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

- **Feng Yun 3D (2017)** – Chinese GHG satellite on an operational meteorological bus
  - GAS FTS for O₂, CO₂, CH₄, CO, N₂O, H₂O

- **Sentinel 5p (2017)** - Copernicus pre-operational Satellite
  - TROPOMI measures O₂, CH₄ (1%), CO (10%), NO₂, SIF
  - Imaging at 7 km x 7 km resolution, daily global coverage

- **Gaofen 5 (2018)** - 2nd Chinese GHG Satellite
  - Spatial heterodyne spectrometer for O₂, CO₂, and CH₄

- **GOSAT-2 (2018)** – Japanese 2nd generation satellite
  - CO as well as CO₂, CH₄, 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
  - First CO₂ sensor to fly in a low inclination, precessing orbit
Future GHG Satellites (2)

- **CNES/UK MicroCarb (2021+)** – compact, high sensitivity
  - Imaging grating spectrometer for O₂ A, O₂ $^{1}\Delta_g$, and CO₂
  - ~1/2 of the size, mass of OCO-2, with 4.5 km x 9 km footprints

- **CNES/DLR MERLIN (2021+)** - First CH₄ LIDAR (IPDA)
  - Precise (1-2%) $X_{CH4}$ retrievals for studies of wetland emissions, inter-hemispheric gradients and continental scale annual CH₄ 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*
• A broad range of GHG missions will be flown over the next decade.

• Most are “science” missions, designed to identify optimal methods for measuring CO₂ and CH₄, not “operational” missions designed to deliver policy relevant GHG products focused on anthropogenic emissions.
The CO₂ and CH₄ 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.

<table>
<thead>
<tr>
<th>Variable / Parameter</th>
<th>Horizontal Resolution</th>
<th>Vertical Resolution</th>
<th>Temporal Resolution</th>
<th>Accuracy</th>
<th>Stability/Decade*</th>
<th>Stability/Decade**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropospheric CO₂ column</td>
<td>5-10km</td>
<td>N/A</td>
<td>4 h</td>
<td>1 ppm</td>
<td>0.2 ppm</td>
<td>1.5 ppm</td>
</tr>
<tr>
<td>Tropospheric CO₂</td>
<td>5-10 km</td>
<td>5 km</td>
<td>4 h</td>
<td>1 ppm</td>
<td>0.2 ppm</td>
<td>1.5 ppm</td>
</tr>
<tr>
<td>Tropospheric CH₄ column</td>
<td>5-10 km</td>
<td>N/A</td>
<td>4 h</td>
<td>10 ppb</td>
<td>2 ppb</td>
<td>7 ppb</td>
</tr>
<tr>
<td>Tropospheric CH₄</td>
<td>5-10 km</td>
<td>5 km</td>
<td>4 h</td>
<td>10 ppb</td>
<td>2 ppb</td>
<td>0.7 ppb</td>
</tr>
<tr>
<td>Stratospheric CH₄</td>
<td>100-200 km</td>
<td>2 km</td>
<td>Daily</td>
<td>5%</td>
<td>0.30%</td>
<td>0.30%</td>
</tr>
</tbody>
</table>

* from GCOS 2011
** from GCOS 2016
Timely inputs to policy makers

Paris Agreement

CO₂ Task Force

2015 2017 2021

Global Stock Take 1
using inventories of
2021 2023

Global Stock Take 2
using inventories of
2026

Launch target for
Copernicus S-7
constellation

Initial system capacity built up

Mission Requirement Document

CO₂ Follow-up Report
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 km²
  - 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, NO₂, CO₂ and/or CH₄ 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 CO₂ Sentinel (2025+)**
  - 3 or 4 LEO satellites in an operational GHG constellation
  - Primary instruments measure O₂ (0.76 µm A-band), CO₂ (1.61 and 2.06 µm), CH₄ (1.67 µm) and NO₂ (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

- **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 CO₂ (1.61 and 2.06 µm), CH₄ and CO (2.3 µm) as well as the O₂ A-band (0.76 µm) across a 100-km cross-track swath
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