The Orbiting Carbon Observatory (OCO) Mission

Watching The Earth Breathe...Mapping CO₂ From Space.

OCO Project and Science Status

Charles Miller, JPL

3rd International Workshop on Greenhouse Gas Measurements from Space
30 May, 2006 Tsukuba, Japan
Project Overview

The Orbiting Carbon Observatory (OCO)
Watching The Earth Breathe...Mapping CO2 From Space

Salient Features
- High Resolution, three Channel Grating Spectrometer
- Partnership with HS (Instrument) and OSC (Spacecraft)
- High Heritage Spacecraft, Flies in Formation with the A-Train
- Launch date: September 2008 on Taurus XL
- Operational life: 2 years
- PI: Dr. David Crisp
- Deputy PI: Dr. Charles Miller
- Project Manager: Rod Zieger, Deputy: Bharat Chudasama
- JPL Program Manager: Dr. Steven Bard
- Program Scientist: Dr. Philip DeCola, NASA HQ
- Program Manager: Eric Ianson, NASA HQ

Science
- Collect the first space-based measurements of atmospheric CO₂ with the precision, resolution, and coverage needed to characterize its sources and sinks on regional scales and quantify their variability over the seasonal cycle.
- Use independent data validation approaches to ensure high accuracy (1-2 ppm, 0.3% - 0.5%)
- Reliable climate predictions require an improved understanding of CO₂ sinks
  - What human and natural processes are controlling atmospheric CO₂?
  - What are the relative roles of the oceans and land ecosystems in absorbing CO₂?
Mission Overview

Ground Validation Sites

Mission Ops (OSC)

Ground Stations (GSFC/NASA)

Please visit http://oco.jpl.nasa.gov for more information
Mission Architecture

Project Management (JPL)
- Science & Project Team
- Systems Engineering, Mission Assurance
- Ground Data System

Single Instrument (Hamilton Sundstrand)
- 3 high resolution grating spectrometers

Dedicated Bus (Orbital Sciences)
- LEOstar2: GALEX, SORCE, AIM

Dedicated Launch Vehicle (Orbital Taurus 3110)
- September 2008 Launch from Vandenberg AFB

Mission Operations (JPL/Orbital Sciences)
- NASA Ground Network, Poker Flats, Alaska
OCO Project MCR Schedule 9/15/08 Launch

<table>
<thead>
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<th>2002</th>
<th>2003</th>
<th>2004</th>
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<td>Q3</td>
<td>Q4</td>
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<td>Q2</td>
<td>Q3</td>
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<td>PDR/MDR</td>
<td>MCR</td>
<td>Mission CDR</td>
<td>ARR</td>
<td>Launch</td>
<td>9/15</td>
<td>11/14 PLAR</td>
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<td>4/12</td>
<td>11/14 PLAR</td>
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**Legend**
- Phase A
- Phase B
- Phase C/D
- Phase E
- Critical Path
- Reserve

**Legend**
- ARR - ATLO Readiness Review
- CDR - Critical Design Review
- EOM - End Of Mission
- GDS - Ground Data System
- I-Del - Instrument-Delivery
- MCR - Mission Confirmation Review
- MOS - Mission Operations System
- Mos PDR | 7/26 | 1/19 | MOS PDR | 7/15 | 7/11 | MOS CDR | 10/31 | 6/16 |
- Mos Del | 10/31 | MOS ORR | 10/16 Operations | 10/11EOM |
- MOS & GDS Development | B1.0 | B1.1 | B2.n | B3.0 |

**Overview**
- **Instruments**
  - Prelim Dsn
  - Detail Dsn
  - Instr Dsn
  - Fab, Build & Test
- **Spacecraft**
  - Prelim Design
  - Detail Dsn
  - Bus CDR
  - ARR
  - S/C Sim Del
  - S/C Del
  - 10/31
- **Observatory**
  - MOS PDR
  - MOS CDR
  - MOS ORR
  - B1.0
  - B1.1
  - 9/30
  - 6/12

**POCS**
- Development
- Operations
- Reserve

**POCS**
- Phase A
- Phase B
- Phase C/D
- Phase E
- Critical Path
- Reserve
OCO Schedule

- 7/2001: Step-1 Proposal Submitted
- 7/2003: Selected for Formulation
- 7/2004: System PDR
- 5/2005: Mission Confirmed for Implementation
- 10/2005: Instrument CDR
- 12/2005: OCO selected as ESA 3rd Party Mission
- 2/2006: Spacecraft CDR
- 3/2006: 4th OCO Science Team Meeting
- 7/2006: MOS/GDS CDR
- 8/2006: System CDR
- 5/2007: Instrument Delivery to SC
- 10/2007: Observatory Integration begins
- 6/2008: Launch Vehicle Integration begins
- 9/2008: Launch from VAFB
- 10/2010: End of Nominal Mission
OCO Instrument Status

- Instrument Design Complete
  - Instrument CDR October 2005
- Electronics boards testing – March – May 2006
- OBA casting delivered – March 2006
- Detector tests – May 2006
- Cryosystem delivery – May 2006
- Gratings delivery – Summer 2006
- Detector delivery – Summer 2006
- Instrument integration – Summer/Fall 2006
- Instrument delivery to JPL – Nov 2006
- Final alignment – Dec 2006
- Engineering tests – Jan 2007
- CPT 1 (calibration)– Feb 2007
- Environmental tests – March 2007
- CPT 2 (calibration) – April 2007
- Instrument Delivery – May 11 2007
Inverse Method

Finds $dx$ that minimizes spectral residuals & cost fn:

$\left( K^T S_e^{-1}K + (1+?S_a)^{-1} \right) dx = \left[ K^T S_e^{-1}(y-f(x)) + S_a^{-1}(x-x_a) \right]$
$X_{CO2}$ Retrieval Processing Flow

GDS pipeline

L0 → L1A → L1B → Cloud Screening → L2 XCO2

Command-line interface

OCO & FTS L1B granule

Sounding ID selection

OCO & FTS L2 products

Algorithm processing

L2 output wrapper

GUI interface
Early Testing and Validation with SCIAMACHY and FTS Data Reduce Algorithm Risks

Space-based Near-infrared CO₂ Retrievals: Testing the OCO Retrieval and Validation Concept Using SCIAMACHY Measurements over Park Falls, Wisconsin

H. Bösch¹, G. C. Toon¹, B. Scn¹, R. Washenfelder², P. O. Wennberg², M. Buchwitz³, R. de Beek³, J. P. Burrows³, D. Crisp¹, M. Christi⁴, B. J. Connor⁵, V. Natraj², and Y. L. Yung²


O₂ A-band (Ch. 4, FWHM = 0.5 nm)

1.58 µm CO₂ band (Ch. 6, FWHM = 1.5 nm)
Clever sampling strategies will improve the XCO2 product and require the processing of fewer soundings.

Naïve sampling strategy leaves large regional $X_{CO2}$ errors.

Statistically driven sampling strategy reduces regional $X_{CO2}$ errors below 1 ppm.
Global Simulations of OCO Data
H. Boesch, JPL

Surface Type:
MODIS L3 product (annual average)

AIRS Orbit:
• Lat/Lon/Time
• Temperature profile
• H₂O profile
• Surface pressure

Surface Albedo: MODIS L3 product (16 day average)

CO₂

Aerosol

OD: MISR L3 Product (monthly average)

July 1, 2005
Impact of OCO $X_{CO2}$ Data on Source/Sink Modeling

W/ noise, w/ prior: 5-day, 6°x10° resolution, reduced error

Prior - Truth

Estimate - Prior

Estimate - Truth

Improvement = |Prior-Truth| - |Est-Truth|

Significant improvement in CO$_2$ flux estimates can be achieved with OCO $X_{CO2}$ data accumulated over 5-day periods.

D. Baker (NCAR), S. Doney (WHOI)

Significant improvement in CO$_2$ flux estimates can be achieved with OCO $X_{CO2}$ data accumulated over 5-day periods.

Up to 40% error reduction in CO$_2$ fluxes. Chevallier, Rayner and Breon, LSCE
Establishing a Global FTS Network to Link Space-based $X_{CO2}$ to WMO Standards
Pre-launch FTS $X_{\text{CO}_2}$ Validation
Park Falls, USA

Validate FTS $X_{\text{CO}_2}$ by aircraft overflights
Required Precision = 0.3%

<table>
<thead>
<tr>
<th>Mission</th>
<th>Date</th>
<th>Site</th>
<th>Precision</th>
<th>Accuracy</th>
</tr>
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<tbody>
<tr>
<td>INTEX</td>
<td>Jul 2004</td>
<td>Park Falls</td>
<td>0.1%</td>
<td>0.68%</td>
</tr>
<tr>
<td>COBRA</td>
<td>Aug 2004</td>
<td>Park Falls</td>
<td>0.1%</td>
<td>0.68%</td>
</tr>
<tr>
<td>TWP ICE</td>
<td>Jan 2006</td>
<td>Darwin</td>
<td>13 profiles on 12 days!</td>
<td></td>
</tr>
</tbody>
</table>
OCO FTS Mobile Laboratory
Deployed @ Darwin TWP ARM Site
FTS Mobile Lab installation at the Darwin ARM-TWP site

- Rebecca Washenfelder, Yael Yavin (Caltech) and Nick Deutscher, David Griffith (Wollongong)
- Testing: Sep – Dec 2005
- Aircraft in situ validation overflights during Jan 2006
- Operations: Feb 2006 - EOM
Jan/Feb 2006: TWP/ICE Campaign

Proteus aircraft (ceiling >15 km) carrying COBRA in situ CO$_2$ sensor over Darwin TWP site

Comparison against FTS $X_{CO_2}$ retrievals will validate this station
In situ CO$_2$ measured over Darwin FTS

Wofsy instrument (DOE Proteus):

- 2 flights dedicated to FTS validation
  - 2 and 4 Feb 2006
- 3 flights of opportunity
  - 27, 29, and 31 Jan 2006

Volk instrument (ESA Geophysica):

- 8 flights of opportunity
  - 12, 19, 23, 25, 29, 30 (two flights) Nov 2005 and 6 Dec 2005

These in situ CO$_2$ profiles will yield excellent inter comparisons with ground based FTS measurements of X$_{CO2}$

The OCO validation team is very pleased with the results of the Darwin overflight campaign, and looks forward to showing results at an upcoming MMR
Darwin FTS Pre-launch Validation
4 Feb 2006

Preliminary

FTS \( X_{CO2} \)
\(~0.1 \text{ ppm rms (0.03\%)}\)
Acquire solar spectra simultaneously with the OCO flight instrument and one of the FTS.

Validate flight instrument performance for real atmospheric data.

Verify that the OCO retrieval algorithm contains an accurate instrument model.
Heliostat Sunrise and Sunset Views

Summer

Sunrise View

Winter

Sunset View

Summer

Winter
Rigorous Spectroscopy Testing Using Atmospheric Remote Sensing Data

Bruker 125 HR deployed in a solar-viewing mobile laboratory, Park Falls WI

Single spectrum, 9:30 am, 9 Sept 2004. Resolution = 0.02 cm$^{-1}$. 
## Spectroscopic Parameter Requirements for CO₂ Atmospheric Remote Sensing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mid-IR Remote Sensing Precision Requirement</th>
<th>OCO Remote Sensing Precision Requirement</th>
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<tbody>
<tr>
<td>Column CO₂ uncertainty</td>
<td>Best Effort</td>
<td>&lt; 0.3%</td>
</tr>
<tr>
<td>Range</td>
<td>600 – 2500 cm⁻¹</td>
<td>4000 – 6500 cm⁻¹</td>
</tr>
<tr>
<td>Line position uncertainty</td>
<td>0.0003 cm⁻¹</td>
<td>&lt; 0.0002 cm⁻¹</td>
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<tr>
<td>E&quot; uncertainty</td>
<td>0.5%</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Line Intensity uncertainty</td>
<td>&lt; 3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Lorentz Width uncertainty</td>
<td>&lt; 3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Pressure Shift uncertainty</td>
<td>&lt; 0.0003 cm⁻¹ atm⁻¹</td>
<td>&lt; 0.0002 cm⁻¹ atm⁻¹</td>
</tr>
<tr>
<td>Line Mixing</td>
<td>Q-branches only</td>
<td>P-, Q- and R-branches</td>
</tr>
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</table>
Existing Spectral Databases Do Not Provide Sufficient Accuracy for \( \text{CO}_2 \) Remote Sensing

3 retrievals of the same \( \text{CO}_2 \) spectrum using the most recent versions of the HITRAN database

- HITRAN 1996 provides the benchmark
- No Change found using HITRAN 2000
- 15% improvement in the rms residual when using HITRAN 2004

Fit using HITRAN 2004 still exhibits persistent systematic errors in intensities throughout the band
New CO₂ Spectroscopic Database Developed from New Laboratory Data

New data acquired with excellent knowledge and control of the experimental state

- Temperature
- Pressure
- Composition
- Path length

Spectroscopic parameters determined using standard fitting methods (Toth et al.)

Small residuals from unfit lines due to weak CO₂ hot bands and isotopologues (³¹CO₂)
Atmospheric Remote Sensing Retrievals Show Excellent Precision and Accuracy

- Precision and accuracy demonstrate spectroscopic parameters are high quality
- FTS $X_{\text{CO}_2}$ retrievals validated against integrated CO$_2$ column obtained from in situ CO$_2$ sampling during aircraft over flights of the FTS site.

$$X_{\text{CO}_2} = \frac{\text{column CO}_2}{\text{column O}_2 / 0.2095}$$

RMS (2 min measurement) $\sim 0.1$ ppm (0.03%)

FTS Column = 1.0068 x Aircraft Column

- Accuracy $\sim (0.7\%)$

Ideal 1:1 line
Airmass-dependent Effects Observed for Small Changes in Strengths & Widths

Test Line List #1
- Different widths
- Different intensities

Test Line List #2
- MAM = March April May (2005)

Ratio Linestrength: NEW / OLD

Ratio ABH-W: NEW / OLD

OCO Status, 3rd IWGGMS, 30 May, 2006
Non-Voigt Line Shapes Yield Different Width Parameters for Same Spectral Data

Compare retrievals from two methods
Constrained Multispectrum vs unconstrained
(Line Mixing + non-Voigt) (Voigt)

Average Differences in Retrievals
Intensities (self-) widths
0.25% 1.52%

Miller et al., manuscript in preparation
Devi et al., manuscript in preparation
Line Shape Choice Affects Simulations of Laboratory Data

(a) 8 observed spectra

(b) Voigt profile modified with full relaxation matrix

(c) Voigt profile modified with Rosenkranz line mixing

(d) No line mixing (Voigt profile)

(e) 8 CO₂ self-broadened spectra

L=25m and 49m

P=11 to 697 Torr

T= -31°C

SIGNAL vs WAVENUMBER (cm⁻¹)
• Line mixing observed in the 6220 even though this band has no Q-branch, no perturbations and adjacent lines are spaced by \( \sim 1 \text{ cm}^{-1} \)
Multispectrum Fitting  

- Fit all lines and spectra simultaneously
- Use physical constraints for positions and intensities
- Increases sensitivity to subtle effects in line shapes
- Updated capabilities include non-Voigt line shapes, line mixing, speed dependence (Benner et al., in preparation)

Line Positions:
\[ n_i = n_0 + B(J(J+1)) + D(J(J+1))^2 + H(J(J+1))^3 + \ldots \]
- \( n_i \) resonant frequency
- \( n_0 \) band origin
- B, D, H rotational constants
- J rotational quantum number

Line Shape Parameters:
\[ \gamma_i = a_1 + a_2m + a_3m^2 + a_4m^3 + \ldots \]
- Measured half-width at half-max at each line position

Line Intensities:
\[ S_i = (\nu/\nu_0)(S_v/L_i) \exp(-hcE_i/\kappa T)[1-\exp(hcv/kT)].F \]
- \( S_i \) observed individual line intensity
- \( S_v \) vibrational band intensity
- \( L_i \) Hönl-London factor, where \( I = (m^2 - m^2)/|m| \) for CO2
  - \( m = J''+1 \) for the R branch, \( m = -J'' \) for the P branch
- \( J'' \) lower-state rotational quantum number
- \( I \) angular momentum quantum number
- \( Q_r \) lower state rotational partition function at \( T_0 = 296 \, \text{K} \)
- \( E_i'' \) lower state rotational energy
- \( F \) Herman-Wallis factor = \[1 + A_1m + A_2m^2 + A_3m^3\]
Opportunities for Cooperation

- Sub-orbital calibration of space-based data
- Simulation and modeling of space-based $X_{CO2}$ data
- Spectral line databases
- Data archive and distribution