Committee on Earth Observation Satellites

CEOS AC-VC Whitepaper

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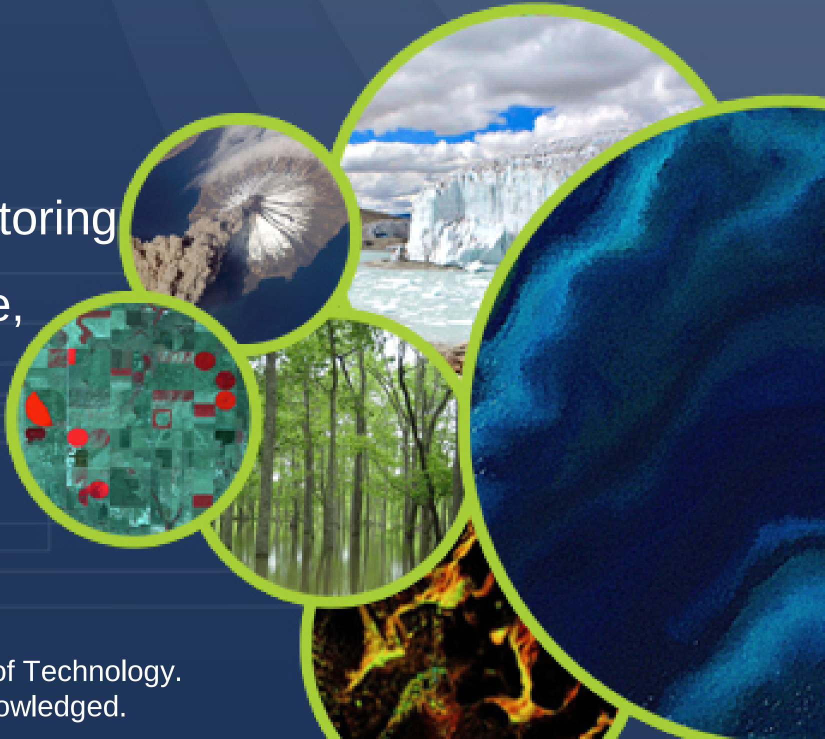
CEOS Chair Priority Workshop on GHG Monitoring

European Commission Joint Research Centre,

Ispra, Italy

18-19 June 2018



Chapters

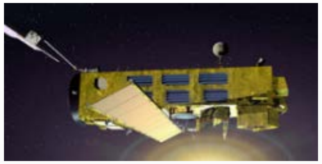
Contributions from participants at the CEOS SIT and CEOS AC-VC meetings were incorporated into the White Paper structure:

Executive Summary

1. Introduction
2. Using atmospheric GHG measurements to improve inventories
3. Space-based GHG measurement capabilities and near term plans
4. Lessons Learned from SCIAMACHY, GOSAT and OCO-2
5. Integrating GHG Satellites into Operational Constellations
6. Towards an operational constellation measuring anthropogenic CO_2 emissions
7. The Transition from Science to Operations
8. Conclusions

Past and Present GHG Satellites

- **SCIAMACHY (2002-2012)** – First sensor to measure O_2, CO_2, and CH_4 using reflected NIR/SWIR sunlight
  - Regional-scale maps of X_{CO2} and X_{CH4} over continents



- **GOSAT (2009 …)** – First Japanese GHG satellite
  - FTS optimized for high spectral resolution over broad spectral range, yielding CO_2, CH_4, and chlorophyll fluorescence (SIF)

- **OCO-2 (2014 …)** – First NASA satellite to measure O_2 and CO_2 with high sensitivity, resolution, and coverage
  - High resolution imaging grating spectrometer small (< 3 km^2) footprint and rapid sampling (10^6 samples/day)

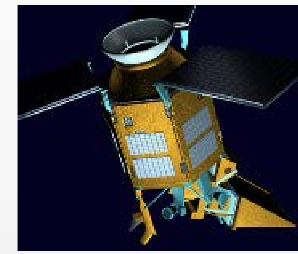
- **TanSat (2016 …) -** First Chinese GHG satellite
  - Imaging grating spectrometer for O_2 and CO_2 bands and cloud & aerosol Imager
  - In-orbit checkout formally complete in August 2017

The Next Generation

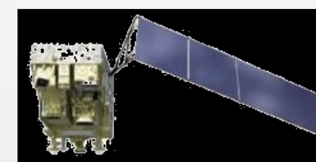
In orbit Checkout

- **Feng Yun 3D (2017)** – Chinese GHG satellite on an operational meteorological bus
    - o GAS FTS for O_2, CO_2, CH_4, CO, N_2O, H_2O

- **Sentinel 5p (2017)** - Copernicus pre-operational Satellite
    - o TROPOMI measures O_2, CH_4 (1%), CO (10%), NO_2, SIF
    - o Imaging at 7 km x 7 km resolution, daily global coverage



- **Gaofen 5 (2018)** - 2nd Chinese GHG Satellite
    - o Spatial heterodyne spectrometer for O_2, CO_2, and CH_4

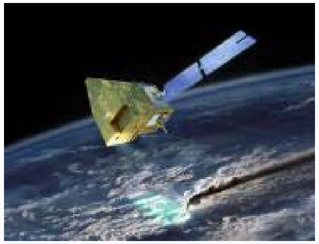


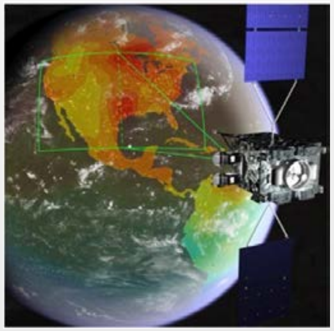
- **GOSAT-2 (2018)** – Japanese 2nd generation satellite
    - o CO as well as CO_2, CH_4, with improved precision (0.125%), and active pointing to increase number of cloud free observation

- **OCO-3 (2019)** – NASA OCO-2 spare instrument, on ISS
    - o First CO_2 sensor to fly in a low inclination, precessing orbit

Future GHG Satellites (2)

- **CNES/UK MicroCarb (2021+)** – compact, high sensitivity
  - Imaging grating spectrometer for O_2 A, O_2 $^1\Delta_g$, and CO_2
  - ~1/2 of the size, mass of OCO-2, with 4.5 km x 9 km footprints
- **CNES/DLR MERLIN (2021+)** - First CH_4 LIDAR (IPDA)
  - Precise (1-2%) X_{CH4} retrievals for studies of wetland emissions, inter-hemispheric gradients and continental scale annual CH_4 budgets
- **NASA GeoCarb (2022*) – First GEO GHG satellite**
  - Imaging spectrometer for X_{CO2}, X_{CH4}, X_{CO} and SIF
  - Stationed above ~85° W to view North/South America
- **Sentinel 5A,5B,5C (2022) - Copernicus operational services for air quality and CH4**
  - Daily global maps of XCO and XCH4 at < 8 km x 8 km

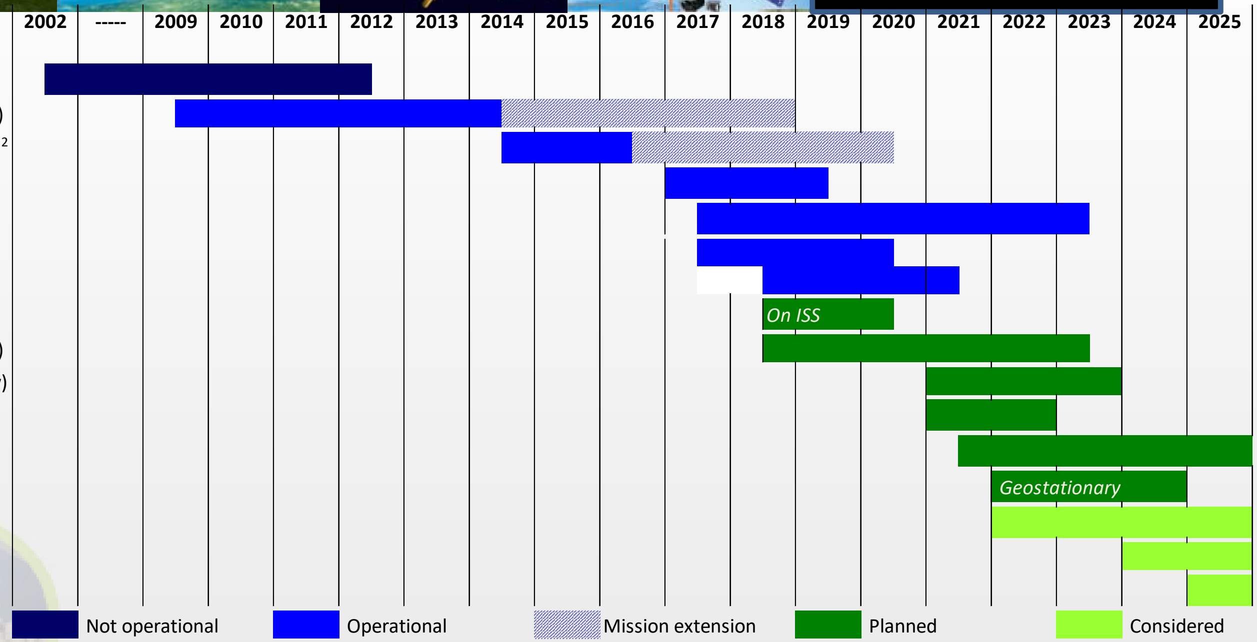




“ Pre-Decisional Information -- For Planning and Discussion Purposes Only

GHG Mission Timeline

Satellite, Instrument (Agencies)	CO_2	CH_4	Swath	Sample
ENVISAT SCIAMACHY (ESA)	●	●	960 km	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	●	●	3 pts	10.5 km (d)
OCO-2 (NASA)	●		10.6 km	1.3x2.3 km^2
TanSAT (CAS-MOST-CMA)	●		20 km	1x2 km^2
Sentinel 5P TROPOMI (ESA)		●	2600 km	7x7 km^2
Feng Yun 3D GAS (CMA)	●	●		10 km (d)
GaoFen-5 GMI	●	●		10 km (d)
OCO-3 (NASA)	●		11 km	~4 km^2
GOSAT-2 TANSO-FTS (JAXA-MOE-NIES)	●	●	5 pts	10.5 km (d)
MERLIN (DLR-CNES)		●	100 m	0.14 km (w)
MicroCarb (CNES)	●		13.5 km	40 km^2
MetOp Sentinel-5 series (Copernicus)		●	2670 km	7x7 km^2
GEOCARB (NASA)	●	●		4x4 km^2
Feng Yun 3G (CMA)	●	●		1x1 km^2
GOSAT-3 (JAXA-MOE-NIES)	●	●		
CO2 Monitoring series (Copernicus)	●	●		2x2 km^2



- A broad range of GHG missions will be flown over the next decade.
- Most are "science" missions, designed to identify optimal methods for measuring CO_2 and CH_4, not "operational" missions designed to deliver policy relevant GHG products focused on anthropogenic emissions

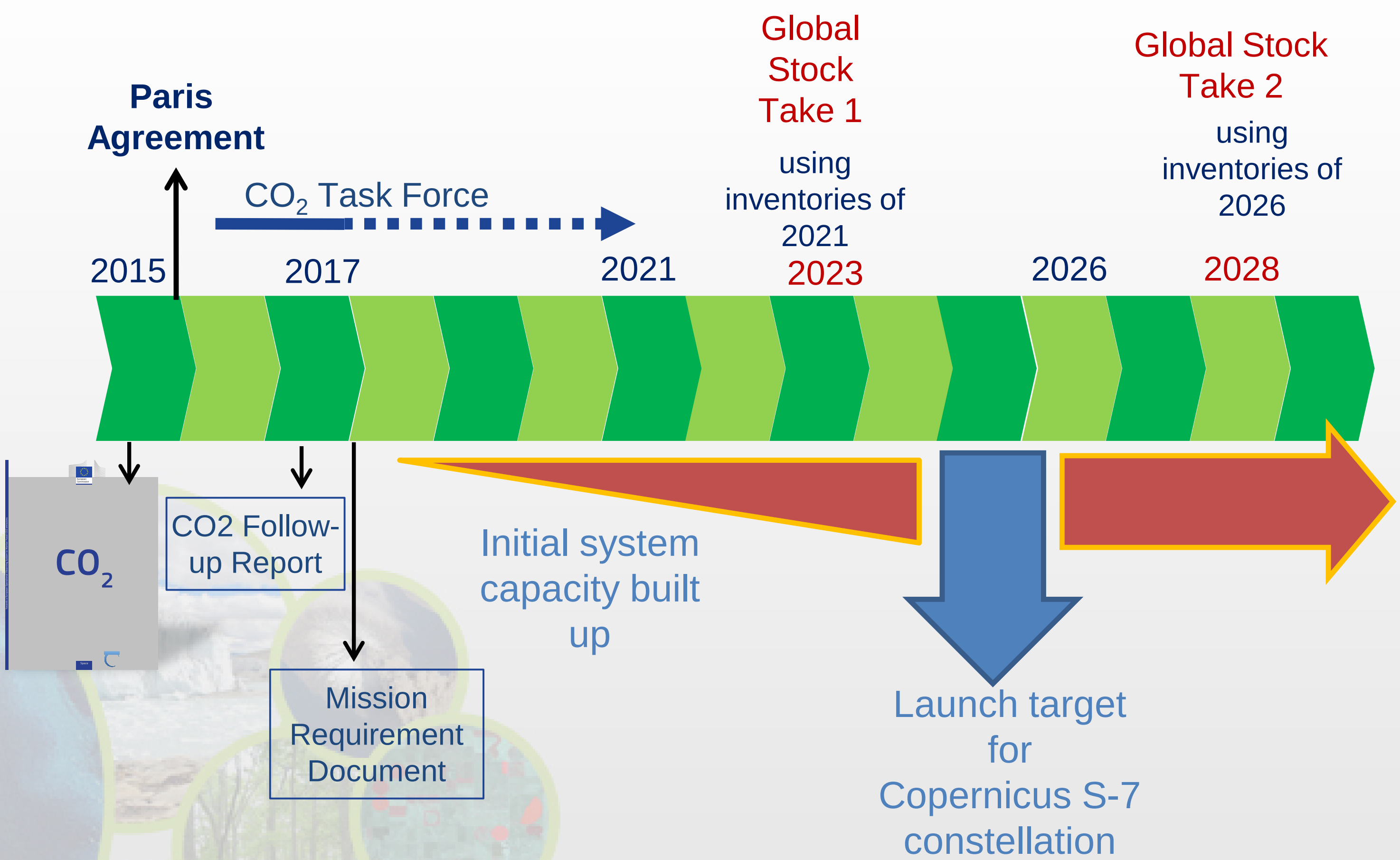
GCOS CO_2 and CH_4 Requirements.

The CO_2 and CH_4 measurement requirements in the 2011 update for the Global Climate Observing System (GCOS) Systematic Observation Requirements for Satellite-Based Data Products for Climate (GCOS, 2011) and GCOS 2016 Implementation Plan (GCOS, 2016) were adopted as targets for a future GHG constellation.

Variable / Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability/ Decade*	Stability/ Decade**
Tropospheric CO_2 column	5-10km	N/A	4 h	1 ppm	0.2 ppm	1.5 ppm
Tropospheric CO_2	5-10 km	5 km	4 h	1 ppm	0.2 ppm	1.5 ppm
Tropospheric CH_4 column	5-10 km	N/A	4 h	10 ppb	2 ppb	7 ppb
Tropospheric CH_4	5-10 km	5 km	4 h	10 ppb	2 ppb	0.7 ppb
Stratospheric CH_4	100-200 km	2 km	Daily	5%	0.30%	0.30%

* from GCOS 2011
** from GCOS 2016

Timely inputs to policy makers



A Candidate GHG Constellation Architecture

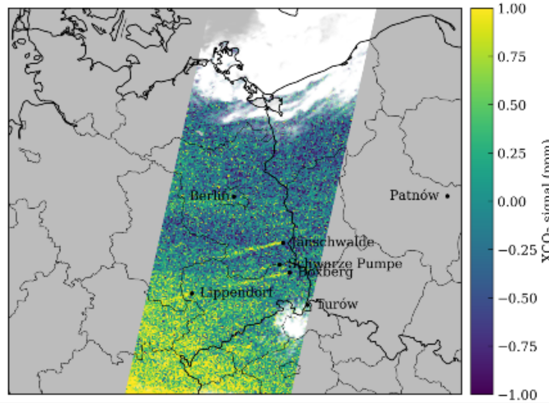
The accuracy, precision, resolution, and coverage requirements could be achieved with a constellation that incorporates

- A constellation of 3 (or more) satellites in LEO with
  - A broad (> 200) km swath with a mean footprint size < 4 km^2
  - A single sounding random error near 0.5 ppm, and vanishing small regional scale bias (< 0.1 ppm) over > 80% of the sunlit hemisphere
  - One (or more) satellites carrying ancillary sensors (CO, NO_2, CO_2 and/or CH_4 Lidar)
- A constellation with 3 (or more) GEO satellites
  - Monitor diurnally varying processes (e.g. rush hours, diurnal variations in the biosphere)
  - Stationed over Europe/Africa, North/South America, and East Asia
- This constellation could be augmented with one or more HEO satellites to monitor carbon cycle changes in the high arctic

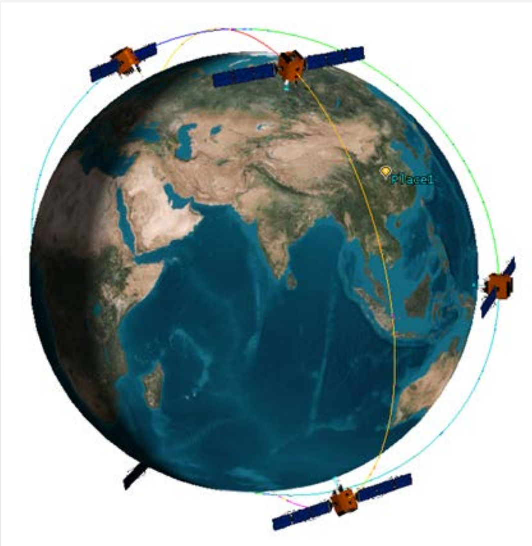
Future LEO GHG Constellations in the Planning Stages

- Copernicus CO_2 Sentinel (2025+)
  - 3 or 4 LEO satellites in an operational GHG constellation
  - Primary instruments measure O_2 (0.76 μm A-band), CO_2 (1.61 and 2.06 μm), CH4 (1.67 μm) and NO_2 (0.450 μm) at a spatial resolution of 2 km x 2 km along a 200-300 km swath
  - A dedicated cloud/aerosol instrument is also under consideration

X_{CO2} (σ= 0.5 ppm)



- TanSat-2 Constellation
  - 6 satellites, with 3 flying in morning sun-synchronous orbits and 3 flying in afternoon sun-synchronous orbits
  - primary GHG instrument on each satellite with measure CO_2 (1.61 and 2.06 µm), CH_4 and CO (2.3 µm) as well as the O_2 A-band (0.76 µm) across a 100-km cross-track swath



TanSat Constellation

Merging Science and Operations

- Because of the unprecedented requirements for precision and accuracy, the space based elements of the an operational GHG constellation architecture must be accompanied by
  - Rigorous pre-launch and on-orbit measurement calibration and product validation methods that evolve to meet emerging needs
  - Continuous refinements in remote sensing retrieval and flux inversion modeling methods that improve the products over time
- CEOS could play an essential role in coordinating these activities among its partner agencies
- Any operational architecture will also have to address
  - orbit and mission coordination, data distribution, data exchange, and data format requirements
  - Training and capacity building and public outreach will be needed to fully exploit the value of the space based GHG measurements
- CEOS should collaborate with CGMS and other operational organizations to foster the development of these capabilities