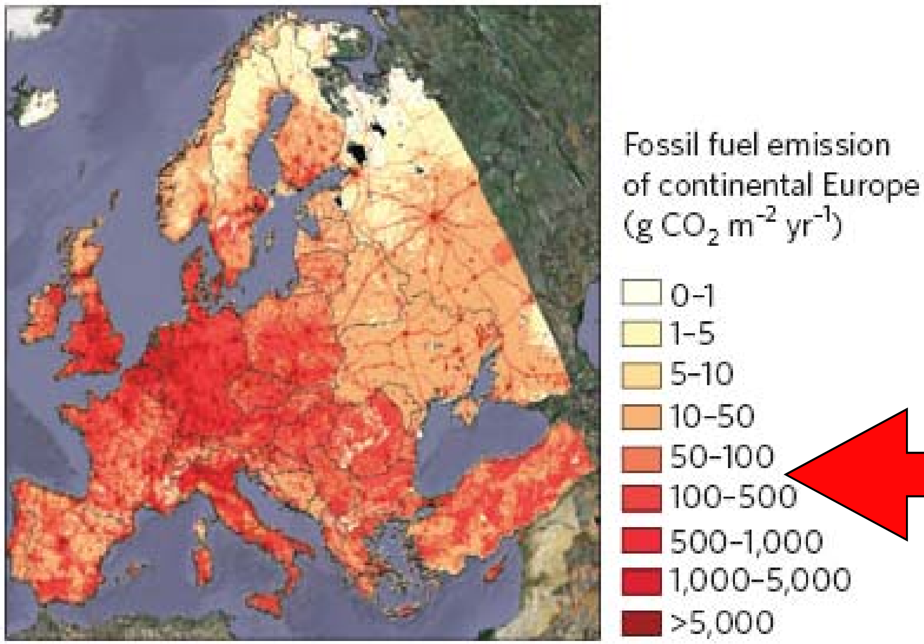
Example: Carbon Balance of Europe



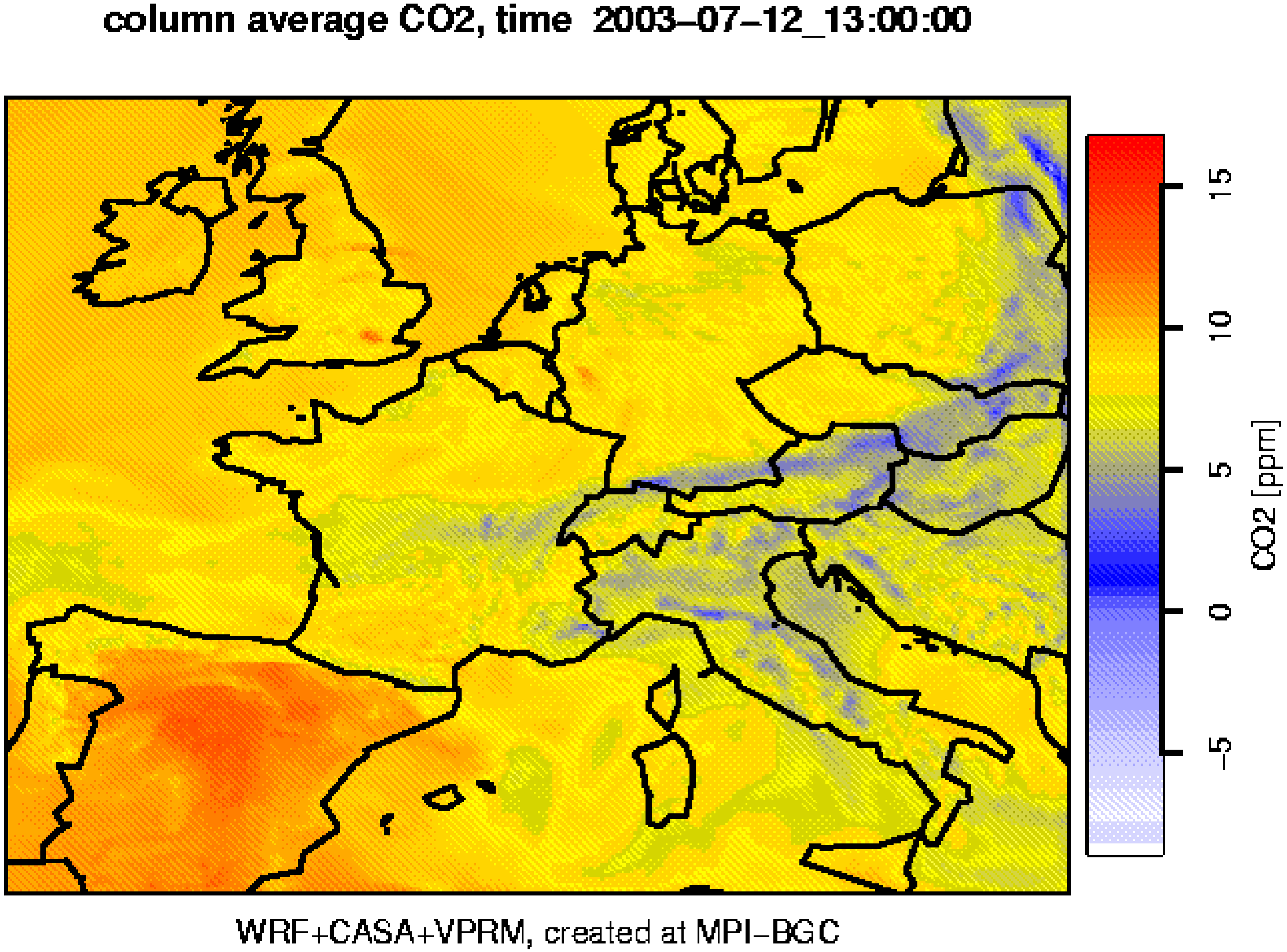
ecosystem CO_2 flux

error on ecosystem CO_2 flux



E. D. Schulze, NGEO, 2009

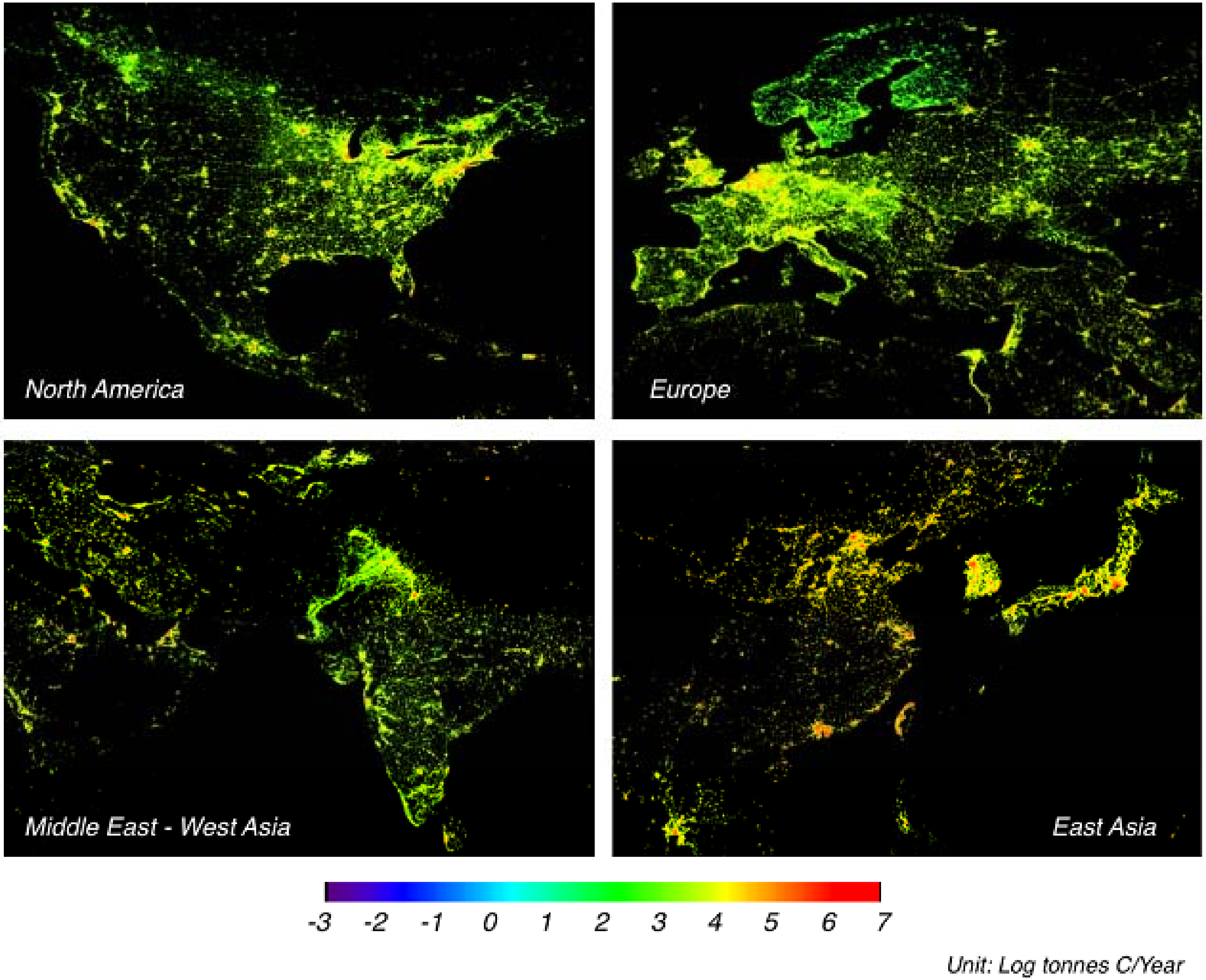
Fluxes AND Meteorology determine XCO2



Resolution: 10 km x 10 km

D. Pillai et al. 2010 ACP, MPI Jena

NH CO_2 Emissions 2006



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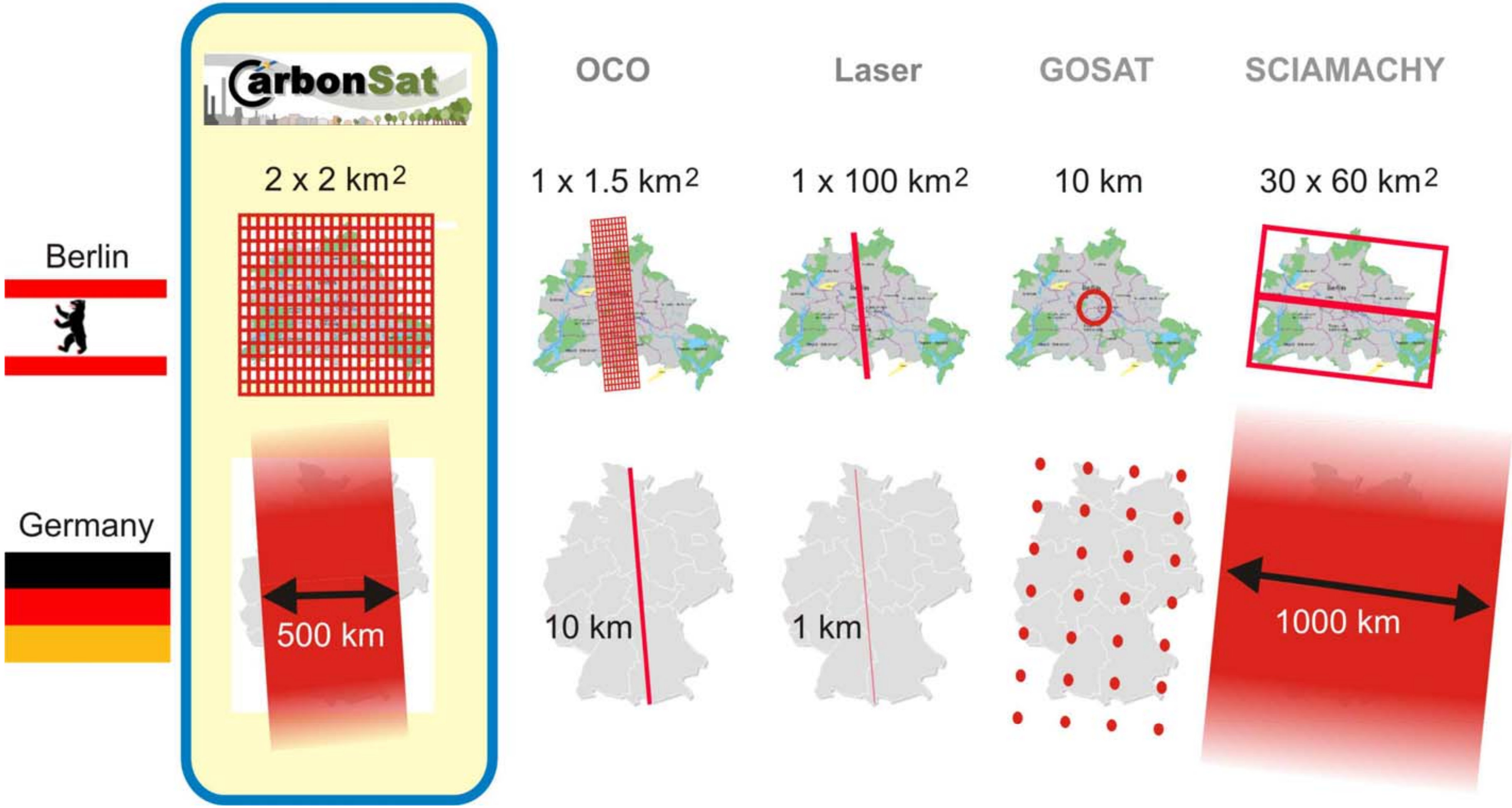
Oda and Maksyutov, ACP 2011

CO_2 and CH_4 surface fluxes have spatially extended (diffuse) and localised components, both temporal variable

- ground based measurements are very accurate but have a "footprint" of at least several 100 km
- limited knowledge about localised emissions limits the quantification of the NH CO_2 land sink below continental scales (Guerney et al. 2005, Schulze et al. 2009, Ciais et al. 2010 etc.)
- Current satellite missions start to deliver GHG data of sufficient quality, but do not sample adequately atmospheric CO_2 and CH_4 (temporal, spatial resolution and coverage)
- CarbonSat aims to better separate biogenic and anthropogenic fluxes with global CO_2 and CH_4 data and "imaging" of strong localised CO_2 and CH_4 emission areas in combination of with inverse modelling.

CarbonSat - Spatial resolution & coverage

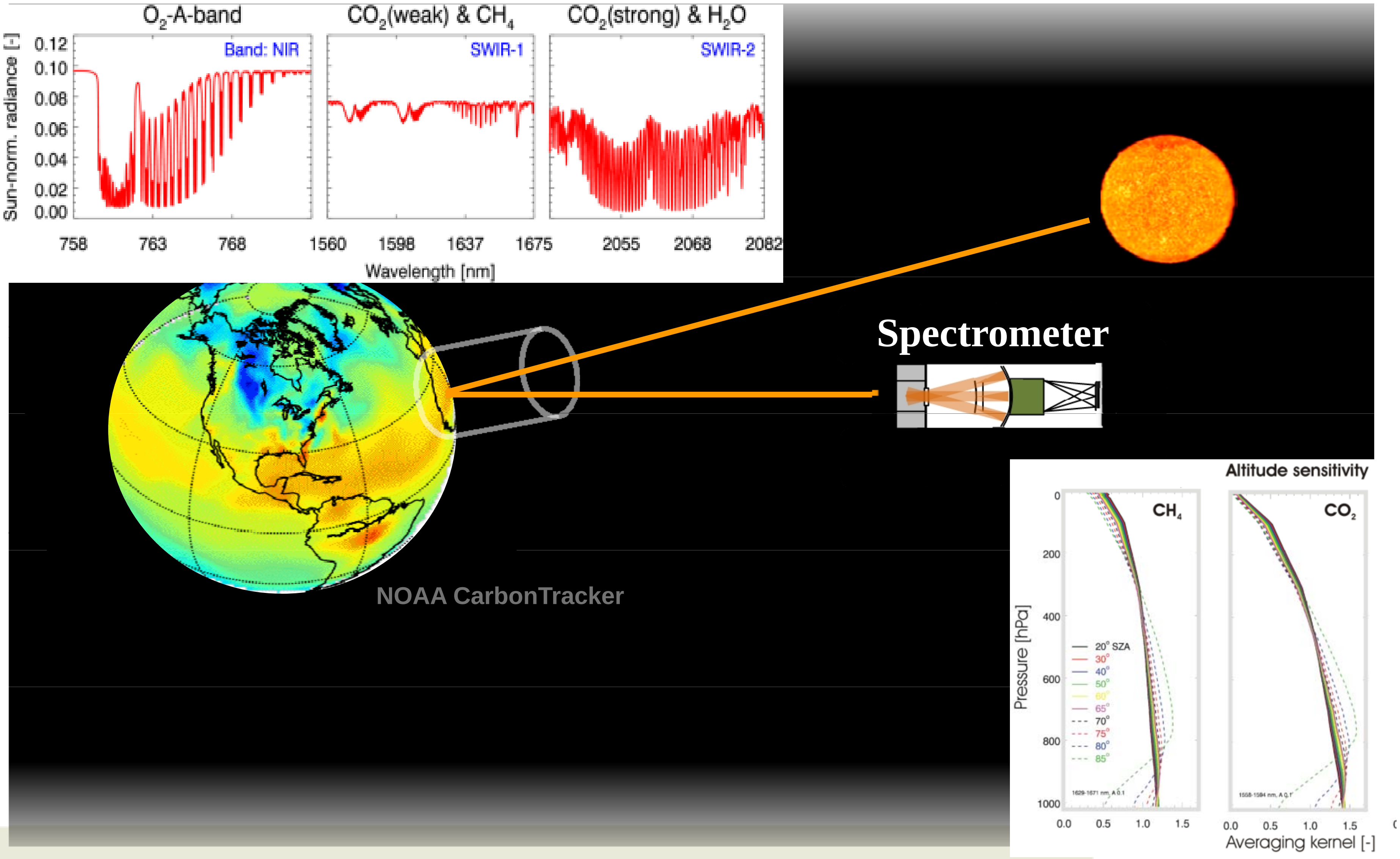


CarbonSat spatial resolution and coverage enables new important application areas: CO_2 and CH_4 emission from large point sources

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)

Measurement Technique: Solar Absorption Spectroscopy

(as SCIAMACHY, GOSAT and OCO)



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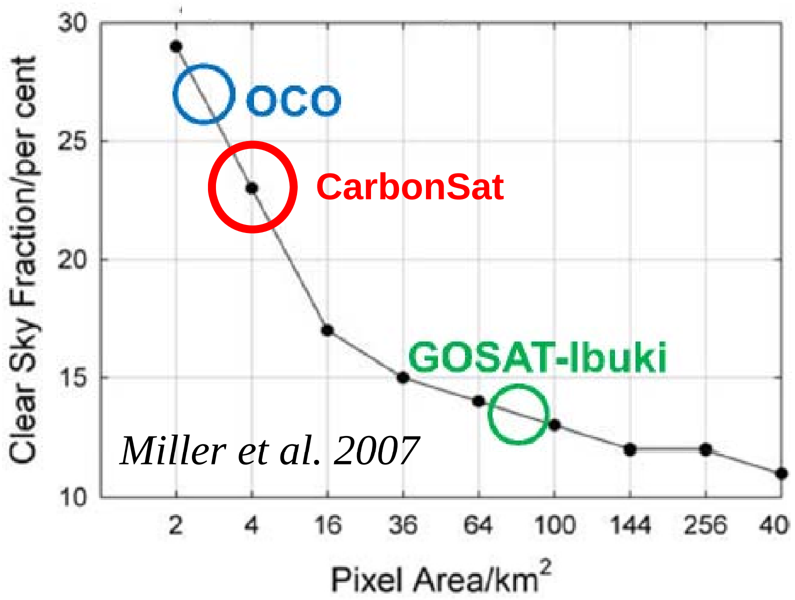
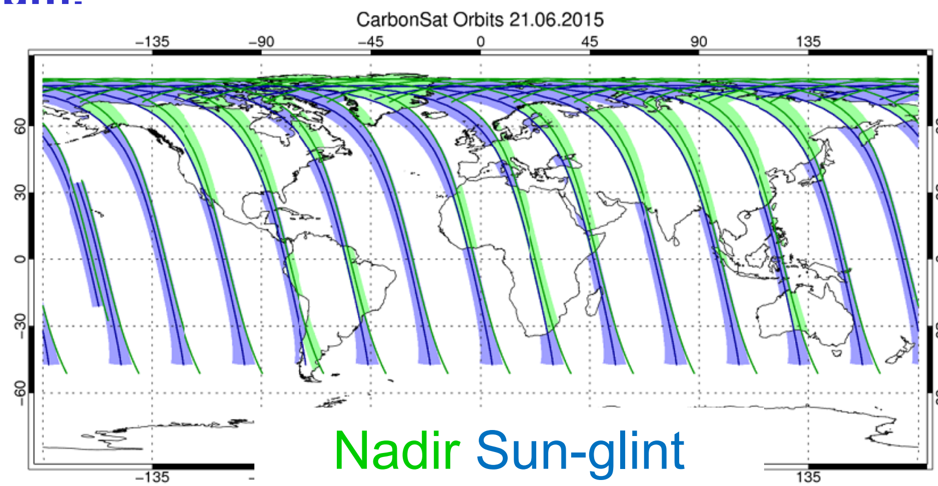
Details: Bovensmann et al. AMT, 2010

CarbonSat mission requirements survey

- Based on lessons learned from SCIA, OCO, GOSAT
- Single measurement error
  - XCO_2 < 1-3 ppm
  - XCH_4: < 10 -18 ppb
- Orbit:
  - LEO polar-sun-sync, early afternoon,
  - JPSS and S5P
- High spatial resolution and coverage:
  - **2×2 km² ground pixel (T)**
  - **500 km swath width (G)**
- Spectrometer for **O_2, CO_2 and CH_4** absorption bands around **765 nm, 1.6 µm, and 2.0 µm.**
- **spectral resolution (0.05 – 0.3 nm),**
- **high SNR (300-600)**
- nadir imaging (main mode), glint mode, calibration modes
- 5 years mission lifetime

Clear Sky Fraction





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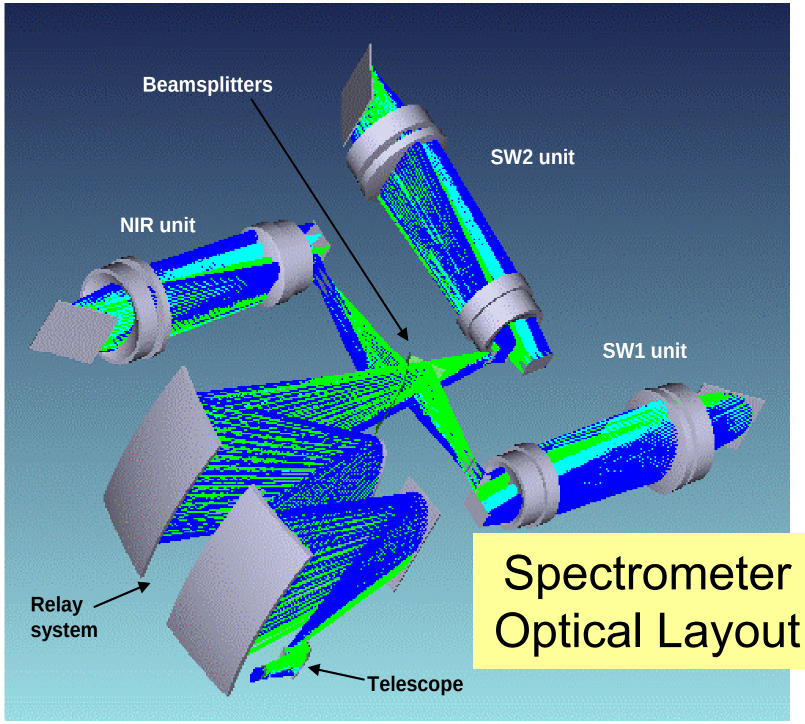
CarbonSat spectrometer (Phase 0 by Kayser Threde)

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

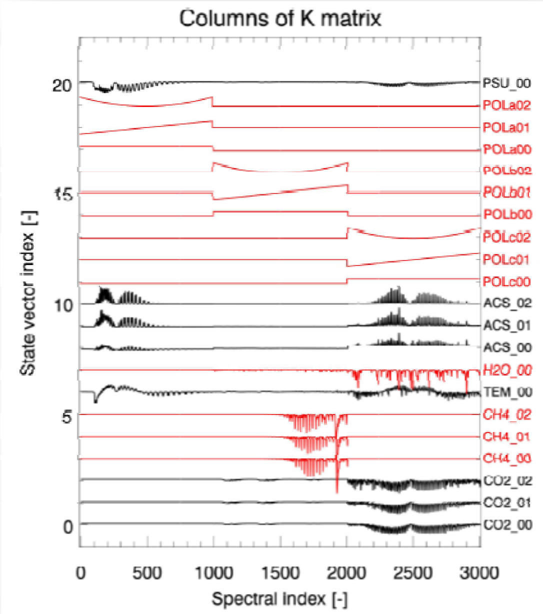


Spectrometer Optical Layout

- 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

Simulated Retrievals -> Retrieval Precisions

Bovensmann et al., 2010



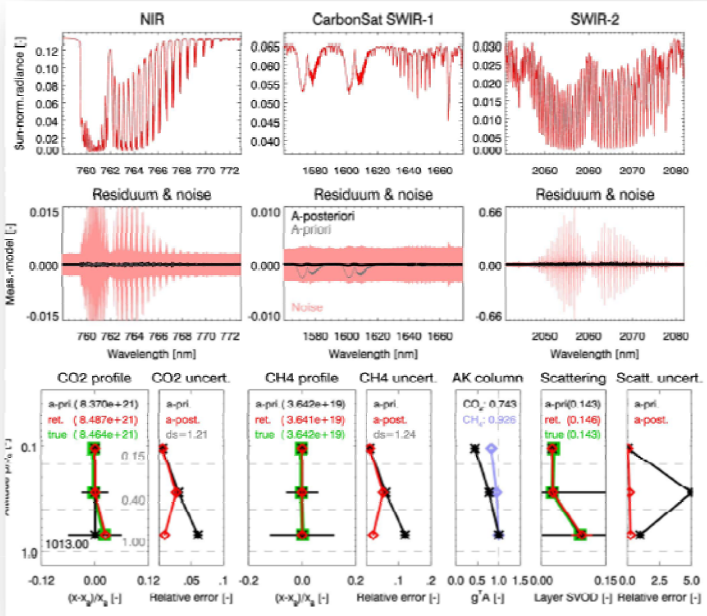


Table 3. Specification of eight scenarios and corresponding retrieval precisions for CO_2 and CH_4 columns, surface pressure (p_o), $XCO_2(p_o)$ and $XCO_2(CH_4)$ for CarbonSat nadir mode observations. $XCO_2(p_o)$ refers to XCO_2 obtained using the "p_o-proxy method" and $XCO_2(CH_4)$ refers to XCO_2 obtained using the "CH_4-proxy method" (see main text for details). Aerosol scenario: single scattering albedo 0.999, Henyey-Greenstein phase function with asymmetry parameter 0.7, aerosol optical depth (AOD) 0.2 at 550 nm with λ^{-1} wavelength dependence.

Scenario		Surface albedo (–) NIR / SWIR-1 / SWIR-2	SZA (deg.)	Retrieval precision CO_2 col. (%)	p_o (%)	CH_4 col. (%)	$XCO_2(p_o)$ (ppm)	$XCO_2(CH_4)$ (ppm)
VEG_25:	Vegetation, SZA=25°	0.20/0.10/0.05	25	0.26	0.08	0.37	1.1	1.8
SAS_25:	Sand/soil, SZA=25°	0.20/0.30/0.30	25	0.14	0.07	0.21	0.6	0.9
VEG_50:	Vegetation, SZA=50°	0.20/0.10/0.05	50	0.29	0.06	0.42	1.2	2.0
SAS_50:	Sand/soil, SZA=50°	0.20/0.30/0.30	50	0.17	0.06	0.23	0.7	1.1
A01_50:	Albedo=0.1, SZA=50°	0.10/0.10/0.10	50	0.27	0.07	0.42	1.1	1.9
A005_60:	Albedo=0.05, SZA=60°	0.05/0.05/0.05	60	0.43	0.14	0.77	1.8	3.4
VEG_75:	Vegetation, SZA=75°	0.20/0.10/0.05	75	0.40	0.11	0.63	1.6	2.9
SAS_75:	Sand/soil, SZA=75°	0.20/0.30/0.30	75	0.24	0.11	0.31	1.0	1.5

-> XCO_2, XCH_4 precision ~0.5%

ie CO_2: 1-2 ppm

CH_4: 8 ppb

CarbonSat Orbits + MODIS Clouds

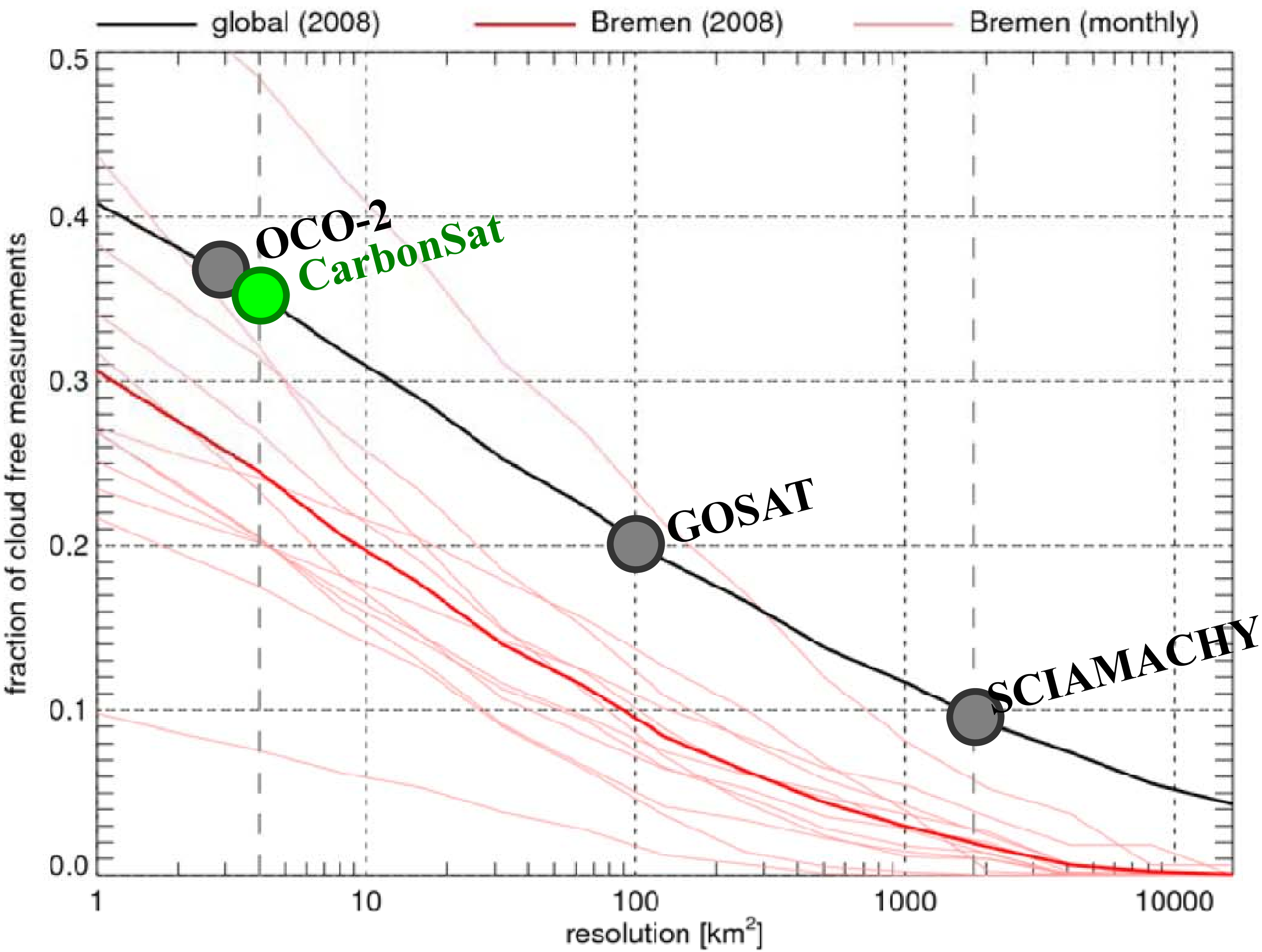


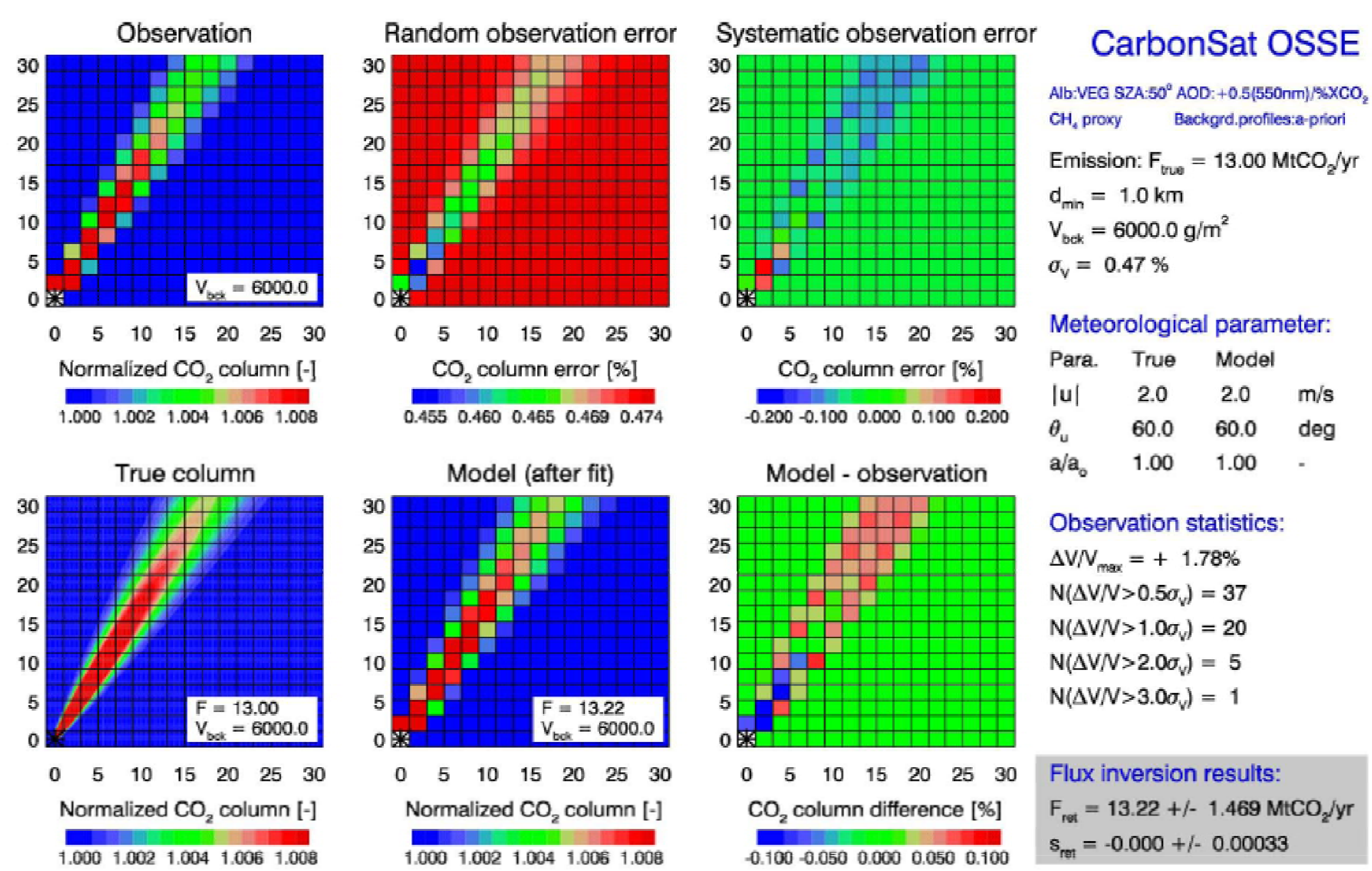
Figure 42: Estimated of number of cloud free observations (relative). Fig. M. Reuter, IUP.

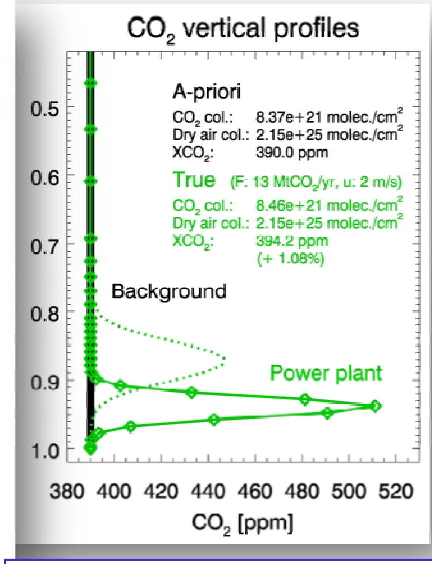
CarbonSat Orbits + MODIS Clouds

CarbonSat Number of Clear-Sky Observations				
Instrument	**Spatial resolution [km^2]**	**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 3-1: Estimate of CarbonSat's number of total and clear-sky observations per day compared to other missions.

Local Hot Spot Example: Power Plant CO_2





SZA: 50°
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, see poster

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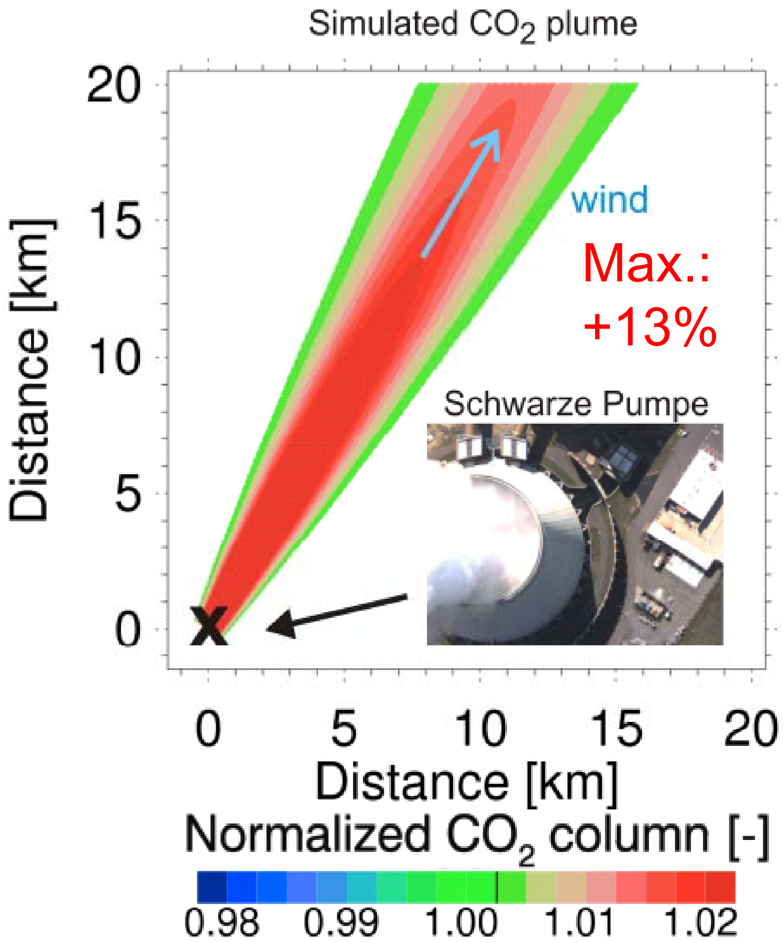
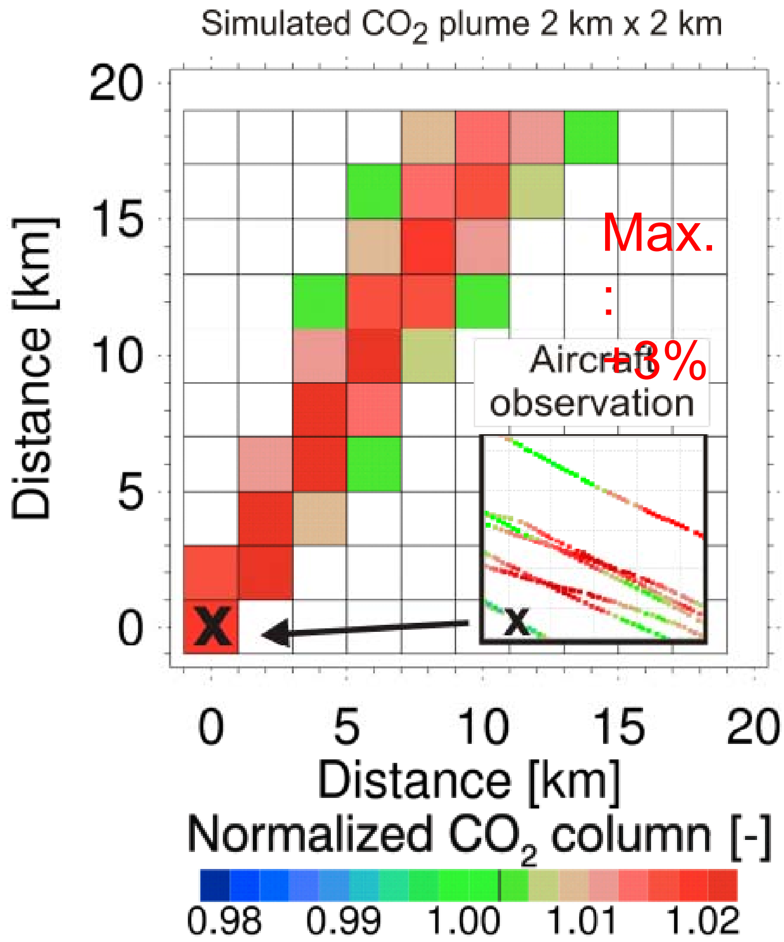
Bovensmann et al. AMT, 2010

CarbonSat: Simulation of power plant CO_2





Emission: **13 MtCO2/year**

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

Emission uncertainty single overpass (+/- 2 ppm XCO_2 error, u = 1 m/s): **+/- 0.8 $MtCO_2$/year** (1-sigma)

Approx. proportional to wind speed u & statistical measurement error

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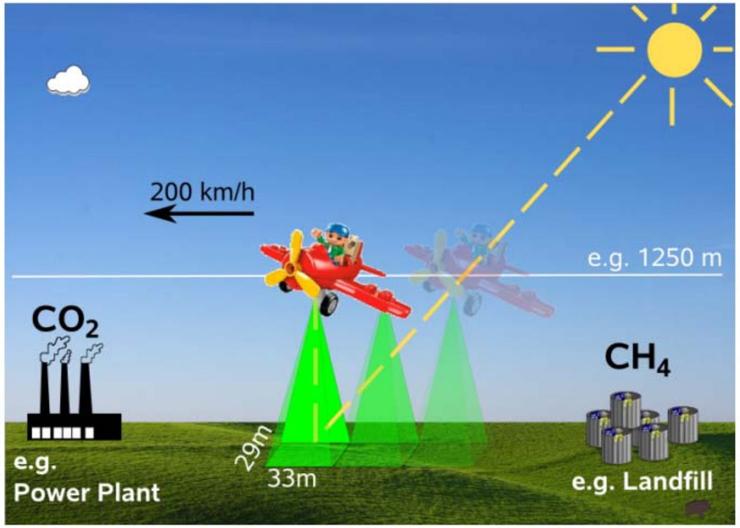
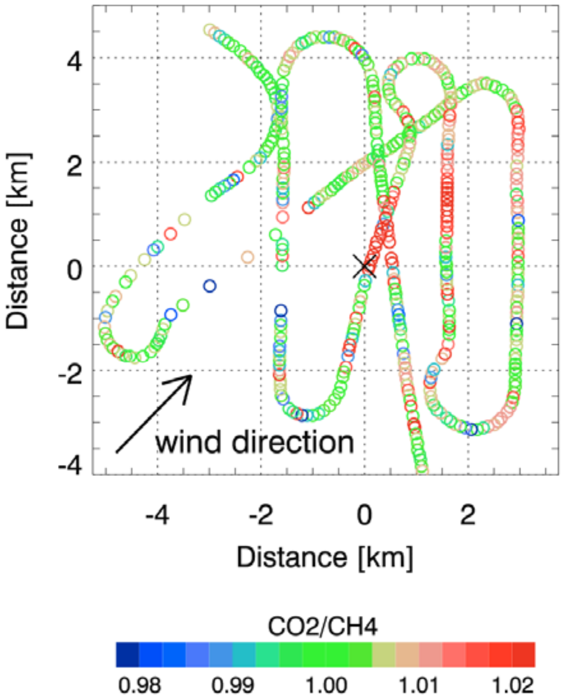
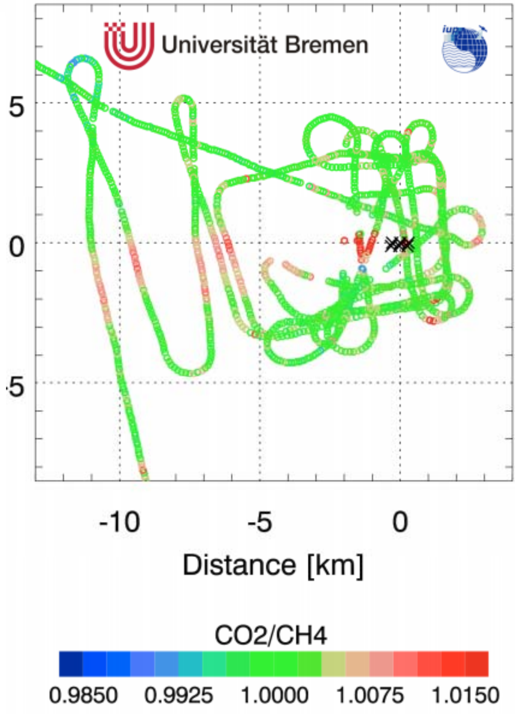
Bovensmann et al., AMT, 2010

Local Point Sources as seen by MAMAP







- MAMAP: O2A and 1.6 µm channels
- Jänschwalde power plant (~24 Mt CO2/yr)
- no smoothing !
- Improvement in instrument performance: factor 3-4 improvement in RMS

MAMAP: Gerilowski et al. AMT, 2011
First inversion results see Krings et al , AMTD, 2011

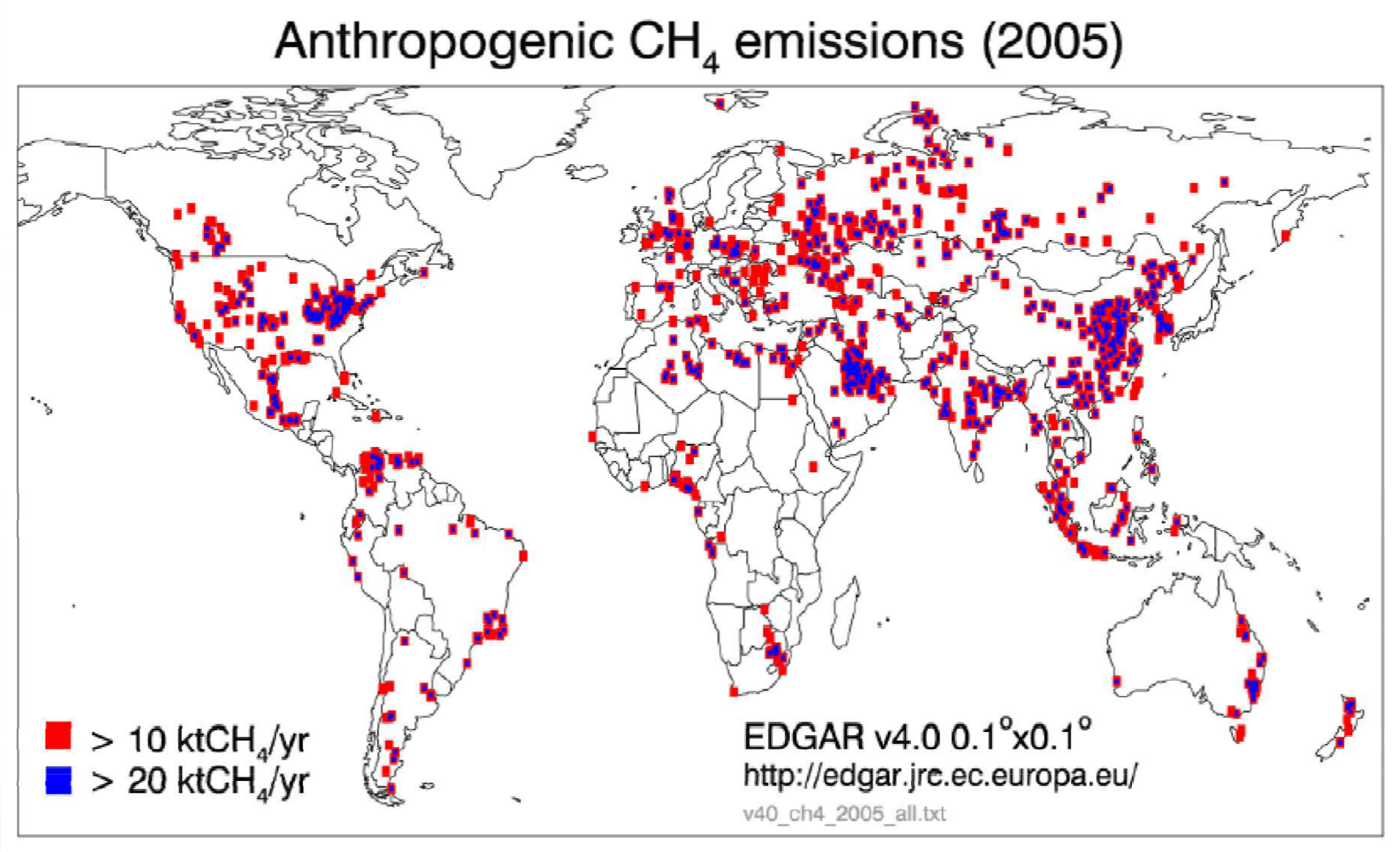
CarbonSat: Methane hot spot emission targets

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)

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)



Bovensmann et al. AMT, 2010

CarbonSat Contributions: XCO_2

CO_2

spatial scale	synoptic	seasonal	annual	interannual
global			interhemispheric gradient 3 ppm	global growth rate 1.5-2.5 ppm/yr
continent		seasonal cycle, wetlands/ biosphere midlatitudes: ~8 ppm	annual budget, spatial gradients: Midlatitudes Atlantic-Europe: ~.4 ppm Tropics: Pacific-SAmerica: ~1 ppm	El Niño response Δ growth rate: ~ 1.6 ppm/yr
country		amplitude of seasonal cycle Germany ~ 9 ppm	annual budget, gradient Germany - Poland <0.1 ppm	Kyoto-like monitoring small
point/small scale sources	forest fires, weather systems ~ [illegible] ppm		power plant emissions ~16 ppm	interannual variability of power plant emissions (monitoring) ~1 ppm

time scale

Goal XCO2: 1 ppm

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Max-Planck-Institut für Biogeochemie

CarbonSat Contributions XCH4

CH_4

spatial scale	synoptic	seasonal	annual	interannual
global			interhemispheric gradient 100 ppb	global growth rate 1990's: ~ 7 ppb/yr 2000's: ~5 ppb/yr
continent		seasonal cycle, wetlands/ biosphere/OH signal midlatitudes: ~10 ppb	annual budget, spatial gradients: Midlatitudes NAtlantic-Europe: ~10 ppb Tropics: Atlantic-Africa: ~30 ppb	El Niño response Δ growth rate: ~20 ppb/ yr
country		amplitude of seasonal cycle Germany ~15 ppb	annual budget, gradient Germany - Poland ~3 ppb	Kyoto-like monitoring small
point/small scale sources	forest fires, weather systems ~30 ppb		landfill emissions ~30 ppb	interannual variability of landfill emissions ~2 ppb

time scale

Goal XCH4: 10 ppb

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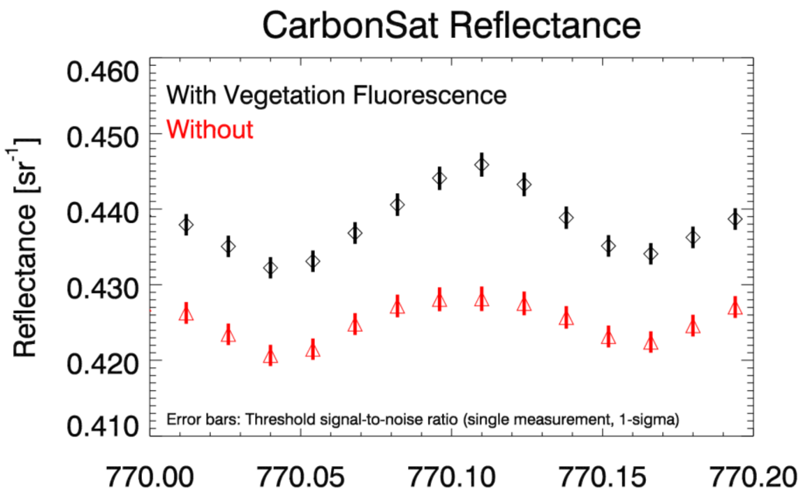
CarbonSat Secondary Product: Vegetation Fluorescence



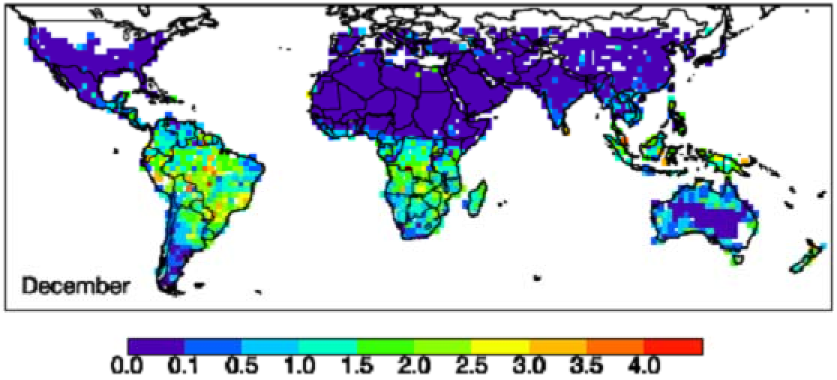
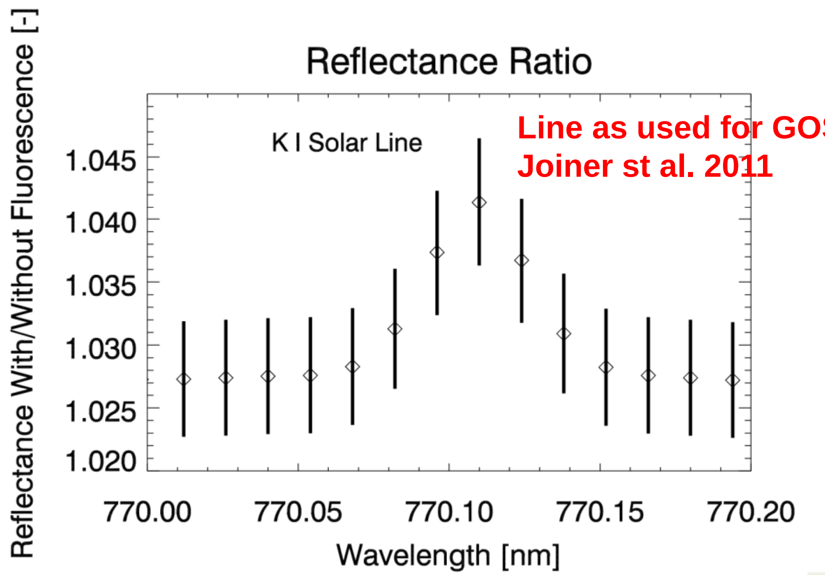
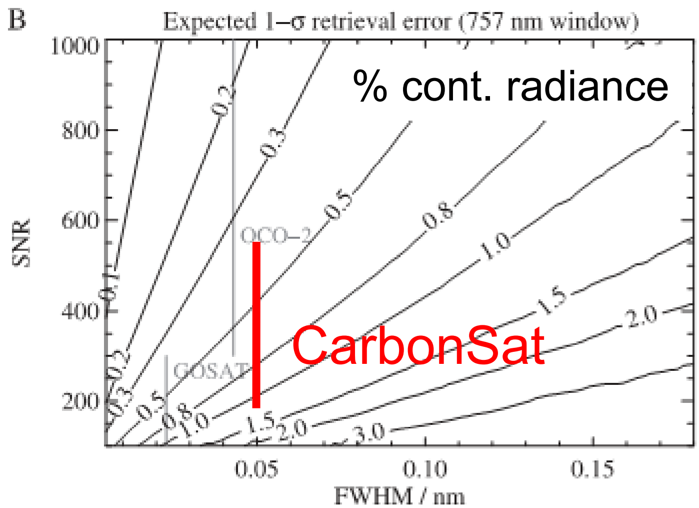


Fig. 11. Derived monthly averages for scaled fluorescence (unitless) from GOSAT for July and December 2009.

Joiner et al.,BGD, 2011



Line as used for GOSAT, Joiner st al. 2011



Michael.Buchwitz@iup.physik.uni-bremen.de

Method: Joiner et al., Biogeosciences Discuss., 2010

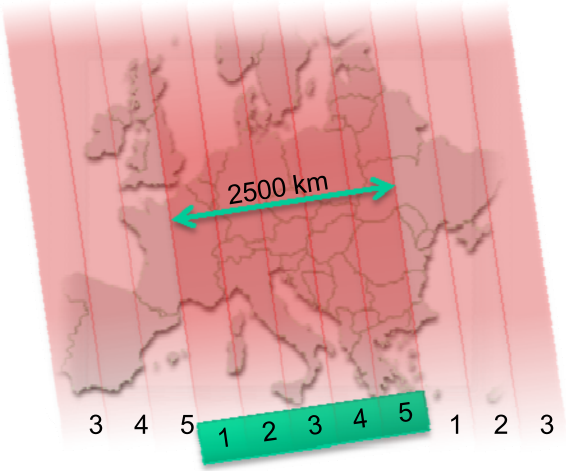
Frankenberg et al., GRL, 2011

Summary & Conclusions

- **CarbonSat aims to better separate biogenic and anthropogenic fluxes by "imaging" regions of strong localised CO_2 and CH_4 emissions.**
- CarbonSat mission concept is designed to provide for the first time data on XCO_2 and XCH_4 with local spatial resolution (2×2 km^2) and good global coverage (500 km swath)
- in November 2010 CS 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

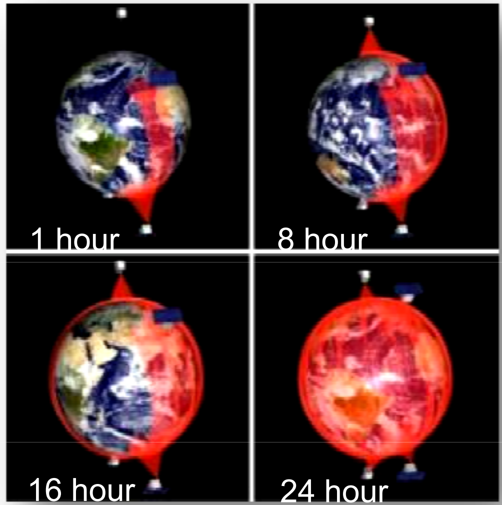
CarbonSat Constellation

- With increased spatial resolution of < 2km and adequate accuracy



5 Satellites cover 2500 km on ground in 1 orbit

global coverage every day with 2 km spatial resolution



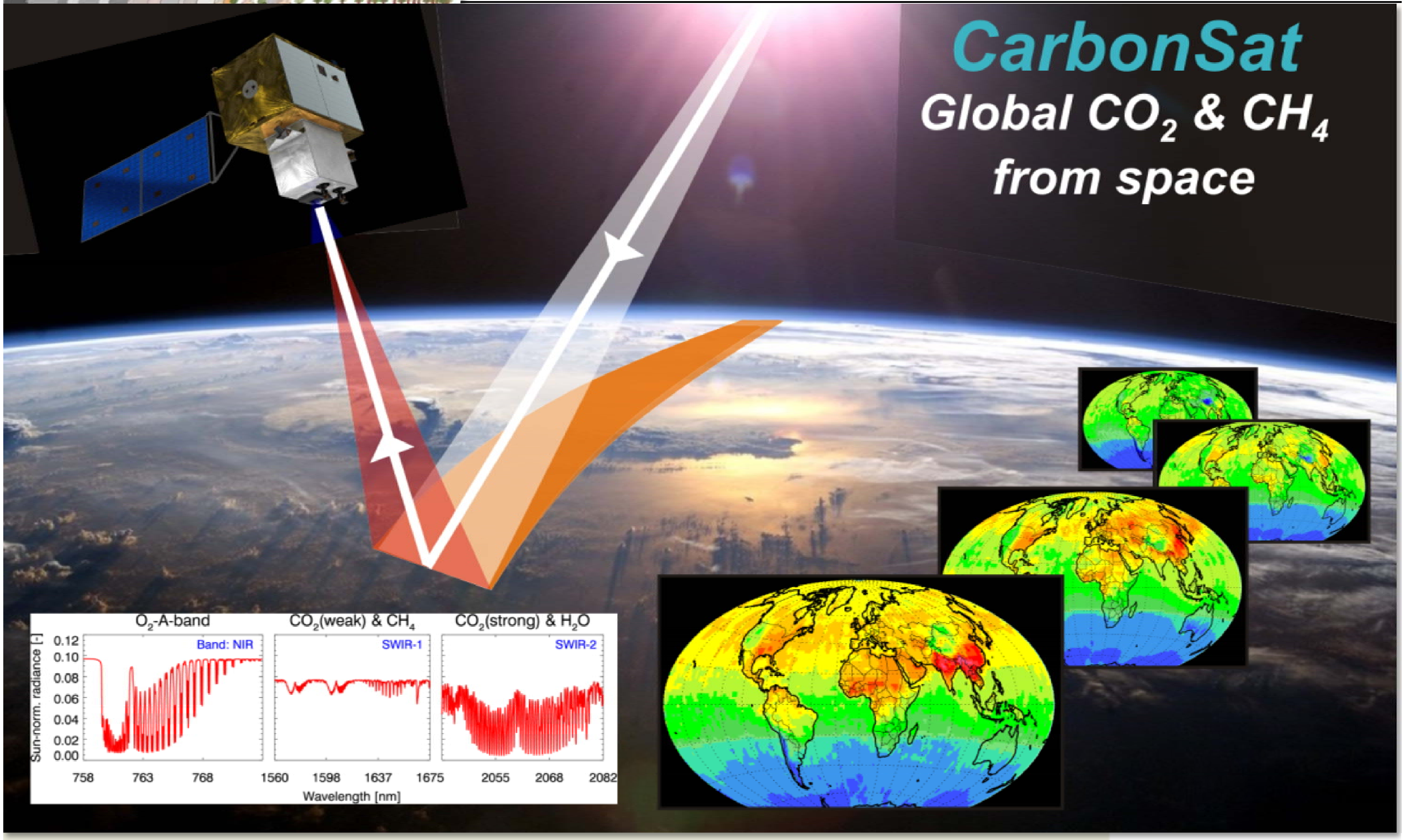
CarbonSat constellation

- Globally comparable data
- Timely detection of changes
- improves our understanding of the CO_2 and CH_4 sources and sinks for better attribution and prediction of climate change
- Contributes to monitoring, assessement and attribution in support the Kyoto and post Kyoto protocols
- Reliable and timely services

CarbonSat

Earth Explorer 8 Candidate

esa



The End

Further Reading …

Atmos. Meas. Tech., 3, 781–811, 2010
www.atmos-meas-tech.net/3/781/2010/
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

Further Reading: Airborne Demonstration …

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Atmospheric Measurement Techniques

MAMAP – a new spectrometer system for column-averaged methane and carbon dioxide observations from aircraft: instrument description and performance analysis

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Atmospheric Measurement Techniques Discussions

MAMAP – a new spectrometer system for column-averaged methane and carbon dioxide observations from aircraft: retrieval algorithm and first inversions for point source emission rates

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New "Full Physics" Retrieval Algorithm

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Atmospheric Measurement Techniques

A method for improved SCIAMACHY CO_2 retrieval in the presence of optically thin clouds

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Retrieval of atmospheric CO_2 with enhanced accuracy and precision from SCIAMACHY: Validation with FTS measurements and comparison with model results

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