Measuring Carbon Dioxide from Space: Prospects for the Orbiting Carbon Observatory-2

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The Promise and Challenge for Space Based CO₂ Measurements

- Spatial coverage
  - Observations over both land and ocean

- Temporal resolution and sampling
  - Daily/Weekly sampling needed to resolve CO₂ weather
  - Monthly measurements required over > 1 year to resolve seasonal and inter-annual variability in CO₂

- Spatial resolution and sampling
  - Sensitivity to point sources scales with area of footprint
  - Small measurement footprints enhance sensitivity to point sources and reduce data losses due to clouds

- Primary Challenge: Precision and accuracy
  - High precision required to resolve small (0.2-0.3%) variations in CO₂ associated with sources and sinks
  - High accuracy essential to avoid regional-scale biases
Measuring CO₂ from Space

- **Record** spectra of CO₂ and O₂ absorption in reflected sunlight

- **Retrieve** variations in the *column averaged CO₂ dry air mole fraction*, $X_{CO2}$ over the sunlit hemisphere

- **Validate** measurements to ensure $X_{CO2}$ accuracy of 1 - 2 ppm (0.3 - 0.5%)
Remote Sensing of CO$_2$ using Reflected Sunlight: The Pioneers

SCIAMACHY (2002 - 2012)

- First solar NIR/SWIR CO$_2$ / CH$_4$ sensor
- Provided regional-scale maps of CO$_2$ and CH$_4$ over continents on seasonal time scales
- Low precision (3-6 ppm) and high probability of cloud bias within large footprint (18,000 km$^2$) reduced accuracy
- Lack of ocean glint pointing further limited coverage

GOSAT (2009 - Present)

- Optimized for spectral coverage and fast repeat cycle
  - Combination of high spectral resolution over broad spectral range yields high sensitivity to CO$_2$, CH$_4$, and chlorophyll fluorescence
  - 4-second integration time and 10.5 km diameter footprint limits resolution and number of cloud free soundings (1000/day)
  - Lack of ocean glint at high latitudes limits coverage
The ACOS/GOSAT Collaboration

After the loss of OCO, NASA reformulated the OCO Team under the Atmospheric CO₂ Observations from Space (ACOS) task to continue the collaboration with the GOSAT Project Team at JAXA and NIES to:

- Conduct vicarious calibration campaigns in Railroad Valley, Nevada, U.S.A. and analyze results of those campaigns

- Retrieve $X_{\text{CO}_2}$ from GOSAT spectra
  - Model development, and testing
  - Data production and delivery

- Validate GOSAT retrievals by comparing
  - GOSAT retrievals with TCCON measurements
  - Other validation standards (surface pressure, aircraft and ground-based CO₂ measurements)
Retrieving $X_{CO2}$ from TANSO-FTS Spectra with the ACOS/OCO-2 Algorithm

GOSAT Data have provided a critical validation of the OCO Algorithm

Crisp: OCO-2 Mission
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Validation against TCCON

- Ground-based Fourier transform spectrometers
- Remote sensing of total columns of CO$_2$, CH$_4$, N$_2$O, CO, H$_2$O, HDO, O$_2$ via solar absorption
- Divide trace gas columns by O$_2$ column to get dry-air mole fractions: $X_{CO_2}$, $X_{CH_4}$, $X_{N_2O}$, $X_{CO}$, $X_{H_2O}$, $X_{HDO}$

Molecule | Precision | Accuracy
--- | --- | ---
CO$_2$ | ~0.8 ppm | ~0.8 ppm
CH$_4$ | ~5 ppb | ~7 ppb
N$_2$O | ~1.5 ppb | ~3 ppb
CO | ~0.5 ppb | ~4 ppb

Over 20 Operating Sites and Growing

Validated against in situ sensors
New Validation Capabilities

New Column Measurements: AirCore
- Contributes to TCCON calibration
- Provides validation at additional locations

Post Processing Screening
1. Southern Hemisphere Approximation:
   - Identifies spurious correlations between $X_{\text{CO}_2}$ retrievals and other environment parameters at mid latitudes in the southern hemisphere, where $X_{\text{CO}_2}$ variations are known to be small.

2. Multi-Model Means:
   - Compare ACOS GOSAT $X_{\text{CO}_2}$ retrievals to the average $X_{\text{CO}_2}$ fields generated by flux inversion models
ACOS GOSAT B2.10 $X_{\text{CO}_2}$ Retrievals

- Jul 2009
- Aug 2009
- Sep 2009
- Oct 2009
- Nov 2009
- Dec 2009
- Jan 2010
- Feb 2010
- Mar 2010
- Apr 2010
- May 2010
- Jun 2010
Zonal profiles of ACOS/GOSAT XCO2 estimates (green and grey triangles) are compared to the monthly mean XCO2 estimates from TCCON stations (red diamonds) for July 2009. The precision (scatter), bias, and yield of the ACOS/GOSAT products have improved over time (Crisp et al. 2011).
The Next Step - The NASA Orbiting Carbon Observatory-2 (OCO-2) Mission
The OCO-2 Mission Overview

- 3-Channel Grating Spectrometer (JPL)
- Dedicated Spacecraft Bus (OSC)
- Delta-II Launch Vehicle

Data Product Generation (JPL) - NASA NEN (GSFC) and SN (TDRSS) - Formation Flying in the A-Train Constellation

Crisp: OCO-2 Mission
The OCO Instrument – Optimized for Sensitivity

3 co-bore-sighted, high resolution, imaging grating spectrometers
- Resolving Power 17,000 - 20,000
- High Signal-to-Noise Ratio
- Collects 24 soundings / sec
  - $10^6$ soundings / day over the sunlit hemisphere

GOSAT (black) vs. OCO-2 instrument line shape (ABO2, WCO2, SCO2).

GOSAT (black) vs. OCO-2 SNR (b).

Fraction of Max Signal

Crisp: OCO-2 Mission
Pre-flight Heliostat/TCCON Observations
Verify End-to-End Instrument Performance

Observations of the sun with the flight instrument taken during TVAC tests provide an end-to-end verification of the instrument performance.

1.6 μm CO₂

TCCON/OCO-2 comparison – Still a work in progress!!

21 April 2012
Observatory I&T Activities Ongoing
Launch Date Driven by Launch Service Availability

- OCO-2 will fly on a United Launch Alliance Delta II 7320
  - Selected by NASA in July 2012, (along with launch vehicles for SMAP, JPSS-1, and Jason-3)

- The OCO-2 Team is currently working closely with Launch Vehicle team to accommodate OCO-2 on the Delta-II
  - Substantially different interface and launch environment

- The nominal OCO-2 launch date is “no earlier than 1 July 2014”
OCO-2 will fly at the head of A-Train (now called the 705-km Constellation), but has changed its flight path to share the ground track with CloudSat and CALIPSO, which is 217 km East of the AQUA (WRS-2 Standard) track.
**Nadir vs. Glint Coverage**

- OCO-2 will collect ~380 Soundings/degree of latitude (>10⁶ soundings/day)
- OCO-2 will obtain Nadir and Glint observations of the sunlit hemisphere on alternate 16-day ground track repeat cycles.

**Nadir observations provide better coverage over continents**

**Glint observations provide better coverage over oceans**
**Conclusions**

- Space-based remote sensing observations hold substantial promise for future long-term monitoring of CO$_2$ and other greenhouse gases
  - These measurements will complement those from the existing ground-based greenhouse gas monitoring network with increased: spatial coverage and sampling density
- The principal challenge is the need for high precision (~0.3% or 1 ppm)
- The Japanese GOSAT mission (Nicknamed “Ibuki”) has provided a valuable pathfinder for analysis techniques
- Once it is launched in 2014, the NASA OCO-2 mission will demonstrate the measurement precision, coverage, and resolution needed to:
  - Quantify CO$_2$ sources on the scale of an average-sized nation
  - Find the natural “sinks” that are absorbing over half of the CO$_2$ emitted by human activities
Thanks for your Attention

Questions?