Instrument Update

• Flight Instrument
  – In storage at Orbital’s facility in Gilbert, AZ
  – Currently removed from the spacecraft, will be reinstalled in June
  – Thermal Vacuum testing in December show no evidence of performance changes since the final instrument-level Tvac at JPL in April of 2012

• Spare Instrument
  – Largely assembled to start process of focusing the detectors next week
  – Should start the first characterization/calibration testing in May (once acceptable focus is achieved)
  – Testing should wrap up in June
Calibration And It’s Role In Data Processing

- Calibration Team provides instrument related parameters used to:
  - Convert spacecraft pointing/time data into geolocation information
  - Convert raw detector data into calibrated radiances including noise estimates
  - Convert FPA columns into wavelengths (non-Doppler corrected)
  - Model the Instrument Line Shape (ILS)
  - Model the polarization performance

L0 Files
(raw data)

SDOS Processing

L1a Files
(Modes Separated, H/K converted to physical units)

SDOS Processing

Calibration L1a Files

Calibration Statistics

Spectral & Radiometric Parameters (aka ARP*)

Pointing Parameters (aka AGP*)

Calibration L1b Files

Science L1b Files
(Geofolocation, Spectral & Radiometric Conversion Complete)

Orange line = Calibration Team Code

Black line = SDOS Code

* ARP = Ancillary Radiometric Product / AGP = Ancillary Geometric Product
Notes about OCO-2 versus OCO Calibration

• General
  – Much better set of dark data interspersed in test data

• Radiometric Calibration
  – Added spectrometer to monitor sphere to \textit{MEASURE} color temperature issues
  – Had NIST visit to calibration the sphere-chamber system
  – All three channels are measured simultaneously

• Spectral Calibration
  – Better job removing laser speckle
  – Lasers were running multimode during many tests (BAD)
    ▪ Trying to fix for calibration of spare hardware
  – Took laser scans at far, far more wavelengths

• Heliostat Data
  – Learned that the heliostat is a little undersized
    ▪ Small changes in alignment and/or uniformity of illumination create subtle (or sometimes not subtle) changes in the ILS and the radiometric calibration
    ▪ This is greatly complicates the TCCON to OCO ILS comparisons and L2 code testing
    ▪ Need to be vigilant against correcting for test equipment issues with flight calibration parameters
The OCO-2 Bad Pixel Map At Instrument Delivery

853/163840

1606/163840

1400/163840
Dark Subtraction
First Step of Radiometric Calibration

• Dark subtraction is critical to getting a good radiometric calibration

• Data taken in Tvac for the instrument provided the coefficients to correct for dark current drifts related to the optics and/or FPA temperature

• Simple linear corrections still leave a small residual – working to find ways to further correct this

• In flight, the instrument should be much more stable than on the ground and the dark subtraction should be good to a fraction of the noise level over a period of a week or two without significant correction
  – This will be one of the first things the calibration team will validate during early operations
Radiometric Calibration Summary

- Absolute uncertainties are all probably in the 2-4% range
  - Still working on final error estimates
  - Several small terms remain to be captured, but we do not expect them to influence the results significantly
- Non-linearity is minimal – cubic function captures it well

A linear fit yields only a small residual due to non-linearity
Non-linearity Varies across FPA

- **Linear** coefficients capture
  - Variability in transmission versus wavelength
  - Grating anamorphic magnification

- **Quadratic** coefficients capture
  - Non-linearity that varies with position in multiplexer grouping of 64 columns

- **Cubic** coefficients capture
  - Largely, but not entirely cancel the quadratic
  - Combination better captures the high dynamic range performance

- Quartic and high coefficients do not improve the fits in any meaningful way, so we are stopping at cubic

- Once again, all three channels look largely the same
Non-linearity in CO2 Channels

Weak CO$_2$

Strong CO$_2$

[Graphs showing linear, quadratic, and cubic gain coefficients for weak and strong CO$_2$]
Validating Non-linearity

By taking the ratio of a fully illuminated heliostat data set and one with ~50% of the light blocked, we can validate that the non-linearity of the instrument is well captured by the gain coefficients. If it is, then the ratio of the two spectra should be a flat line and all three bands should agree on how much light was blocked.
OCO Versus OCO-2
Residual Image

- Strong CO$_2$ shows similar performance, but the noise floor is higher $\Rightarrow$ more margin
- A-band response falls off even faster than CO$_2$ channels – no 2$^{nd}$ derivative issues
- Residual image appears to be almost, but perhaps not completely, negligible
  - Working on how best to avoid XCO2 basis from this (ignore it? flag data? fix data?)

Keep out zone per calibration spec (L3-CAL-39):
“Post-saturation magnitude and settling characteristics shall be characterized such that residual image errors can be corrected to less than the instrument noise with 1 second of a transition corresponding to 50% of the dynamic range.”

This requirement applies after L1a to L1b processing, so if the detector showed points in the Keep Out Zone, we would need a RICA.
## Spectral Calibration Overview

<table>
<thead>
<tr>
<th>Step #</th>
<th>Process</th>
<th>Response</th>
<th>Wavelength scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TVac measurements</td>
<td>lasers using OCO-2 as power meter</td>
<td>laser wavemeters (problems)</td>
</tr>
<tr>
<td>2</td>
<td>Spectral Calibration</td>
<td>ILS relative response (+ ILS delta lambda)</td>
<td>dispersion relation (from lasers)</td>
</tr>
<tr>
<td>3</td>
<td>Spectral Verification</td>
<td>optimized ILS relative response (+ optimized ILS delta lambda)</td>
<td>optimized dispersion</td>
</tr>
<tr>
<td>4</td>
<td>Spectral Calibration</td>
<td>new ILS relative response using optimized dispersion</td>
<td>dispersion</td>
</tr>
<tr>
<td>5</td>
<td>Spectral Verification</td>
<td>new optimized ILS relative response (+ new optimized ILS delta lambda)</td>
<td>new optimized dispersion</td>
</tr>
</tbody>
</table>

*Exploring further optimization, but cautious of over fitting the data…*
Spectral Calibration Process

Step 1: Single laser fine-step scan as seen by a single sample

Step 2: Look at simultaneous data for stable laser periods as seen by neighboring samples

Step 3: Center all local data by subtracting center wavelength

Step 4: Interpolate through all laser fine-step scans to estimate ILS at all wavelengths
OCO-2 Collected Far More Spectral Calibration Data

- Each symbol represents a position on the FPA where a fine laser scan was completed.
OCO-2 Data Resolved Features Not Seen on OCO

• Slopes differ to OCO being in slightly better focus than OCO-2 for the A-band
• Main point is that OCO-2’s richer data set allows a mapping of high-frequency changes in the ILS that correspond to the W-patter.
  – If they were present in the OCO data, we could never have resolved them.
ILS and Dispersion Verification Uses FTS Data

Note much higher FTS resolution
Convolving FTS Data and Laser-Based ILS Provides Simulated OCO-2 Data

FTS spectrum

OCO-2 ILS

Simulated OCO-2 spectrum

Simulated OCO-2 spectrum

Measured OCO-2 spectrum

Spectral Residuals
RMS of Residuals Validates ILS & Dispersion

• Residuals look small and constant over the entire range of atmospheric paths
Instrument Level Geolocation Data

- Measured with a pin-hole used on a raster scan (see below)
- SDOS gets a table of data with the center and width in the cross-slit and along-slit directions
  - For geolocation data, the footprint is represented as a parallelogram based on the IFOV FWHM points combined with the spacecraft motion

<table>
<thead>
<tr>
<th>FP #</th>
<th>xmax (arcsec)</th>
<th>ymax (arcsec)</th>
<th>Δx (arcsec)</th>
<th>Δy (arcsec)</th>
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</thead>
<tbody>
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<td>78.2</td>
<td>1100.6</td>
<td>105.3</td>
<td>358.8</td>
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<td>733.9</td>
<td>87.6</td>
<td>374.6</td>
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<td>150.2</td>
<td>361.8</td>
</tr>
</tbody>
</table>
Polarization

- The ripples seen here are due to stress-induced birefringence in the chamber window (expected)
- The footprint-to-footprint offsets are probably real
  - Will be adding the median value to ARP in a 3 x 8 array
  - This will slightly tweak the Muller Matrices in the L1b files
Conclusions

- Radiometric Calibration
  - Largely complete
  - Finishing write-up on requirements
  - Still making the call on the need for a tiny residual image correction
- Spectral Calibration
  - Largely complete
  - Moving from FTS-based validation to looking at L2 residuals
- Spatial Calibration
  - Complete until first lunar calibration in orbit
- Polarization Calibration
  - Complete

- After the spare instrument Tvac is complete, the calibration team will be moving on to developing and/or validating the tools to maintain the calibration in flight