Carbon Monitoring Satellite (CarbonSat) as an Earth Explorer Opportunity Mission

Mission Overview

The quantification of natural and anthropogenic greenhouse gas surface fluxes using satellite observations of atmospheric CO_2 and CH_4 column amounts

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On behalf of the CarbonSat team

Introduction

The column amounts of carbon dioxide (CO_2) and methane (CH_4) are modulated directly by anthropogenic activity (fossil fuel combustion, biomass burning, agriculture and land usage change) and natural phenomena. Increases of these greenhouse gases are predominantly responsible for global climate change (IPCC 2007). Adequate knowledge of the sources and sinks of these gases and their feedbacks is a pre-requisite for the reliable prediction of the climate of our planet. In spite of the recognised importance of this issue, our current understanding about sources and sinks of the greenhouse gases CO_2 and CH_4 is inadequate. Whilst measurements of fluxes and ground based measurements of CO_2 and CH_4 are highly accurate, they are sparse. Global measurements of the CO_2 and CH_4 from instruments on satellite platforms coupled with inverse modelling schemes, are required to study local and regional surface fluxes. Data from SCIAMACHY on ENVISAT have already demonstrated that atmospheric columns of CH_4 provide unique and valuable information about their regional fluxes. Currently, SCIAMACHY, the Japanese Greenhouse Gases Observing Satellite, GOSAT (launched in 2009) and from 2013 onwards the orbiting Carbon Observatory, OCO, focused on CO_2 only, will deliver data on global greenhouse gas distributions. They all have a good sensitivity down to the surface where the emissions occur, using measurements of spectra of reflected solar radiation in the near-infrared/short-wave-infrared (NIR/ SWIR) spectral regions. To significantly improve global greenhouse gas monitoring capabilities and extend it to the local to regional scale, we propose a new satellite mission named **CarbonSat**, which is based on the same observational principles as SCIAMACHY, but optimized with respect to data accuracy, spatial and spatial coverage. CarbonSat determines the dry column mixing rations of CO_2 and CH_4 with high accuracy, high spatial resolution (2 km) and 5-6 days global coverage, to allow for the first time to quantify anthropogenic and natural localised sources CO_2 and CH_4 – so called "emission hot spots" – like power plants, seeps, volcanoes, large cities etc. from space. This will result in a better discrimination between natural and anthropogenic greenhouse gas fluxes. In addition, it will provide Europe with data to quantify global greenhouse gas emissions independently.

CarbonSat Mission Objectives

The recent IPCC Assessment Report 4 (IPCC 2007) pointed out clearly the importance of the release to the troposphere of CO_2, and CH_4 - both being long lived greenhouse gases (GHG) - by anthropogenic activity. The increase in atmospheric loading of these radiatively active gases is the dominant process driving global climate change. The key scientific issue is now to understand the regional consequences of global climate change and to predict accurately the future changes. This is required for policymakers in respect of mitigation, adaptation and the management of ecosystem services in a changing climate. Surprisingly and in spite of the importance, our knowledge about variable natural sources and sinks of CO_2 and CH_4, which are determined by the underlying biogeochemical cycles and feedbacks, is inadequate. This results in large uncertainty in our prediction of global climate change. Figure 1 illustrates this.

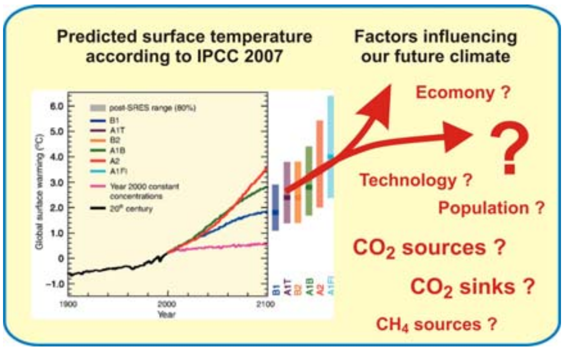


Figure 1: *Reliable climate prediction requires appropriate knowledge about the sources and sinks of CO_2 and methane.*

Over the past two decades significant progress has been made in quantifying carbon fluxes at selected locations and regions within Europe and the United States. Globally, however, the current observational network, whilst comprising very precise and accurate measurements, relies on sparse surface and aircraft observations. Coupled with a model, these measurements yield surface fluxes at continental and ocean basin scale having large uncertainties (often 100%). Regions of critical importance are essentially unobserved e.g. the tropics and most parts of Siberia.

An adequate knowledge of the sources and sinks of CO_2 and CH_4 and their response to a changing climate is a pre-requisite for the accurate prediction of the regional variation of the climate of our planet. To achieve this, the following scientific questions need to be answered:

- What are the magnitudes and distribution of the natural and anthropogenic sources and sinks of CH_4 and CO_2 and what is their spatial and temporal variability?
- Where and what magnitude is the CO_2 emission from the combustion of fossil fuels and biomass burning, the terrestrial biosphere and volcanoes?
- How is this emission taken up by the terrestrial biosphere and the ocean? The issue of the “unidentified CO_2 sink” is unsolved.
- How will the sources and sinks of CH_4 and CO_2 respond to a changing climate?
- How are high latitude carbon reservoirs (e.g. methane clathrates in permafrost and the ocean, northern wetlands) responding to the expected dramatic change in temperatures in these regions?

Within the United Nations Framework Convention on Climate Change, UNFCCC, and its amendments, the monitoring, verification and reporting of CH_4 and CO_2 emissions is required. After the COP 15 at Copenhagen, it is likely that these requirements will be strengthened and transparent reporting schemes are needed. Anthropogenic emissions are typically assessed on economic statistical data compiled by national authorities using a variety of procedures. For the NOx inventories, the advent of relevant satellite measurements has shown dramatically the potential deficits of this approach. Independent verification of reported emissions is required but currently not possible due to the lack of appropriate observational networks. The following important question arises:

- Can atmospheric measurements of the dry column of CO_2 and CH_4, i.e., XCO_2 and XCH_4, coupled with models independently verify the reported emissions and sinks in the context of the UNFCCC and post Copenhagen agreements?

To provide answers to the scientific and societal questions above, **CarbonSat** - a dedicated satellite mission to determine atmospheric CO_2 and CH_4 concentrations - is proposed and described in this document.

The **Primary Mission Objective** is the global determination of sources and sinks of CO_2 and CH_4 from the local to the regional scale for i) a better understanding of the processes that control the Carbon Cycle and ii) an independent estimate of local greenhouse gas emissions (fossil fuel, geological CO_2 and CH_4, etc.) for the verification of international treaties (NRC 2010). This objective is achieved by a unique combination of high spatial and temporal sampling with a passive remote sensing instrument observing from low earth orbit, coupled with inverse modeling techniques.

The mission addresses directly **the data needs** on greenhouse gas monitoring from space identified and defined by the WMO, GCOS, IGOS and IGACO, and now used by GEO/GEOSS. It will also serve explicitly the data needs of the European GMES Atmosphere Greenhouse Gas service chain.

The mission objectives address the need to improve our knowledge of the natural carbon budget, providing a better quantification of the terrestrial and oceanic CO_2 sinks, as well as assessing the feedbacks between the earth surface and the atmosphere in the most vulnerable regions (e.g., tropical and Siberian wetlands, permafrost areas, continental shelf areas, especially the methane-clathrate de-stabilization zones).

As a result of its high spatial resolution measurements CarbonSat will also contribute significantly to needs of policymakers by the provision of the

- **quantification of strong local greenhouse gas sources**
- thereby contributing to independent monitoring, verification and transparent reporting of the anthropogenic emissions of CO_2 and CH_4.

The effectiveness of global measures taken to sequester CO_2 through the development of biofuel crops, changing land management, the reduction of CO_2 emissions from coal-fired power plants, localized industrial complexes, and other large CO_2 emitters, will be assessed globally and objectively with CarbonSat.

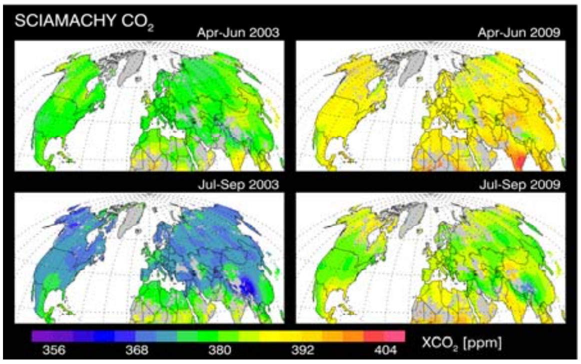


Figure 2: *SCIAMACHY CO_2 maps (Schneising et al., 2008).Similar maps but at much higher spatio-temporal resolution will be delivered from CarbonSat.*

Similarly the monitoring of natural gas pipelines and compressor station leakage will become feasible, and the detection and quantification of the substantial geological greenhouse gas emission sources such as seeps, volcanoes and mud volcanoes will be achieved for the first time.

Having demonstrated the potential of the measurements of greenhouse gases from space using SCIAMACHY, the time is now ripe for a focused mission aimed at the detection and quantification of CO_2 and CH_4 sources and sinks from the local and regional scales.

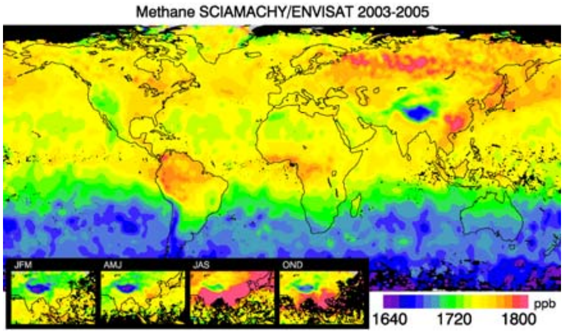


Figure 3: *SCIAMACHY CH_4 maps (Schneising et al., 2009). Similar maps but at much higher spatio-temporal resolution will be delivered from CarbonSat.*

The **CarbonSat** mission elements build on the heritage and the lessons learned from SCIAMACHY, GOSAT and OCO to yield the scientifically and strategically important measurements of the amounts and distribution of CO_2 and CH_4, during a key period in the evolution of the Anthropocene.

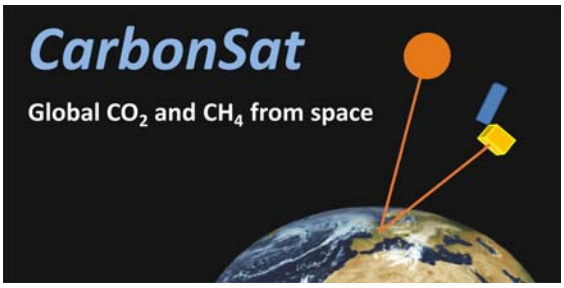
In the following more details about the CarbonSat mission are given.

CarbonSat Mission Overview

The CarbonSat payload comprises of the following instruments:

- An Imaging Spectrometer for nadir observations and sun-glint tracking which is the core instrument of the CarbonSat mission.
- A Cloud and Aerosol Imager (CAI) to deliver additional information on clouds and aerosols, including sub-scene and around scene information.

Following the successes of SCIAMACHY and GOSAT, the challenge for the new measurement systems is to retrieve the dry column amounts of CO_2 and CH_4 at high spatial resolution and temporal sampling. CarbonSat is designed to meet this need and achieve high spatial resolution (2 x 2 km^2) combined with sufficient spatial coverage (500 km swath width) for a single instrument. This spatial resolution and coverage is illustrated in Figure 4 where it is compared with other relevant missions. Figure 5 shows the orbital coverage for one day. High spatial resolution is important in order to maximize the probability for clear-sky observations (see Fig. 6) and to identify flux hot spots.



The relevant quantity is not the clear-sky probability but the total number of useful observations, defined as those being sufficiently cloud-free. This number, defined as the clear-sky probability multiplied by the total number of measurements, is shown in Table 1 for CarbonSat and other missions. As can be seen, CarbonSat will deliver more than 6 million cloud free observations each day – more than an order of magnitude more than any of the other existing or planned missions. High spatial resolution is needed to detect and quantify emission from local sources such as coal-burning power plants, large urban areas, land fill sites, seeps, volcanic eruptions etc. In Figure 7 the enhancement of the dry column of CO_2 in the plume form a power plant is calculated and compared with measurements from an airbone instrument MaMap, which is a proof of concept instrument of CarbonSat built by the University of Bremen and the GFZ in Germany. An overview of the characteristics of the CarbonSat mission is given in Table 2. Ideally, the mission will fly in parallel to an active greenhouse gas mission (ASCEND, MERLIN), as active remote sensing will add synergistic data under low sun conditions (northern high latitudes) for large area targets (100 km).

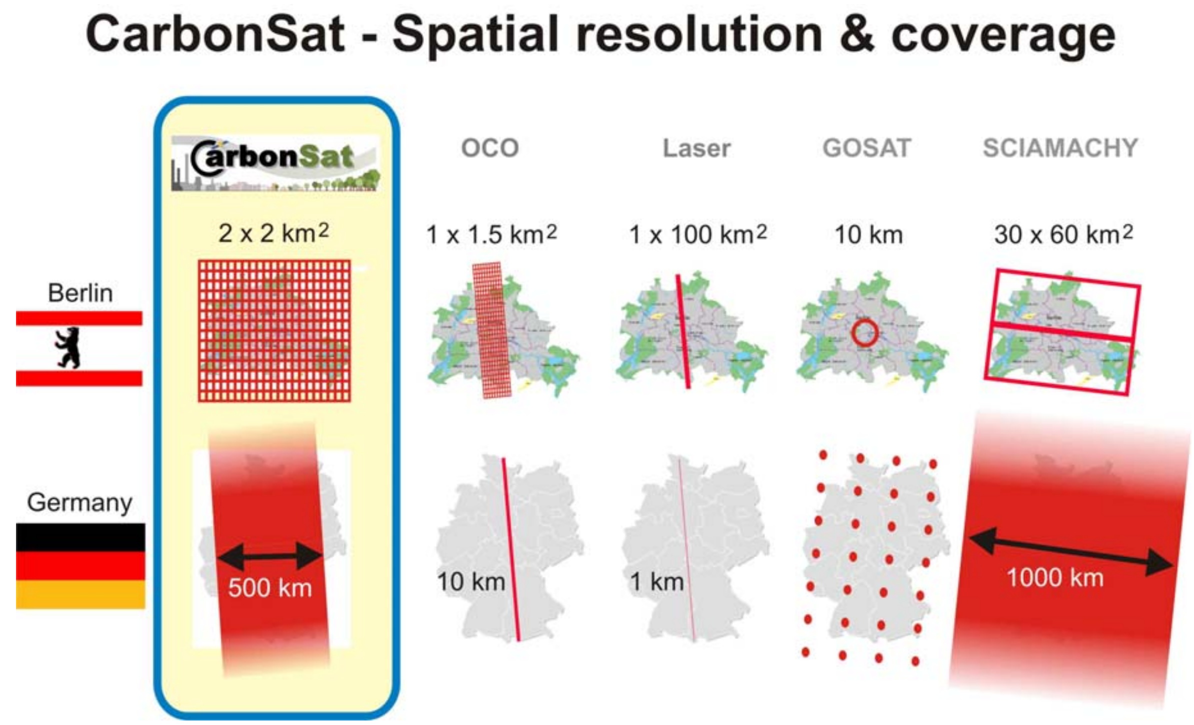


Figure 4: *Examples of the spatial resolution of CarbonSat (top row; as illustrated the city of Berlin) and orbital coverage (bottom row; as illustrated for Germany) compared to a potential LIDAR instrument, the existing GOSAT and SCIAMACHY missions as well as to the planned OCO-2 mission.*

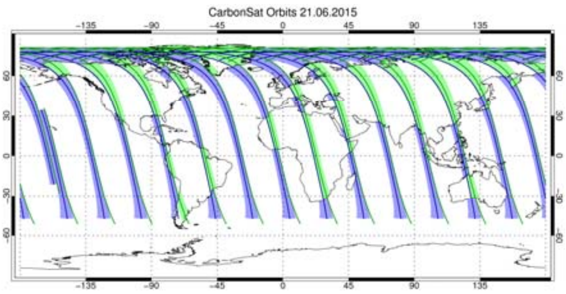


Figure 5: *CarbonSat orbital coverage (swath width 500 km). Green indicates the coverage obtained in nadir mode over land. Blue indicates the coverage in sun-glint mode over water. The orbits are for daylight for midsummer in the northern hemisphere.*

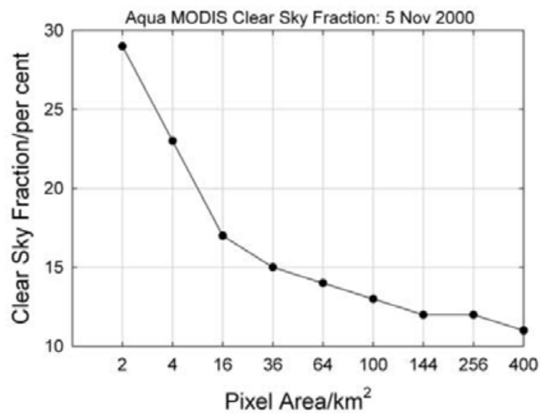


Figure 6: *Global clear-sky frequency determined as a function of spatial resolution and computed using MODIS 1-km cloud product (from: Miller et al., 2007).*

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

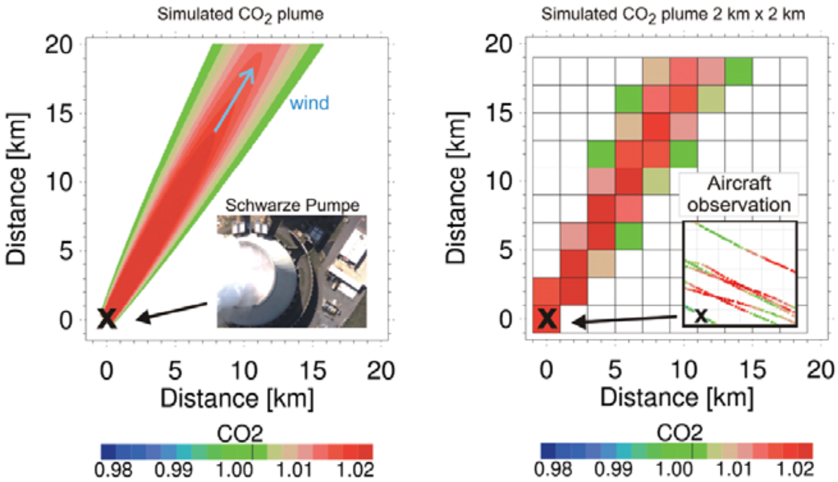


Figure 7: *Left: Simulation of the enhanced atmospheric dry CO_2 column, resulting from CO_2 emission by a power plant using a quasi-stationary Gaussian plume model. The power plant location is indicated by the black cross. A value of 1.0 (green) corresponds to the background CO_2 column. A value of 1.02 (red) corresponds to a column enhancement of 2% or larger relative to the background. The wind speed is 1 m/s. The assumed power plant emission is 13 MtCO_2/year corresponding to a power plant such as Schwarze Pumpe located in eastern Germany near Berlin (see photo taken during an overflight with the MAMAP aircraft instrument). Right: as left hand side but at a spatial resolution of 2×2 km2 obtained by box-car averaging the high resolution plume shown on the left hand side. The inset shows MAMAP CO_2 column retrievals around the location of the power plant Schwarze Pumpe. The maximum value of the CO_2 normalized column is 1.126 for the high resolution plume on the left (resolution 20×20 m2) and 1.031 for the 2×2 km2 resolution plume shown on the right. To better visualize the extent of the CO_2 plumes values below 1.0025 are shown in white (see also the black vertical line in the color bar). From Bovensmann et al., 2010, where more details are given.*

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)
Ground pixel size Coverage	2 x 2 km^2 Global within 1 – 6 days
Main obs. modes	Nadir, sun-glint tracking, sun over diffuser
Payload	Main instrument: GHG Imaging Spectrometer: Passive 3-band spectrometer system (1x NIR, 2x SWIR). Additional instrumentation: Cloud and Aerosol Imager (CAI): Several bands UV-NIR/SWIR
Lifetime	7 (5) years; Launch 2016 or later
Orbit	Baseline: Sun-synchronous polar LEO, LTAN 13:30, swath: 500 km

Table 2: *CarbonSat mission requirements overview. All precision are 1-sigma values. The Level 4 requirements are valid for cloud free land regions.*

GHG Imaging Spectrometer

CarbonSat's primary sensor will be an imaging NIR/SWIR spectrometer system (SCIAMACHY, OCO, GOSAT heritage) to perform measurements of CO_2 and CH_4 in combination with O_2 to yield their dry column amounts.

Spectral absorptions of CO_2 (~1.6 µm and ~2 µm), O_2 (~760 nm) and CH_4 (~1.65 µm) are measured with high spectral resolution (~0.03-0.3 nm) and high signal-to-noise ratio (SNR) (see table 3).

Simulations of the CarbonSat spectral bands for a selected scene are shown in Figure 8. The relatively transparent band SWIR-1 delivers information on the vertical columns of CO_2 and CH_4 with high near-surface sensitivity. Bands NIR and SWIR-2 contain strong absorption bands of O_2 and CO_2, respectively, and provide additional information on aerosols and clouds. This information are needed

a) for the conversion of the vertical columns into column-averaged mixing ratios (via O_2) and
b) to identify the scattering by aerosols and clouds .

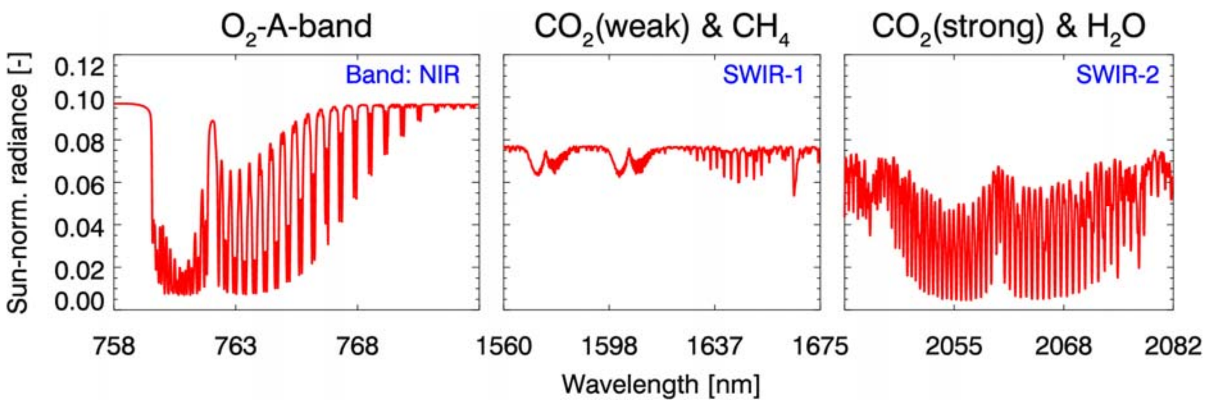


Figure 8: *CarbonSat's spectral bands covered by the Imaging Spectrometer.*

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)

Table 3: *Overview of the main characteristics of CarbonSat's Imaging Spectrometer. The numbers without brackets are the goal requirements, the numbers in brackets are the threshold, i.e., minimum requirements.*

Cloud and Aerosol Imager (CAI)

CarbonSat will be equipped with a Cloud and Aerosol Imager (CAI), similar as GOSAT, in order to obtain additional information on clouds and aerosols, and sub-scene information.

The spatial resolution of CAI is planned to be 500 x 500 m^2, yielding 16 measurements per ground scene of the imaging spectrometer. The CAI swath width is somewhat larger than the swath width of the imaging spectrometer, which is 500 km.

Table 4 lists the main characteristics of the CarbonSat CAI spectral bands.

Additionally, usage of cloud information from operational meteorological imagers (for example VIIRS on NPOES) will allow cloud flagging and correction, assuming that adequate co-registration is achieved.

CarbonSat Cloud and Aerosol Imager (CAI)				
Band	**Band center wavelength [nm]**	**Band width [nm]**	**SNR [-]** (A=0.1, SZA=50^o, t_{int}= 76 ms)	**Special purpose**
2	380	20	450	AAI
6	675	20	450	Clouds & aerosols NDVI
10	870	20	450	Clouds & aerosols, NDVI
13	1653	35	450	Clouds & aerosols

Table 4: *Overview of the main characteristics of CarbonSat CAI as currently proposed as threshold channels (GOSAT heritage). Abbreviations: AAI = Absorbing Aerosol Index, NDVI = Normalized Differenced Vegetation Index.*

Selected References

Bergamaschi et al., 2009: Bergamaschi, P., C. Frankenberg, J. F. Meirink, M. Krol, M. G. Villani, S. Houweling, F. Dentener, E. J. Dlugokencky, J. B. Miller, L. V. Gatti, A. Engel, and I. Levin, Inverse modeling of global and regional CH_4 emissions using SCIAMACHY satellite retrievals, J. Geophys. Res., 114, doi:10.1029/2009JD012287, 2009.

Bovensmann et al., 2010: Bovensmann, H., M. Buchwitz, J. P. Burrows, et al., A remote sensing technique for global monitoring of power plant CO_2 emissions from space and related applications, Atmos. Meas. Tech. Discuss., 3, 55–110, 2010.

Bovensmann et al., 1999: Bovensmann, H., J. P. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. V. Rozanov, K. V. Chance, and A. H. P. Goede, SCIAMACHY - Mission objectives and measurement modes, J. Atmos. Sci., 56, (2), 127-150, 1999.

Crisp et al., 2009: Crisp, D., et al., The Need for Atmospheric Carbon Dioxide Measurements from Space: Contributions from a Rapid Reflight of the Orbiting Carbon Observatory, May12, 2009, OCO White Paper, 2009.

IPCC 2007: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., eds.: Climate change 2007: The physical science basis, Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, 2007.

Kuze et al., 2010: Kuze, A., Suto., H., Nakajima, M., and Hamazaki, T., Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gas monitoring, Applied Optics, Vol. 48, No. 35, 6716-6733, 2010.

Miller et al., 2007: Miller, C. E., Crisp, D., DeCola, P. L., et al., Precision requirements for space-based XCO_2 data, J. Geophys. Res., Vol. 112, D10314, 2007.

NRC 2010: National Research Council – Committee on Methods for Estimating Greenhouse Gas Emissions, Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements, ISBN: 0-309-15212-7, 144 pages, http://www.nap.edu/catalog/12883.html, 2010.

Schneising et al., 2008: Schneising, O., Buchwitz, M., Burrows, J. P., Bovensmann, et al., T.: Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite - Part 1: Carbon dioxide, Atmos. Chem. Phys., 8, 3827–3853, 2008.

Schneising et al., 2009: Schneising, O., Buchwitz, M., Burrows, J. P., Bovensmann, H., Bergamaschi, P., and Peters, W.: Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite - Part 2: Methane, Atmos. Chem. Phys., 9, 443–465, 2009.

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CarbonSat web site

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