Passive Satellite Remote Sensing
Methane and Carbon Dioxide:
From SCIAMACHY towards CarbonSat and CarbonSat Constellation

J. P. Burrows, M. Buchwitz, H. Bovenmann, O. Schneising, and M. Reuter
Institute of Environmental Physics (IUP)
University of Bremen FB1, Bremen, Germany
Anthropogenic Modification of Climate

- GHGs driving global climate change
  - CO₂ accounts for ~ 60%
  - CH₄ accounts for ~ 20%

- Geological time scales
  - Past: 1 ppmv/200 years
  - Today: 1 ppmv/year

- Since industrialisation
  - Temperature has increased +0.8K (+2K is the limit)
  - Sea level has increased +20cm

CO₂ and CH₄ are the Most Important Greenhouse Gases being changed by Anthropogenic activity: fossil fuel exploration and combustion, biomass burning landuse change
An accurate understanding of the $\text{CO}_2$ and $\text{CH}_4$ sources and sinks form local to global scale is a pre-requisite for reliable prediction of climate change!
SCIAMACHY

Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY
### SCIAMACHY tropospheric data products

<table>
<thead>
<tr>
<th>NO2</th>
<th>SO2</th>
<th>CO</th>
<th>H2O</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="NO2 Image" /></td>
<td><img src="image2" alt="SO2 Image" /></td>
<td><img src="image3" alt="CO Image" /></td>
<td><img src="image4" alt="H2O Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HCHO</th>
<th>BrO</th>
<th>CO2</th>
<th>CH4</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5" alt="HCHO Image" /></td>
<td><img src="image6" alt="BrO Image" /></td>
<td><img src="image7" alt="CO2 Image" /></td>
<td><img src="image8" alt="CH4 Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHOCHO</th>
<th>IO</th>
<th>Aerosols</th>
<th>Clouds</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image9" alt="CHOCHO Image" /></td>
<td><img src="image10" alt="IO Image" /></td>
<td><img src="image11" alt="Aerosols Image" /></td>
<td><img src="image12" alt="Clouds Image" /></td>
</tr>
</tbody>
</table>

... and more.
The Dry Column of CO2, XCO2

Carbon Dioxide SCIAMACHY/ENVISAT 2004

CO₂ column averaged mixing ratio [ppm]

355.0  365.0  375.0  385.0  395.0
SCIAMACHY XCH4 and XCO2 2003 to 2009

Methane SCIAMACHY/ENVISAT 2003 01

Carbon dioxide SCIAMACHY/ENVISAT 2003 01

O. Schneising, Michael Buchwitz@iup.physik.uni-bremen.de

O. Schneising, Michael Buchwitz@iup.physik.uni-bremen.de
SCIAMACHY and CH$_4$ emissions

Bergamaschi et al., JGR, 2009

Inverse modeling of global and regional CH$_4$ emissions using SCIAMACHY satellite retrievals

... SCIAMACHY dry column data products constrain the smaller-scale i.e. 100km to regional spatial distribution of emissions. Remote surface measurements constrain the emissions locally and those from larger regions upwind.

Bloom et al., Science, 2010

Large-Scale Controls of Methanogenesis Inferred from Methane and Gravity Spaceborne Data

Two main application areas:
• Improved emission inventories (for different categories, e.g., wetlands, rice, ...)
• Improved process understanding (e.g., land biosphere & related emissions)

Better climate prediction, ...
SCIAMACHY Methane 2003-2009

SCIAMACHY WFMDv2.0 XCH4

Annual averages 2003 - 2009

Global Mean (land+ice-free)

<table>
<thead>
<tr>
<th>Latitude band</th>
<th>Mean amplitude seasonal cycle [ppb]</th>
<th>Anomaly since 2007 [ppb/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td>SCIA 13.8±2.4  TM5(2003) 9.4±0.4</td>
<td>SCIA 8.5  TM5(2003) -0.5</td>
</tr>
<tr>
<td>SH</td>
<td>SCIA 10.2±3.5  TM5(2003) 8.5±1.7</td>
<td>SCIA 5.3  TM5(2003) -0.7</td>
</tr>
<tr>
<td>30°N–90°N</td>
<td>SCIA 13.0±7.3  TM5(2003) 11.1±0.7</td>
<td>SCIA 7.5  TM5(2003) -0.7</td>
</tr>
<tr>
<td>30°S–30°N</td>
<td>SCIA 7.4±3.4  TM5(2003) 5.1±0.9</td>
<td>SCIA 8.1  TM5(2003) -0.2</td>
</tr>
<tr>
<td>30°S–90°S</td>
<td>SCIA 10.8±2.2  TM5(2003) 8.4±3.1</td>
<td>SCIA 5.8  TM5(2003) 0.0</td>
</tr>
</tbody>
</table>


Schleissing et al., ACP (submitted), 2010
SCIAMACHY CO₂ 2003-2009

**Annual averages 2003 - 2009**

**SCIA – CarbonTracker**

*Northern Hemisphere*

- **SCIAMACHY**
  - Values: 395, 396, 397 ppm
- **CarbonTracker**
  - Values: 395, 396, 397 ppm

*Southern Hemisphere*

- **SCIAMACHY**
  - Values: 395, 396, 397 ppm
- **CarbonTracker**
  - Values: 395, 396, 397 ppm

**CarbonTracker (Fitted scaling factor: 1.372)**

Schneising et al., ACP (submitted), 2010
Fig. 1. TANSO-FTS and CAI photos and design view of the GOSAT satellite on orbit.

**TANSO-FTS Spectra**

- Wavenumber (cm⁻¹)
- Radiation (W/m²/μm/str)
- Absorption band of water vapor (H₂O)
- Absorption band of carbon dioxide (CO₂)
- Absorption band of methane (CH₄)
- Absorption band of oxygen (O₂)
- Absorption band of ozone (O₃)

**TANSO-FTS Scan Pattern**

- Wavelength (μm)

---

**TANSO-CAI Images**

- XCO₂
- XCH₄

---

Kuze et al., 2009

---

JAXA & NIES GOSAT web sites
### GHG Missions with PBL sensitivity

<table>
<thead>
<tr>
<th>Year</th>
<th>SCIAMACHY</th>
<th>GOSAT</th>
<th>GOSAT-2 ?</th>
<th>OCO-2</th>
<th>Sentinel 5 Precursor</th>
<th>Sentinel 5: CH₄, no CO₂</th>
<th>CO₂ Laser ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **SCIAMACHY**
- No CH₄ (launch Feb 2013, 2 years)
- No CO₂ and before 2020 no dedicated CH₄
- No CO₂ (launch 2014 ?, 3 years ?)
- **GOSAT**
- OCO-2
- Sentinel 5 Precursor: CH₄, no CO₂
- G/F CH₄ Laser
- **Data gap !:** No CO₂ (2016 – 2020+) !
  Limited (or no) CH₄ !
Carbon Sat

Global CO$_2$ and CH$_4$ from space

NOAA CarbonTracker
**CarbonSat Daily Orbital Coverage**

**Clear Sky Fraction**

- XCO\textsubscript{2} & XCH\textsubscript{4}
- 500 km swath
- 2 km x 2 km pixel
- 250 meas. per 0.3 s

6 million cloud free observations / day!

**CarbonSat Number of Clear-Sky Observations**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spatial resolution [km\textsuperscript{2}]</th>
<th>Total number observations per day</th>
<th>Clear-sky frequency</th>
<th>Total number clear-sky observations per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>CarbonSat</td>
<td>4</td>
<td>28,000,000</td>
<td>23%</td>
<td>6,440,000</td>
</tr>
<tr>
<td>OCO</td>
<td>3</td>
<td>1,680,000</td>
<td>27%</td>
<td>453,600</td>
</tr>
<tr>
<td>GOSAT</td>
<td>85</td>
<td>10,000</td>
<td>13%</td>
<td>1,300</td>
</tr>
<tr>
<td>SCIAMACHY</td>
<td>1800</td>
<td>70,000</td>
<td>5%</td>
<td>3,500</td>
</tr>
</tbody>
</table>
CarbonSat enables new important application areas:
CO$_2$ and CH$_4$ emission „hot spot“ detection and monitoring (power plants, …)
CarbonSat: CO$_2$ emission hot spot targets

**Coal-fired power plants**

Belchatov, Poland
(~35 MtCO$_2$/year)

Jänschwalde, Germany
(~27 MtCO$_2$/year)

Kendal, South Africa
(~27 MtCO$_2$/year)

**Volcanoes**

Spinetti et al., 2008

Aircraft obs. AVIRIS
Pu‘u‘O‘o @ Kilauea
High-resolution CO₂ emission maps

A very high-resolution global fossil fuel CO₂ emission inventory derived using a point source database and satellite observations of nighttime lights, 1980–2007

T. Oda and S. Maksyutov

Center for Global Environmental Research, National Institute for Environmental Studies,
A remote sensing technique for global monitoring of power plant CO\textsubscript{2} emissions from space and related applications

H. Bovensmann\textsuperscript{1}, M. Buchwitz\textsuperscript{1}, J. P. Burrows\textsuperscript{1}, M. Reuter\textsuperscript{1}, T. Krings\textsuperscript{1}, K. Gerilowski\textsuperscript{1}, O. Schneising\textsuperscript{1}, J. Heymann\textsuperscript{1}, A. Tretner\textsuperscript{2}, and J. Erzinger\textsuperscript{2}

\textsuperscript{1}Institute of Environmental Physics (IUP), University of Bremen FB1, Otto Hahn Allee 1, 28334 Bremen, Germany
\textsuperscript{2}Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Received: 6 November 2009 – Published in Atmos. Meas. Tech. Discuss.: 7 January 2010
Revised: 14 June 2010 – Accepted: 15 June 2010 – Published: 1 July 2010

Abstract. Carbon dioxide (CO\textsubscript{2}) is the most important anthropogenic greenhouse gas (GHG) causing global warming. The atmospheric CO\textsubscript{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 CO\textsubscript{2} emissions is required by the Kyoto protocol. Independent verification of reported emissions, which are typically not directly measured, by methods such as inverse modeling of measured atmospheric CO\textsubscript{2} concentrations is currently not possible globally due to lack of appropriate observations. Exemplary, both from a single pass and from a time series of measurements. From single pass measurements, we estimate that the CO\textsubscript{2} emission due to instrument noise is in the range 1.6–4.8 MtCO\textsubscript{2}/yr for single overpasses. This corresponds to 12–36\% of the emission of a mid-size PP (13 MtCO\textsubscript{2}/yr). We have also determined the sensitivity to parameters which may result in systematic errors such as atmospheric transport and aerosol related parameters. We found that the emission error depends linearly on wind speed, i.e., a 10\% wind speed error results in a 10\% emission error, and that neglecting enhanced aerosol concentrations in the PP plume may result in errors in the range 0.2–2.5 MtCO\textsubscript{2}/yr, depending on PP...
CarbonSat: Simulation of power plant CO$_2$ plume

Emission: **13 MtCO$_2$/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.

Bovensmann et al., AMT, 2010
CarbonSat: Observing System Simulation Experiment (OSSE)

F: SysErr = 0.2 (+1.5%), RndErr = 1.6

Bovensmann et al., AMT, 2010
CarbonSat: Methane @ high latitudes

CarbonSat sun-glint mode allows observation of methane in vulnerable high latitude regions including Arctic sea and shelf areas. Very difficult with SCIAMACHY & GOSAT. Not possible with OCO.
CarbonSat: CH$_4$ emission hot spot targets

- Oil and gas fields
- Pipelines incl. compressor stations

**Seeps**

Leifer et al., 2006

**Landfills / Waste**

**Mud volcanoes**

Mazzini et al., 2007
CarbonSat: Methane hot spot emission targets

Target must produce a detectable methane column enhancement (1%) at 2x2 km² resolution:
=> Single overpass detection limit is **4 - 8 ktCH4/year** (u = 2 - 6 m/s, precision 8 ppb)

<table>
<thead>
<tr>
<th>Methane hot spot targets</th>
<th>Comparison with CarbonSat detection limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pipelines incl. compressor stations</strong></td>
<td>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 <strong>29 ktCH4/year</strong></td>
</tr>
<tr>
<td><strong>Oil and gas fields</strong></td>
<td>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: CH₄ columns enhanced by about 5% along several km)</td>
</tr>
<tr>
<td><strong>Landfills</strong></td>
<td>Many landfills emit more than <strong>10 ktCH4/year</strong> (e.g., European Pollutant Release and Transfer Register)</td>
</tr>
<tr>
<td><strong>Mud volcanoes</strong></td>
<td>Under certain conditions (e.g., eruption) detection may be possible even at SCIAMACHY resolution of 30x60 km² (Kourtidis et al., 2006)</td>
</tr>
<tr>
<td><strong>Seeps</strong></td>
<td>Several, e.g. Coal Oil Point (COP) marine seeps, Santa Barbara, California (Leifer et al, 2006): about <strong>25 ktCH4/year</strong> (1.15 m³/s) or Georgia Black Sea seeps (Judd et al., 2004): about <strong>40 ktCH4/year</strong></td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Potentially many other more or less localized targets such East Siberian Arctic Shelf (ESAS): up to +8 ppm over Laptev Sea along &gt; 100 km (Shakhova et al., 2010)</td>
</tr>
</tbody>
</table>

See: Bovensmann et al., AMT, 2010
CarbonSat: Methane hot spot emission targets

Anthropogenic CH$_4$ emissions (2005)

- Red squares: > 10 ktCH$_4$/yr
- Blue squares: > 20 ktCH$_4$/yr

EDGAR v4.0 0.1°x0.1°
http://edgar.jrc.ec.europa.eu/
v40_ch4_2005_all.txt

Bovensmann et al., AMT, 2010
<table>
<thead>
<tr>
<th>Application area &amp; other criteria</th>
<th>SCIAMACHY</th>
<th>GOSAT</th>
<th>OCO</th>
<th>Sentinel 5 Precursor</th>
<th>CH$_4$ Laser (MERLIN)</th>
<th>CarbonSat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional CO$_2$ fluxes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regional CH$_4$ fluxes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$ „hot spots“ (eg power plants)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH$_4$ „hot spots“ (eg oil fields)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical maturity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day &amp; night</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Services to initiate long term monitoring systems and services

Science to better understand the Earth System

Earth Explorers

ERS-1, -2 → ENVISAT

GEO

METEOSAT M-1, 2, 3, 4, 5, 6, 7

Op Meteo with EUMETSAT

METEOSAT Second Generation MSG-1, -2, -3

Metal-1, -2, -3 → Post-EPS

LEO

Earth Watch

GMES in cooperation with EC

ERS-1, -2 → ENVISAT

Sentinel 3

Sentinel 4

Sentinel 5p/5

Sentinel 1

Sentinel 2

Sentinel 1

GMES in cooperation with EC

Sentinel 1

Sentinel 2

Sentinel 4

Sentinel 5p/5

SMOS (Soil Moisture and Ocean Salinity)

CryoSat2 (Polar Ice Monitoring)

ADM/Aeolus (Atmospheric Dynamics Mission)

SWARM (Magnetic Mission)

EarthCare (Clouds, Aerosols & Radiation Mission)

EE7 Biomass/CoreH2O/PREMIER

EE8 CarbonSat / FLEX

Since 1977

1990 2000 2010 2020 2030
How to achieve the required spatial and temporal sampling

SCIAMACHY is the First Greenhouse Gas Measurement in Space

- Unique experience on greenhouse gas measurements from space (IUP, University of Bremen)
- However, SCIAMACHY requires averaging of 3 years of data to detect man-made emissions

Global CO$_2$ and CH$_4$ measurement from SCIAMACHY on ENVISAT

- Swath: Up to 1000 km
- Spatial resolution: 30 x 60 km$^2$

OCO
- Swath: 10 km
- Spatial resolution: 1 x 1.5 km$^2$

GOSAT
- Swath: ~ 600 km
- Spatial resolution: 10 km diameter circles (150 km gaps)

CarbonSat Constellation
- Swath: 500 - 1000 km
- Spatial resolution: 2 x 2 km$^2$

Satellites can add important missing global information but timely, higher resolution and accuracy measurement are required
## Comparison of Products and Potential applications

<table>
<thead>
<tr>
<th></th>
<th>GOSAT</th>
<th>CarbonSat convention</th>
<th>CarbonSat Constellation</th>
<th>Benefits/Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>10km² (150km gaps within 650 km swath)</td>
<td>2 km² (continues, swath 500 km)</td>
<td>2 km² (continues, swath 500 km)</td>
<td><strong>Increased number of cloud free measurement</strong></td>
</tr>
<tr>
<td>Revisit time</td>
<td>44 days</td>
<td>5 days</td>
<td>1 day</td>
<td><strong>Increased number of cloud free measurement over target areas</strong></td>
</tr>
<tr>
<td>CO₂ uncertainty</td>
<td>4ppm</td>
<td>&lt; 1-2 ppm</td>
<td>&lt; 1-2 ppm</td>
<td>Single measurement, WMO GCOS requires 1 – 3 ppm</td>
</tr>
<tr>
<td>(single measurement)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ uncertainty</td>
<td>4ppm</td>
<td>0.4ppm</td>
<td>0.15ppm</td>
<td>Increased precision due to increased number of cloud free measurements per month in 10km²</td>
</tr>
<tr>
<td>(10 km x 10 km, monthly)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ hot spot</td>
<td>Unlikely</td>
<td>Yearly</td>
<td>Quarterly</td>
<td>e.g. Power plant (cloud free 20%; wind 4 m/s; uncertainty 1Mt/yr)</td>
</tr>
<tr>
<td>CO₂ Regional Flux</td>
<td>3 years</td>
<td>Half year</td>
<td>Quarterly</td>
<td>Weak extended sources/sinks</td>
</tr>
<tr>
<td>CH₄ hot spot</td>
<td>Unlikely</td>
<td>Yearly</td>
<td>Quarterly</td>
<td>e.g. Pipeline/Oil and gas fields (wind 4m/s, 20% cloud free, uncertainty 16kt/y)</td>
</tr>
<tr>
<td>CH₄ Regional Flux</td>
<td>3 years</td>
<td>Half year</td>
<td>Quarterly</td>
<td>e.g. Rise field</td>
</tr>
<tr>
<td>CO₂ Urban source</td>
<td>Unlikely</td>
<td>Possible</td>
<td>Possible</td>
<td>e.g. Cities (needs further investigation)</td>
</tr>
</tbody>
</table>
• An adequate understanding of GHG sources and sinks for CO\textsubscript{2} CH\textsubscript{4} and N\textsubscript{2}O, is a pre-requisite for reliable climate change prediction and monitoring, verification and transparancy!

• SCIAMACHY has demonstrated that satellite observations of greenhouse gases (GHG) constrain surface fluxes (sources & sinks)! \(\Rightarrow\) inverse modelling of fluxes at monthly regional scale

• But: Data gap: No or limited CO\textsubscript{2} and CH\textsubscript{4} from space after \(~2016\) !?

• In addition: “Hot spot” emission sources such as power plants seeps etc. need to be monitored objectively! Existing satellites limited by sampling and S/N to say 200kmx200km.

• CarbonSat/CarbonSat Constellation meets this need and closes the data gap in carbon Gases and delivers the needed high spatial resolution information on CO\textsubscript{2} and CH\textsubscript{4} at adequate sampling!