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Capabilities vs Expectations for OCO-2

• A decade ago, when the OCO mission was proposed, the primary objective was to acquire global, space-based observations of CO$_2$ with the precision, coverage, and resolution needed to characterize regional scale natural CO$_2$ sinks, which are now absorbing more than half of the CO$_2$ that is being emitted by human activities.

• More recently, the interest in global, space-based observations of greenhouse has intensified, but the focus has shifted, emphasizing the need to quantify emissions from human activities:
  – The current emphasis is on monitoring treaty compliance and the efficacy of greenhouse gas mitigation strategies.

• This change in focus, combined with new insight into the carbon cycle has introduced new challenges for remote sensing observations of greenhouse gases.

• While OCO-2 is not optimized for that mission, it will provide opportunities to validate observation strategies for future CO$_2$ monitoring missions.
Global Measurements are Essential

• To limit the rate of atmospheric carbon dioxide buildup, we must
  – Control emissions associated with human activities
  – Understand & exploit natural processes that absorb carbon dioxide

We cannot manage what we cannot measure

• Identifying sources and sinks of atmospheric carbon dioxide from atmospheric measurements is intrinsically challenging

Plumes from medium-sized power plants (4 MtC/yr) elevate $X_{\text{CO}_2}$ levels by ~0.5% (2ppm) for 10's of km downwind [Yang and Fung, 2010].

Variations of CO$_2$ are rarely larger than 1-2% on 100 – 1000 km scales [Kawa et al., 2008].
Is 1 ppm Good Enough?

Large metropolitan areas with strong, discrete sources are easier to detect, but also rarely produce full column $X_{\text{CO}_2}$ perturbations larger than 1 ppm.

### TABLE B.3 Expected CO$_2$ Signals for Selected Metropolitan Areas

<table>
<thead>
<tr>
<th>City</th>
<th>Area (km$^2$)$^a$</th>
<th>Emissions (Mton CO$_2$ yr$^{-1}$)</th>
<th>Emissions (μmol m$^{-2}$ s$^{-1}$)</th>
<th>Total Column (ppm)</th>
<th>PBL (1 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles</td>
<td>3,700</td>
<td>73.2</td>
<td>14.2</td>
<td>0.49</td>
<td>4.3</td>
</tr>
<tr>
<td>Chicago</td>
<td>2,800</td>
<td>79.1</td>
<td>20.3</td>
<td>0.60</td>
<td>5.4</td>
</tr>
<tr>
<td>Houston</td>
<td>3,300</td>
<td>101.8</td>
<td>22.2</td>
<td>0.72</td>
<td>6.4</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>900</td>
<td>20.1</td>
<td>16.1</td>
<td>0.27</td>
<td>2.4</td>
</tr>
<tr>
<td>Tokyo</td>
<td>1,700</td>
<td>64</td>
<td>27</td>
<td>0.63</td>
<td>5.6</td>
</tr>
<tr>
<td>Seoul</td>
<td>600</td>
<td>43</td>
<td>52</td>
<td>0.71</td>
<td>6.3</td>
</tr>
<tr>
<td>Beijing</td>
<td>800</td>
<td>74</td>
<td>67</td>
<td>1.1</td>
<td>9.4</td>
</tr>
<tr>
<td>Shanghai</td>
<td>700</td>
<td>112</td>
<td>116</td>
<td>1.8</td>
<td>15</td>
</tr>
</tbody>
</table>

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A satellite instrument with a 1 ppm sensitivity over a ~100 km down-track segment of its orbit might not detect Los Angeles, Chicago, Houston, or Tokyo.
The Minimum Measurable Point Source Flux

- For a satellite like OCO, designed to measure the column averaged dry air mole fraction, $X_{CO2}$, the minimum measurable flux can be approximated as follows:
  - Assume the minimum detectable change in $X_{CO2}$ is $\Delta X_{CO2_{min}}$ (e.g. 1 ppm)
  - If the CO2 flux, $F$, is constant over an accumulation time interval, $t$, the change in $X_{CO2}$ is given by: $\Delta X_{CO2} = F \cdot t$
  - If we have an average horizontal wind speed, $u(\theta)$, in direction, $\theta$, over time, $t$, and a footprint has a horizontal dimension, $x(\theta)$, then the residence time, $t = x/u$
  - The minimum increase in the vertical column is therefore related to the minimum detectable flux as follows
    $$\Delta X_{CO2_{min}} = F_{min} \cdot x / u$$
  Rearranging, gives
    $$F_{min} = u \cdot \Delta X_{CO2_{min}} / x$$

For a given $X_{CO2}$ sensitivity, the minimum measurable CO2 flux is proportional to wind speed and inversely proportional to footprint size
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%)

Initial Surf/Atm State → Generate Synthetic Spectrum

New State (inc. $X_{CO₂}$) → Instrument Model → Difference Spectra → Inverse Model → $X_{CO₂}$
## OCO-2 and GOSAT

<table>
<thead>
<tr>
<th></th>
<th>GOSAT</th>
<th>OCO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gases Measured</strong></td>
<td>CO₂, CH₄, O₂, O₃, H₂O</td>
<td>CO₂, O₂</td>
</tr>
<tr>
<td><strong>Instruments</strong></td>
<td>SWIR/TIR FTS, CAI</td>
<td>Grating Spectrometer</td>
</tr>
<tr>
<td><strong>IFOV / Swath (km)</strong></td>
<td>FTS: 10.5 / 80-790 (160) CAI: 0.5 / 1000</td>
<td>1.29 x 2.25 / 5.2-10.4</td>
</tr>
<tr>
<td><strong>Spectral Ranges (µm)</strong></td>
<td>0.758-0.775, 1.56-1.72, 1.92-2.08, 5.56-14.3</td>
<td>0.757-0.772, 1.59-1.62, 2.04-2.08</td>
</tr>
<tr>
<td><strong>Soundings/Day</strong></td>
<td>10,000</td>
<td>500,000 to 1,000,000</td>
</tr>
<tr>
<td><strong>Sampling Rate</strong></td>
<td>0.25 Hz</td>
<td>12 to 25 Hz</td>
</tr>
<tr>
<td><strong>Orbit Altitude</strong></td>
<td>666 km</td>
<td>705 km</td>
</tr>
<tr>
<td><strong>Local Time</strong></td>
<td>12:48</td>
<td>13:30</td>
</tr>
<tr>
<td><strong>Revisit Time/Orbits</strong></td>
<td>3 Days/72 Orbits</td>
<td>16 Days/233 Orbits</td>
</tr>
<tr>
<td><strong>Launch Vehicle</strong></td>
<td>H-IIA</td>
<td>Taurus 3110 (TBD)</td>
</tr>
<tr>
<td><strong>Launch Date</strong></td>
<td>January 2009</td>
<td>February 2013</td>
</tr>
<tr>
<td><strong>Nominal Life</strong></td>
<td>5 Years</td>
<td>2 Years</td>
</tr>
</tbody>
</table>

GOSAT was optimized for spectral & spatial coverage.

OCO-2 was optimized for sensitivity and resolution.
The OCO and GOSAT teams formed a close partnership during the implementation phases of these missions to:

- Cross calibrate the OCO instrument and TANSO-FTS
- Cross validate OCO and GOSAT $X_{\text{CO}_2}$ retrievals against a common standard

The primary objectives of this partnership were to:

- Accelerate understanding of this new data source
- Facilitate combining results from GOSAT and OCO

3-day ground track repeat cycle resolves weather
Continuous high resolution measurements along track
The Launch of GOSAT & Loss of OCO

GOSAT launched successfully on 23 January 2009

OCO was lost a month later when its launch system failed
Working with the GOSAT Team

• Immediately after the loss of OCO, the GOSAT Project manager invited the OCO Team to participate in GOSAT data analysis

• NASA reformulated the OCO team as the “Atmospheric CO₂ Observations from Space” (ACOS) team

• This collaboration benefits the GOSAT team by:
  – Combining the ground based calibration and validation resources of both teams to maximize the accuracy of the GOSAT data
  – Combining the scientific expertise from both teams to accelerate our understanding of this new, space-based data source

• This collaboration benefits the NASA OCO by
  – Providing direct experience with the analysis of space based CO₂ measurements
  – Accelerating the delivery of precise CO₂ measurements from future NASA carbon dioxide monitoring missions
Scope of the ACOS/GOSAT Collaboration

• The ACOS team is collaborating closely with the GOSAT teams 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, implementation, & testing
    - Data production and delivery

  – Validate GOSAT retrievals by comparing
    - GOSAT retrievals with TCCON measurements
    - Other validation standards (surface pressure, aircraft and ground-based CO$_2$ measurements)
Retrieving $X_{CO_2}$ from GOSAT Data

The OCO Retrieval Algorithm was modified to retrieve $X_{CO_2}$ from GOSAT measurements
- “Full-physics” forward model
- Inverse model based on optimal estimation

Calibrated GOSAT Spectra (L1B Data) → Forward Model Spectra + Jacobians → State Vector First Guess

Apriori + Covariance → Inverse Model (Optimal Estimation) → Update State Vector

- Calculate $XCO_2$
- Diagnostics

State Vector
- CO$_2$ profile (full)
- H$_2$O profile (scale factor)
- Temperature profile (offset)
- Aerosol Profiles
- Surface Pressure
- Albedo (Mean, Slope)
- Wavelength Shift (+ stretch)

The OCO Retrieval Algorithm was modified to retrieve $X_{CO_2}$ from GOSAT measurements

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ACOS/GOSAT Data Products: X$_{CO_2}$ Retrievals

X$_{CO_2}$ Retrievals for July 2010

Mean XCO$_2$ (ppm)

370  376  382  388  395
The ACOS Cloud Screen

• A Spectroscopic cloud screening algorithm based on the O$_2$ A-band is currently being used for GOSAT retrievals
  • Fits a clear sky atmosphere to every sounding in the O$_2$ A band.
  • High values of $\chi^2$ and large differences between the retrieved surface pressure and the ECMWF prior indicate the presence of clouds.
  • Over non-glint ocean, a simple albedo test is also used.

Example A-Band fit

Poor fit ($\chi^2 = 9.6$) indicates presence of cloud

Small residuals and good agreement between retrieved and ECMWF surface pressure indicates cloud free
Errors can be further reduced by post-screening retrievals, based on a series of criteria, including:

- Measurement SNR
- Convergence
- Goodness of spectral fit
- Surface pressure error
- Evidence for clouds or optically thick aerosols
- A posteriori retrieval error
- Evidence of known biases

The cloud screen is responsible for the largest data reductions.

- Improved cloud screening algorithms are a major focus of our development effort
Validation of GOSAT Products

GOSAT $X_{CO2}$ retrievals are being compared with those from the ground based Total Carbon Column Observing Network to verify their accuracy.
Comparisons of GOSAT and TCCON

• ACOS GOSAT retrievals show
  • A consistent global bias of ~2% (7 ppm) in $X_{CO2}$ when compared with TCCON and aircraft measurements.
  • $X_{CO2}$ variations that are a factor of 2 to 3 larger than that measured by TCCON.

Wunch et al.
Sources of Bias in the $X_{CO2}$ Maps

• About half of the global 2% bias is caused by a $\sim$10 hPa (1%) high surface pressure bias associated with:
  – Radiometric and spectroscopic calibration errors
    ▪ Non linearity and ILS corrections currently being implemented
  – Uncertainties in the $O_2$ A-band absorption cross sections
    ▪ Oversimplified treatment of line mixing and line shape

• Improvements in the CO$_2$ spectroscopy and aerosol retrieval approach are also being implemented to address remaining bias

Typical $O_2$ A-band retrieval residuals.
Once the known biases are removed, retrievals of $X_{\text{CO}_2}$ compare well against “ground truth” from the TCCON (Total Carbon Column Observing Network).

Both the hemispheric gradients and the seasonal cycles are captured in the bias-corrected GOSAT $X_{\text{CO}_2}$ retrievals.
Experiences with its operations:
A Year of ACOS/GOSAT $X_{CO2}$
ACOS GOSAT Data Release

• The ACOS L2 Standard Products are now being distributed on the GSFC Mirador site.

  http://mirador.gsfc.nasa.gov/

• You can find the data, along with a README and a Data Quality Statement at the site:

  http://disc.sci.gsfc.nasa.gov/acdisc/documentation/ACOS.shtml
The Loss of OCO and the Birth of OCO-2

• NASA’s Orbiting Carbon Observatory (OCO) was designed to provide the measurements needed to estimate the atmospheric CO$_2$ dry air mole fraction ($X_{CO_2}$) with the sensitivity, accuracy, and sampling density needed to quantify regional scale carbon sources and sinks over the globe and characterize their behavior over the annual cycle.

• February 2009: The OCO spacecraft was lost when its launch vehicle’s fairing failed to deploy

• December 2009: The U.S. Congress added funding to the NASA FY2010 budget to restart the OCO Mission

• The OCO-2 spacecraft bus and instrument are currently on track for a February 2013 launch
OCO Mission Overview

3-Channel Spectrometer  Dedicated Spacecraft bus  Dedicated Launch Vehicle  “Routine” Mission Operations  Formation Flying as part of the A-Train Constellation  NASA NEN (GSFC) and SN (TDRSS)

Please visit http://oco.jpl.nasa.gov for more information
The OCO-2 Instrument

- 3 co-bore-sighted, high resolution, imaging grating spectrometers
  - $O_2$ 0.765 $\mu$m A-band
  - $CO_2$ 1.61 $\mu$m band
  - $CO_2$ 2.06 $\mu$m band
- Resolving Power > 20,000
- Optically fast: f/1.8 (high SNR)
- Swath: < 0.8° (10.6 km at nadir)
  - 8 cross-track footprints
  - 1.29 x 2.25 km at nadir
- Mass: 140 kg, Power: ~105 W

Changes from OCO
- Design modified to mitigate residual image & slit alignment anomalies found in testing
- New cryocooler
OCO-2 Spacecraft

Orbital Sciences LEOStar-2 Bus
- 0.94 m x 2.1 m hexagonal structure
- 128 Gb of data storage
- 150 Mb/s X-band + 2 Mb/s S-band
- 3-axis stabilized: 4 Reaction wheels + 3 torque bars
- Articulated solar arrays
- Propulsion system for orbit maintenance

- Minimal changes to replace obsolete parts
  - RAD6000 modified to replace the static read-only memory (SRAM)
  - S-band updated from analog to digital
  - Reaction wheels modified to address lifetime issues
  - Star tracker replaced with new model
  - Obsolete Si course sun sensors replaced with GaAs sensors
Spatial/Temporal Sampling Constraints

Factors Limiting Sampling Density
• Orbit ground track
• Clouds and Aerosols
  – OCO can collect usable samples only in regions where the cloud and aerosol optical depth < 0.3
• Low surface reflectance
• Very rough surfaces
OCO-2 Is Optimized for High Precision

- CO₂ sources and sinks must be inferred from small (<2%) spatial variations in the (387 ± 5 ppm) background CO₂ distribution
  - Space based NIR measurements constrain the column averaged CO₂
  - Largest variations near the surface
- High precision is essential to resolve small spatial variations in X_{CO₂}
  - OCO-2 yields single-sounding random errors < 1 ppm over most of the sunlit hemisphere

Small spatial gradients in X_{CO₂} verified by HIPPO flights [Wofsy et al. 2010]

Plumes from medium-sized power plants (4 MtC/yr) elevate X_{CO₂} levels by > 0.5% (2ppm) for 10’s of km downwind [Yang and Fung, 2010].

Kawa et al. 2008
OCO-2 Optimized for High Spatial Resolution

High Sampling Rate:
• OCO-2 collects up to up to 8 soundings @ 3 Hz along a narrow swath (<10.6 km at nadir)
  • Yields 200 – 400 soundings per degree of latitude over sunlit hemisphere
  • Soundings that can be averaged along the track to increase precision

Small footprint (<3 km² at nadir):
• Increases sensitivity to CO₂ point sources
  • The minimum measurable CO₂ flux is inversely proportional to footprint size
• Increases probability of recording cloud free soundings in partially cloudy regions
  • OCO: 27% @ Nadir, 19% for Glint
  • GOSAT (85 km²): ~10%
Observation Modes Optimize Sensitivity and Accuracy

Nadir Observations:
+ Small footprint (< 3 km²)
  - Low Signal/Noise over dark surfaces (ocean, ice)

Glint Observations:
+ Improves Signal/Noise over oceans
  - More cloud interference

Target Observations:
• Validation over ground based FTS sites, field campaigns, other targets

447-m WLEF Tower
Park Falls, WI

Local Nadir
Glint Spot
Ground Track
Strong CO₂
Weak CO₂
O₂ A Band

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OCO-2 Provides High SNR over both Continents and Oceans

Full global coverage is needed to:

- Resolve $X_{\text{CO}_2}$ over land and ocean for the full range of latitudes,
- Minimize errors from CO$_2$ transport in and out of the observed domain

Near IR solar measurements of CO$_2$ over the ocean are challenging

- Typical nadir reflectances: 0.5 to 1%
- Most of the sunlight is reflected into a narrow range of angles, producing the familiar “glint” spot

OCO-2 combines glint and nadir measurements to optimize sensitivity

OCO single sounding random errors for nadir and glint [Baker et al. ACPD, 2008].
Like OCO, OCO-2 will fly at the head of the A-Train. However, OCO-2 may fly along the CloudSat/CALIPSO path, rather than the Aqua path to maximize synergy with CloudSat/CALIPSO/MODIS products.
Measuring CO₂: Synergy with AIRS and TES

Atmospheric CO₂ can be inferred from both thermal IR or solar remote sensing data

• Thermal IR instruments (AIRS, TES, IASI) measure CO₂ above the mid-troposphere
  – Directly measure the greenhouse forcing by CO₂ in the present climate
  – Provides limited information on sources/sinks

• Solar NIR instruments (GOSAT, OCO-2) measure the total CO₂ column
  – Most sensitive to surface fluxes
  – Provides insight needed to predict future rates of CO₂ buildup and climate impacts

• Combining solar NIR and thermal IR measurements could provide insight into vertical atmospheric transport of CO₂
Operational Uses by NOAA: OCO-2
Surface Pressure Measurements

- OCO-2 will collect 0.5 to 1 million soundings over the sunlit hemisphere each day
  - Over 100,000 of these soundings were expected to be sufficiently cloud free to enable surface pressure (and $X_{CO2}$) retrievals
  - For each $X_{CO2}$ retrieval, the O$_2$ A-Band measurement yields a surface pressure retrieval, with typical accuracies of $\pm 1$ hPa.

- OCO-2 surface pressure measurements can be combined with AIRS temperature and moisture measurements in meteorological data assimilation models to assess their impact on weather forecasts.
  - Largest impacts expected in data sparse regions—such as over oceans.

- OCO-2 would demonstrate this capability, but is not (currently) designed to deliver measurements on NWP time scales (2.75 hr).
Looking ahead

- **OCO-2**: Launch may be delayed due to launch vehicle problems
  - 2-year nominal mission
    - The only life limiting consumable is fuel for orbit maintenance (> 5 years)
- **OCO-3**: NASA’s Architecture for Earth Science (June 2010) and the Presidents 2012 NASA budget proposal include funds to assemble the OCO-2 instrument spares to produce a follow-on instrument
  - Available for a flight of opportunity as early as 2015
  - Currently assessing a wide range of host missions
    - ISS, conventional nadir pointing platforms (JPSS), as well as agile (OCO-like) spacecraft in sun-sync & non sun-sync orbits
    - A pointing mechanism is under development to preserve glint and target capabilities on nadir-pointing platforms
- **ASCENDS**: NASA’s next step in CO$_2$ measurements
  - Uses LIDAR to provide day/night measurements for all seasons and latitudes
  - Baselined for a launch in the 2020 time frame

*Proposed Mission Only – Pre-decisional for planning and discussion purposes only*
Summary

• OCO-2 is currently on track for a 2013 - 2014 Launch

• The OCO-2 Instrument will collect over 500,000 to 1,000,000 soundings/day along a narrow swath, either along the ground track, or in the direction of the local “glint” spot

• Integration with ground and airborne networks is essential for validating, interpreting, and maximizing the benefit of remote sensing observations

• OCO-2 surface pressure measurements can be used to assess the value of future space-based surface pressure measurements in weather prediction models

• Need a long-term vision to establish and address community priorities
  – Must incorporate ground, air, and space-based assets
  – Must balance calls for new observations with need to maintain climate data records