CO₂ Human Emissions

Stakeholder Report on the Requirements for Future Space-based Instruments to Deliver Products Suitable for CO_2 Emissions Monitoring

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Co-ordinated by ECMWF

D1.4 Stakeholder Report on the Requirements for Future Space-based Instruments to Deliver Products Suitable for CO_2 Emissions Monitoring

Dissemination Level:	Public
Author(s):	Rosemary Munro (EUMETSAT)
Date:	15/12/2020
Version:	2.0
Contractual Delivery Date:	31/12/2020
Work Package/ Task:	WP1/T1.4
Document Owner:	EUMETSAT
Contributors:	EUMETSAT, ADS GmbH
Status:	Final

CHE: CO2 Human Emissions Project

Coordination and Support Action (CSA)
H2020-EO-3-2017 Preparation for a European capacity to monitor CO2 anthropogenic emissions

Project Coordinator: Dr Gianpaolo Balsamo (ECMWF)
Project Start Date: 01/10/2017
Project Duration: 39 months

Published by the CHE Consortium

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The CHE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776186.

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1. Executive Summary

In recent years much effort has been devoted to exploring the potential of observations of atmospheric CO_2 to contribute to the monitoring and verification of anthropogenic emissions within an overall Monitoring and Verification Support (MVS) capacity [RD1], [RD5], [RD6] [RD8], and [RD15]. These efforts have resulted in the elaboration of a need for an operational virtual[1] constellation of satellites (where a virtual constellation is understood to refer to a coordinated set of space and/or ground segment capabilities from different partners that focuses on observing a particular parameter or set of parameters of the Earth system), with contributions from a range of international satellite operators, comprising a fleet of satellites in Low Earth Orbit (LEO), Geostationary Earth Orbit (GEO) and Highly Elliptical Earth Orbit (HEO) [RD8]. To respond to the need for a capability for the detection of hot spot emissions and trends, it is expected that individual missions, with the exception of any possible active lidar missions, would provide an imaging capability, a typical pixel size approximately < 3 – 5 km^2, a precision of < 1 ppm for individual measurements of the dry air mole fraction of CO_2 (XCO_2, i.e., between the surface and the satellite), with systematic errors < 0.5 ppm, and global coverage. Observations of co-emitted species e.g., NO_2 and CO for source attribution and specifically NO_2 for plume detection are considered essential as are co-registered observations of aerosol and cloud, needed for high quality retrieval of XCO_2.

The Copernicus CO_2 Monitoring (CO_2M) mission, currently in preparation, broadly addresses these requirements and in the near future is expected to make a significant contribution towards addressing the requirements for the LEO component of the anticipated operational virtual constellation. It is also hoped that the GeoCarb mission will serve as a successful demonstrator for the measurement of greenhouse gas emissions from GEO, paving the way for operational agencies to include greenhouse gas emissions monitoring capabilities on their GEO platforms. Missions in HEO currently, however, remain in the study phase and a successful demonstrator mission would be required before any transition to operational HEO missions could be anticipated.

In future, in support of the further expansion of the virtual constellation, it is also essential that international efforts are made in areas such as constellation design and orbit coordination to ensure that the space-based assets put in place maximise potential benefit in the context of the overall system, particularly with regard to coverage and sampling frequency, and also to address the need for sun-glint observations in coastal areas. Significant international efforts are also needed in the area of calibration and validation both pre-launch and in-orbit, including development of a long-term monitoring capability, to ensure well-characterised and consistent product quality. These efforts are expected to take place using existing coordination mechanisms such as the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) and the WMO Global Space-based Intercalibration System (GSICS). Development of additional vicarious calibration sites will also be needed as will be the expansion of ground-based remote sensing and in-situ observation networks with the associated need for sustained funding and operational provision of data.

Research and development activities are also required to support further improvements in satellite-based XCO_2 retrievals, both to address the need for faster algorithms required due to the expected increases in data volumes, but also to address systematic biases which remain both in ‘proxy’ and ‘full-physics’ retrievals, despite considerable improvements in this area, also during the CHE project. International coordination is also required for the assessment

[1] In this document a “virtual constellation” refers to the concept developed by the Committee on Earth Observation Satellites (CEOS) and is understood to refer to a coordinated set of space capabilities from different partners that focus on observing a particular parameter or set of parameters of the Earth system. For further information, see http://ceos.org/ourwork/virtual-constellations/.

and community endorsement of retrieval methodologies, which will be underpinned by the developments in the area of calibration and validation mentioned above, building on the successful collaboration mechanisms established and demonstrated by the OCO-2 and GOSAT teams.

With respect to co-emitted species, many satellite observations of co-emitted species are already available from operational missions targeting air quality applications. In the specific case of NO_2 being used for plume detection, as is planned for the CO_2M mission, co-registered observations are required, as are co-registered observations of cloud and aerosol in order that the XCO_2 retrievals can meet the stringent requirements.

In conclusion, the primary need for the further development of the space component in the near term is the strengthening of international coordination efforts to address a range of issues including constellation design and orbit coordination, further development of the ground-based calibration and validation infrastructure to ensure robustness and sustainability, and that the ground-based networks are fit for purpose, and the coordination of research and development activities which will necessarily underpin any future operational virtual constellation for greenhouse gas monitoring. These efforts will be critical to ensure that the final operational virtual constellation will fully achieve the needs of an operational MVS capacity.

2. Introduction

2.1. Background

As elaborated in [RD1] the current means of estimating anthropogenic greenhouse gas emissions using bottom-up inventories, is known to suffer from a number of limitations. The derived emissions are difficult to verify independently, difficult to scale, their quality is highly variable between countries, and whilst internationally accepted guidelines for reporting exist ([RD3] and [RD4]), variability in available economic information from country to country can lead to biased emissions estimates. It is therefore considered necessary to establish an independent means of estimating anthropogenic emissions to allow assessment and evaluation, and ultimately improvement of the emission inventories and also to monitor the effectiveness of emission reduction measures taken as a result of national commitments and voluntary efforts at a sub-national scale.

The concept of a Monitoring and Verification Support Capacity, based on independent, internationally accepted observations of atmospheric CO_2 was further explored in [RD5] and [RD6]. A prototype of such a MVS capacity is being developed through this H2020 CHE project and will be further developed to a full operational system in follow-on activities. The primary difficulty to be addressed in the development of such an MVS capacity is to effectively separate anthropogenic emissions contributions from natural CO_2 exchange processes. In order to overcome this difficulty, an MVS capacity, incorporating an inversion of atmospheric observations, both from ground-based and space-based systems, requires not only a high density of observations, especially over hotspots, but also a very good representation of regional atmospheric transport processes in atmospheric models, and a more detailed provision of gridded emissions data to be used as *a priori* information for inversions. These components are being explored in other parts of the CHE project. This deliverable is specifically focused on the requirements for future space-based missions needed to contribute to an operational MVS capacity.

2.2. Scope of this deliverable

2.2.1. Objectives of this deliverables

This deliverable provides an overview of the current state of knowledge with respect to the requirements for space-based observations of atmospheric CO_2, associated auxiliary data, and calibration and validation needs, in the context of an operational MVS capacity.

2.2.2. Work performed in this deliverable

During the course of the CHE project there have been a number of initiatives and on-going activities, also in the wider community, that have contributed to the further definition of the requirements for space-based measurements to contribute to an operational MVS capacity. A review of these activities has been performed and a synthesis provided in this deliverable. Particular attention is given to the perspective of an operational virtual constellation, comprising contributions from a number of international satellite operators, implying the need for the further development of coordination mechanisms in a number of areas.

2.2.3. Deviations and counter measures

None.

3. Role of Space Based Products within an MVS Capacity

In recent years much effort has been devoted to exploring the potential of observations of atmospheric CO_2 to contribute to the monitoring and verification of anthropogenic emissions within an overall Monitoring and Verification Support (MVS) capacity. In order to achieve this goal, it was noted in [RD1] that two complementary approaches to increasing the density and spatial resolution of atmospheric CO_2 observations were required for the further development of observation capabilities, specifically because anthropogenic emissions are known to be highly concentrated over small areas. The first approach proposed was to focus on the dense sampling of selected emission hotspots, such as mega-cities, major industrial areas and large power plants. This approach is being successfully used by the OCO-3 mission, in particular using the 'Snapshot Area Mapping' mode (https://ocov3.jpl.nasa.gov/sams/) [RD2]. In it considered that such hot spots would typically produce plumes that may be mapped from space by instruments with high-spatial resolution sampling and can additionally be monitored with urban *in situ* CO_2 measurement networks. The second approach proposed is to ensure the availability of measurements of additional trace species such as radiocarbon (^{14}C in CO_2) and carbon monoxide and nitrogen dioxide for separation of the fossil CO_2 component from the natural CO_2 fluxes at regional scale.

Characterisation of atmospheric CO_2 and CH_4 at global scales is possible using the ground-based *in situ* measurements from the series of networks coordinated by the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) program [RD7]. However, although this network now includes about 145 stations worldwide, it still does not have the spatial resolution and coverage needed to identify or quantify sources emitting CO_2 and CH_4 into the atmosphere on the scale of individual countries, or to quantify removals by natural sinks [RD8]. The Integrated Carbon Observation System (ICOS) is a contributing GAW network, providing standardised and open data from more than 140 measurement stations across 12 European countries. In ICOS, atmospheric measurements are coordinated via the Atmospheric Thematic Centre at Laboratoire des Sciences du Climat et de l'Environnement (LSCE) that is composed of a data center and a Metrology Laboratory. The data center develops and maintains in house software to centrally process and quality control the data from the European atmospheric ICOS networks. Applications are designed to provide near real time data products. The data treatment is traceable to the international primary standards for greenhouse gases maintained in NOAA CMDL, Boulder, Colorado, USA. For further information see [RD9]. In this document the focus is on the space-based component of the observing system, however additional observations needed for calibration and validation of satellite observations are also addressed (see Section 8.2).

The requirements for space-based observations in the context of an MVS capacity were further explored in [RD5]. Specifically, the need for detection of hot spots was reiterated with a hot spot defined as a small area surrounded by a strong CO_2 concentration gradient, resulting from the existence of a large emitting CO_2 source within the area e.g., a large power plant, a megacity or any other activity characterized by strong CO_2 emissions with specific time evolution. To estimate the emissions of the hot spot it is not only necessary to detect the hot spot, but also to monitor the emissions of the hot spot with consecutive traceable measurements such that local emission reductions within the hot spot can be assessed. A critical point is that the accuracy of the measurements must ensure the capability to attribute CO_2 emissions anomalies relative to the CO_2 concentration background level. These capabilities require relatively high spatial and temporal resolutions, i.e., daily observations at approximately 1 km resolution. Given that the current network of in situ stations largely samples background conditions, the space component is expected to make an important contribution to the overall system, assuming observations with a frequent revisit time at typically a 1 km scale resolution can be provided. [RD5] goes further to estimate the percentage of emissions that could be covered by satellite-based observations with 1 x 1 km spatial resolution and with an individual sounding precision of 1 ppm. This assessment shows that the percentage of daily emissions emitted during the 3 to 6 hour period before the satellite overpass is a critical quantity for the ability of a satellite based system to quantify a significant fraction of anthropogenic emissions. Indications are that approximately 67% of the emissions would be covered but assuming mitigation activities focus on high emission point sources, a larger share of the mitigations could be monitored. Similar analyses were performed in [RD10], [RD11] and [RD12] and also for further refinement of the mission requirements of the Copernicus CO_2 Monitoring mission (CO_2M) [RD13]. These studies consistently indicate that with a single sounding precision of <1 ppm and with a systematic error of <0.5 ppm, space-based observations should make a meaningful contribution to the MVS capacity on a timeframe that is shorter than the one made possible from national statistics (typically 1.5 – 2 years). However, the issue of detection of emission changes was recently further explored using data from the Covid-19 lockdown periods in 2020 [RD14]. In this study it was found that, as space-based column-averaged dry air mole fraction of CO_2 (XCO_2) retrievals are currently limited to areas with very low cloud cover, this presents a problem for the identification of changes in CO_2 emissions using satellite retrievals. During the 2020 lockdown periods, large emissions changes have been noted in the presence of clouds and also in locations that were cloud-free. Given that previous years will have experienced different cloud conditions, the comparison between 2020 and previous years becomes difficult as there is an implicit sampling bias related to cloud cover. The study concluded furthermore that to support the goals of the 2015 International Paris Agreement on climate, priority should be given on the development of all-weather CO_2 monitoring systems, ideally from space but at least *in situ*. The difficulty to detect emission changes related to the Covid-19 lockdowns also underscores the need for an integrated effort as the basis for an MVS capacity.

4. Proposed Greenhouse Gas Monitoring Constellation

A preliminary proposal for a greenhouse gas constellation was presented in [RD1] which was suggested to consist of a minimum of two to three Low Earth Orbiting (LEO) satellites, three Geostationary Earth Orbit (GEO) satellites, and at least one Highly Elliptical Orbit (HEO) satellite. It was recognised that such a constellation would require international cooperation, and that it would be of strategic importance for Europe to acquire the capacity of quantifying fossil CO_2 emissions by 2025. This would be achieved by implementing a carbon mission delivering XCO_2 retrievals with high spatial resolution, to resolve emission hotspots and minimise cloud contamination in the pixel, implying a typical pixel size < ~3-5 km^2, imaging capabilities, a precision of ~1 ppm for individual XCO_2 measurements with systematic errors <0.5 ppm, and global coverage. A follow-up of four instruments with characteristics comparable to e.g., the CarbonSat instrument was considered able to provide a daily coverage of the sunlit part of the Earth approximately every 7 days at the equator and approximately every 3 days in the mid-latitudes, thereby delivering data suitable for the improvement of emissions estimates and monitoring of their trends. In the long-term (by 2030) it was stated that a set of (European and non-European) carbon missions with similar or better capabilities would be required for the frequent detection, quantification and monitoring of emissions. In this context, consideration of combined active and passive space-borne sensors was recommended, in particular to improve coverage of the high latitudes in winter which will remain low with passive instruments only. It was also noted that satellites with pointing capabilities could improve the coverage of emissions hotspots by more frequent sampling of cities and large point sources. Such a closely coordinated space-based constellation would also provide continuity and resiliency to losses of data from individual satellites. It was further stated that the possibility to measure carbon monoxide in addition to XCO_2 should be considered for separation of anthropogenic emissions from surrounding biogenic fluxes.

This concept was further developed in [RD5] which called for four capabilities: the first, the detection of hot spots; the second, monitoring of the emissions of the hot spots; the third, assessing emissions changes against local reduction targets, and the fourth assessing the national emissions and changes with five yearly time steps. Requirements on the space component follow from the analysis of these capabilities. The first capability requires relatively high spatial and temporal resolution of the order of a kilometer resolution and at a daily frequency. With respect to this capability the space segment is expected to make an important contribution to the overall system, given that this cannot be covered with the current network of *in situ* stations which mainly represent background observations. By contrast, capability four was considered to set the most demanding requirements in terms of precision and accuracy. Detection of changes of the order of 0.1 - 0.5 Mton CO_2_ff /yr for a small country (a few grid cells of 0.1° x 0.1° corresponding to 5 x 5 km^2 to 10 x10 km^2 over Europe) and a coverage of the entire land area of all the world's countries would be needed in order to contribute significantly to the estimates provided by the current self-reporting methodologies based on inventories. It was concluded that a constellation of satellites should therefore be in operation by 2026 in order to deliver atmospheric observations globally for verifying the global stock take and supporting estimates from current inventories. By that time the proposed observation-based CO_2 MVS capacity should have also reached a pre-operational status.

In the design of an optimal constellation of satellites the characteristics of the specific orbits and instrument types that could potentially contribute to the constellation should be taken into account. An extensive discussion of a potential constellation architecture is provided in [RD8]. The constellation proposed responds to the WMO Global Climate Observing System (GCOS) requirements for precision, accuracy, spatial and temporal resolution, and coverage [RD19] over continental regions whilst providing somewhat lower resolution and coverage over the oceans. It was concluded that a constellation of satellites with measurement capabilities for CO_2 and CH_4 fully exploiting the opportunities offered by LEO, GEO, and HEO missions would be needed. The full details of the proposed constellation are summarised in [RD8] however the main elements are listed below.

4.1. Low Earth Orbit (LEO) Constellation Elements

The proposed LEO contribution to the envisaged constellation is three or more satellites flying in a common sun-synchronous orbit, each carrying an imaging spectrometer measuring reflected sunlight in the near-infrared (NIR) and shortwave infrared (SWIR) spectral regions, specifically the 0.765 μm O_2 A-band, the CO_2 bands at 1.61 and 2.06 μm and the CH_4 bands near 1.67 or 2.33 μm with the O_2 A-band channel needing to be sufficiently wide to include the solar Fraunhofer lines near 0.757 and 0.772 μm to quantify and remove contamination from solar induced fluorescence (SIF). It is also recommended in [RD8] that the payload includes the capability to measure the 0.43 μm NO_2 band and/or the 2.33 μm CO band for use in identifying the spatial extent of discrete emission plumes. As these spectral bands are in the reflected solar domain, observations from such spectrometers will only be possible in the sunlit hemisphere. In order to achieve sampling at approximately weekly intervals, instruments with a spatial resolution of < 5 km^2 and with a swath width of > 200 km are required. Note however that for instruments having a wider swath, despite providing improved sampling, observations at the swath edges are more likely to be more contaminated by optically thick clouds and aerosols due to the observation geometry. Again, the need for high resolution, accuracy, and stability in order to achieve single sounding random errors in XCO_2 < 0.125% (0.5 ppm) and XCH_4 < 0.25% (4.5 ppb) and very small systematic biases (< 0.06%) on scales ranging from cities (~100 km^2) to continents (10^7 km^2) was emphasised. It should be noted that although such a constellation could achieve weekly observations in optimal conditions, the ability to make full column observations will be severely impacted by optically thick clouds and aerosols for a significant portion of the time. To improve the coverage and accuracy of the products it was therefore recommended to add instruments to the payload that contribute to the screening or characterisation of clouds and aerosols within the spectrometer field of view. They should ideally have adequate spatial resolution and sensitivity required to detect optically thick clouds occupying more that 5% of an individual pixel. The Field of View (FOV) should cover the full swath and extend ideally 20 km beyond its edge to identify clouds or aerosols potentially casting shadows or reflecting solar radiation into the outermost regions of the swath.

Over the oceans, due to the dark underlying surface, passive spectrometers operating in the near infrared to shortwave infrared spectral range must be capable of maximizing observations in sun-glint geometry. As the sun-glint area is generally considered to be only a fraction of the swath for wide swath instruments, although also dependent on surface wind speed, coverage over the oceans is necessarily reduced. As there are few known small-scale sources or sinks over the oceans a constellation including three LEO satellites is expected to provide adequate resolution to sample synoptic scale anomalies. However, the need to take observations over oceans in sun-glint geometry is particularly pertinent for the measurement of plumes from compact sources in coastal regions.

The strategy for maximizing the data quality and coverage of coastal regions represents one of the system-level challenges for both individual missions and for multi-mission virtual constellations. The satellite design can significantly enhance the coverage of coastal regions by implementing sufficient agility in repointing the instrument line-of-sight. At the level of an individual satellite, the along-track slewing ability is most important. In certain geographic and lighting situations, this capability can completely eliminate coastal coverage gaps, e.g., when the satellite is approaching a coastline with the sun-glint in flight direction. In this case the satellite remains in glint attitude until the line-of-sight reaches the coast, after which a pitch manoeuvre begins which keeps the line of sight fixed on the coastline. Once the line-of-sight reaches nadir, the manoeuvre ends and nominal land imaging commences without a gap. In other configurations coverage gaps may be unavoidable at the level of a single satellite. Here, the design and operation of the overall constellation can provide solutions. By providing coverage redundancy, different satellites can focus on land or sea observations in the critical coastal areas, with the combined product still satisfying coverage requirements. More elaborate variations of such schemes may also call for a cross-track pointing capability of the satellites. It is vital to establish these operating schemes in the constellation context early enough to be able to implement the corresponding agility requirements in the satellite and mission designs. Some points for further study related to this topic are outlined in Section 8.6.

Inclusion of active CO_2 and CH_4 lidar instruments on LEO platforms would allow accurate observations to be obtained over a very narrow swath (100 – 200 m) at the local nadir. Importantly lidar observations can be made in both sunlit and night-time hemispheres providing observations when passive spectrometers operating in the near infrared to shortwave infrared spectral range are unable to measure, and also providing an accurate reference for bias correction of other observations.

As noted in [RD1] thermal infrared sensors, such as the Atmospheric Infrared Spectrometer (AIRS) (http://airs.jpl.nasa.gov/), the Tropospheric Emission Spectrometer (TES) [RD16] and the Infrared Atmospheric Sounding Interferometer (IASI) [RD17] can make both day and night-time observations of CO_2 and CH_4. However, thermal infrared observations are mostly sensitive to the mid to upper tropospheric distribution of these gases, with reduced surface sensitivity, which is needed for detection of surface sources and sinks. Additionally, the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) measures limb solar occultation profiles of CO_2 and CH_4 spanning the upper troposphere and stratosphere, but also lacks the capability to measure variations in these gases near the surface [RD8].

4.2. Geostationary Earth Orbit (GEO) Constellation Elements

A suite of three or more GEO satellites stationed at longitudes centered over North and South America, Europe and Africa, and South and East Asia would complement the global measurements from LEO. The improved time resolution offered by instruments in geostationary orbit would allow the diurnal variation in CO_2 and CH_4 emissions, associated with fossil fuel extraction, transportation and use, to be constrained [RD8]. This is a similar model to that employed by the operational meteorological satellite operators and recently adopted by the GEO air quality constellation, consisting of TEMPO, Copernicus Sentinel-4, and GEMS [RD18] although this constellation is primarily focused on the Northern Hemisphere. Each GEO satellite should carry an imaging spectrometer similar to that described for the LEO component. To meet the GCOS [RD19] revisit time requirements, the spectrometers should measure with a spatial resolution of 4 km^2 to 10 km^2, at 4 hourly intervals between sunrise and sunset over land areas within their fields of regard. As for the LEO CO_2 and CH_4 spectrometers, complementary instruments to characterize SIF and screen and/or correct for contamination by clouds, aerosols, and SIF within the spectrometer fields of view are considered highly desirable. It is further recommended that methods to optimize the observing strategy in near real time to avoid persistently cloudy areas and to maximize the number of cloud-free soundings in partially cloudy regions should be pursued. Time resolved measurements of NO_2 and/or CO are also considered to be of great value in identifying and tracking CO_2 emission plumes associated with fossil fuel and biomass burning.

In general, multiple observations per day will also increase the likelihood of observing cloud free scenes, particularly in persistently cloudy areas e.g., tropical land regions. Coincident observations of both NO_2 and CO may also be essential for the discrimination of CO_2 emission plumes from the background in tropical regions, where fossil fuel combustion produces compact plumes that include both NO_2 and CO, while biomass burning contributes larger-scale plumes that include CO_2 and CO. Proxy measurements will be even more important for tracking plumes if the GEO CO_2 and CH_4 spectrometers have larger footprints or lower CO_2 sensitivities, because both factors will reduce the detectability of given mass of CO_2 that is emitted into the atmosphere. Long-term observations of CO_2, and SIF from GEO could also yield valuable insights into diurnal, seasonal, and longer-term variations in CO_2 uptake by the land biosphere, as it responds to heat and drought stress associated with climate change.

4.3. Highly Elliptical Orbit (HEO) Constellation Elements

High latitude observations from instruments on HEO platforms have the capability to provide frequent revisit time observations over boreal and arctic regions, areas which cannot be observed from geostationary satellites. At least two HEO satellites would be needed to provide continuous daytime observations equivalent to geostationary observations. However, even a single HEO satellite, in addition to the LEO constellation, could act as a demonstration mission and help in the detection of major emission events [RD8]. The instrumentation requirements are similar to those of the LEO and GEO platforms and target a spatial resolution of 4 to 10 km^2 at 4 hourly intervals during sun illuminated hours. For the highest latitudes, this would result in between 12 and 24 hours of potential observing time in the summer and 0 to 12 hours during the winter. During winter, when the highest northern latitudes are dark and cannot be observed with passive measurements, a HEO mission could focus on mid-latitudes for increased overlap with GEO observations.

As for the LEO and GEO platforms, coincident observations of NO_2 or CO would facilitate the interpretation of the HEO XCO_2 and XCH_4 observations. A dedicated cloud/aerosol imager may be even more beneficial for detecting and correcting the effects of scattering particles at such high latitudes. Observations of Solar Induced Fluorescence (SIF) would be useful for constraining the spatial extent of CO_2 uptake during the short but intense growing season (see also Section 6.2). All missions would have to be optimized for use at high latitudes, where the solar illumination is lower, and where there would frequently be snow and ice-covered surfaces which have reduced reflectance at wavelengths in the shortwave infrared. They should also be designed to collect multiple observations per day or use cloud avoidance strategies such as those suggested above for GEO platforms to increase the likelihood of obtaining some cloud-free observations in the arctic and boreal regions which are predominantly cloudy. Observations from HEO would also overlap with those from the northern extent of the GEO mission’s field of regard and would provide opportunities for intercomparison through the diurnal cycle.

5. Current and Planned GHG Satellite Missions

5.1. Overview

A comprehensive summary of current and planned GHG missions is provided in [RD6] and a timeline of past, current, and future missions, adapted from [RD6] Fig 7.1, is included below in Figure 1 for convenience.

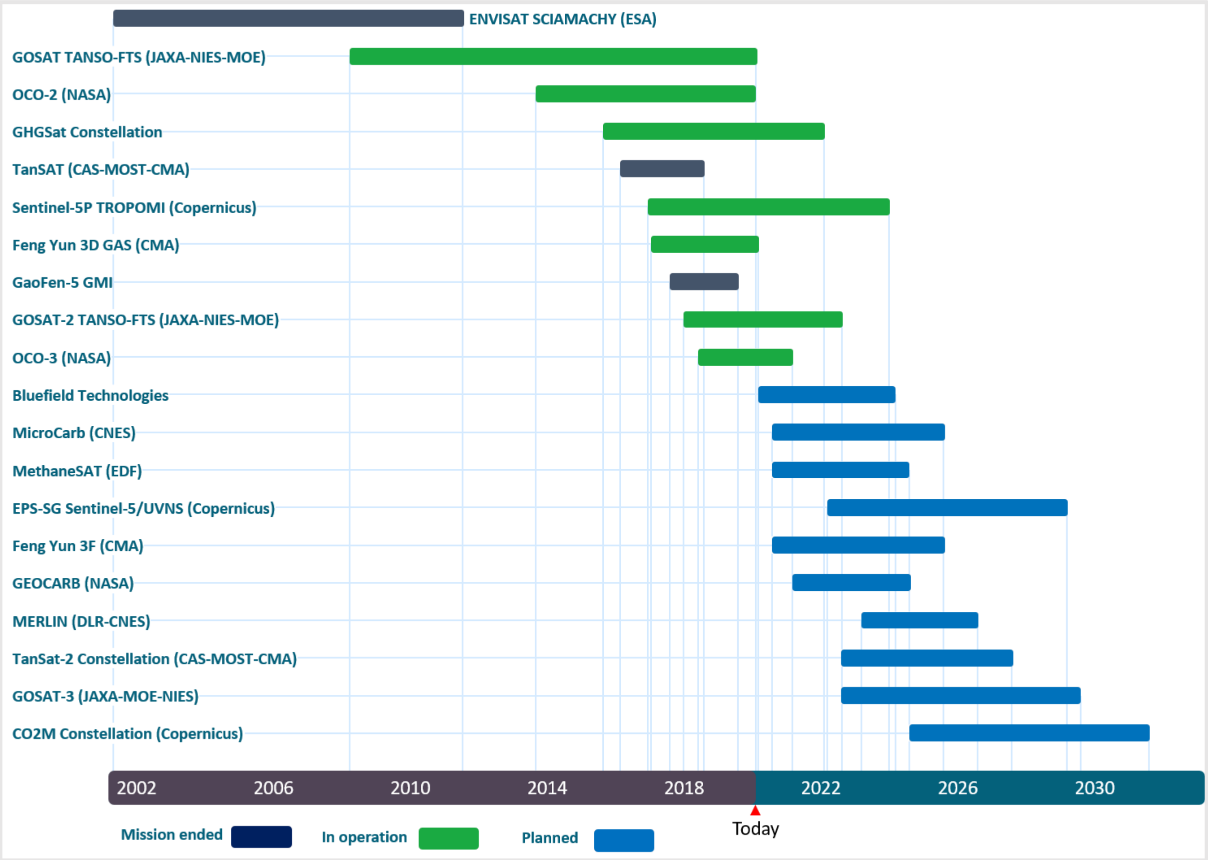

Figure 1: Timeline of past, current and planned greenhouse gas missions.

We are in a period of very rapid development for remote sensing of greenhouse gases from space however we are not yet in the position whereby a robust constellation of operational missions is available. To date almost all missions currently flying exist in the research domain, and do not by default include recurrent satellites to ensure long-term continuity. Neither are they planned in the context of an overall constellation, instead being designed to meet individual mission requirements, which although broadly similar have not been established with an international constellation in mind. In the 2020-2021 timeframe the primary missions flying which are specifically designed for observation of CO_2 will be GOSAT-2 and MicroCarb in LEO orbits, OCO-3 on the International Space Station (ISS) with the anticipation of GeoCarb in 2021 in GEO orbit. Whilst these missions are expected to make significant contributions to the continued research and development activities that will lead to an operational MVS capacity, the collective coverage is still less that that envisaged in [RD1], [RD5] and [RD8] to be required from an operational fleet of satellites, and only OCO-3 achieves the target pixel size. In the time frame to 2025 new missions will incrementally become available that will further address the needs of an operational MVS capacity, and a large contribution to this incremental expansion and transition to operational status of the international CO_2 monitoring satellite fleet will come from the Copernicus CO2 Monitoring (CO_2M) Mission, conceived as an operational European capacity that contributes to the global monitoring of anthropogenic CO2. A description of the high-level requirements of the CO_2M mission is provided in the following sections.

5.2. Copernicus CO_2 Monitoring Mission (CO_2M)

5.2.1. High Level Requirements

The objective of the CO_2Monitoring (CO_2M) mission is to provide the European Union with an operational capacity that contributes to the global monitoring of anthropogenic CO_2 emissions. It is responding to the needs expressed in [RD1] and aims to meet the high-level objectives expressed in [RD5] mentioned previously, namely:

- the detection of emissions from hot spots, such as megacities and power plants,
- the monitoring of hot spot emissions to assess emission changes,
- the assessment of emission changes against local reduction targets to monitor the impacts of nationally determined contributions, and
- the assessment of national emissions and changes in 5-year time steps to support the global stock take.

The detailed requirements pertaining to the CO_2M mission are provided in [RD15] as a result of extensive work on the part of the CO_2M Mission Advisory Group. A summary of the most pertinent high-level requirements is given below.

The CO_2 Monitoring Mission is expected to be implemented as a constellation of satellites with each satellite providing global coverage and carrying as the main payload a push-broom imaging spectrometer operating in three spectral bands, one in the near infrared spectral range (747 – 773 nm) and two in the short-wave infrared spectral range (1590 – 1675 nm and 1990 – 2095 nm), comparable to those bands recommended in [RD8]. An additional band in the visible spectral range, to support the retrieval of NO_2 (405 – 490 nm) is expected, as is a push-broom imager with visible and short-wave infrared bands for cloud detection. A multi-angle polarimeter will additionally allow the retrieval of aerosol information in support of the CO_2 retrieval.

The spacecraft will fly in phased near-polar, sun-synchronous quasi-circular frozen Low Earth Orbit (LEO). The local equator crossing time will be around 11:30am. The standard operations scenario foresees a nadir looking configuration which will be the nominal land observation mode. Additionally, optimised operations planning is intended to maximise the time the instrument is pointing towards the specular reflection of the incident sunlight (so called sunglint mode) over the oceans and over snow and ice-covered surfaces, such that the coverage over water bodies is maximized without compromising land coverage.

The primary measurements of the CO_2M mission, will be absorption spectra in selected wavelength bands (level 1). The primary geophysical (level 2) product delivered by the CO_2M mission will be XCO_2. It is also noted in [RD15] that additional observations of NO_2 and CO, two key species co-emitted with anthropogenic CO_2 in combustion processes, can be used to better localise the plumes of anthropogenic CO_2 (see also [RD5]). Of these two species, NO_2 is considered to be easier to detect at the same spatial scale as CO_2 and to be more characteristic of high temperature combustion of fossil fuels than CO. The ESA SMARTCARB study led by the Swiss Federal Laboratories for Materials Science and Technology (EMPA) (https://www.empa.ch/web/s503/smartcarb) simulated plumes of NO_2 and XCO_2 from power plants and cities in eastern Germany and it was estimated that the required precision of the NO_2 observations is better than $1–2{\cdot}10^{15}$ molec./cm^2 in a sampling area equal to the XCO_2 measurements. In addition, this study investigated the effect of plume rise from power plant stacks and concluded the heat content in the exhaust plume results in the plume being injected into the local wind field at a height, higher than the top of the stack, which can significantly affect the CO_2 emission estimates if not taken into account in the assessment of the local wind field affecting the plume. Dedicated measurements of NO_2 are therefore recommended in order to support detection of the plume.

As noted in previous sections, the precision and accuracy requirements for retrieving XCO_2 to quantify anthropogenic emissions are very stringent, and strongly depend on the ability to determine the light scattering effects in the atmosphere [RD15] as light scattering by clouds and aerosol introduces uncertainties in the optical path length that affect the accuracy of the XCO_2 retrieval. The results of an ESA study carried out by SRON indicate that the high accuracy requirements for CO_2 can be met using additional observations from a dedicated multi-angle polarimeter, also at larger SZAs and up to a total AOD up to 0.5. This is the primary motivation for the inclusion of the multi-angle polarimeter in the CO_2M payload.

5.2.2. Requirements for Geophysical Products

The following table reproduced from [RD15] captures the main requirements for the geophysical products to be produced by the CO_2M mission. It is clear that these requirements respond specifically to those expressed in more general terms in [RD1], [RD5], [RD6] and [RD8] and in particular to the requirements for the LEO component of the envisaged CO_2 monitoring constellation.

Table 1: Characteristics of the geophysical products as required from the space component of the anthropogenic CO_2 monitoring system.

Parameter	Level 2 Requirement
XCO_2 precision	0.7 ppm for vegetation scenario at SZA of 50 degrees
XCO_2 systematic error	< 0.5 ppm, see also note
XCO_2 spatial resolution	4 km^2, aspect ratio ≤ 2
XCO_2 plume image	Imaging capability of 250 x 250 km^2 spatial scale
XCO_2 emission area temporal coverage	Global coverage and on average once per week effective coverage over land for latitudes above 40 degrees, where the strongest emitting areas are located.
Aerosol and cloud information for accurate XCO_2 retrieval	High accuracy XCO_2 retrieval requires spatially and temporally collocated: 1. aerosol & cloud information (e.g., vertical profile, optical depth, size distribution and composition) needed to calculate their effect on optical path length in CO_2 spectral bands, 2. detection of low cloud fractions (5%) of optically thick clouds, 3. measuring CH_4 spectral bands (allowing proxy retrieval of XCO_2), 4. measuring solar induced fluorescence for correction in O_2-A band

NO_2 plume images for locating CO_2 plumes	Tropospheric NO_2 shall be measured spatially and temporally collocated with XCO_2 at the same spatial resolution and with an NO_2 precision of $1.5 \cdot 10^{15}$ molec./cm^2. This anthropogenic proxy supports the emission estimates by identifying the XCO_2 source, plume direction and local wind speed.

Note 1: applications exploiting the CO_2 plume imaging capability drive the precision requirement.

Note 2: aerosol and (thin) cloud information are expected to come from measurements using a multi-angle polarimeter (MAP), which shall enable good CO_2 observations up to an AOD of 0.5.

Note 3: one satellite may not be enough to deliver the required effective coverage. The overall system requirements will be reached after the full deployment of a constellation of several satellites.

Note 4: XCO_2 systematic error is assumed to be after bias correction.

Note 5: aerosol measurements serve for correction purposes but will also generate as 'by-product' aerosol height with ~500 m uncertainty and AOD with uncertainty of ~0.05.

The primary level 2 products of the CO_2M mission are expected to be available to users 24 hours after sensing. As a result of the imaging capability of the CO_2M mission, and the high spatial resolution this poses a particular challenge for XCO_2 retrieval algorithm development. Full physics retrievals, i.e., those making use of full online radiative transfer calculations within a non-linear minimization framework, have often been considered the most robust means to obtain the high quality XCO_2 retrievals need for the estimation of CO_2 emissions. Such retrievals are however very computationally expensive. Given the high data rate of the CO_2M mission the focus is on the implementation of a robust 'proxy' retrieval method, requiring the use of CH_4 absorption bands. Within the CHE project, the group of the Institute of Environmental Physics at the University of Bremen has shown that the Fast atmOspheric traCe gAs retrievaL for OCO-2 (FOCAL-OCO2) method [RD21] can produce good quality XCO_2 products with low biases compared to TCCON with significantly lower computational costs that a full-physics approach. Both of these retrieval approaches still, however, require improvements in particular with respect to systematic errors. Comparative inversions using either FOCAL or OCO-2 XCO_2 data products have shown that small differences in coverage and values lead to substantial changes in the estimated fluxes, even when considering data over land only. Within CHE the issue of statistical inconsistencies between the retrievals and the atmospheric inversion systems has started to be addressed and this work is still on-going. Additionally, with a specific view to the CO_2M mission needs, EUMETSAT has initiated a number of studies to address improvements and developments required for XCO_2 retrievals.

Furthermore, in the study presented in [RD22] pseudo-observations are assimilated in a global atmospheric inversion system to assess the performance of a constellation of one to four sun-synchronous low-Earth orbit (LEO) imagers, similar to the CO_2M mission, to monitor anthropogenic CO_2 emissions. This study assesses the uncertainties in the inversion estimates of emissions and concludes that for all constellation configurations assessed, only the cities and power plants with an annual emission higher than 0.5 MtC per year can have at least one 8:30–11:30 time window during one year when the emissions can be constrained to better than 20%. It was concluded that the potential of satellite imagers to constrain annual emissions depends not only on the design of the imagers, but also depends strongly on the temporal error structure in the prior uncertainties, which needs to be objectively assessed in the bottom-up emission maps.

6. Needs for Additional Satellite Data

6.1. Co-emitted Species

Assessments have been provided in [RD1], [RD5], [RD6], [RD8]and [RD15] indicating the anticipated value of observations of co-emitted species. The role of co-emitted species in providing constraints on emission inventories and for monitoring trends and regional scale combustion, has been discussed in a number of publications. In these publications it has been shown that satellite observations can be used to distinguish differences in combustion source characteristics through analysis of the relative enhancement patterns of CO and CO_2, and NO_2 and CO, respectively and that that satellite observations of NO_2 and CO can further constrain combustion processes in megacities [RD23]. In addition, as discussed previously, satellite observations of NO_2 collocated with CO_2 observations have been shown to be valuable for locating plumes from point source and city emissions where NO_2 and CO_2 are co-emitted. Studies have estimated regional CO_2 emissions based on satellite-derived NO_x emissions and the NOx to CO_2 emission ratios from bottom-up emission inventories [RD24], [RD25], and [RD26], from co-located satellite retrievals of CO_2 and NO_2 [RD27] or from satellite based NO_2 observations and Continuous Emissions Monitoring System (CEMS) data [RD28]. In another recent study [RD29], the co-located regional enhancements of CO_2 observed by OCO-2 and NO_2 observed by TROPOMI were analysed to infer localized CO_2 emissions for six hotspots including one power plant globally.

In addition to the NO_2 observations planned for the CO_2M mission, specifically for the purpose of location of the CO_2 plume, there are a number of other satellite instruments available that can contribute observations of CO and NO_2 within an overall operational MVS capacity. Many of these missions have been designed with a view towards air quality applications. However, the requirements are not significantly different than those that would be required for source attribution within an MVS capacity. A specific exception is where there are stringent needs for co-registration of observations such as between the NO_2 and CO_2 imagers on CO_2M.

An overview of the satellite missions which can contribute observations of NO_2 and CO in the coming years is provided both in the WMO Observing Systems Capability Analysis and Review Tool (OSCAR) Space database (https://www.wmo-sat.info/oscar/spacecapabilities) and the CEOS EO handbook database (http://database.eohandbook.com/index.aspx). Notably, a number of the missions capable of providing NO_2 and CO information are fully operational missions, in some cases part of a multi-satellite series ensuring availability of observations over a period of more than 20 years.

6.2. Solar Induced Fluorescence

In recent years there has been much activity in the development of techniques for the remote sensing of Solar Induced Fluorescence (SIF) and SIF is widely considered as a proxy for Gross Primary Production (GPP) ([RD30] and [RD31]). As noted previously, it is also necessary to account for and correct SIF contamination in the O_2 A-band during retrieval of XCO_2 products [RD32]. The retrieval and interpretation of SIF products continues to be a very active area of research and development. In light of the large number of studies, a detailed review of current SIF remotely sensed data products from the ground, UAV, airborne, and spaceborne platforms has been carried out in [RD33]. In this review, the authors have discussed the in-depth interpretation of each SIF study using each of the remote sensing platforms mentioned. Joiner et al. 2020 [RD34], also examined in detail the orbital geometry dependent variations in SIF retrievals from Metop GOME-2 and Sentinel-5P TROPOMI. It is fully expected this will continue to be a very dynamic area of research and development in coming years.

The SIF spectrum broadly covers the range from 640 – 800 nm and it is recommended that observations of the O_2 A-band are sufficiently broad to include the Fraunhofer lines in the vicinity of the O_2 A-band, in particular around 757 and 772 nm. The necessary observations are available from a number of satellite missions including, from a European perspective, Metop GOME-2, the Copernicus Sentinel-5 Precursor and in future the Copernicus Sentinel-4 and the Copernicus Sentinel-5 missions. Efforts should be made to facilitate the development of SIF products from these sensors. The CO_2M mission has also considered the need to characterise and measure SIF [RD15].

6.3. Night-light Data

Satellite observations of the light emitted from the Earth's surface at night can be used as a proxy for energy consumption and can provide information on the spatial distribution of CO_2 emissions, potentially contributing to a better understanding of trends in emissions and changes in the spatial distribution of emissions. The primary source of satellite-based night light data is currently from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument which is flying on the Suomi NPP and NOAA-20 satellite missions. VIIRS will also be flown on the JPSS-2, -3 and -4 satellite missions (https://www.jpss.noaa.gov/viirs.html). The specific band needed for the measurement of night-light data, is the Day/Night Band. This band is not available on the EUMETSAT METimage instrument which otherwise has very similar capabilities to VIIRS. An overview of available night light data sets is given in [RD35]

6.4. Meteorological Data

It is generally assumed that the satellite data required in the context of meteorology and Numerical Weather prediction is sufficient for the needs of transport modelling within the context of an operational MVS capacity. The definition of end user requirements for meteorological satellite systems is typically established by the individual operational meteorological satellite operators, however responding to needs articulated by their user communities and in particular through the World Meteorological Organisation (WMO). Within the WMO Space Program coordinates the activities of Members related to the space-based observing system component of the WMO Integrated Global Observing System (WIGOS) to ensure sustained and interoperable satellite observations and to promote their applications (for further information see https://public.wmo.int/en/programmes/wmo-space-programme).

In addition, the Coordination Group on Meteorological Satellites (CGMS) aims to globally coordinate operational and research and development meteorological satellite systems, including protection of in-orbit assets, contingency planning, improvement of quality of data, provision of support to users, facilitation of shared data access and development of the use of satellite products in key application areas. The coordination is pursued from an end-to-end perspective, through development of multilateral coordination and cooperation across all meteorological satellite operators and with the user community, in particular the WMO and IOC-UNESCO, but also other entities. EUMETSAT joined the CGMS in 1987 and has been its permanent Secretariat since then.

7. Gap Analysis

7.1. Overview

The overall space component required in support of an operational MVS capacity is foreseen to be a virtual constellation with contributions from a number of international satellite operators.

Whilst the overall ambition is, in the longer term, to establish a fully operational constellation it is recognised that in the medium term such a constellation will be largely composed of a number of research missions complemented by a gradually increasing number of operational missions, in particular the Copernicus CO_2M mission, which is expected to comprise more than one satellite. In this transitional period, individual missions are typically being designed according to their specific mission objectives and the requirements definition process of the satellite operator in question. It is not guaranteed that the context of an overall constellation is taken into account.

7.2. Currently Planned Missions versus Anticipated Virtual Constellation

As previously discussed in Section 4, an operational greenhouse gas virtual constellation would ideally consist of a number of both GEO and LEO satellites complemented by one or ideally more HEO missions, all carrying passive spectrometers operating in the near infrared to shortwave infrared spectral range, and in the case of the LEO component, complemented by active lidar instruments. A detailed description of current and planned missions is provided in [RD8] and a summary is given below.

7.2.1. LEO Component

Currently the LEO component of the envisaged operational CO_2 monitoring constellation is the most well populated by current and planned CO_2 monitoring missions. The planned Copernicus CO_2M mission is expected to make a strong contribution to the overall LEO constellation of a virtual constellation. As described in Section 5.2, the mission responds to the needs and objectives expressed in [RD1], [RD5] and [RD6] providing an imaging capability combined with a ground pixel size of 4 km^2. It will include a measurement capability for NO_2 targeting plume detection, as well as additional capabilities for the measurement of cloud and aerosol, needed for the retrieval of high quality XCO_2 products. The CO_2M mission is expected to consist of a number of satellites, the exact number is currently to be confirmed, but is expected to be, at a minimum, two.

In addition to the CO_2M mission, OCO-2, GOSAT-2 TANSO-FTS-2, TanSat ACGS, Feng Yun 3D GAS, Feng Yun 3E GAS-2, and MERLIN all fly (or are planned to fly) in sun-synchronous polar LEO, with observations over ocean generally being taken in sunglint geometry. In addition, the OCO-3 mission is currently flying on the international space station in a low earth precessing orbit. However, none of these missions provide the combination of coverage and ground-pixel size offered by the CO_2M mission. They nonetheless are still expected to provide a valuable contribution to the overall constellation and to continued research and development activities targeting improvements in space-based observations of XCO_2.

Additionally, the Methane Remote Sensing Lidar Mission (MERLIN) is an active LIDAR instrument targeting the measurement of methane. Currently no lidar missions for the measurement of CO_2 are planned.

7.2.2. GEO Component

To date the only GEO mission under consideration for the monitoring of anthropogenic GHG emissions is the NASA Geostationary Carbon Cycle Observatory (GeoCarb) mission which will measure column-averaged dry air mole fractions of CO_2, CH_4, CO and SIF from geostationary orbit (GEO) with a spatial resolution of approx. 10 – 20 km, several times per day. Whilst the spatial resolution is lower than that targeted by the CO_2M mission, the higher temporal sampling will facilitate an improved understanding of the natural and anthropogenic carbon cycles at regional scales. The mission will also serve as a demonstrator for measurements of greenhouse gases from geostationary orbit. The GeoCarb mission is currently under development for a mid-2022 launch and it will be stationed at 75 – 100 degrees west longitude.

7.2.3. HEO Component

The Canadian Space Agency (CSA) has explored the potential of a HEO mission for some time. AIM-North (www.aim-north.ca) is a concept study targeting measurements of XCO_2, XCH_4, XCO and SIF, NO_2, SO_2 and other reactive trace gas species that affect air quality, with the aim of monitoring both anthropogenic and natural carbon cycle activity at latitudes between 40° N and 80° N. From this orbit, observations could be collected at 60 to 90 minute intervals throughout the day at a spatial resolution of 3 x 3 km^2. Extending the CO_2, CH_4 and air quality observations to high latitudes through a mission in HEO will allow better quantification of emissions for regulatory purposes, improve air quality forecasting, and track climate-related changes in the boreal and Arctic. However, currently this remains a concept mission and there are no firm commitments for HEO missions targeting anthropogenic greenhouse gas emissions.

7.2.4. Current Status

Currently, as an international community, we are unable to meeting the expectations for and objectives of a full operational virtual constellation for operational anthropogenic greenhouse monitoring through the currently operational and planned missions. It is fully expected that the LEO component of such an envisaged operational virtual constellation will evolve to a mature state more quickly that the GEO and HEO components, given the strong demonstration missions that already exist in orbit. In this context the CO_2M mission is expected to make a significant contribution to the LEO component of an anticipated virtual constellation but there will still be a significant reliance on research missions, both through the experience gained in the exploitation of the data and through on-going research and development activities. With regard to the GEO component, depending on the success of the GeoCarb mission it can be expected that the GEO component may slowly be populated at other longitudes however it is currently difficult to assess on what timescales. For the HEO component the situation is even more unclear as there are currently no demonstration missions planned.

During the period of transition to a fully operational constellation, one challenge that remains is to put in place mechanisms that ensure overall coordination of orbit planning and constellation design. These issues are addressed further in Section 8.6

8. Additional Elements

The sub-sections below address additional elements that are needed to support the operational calibration and validation of a constellation of green-house gas satellites, and to facilitate the use.

8.1. Coordination Mechanisms

Given that the space component of the anticipated operational MVS capacity is conceived as a constellation of operational satellites contributed by a number of international partners, coordination mechanisms are essential for achieving an optimised constellation with consistent high-quality data products.

To this end, the Committee on Earth Observation Satellites (CEOS) / Coordination Group for Meteorological Satellites (CGMS) Working Group on Climate was tasked, by the 32nd CEOS Plenary and the 46th CGMS Plenary to coordinate the joint efforts between CEOS and CGMS to monitor GHGs from space. In March 2019 WGClimate formed a dedicated GHG Monitoring Task Team to coordinate the CEOS Carbon Strategy and to develop a Roadmap for Implementation of a Constellation Architecture for Monitoring Carbon Dioxide and Methane from Space, based on the endorsed recommendations in the CEOS Atmospheric Composition-Virtual Composition (AC-VC) GHG Whitepaper on A Constellation Architecture for Monitoring Carbon Dioxide and Methane from Space [RD8]. The first version of this roadmap was subsequently published in 2020 [RD36].

WGClimate was tasked because it is the only joint working group of CEOS and CGMS, and has an existing interface, that functions well, with the United Nations Framework Convention on Climate Change (UNFCCC), the Subsidiary Body for Scientific and Technological Advice (SBSTA), and the Global Climate Observing System (GCOS). Through this interface WGClimate is able to represent CEOS and CGMS and provide visibility of the space agencies' activities to the main user communities. In addition, links have been established to CEOS AC-VC, CEOS Working Group on Calibration and Validation (WGCV) and other CGMS entities such as the Global Space-based Intercalibration System (GSICS). It is the role of the GHG Task Team to develop and maintain the roadmap defining the overall distributed work plan, and to coordinate all CEOS and CGMS efforts including those needed to implement the recommendations of the CEOS ACVC GHG Whitepaper [RD8].

Within this international coordination framework and captured in the first version of the CEOS-CGMS GHG Roadmap [RD36], there are elements that address the need for *in situ* data in the wider context of calibration, inter-calibration and validation. These are anticipated to be addressed through two existing groups addressing both research and operational elements: the CEOS -WGCV through the Atmospheric Composition Subgroup (ACSG), and the GSICS through the Reflective Solar Spectrometers Subgroup (UVSG).

GSICS is an international collaborative effort initiated in 2005 by the WMO and CGMS to monitor, improve and harmonize the quality of observations from operational weather and environmental satellites of the Global Observing System (GOS). GSICS aims at ensuring consistent accuracy among space-based observations worldwide for climate monitoring, weather forecasting, and environmental applications (https://gsics.wmo.int/en/welcome).

GSICS contributes to the integration of satellite data within the WMO Integrated Global Observing Systems (WIGOS) and within the Global Earth Observation System of Systems (GEOSS) of the Group on Earth Observations (GEO) in particular through the Reflective Solar Spectrometer Subgroup, the subgroup addressing spectrometers operating in the UV –SWIR range, which has the following focus areas:

- pre-launch calibration and characterisation which is of critical importance;

- solar calibration including interactions with the solar community which have already been initiated;
- lunar calibration where the focus will be on UV and spectrally resolved data, as a contribution to other lunar calibration activities being carried out within GSICS;
- polarization (also for lunar calibration where possible);
- inter-calibration and development of common methods for use of pseudo-invariant targets and vicarious calibration sites (with a homogeneous surface over a sufficiently large area) noting that the focus is on the atmospheric absorption.

This activities in GSICS will be complemented by additional efforts in CEOS WGCV/ACSG which will address the following two main activities in the short-term. The first activity aims to develop a list of reference standards for CO_2 and CH_4 products that are suitable for inter-comparison of multiple missions, needed for interoperability. The second activity will identify current shortcomings and gaps in availability and sustainability of reference observations for GHG calibration and validation, and formulate recommendations for the way forward, with a specific focus on GHG Fiducial Reference Measurements (FRM). Subsequently, in the medium to long term, the aim is to address needed improvements in the inter-calibration of sensors in co-operation with GSICS. GHG level-2 validation infrastructures will also be assessed e.g., the need for ground-based algorithm inter-comparisons and geographical and/or geophysical gaps in available FRMs, identifying long-term validation and potentially also process study needs from 2025 onwards. The aim is to work towards an operational reporting on the quality of space-borne GHG measurements and the underlying calibration and validation infrastructure.

8.2. Ground-based Data Needs for Satellite Calibration and Validation

The needs and high-level requirements for in situ measurements required in support of an operational Monitoring & Verification Support (MVS) capacity to quantify anthropogenic CO2 emissions have been comprehensively addressed in [RD37] and further in [RD38]. The analysis presented in [RD37] addresses the needs for in-situ data from all core elements of an operational MVS capacity including the specific needs of the space component. The report is comprehensive in its analysis, which will not be repeated here with the exception of the recommendation that by mid-2020 EUMETSAT and ESA should elaborate a first version of a detailed plan for the calibration and validation of the space component from which *in situ* measurement requirements will be derived. This work is on-going and will be supported by an upcoming Copernicus funded study to be carried out by EUMETSAT on the “Definition of Requirements for an Integrated Function for Cal/Val and Monitoring of GHG Products from CO_2M” as part of the CO_2M ground-segment development activities at EUMETSAT. In preparation for this study EUMETSAT has also initiated a short exploratory (2-month) study on ground-based network capacity analysis for CO_2M Cal/Val. This study will identify existing components and infrastructure of the European component of the Total Carbon Column Observing Network (TCCON), as well as the COllaborative Carbon Column Observing Network (COCCON), which are fit-for-purpose to support the operational Cal/Val of CO_2M during commissioning, and in particular during the continuous operations phase, and to make proposals for required improvements of data-handling, transmission, processing, (software) maintenance, and operations of network data to facilitate the needs of operational Cal/Val for CO_2M. This short exploratory study is currently in the final phases.

8.3. Cross-calibration and Continuous Calibration Monitoring

As highlighted in [RD37], in order to integrate the measurements collected by instruments deployed on a constellation of satellites into a single consistent data record, these instruments must be cross-calibrated against common standards to characterize the precision, accuracy and information content of their measurements. The XCO_2 and XCH_4 estimates retrieved from these measurements must then be validated against common standards before they can be combined in atmospheric inversion systems to estimate CO_2 and CH_4 fluxes. Both of these efforts pose challenges for a virtual constellation that comprises a range of instrument types with potentially different observation geometries, and with extremely demanding accuracy and precision requirements.

The efforts of the GOSAT and OCO-2 teams to address these challenges in a bilateral partnership, have resulted in a range of recommendations that can inform the activities required within a virtual constellation including:

- visiting partners test facilities and cross-calibrating radiometric standards
- directly involving National Institute of Standards and Technology (NIST) in the pre-launch radiometric calibration process [RD39]
- exchanging information on experiences and best practice.

The information gained in this way has contributed to the diagnosis and correction of trends in performance of these instruments discovered after launch. However, currently, there are no programs supporting the cross-calibration of radiometric standards used in pre-launch testing of CO_2 and CH_4 sensors. The strategy for cross-calibrating the GOSAT and OCO-2 instruments has also included use of additional common standards, including observations of the sun, Moon, and vicarious calibration surface sites.

Additional efforts by WGCV and GSICS are needed to maintain and to improve the quality of these standards and methods, in particular vicarious calibration sites, to better address the calibration needs of the constellation of space-based CO_2 and CH_4 sensors. In support of the vicarious calibration efforts for OCO-2 and GOSAT, the Railroad Valley Vicarious Calibration Site was upgraded to include additional atmospheric measurements. The routine surface reflectance and atmospheric aerosol measurements were supplemented with radiosonde profiles of pressure, temperature, and water vapor and with upward-looking XCO_2 and XCH_4 measurements from ground-based instruments such as TCCON, thus allowing a comprehensive assessment of the spectrally-dependent radiances in each of the relevant spectral bands. In order to use this site for future CO_2 and CH_4 missions, the ground-based measurement campaigns initiated by the GOSAT and OCO-2 teams must be maintained. In addition, similar sites in the Asian/Oceania and Europe/African domains would be needed to cross calibrate any GEO satellites located over these domains. Observations of such sites can, when available, be incorporated into in-flight calibration activities [RD40]. As also noted above, it was recommended that CEOS WGCV-ACSG, and CGMS through the WMO GSICS UVSG play an important role in coordinating the development of these sites and distributing ground-based calibration data collected during calibration campaigns. The inter-calibration of satellite data has a long history within GSICS. The activities initially focused on inter-calibration of infrared instruments but GSICS has over time expanded its activities and now includes a number of sub-groups targeting specific spectral ranges. GSICS encourages the development of community tools and inter-calibration methods and standards as well as facilitating information and inter-calibration data exchange, all of which are important elements for the development of a robust virtual constellation.

8.4. Cross-validating XCO_2 and XCH_4 estimates across the constellation

Cross-validation of XCO_2 and XCH_4 estimates is equally as important as cross-calibration and is also comprehensively addressed in [RD37] and will not be repeated here. Cross-validation of XCO_2 products from GOSAT and OCO-2 relied on close cooperation with the TCCON consortium and aircraft programs as a means to develop internationally recognized standards for validating space-based XCO_2 and XCH_4 estimates. The TCCON network is currently providing the primary method for relating the space-based XCO_2 and XCH_4 measurements to the ground-based in situ standards maintained by the WMO GAW network [RD41], providing a cross-validation standard with accuracies near 0.1% (~0.4 ppm) [RD42]. The current geographical distribution of the network is adequate for identifying and correcting biases on regional to hemispheric scales, but a much denser network would be needed to support a constellation designed to quantify anthropogenic CO_2 fluxes at regional scales. In particular, geographical expansion of the network is required to address the needs of the anticipated GEO elements of the constellation. In addition, [RD37] notes that a more sustained and coordinated mechanism for funding of TCCON stations and distribution of data, is required if they are to support an operational space-based CO_2 and CH_4 constellation. With more constellation satellites in orbit, opportunities for cross-validation between satellites will also become more common and whilst not providing an absolute validation reference will be very beneficial in determining the consistency of the constellation products and in removing inter-satellite biases. The COllaborative Carbon Column Observing Network (COCCON) [RD43] instrument and the The AirCore system [RD44] offer additional possibilities for an operational validation network, however currently both remain in the research domain.

With respect to the satellite instrumentation itself, if the imaging CO_2 spectrometers on one or more of the LEO platforms were to be combined with an active CO_2 and/or CH_4 Lidar, the Lidar would in addition to providing some coverage of the night side hemisphere and Polar regions during polar night, provide an opportunity for cross-validation with the passive spectrometer data, for identification of systematic biases in both instruments. Due to the different measurement techniques, the observations themselves have different sensitivity to uncertainties in clouds, aerosols, and other sources of bias so cross-comparison would be very valuable.

However, the most pressing issue with respect to cross-validation activities is the need to transition the ground-based validation networks such that they are able to provide a fully sustainable, operational provision of validation data, taking into account the need for the expansion of the networks and provision of sustained funding sources. As a result, there is an urgent need for CEOS and CGMS to encourage their member agencies and partners to support such activities and initiatives. As noted above, CEOS WGCV/ACSG is expected to play an important role in these needed developments.

8.5. Interoperability and Analysis Ready Data

The understanding of the need for interoperability is well established in the Operational Meteorological Community and is a key focus of the WMO Integrated Global Observing System (WIGOS). Concepts of interoperability are based on a principle of standardization to facilitate the use of data and products from a diverse range of sources and range of providers. The principal areas of standardization include:

- instruments and methods of observation across all components, including surface-based and space-based elements (observations and their metadata);
- WMO Information System (WIS) exchange as well as discovery, access and retrieval services, and;
- data management (data processing, quality control, monitoring and archiving), particularly with respect to usage of common formats, standards and dissemination methods.

In order to transition to a fully operational MVS capacity for anthropogenic greenhouse gas monitoring, the adoption and application of similar principles is needed. In particular with respect to the space component, attention should be paid to efficient and interoperable data representation and dissemination methodology given the anticipated continued growth in data volumes [RD45].

In the context of CEOS, the concept of Analysis Ready Data is used. This is a somewhat looser concept and refers to satellite data that have been processed to a minimum set of requirements and organized into a form that allows immediate analysis with a minimum of additional user effort, and interoperability both through time and with other datasets. The intention is to lower the barrier for access and use of space-based data, and also to take into account the expected increase in satellite data volumes. The Analysis Ready Data Strategy is arguably less mature than the WMO WIGOS which is the result of WMO efforts in the coordinated provision of a wide variety of data, including space data, in support of weather and climate applications over many years. The CEOS ARD strategy [RD46] is based around four pillars: CEOS ARD user needs & specifications; assured production and access; pilots and feedback; communication & promotion. In the specific case of atmospheric greenhouse gas data, no dedicated CEOS pilot study currently exists, however the concept of Analysis Ready Data is beginning to be discussed in the frame of the CEOS AC-VC.

Given that an operational MVS capacity is anticipated to need a constellation of satellites in a variety of orbits, contributed by a number of satellite operators, in addition to a comprehensive suite of in-situ and auxiliary data, there is an urgent need for activities to address development of interoperable datasets. This includes establishing the requirements for standardization in areas such as data formats, data dissemination mechanisms, use of metadata including quality control, and also development of recommendations for best practice in atmospheric retrieval methodology. To this end, using WIGOS as a reference starting point for this activity would be both logical and beneficial, building on the long experience of WMO in this area. It is envisaged in [RD36] that other CGMS working groups could make significant contributions to the GHG roadmap. For example, CGMS Working Group I could assist in ensuring that the implementation of the GHG roadmap addresses the objectives of the WIGOS vision. Interactions with CGMS Working Group-II could facilitate the definition and application of standards for operational GHG constellation products and operational aspects of the satellite data production systems at international level, and CGMS Working Group-IV could address operational access and end user support for GHG constellation products in cooperation with CEOS Working Group on Information Systems and Services (WGISS). A more precise definition of the expected involvement of the CGMS Working Groups is expected to be provided in future version of [RD36].

8.6. Constellation planning

In order to fully optimize the design of an operational virtual constellation for anthropogenic CO_2 emissions monitoring it is necessary to address the issue of the overall orbit planning and constellation design. The design of an optimal constellation can be addressed through the use of Observing System Simulation Experiments (OSSEs), to compare the performance of proposed new satellites against current platforms, help guide the design of new instruments and to establish the necessary sampling and coverage for maximization of impact. The possibilities for performing such studies has been greatly enhanced through the CHE project.

Based on the observation needs established through OSSEs and a gap analysis with respect to existing and planned missions, system architecture and design studies should be performed to determine how best to efficiently implement the required capabilities. A particular aspect that is currently not optimized in most system concepts is the coverage of coastal regions. As pointed out in Section 4.1, the challenge stems from the competing objective of observing sea areas in sun-glint mode and land areas in nadir mode, which can be difficult to achieve without creating coverage gaps. Studies should seek solutions by examining strategies at individual-satellite level, individual-mission level, and multi-mission-constellation level. Importantly, several parameters that define the solution space are in need of further study. These include an improved understanding of how measurement accuracy degrades with larger off-nadir observation angles and how the measurement accuracy is impacted by scanning the ground at rates larger or smaller than those dictated by nominal orbital velocity. These factors determine the possibility to minimise coastal gaps with along-track repointing and scanning strategies of individual satellites, as well as constellation-level strategies that involve cross-track repointing of the line of sight. A related area of study is on operational concepts for coastal regions that maximize observation impact by focusing resources on known high-emission areas, for instance by repointing in cross-track direction based on this information. Finally, it should be noted that the optimal observation of high-latitude and arctic regions will benefit from further study of glint-pointing strategies between land and water. The fact that snow-covered areas allow good observations under geometries similar to sun-glint observations over water, potentially allows the conflict between land and water observation geometries to be reconciled at high latitudes. It can also help extend the useful land observations to higher latitudes in general.

Lessons can be learnt from the operational meteorological satellite community who have been addressing similar issues related to constellation design for many years. The Coordination Group on Meteorological Satellites (CGMS) includes harmonisation of meteorological satellite mission parameters (such as orbits, sensors, data formats and downlink frequencies) in its charter. The possibility to build on this experience to address similar issues for missions targeting the monitoring of anthropogenic greenhouse gases should be explored. For further information see https://www.cgms-info.org.

9. Summary & Conclusions

We are currently in a transition phase where the backbone of the greenhouse gas space-based observing system is provided by number of research missions which, whilst providing the space-based contribution for a pre-operational MVS capacity, and enabling progress in needed research and development activities, none yet fully achieve the broad requirements outlined in [RD1], [RD5], and [RD8]. In the near future, the CO_2M mission, currently in preparation, is expected to make a significant contribution towards addressing the requirements for the LEO component of the anticipated operational virtual constellation. It is also hoped that the GeoCarb mission will serve as a successful demonstrator for the measurement of greenhouse gas emissions from GEO, paving the way for operational agencies to include greenhouse gas emissions monitoring capabilities on their GEO platforms. Missions in HEO currently, however, remain in the study phase and a successful demonstrator mission would be required before any transition to operational HEO missions could be anticipated.

In future, in support of the further expansion of the virtual constellation, it is also essential that international efforts are made in areas such as constellation design and orbit coordination to ensure that the space-based assets put in place maximise potential benefit in the context of the overall system, particularly with regard to coverage and sampling frequency, and also to address the need for sun-glint observations in coastal areas. Significant international efforts are also needed in the area of calibration and validation both pre-launch and in-orbit, including development of a long-term monitoring capability, to ensure well-characterised and consistent product quality. These efforts are expected to take place using existing coordination mechanisms such as the CEOS WGCV and GSICS. Development of additional vicarious calibration sites will also be needed as will be the expansion of ground-based remote sensing and in-situ observation networks with the associated need for sustained funding and operational provision of data.

Research and development activities are also required to support further improvements in the satellite-based XCO_2 retrievals, in particular systematic biases which remain both in ‘proxy’ and ‘full-physics’ retrievals, despite considerable improvements in this area, also during the CHE project. International coordination is also required for the assessment and community endorsement of retrieval methodologies, which will be underpinned by the developments in the area of calibration and validation mentioned above.

With respect to co-emitted species, many satellite observations of co-emitted species are already available from operational missions targeting air quality applications. In particularly NO_2 is currently available from the Sentinel-5P TROPOMI instrument and in future Sentinel-4 and -5 which will fly on EUMETSAT's MTG and EPS-SG series of satellites respectively. Operational observations of CO are also available from the Metop IASI instruments and in future from the EPS-SG IASI-NG and MTG IRS instruments. The necessary observations also exist for the generation of operational SIF products e.g., from Sentinel-5P, Sentinel-4 and Sentinel-5, although at somewhat coarser spatial resolution than that envisaged for the CO_2M mission.

In the specific case of NO_2 being used for plume detection, as is planned for the CO_2M mission, co-registered observations are required, as are co-registered observations of cloud and aerosol in order that the XCO_2 retrievals can meet the stringent requirements. These needs should be expressed as part of the overall mission requirements, as is done for the CO_2M mission.

In conclusion, the primary need for the further development of the space component in the near term is the strengthening of international coordination efforts to address a range of issues including constellation design and orbit coordination, further development of the ground-based calibration and validation infrastructure to ensure robustness and sustainability, and that the ground-based networks are fit for purpose, and the coordination of research and development activities which will necessarily underpin any future operational virtual constellation for greenhouse gas monitoring. These efforts will be critical to ensure that the final operational virtual constellation will fully achieve the needs of an operational MVS capacity.

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Document History

Version	Author(s)	Date	Changes
0.1	Rosemary Munro (EUMETSAT)	19/11/2020	First draft version of document.
0.2	Rosemary Munro (EUMETSAT)	30/11/2020	First version of the document for internal review.
1.0	Rosemary Munro (EUMETSAT)	15/12/2020	Final version of document.

Internal Review History

Internal Reviewers	Date	Comments
Michael Buchwitz (University of Bremen)	02/12/2020	Approved with comments
Nicolas Bousserez (ECMWF)	13/12/2020	Approved with comments

Estimated Effort Contribution per Partner

Partner	Effort
EUMETSAT	1.83
ADS GmbH	0.55
Total	**2.38**