CarbonSat Constellation

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Abstract

Carbon dioxide (CO_2) and methane (CH_4) are the most important manmade greenhouse gases (GHGs) which are driving global climate change. Despite their importance, our knowledge about their sources and sinks has significant gaps. Satellites can add important missing global information complementing the measurements of the ground observing network whose coverage is sparse.

CO_2 monitoring and trading is often based mainly on bottom-up calculations and an independent top down verification is limited due to the lack of appropriate global measurements. Those satellites add important missing information as has already been demonstrated by SCIAMACHY on ENVISAT satellite. Current GHG measurement satellites such as SCIAMACHY and GOSAT have however not been optimized to quantify CO_2 and CH_4 emissions from localized man-made or natural sources such as power plants or (mud) volcanoes. CarbonSat is first proposed to meet the demand of both higher resolution 2 km² and good coverage (500km). To monitor man-made emissions, global, high frequent and higher spatial resolution measurements are required. The CarbonSat constellation idea comes out the trade off of resolution and swath width during CarbonSat mission definition studies. In response to the urgent need to support the Kyoto and upcoming protocols, a feasibility study has been carried out. The proposed solution is a constellation of five CarbonSat satellites, which is able to provide global, daily CO_2 and CH_4 measurement with high spatial resolution 2 × 2 km² .The unique global daily measurement capability significantly increases the number of cloud free measurements, which enables more reliable services associated with reduced uncertainty, e.g. better than 1 ppm for CO_2 per month in 10km².

The CarbonSat Constellation in combination with inverse modelling techniques will be able to provide information services, such as global quarterly CO_2 and CH_4 regional flux updates, CO_2 emission reporting from hot spots such as power plants and CH_4 emission reporting from hot spots such as pipeline/oil and gas fields.

A central coordination will be set up for the constellation operation, data calibration and data distribution. The proposed approach provides independence for each partner and is financially more feasible. The world wide transparency provided by this forum is critical in supporting Kyoto protocol and upcoming international agreement in man-made Greenhouse emission reduction.

The paper first introduce the urgent needs for a global CO_2 and CH_4 monitoring system and the evolution of the greenhouse gas observation missions which leads to the optimised the design – CarbonSat, and followed with the description of the CarbonSat Constellation design and the proposed products/ services to verify CO_2 and CH_4 sources and sinks from a constellation of five CarbonSat satellites through a multilateral collaboration.

1 Introduction

Climate Change is the major problem of the 21th Century. Greenhouse Gases are the main drivers of global climate change. According to Intergovernmental Panel for Climate Change (IPCC) reports, CO_2 accounts for ~60% and CH_4 accounts for ~20 % of the Greenhouse Effect. In contrast to 1 ppmv / 200 years increase in the pre-industial times, CO_2 has been increasing at the speed of 1 ppmv / year since industrialization, which resulted in a global temperature increase of +0.8K. The internationally agreed limit is set to +2℃, to prevent global severe issues leading to increasing incidence of droughts, occurrence of weather extremes, sea level rise and other severe consequences. A good understanding of the CO_2 and CH_4 sources and sinks is a pre-requisite for reliable climate prediction to maintain a stable global environment for all humankind. Figure 1-1 shows the evolution of the Greenhouse gas concentrations of the past in comparison with the significant changes since industrialization, according to IPCC 2007 statistic.

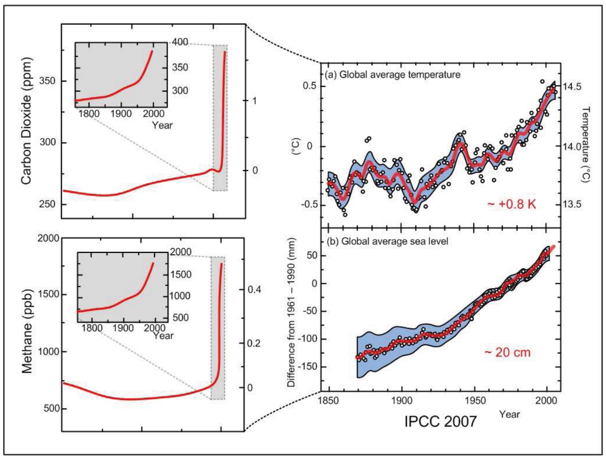

Figure 1-1 Intergovernmental Panel on Climate Change (IPCC) statistic

Most of our knowledge about CO_2 and CH_4 sources and sinks on the global scale stems from a network of highly accurate and precise in-situ surface observations (e.g., NOAA ESRL). This network is however sparse (about 100 stations with poor coverage in many regions) and can inform only about very large regions such as continents and ocean basins. Recently the ground network has been expanded using spectrometers which measure the concentrations of gases in the air column above the sites. This network, Total Carbon Column Observing Network (TCCON), has been set up, e.g., to validate satellite column observations. Figure 1-2 shows the current location of TCCON sites.

Thus, there are significant gaps in our knowledge of CO_2 and CH_4 sources and sinks.

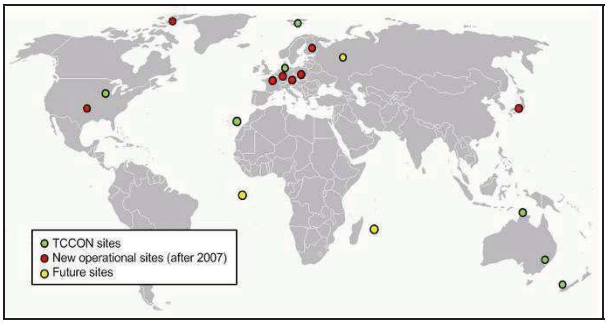

Figure 1-2 Total Carbon Column Observing Network (TCCON)

Figure 1-3 shows the European 2007 CO_2 emission report in the implementation of the Kyoto protocol. It is a collection of reports from every company above a certain level of emission, based on pre-set calculation rules.

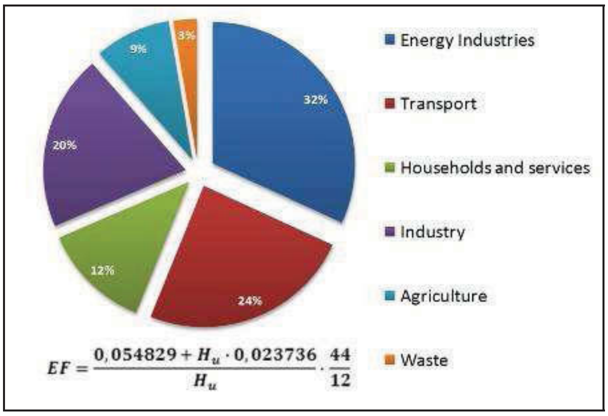

Figure 1-3 Reported 2007 CO_2 Emission based on calculation

Clearly, Kyoto protocol and upcoming international agreements also stimulate the need for global, independent, and transparent verification of sources and sinks.

2 Greenhouse gas Observation Mission Evolution

Data from observing satellites can help to get a better understanding of these sources and sinks of CO_2 and Methane due to their global coverage. First global measurements of CO_2 and Methane are already obtained, for example by the "Scanning Imaging Absorption Spectrometer for Atmospheric ChartographY" (SCIAMACHY) on ENVISAT satellite.

SCIAMACHY which provided the first greenhouse gas measurements from space covers the relevant absorption bands of CO_2, CH_4, and O_2, in the NIR/SWIR spectral regions; albeit at quite low spectral and spatial resolution. The number of cloud free observations is small due to coarse spectral resolution

Due to instrument issues several important spectral regions have not been used so far. Work around solutions had to be developed in the years after launch in order to produce accurate CH_4 and CO_2 data products.

It has been demonstrated using inverse modelling that the SCIAMACHY measurements provide strong constraints on regional methane fluxes – information that cannot be obtained from the sparse ground based or aircraft observations.

SCIAMACHY covers a broad range of applications (stratospheric ozone chemistry, tropospheric air quality, etc.) and is not a dedicated GHG mission such as OCO and GOSAT, very useful data products have been generated. Figure 2-1 shows an example of SCIAMACHY CO_2 retrievals. These maps base on three years data collection by SCIAMACHY on ENVISAT.

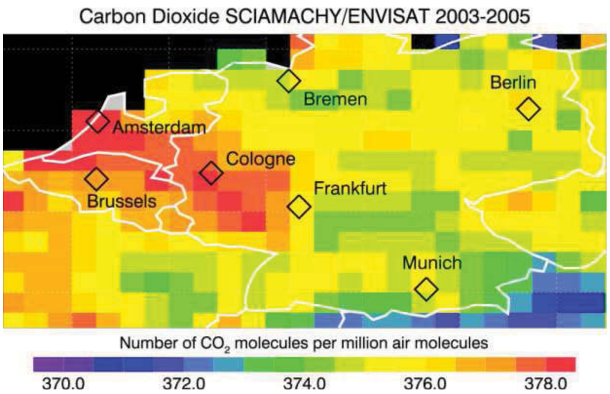

Figure 2-1 regional CO_2 map

2.1 CarbonSat is the best solution

Building on the heritage and lessons learned from SCIAMACHY, the satellite concept CarbonSat is developed to make strategically important measurements of the amounts and distribution of CO_2 and CH_4, during a key period in the evolution of the Anthropocene.

CarbonSat will follow the typology of the SCIAMACHY instrument. A spectrometer measures the reflected light energy in the selected spectral bands which are sensitive to CO_2 and CH_4. The concentration of CO_2 and CH_4 in the air column along the light path can then be derived from the measurements via absorption spectroscopy.

CarbonSat's core sensor will be an imaging NIR/SWIR spectrometer system. 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 (~0.04-0.3 nm) and high signal-to-noise ratio (SNR).

The CarbonSat spectral bands are shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The relative 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. They are needed for the conversion of the vertical columns into column-averaged mixing ratios (via O_2) and to reduce scattering related errors caused by aerosols and clouds.

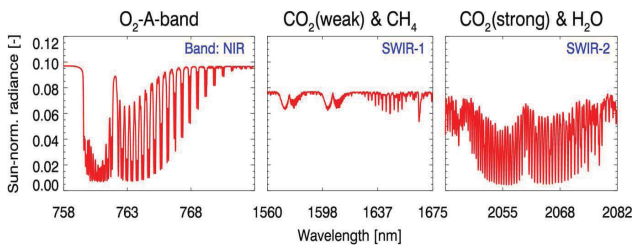

Figure 2-2 CarbonSat spectral bands

CarbonSat shall continue the global CO_2 and CH_4 monitoring from space which started with SCIAMACHY on ENVISAT and is currently being continued with GOSAT.

After SCIAMACHY (2002-2013) and GOSAT / OCO2 (2009-2014/15) there is high risk for an observational gap in the 2016-2020 time period, especially for CO_2 but also for CH_4. This is illustrated in Figure 2-3. CarbonSat can close this gap.

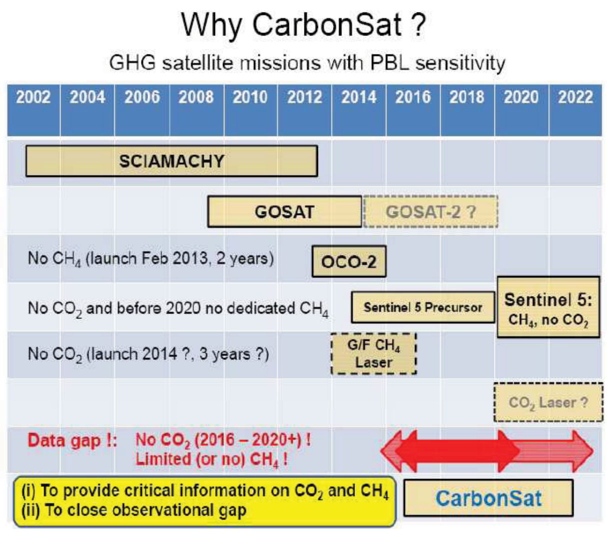

Figure 2-3 GHG satellite missions with PBL sensitivity

A comparison of missions with similar scientific objectives in Figure 2-4 shows, that none of the current or planned future missions can achieve two important and essential goals simultaneously (either high resolution or large swath width). CarbonSat achieves these goals with a high spatial resolution (2 x 2 km^2) and good coverage (500km), which best meets the demand of a single satellite mission.

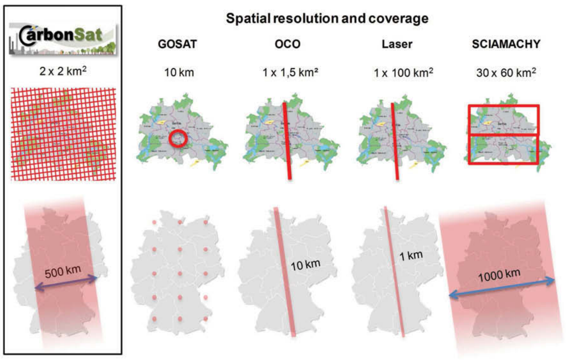

Figure 2-4 Comparison of missions with similar scientific objectives as CarbonSat

To provide more reliable and timely operational services the CarbonSat concept includes the extension to a multi satellite mission.

2.2 CarbonSat Constellation

The target of the constellation design is to provide daily global CO_2 and Methane measurements everywhere on Earth. A constellation of six CarbonSat (with 500km swath width instruments) satellites is required to meet this design target. With 5 satellites, the constellation will be able to measure any point on the Earth once per day with some gaps in the equator but more frequent measurements on higher latitudes. The combined ground coverage of the constellation is equal to 2500 km on ground, obtained in a single orbit phase, leading to a 98% global coverage per day. This is sufficient to provide global, more frequent, high resolution and accuracy improved measurements.

The CarbonSat constellation comprises a conventional and four compact satellites. The proposed orbit is 618 km and 13:00 am LTAN.

The CarbonSat constellation will significantly reduce the CO_2 measurement uncertainty and first to achieve less than 1ppm accuracy on the CO_2 pinpoint measurement which is the requirement defined by IPCC. Subject to the cloud and wind statics, the constellation is able to deliver much more timely data:

- For CH_4, the constellation will be able to deliver global updates at accuracy 7kt/y once per month to once per half year, in average, once per three months.
- For CO_2, the constellation will be able to deliver global updates at accuracy 1Mt/y once per month to once per half year, in average, once per three months

It is expected that many new applications could be made available by the CarbonSat Constellation data which have to be further evaluated.

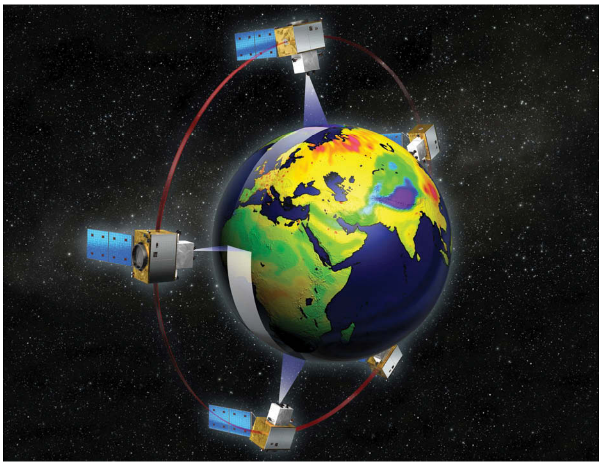

Figure 2-5 Satellite constellation observing the earth

The ideal deployment of the constellation will be all five satellites launched in the same orbit using one launcher and equally spaced. It is easy to manage with funding for all five satellites come from the same source; however, an internationally coordinated constellation has its attractions. The organisation itself is naturally “global and independent”. With members from both developed and developing countries, it will be possible to encourage knowledge and technology transfer and help to establish common understandings of the climate change.

The member of the CarbonSat Constellation Consortium will be able to access the entire constellation and its operational services through the investment on only one satellite, which is financially more feasible for most of nations.

The constellation deployment will be coordinated by the CarbonSat Constellation Consortium. Each participating satellite will be controlled by its own ground station for national applications. To provide global daily coverage the Constellation Coordination Centre (CCC) coordinates the constellation operation (incl. calibration) and international data distribution.

The constellation coordination is to assure permanently an optimal coverage of earth even in case one satellite is not available (e.g. due to maintenance) and to keep all satellites on track for best constellation data output.

The payload on the satellite is monitoring permanently Earth atmosphere, therefore a dedicated mission plan for payload is not required. The collected data is downloaded during the next X-Band communication. As the satellites have a steerable X-Band antenna, data download can be performed independently from payload activities.

The collected raw data from the satellites will processed automatically within the Satellite Control groundstation to Level 1B products. These products will be both distributed to users and the “CarbonSat Fusion Centre” (CFS). The Carbon Fusion Centre (CFC) will than combine the gathered raw data to produce the CO_2 and CH_4 Emission global flux maps and hot spot measurements, with advanced precession and high time resolution. The CFS produces higher level products.

The Fusion Centre will as well make use of external sources of data, like for example GOSAT,OCO, SCIAMACHY, Airborne and in Situ measurements.

3 Example Products

Level 0: Raw data

The Level 0 data are basically the original data as sent from the satellite. This includes the detector readouts in binary units (counts) and auxiliary data such as time information, orbit information, and information from various sensors such as temperature sensors.

Level 1: Calibrated and geolocated radiances

The Level 0 data are processed on ground to Level 1. At least two Level 1 data products will be available, Level 1b and Level 1c.

The Level 1b data product (one file per consolidated orbit) contains the uncalibrated spectra and calibration parameters needed to calibrate the spectra. The calibration parameters are however not yet applied. The Level 1b data will be delivered to users plus a tool that allows to convert the Level 1b data product to calibrated and geo-located spectra, i.e., the Level 1c data product. The conversion depends on various flags for the different calibration options which can be chosen by the user. Examples are options to switch on or off the radiometric calibration or the wavelength calibration.

Level 2: Geophysical data product for individual readouts ("swath data")

The Level 1c data are converted to Level 2 using retrieval algorithms. This data product provides the information on the atmospheric CO2 and CH4 information at ground pixel resolution (i.e., 2 x 2 km2). This data product contains:

- Dry-air column-averaged mixing ratio of CO2, denoted XCO2, in part per million (ppm) plus error estimate
- Dry-air column-averaged mixing ratio of CH4, denoted XCH4, in part per billion (ppb) plus error estimate
- Total column of CO2 in molecules/cm2 plus error estimate
- Total column of CH4 in molecules/cm2 plus error estimate
- Auxiliary information such as:

measurement time, ground pixel centre and corner coordinates, solar zenith angles (zenith and azimuth), scan angles (zenith and azimuth), nadir / sun-glint observation flag, averaging kernels and a-priori vertical profiles, cloud information, quality flags

Level 3: Geophysical data product after spatio-temporal averaging ("maps")

This data product consists of gridded (e.g., 0.5 deg x 0.5 deg and/or 0.1 deg x 0.1 deg) daily, weekly and/or monthly data and comprises; XCO2, XCH4, error estimates, standard deviation, number of data points averaged, etc.

Level 4: Surface fluxes

The Level 2 data are converted into surface flux (emission) data products using inverse modelling. Inverse modelling is based on the satellite observations, optionally additional (surface) observations, a-priori information on emissions, meteorological information (e.g. wind fields) and (global) models. Several Level 4 data products will be generated:

- Regional scale CO2 flux maps at different resolutions
- (e.g. 8 deg x 10 deg weekly and/or 4 deg x 5 deg monthly)
- Regional scale CH4 flux maps at different resolutions (e.g. 8 deg x 10 deg weekly and/or 4 deg x 5 deg monthly)
- CO2 hot spot emission data product for various localized emission sources including power plants
- CH4 hot spot emission data product for various localized emission sources including pipeline compressor stations, large waste disposal sites, geological sources (e.g. seeps, mud volcanoes)

These data products will be the basis for the CarbonSat services which will comprise:

- Delivery of Level 1 data products
- Delivery of Level 2 data products
- Delivery of Level 3 data products

- Delivery of Level 4 data products
- Delivery of special data products for dedicated users

Product and Services of the CarbonSat Constellation are for example high resolution CO_2 Concentration maps and Hot Spot monitoring of emissions as shown in Figure 3-1. These products include the Hot Spot observation of for example Power plants, Steelworks, Cities and Volcanoes.

Figure 3-1 Example of high resolution CO_2 map *(Oda and Maksyutov, 2009)*

Figure 3-2 shows a CH_4 observation example of CarbonSat Constellation, providing high resolution Methane maps as well as Hot Spot measurements of for example Pipelines, Compressor Stations, Landfills / Waste, Seeps, Oil & Gas Fields, Mud Volcanoes

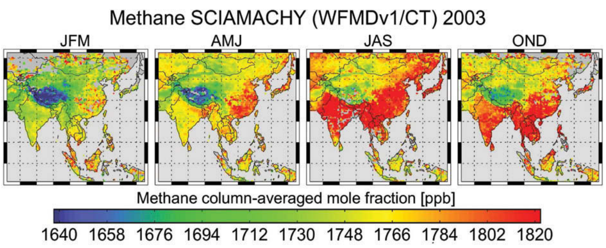

Figure 3-2 Example of high resolution Methane maps *(SCIAMACHY / IUP)*

4 CarbonSat Design

The CarbonSat Constellation Concept foresees two types of Satellite designs. The conventional design is a so called full design, housing the payload which is directly derived from the requirements for the CarbonSat mission. It will make use of a 3 band spectrometer with the spectral absorptions of CO_2 (~1.6 µm and ~2 µm), O_2 (~760 nm) and CH_4 (~1.65 µm) which are measured with high spectral resolution (~0.04-0.3 nm). The compact design is a cost reduced approach, which is hosting only a 1 band spectrometer of CO_2 (~1.6 µm). The Constellation should at least make use of one conventional and up to four compact satellites, to provide good results.

4.1 Conventional Design

For the CarbonSat mission, a mission highly dependent on finding a cost-effective solution but still providing high class measurement data, OHB-System proposes to make use of its EnMAP platform. The platform is already today in an advanced development status, thus enabling lower development time and cost for CarbonSat.

EnMAP results as the best heritage baseline, providing precise pointing, orbit propulsion, flexible payload resources for power, mass and volume. Also the CarbonSat schedule constraints for launch in 2014 lead to the selected platform concept, since the EnMAP project is already in its realization in Phase C/D and currently performing the CDR . The EnMAP satellite will be operational in 2013 with mission duration of 5 + 2 years. The satellite will operate in an SSO orbit of 643 km and have a mass of about 850 kg. EnMAP's satellite platform is based on the space proven SAR-Lupe platform having five satellites in orbit with a cumulative in-orbit life time of >13 years. With this platform OHB-System is able to offer a very suitable and cost effective satellite platform for accurate, high resolution Earth observation purposes.

High spectral resolution requirements and necessity to detect CH_4 and CO_2 gasses with high accuracy lead to the design with three spectrometer units, which is a baseline for the conventional payload. The spectrometer units, named NIR, SWIR-1 and SWIR-2, are designed for spectral regions around 760nm, 1600nm and 2060nm accordingly.

The presence of clouds and aerosols in the atmosphere can degrade accuracy of gas measurements and therefore has to be accounted for. The Cloud and Aerosol Imager (CAI) detects affected areas by observing in several spectral bands the same swath as the CarbonSat spectrometers. Spectral bands are chosen to provide the best sensing of different types of clouds.

CAI comprises a telescope similar to the telescope of the spectrometer payload and detector with a number of filters in front of it. Such design has relatively small dimensions and allows combining the CAI instrument with any other payloads.

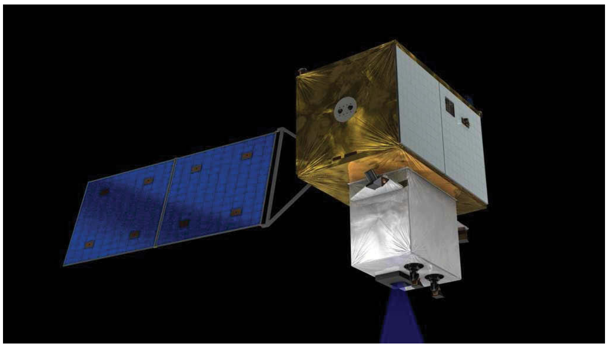

Figure 4-1 Example of CarbonSat Layout

The preliminary S/A baseline design for the CarbonSat mission will use sun pointing solar panels driven by a SADM. As seen in Figure 4-1. It is hence concluded that a Nadir side mounting is the best choice for the CarbonSat mission, being based upon the EnMAP P/F capabilities.

Sun-glint imaging does not occur too often and is not a standard operation mode, like the Nadir pointing mode (Nominal), and has to be treated as a deviation from the nominal pointing. Hence, the S/C will nominally keep a Nadir profile, due to the fact that it is there where most of the observations are performed.

Once the Sun-glint point no longer fulfils all restrictions, the FOV needs to return to its nominal Nadir pointing profile.

With spacecraft pointing, CarbonSat no longer maintains a Nadir pointing profile at all times, but rather slews itself so that the FOV points towards the Sun-glint. As a result, no pointing mirror is required and the instrument becomes less complex and the total system cost goes down.

Figure 4-2 shows the major/main constituents of the satellite in an exploded view. The P/L and the optical bench, together with a surrounding envelope, are illustrated. Two star trackers are also mounted on the optical bench which in turn is attached to the P/F.

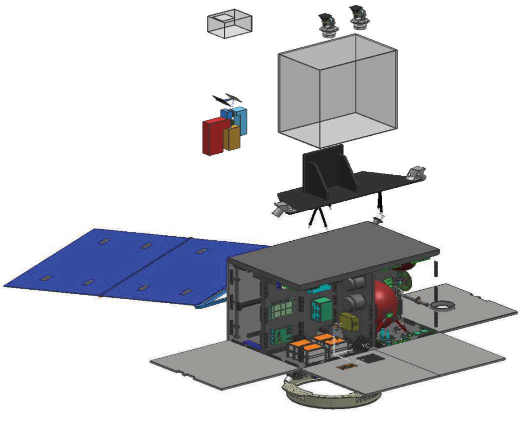

Figure 4-2 Exploded view of the CarbonSat S/C

Figure 4-3 depicts a close-up view of a first estimate of the P/L compartment configuration. It shows the 3 detectors (NIR, SWIR-1 & SWIR-2) and Cloud Imager (CAI) mounted vertically. On top, there is the instrument slit assembly that focuses the incoming light (coloured in blue) into the different units. The green marked units are Beam Splitters. Surrounding the entire set-up is a protective envelope. This envelope is not attached to the Optical Bench (although the detectors and Pointing Mirror are); rather it is mounted directly on the P/F. On top of the envelope there is mounted 2 Antenna Pointing Mechanisms. The envelope has been made transparent for better understanding; it is to be, just like the P/F, covered with Multi Layered Insulation (MLI).

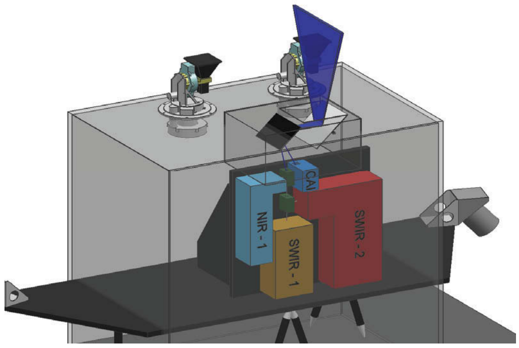

Figure 4-3 Close-up view of the P/L compartment (preliminary estimate)

Budgets including margin	
Mass [kg]	704 + 62 propellant
Peak Power [W]	503
Standby Power [W]	406
Volume Spacecraft [m]	1.8 x 1.96 x 1.17
Size of Solar Panel [m²]	4.68
Data per Orbit [Gbit]	175 uncompressed
X-Band Downlink [Mbit/s]	320

Table 4-1 Budgets of conventional design

4.2 Compact Design

The CarbonSat Constellation system will be composed by different satellites platforms. Besides the previously described conventional platform a compact platform will be developed. The main difference between these two satellites is the size reduction due to a reduced payload embarked on the compact satellite. This leads to different needs which will be reflected on the platform design. The platform in fact shall provide all the resources required by the payload and by the system in order to satisfy the mission objectives.

The satellite will be equipped by 3 solar panels, one fixed and 2 deployable as it is possible to see in the following sequence of figures:

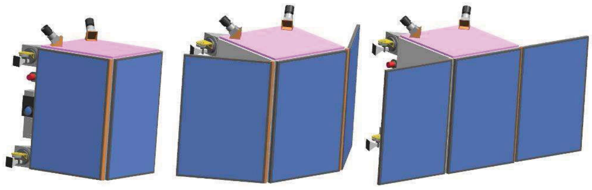

Figure 4-4 Compact CarbonSat solar panel deployment sequence

The Communication subsystem is composed by two indigested pats, one dedicated to bus monitoring and control (TMTC full-duplex link) and one dedicated to P/L Data transmission (PDT). It is based on an S-Band link able to guaranty attitude independent commendably / monitoring of the satellite (onboard antenna pattern near-omnidirectional).

A low bitrate (4kbps) uplink channel form Telemetry (TC) and a convolutional coded 1Mbps link for stored and real-time telemetry (TM) are foresee, able to cover both nominal and LEOP/Contingency needs. Single box, full redundant unit is foreseen. The Data Transmission section has a baseline of two 155 Mbps modulator-transmitter units (high efficient modulation), that can be used at the same time. In case of failure of one transmitter, the data download capability will be reduced.

An antenna coupling network permits the use of both transmitters with whichever antenna. Two high gain gimballed antennas permit to achieve high speed data download with low power consumption.

The ACS is in charge of managing the satellite attitude.

The sensor set is able to perform precise attitude determination by using the star tracker. Gyroscopes provide the angular rate measurements in order to perform fine attitude control. Sun sensors and magnetometers are used for coarse attitude determination during the initial phase of the mission and to guarantee the required reliability for saving. Magnetometers are used to drive the selection of torque-rods during their operations and as safe sensors.

The reaction wheel assembly permits fine attitude control when required and allows performing manoeuvres if necessary. Torque-rods are used to de-saturate reaction wheels and as safe actuators.

Thermal subsystem is designed to guarantee that the temperature of each satellite unit remains within the accepted range.

In order to obtain this result the thermal subsystem will use suitable hardware and concepts for managing the internal dissipated heat, and coping with the environmental heat loads and the radiative environment proper of the orbiting object.

It will also foresee an efficient accommodation of the internal units to minimize the thermal subsystem requirements in terms of power.

The passive thermal subsystem design will take into consideration all the satellite attitudes and configurations foreseen in the mission profile.

Selected general concept for the structure is a skin-frame structure. This structure has a skeletal framework with machined frames surrounded by machined or sandwich panels.

CarbonSat has a modular structure. The concept is to have all panels with the possibility to integrate all instrumentations separately in different moments and assembly the satellite in one step. The following figure shows the satellite structure and the accommodation of the platform subsystems and of the payloads:

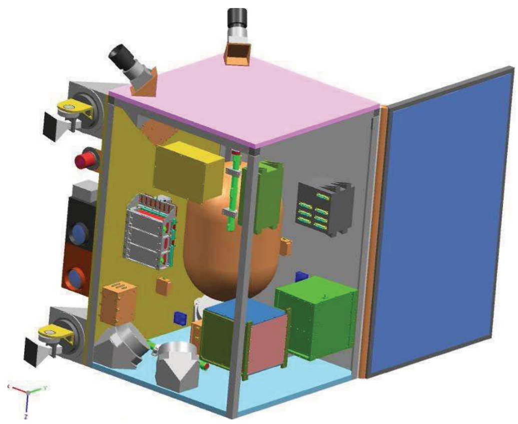

Figure 4-5: Compact CarbonSat accommodation

The mass budget has been evaluated considering the various subsystems and payload and with an estimation of the fuel required for the orbit maintenance and the de-orbiting. The result is a satellite with a weight of 250 kg, including all margins.

Budgets including margin	
Mass [kg]	250
Peak Power [W]	250
Standby Power [W]	213
Volume Spacecraft [m]	0.8 x 0.8 x 1.30
Size of Solar Panel [m²]	2.7
Data per Orbit [Gbit]	55 uncompressed
X-Band Downlink [Mbit/s]	320

Table 4-2 Budgets of compact design

5 Conclusion

CarbonSat is first, leads the CO_2 and Methane monitoring from demonstration to operational service. It is, based on experience from SCIAMACHY, optimized for CO_2 and Methane monitoring with significant increased spatial resolution, enabling Hot Spot measurements of for example power plants, steelworks, cities and volcanoes. It achieves a high spatial resolution (2 x 2 km^2) and good coverage (500km) simultaneously, which best meets the demand of a single satellite mission.

With the extension to a constellation of five CarbonSat satellites, the combined ground coverage of the constellation leads to a global coverage per day. CarbonSat constellation will significantly reduce the CO_2 measurement uncertainty and be the first to achieve less than 1ppm accuracy on the CO_2 pinpoint measurement which is the requirement defined by IPCC.

With respect to the urgent need of a global greenhouse gas observation system, it is the best solution to provide reliable, transparent, global and fast information of the two most important greenhouse gases.

It enables a better understanding of regional and local sources and sinks of CO_2 and Methane to contribute to a more reliable climate change predictions and in addition to support the Kyoto protocols and upcoming international agreements. It will be able to provide independent and non-intrusive CO_2 and Methane emissions verification with transparency and therefore helps on reaching international agreements on CO_2 and Methane emission reduction and subsequent enforcement.