Committee on Earth Observation Satellites

Calibration of GHG Sensors

Report to CEOS AC-VC

June 28, 2017

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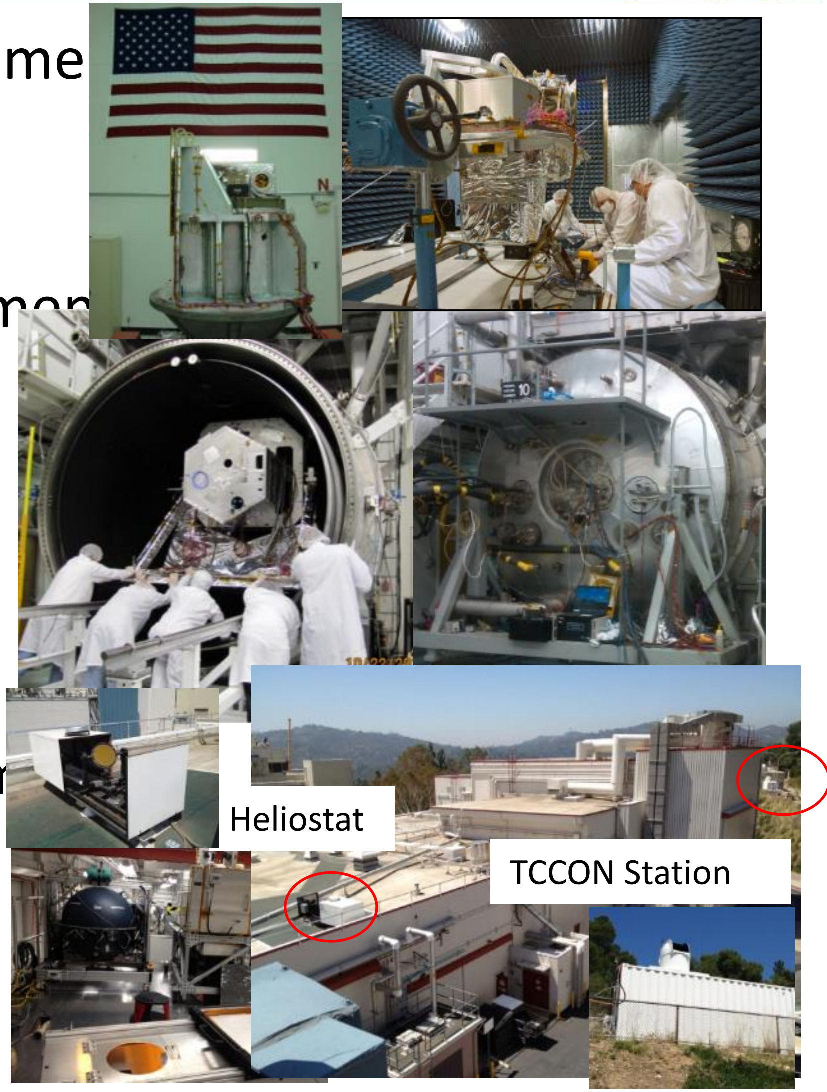
Pre-Flight Instrument Characterization and Calibration

- Pre-flight testing quantifies key Instrume knowledge parameters
  - **Geometric**
    - Field of view, Bore-sight alignmen
  - **Radiometric**
    - Zero-level offset (bias)
    - Gain, Gain non-linearity
  - **Spectroscopic**
    - Spectral range, resolution, sam
    - Instrument Line Shape (ILS)
  - **Polarization**
  - **Instrument stability**

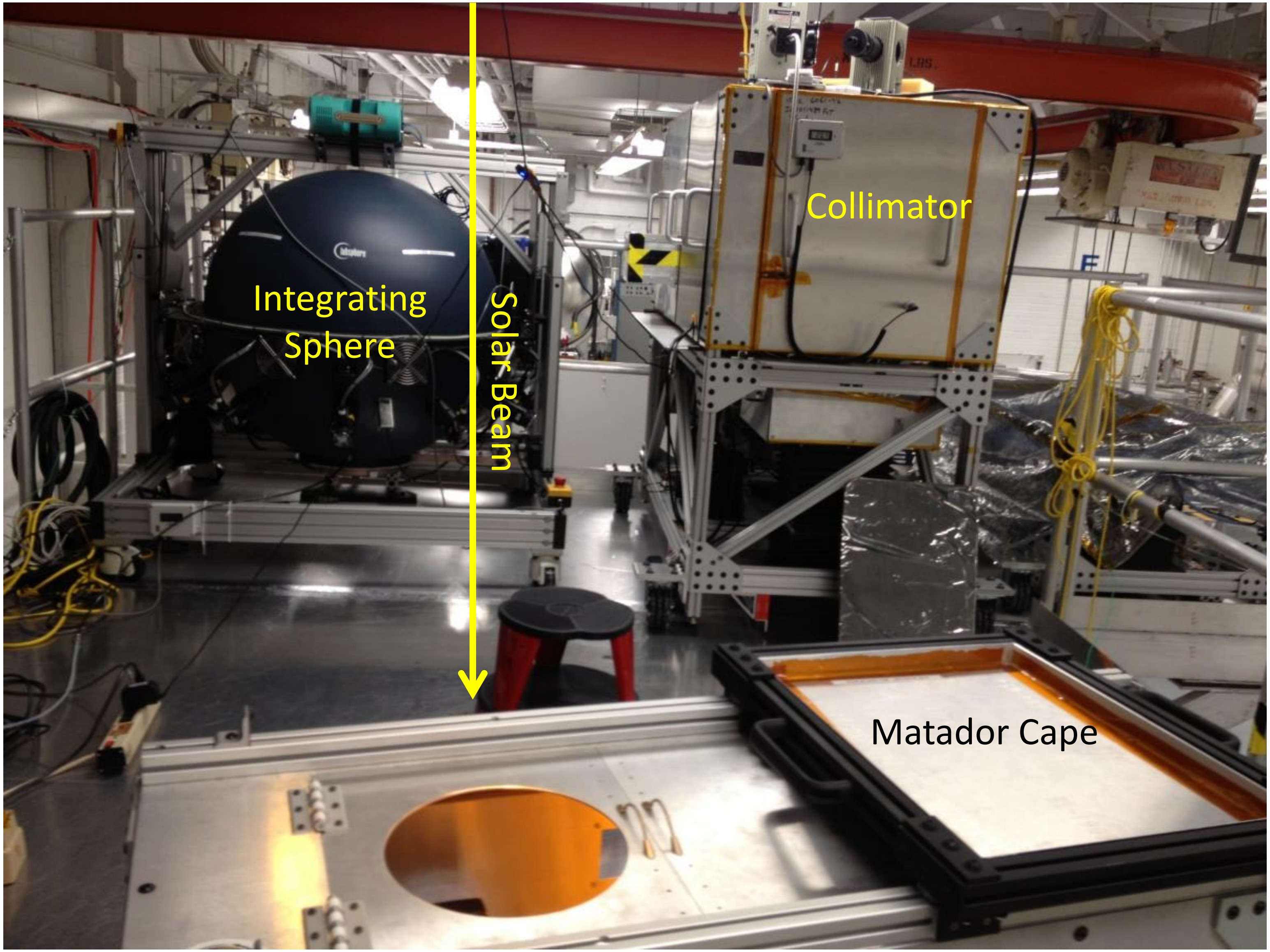


Optical Ground Support Equipment

OCO-2 employed four types of optical ground support equipment

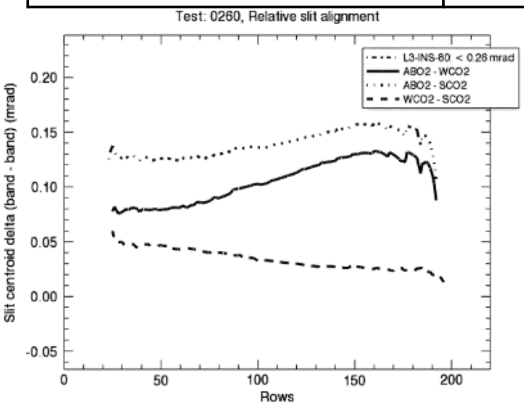
- **Collimator**: spatially-defined continuum and laser light sources to
  - Establish the spectrometer focus
  - Define the instrument field of view (including slit alignment, spatial stray light)
  - Define the spectrometer instrument line shape and spectral scattered light
  - Determine the angle of polarization
- **Integrating Sphere**: spatially uniform continuum light sources to
  - Characterize and calibrate radiometric performance (minimum and maximum measureable signal, radiometric gain and its linearity, signal to noise ratio)
  - Provide a baseline for the pixel-to-pixel variability in gain
- **Step-scan FTS**: for assessing spectral stray light rejection
- **Heliostat**: acquire atmospheric spectra using direct sunlight
  - Validate the instrument line shape and dispersion
  - Test instrument linearity and transient response over a range of illumination levels
  - Provide an end-to-end test of instrument calibration & retrieval algorithm performance, through comparisons with TCCON XCO2 retrievals

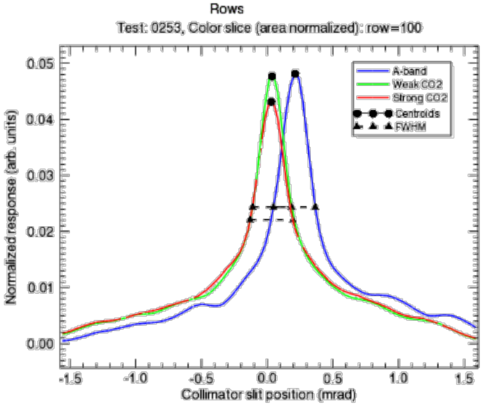
Calibration Deck

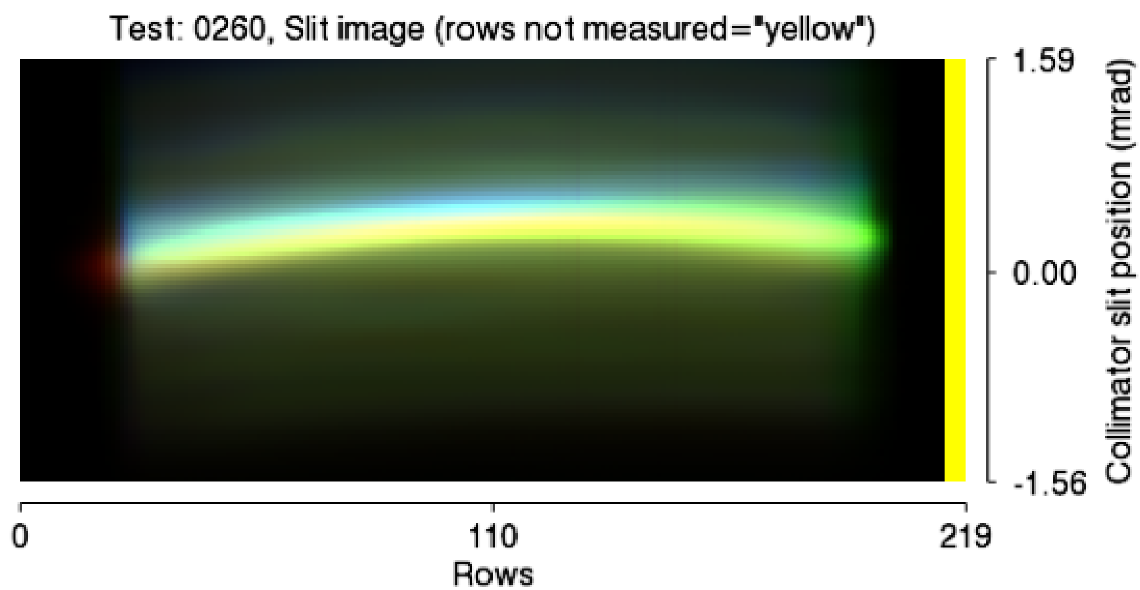


Geometric: Slit Alignment

Requirement	Value	Measured	Notes
Slit Width	< 2 mrad	~**0.5** mrad (typical) **0.7** mrad (worst case)	~3x Margin
Slit Misalignment	< 0.26 mrad	~**0.1** mrad (typical) **0.15** mrad (worst case)	~70% Margin



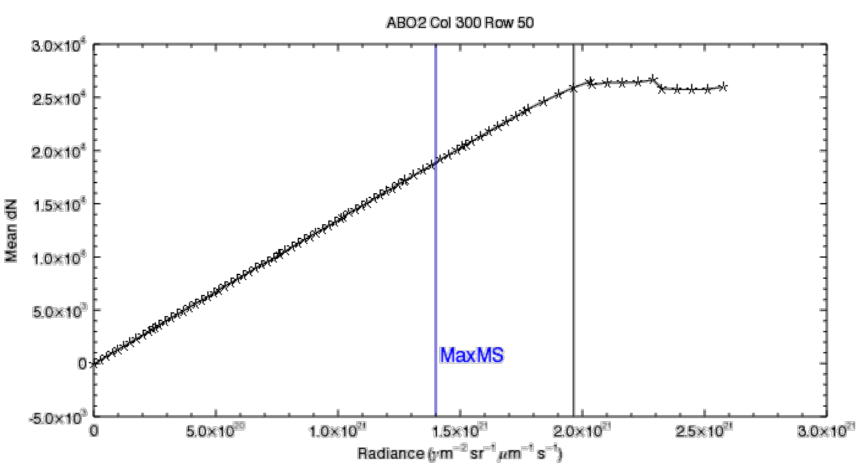


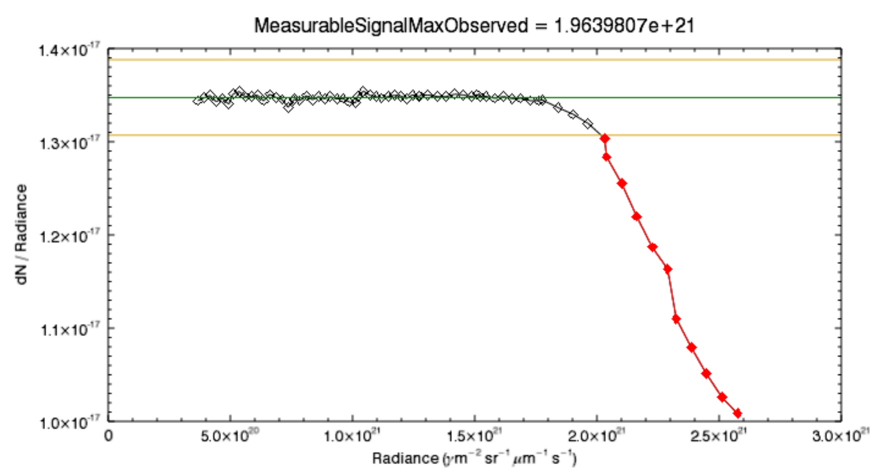


Impacts of slit misalignment and scene non-uniformity mitigated by defocusing the entrance telescope.

Radiometric: Dynamic Range

Requirement	Value	Measured	Notes
Max Measureable Signal – A-band	≥ 1.4 x 10^{21} *	**~1.8 x 10^{21}** *	• ~30% Margin
Max Measureable Signal – Weak CO_2	≥ 4.9 x 10^{20} *	**> 8.7 x 10^{21}** *	• Very large margins • Sphere isn't bright enough to saturate the detectors in CO_2 channels
Max Measureable Signal – Strong CO_2	≥ 2.5 x 10^{20} *	**> 3.8 x 10^{21}** *	

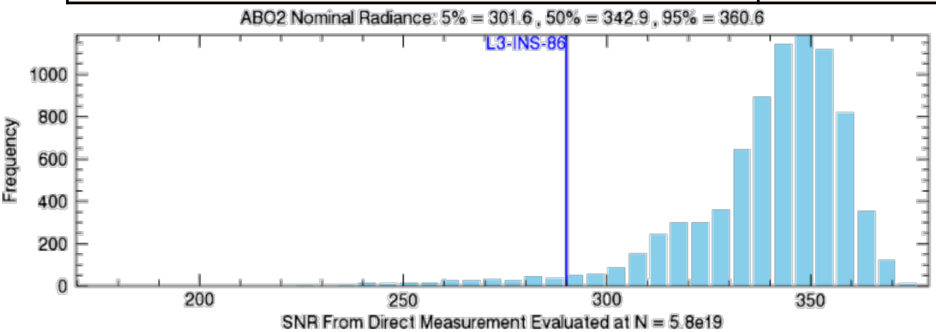


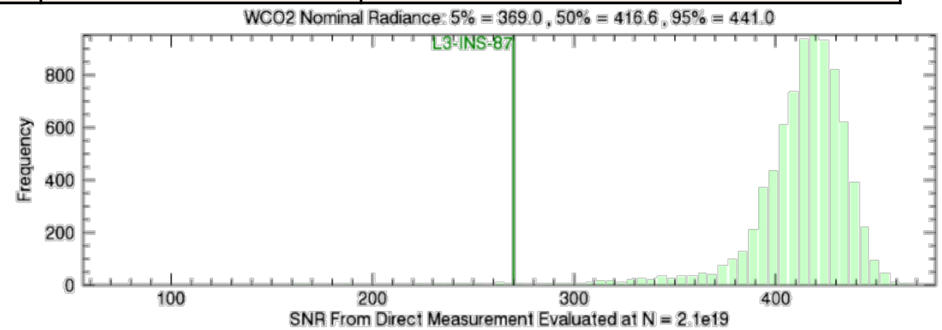


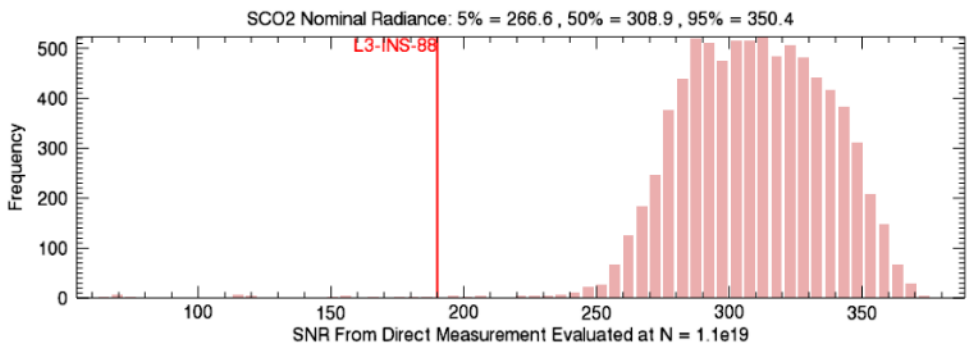
* OCO Radiance Units are: photons/m^2/sr/µm/s

Radiometric: Signal-to-Noise Ratio at Nominal Signal

Requirement	Value	Measured	Notes
Signal-to-Noise Ratio – A-band	> 290	**302 – 361**	At 5.9 x 10^{19} photons/m^2/sr/µm/s
Signal-to-Noise Ratio – Weak CO_2	> 270	**369 - 441**	At 2.1 x 10^{19} photons/m^2/sr/µm/s
Signal-to-Noise Ratio – Strong CO_2	$\geq$ 190	**267 - 350**	At 1.1 x 10^{19} photons/m^2/sr/µm/s

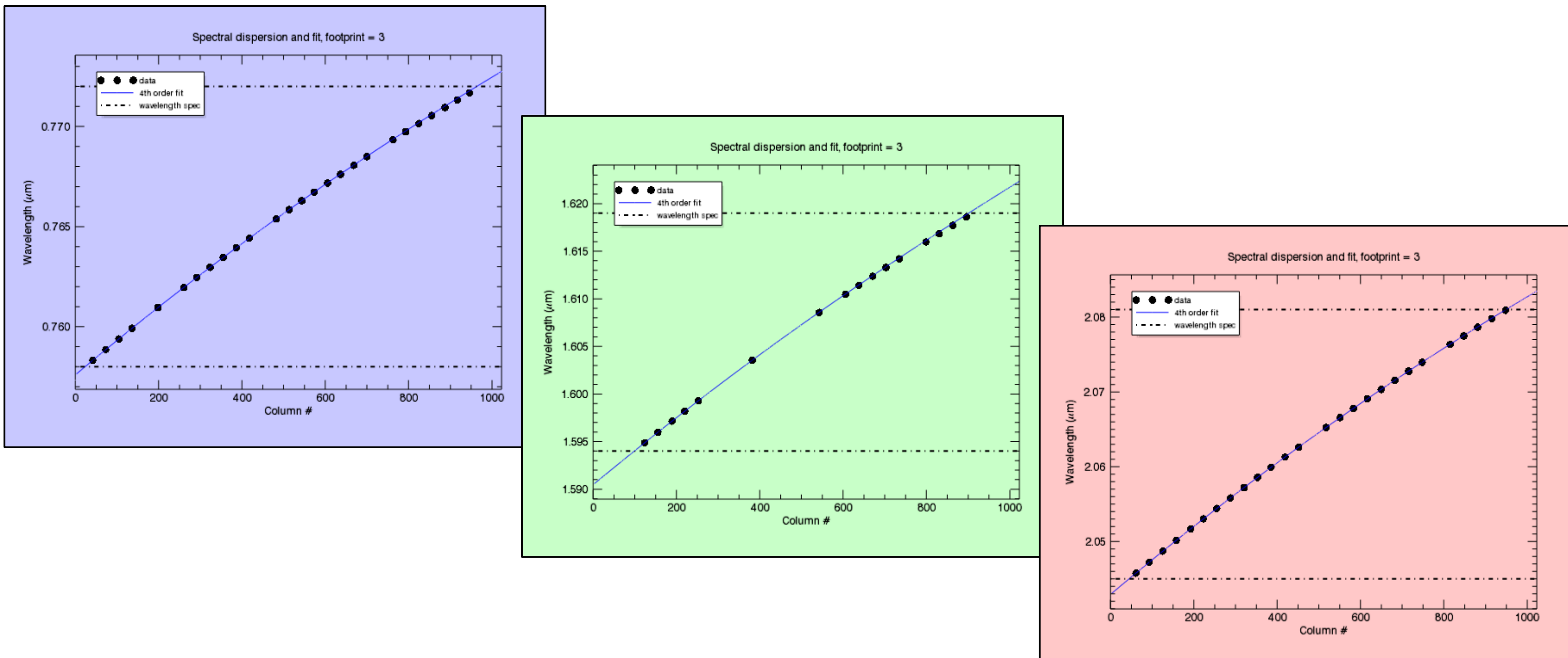






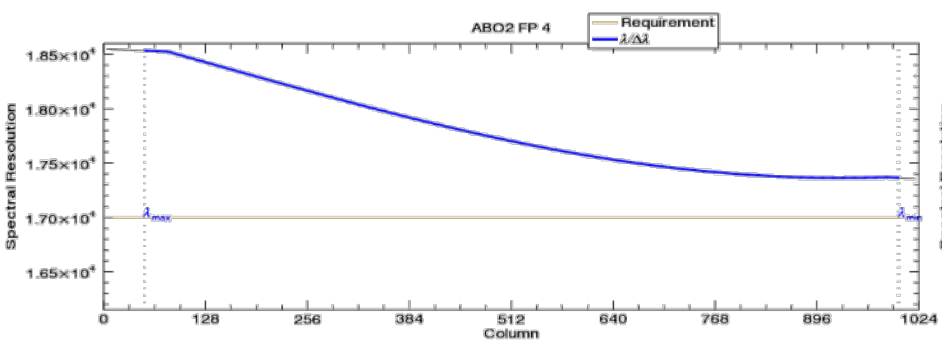
Spectroscopic: Spectral Range

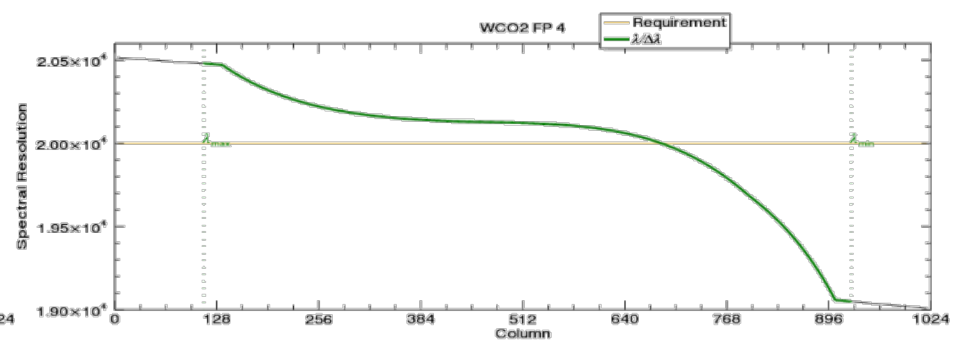
Requirement	Value	Measured	Notes
Spectral Range – A-band	758 to 772 nm	**757.6 – 772.6** nm	Bands are well centered for OCO-2
Spectral Range – Weak CO_2	1,594 – 1,619 nm	**1,590.6 – 1,621.8** nm	
Spectral Range – Strong CO_2	2,045 – 2,082 nm	**2,043.1 – 2083.3** nm	

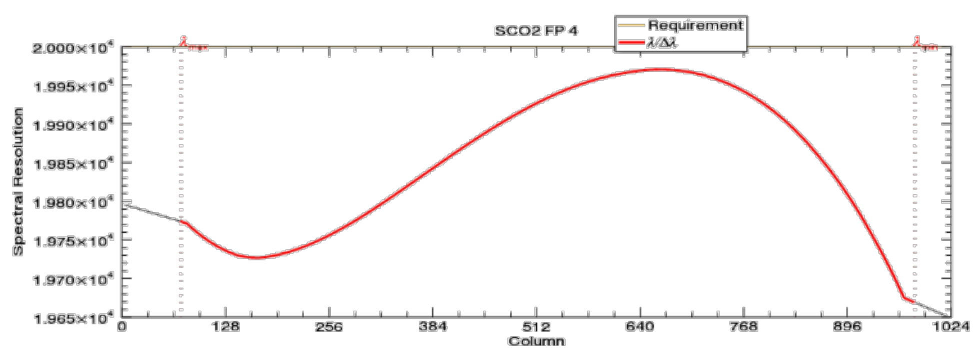


Spectroscopic: Spectral Resolution

Requirement	Value	Measured	Notes
Spectral Resolution – A-band	> 17,000	17,500 – 18,500	Resolving power is slightly low in CO2 channels. L2 Algorithm Team found found no impact on OCO-2 Level 1 requirements
Spectral Resolution – Weak CO_2	> 20,000	19,100 – 20,500	
Spectral Resolution – Strong CO_2	> 20,000	19,700 – 19,900	

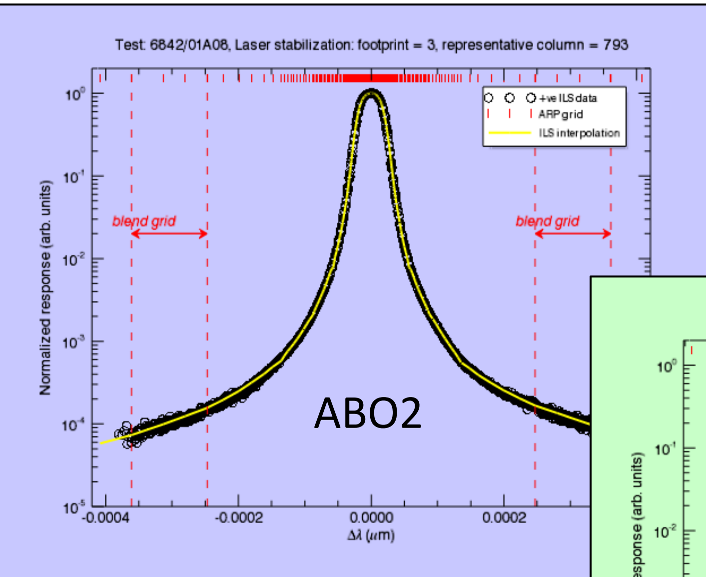


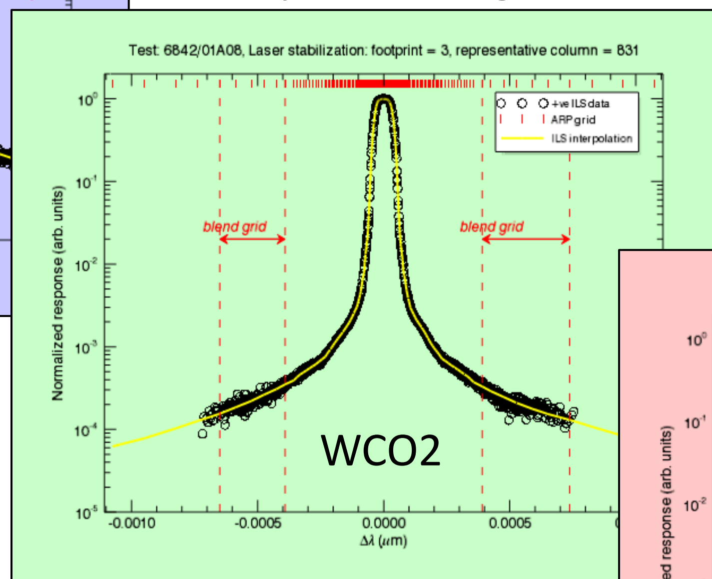


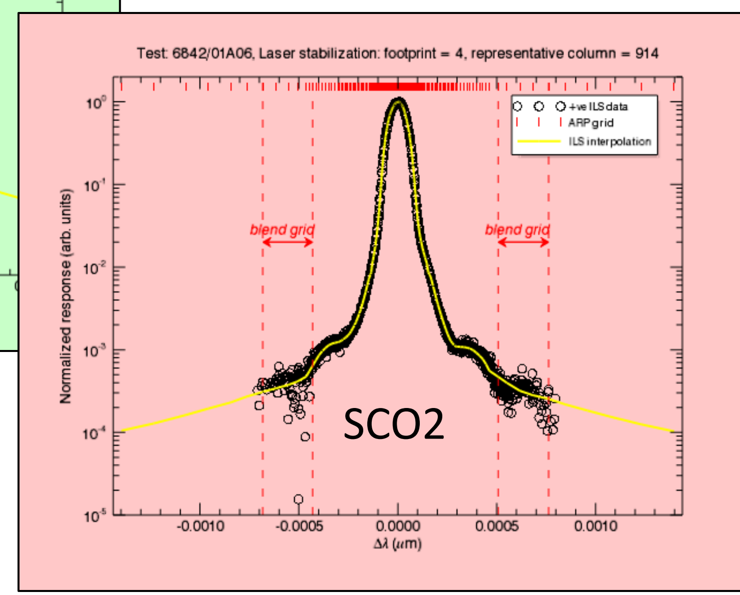


Spectroscopic; Instrument Line Shapes

- Tunable diode lasers were used to characterize the width and shape of the ILS across each of the three spectral ranges.
- This method could characterize the ILS shape over a dynamic range of 1000 to 10000.





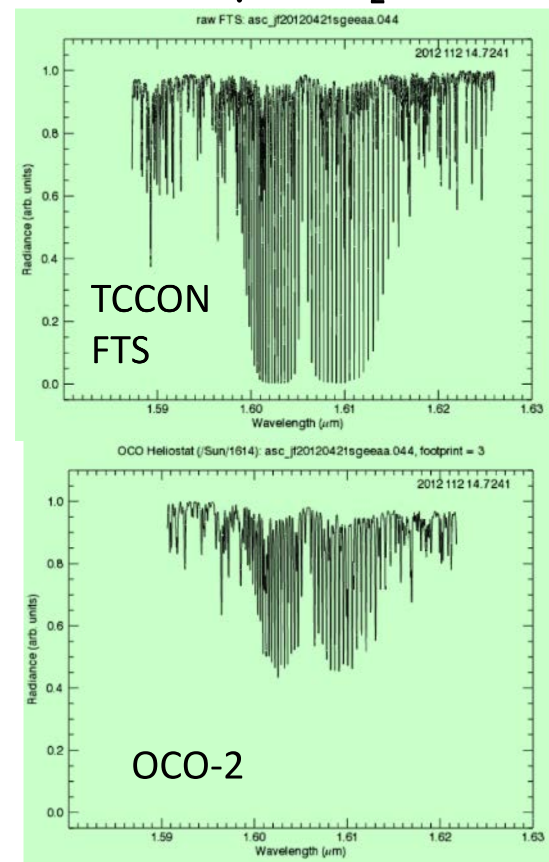


These results provided valuable information about the ILS shape, width (resolving power) and dispersion, but these results were not adequate to meet the OCO-2 requirements

Pre-flight Heliostat/TCCON Observations

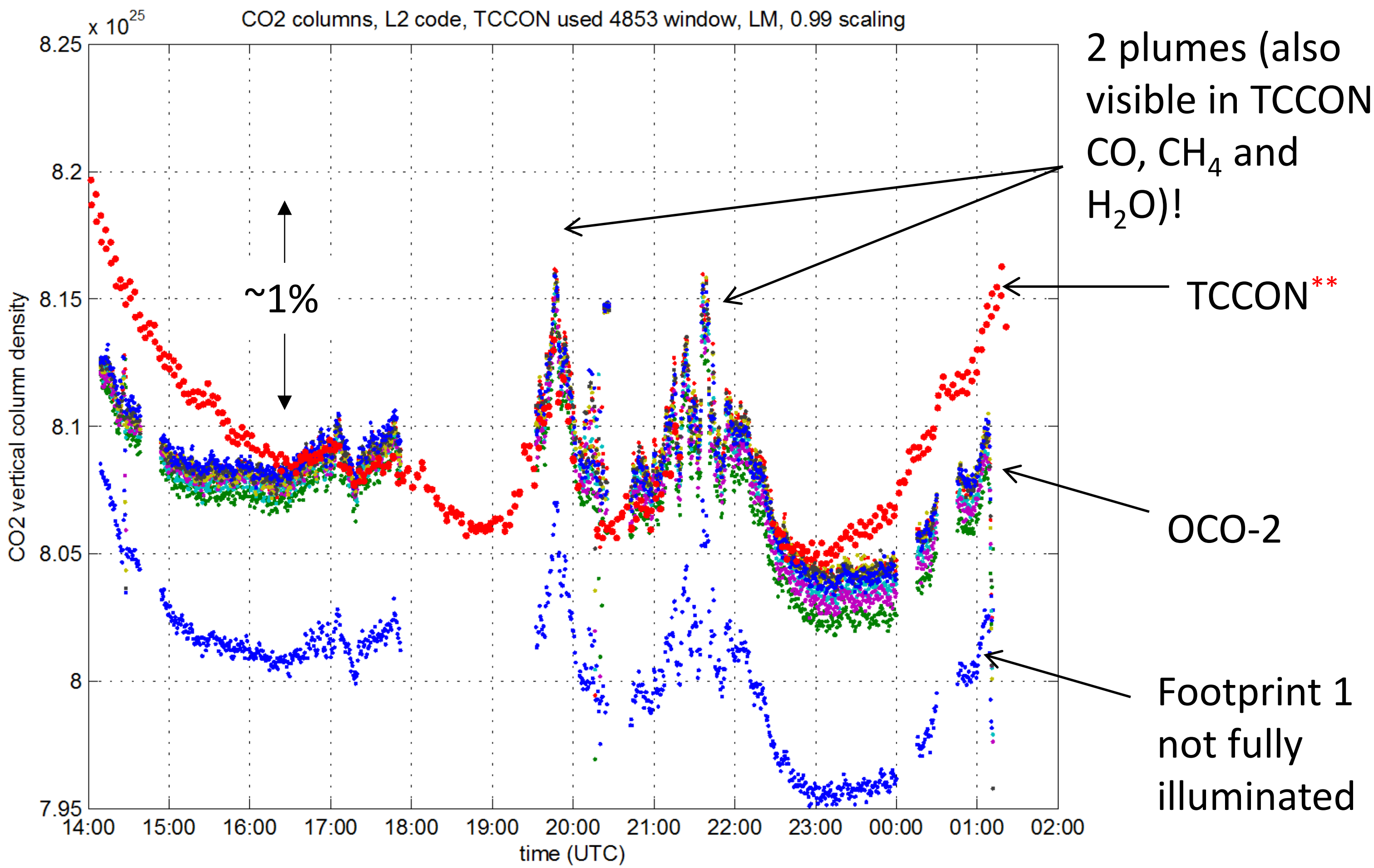
Observations of the sun with the flight instrument taken during TVAC tests provide an end-to-end verification of the instrument performance.

1.6 μm CO_2



21 April 2012

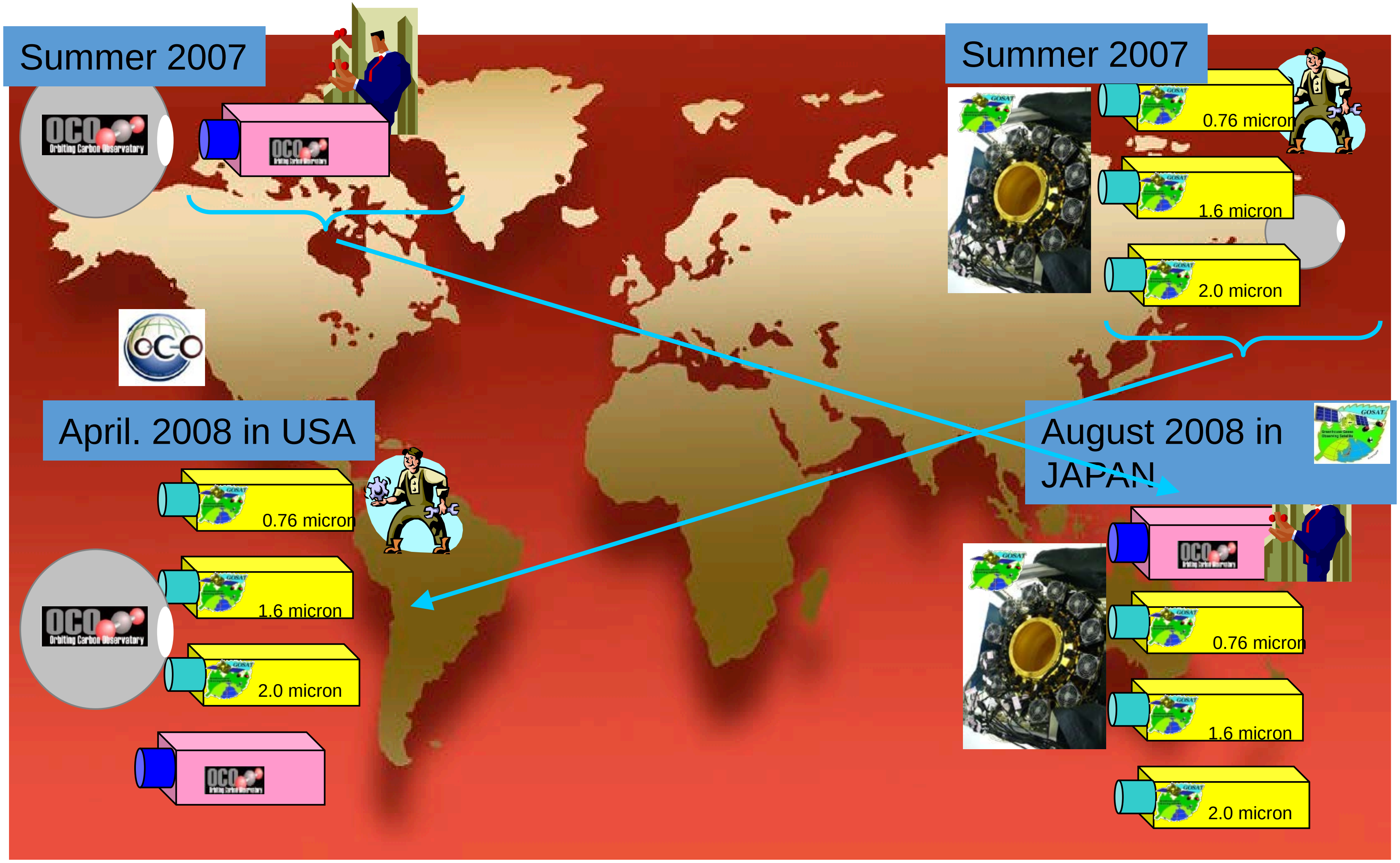
CO_2 Column Retrievals from the Strong CO_2 (SCO2) Channel at 2.06 µm



7 of the 8 footprints in the SCO2 channel produce CO_2 column estimates within ±0.25%.

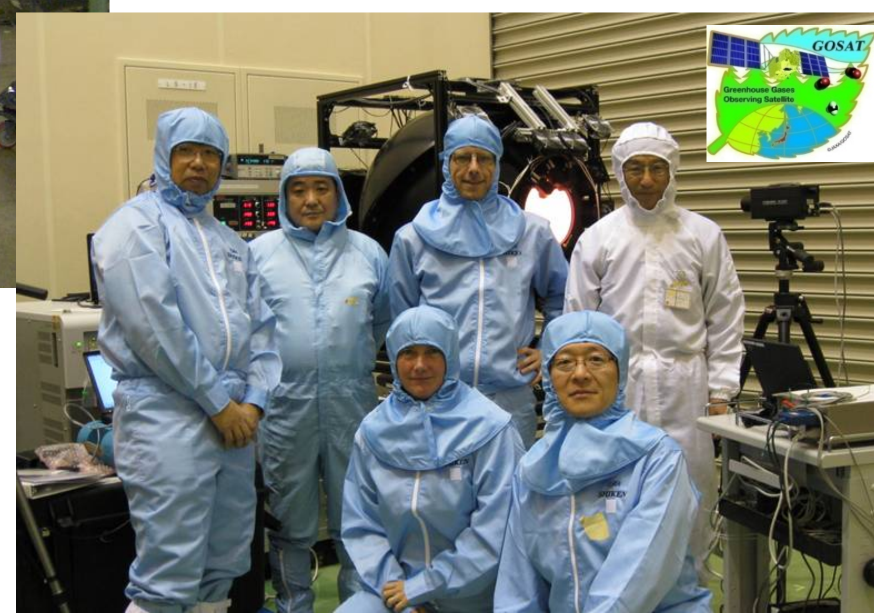
** *TCCON does not use this channel to retrieve X_{CO2}. This is a custom retrieval by D. Wunch.*

OCO/GOSAT Cross Calibration



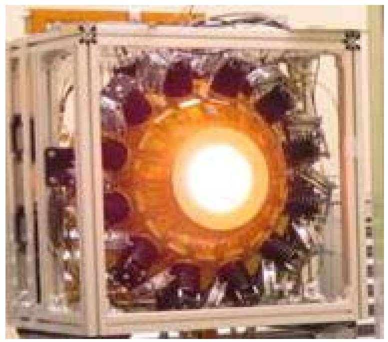
OCO-GOSAT Cross-Calibration Experiment – JPL, 14.04.2008

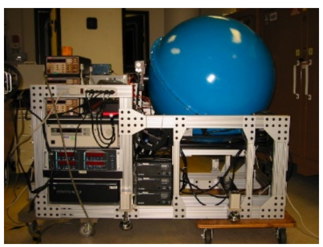
Intercomparison of OCO and GOSAT radiometric standards at JPL in April 2008 and then at Tsukuba in December of 2008



Radiometric Calibration

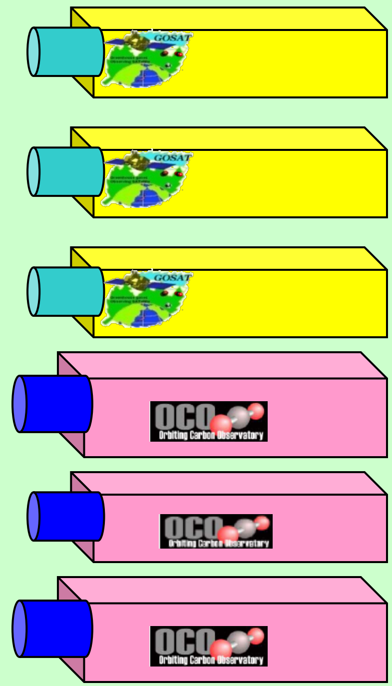
GOSAT Inner-Illuminated Integrating Spheres (1m ($BaSO_4$) and 50 cm (Gold)





NIST standard lamp + Spectralon Diffuser

Portable standard radiometers
3 spectral bands (GOSAT) 3 detectors (OC



0.76 micron (B1)

1.6 micron (B2)

2.0 micron (B3)

0.76 micron (AO2)

1.6 micron (WCO2)

2.0 micron (SCO2)

GOSAT ASD (Field Spec)

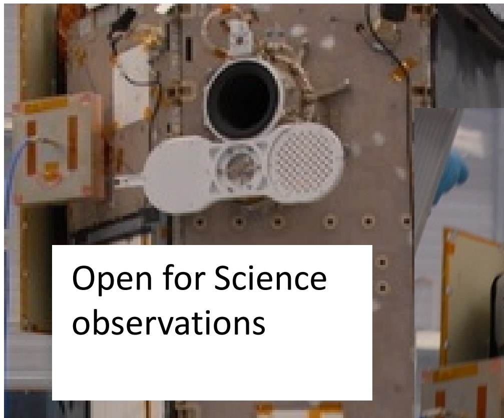
OCO ASD (Field Spec)

Cross-Calibration Results

- The OCO and GOSAT radiometric standards showed
  - Excellent agreement in linearity over the full range of illumination conditions considered
  - The O2 A-band and 1.61 micron CO2 radiometers showed very good agreement (<1% differences) in radiometric gain
  - The 2-micron radiometers showed larger differences
    - Traced to spatial inhomogeneity within the integrating sphere, due to reduced reflectance of coating
    - Other issues associated with temperature drift in radiometers

Post-Launch Calibration

Verifying Radiometric Calibration: The On-board Calibration System

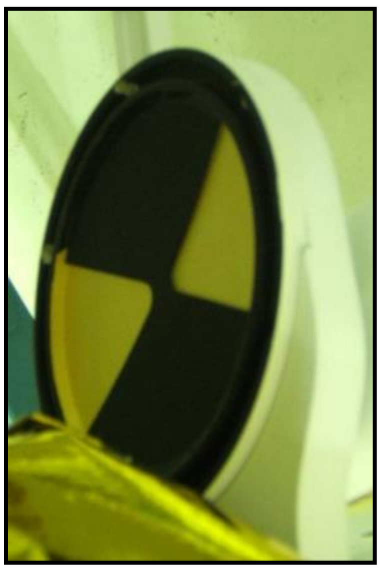


Open for Science observations

Closed for lamp calibration

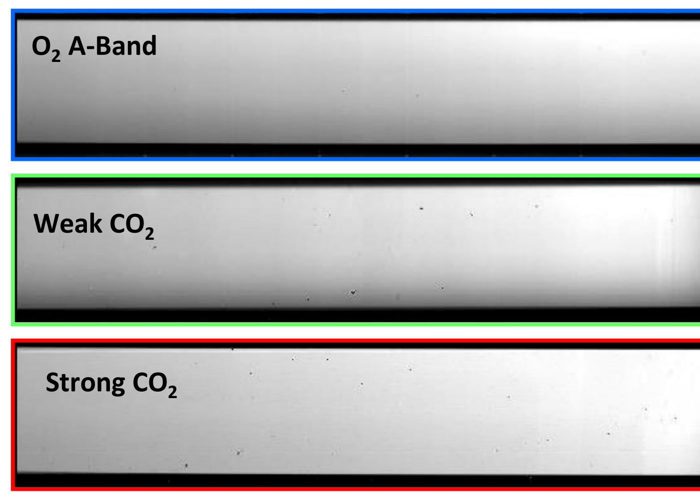
The on-board calibration (OBC) system consists of a rotating calibration paddle that carries:

- an aperture cover, with a reflective diffuser illuminated by on-board lamps for monitoring pixel-to-pixel variations
- A transmission diffuser for making observations of the solar disk for monitoring radiometric calibration



Reflective diffuser

Telescope baffle assembly, showing lamps for flat fields



Lamp “flat fields” from each channel.

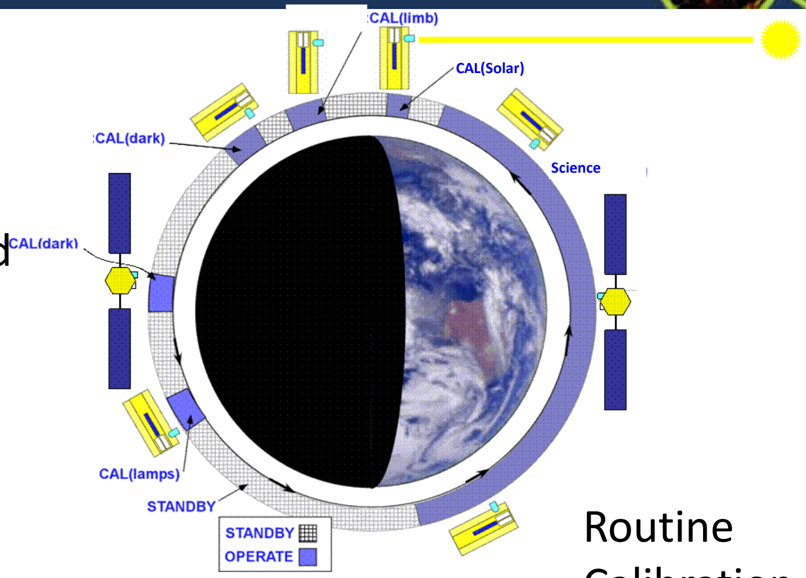
On-orbit Calibration Operations

Routine Calibration (every orbit)

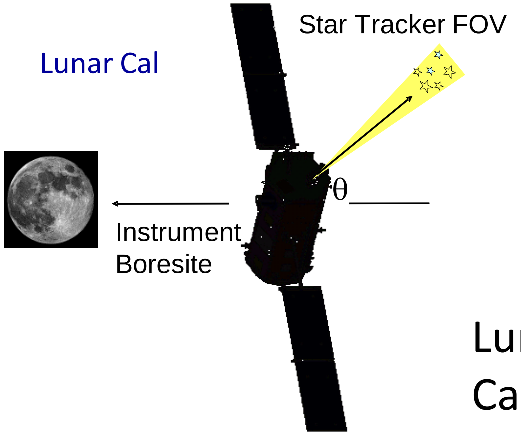
- OCO-2 will look at the sun through a solar diffuser
- Dark calibration with aperture door closed and lamps off

Special Calibration Activities

- Solar Doppler calibration
  - Observe sun through an entire daylight side of an orbit to calibrate ILS
  - once every six months)
- Lunar calibration required for absolute and relative pointing
  - Verifies alignment between instrument bore sight and the star tracker.
  - Used in radiance calibration
  - performed once every lunar month



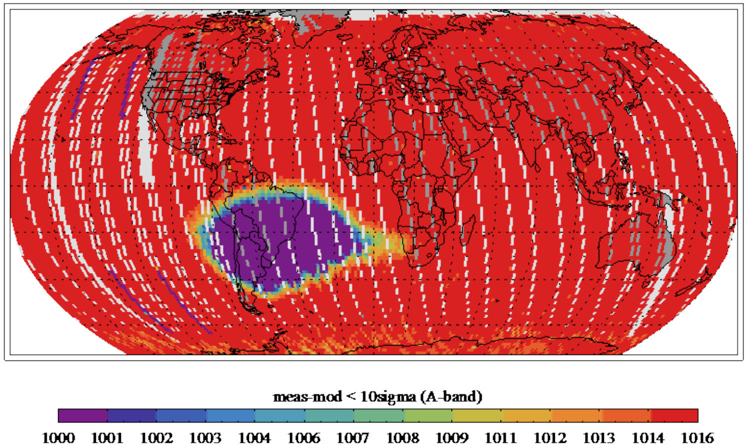
Routine Calibration

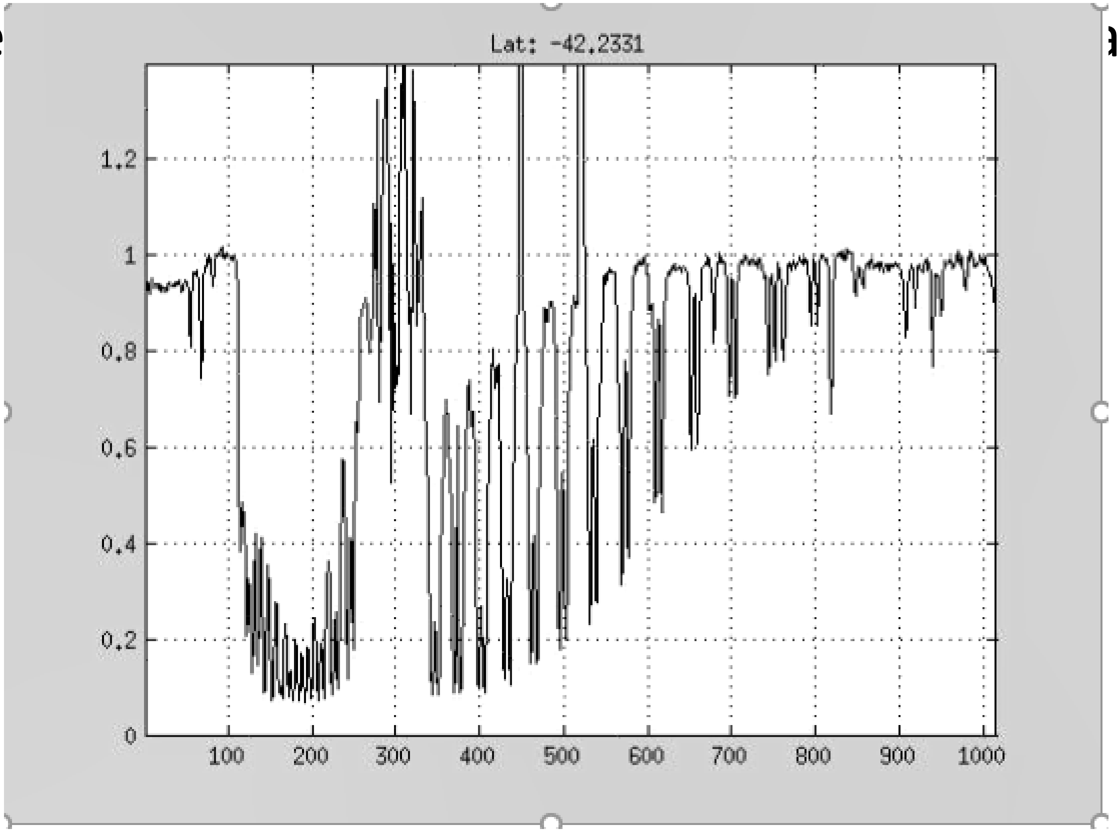


Lunar Calibration

Calibration Challenges: Cosmic Rays

Cosmic rays a particular problem, especially on orbits that pass through the





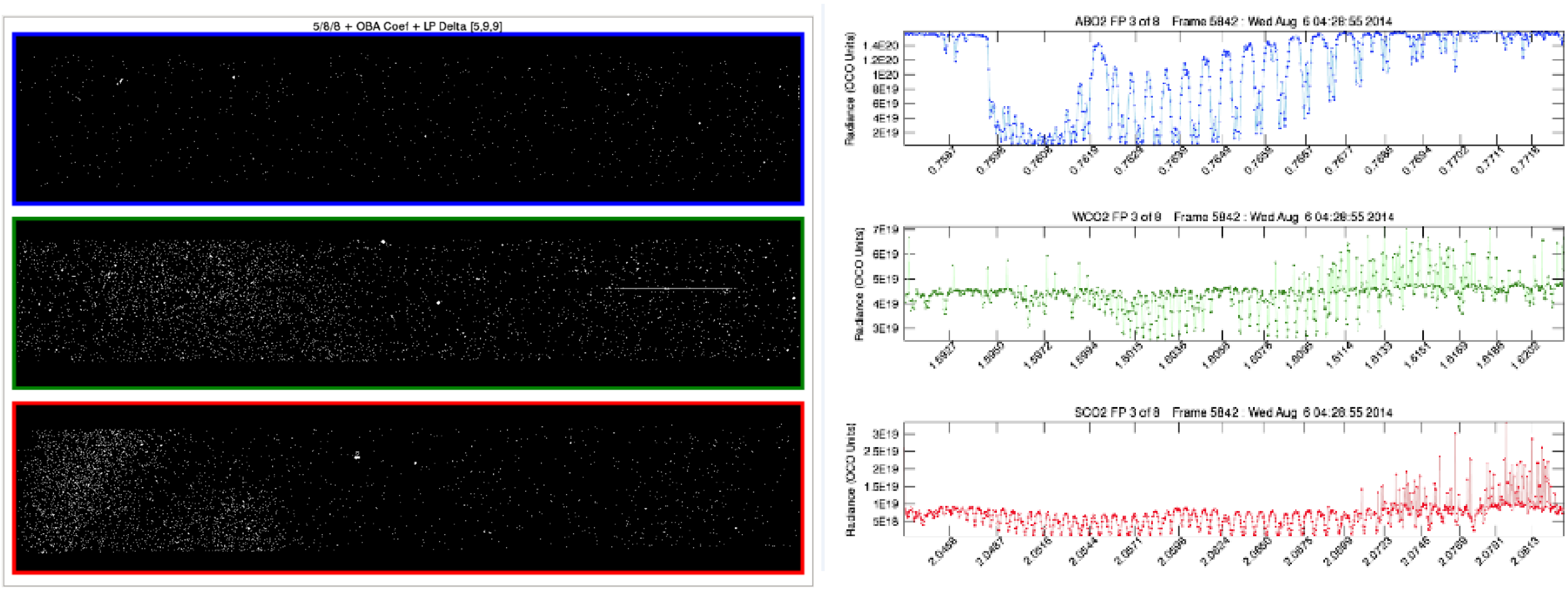
OCO-2 A-band spectra from the South Atlantic Anomaly

- The largest effects are seen in the O_2 A-band.
- An algorithm to screen the specific colors affected by cosmic rays has been implemented.

Bad Pixels

The number of bad pixels increased substantially between the pre-flight testing (April 2012) and launch (July 2014)

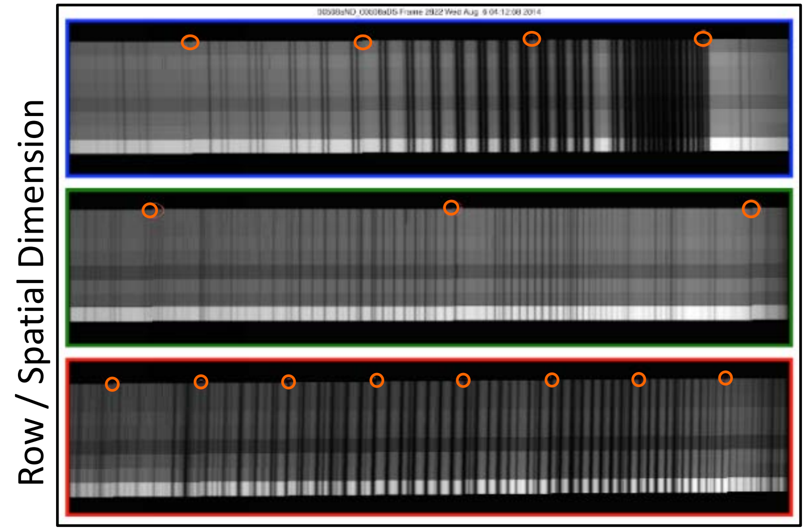
- Improved bad pixel maps were an early focus of Calibration team



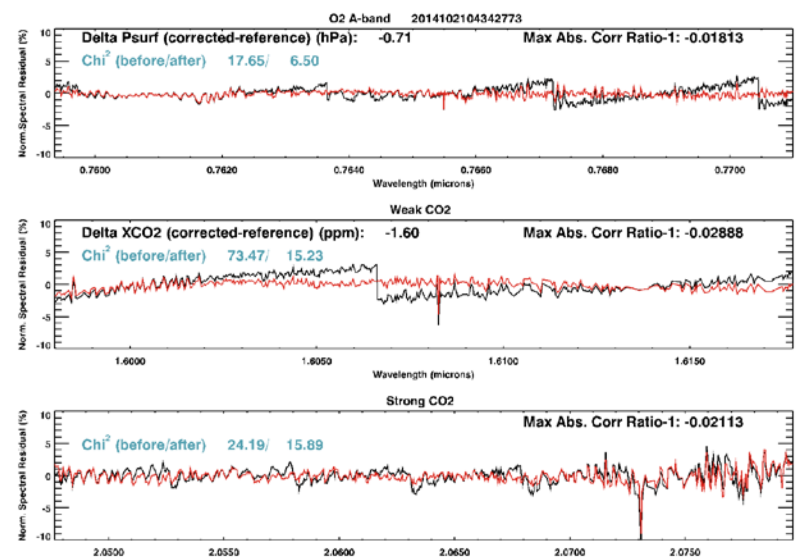
Bad pixels (left) are shown along with their associated bad samples (right) for the A-Band (top), Weak CO_2 (middle) and Strong CO_2 (bottom) channels

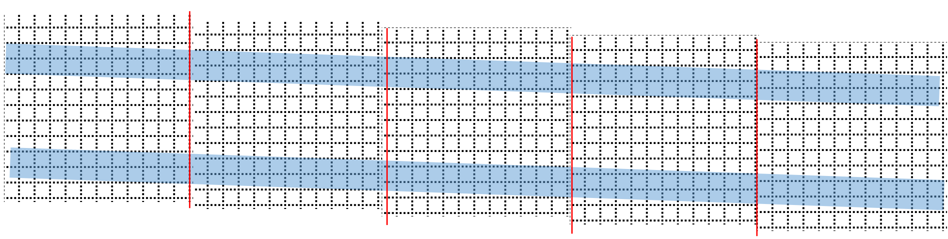
Radiance Discontinuities due to FPA Rotation (Clocking)

- The OCO-2 FPA's are rotated slightly with respect to the slit and grating
- With these *FPA Clocking Errors,* the FPA rows recording a given spatial footprint varies across the spectral range (columns)
- To record the same spatial footprint across an entire spectrum, the starting pixel of each spatial footprint can be adjusted from one column (wavelength) to another (by one pixel)



Christian Frankenberg & Fabiano Oyafuso

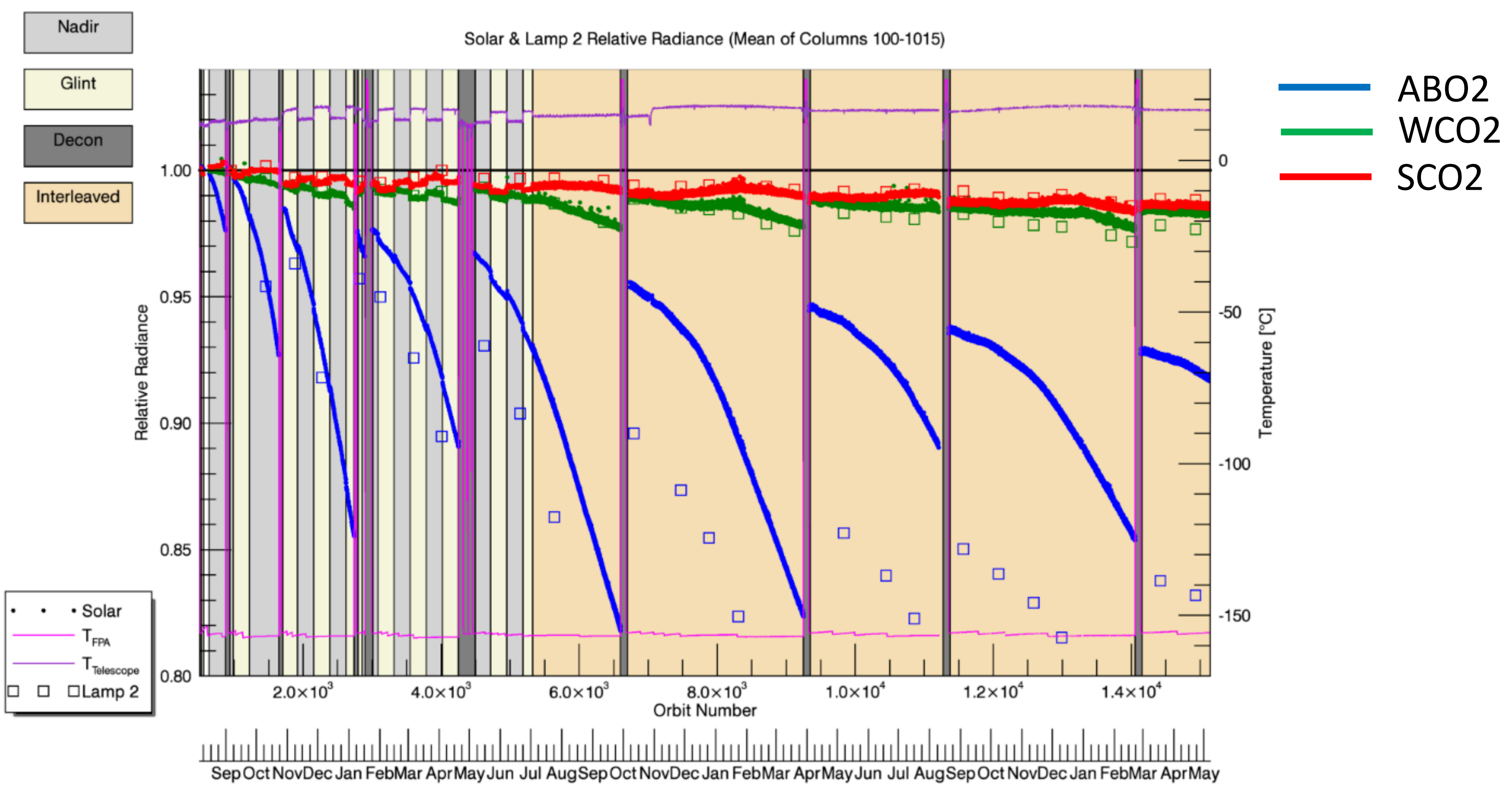




A-Band Channel Sensitivity Variations

- The sensitivity of the OCO-2 ABO2 channel has varied over time, while the WCO2 and SCO2 show much less variability
- The ABO2 sensitivity degradation has two components
  - A "fast degradation" reversed by decontamination activities
    - This component has been attributed to temporary degradation of the anti-reflection coating on the A-band focal plane array detector (FPA) due to the accumulation of a thin (< 100 nm) layer of ice on the FPA
  - A monotonic "slow degradation"
    - Lunar and Vicarious Calibration measurements indicate that this change is due to degradation of the solar diffuser rather than a throughput loss in the instrument

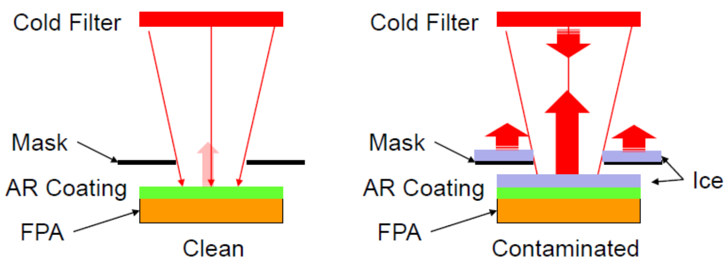
OCO-2 O_2 A-band Sensitivity Degradation



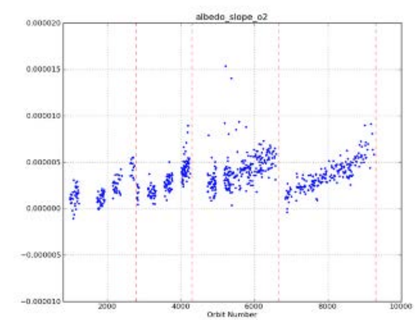
Rate of ice accumulation continues to decrease.

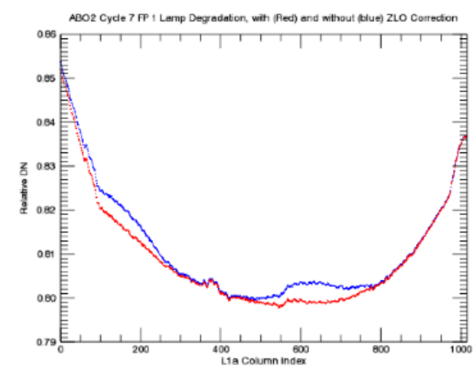
Correcting for the impact of ice accumulation on the FPAs

- The “fast degradation is associated with ice accumulation on the A-band (ABO2) focal plane array (FPA), that degrades the performance of the anti-reflection coating
- The ice contamination also introduces a scattered light that introduces a zero level offset (ZLO), which in turn introduces artifacts in the SIF and aerosol retrievals
- Both the reduced signal and the zero level associated with ice accumulation and the ZLO produced by the scattered light are corrected in version 8 L1B radiances

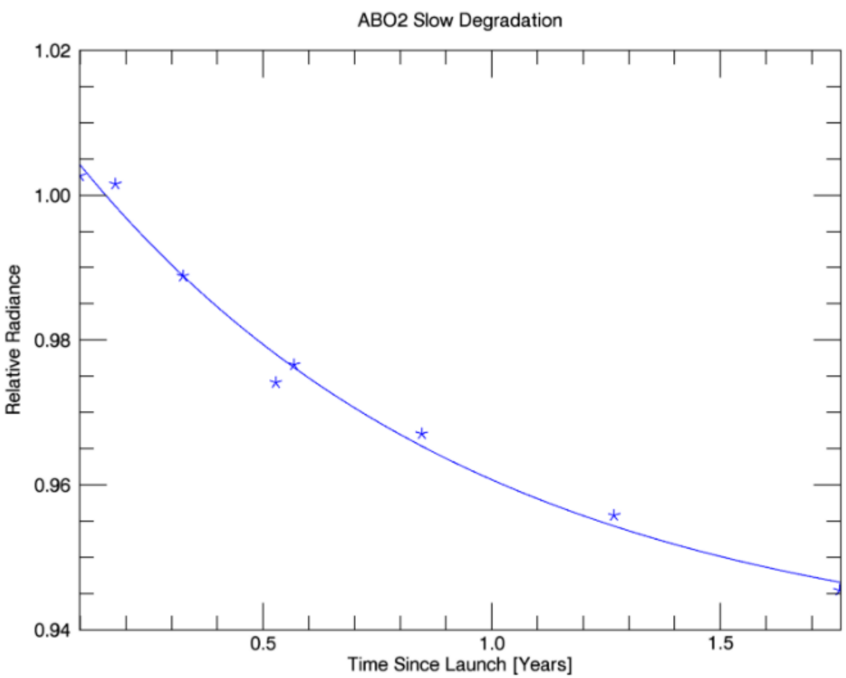


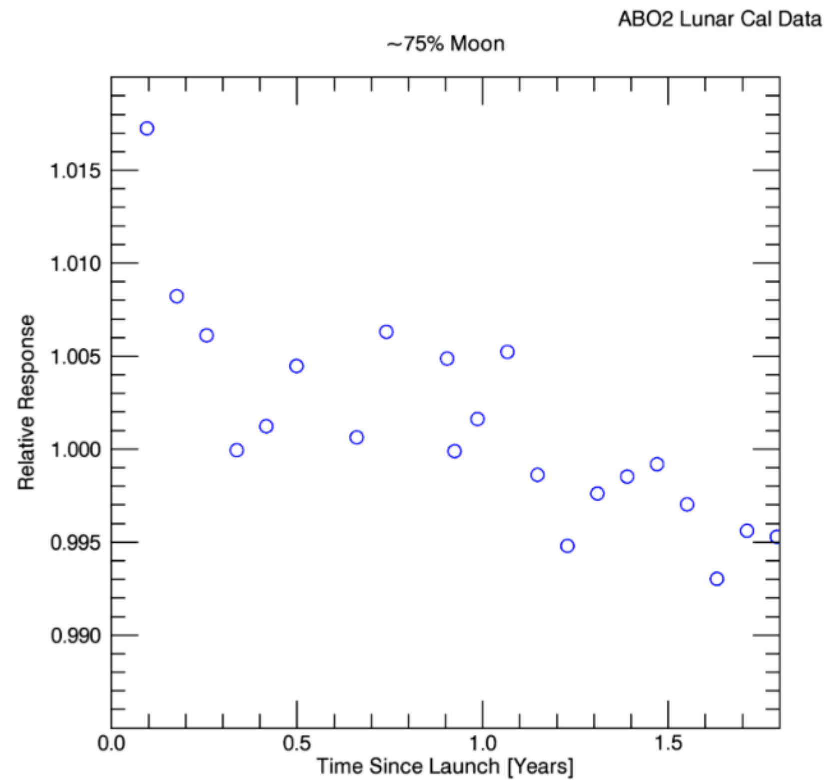
pre-v8 Apply EOF results: O2A Alb Slope





More Insight on the Slow Degradation

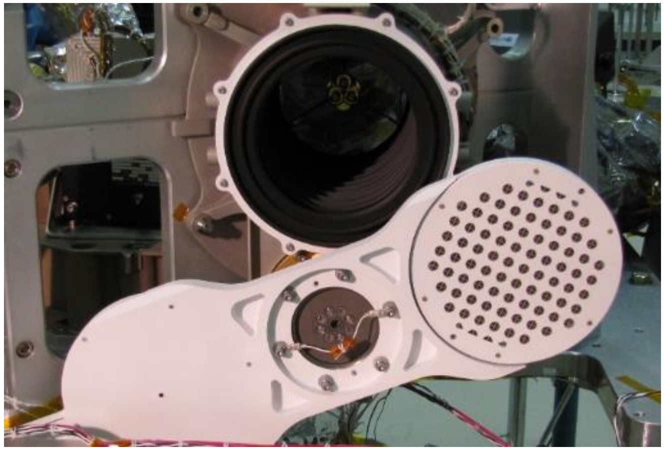




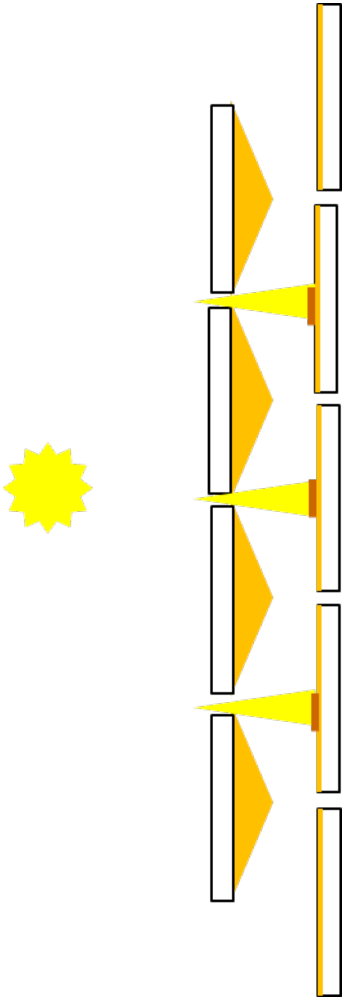
The “slow” component of the degradation is ***mostly*** due to the calibrator, not the instrument.

A reanalysis of the Lunar Calibration Data indicates that about 20% of the slow degradation is in the instrument optics

The Slow Degradation Mechanism



The solar diffuser consists of a pair of plates with a series of pin holes that are offset from each other, with a gold coated internal surface

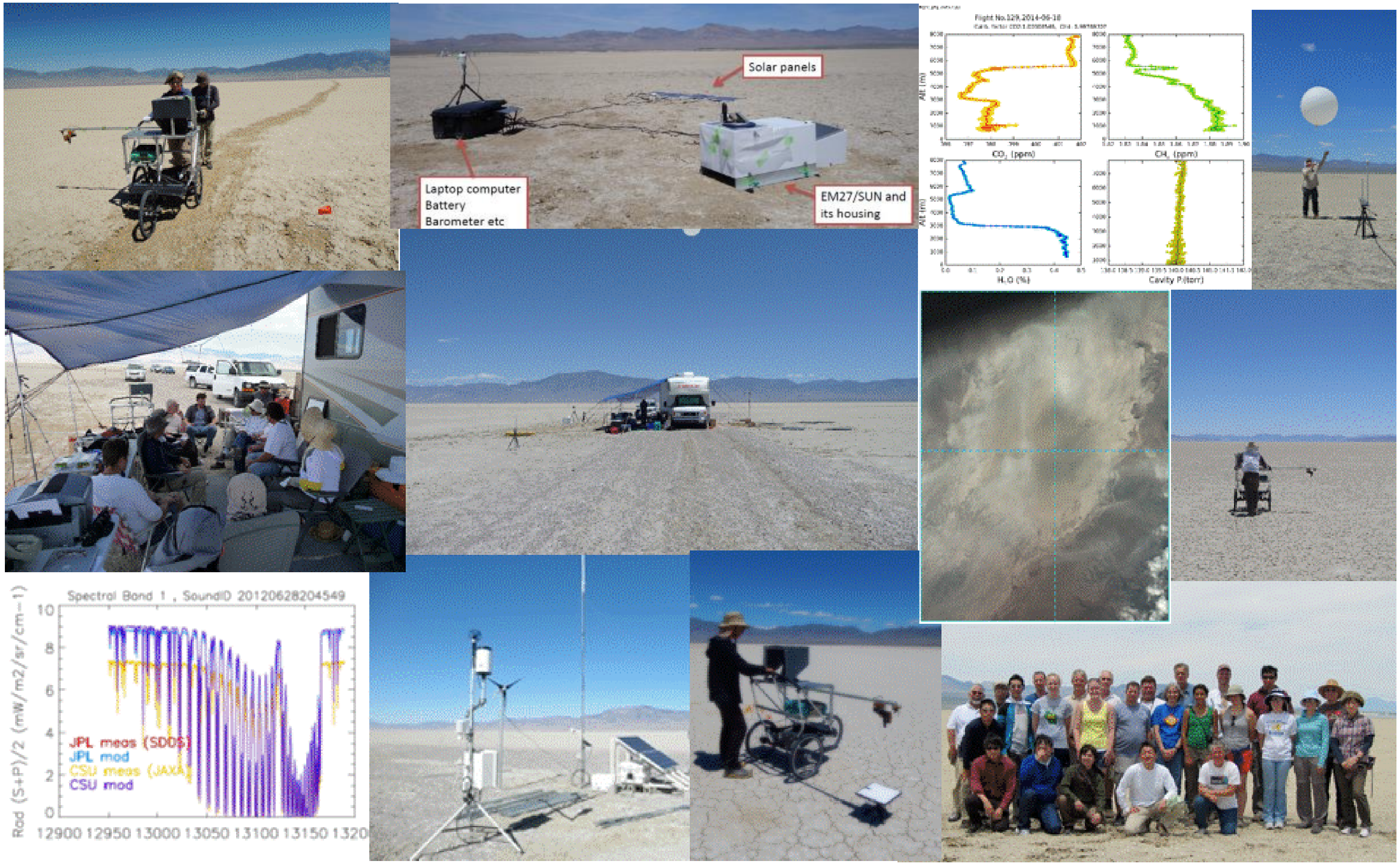


Cartoon showing basic principle only

Hypothesis;

- As solar UV interacts with contaminants on the gold coated inter surface, it causes darkening.
- The most severe darkening is expected in the ABO2 Channel
- The rate of the darkening is uniform, but could not be predicted prior to launch.

Vicarious Calibration in Railroad Valley



Vicarious Calibration Campaigns in Railroad Valley have continued to play a critical role in GOSAT inflight calibration, and now play a similar role for OCO-2.

Summary

- The GOSAT and OCO-2 instruments were extensively characterized and calibrated prior to launch
- As always happens, the instrument you test on the ground is not the one that arrives in space
  - Significant increase in bad pixels in CO_2 bands
  - Sensitivity to non-uniformly illuminated footprints
- Occasionally, you miss things in ground testing
  - Performance reserve is a major contributor to mission success
- Characterizing and correcting for these issues on orbit has been a challenge, but has been enabled by a robust calibration program
- Future missions will face many of these challenges, as well as others associated with:
  - The 2.3 micron channel, which is not shared by OCO-2
  - Those specific to instrument design and vantage point