Providing expert support on topics like mission/observation/data requirements:

- Heinrich Bovensmann, IUP, University of Bremen, Bremen, D (Chair)
- Hartmut Bösch, University of Leicester, UK
- Dominik Brunner, EMPA, Dübendorf, CH
- Philippe Ciais, LSCE, Gif-sur-Yvette, F
- David Crisp, JPL, Pasadena, USA
- Han Dolman, Free University, Amsterdam, NL
- Gary Hayman, Centre for Ecology and Hydrology, Wallingford, UK
- Sander Houweling, SRON, Utrecht, NL
- Günter Lichtenberg, DLR-IMF, Oberpfaffenhofen, D

ESA: Paul Ingmann (science), Armin Löscher (implementation – system), Yasjka Meijer (science), Bernd Sierk (optical engineering)
EE8 within ESA’ Living Planet Programme

Earth Explorer (EE)

- Research driven

Core Missions
- GOCE launched
- ADM-Aeolus 2013
- EarthCARE 2015

Opportunity Missions
- CryoSat 2 launched
- SMOS launched
- Swarm 2012

EE-7 2019
3 Cand Core
EE-8 2019
2 Cand Opp.

Earth Watch

- Operational Service driven

Meteorology
- Meteosat
- MSG
- EPS (MetOp)
- MTG & Post EPS
- FLEX & CarbonSat

GMES
- Sentinel 1
- Sentinel 2
- Sentinel 3
- Sentinel 4
- Sentinel 5(p)
Earth Explorer 8 – candidate missions

Two missions selected for Phase A/B1 (feasibility/concept):

1. **FLEX**: aims to provide global maps of *vegetation fluorescence*, which can be converted into an indicator of photosynthetic activity.

2. **CarbonSat**: aims to quantify and monitor the distribution of two of the most important greenhouse gases in the atmosphere released through human activity: *carbon dioxide and methane*.

**Programmatic constraints:**

- target budget 100 M€, incl. space segment & mission-specific ground segment but excl. launch, operations, generic ground segment, Level-2 processor and ESA internal cost
- Technology Readiness Level (TRL) of 5 is achieved at the end of Phase B1
Needs to constrain CH₄ and CO₂ fluxes

How much is emitted where, when and by what?

Are the reported Emissions correct?

Radiative forcing:
1. CO₂ accounts for ~ 60%
2. CH₄ accounts for ~ 20%

How much CO₂ is absorbed by land and oceans? (Sinks)

How today's CO₂ sinks will behave in a changing climate?
Will sinks turn into sources and sources into sinks?

How sources and sinks will behave in a changing climate?
CarbonSat: CH$_4$ emission hot spot targets

**Oil and gas fields**

**Pipelines incl. compressor stations**

**Landfills / Waste**

**Mud volcanoes**

Leifer et al., 2006

CarbonSat EE8 candidate

ESA UNCLASSIFIED – For Official Use, ATMOS 2012, 21 June
CarbonSat spatial resolution and coverage enables new important application areas: CO$_2$ and CH$_4$ emission from extended point sources.
High spatial resolution and good coverage:
- 2×2 km² ground pixel,
- 500–160 km swath width (goal–threshold)

Single error of column-averaged mixing ratios
- XCO₂ < 1 – 3 ppm
- XCH₄ < 9 –17 ppb

Orbit: LEO Sun-synchronous, around 11:30 hr LT

Modes:
- Nadir imaging (main); for land & ocean
- Sun-glint; for optimised ocean coverage

Clear Sky Fraction

Miller et al. 2007

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spatial resolution [km²]</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>1,880,000</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>
## Spectral

<table>
<thead>
<tr>
<th>Data product</th>
<th>Wavelength range</th>
<th>Band ID</th>
<th>Band ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud (O\textsubscript{2}-A band)</td>
<td>756 – 773 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerosol (O\textsubscript{2}-A band)</td>
<td>756 – 773 nm</td>
<td>NIR</td>
<td>0.1 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(was 0.045 nm)</td>
</tr>
<tr>
<td>Vegetation Fluorescence*</td>
<td>Fraunhofer lines in range 747 – 773 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH\textsubscript{4} and CO\textsubscript{2} (weak)</td>
<td>1590–1675 nm</td>
<td>SWIR-1</td>
<td>0.30 nm</td>
</tr>
<tr>
<td>CO\textsubscript{2} (strong) and H\textsubscript{2}O</td>
<td>1925–2095 nm (was 2043 – 2095 nm)</td>
<td>SWIR-2</td>
<td>0.5 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(was 0.13 nm)</td>
</tr>
</tbody>
</table>

*needs to be determined to correct O\textsubscript{2}A-band retrieval for vegetation fluorescence interference (see Frankenberg et al., AMTD 2012)

Spectral oversampling of at least 3
RADIOMETRIC

SNR in middle of signal dynamic range:
- >150 per detector pixel

Absolute radiometric accuracy:
- 0.2%

Relative spectral radiometric accuracy:
- 2.0% (between bands)
- 0.05% (within a band)

Relative spatial radiometric accuracy:
- 0.25%

Polarization sensitivity:
- 2%

Cloud and aerosol sub pixel information:
- No imager and no formation flying
- Built-in imager by oversampling along-track

Requirements are to be consolidated during the Phase A/B1 science and system studies.
Consolidating Requirements; Systematic errors and precision of XCO$_2$

- Instrument 7 (blue, extended spectral region, reduced spectral resolution NIR, SWIR-2) gives the lowest bias (best accuracy) for nearly all 15 scenarios.
- XCO$_2$ precision shows less scenario dependence but a pronounced instrument dependence.
- Instrument 7 clearly gives the best performance also for the XCO$_2$ precision.
- Similar for XCH$_4$
Science Study 1 (consortium led by IUP, University of Bremen): focus on consolidating the observational requirements (SNR, spectral resolution, spectral coverage), which is based on consolidated data requirements, see also poster of Bovensmann et al.

Science Study 2 (consortium led by Noveltis): focus on progressing with inverse flux modelling and consolidating related data requirements

System studies:
  - Two parallel studies
    - Study A: with prime Astrium Germany started in April
    - Study B: with prime OHB Germany started in May
  - Studies last until end 2013 and conclude with a “Report for Selection”

Campaigns (see also poster of Schüttemeyer et al.): C-MAPExp; dedicated campaign using MAMAP from University Bremen
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 high spatial resolution (2 x 2 km$^2$) AND good global coverage (goal: 500 km swath)

Scientific and system studies running between early 2012 and end 2013

Final selection of Earth Explorer 8 in 2014

Envisaged launch in 2019, with 3–5 year mission lifetime
END OF PRESENTATION

THANK YOU!
CarbonSat Secondary Product: Vegetation Fluorescence

C. Frankenberg et al. GRL, 2011, in press
<table>
<thead>
<tr>
<th>Satellite</th>
<th>Spatial &amp; spectral specs</th>
<th>Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SCIAMACHY</strong> (launched 2002)</td>
<td>60x30 km: O₂ A-band (FWHM=0.5nm), CO₂ and CH₄ bands (1.6μm, FWHM=1.3nm)</td>
<td>10⁵ soundings per day Full global coverage in 6-days</td>
</tr>
<tr>
<td><strong>GOSAT</strong> (launched 2009)</td>
<td>10x10 km: O₂ A-band (FWHM=0.025nm), Weak CO₂ and CH₄ bands (1.6μm, FWHM=0.06nm), Strong CO₂ band (2μm, FWHM=0.11nm)</td>
<td>10⁴ soundings per day Sun-glint (up to 30deg LZA) Target mode</td>
</tr>
<tr>
<td><strong>OCO-2</strong> (to be launched 2014)</td>
<td>2x2 km: O₂ A-band (FWHM=0.043nm), Weak CO₂ band (1.6μm, FWHM=0.076nm), Strong CO₂ band (2μm, FWHM=0.097nm)</td>
<td>10⁶ soundings per day Sun-glint Target-mode</td>
</tr>
<tr>
<td><strong>CarbonSat EE8</strong> (planned launch 2019)</td>
<td>2 km x 2 km: O₂ A-band (FWHM &lt; 0.1nm), Weak CO₂ and CH₄ (1.6μm, FWHM &lt; 0.3 nm), Strong H₂O &amp; CO₂ band (2μm, FWHM &lt; 0.5 nm)</td>
<td>~10⁷ soundings/day Full global coverage in 6-days (equator) Sun-glint</td>
</tr>
</tbody>
</table>

Table by C. Frankenberg

CarbonSat EE8 candidate

ESA UNCLASSIFIED – For Official Use, ATMOS 2012, 21 June
Greenhouse Gases are driving Climate Change

### Radiative Forcing

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>CO₂</th>
<th>N₂O</th>
<th>CH₄</th>
<th>Halocarbons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-lived greenhouse gases</td>
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<tr>
<td>Ozone</td>
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<tr>
<td>Stratospheric</td>
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<tr>
<td>Tropospheric</td>
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<tr>
<td>Stratospheric water vapour from CH₄</td>
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<tr>
<td>Surface albedo</td>
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<tr>
<td>Land use</td>
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<tr>
<td>Black carbon on snow</td>
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<tr>
<td>Direct effect</td>
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<tr>
<td>Total Aerosol</td>
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<tr>
<td>Linear contrails</td>
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<td></td>
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<tr>
<td>Natural</td>
<td></td>
<td></td>
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<tr>
<td>Solar irradiance</td>
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<tr>
<td>Total net anthropogenic</td>
<td></td>
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</tr>
</tbody>
</table>

### RF values (W m⁻²)

- CO₂: 1.66 [1.49 to 1.83], Global, High
- N₂O: 0.48 [0.43 to 0.53], Global, High
- CH₄: 0.16 [0.14 to 0.18], Global, High
- Halocarbons: 0.34 [0.31 to 0.37], Global, High
- Ozone: -0.05 [-0.15 to 0.05], Continental to global, Med
- Stratospheric: 0.35 [0.25 to 0.65], Continental to global, Med
- Tropospheric: 0.07 [0.02 to 0.12], Global, Low
- Surface albedo: -0.2 [-0.4 to 0.0], Local to continental, Med
- Land use: 0.1 [0.0 to 0.2], Local to continental, Med
- Black carbon on snow: -0.5 [-0.9 to -0.1], Continental to global, Med
- Cloud albedo effect: -0.7 [-1.8 to -0.3], Continental to global, Low
- Direct effect: 0.01 [0.003 to 0.03], Continental, Low
- Linear contrails: 0.12 [0.06 to 0.30], Continental, Low

### Summary

- Total radiative forcing: 1.6 [0.6 to 2.4], Global, Low
High-resolution spectra of $O_2$, $CO_2$, and $CH_4$ absorption bands in NIR/SWIR bands
Heritage from instruments like:
SCIAMACHY, GOSAT and OCO-2

Details: Bovensmann et al. AMT, 2010