The Orbiting Carbon Observatory-2 (OCO-2) Mission

Watching The Earth Breathe…Mapping CO₂ From Space.

Radiometric Comparison of 0.76, 1.6 and 2.0-μm Bands of OCO-2 with Aqua MODIS over Sahara/Arabian Desert Sites

Shanshan Yu, Lars Chapsky, Carol Bruegge, Robert Rosenberg, Dejian Fu, Richard Lee, Peter Lawson, David Crisp, Annmarie Eldering
– NASA/JPL/Caltech

Thomas Taylor, Heather Cronk, Christopher O’Dell
– Colorado State University

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• Orbiting Carbon Observatory approved within the Earth System Science Pathfinder program in July 2002
  - Launched on February 24, 2009 but did not achieve orbit due to launch vehicle failure

• Work on OCO-2 began in March 2010
  - Launched into A-Train successfully from Vandenberg Air Force Base in California on July 2, 2014
  - Exceeded 2-year nominal mission and continues to deliver scientific measurements

• Following the successful OCO-2 launch, work began on converting the spare spectrometer into OCO-3
  - Launched successfully from Cape Canaveral in Florida on May 4, 2019 and docked on ISS on May 6, 2019
  - In-Orbit Checkout through August 2019
  - Planned duration 3 years after In-Orbit Checkout
Quantify variations in column averaged CO$_2$ dry air mole fraction, $X_{CO2}$

Measure O$_2$ & CO$_2$ spectra

8 cross-track footprints

footprint size = ~2.5 km$^2$

Grating spectrometer looking at Earth’s surface in 3 wavelengths

758-772 nm

1594-1619 nm

2045-2081 nm
Schematic of OCO-2’s three spectrometers
Major optical components for a single channel

- **Wavelength direction**
  - Grating disperses light into 1024 sub spectral channels: $\Delta \lambda \sim 0.05$ nm

- **Spatial direction**
  - (8 footprints)

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**Diagram Elements**

- Telescope/ recollimator
- Collimator
- Slit
- Polarizer
- Cold filter
- Grating
- FPA
- Light trap
- FPA image

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**Footnotes**

- Spatial direction (8 footprints)
- Wavelength direction
Inflight calibration chain

- Uncalibrated Level 1A Signal
- Dark Signal (TVAC & updated in flight)
- "ZLO" stray light (unilluminated pixels)
- Preflight Gain (Sphere in TVAC)
- Gain Degradation (change since in orbit checkout)
- Calibrated Level 1B Radiance

Unilluminated pixels are at the bottom and the top of PFA image

Spatial direction (8 footprints)

Wavelength direction
Observations of the sun using the solar diffuser and the lamps using the lamp diffuser show

- **Fast signal losses from water icing that are reversible with decontamination** (ABO2 affected most due to FPA AR coating having an refractive index similar to water ice)

- **Irreversible trends** that combine instrument throughput and lamp aging and lamp/solar diffuser degradation

\[
y = 1 - A + A \times \exp\left[-\left(x - B\right)/C\right] + D \times \left(x - B\right)
\]

\[
A = 0.0356 \\
B = 0.194 \\
C = 0.569 \\
D = -0.01432
\]
Lunar calibration tracks science throughput and solar/lamp diffusers degradation

~75% moon irradiance, corrected for undersampling, icing, distance, phase, liberation & polarization

<table>
<thead>
<tr>
<th></th>
<th>ABO2</th>
<th>WCO2</th>
<th>SCO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar</td>
<td>-0.6</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>Solar</td>
<td>-2.1</td>
<td>-0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>Lamp</td>
<td>-6.1</td>
<td>-0.3</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

- Lunar observations track the long term degradation of the throughput of those parts of the optical system used for science observations.
- Comparisons of Solar (with diffuser) and Lamp (with diffuser) to Lunar are used to track the long term degradation
  - the solar calibration diffuser
  - the lamp output and the lamp diffuser
## Absolute radiometric requirement: ≤5% uncertainty

OCO-2 meets and exceeds its radiometric calibration requirements

<table>
<thead>
<tr>
<th>Calibration Type</th>
<th>OCO-2 Frequency</th>
<th>OCO-3 Frequency</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vicarious @ RRV</td>
<td>3 chances every 16 days ~1x per month planned</td>
<td>Varies ~5x per 3 months planned</td>
<td>Absolute standard</td>
</tr>
<tr>
<td>Lunar calibration</td>
<td>Twice per lunar cycle</td>
<td>4-6x per year (goal)</td>
<td>Pointing &amp; relative radiometric calibration</td>
</tr>
<tr>
<td>Lamp calibration</td>
<td>~10x per day</td>
<td>~15x per day</td>
<td>Short-term stability &amp; Spectrally flat</td>
</tr>
<tr>
<td>Lamp calibration With a lamp diffuser</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar calibration</td>
<td>~10x per day</td>
<td>Not possible</td>
<td>Additional short-term source at different radiance level</td>
</tr>
<tr>
<td>Solar calibration With a solar diffuser</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark calibration</td>
<td>~20x per day</td>
<td>~30x per day</td>
<td>Dark subtraction / trending</td>
</tr>
<tr>
<td>Streak Flats (all footprints observe the same Earth scene)</td>
<td>Every Orbit (for free)</td>
<td>Special request (~1x per week)</td>
<td>Relative radiometric calibration among footprints</td>
</tr>
<tr>
<td>Spacecraft-to-spacecraft cross calibration</td>
<td>1 chance every 16 days</td>
<td>Varies</td>
<td>Long-term stability</td>
</tr>
</tbody>
</table>
• Quantify time-dependence in OCO-2/MODIS radiance ratio (specific to one Build)
• Select only clear sky OCO-2 nadir observations over deserts
• Spectral bands: OCO-2 vs. MODIS
  - 0.76 μm vs. \((B1+B2)/2 = (0.645+0.859)/2 = 0.75 \, \mu m\)
  - 1.605 μm vs. B6 = 1.63 μm
  - 2.06 μm vs. B7 = 2.11 μm
• OCO-2 radiances: B8 L2DIA, continuum level from the OCO-2 full physics retrieval
• MODIS radiances: C6.1 MYD02HKM, half-km radiance collocated to the OCO-2 footprints using a 1km circular region around OCO-2 footprint, divided by 2 to account for total intensity vs single linear polarization for OCO-2
OCO2 has nadir observations over 9 of the 20 sites (green check marks)

- Area of each site is ~100km X 100km

Picture from Lacherade et al 2013
OCO-2 Path 48 over Egypt site

- Find clear sky OCO-2 nadir soundings within the site
- Match MODIS observations (temporal and spatial matches only, viewing geometry match not performed currently)
- Calculate OCO-2/MODIS radiance ratio
- Take mean ratio within each orbit
- Perform linear regression of mean ratio vs orbit (time) to determine intercept and slope
Sample linear regression for single site: Egypt1

OCO2 ABO2 MODIS CrossCal over Egypt1 A =1.099(2) B=-0.6(1) %/year, rms=0.75%

29 data points cross 4 years; Seasonal trend seen in radiance ratio

OCO2 WCO2 MODIS CrossCal over Egypt1 A =1.121(3) B=-0.1(1) %/year, rms=0.90%

OCO2 SCO2 MODIS CrossCal over Egypt1 A =1.229(4) B=-0.1(2) %/year, rms=1.26%
Sample linear regression for single site: Algeria1

**OCO2 ABO2 MODIS CrossCal over Algeria1**

- $A = 1.105(4)$%
- $B = -0.7(2)$%/year
- $\text{rms} = 0.48\%$

11 data points cross 4 years; data too sparse to inform seasonal trend

**OCO2 WCO2 MODIS CrossCal over Algeria1**

- $A = 1.122(3)$%
- $B = -0.3(1)$%/year
- $\text{rms} = 0.26\%$

10 data points cross 4 years

**OCO2 SCO2 MODIS CrossCal over Algeria1**

- $A = 1.209(3)$%
- $B = 0.0(2)$%/year
- $\text{rms} = 1.18\%$

11 data points cross 4 years
### Summary of OCO-2 B8 CrossCal with MODIS

- **ABO2 trend:** $-0.7 \pm 0.2 \%$/yr
- WCO2 and SCO2 trends: no measurable trend, indicating $<0.2\%/yr$
- Intercept varies from site to site; contributions under investigation
  - Absolute radiance calibration; Spectral band adjustment factor, viewing geometry correction, others?

<table>
<thead>
<tr>
<th>Site</th>
<th>Slope (% per year)</th>
<th>Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ABO2</td>
<td>WCO2</td>
</tr>
<tr>
<td>Algeria1</td>
<td>-0.7±0.2</td>
<td>-0.3±0.1</td>
</tr>
<tr>
<td>Algeria2</td>
<td>-0.7±0.2</td>
<td>-0.2±0.2</td>
</tr>
<tr>
<td>Algeria4</td>
<td>-0.8±0.2</td>
<td>0.1±0.2</td>
</tr>
<tr>
<td>Arabia1</td>
<td>-0.7±0.1</td>
<td>0.1±0.2</td>
</tr>
<tr>
<td>Arabia2</td>
<td>-0.5±0.1</td>
<td>0.1±0.1</td>
</tr>
<tr>
<td>Egypt1</td>
<td>-0.6±0.1</td>
<td>-0.1±0.1</td>
</tr>
<tr>
<td>Libya1</td>
<td>-0.7±0.2</td>
<td>0.4±0.4</td>
</tr>
<tr>
<td>Libya2</td>
<td>-0.6±0.1</td>
<td>-0.1±0.1</td>
</tr>
<tr>
<td>Mauritania1</td>
<td>-1.0±0.2</td>
<td>-0.2±0.2</td>
</tr>
</tbody>
</table>
ABO2 linear regression for 9 sites with intercept removed

slope = -0.67 ± 0.05 %/year

Year Since 2014-08-06 (# points = 173)
• OCO-2 has demonstrated that its current calibration approach meets and exceeds its radiometric calibration requirements

• The cross calibration approach in this talk represents one of our efforts to find alternative methods for OCO-3, which lacks solar calibration and has limited lunar calibration opportunities

• Planned OCO-3 cross calibration sensors include MODIS, VIIRS, OCO-2, GOSAT-2, TROPOMI

• For additional long-term stability, directly trending reflectance derived from OCO-2 radiance over desert sites is ongoing, currently we are investigating methods to remove observed seasonal trends
7 Backup slides
Linear regression for Algeria2

OCO2 ABO2 MODIS CrossCal over Algeria2 $A = 1.088(4)$ $B = -0.7(2)$ %/year, $rms = 0.85\%$

OCO2 WCO2 MODIS CrossCal over Algeria2 $A = 1.122(5)$ $B = -0.2(2)$ %/year, $rms = 0.87\%$

OCO2 SCO2 MODIS CrossCal over Algeria2 $A = 1.225(6)$ $B = -0.8(2)$ %/year, $rms = 1.85\%$
Linear regression for Algeria4

OCO2 ABO2 MODIS CrossCal over Algeria4 $A = 1.108(5) \ B = -0.8(2) \% / \text{year}$, $\text{rms} = 0.59\%$

OCO2 WCO2 MODIS CrossCal over Algeria4 $A = 1.112(6) \ B = 0.1(2) \% / \text{year}$, $\text{rms} = 0.72\%$

OCO2 SCO2 MODIS CrossCal over Algeria4 $A = 1.228(8) \ B = -0.2(3) \% / \text{year}$, $\text{rms} = 1.35\%$
Linear regression for Arabia1

OCO2 ABO2 MODIS CrossCal over Arabia1 $A = 1.090(3)$ $B = -0.7(1)$ %/year, $rms = 0.64\%$

OCO2 WCO2 MODIS CrossCal over Arabia1 $A = 1.112(5)$ $B = 0.1(2)$ %/year, $rms = 0.84\%$

OCO2 SCO2 MODIS CrossCal over Arabia1 $A = 1.242(4)$ $B = -0.6(2)$ %/year, $rms = 1.15\%$
Linear regression for Arabia2

OCO2 ABO2 MODIS CrossCal over Arabia2
- Slope: $A = 1.065(2)$
- Offset: $B = -0.5(1)$ \%/year
- RMS: 0.60%

OCO2 WCO2 MODIS CrossCal over Arabia2
- Slope: $A = 1.109(2)$
- Offset: $B = 0.1(1)$ \%/year
- RMS: 0.74%

OCO2 SCO2 MODIS CrossCal over Arabia2
- Slope: $A = 1.222(4)$
- Offset: $B = -0.2(2)$ \%/year
- RMS: 1.13%
Linear regression for Libya1

OCO2 ABO2 MODIS CrossCal over Libya1 $A = 1.107(4)$ $B = -0.7(2)$ %/year, rms=0.69%

OCO2 WCO2 MODIS CrossCal over Libya1 $A = 1.118(5)$ $B = 0.4(4)$ %/year, rms=0.91%

OCO2 SCO2 MODIS CrossCal over Libya1 $A = 1.221(7)$ $B = 1.2(4)$ %/year, rms=1.64%
Linear regression for Libya2

OCO2 ABO2 MODIS CrossCal over Libya2 $A = 1.089(3) \ B = -0.6(1) \%/year$, $rms = 0.46\%$

OCO2 WCO2 MODIS CrossCal over Libya2 $A = 1.125(3) \ B = -0.1(1) \%/year$, $rms = 0.55\%$

OCO2 SCO2 MODIS CrossCal over Libya2 $A = 1.240(4) \ B = -0.5(2) \%/year$, $rms = 0.89\%$
Linear regression for Mauritania1

- **OCO2 ABO2 MODIS CrossCal over Mauritania1**
  - $A = 1.113(3)$
  - $B = -1.0(2) \%/year$
  - $rms = 0.44\%$
  - Time Since Launch (Years, # points=13)

- **OCO2 WCO2 MODIS CrossCal over Mauritania1**
  - $A = 1.130(3)$
  - $B = -0.2(2) \%/year$
  - $rms = 0.82\%$
  - Time Since Launch (Years, # points=14)

- **OCO2 SCO2 MODIS CrossCal over Mauritania1**
  - $A = 1.251(5)$
  - $B = -0.5(2) \%/year$
  - $rms = 1.66\%$
  - Time Since Launch (Years, # points=13)