Committee on Earth Observation Satellites

CEOS AC-VC GHG White Paper

Architecture for Monitoring Carbon Dioxide and Methane from Space

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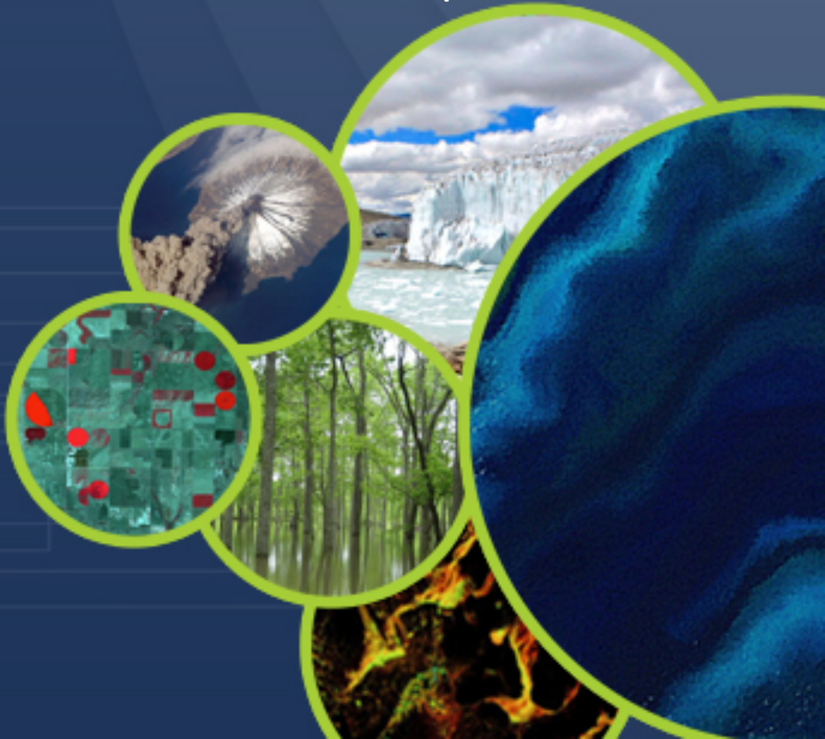
CEOS WGCV IVOS 31, CSIRO, Perth, Australia

25-29 March 2019

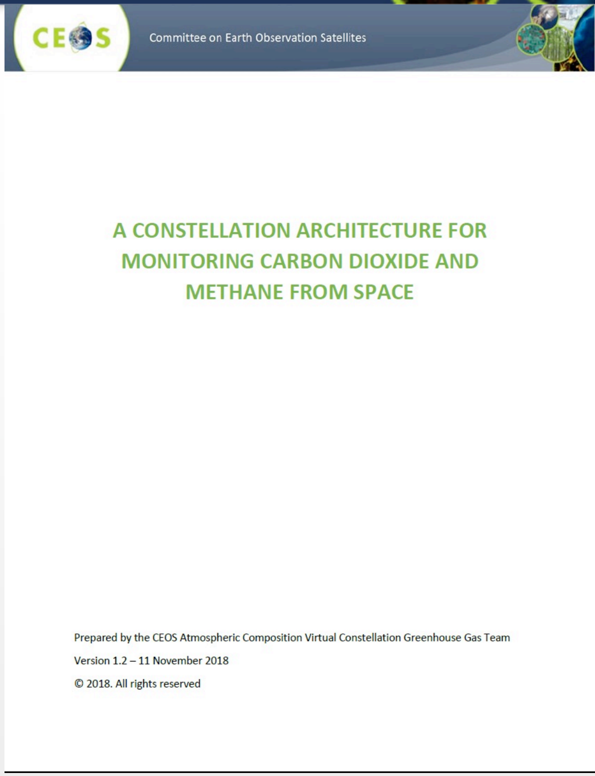


Objectives of the AC-VC GHG White Paper

- The CEOS Chair commissioned the Atmospheric Composition Virtual Constellation (AC-VC) to write a white paper that defines the key characteristics of a global architecture for monitoring atmospheric CO_2 and CH_4 concentrations and their natural and anthropogenic fluxes from instruments on space-based platforms to:
  - reduce uncertainty of national emission inventory reporting;
  - identify additional emission reduction opportunities and provide nations with timely and quantified guidance on progress towards their emission reduction strategies and pledges (Nationally Determined Contributions, NDCs); and,
  - to track changes in the natural carbon cycle caused by human activities (deforestation, degradation of ecosystems, fire) and climate change

AC-VC White Paper Structure

- 166-page document
  - 88 authors representing 47 organizations
- Executive Summary (2 pages)
  - Overview of objectives and approach
  - Intended for policy makers, CEOS/CGMS Agency leads
- Body of report (75 pages)
  - Science background and requirements
  - Current and near-term mission heritage
  - System implementation approach
  - Intended for program scientists and project managers
- Technical Appendices (42 pages)
  - “Textbook” summarizing state-of-the-art in observation capabilities and analysis methods to justify system-level requirements
  - Intended for scientists, engineers, and inventory community


Committee on Earth Observation Satellites

A CONSTELLATION ARCHITECTURE FOR MONITORING CARBON DIOXIDE AND METHANE FROM SPACE

Prepared by the CEOS Atmospheric Composition Virtual Constellation Greenhouse Gas Team

Version 1.2 – 11 November 2018

http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Publication_Draft2_20181111.pdf

White Paper Contents – Main Text

Executive Summary

Chapter 1: Introduction

Chapter 2: Estimating Emissions from Atmospheric CO_2 and CH_4 Measurements

Chapter 3: Space-based CO_2 and CH_4 Measurement Capabilities and Near-term Plans

Chapter 4: The Transition from Science Missions to an Operational Constellation

Chapter 5: Designing an Operational LEO Constellation for Measuring Anthropogenic CO_2 Emissions – The Sentinel CO_2 Initiative

Chapter 6: Integrating CO_2 and CH_4 Satellites into Operational Constellations

Chapter 7: Conclusions and Way Forward

White Paper Contents - Appendices

A1: Remote sensing retrieval methods for estimating XCO_2 and XCH_4 from observations of reflected sunlight

A2: Methods for quantifying surface fluxes of CO_2 and CH_4 from space-based XCO_2 and XCH_4 estimates

A3: Observation system simulation experiments (OSSEs)

A4: Lessons learned from SCIAMACHY, GOSAT and OCO-2

A5: Greenhouse gas monitoring satellites from commercial organizations & non-governmental organizations

A6: Advantages of LEO, GEO and HEO vantage points

A7: CEOS Agencies implementing CO_2 and CH_4 missions

A8: Acronym List

References Cited

A System Approach to an Atmospheric Inventory System

Observations

Satellite Measurements of CO_2 and CH_4

Ground and Airborne Measurements of CO_2 and CH_4

Meteorology
Satellite & in-situ

Auxiliary Data
Satellite observations of CO, NO_2, clouds, aerosols …

Prior Information

Fluxes, model parameters, emission reports, economic statistics.

Integration & Attribution

Estimation system
Data assimilation and uncertainty estimation

Models
Transport, land & ocean carbon cycle, fossil fuel emissions.

Outputs

CO_2 and CH_4 emissions & removal Hot-spots with uncertainties

Country/region CO_2 and CH_4 emissions & removals with uncertainties

Other Carbon Cycle Products

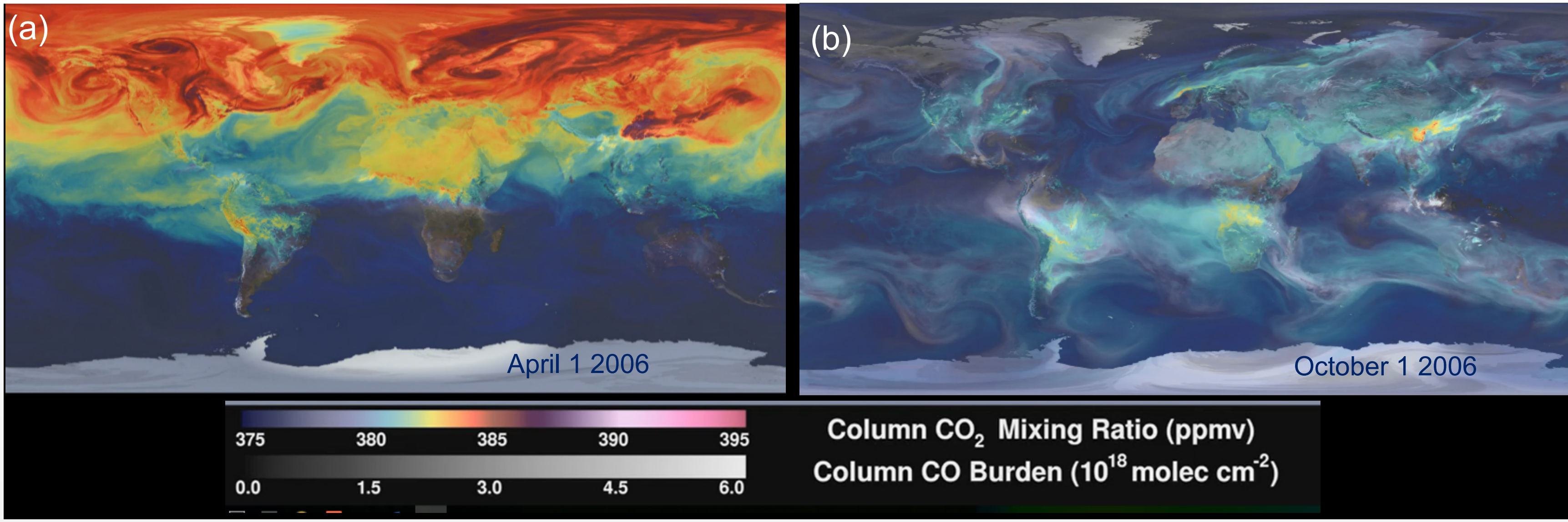
Updating the GCOS CO_2 and CH_4 Requirements

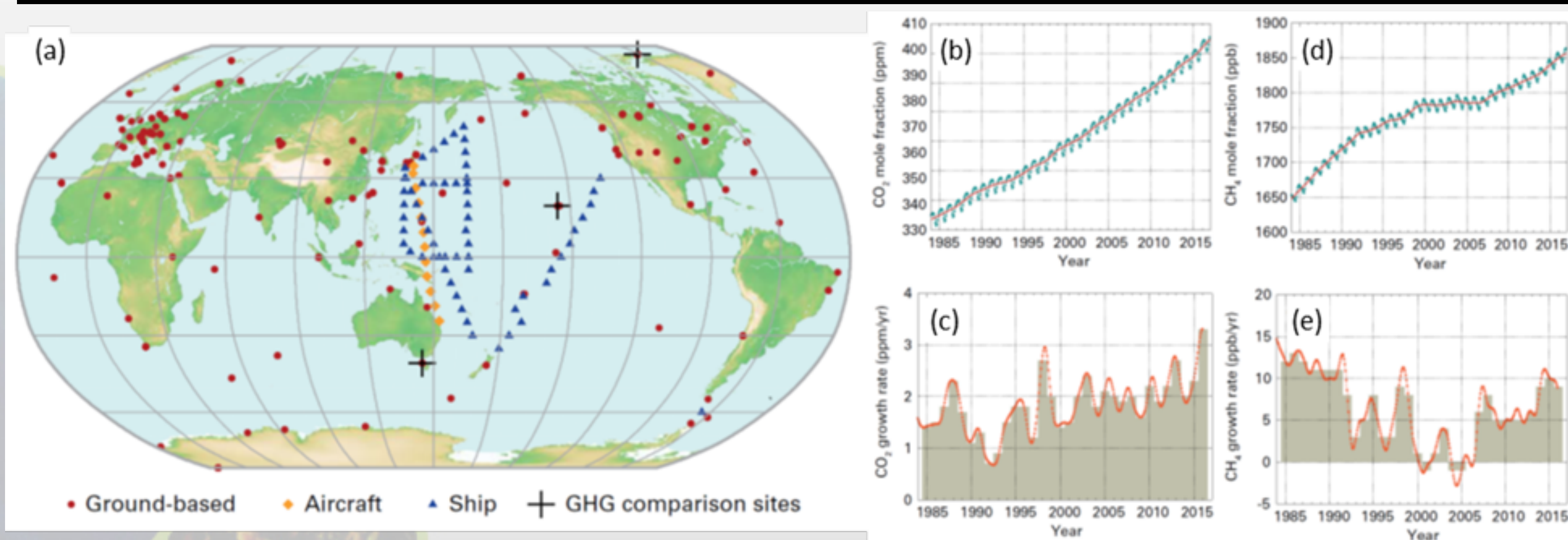
The CO_2 and CH_4 measurement requirements in the 2011 update for the Global Climate Observing System (GCOS) Systematic Observation Requirements for Satellite-Based Data Products for Climate (GCOS, 2011) were adopted as targets for a future GHG constellation.

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

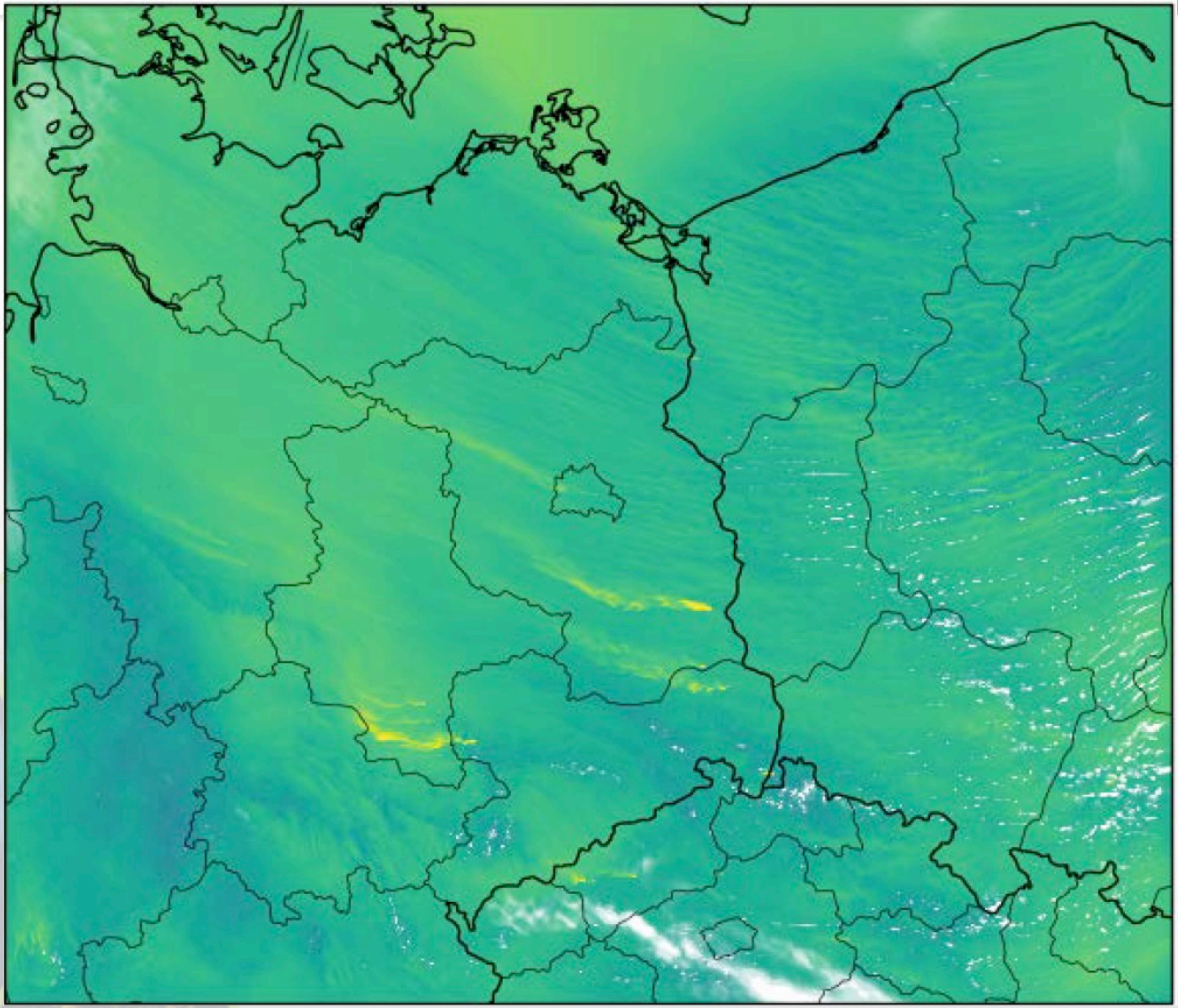
We are currently working with GCOS to refine these requirements

The Ground-based Context

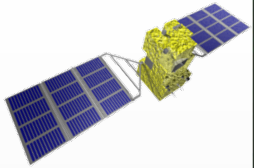


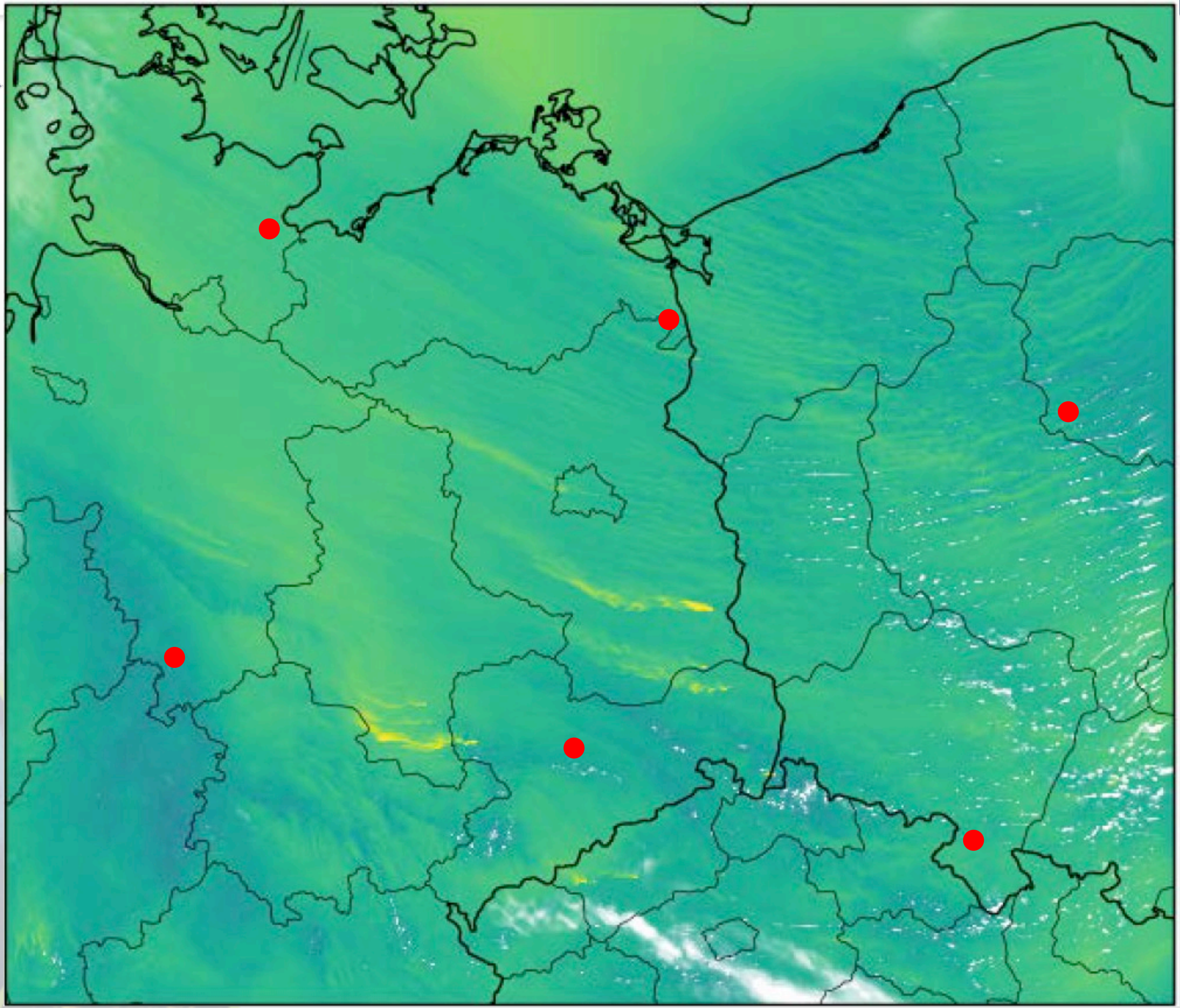


Coverage and Resolution Requirements

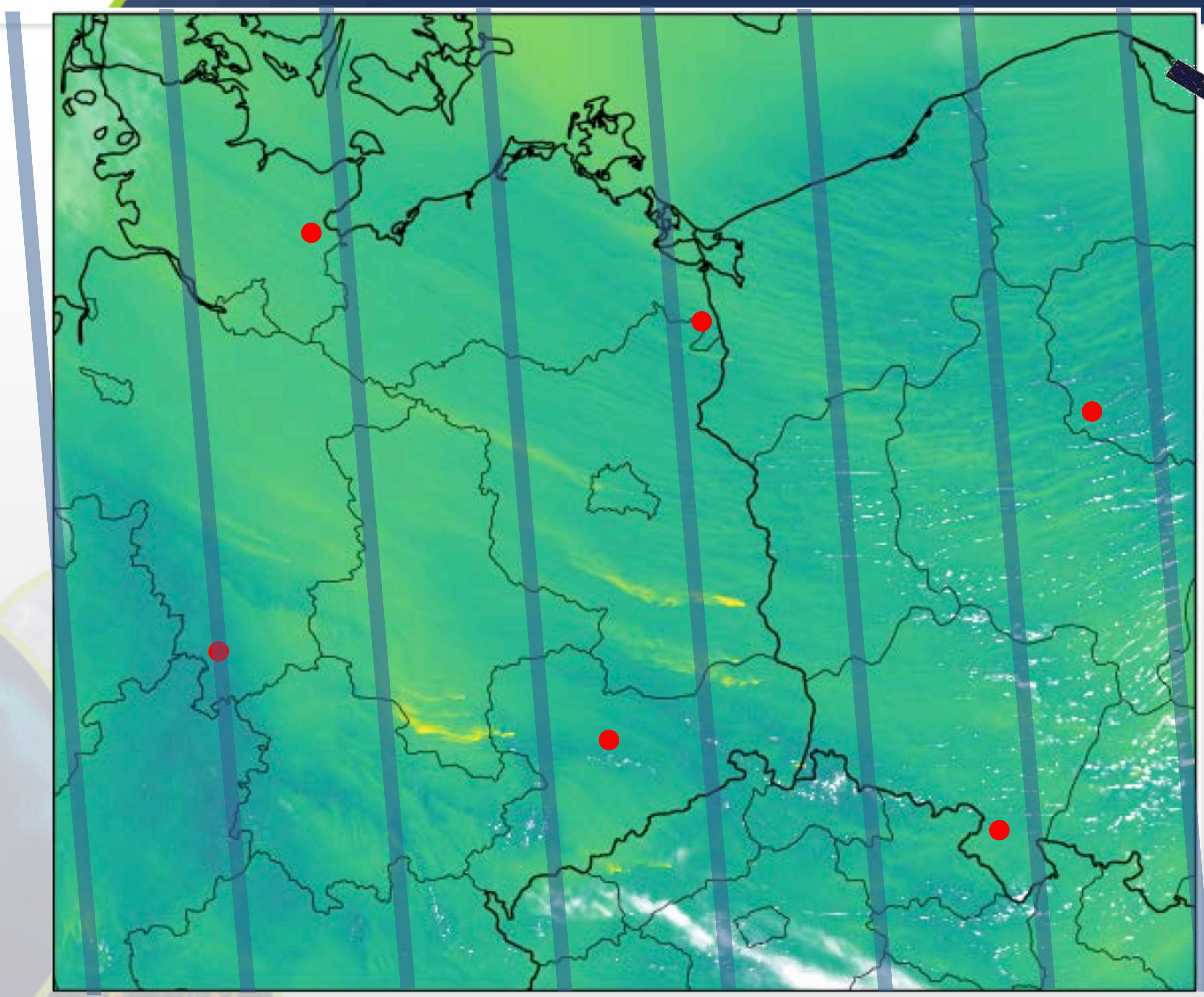


GOSAT Sampling

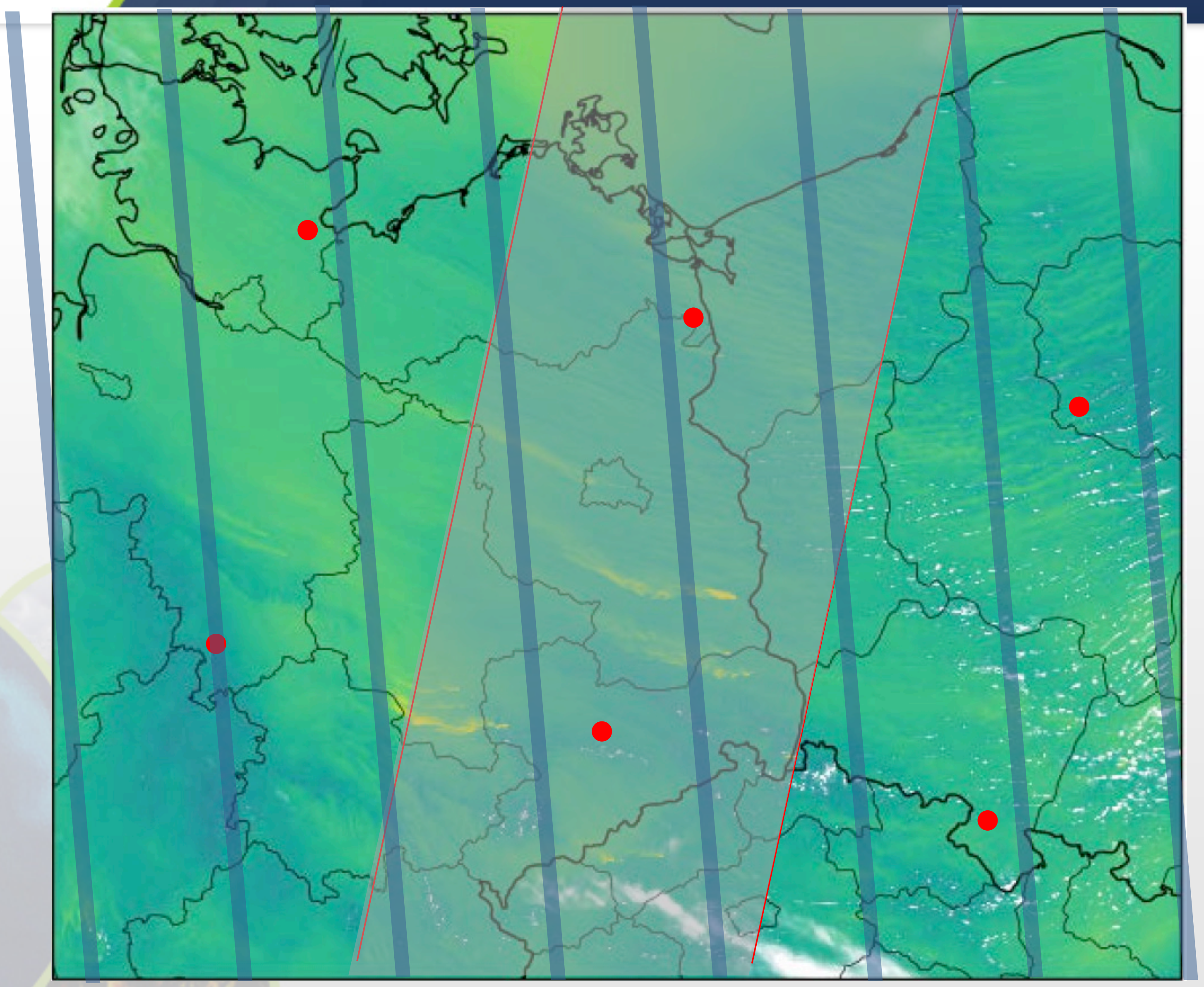




GOSAT+OCO-2 sampling

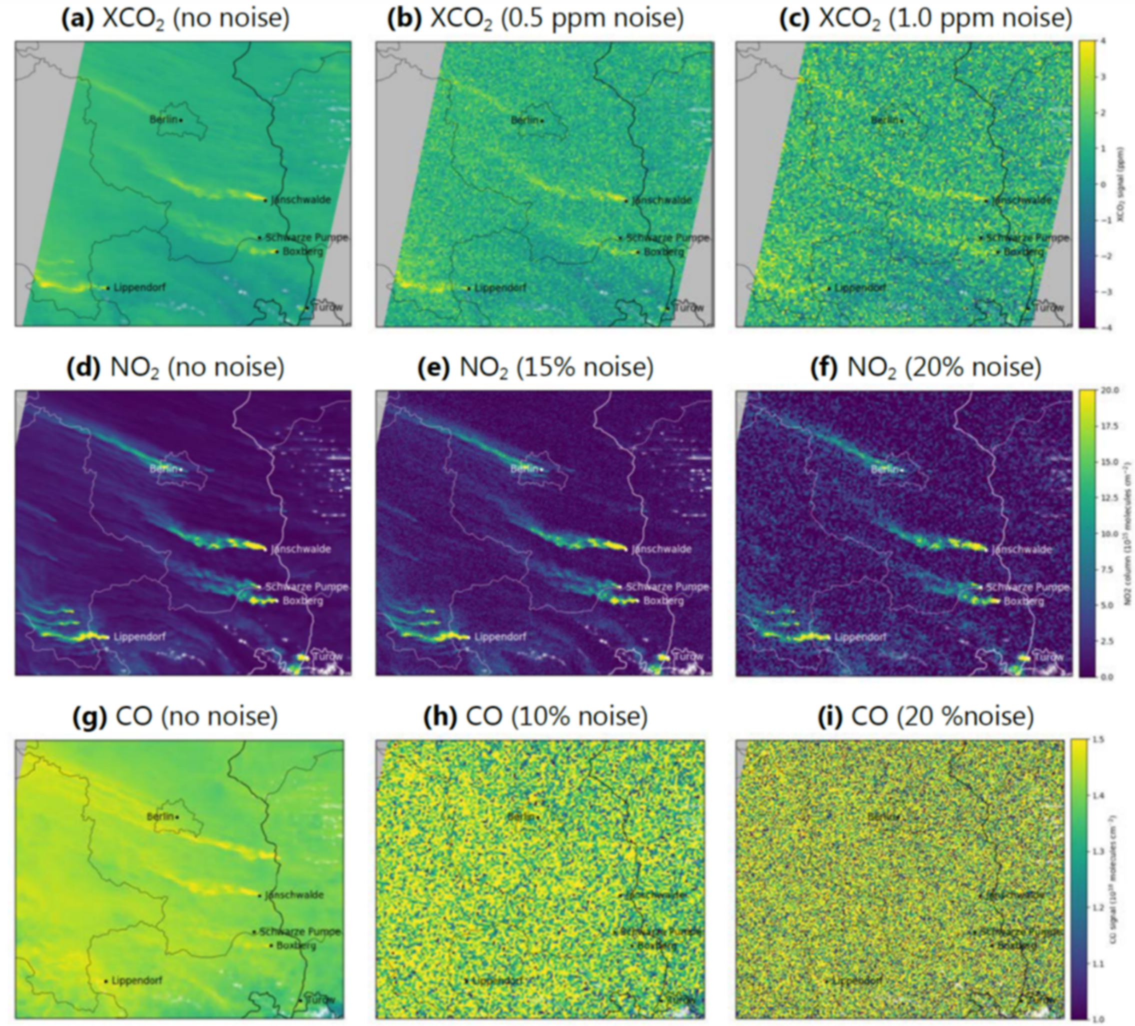


A Future Broad-swath CO2 Imager



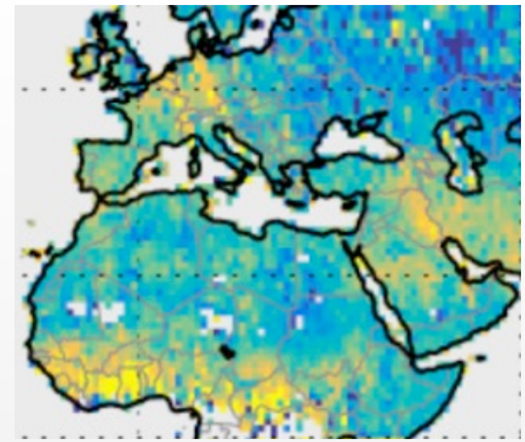
Precision Requirements and Ancillary Measurements

Models

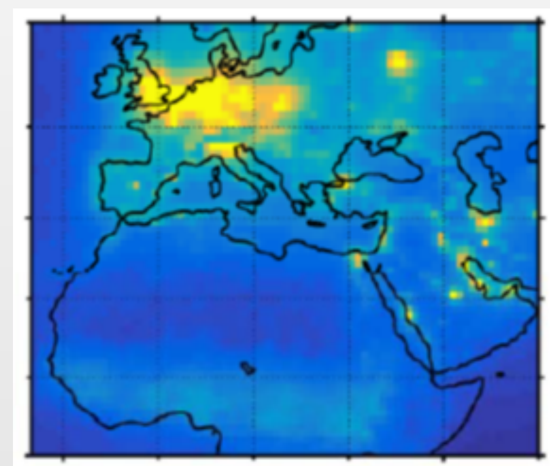


Kuhlmann et al., ESA/SMARTCARB

Measurements



OCO-2 XCO_2



Hakkarainen et al. OMI NO_2

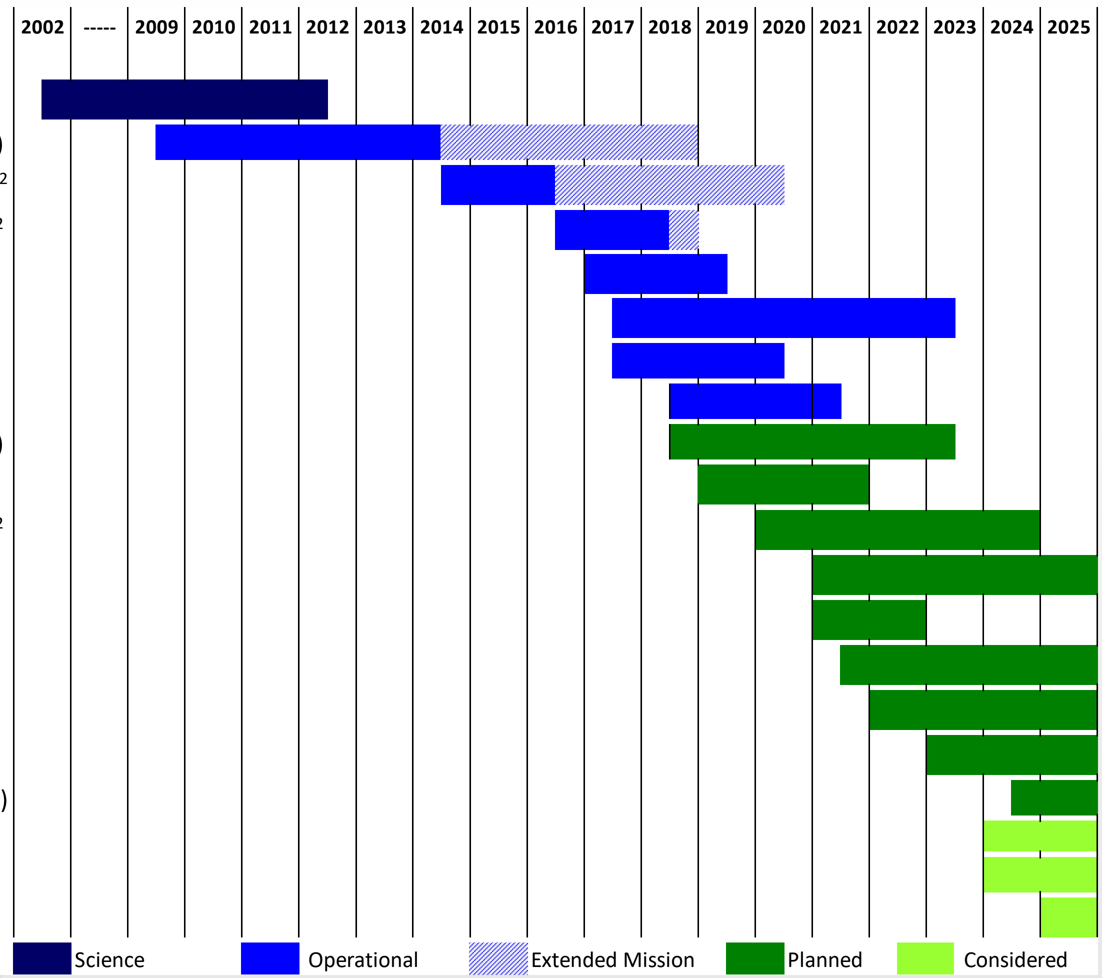
A Candidate Operational CO2/CH4 Constellation Architecture

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

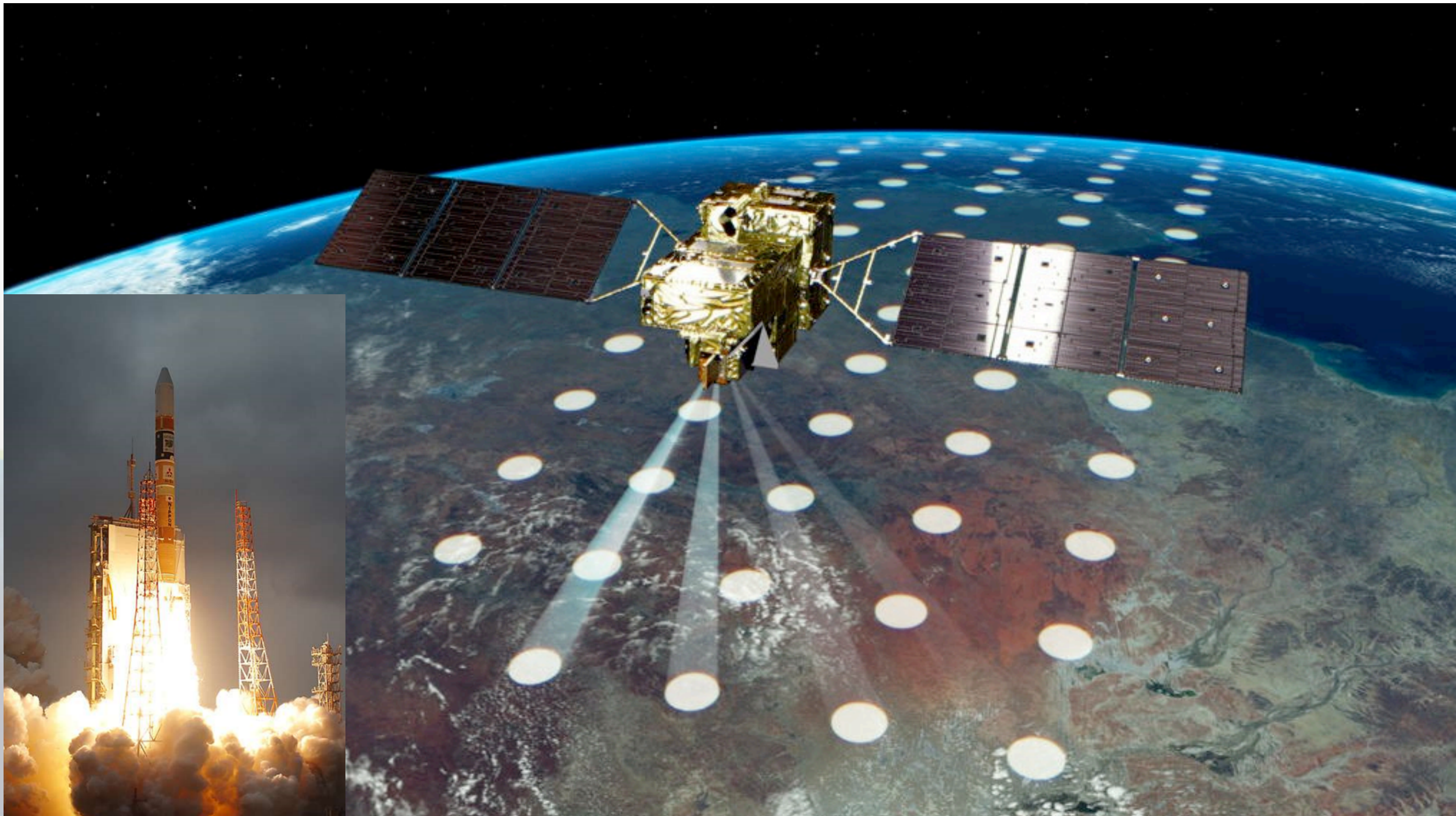
- A constellation of 3 (or more) satellites in LEO with
  - A broad (> 200) km swath with a mean footprint size < 4 km^2
  - A single sounding random error near 0.5 ppm, and vanishing small regional scale bias (< 0.1 ppm) over > 80% of the sunlit hemisphere
  - One (or more) satellites carrying ancillary sensors to identify plumes (CO, NO_2) or to detect and mitigate biases (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

The Evolving CO_2/CH_4 Fleet

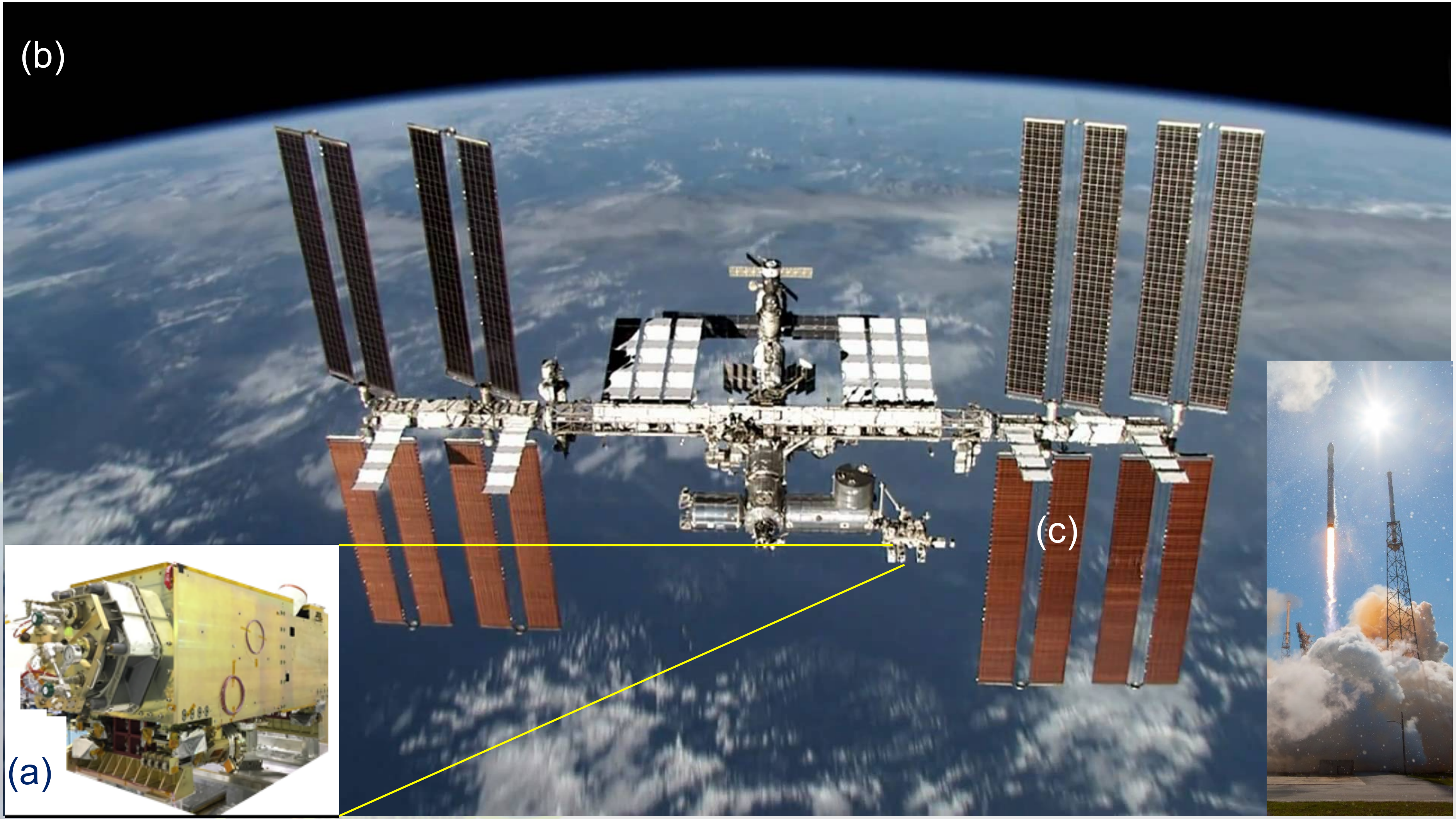
Satellite, Instrument (Agencies)	CO_2	CH_4	Swath	Sample
ENVISAT SCIAMACHY (ESA)	●	●	960 km	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	●	●	3 pts	10.5 km (d)
OCO-2 (NASA)	●		10.6 km	1.3x2.3 km^2
GHGSat (Claire)		●	12 km	0.0004 km^2
TanSAT (CAS-MOST-CMA)	●		20 km	1x2 km^2
Sentinel 5P TROPOMI (ESA)		●	2600 km	7x7 km^2
Feng Yun 3D GAS (CMA)	●	●	7 pts	10 km (d)
GaoFen-5 GMI	●	●	5-9 pts	10 km (d)
GOSAT-2 TANSO-FTS (JAXA-MOE-NIES)	●	●	5 pts	10.5 km (d)
OCO-3 (NASA)	●		11 km	4 km^2
Bluefield Technologies		●	25x20 km	0.0004 km^2
MicroCarb (CNES)	●		13.5 km	40 km^2
MethaneSAT (EDF)		●	200 km	1 km^2
MetOp Sentinel-5 series (Copernicus)		●	2670 km	7x7 km^2
Feng Yun 3G (CMA)	●	●	100 km	< 3 km^2
GEOCARB (NASA)	●	●	2800 km	4x4 km^2
MERLIN (DLR-CNES)		●	100 m	0.14 km (w)
TanSat-2 Constellation	●	●	3x100 km	2x2 km^2
GOSAT-3 (JAXA-MOE-NIES)	●	●	TBD	TBD
CO2 Sentinel (Copernicus)	●	●	3x250 km	2x2 km^2



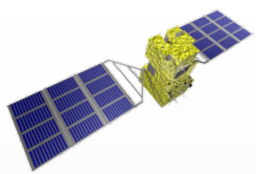
Recent Launches:
GOSAT-2 Launch 29 October 2018

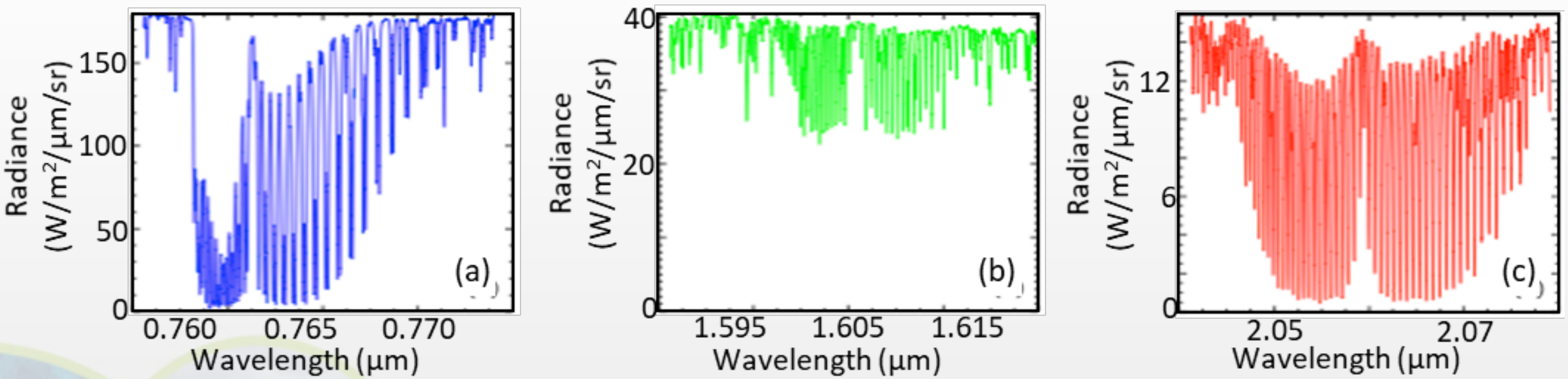


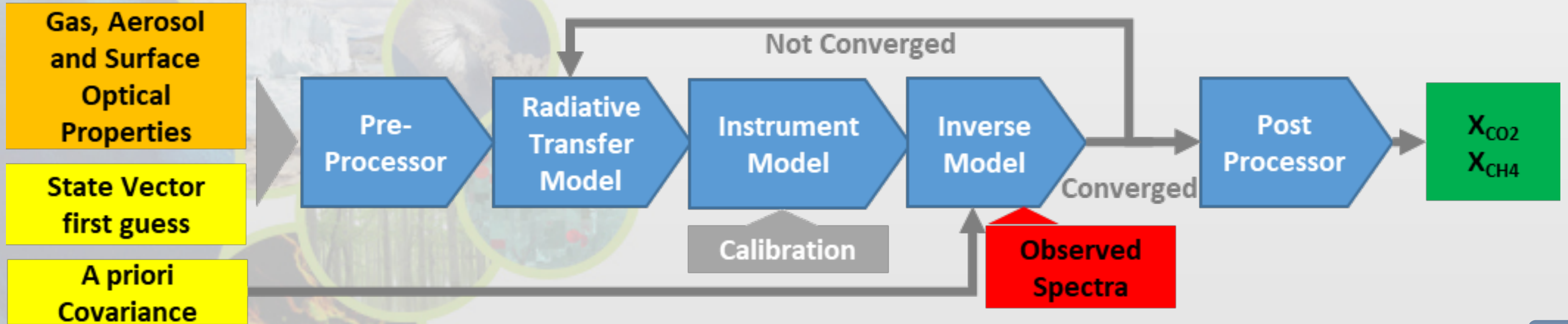
Coming Attractions:
OCO-3 Launch, April 25, 2019



Retrieving XCO_2 and XCH_4 from Space-based Measurements







Tools Needed to Meet New Requirements

- Sensors with improved precision, spatial resolution, and coverage
  - Accuracy/Precision: Improved calibration accuracy and stability
  - Resolution/Coverage: Dedicated LEO and Geo GHG constellations
- Improved remote sensing retrieval algorithms
  - Optical properties: gas absorption and aerosol scattering
  - Retrieval methods: Optimized to exploit information from solar spectra
- Better coordination with ground-based/aircraft networks
  - Validation: TCCON, EM27-Sun, AirCore, Aircraft
  - Complementary coverage: polar regions, persistently cloud regions
- Improved atmospheric inversion models
  - Transport: Higher spatial resolution to resolve mesoscale transport
  - Assimilation techniques: for ground-, aircraft-, and space-based data
- Methods to validate fluxes on local to national/regional scales

Calibration Advances Needed

- Space based sensors for CO_2 and CH_4 must be
  - calibrated to unprecedented levels of accuracy to detect and quantify the small XCO_2 and XCH_4 changes associated with surface fluxes
  - cross-calibrated against internationally-accepted standards prior to launch and in orbit so that their measurements can be integrated into a harmonized data product that meets the accuracy, precision, resolution, and coverage requirements for CO_2 and CH_4
- Efforts by the ACOS and GHG-CCI teams have demonstrated the feasibility of this approach for SCIAMACHY, GOSAT, and OCO-2
  - Rigorous pre-launch and in-orbit calibration methods demonstrated
- Substantial improvements will be needed to meet the much more demanding requirements of anthropogenic emissions monitoring
  - Cross-calibrating a more diverse range of spacecraft sensors
  - Reducing calibration-related biases across multiple spacecraft

Validation Advances Needed

XCO_2 and XCH_4 estimates across the constellation must be cross validated against internationally-recognized standards to yield a harmonized integrated product that meets the demanding precision, accuracy, resolution, and coverage requirements

- The Total Carbon Column Observing Network (TCCON) currently serves a critical transfer standard between the space based measurements and the *in situ* standard maintained by WMO GAW
- TCCON must be maintained and expanded meet the much greater demands of anthropogenic emissions monitoring on national scales
    - Biases must be reduced by a factor of 5-10 from 0.25% on regional scales to < 0.025 to 0.05% to improve inventories
- Innovative validation methods must be developed to support the validation of emissions estimates on scales ranging from that of individual large power plants to that of a nation.

Proposed CEOS Actions

1. Link the atmospheric GHG measurement and modeling communities and stakeholders in the national inventory and policy communities (through UNFCCC/SBSTA), to refine requirements;

2. Exploit the capabilities of the CEOS and CGMS member agencies and the WMO Integrated Global Greenhouse Gas Information System (IG^{3}IS) to integrate surface and airborne measurements of CO_2 and CH_4 with those from available and planned space-based sensors to develop a prototype, global atmospheric CO_2 and CH_4 flux product in time to support inventory builders in their development of GHG emission inventories for the 2023 global stocktake; and

3. Use the lessons learned from this prototype product to facilitate the implementation of a complete, operational, space-based constellation architecture with the capabilities needed to quantify atmospheric CO_2 and CH_4 concentrations that can serve as a complementary system for estimating NDCs in time to support the 2028 global stocktake.

Endorsement and Next Steps

- The 2018 CEOS Plenary endorsed the AC-VC GHG White Paper
  - The Plenary confirmed CEOS interest in continuing collaboration with CGMS through a specific task in WGClimate on GHG monitoring, with dedicated resources and activities based on the mapping table of the actions identified in the Way Forward chapter of the report
    - The 3-point plan and activities are interpreted as recommendations to the CEOS Agencies
  - Plenary also endorsed the revision of the Terms of Reference of the WGClimate to accommodate these changes
  - AC-VC will support GHG constellation development and synergistic GHG and atmospheric composition observations and modelling efforts
  - WGCV will support the definition of the calibration and validation needs
  - The CEOS SIT Chair encouraged the publication of the white paper to facilitate citations and efforts to build on its content
    - WMO and Copernicus have agreed to jointly publish the white paper
    - Publication date ~June 2019

Interaction with WGCV

Work with WGCV and GSICS to define cal/val needs (Rec#9)

- Identify available standards and techniques that can be used to cross-calibrate space based sensors prior to launch and on orbit (lunar, solar, vicarious)
  - Level-1: cross-calibration, common radiometric standards, vicarious calibration, ...
- Identify available standards and techniques that can be used to cross-validate space based estimates (TCCON, AirCore …) (Rec#11)
  - Level-2: cross-calibration, (fiducial) reference measurements, ...
- Discuss possible role of an active mission as flying standard in a GHG constellation (Rec#14)
- Surface flux products: validation approaches and reference estimates

Progress with Interfaces in the GHG Communities

- The White Paper proposes to link atmospheric GHG measurement and modelling communities with stakeholders in national inventory and policy communities to refine requirements
- Existing scientific conferences and workshops are being exploited to encourage interactions among these groups
  - **17-20 Sept 2018: IG³IS/TRANSCOM** - Ground and space-based measurement, flux modeling, and gridded inventory communities
  - 26-29 Nov 2018: ESA ATMOS – Current/future Space based measurements
  - 10-14 Dec 2018: AGU - Ground and space-based measurement, flux modeling, and gridded inventory communities
  - 4-8 March: GSICS – Calibration and operational satellite communities
  - 12-14 March: CHE/VERIFY - Ground and space-based measurement, flux modeling, gridded inventory and national (bottom-up) inventory communities
  - **25-29 March: CEOS WGCV IVOS 31** – CEOS WGCV community
- Principal Challenge – Interface with national inventory community

Near Future Meetings

- 34th CEOS Strategic Implementation Team Meeting (CEOS SIT-34)
  - Miami Florida, 2-4 April 2019
- 15th International Workshop on Greenhouse Gas Measurements from Space (IWGGMS-15)
  - Hokkaido University, Sapporo, Hokkaido, Japan on 3-5 June.
  - The meeting announcement, registration, and abstract submission page here: https://www.nies.go.jp/soc/en/events/iwggms15/
  - Abstracts are due on 1 April
- CEOS WGClimate/WGCV/AC-VC Roadmapping Meeting,
  - JAXA HQ, Tokyo, Japan, (Sunday) 9 June
- CEOS AC-VC Annual meeting
  - Nakano Sunplaza, Tokyo, Japan,10-12 June
  - Webpage is posted here: http://ceos.org/meetings/ac-vc-15/
  - The registration closes on May 3
  - We are still compiling the agenda, but the current plan is to focus on greenhouse gases on Monday, 10 June and air quality on 11-12.