The Orbiting Carbon Observatory-2 (OCO-2) Ground and Flight Calibration

David Crisp

OCO-2 Lead Scientist

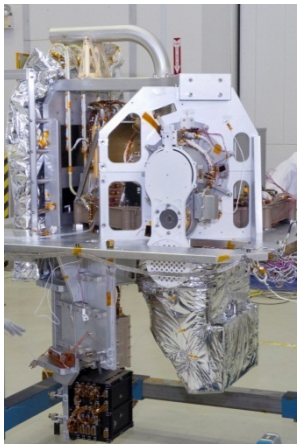
Jet Propulsion Laboratory, California Institute of Technology

9 November, 2012

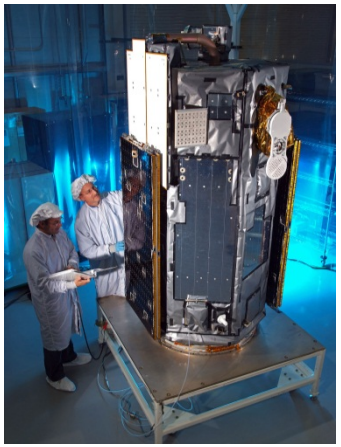
Copyright 2012 California Institute of Technology.
Government sponsorship acknowledged.

The OCO-2 Mission is Under Development

3-Channel Spectrometer (JPL)



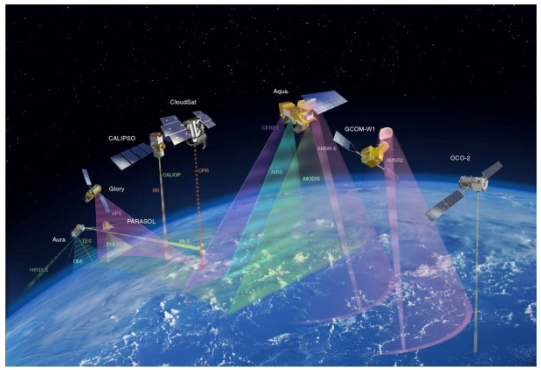
Dedicated Spacecraft Bus (OSC)



TBD Launch Vehicle

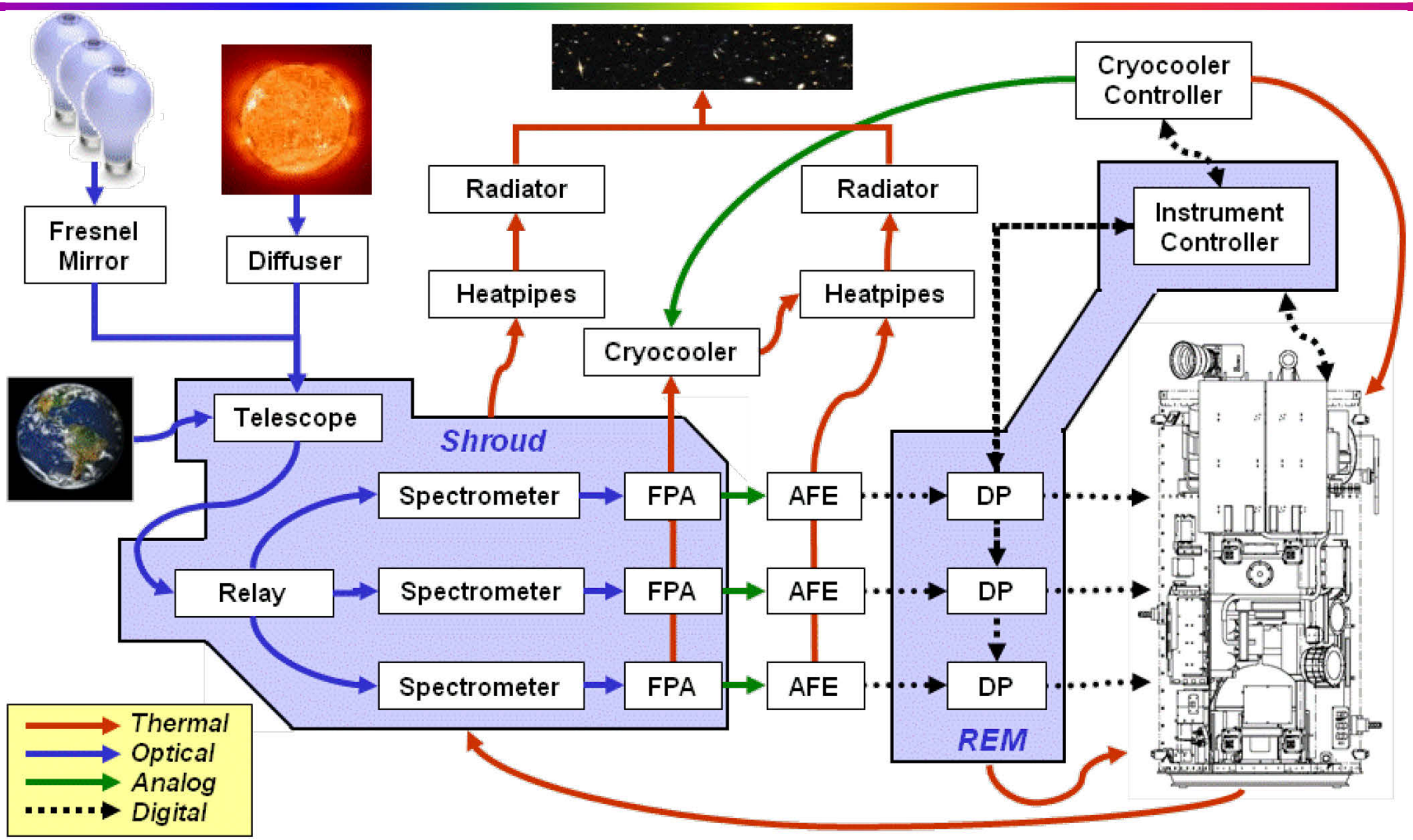
Mission Operations (OSC)

Formation Flying as Part of the A-Train Constellation

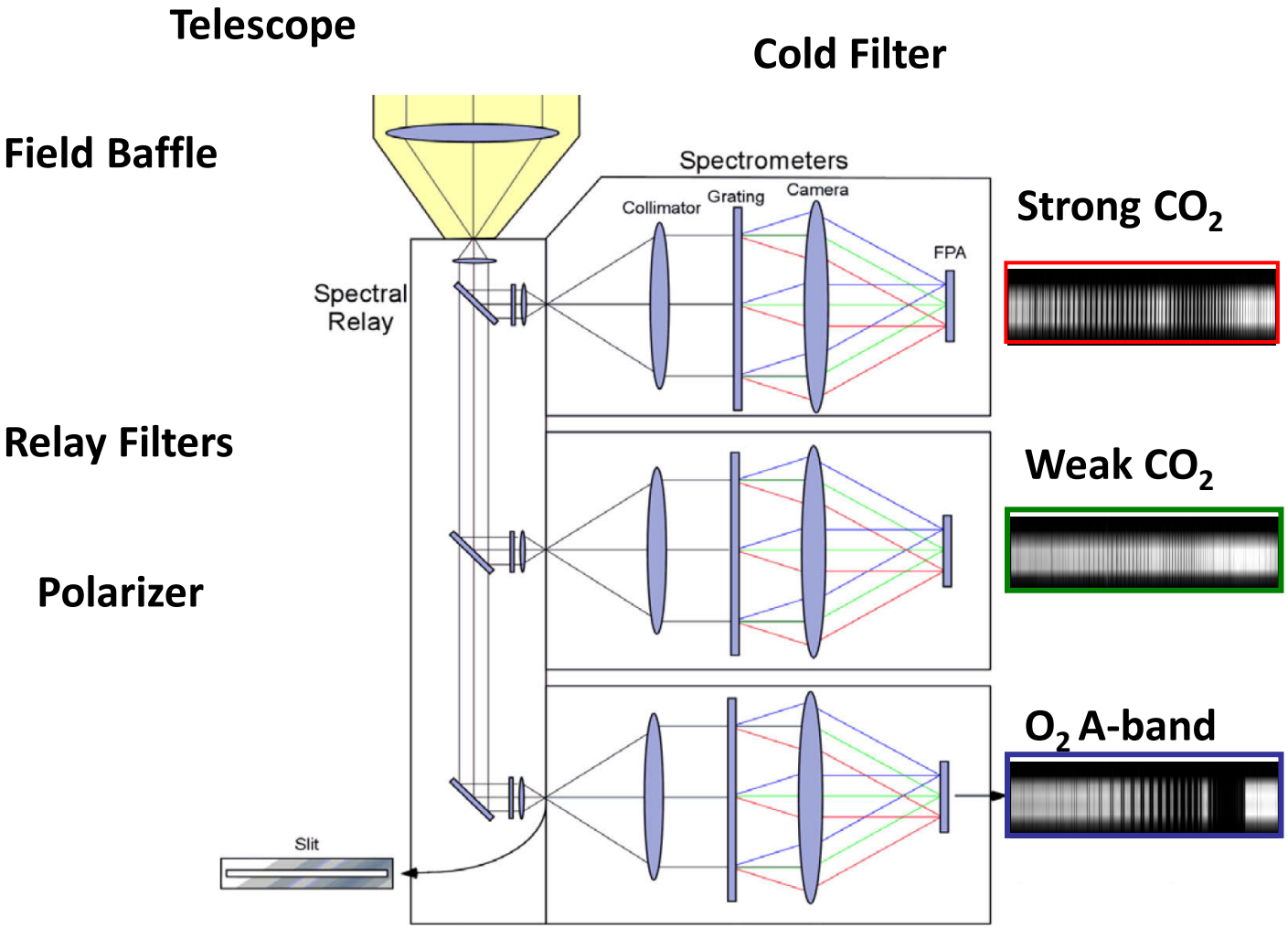


NASA NEN (GSFC) and SN (TDRSS)

Instrument Block Diagram

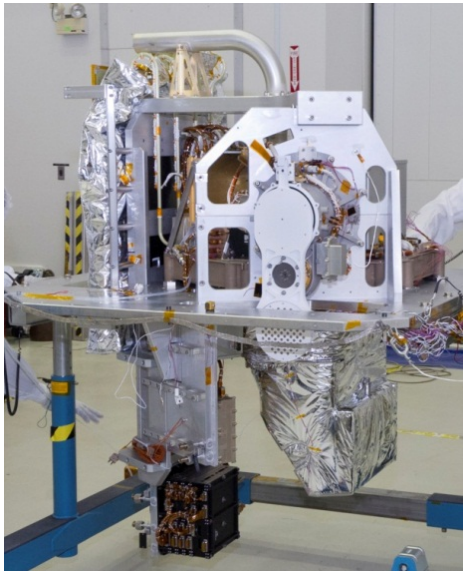


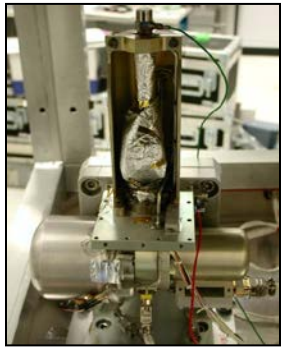
Instrument Optical Block Diagram



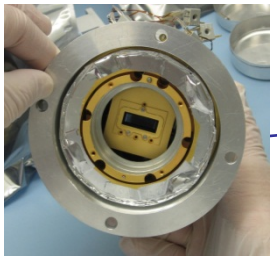
The OCO Instrument – Optimized for Sensitivity

- 3 co-bore-sighted, high resolution, imaging grating spectrometers
  - Resolving Power ~20,000
  - High Signal-to-Noise Ratio
  - Collects 4 to 8 cross-track footprints at 3 Hz





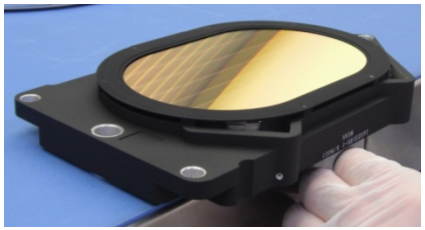
Cryocooler

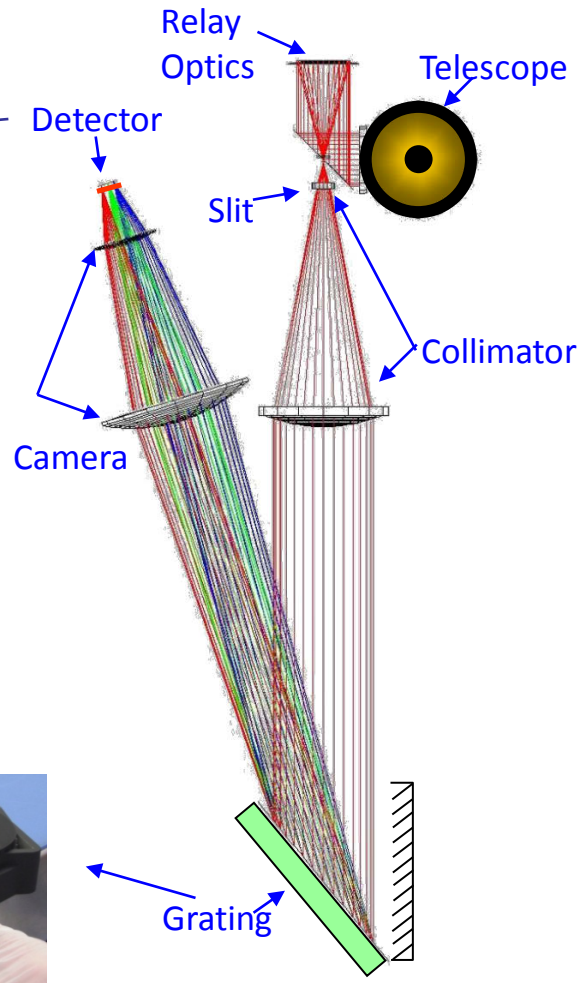


O_2 A-Band

CO_2 1.61μm Band

CO_2 2.06 μm Band





key components of each channel.

Pre-Launch Testing of the OCO-2 Instrument

- The OCO-2 instrument can only be operated under high-vacuum conditions, simulating the conditions of space.
- Prior to launch, the OCO-2 instrument must be extensively tested to ensure that
  - It can survive the environments of launch on on-orbit operation
  - It will meet its geometric, radiometric/polarimetric, and spectroscopic performance requirements
  - Its performance is adequately calibrated to enable the analysis of its results
- Some instrument properties can be recalibrated on orbit
  - slit alignment, zero level offset, pixel-to-pixel radiometric gain, spectral dispersion
- Others can only be established during pre-launch testing
  - Instrument line shape, radiometric linearity, polarization

The OCO-2 Instrument Test Facility

- We used the JPL 10-ft Chamber, a special, 3-meter diameter, space simulation chamber at the Jet Propulsion Laboratory (JPL)

- In addition to the typical features of a space simulation chamber, this chamber was modified for the OCO mission by installing
  - a “calibration deck” for mounting optical calibration equipment
  - a 0.2-meter diameter window on the top of the chamber that allows the instrument to see out, through the calibration deck
  - a “heliostat” on the roof for tracking the sun

- With this system we can record direct measurements of CO_2 in the Earth’s atmosphere prior to launch.

- These heliostat measurements have played a key role in the characterization and calibration of the OCO and OCO-2 instruments

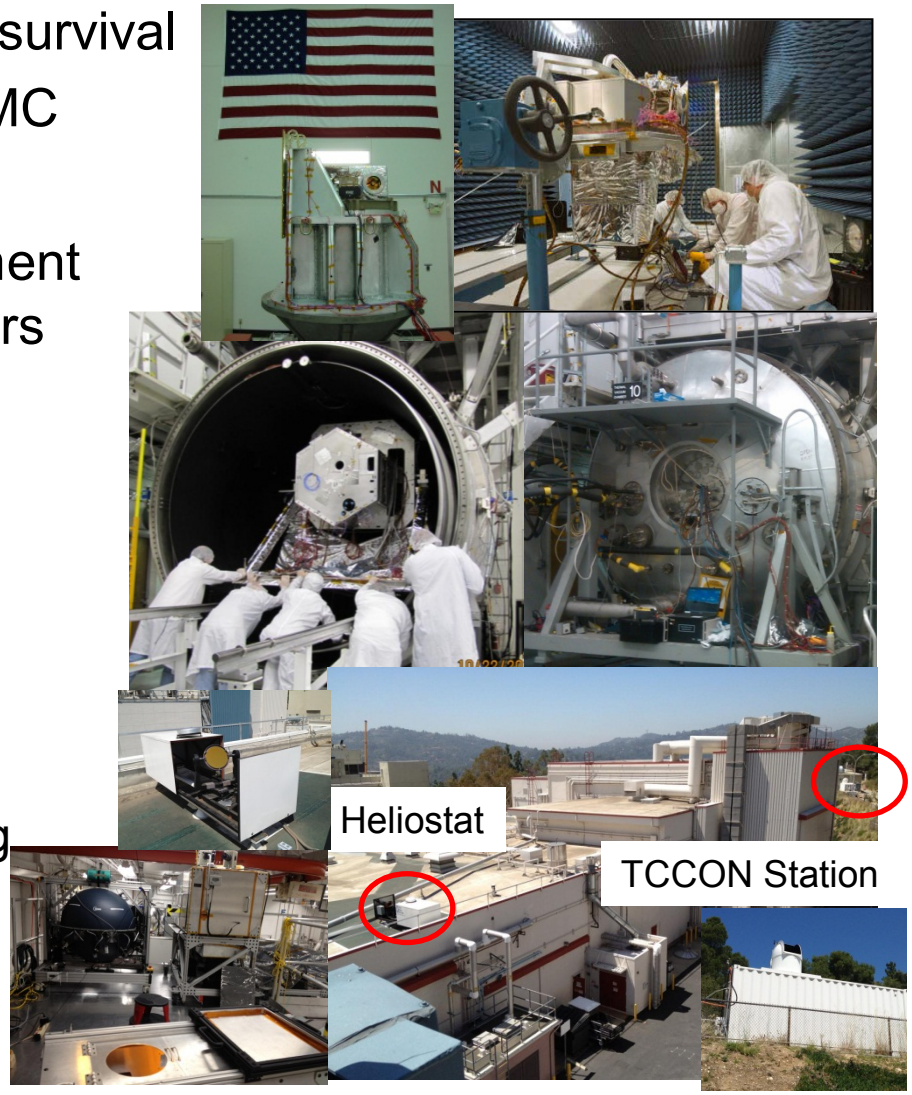
Pre-Flight Instrument Calibration and Characterization

Flight qualification ensures instrument survival

- Thermal, vacuum, vibration, EMI/EMC

Pre-flight testing quantifies key Instrument performance and knowledge parameters

- Geometric
  - Bore-sight alignment
- Radiometric
  - Zero-level offset (bias)
  - Gain, Gain non-linearity
- Spectroscopic
  - Spectral range, resolution, sampling
  - Instrument Line Shape (ILS)
- Polarization
- Instrument stability

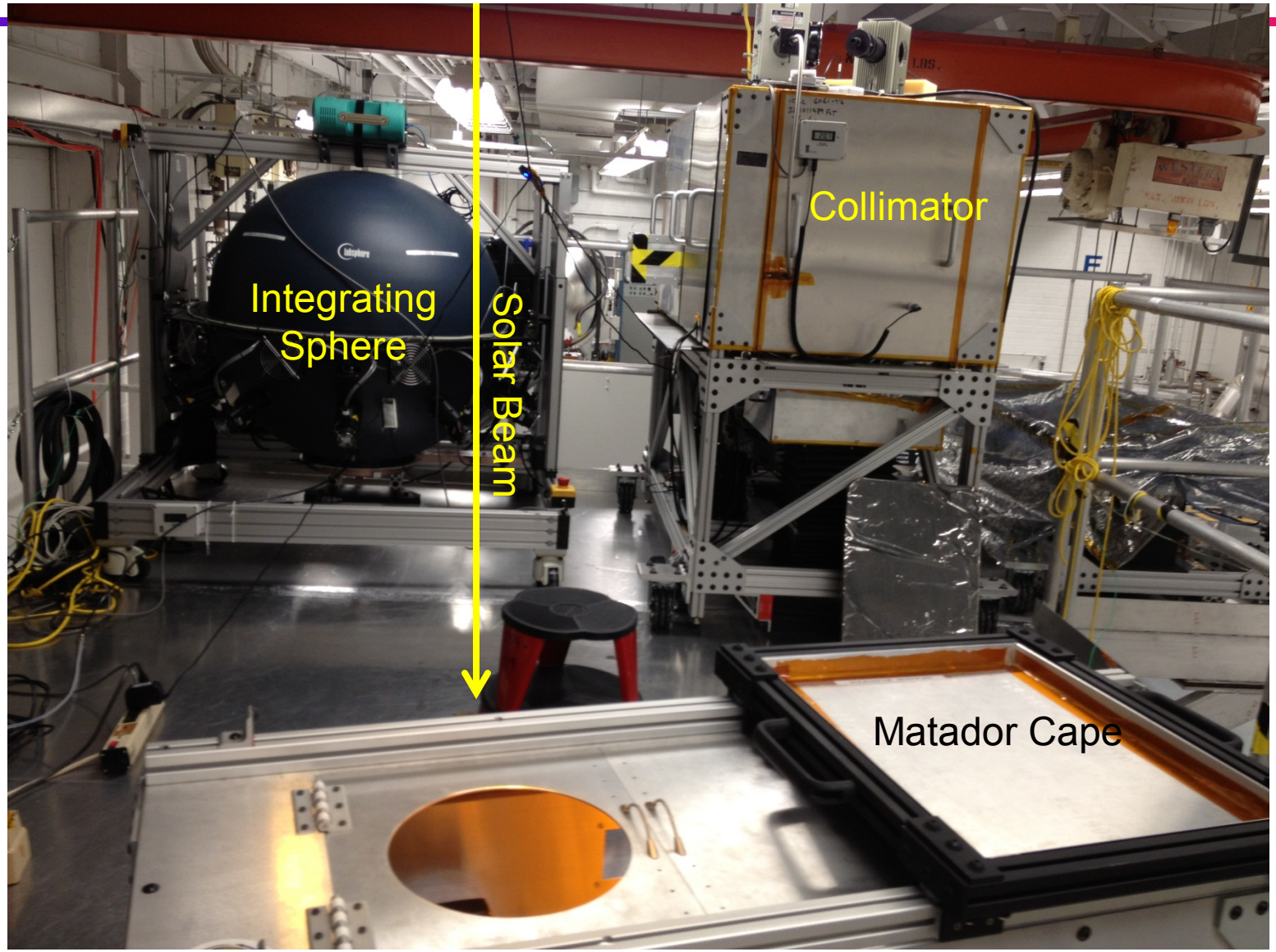


Optical Ground Support Equipment

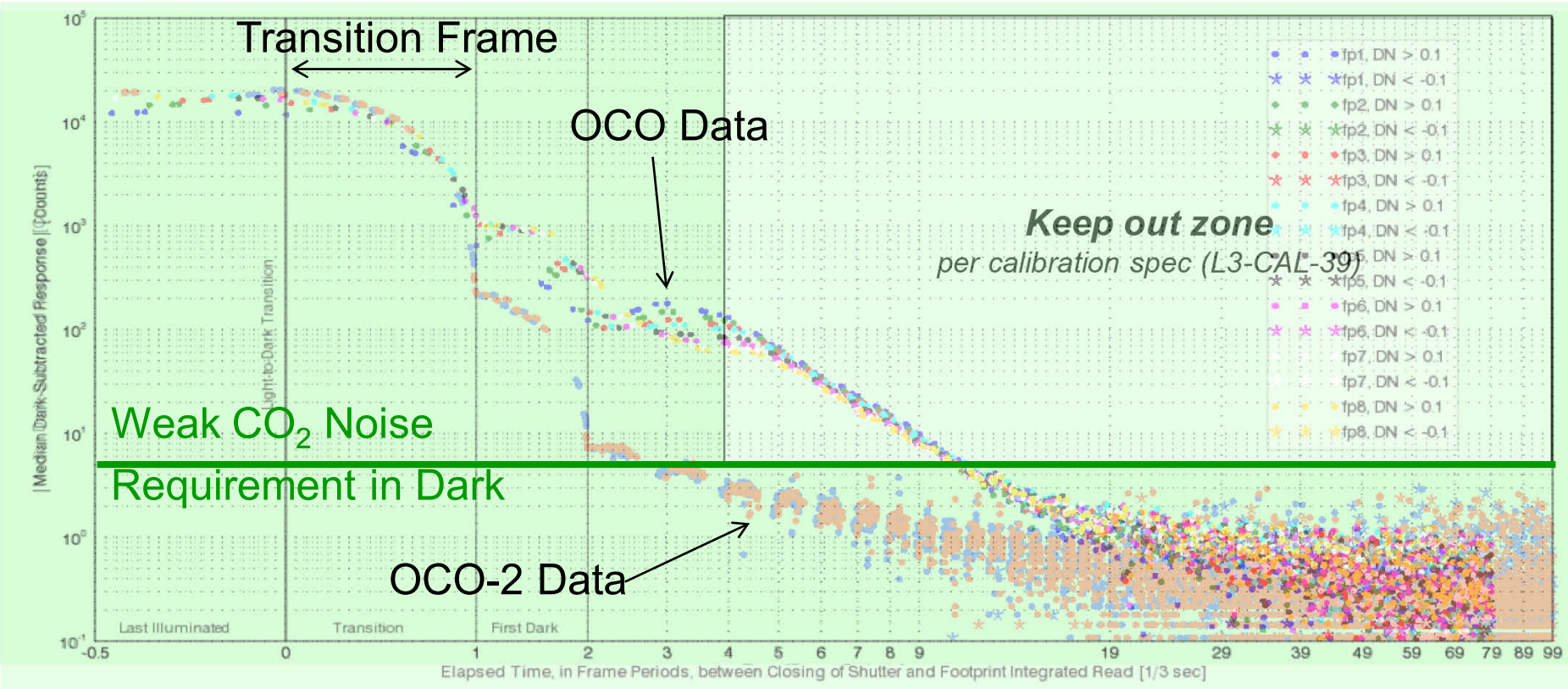
This test employed four types of optical ground support equipment

- **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 the 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

GSE Deck with Heliostat M3/M4 "Periscope"



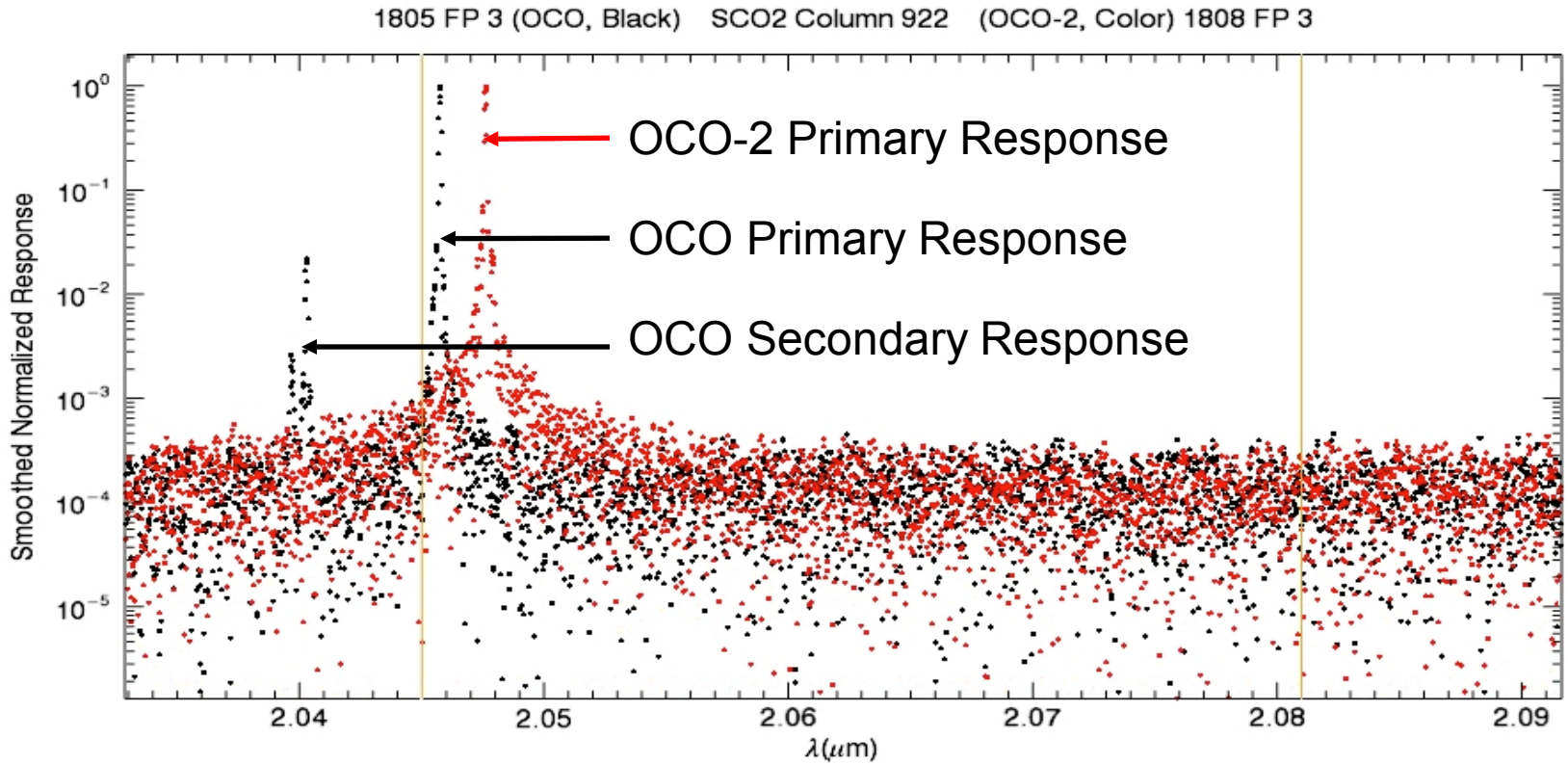
Residual Image Meets Specification



- Other two channels show even better performance
- Based on the above data, it appears that we will ***not*** need a Residual Image Correction Algorithm (RICA) for OCO-2, but still need to confirm that with Level 2 retrievals

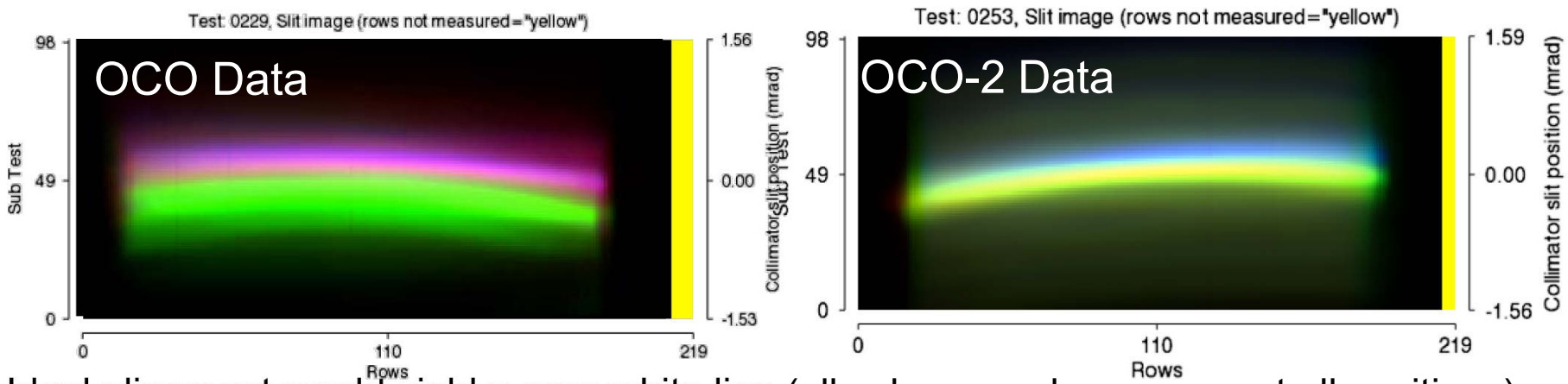
Spectral Stray Light Risk Retired

- OCO showed a significant spectral leak, especially low-λ side of Strong CO_2
- For OCO-2, FPA masks were changed to cast shadows on the edges of FPAs
- This fixed the problem



Spectrometer Slits Meet Specification

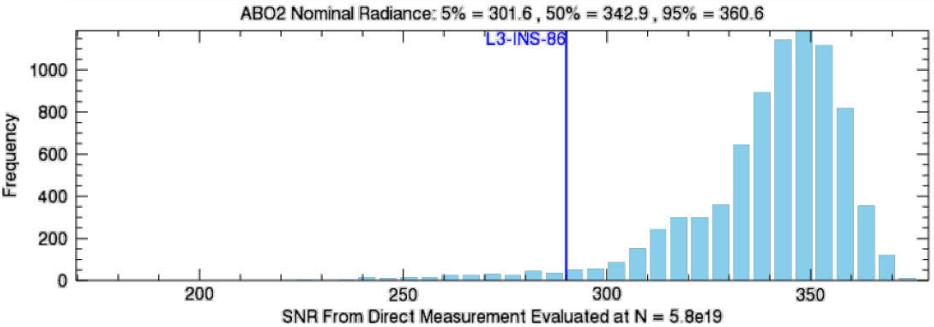
- OCO
  - Weak CO_2 slit moved ~0.4 mrad relative to the other two after vibration
  - Once discovered, the instrument was vibrated again and no significant motion was observed - Decided to fly as-is
- OCO-2
  - All slits are within ~0.15 mrad (spec is < 0.26 mrad)
    - A-band is displaced 0.13 - 0.15 mrad from the SCO2 slit
  - Between TV1c and TV2 no significant changes were observed

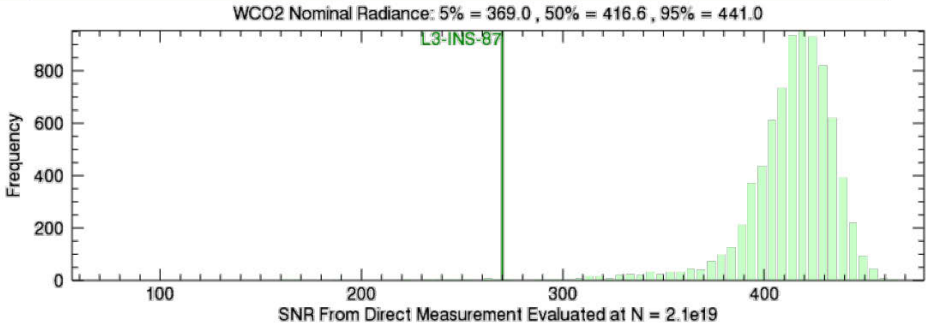


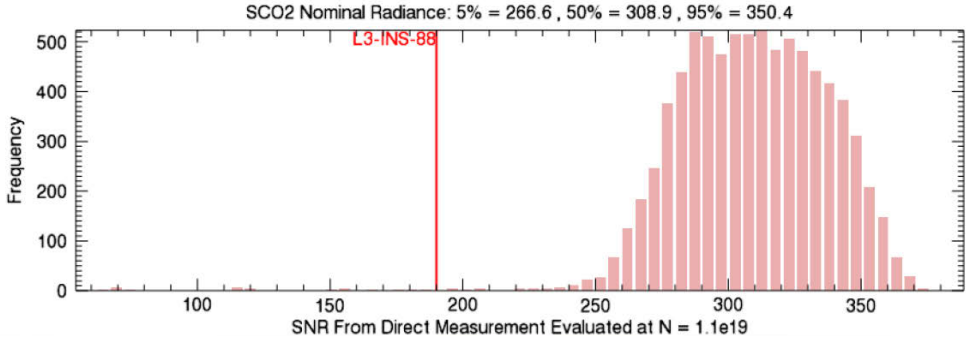
Ideal alignment would yield a grey-white line (all colors equal response at all positions)

Signal-to-Noise Ratio Meets Spec

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

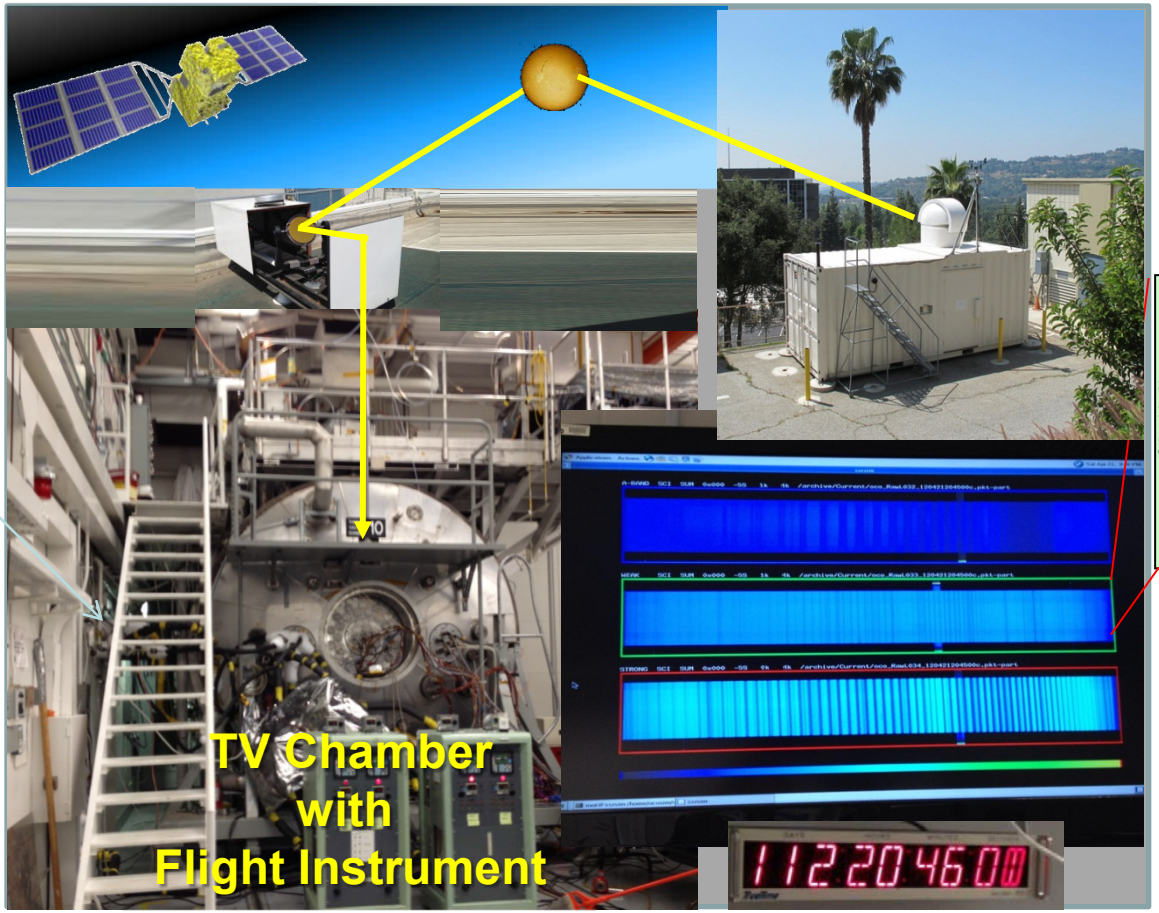




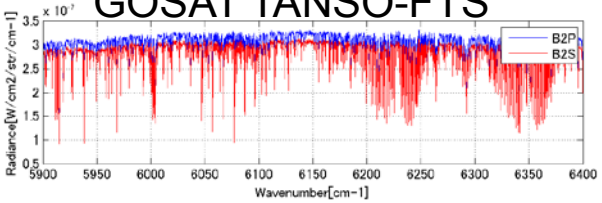


Pre-Flight Instrument Qualification and Characterization

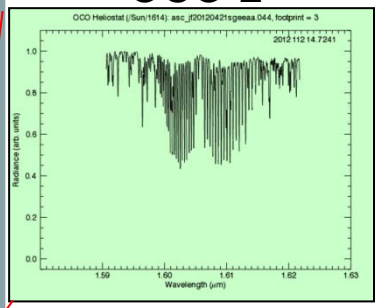
Observations of the sun with the flight instrument taken during the thermo-vacuum tests provided an end-to-end test of the instrument performance.



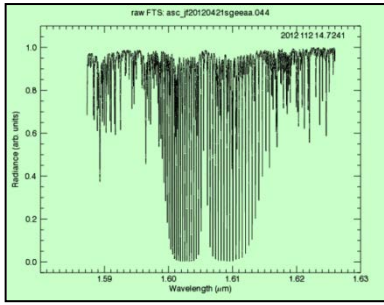
GOSAT TANSO-FTS



OCO-2



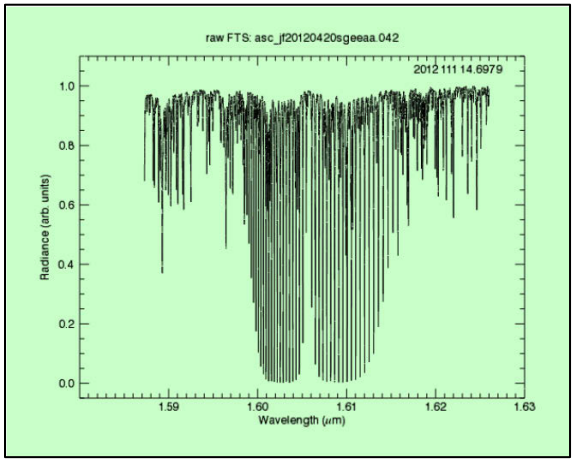
TCCON FTS



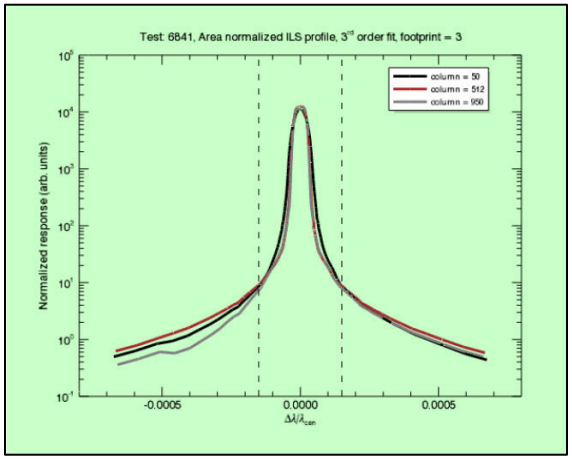
On April 20, 2012, simultaneous observations over the LA Basin were taken by GOSAT, the JPL TCCON Station, and the OCO-2 flight Instrument. Analysis is ongoing.

Initial Spectral Calibration Validated

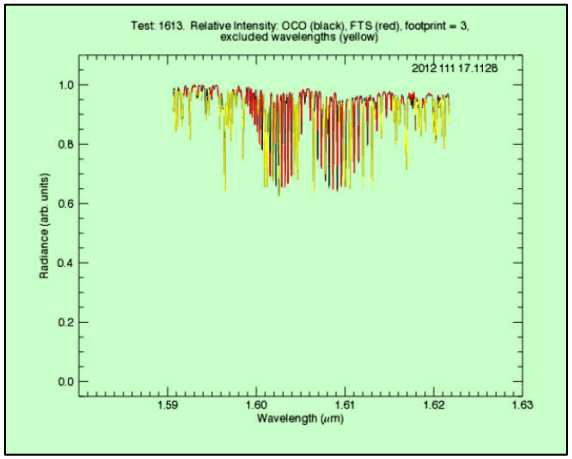
TCCON Data + OCO-2 Instrument Line Shape = Synthetic OCO-2 Spectra



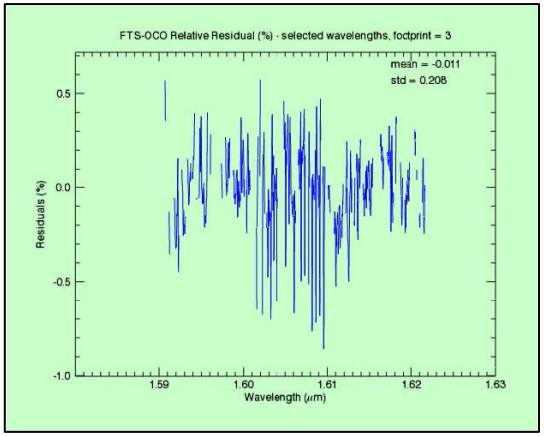
+



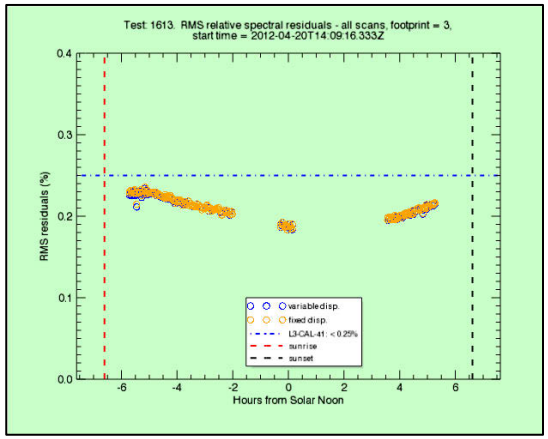
=



Delta for a single measurement (+/- 0.2% - 1σ)

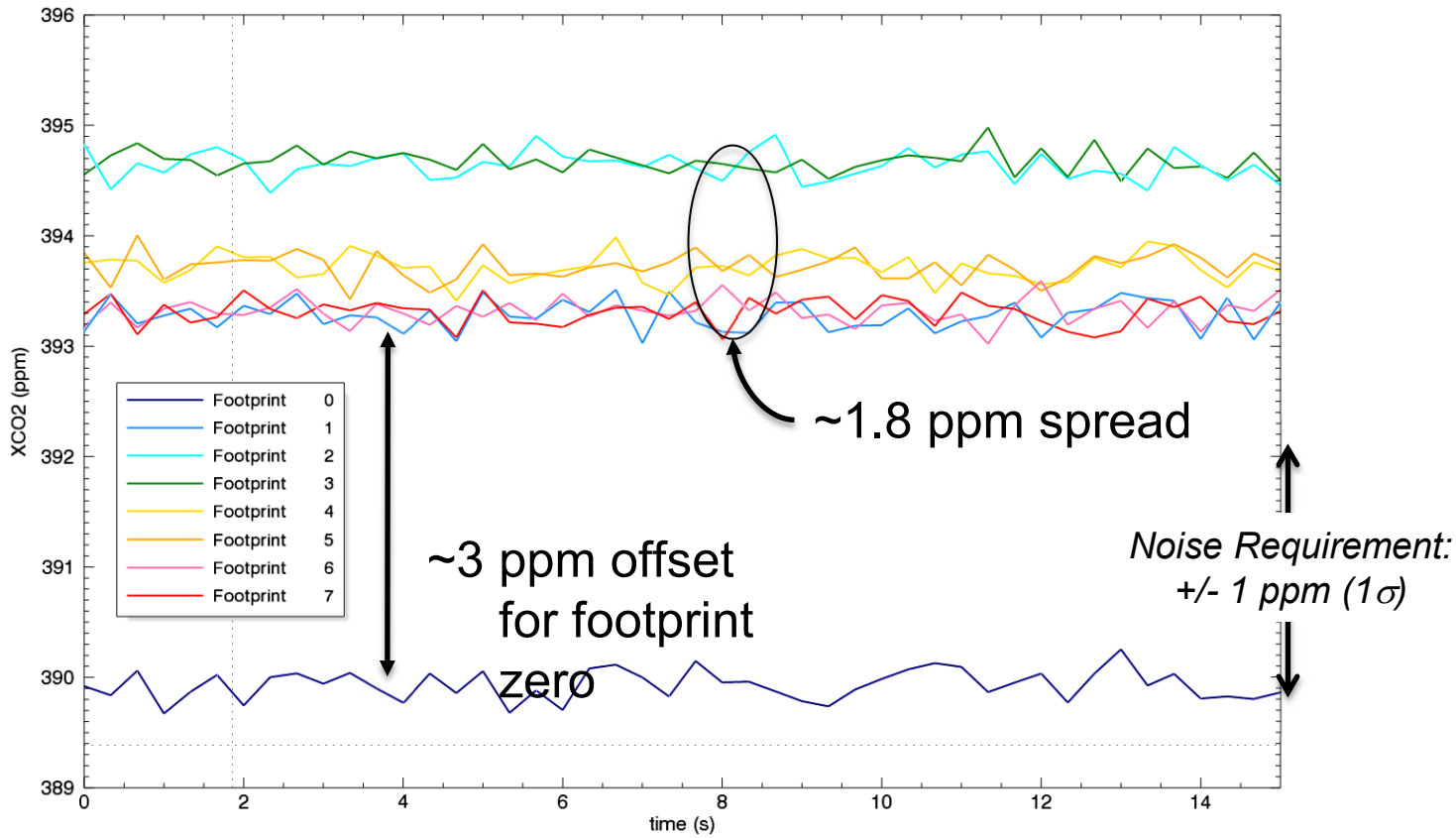


Differences over the course of the day



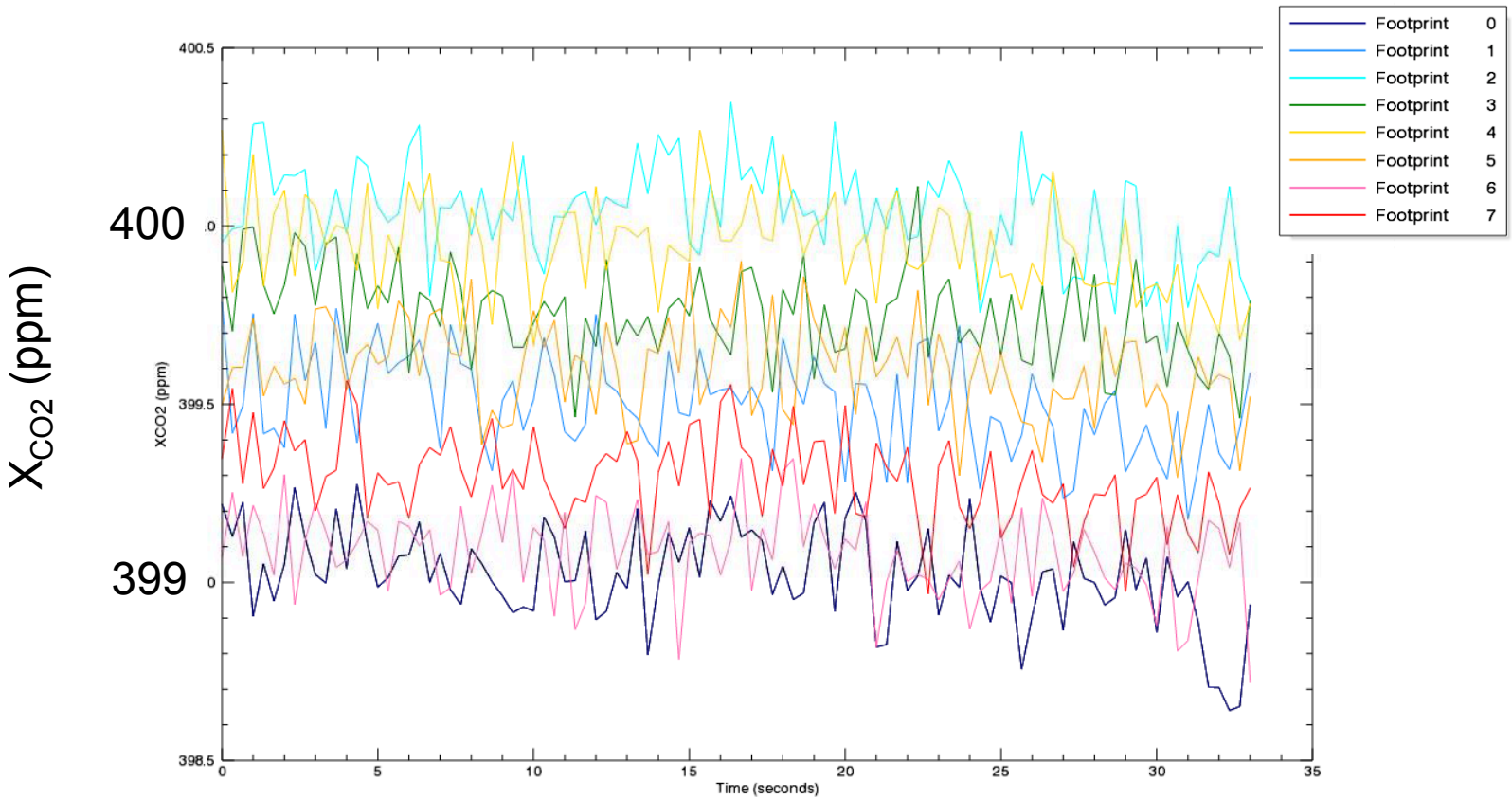
First Attempt at Retrieving X_{CO2} from OCO-2

Each line represents one of 8 independent spatial measurements made each 1/3 of a second



- First attempts to retrieve CO_2 values from heliostat data show extremely low measurement noise
- Spread shows we still have work to do in the calibration parameters

X_{CO2} results are Still Improving



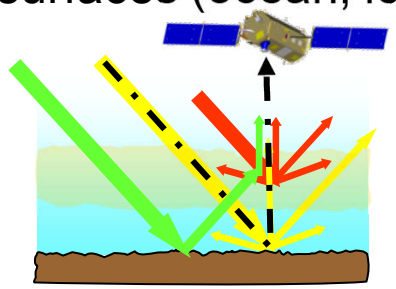
After a few iterations, the calibration yields ~1.1 ppm spread, but may still have a high bias, indicating that we still have some work to do.

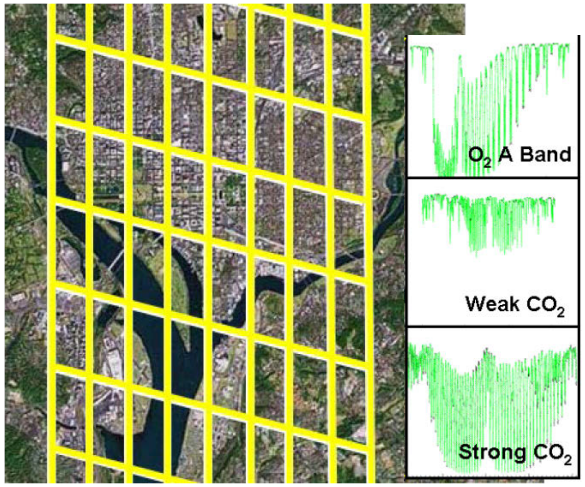
Observation Modes Optimize Sensitivity and Accuracy

Nadir Observations:

+ Small footprint (< 3 km^2)

– Low Signal/Noise over dark surfaces (ocean, ice)

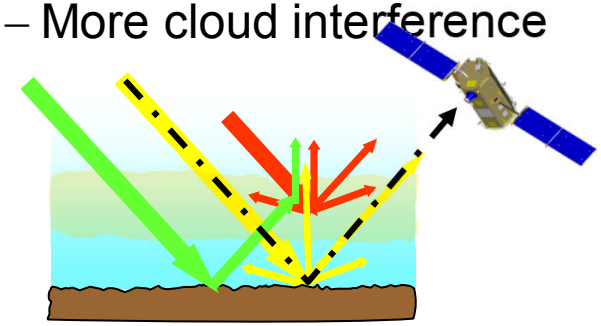


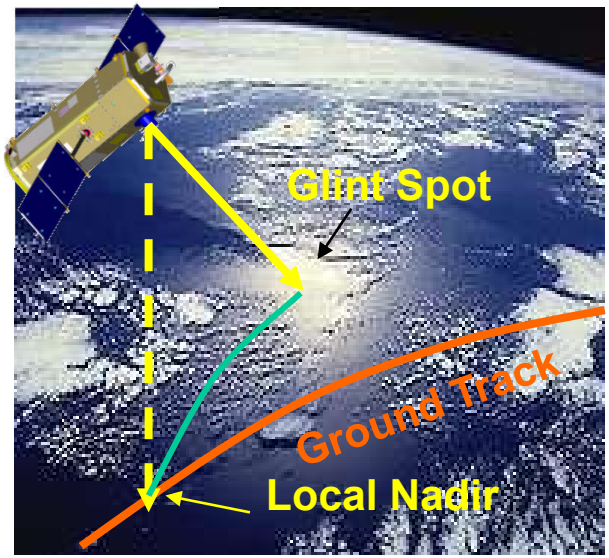


Glint Observations:

+ Improves Signal/Noise over oceans

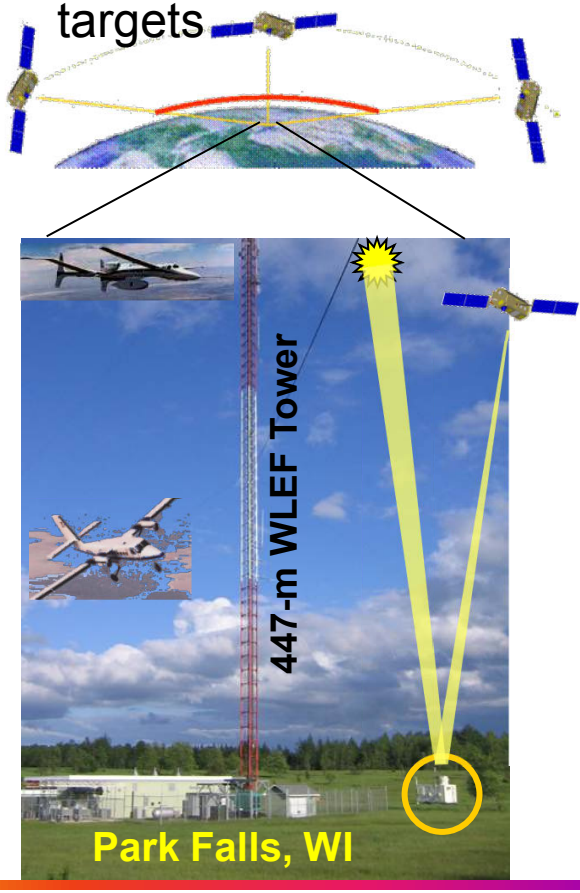
– More cloud interference



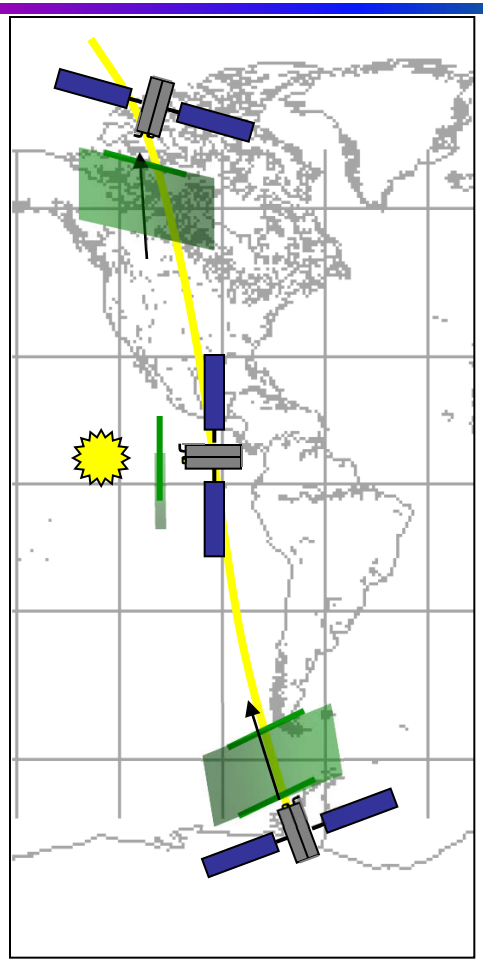


Target Observations:

- Validation over ground based FTS sites, field campaigns, other targets

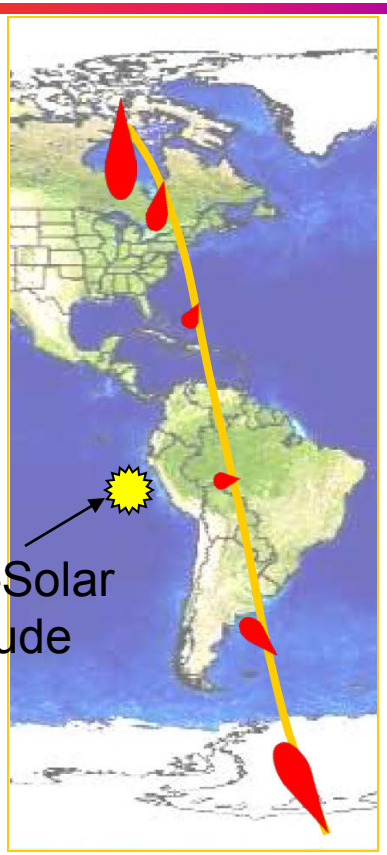


The OCO Footprint



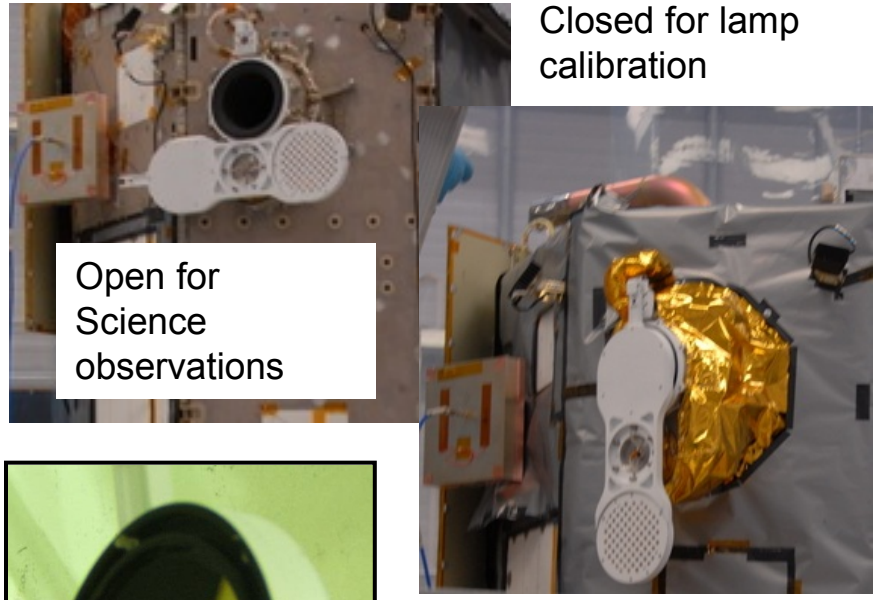
Slit and Footprint orientation and overlap as a function of position in orbit track.

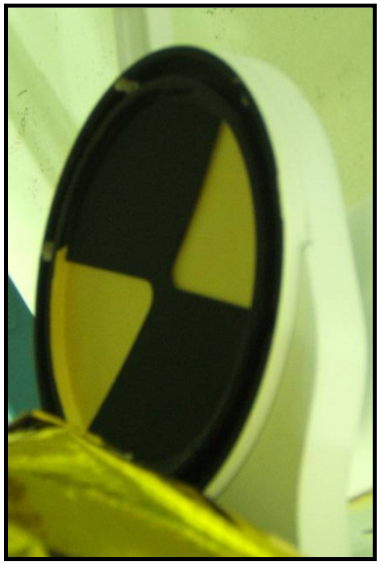
- The azimuth orientation of the OCO spacecraft varies along the orbit track to
  - Maintain alignment of the spectrometer slits orthogonal to the plane defined by the sun-surface spacecraft
  - Maintain constant power on the solar panels
- This approach produces an footprint shape and size that varies along the orbit
  - Surface footprint
  - "Atmospheric" footprint



Orientation and shape of horizontal contribution functions for Nadir observations

Verifying Radiometric Calibration: The On-board Calibration System



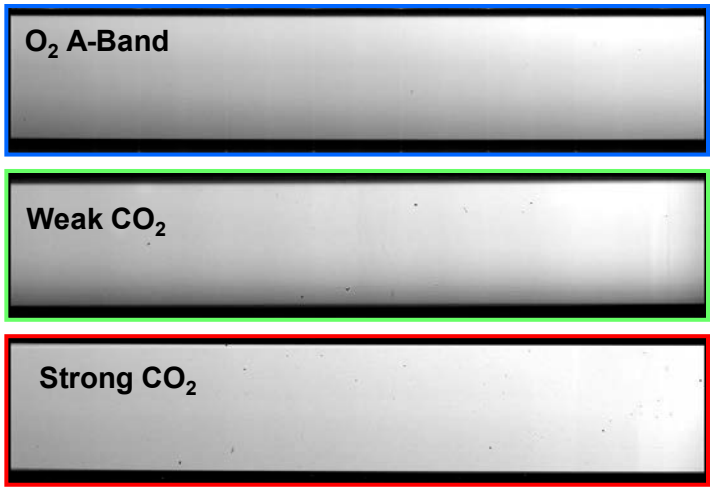


Reflective diffuser

Telescope baffle assembly, showing lamps for flat fields

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



Lamp “flat fields” from each channel.

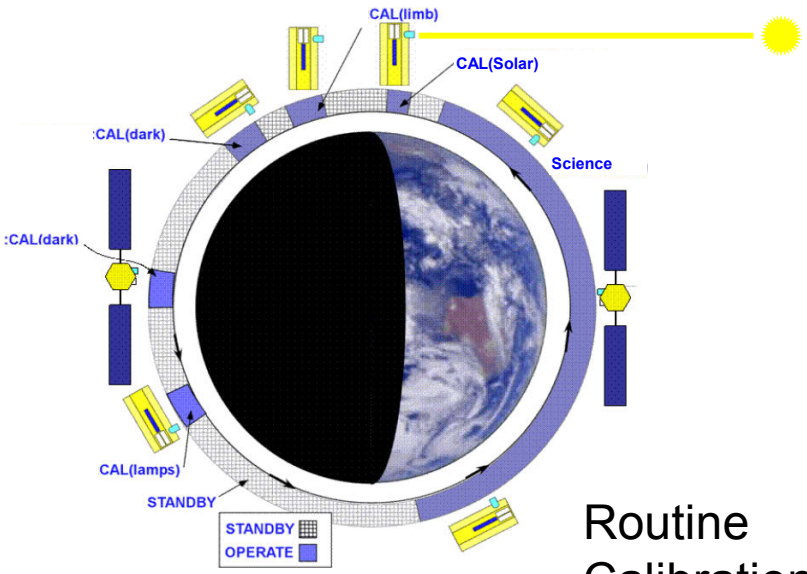
On-orbit Calibration Operations

Routine Calibration (every orbit)

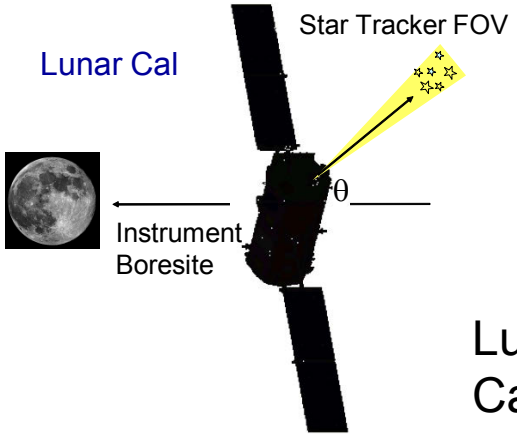
- OCO-2 will look at the sun through a solar diffuser
- Dark calibration with aperture door closed and lamps off

Special Calibration Activities

- Solar Doppler calibration (look at the sun through the entire daylight side of an orbit – 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

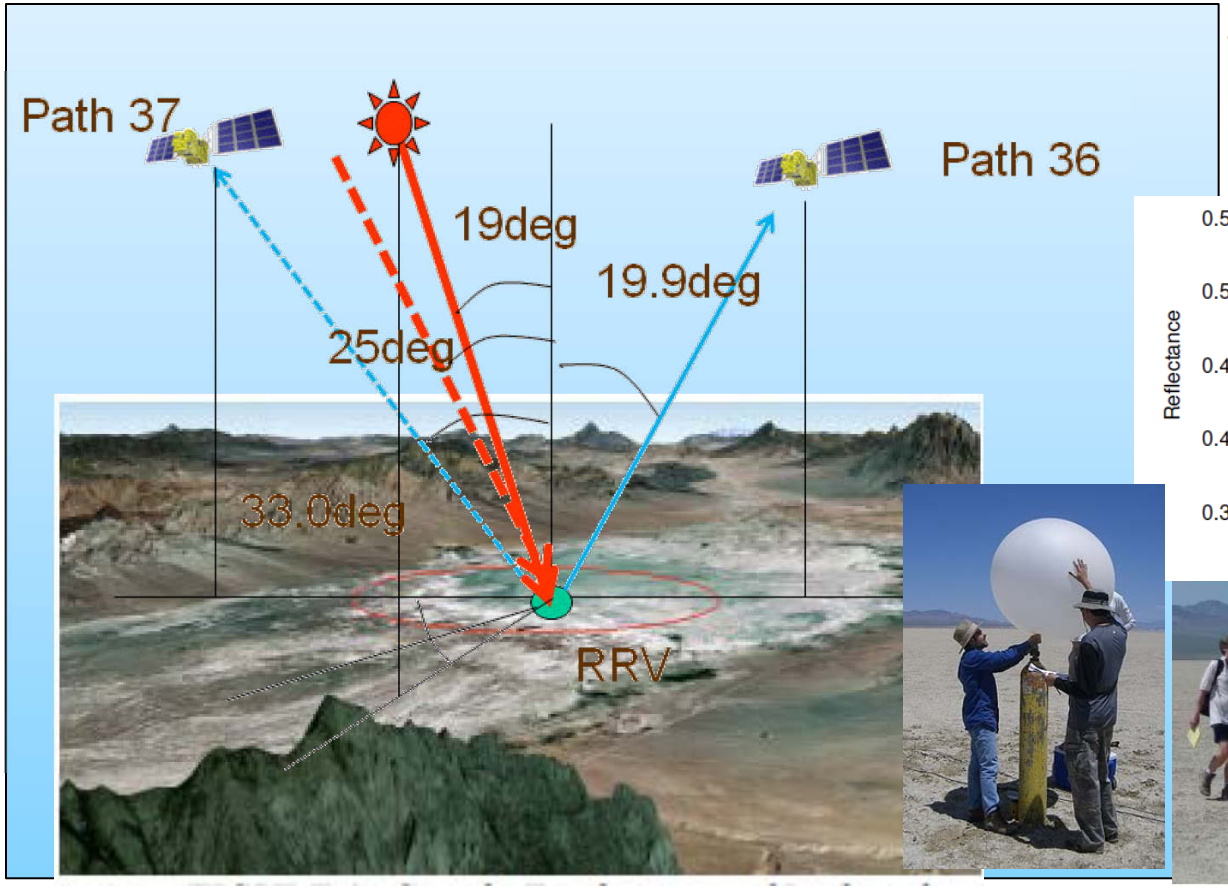


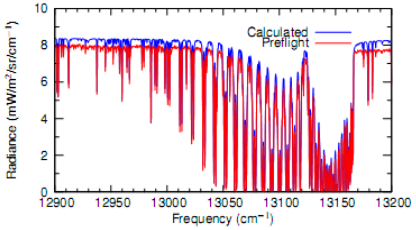
Routine Calibration

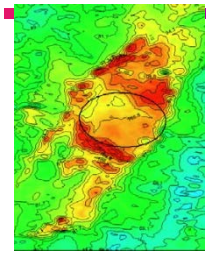


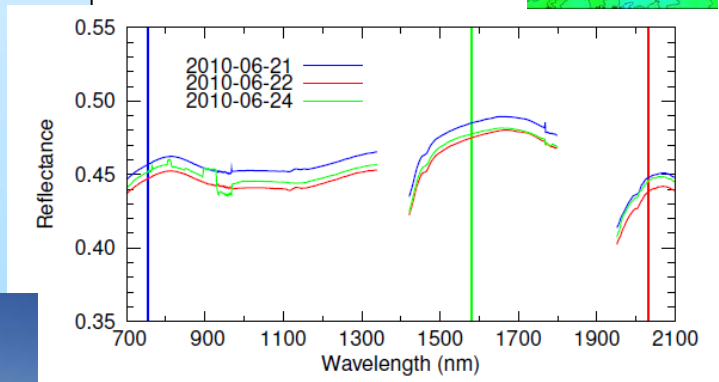
Lunar Calibration

Vicarious Calibration in Railroad Valley, NV









The absolute radiometric calibration will rely on vicarious calibration campaigns, like those conducted by the ACOS and GOSAT teams to collect ground based and aircraft measurements over Railroad Valley (RRV) in conjunction with spacecraft overflights.

Railroad Valley Calibration Campaigns

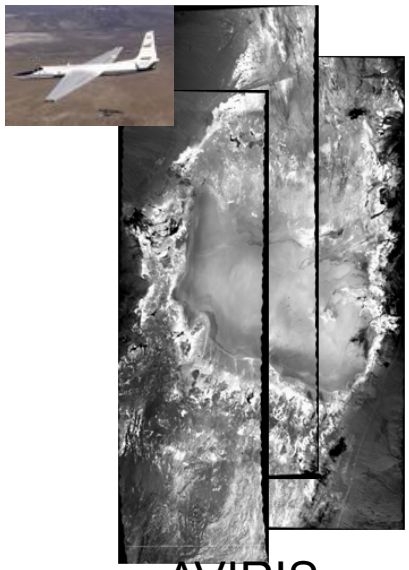
- Campaigns are typically conducted once each year, near summer solstice, when the sun is high in the sky, and probability of clouds is low

- For GOSAT, each campaign was at ~6 days long
  - allows two opportunities for observations from orbit tracks east (path 36) and west (path 37) of the valley
  - Provides resiliency for clouds and instrument problems
  - A similar approach will be adopted for OCO-2

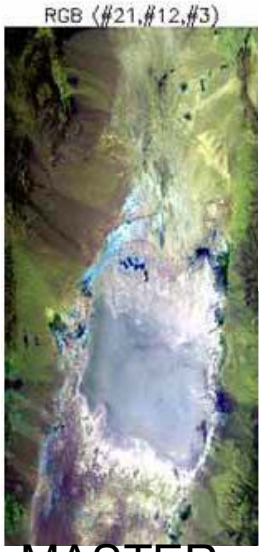
- The primary objective of these campaigns is to track changes in the radiometric calibration, but they also yielded constraints on geometric and polarimetric variations

Characterizing the Surface Reflectance of RRV

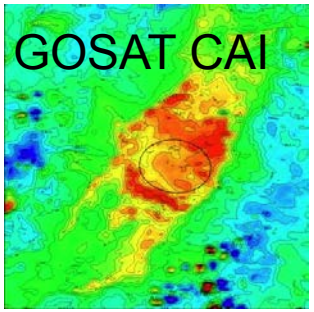
- Because the TANSO-FTS footprint is large compared to the size of Railroad Valley (RRV), spatial variations in surface reflectance were characterized by ground-based measurements collected at several sights across the valley floor.
- Aircraft (ER-2 AVIRIS and MASTER) and spacecraft (ASTER, MODIS, CAI) were used to extrapolate these results to the full valley floor.

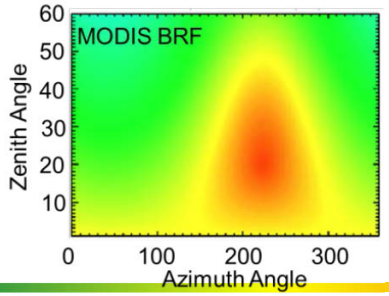


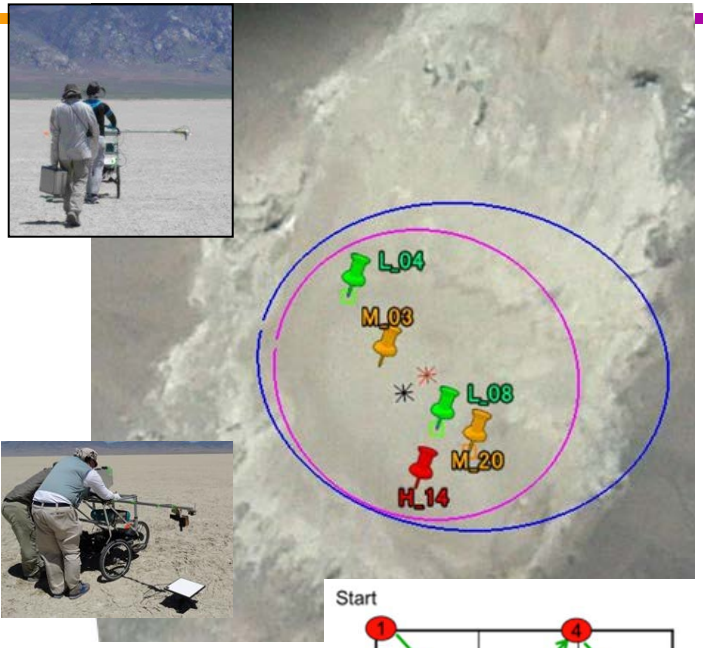
AVIRIS



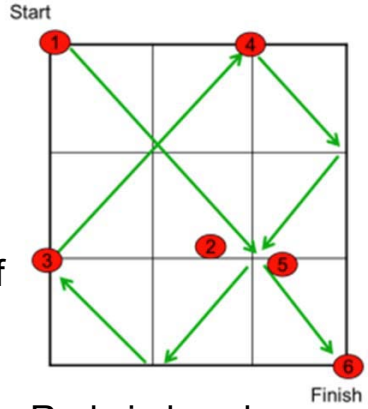
MASTER





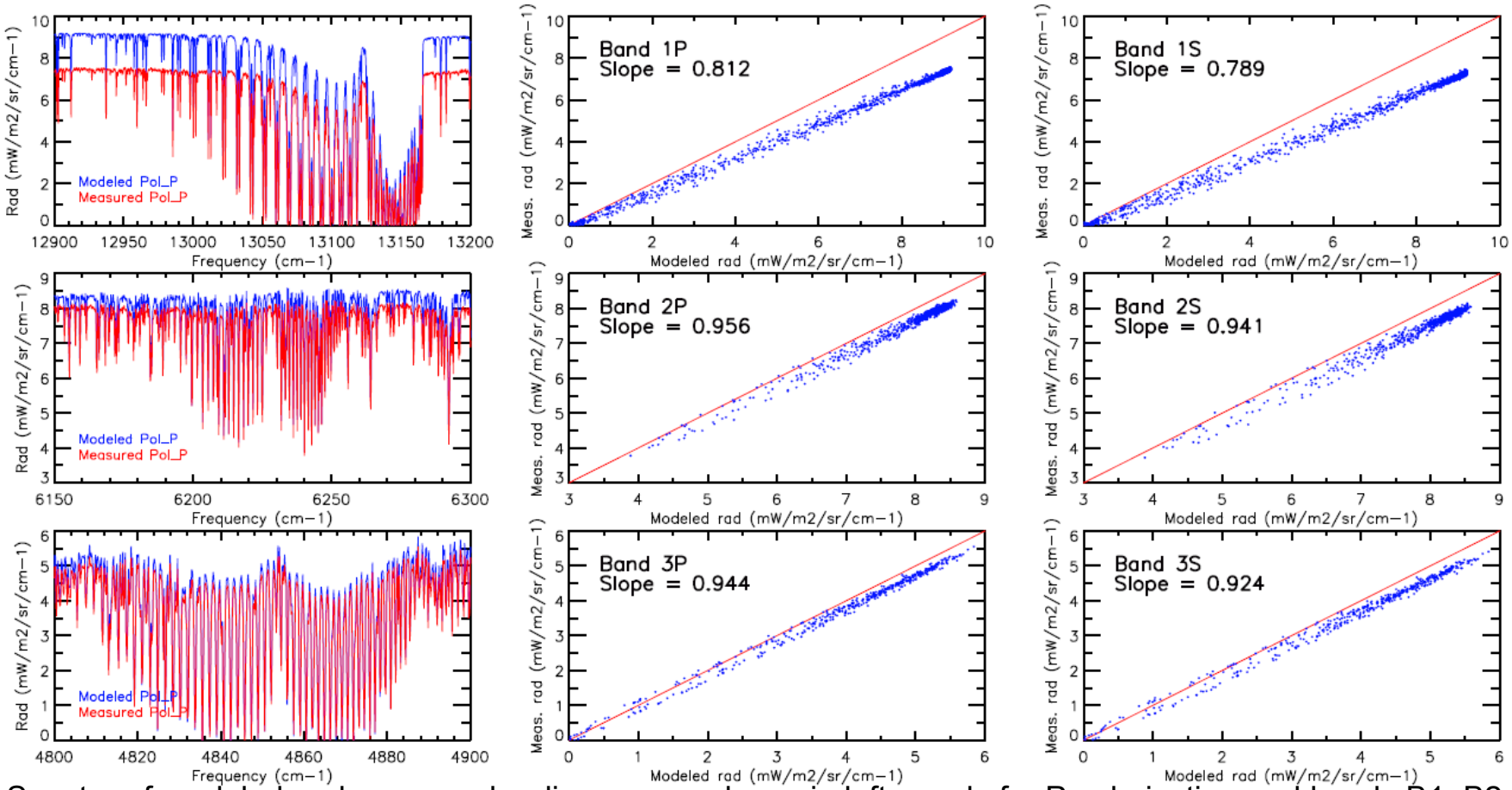


TANSO-FTS CAM image showing footprints for Path 36 (red) and 37 (blue) along with locations of surface measurement grids. Each grid is sampled with a baby buggy-mounted ASD (inset) sampling pattern shown at right.



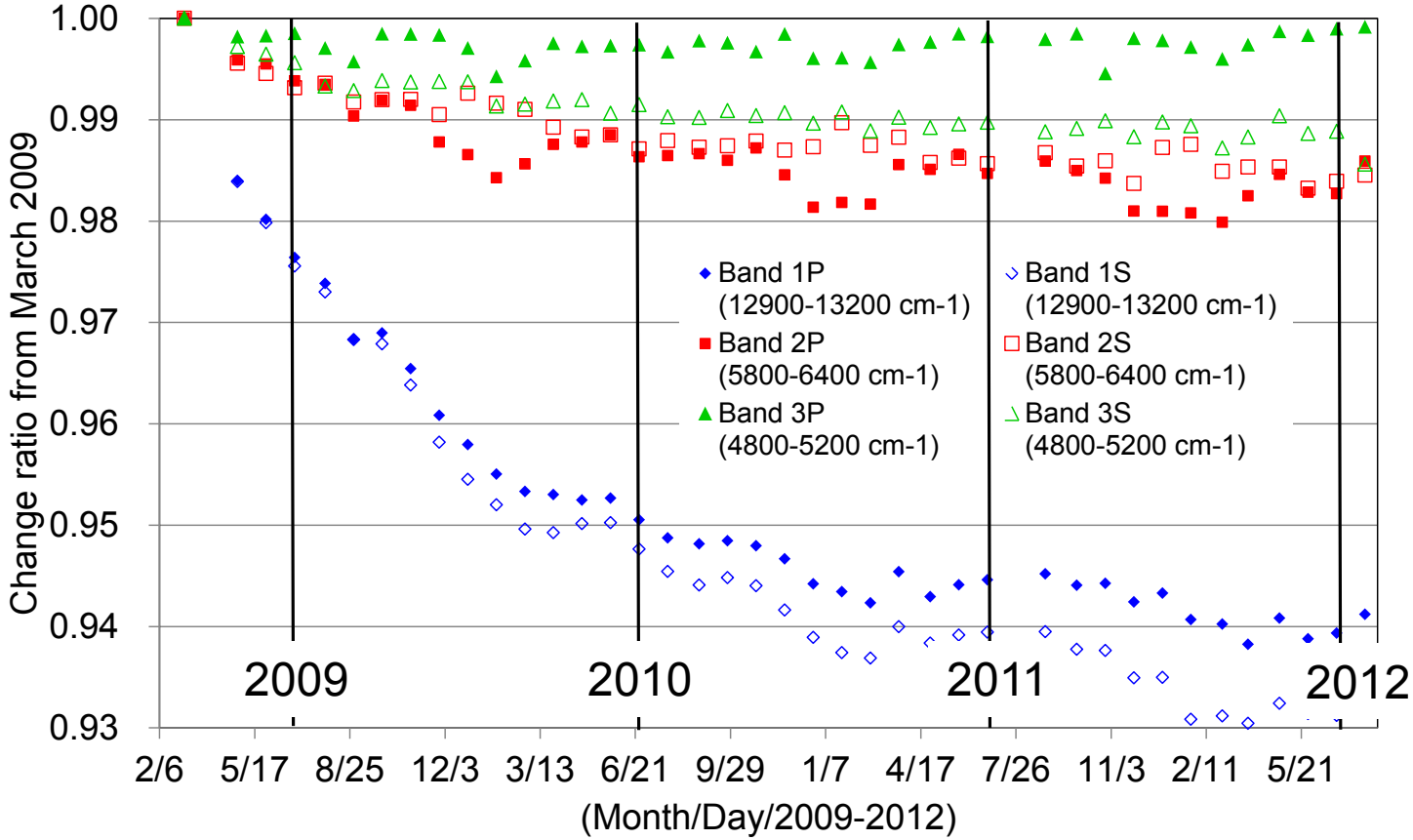
Red circles show ASD calibration locations. *Kuze et al. (in prep - 2012)*

Deriving TANSO-FTS Calibration Coefficients



Spectra of modeled and measured radiances are shown in left panels for P polarization and bands B1, B2, B3 (rows). The measured values are adjusted using the preflight radiance conversion factors. Scatter plots of the measured versus modeled values are shown for P (middle panels) and S (right panels) polarizations. The slope of a linear least square fit line, forced to pass thru the origin, gives the calibration of the measured radiances relative to the modeled values (Kuze et al. in prep. 2012).

Throughput Degradation Rate Decreasing with Time



Results from Railroad Valley and the on-board solar diffuse indicate that the throughput degradation is greatest in Band 1 (O_2 A-Band), but the rate is decreasing in all 3 SWIR bands. The vertical lines indicate the time of the Vicarious Calibration Campaigns in 2009, 2010, 2011, and 2012.

Summary of Radiometric Calibrations for FTS SWIR and CAI

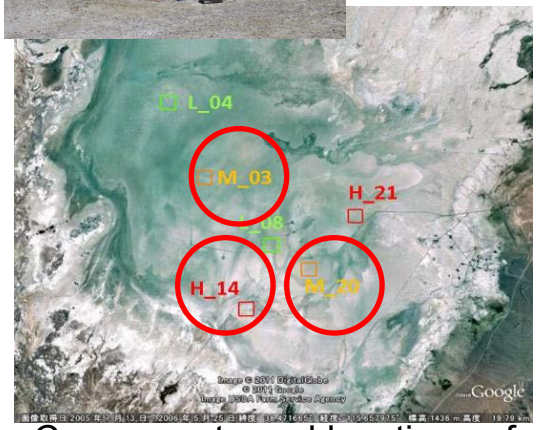
		Days from launch	TANSO-FTS			CAI			
			B1	B2	B3	B1	B2	B3	B4
Vicarious calibration (vs. pre-launch calibration)	June 23-July 4, 2009	160	-11±7%	-3±7%	-4±7%	-17%	+4%	0%	-18%
	June 21-22 2010	520	-14±7%	-2±5%	-6±5%	-21%	-4%	-4%	-20%
Solar diffuser plate (back side) (vs. onboard initial calibration)	June 2009	160	-2.7%	-0.9%	-0.4%	N/A	N/A	N/A	N/A
	June 2010	520	-5.1%	-1.6	-0.5%	N/A	N/A	N/A	N/A
Sahara	2009-2010		-2%	0%	0%	-1.6%	-4.0%	-1.2%	-1.1%
			April-September			June-Sep			

Shiomi et al. IWGGMS8

RRV: Provides the absolute calibration
Solar diffuser plate: relative (monitoring change with time)
Sahara Data: relative (monitoring change with time)

Automated Vicarious Calibration at Railroad Valley

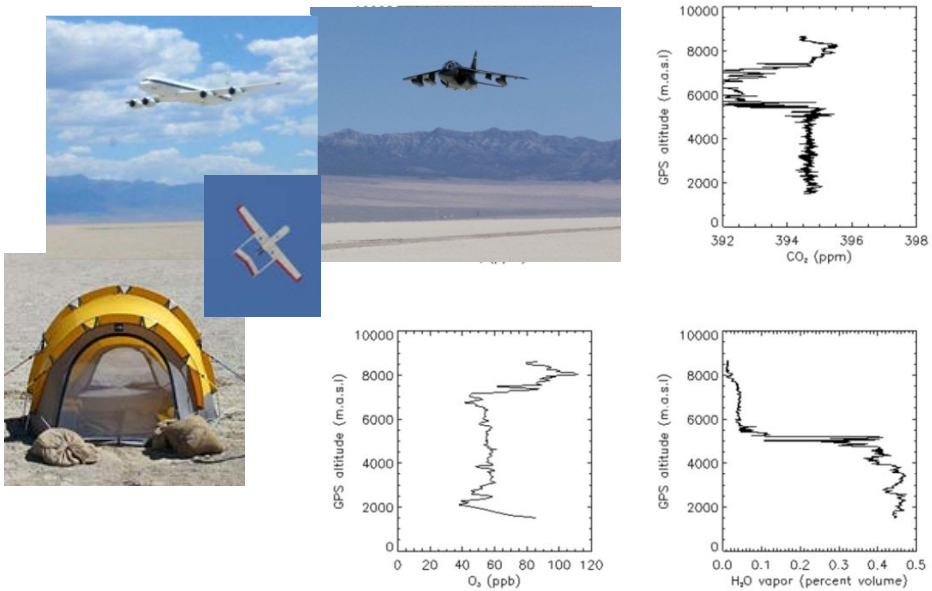
- To augment the temporal coverage provided by the annual RRV Vicarious Calibration campaigns, a series of automated spectrometers have been deployed at 3 locations on the RRV playa
  - Based on heritage from LED Spectrometer (LSPEC) deployment at Frenchman Flat
  - Autonomous LSPEC surface measurements are combined with AERONET observations from University of Arizona installation at RRV, and surface Meteorological data from the JPL station at RRV.
  - Data are uplinked using a PC to satellite modem
- The 2012 RRV campaign was the first opportunity to provide a comprehensive, end-to-end cross calibration of the campaign instruments and the LSPEC installation
  - Results from this intercomparison are being analyzed



Components and locations of LSPEC installation on RRV

Characterizing the Atmosphere above RRV

- Because GOSAT and OCO-2 collect data within atmospheric absorption bands, a comprehensive description of the atmosphere is needed to interpret RRV observations.
  - Meteorological observations are collected by a surface weather station and weather balloons
  - CO_2, CH_4, H_2O, and O_3 measurements are collected by Picarro cavity ringdown spectrometers at the surface, and installed in the Alpha Jet and Sierra UAV (NASA Ames)
- Aerosol measurements are collected by the RRV Aeronet station (University of Arizona)



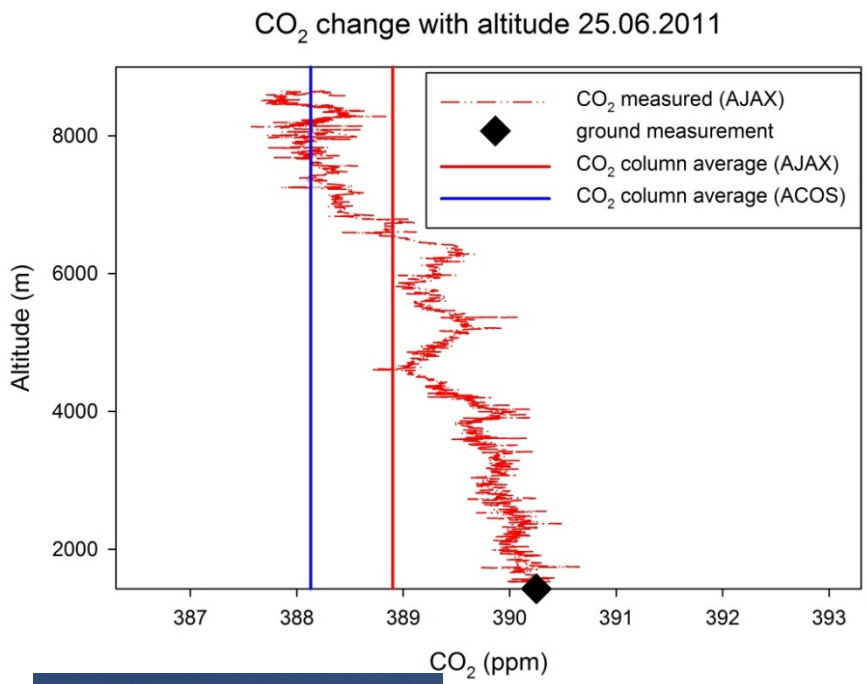
Picarro spectrometers installed in the Alpha Jet, Sierra UAV, and at the surface measure CO_2 and CH_4.

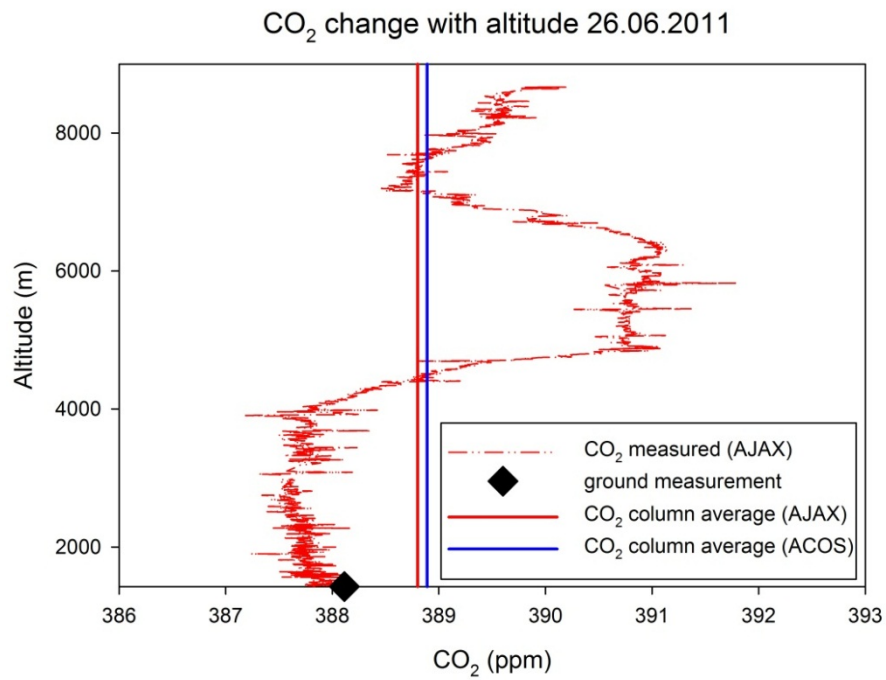
Aerosol Optical Thickness from Aeronet Station

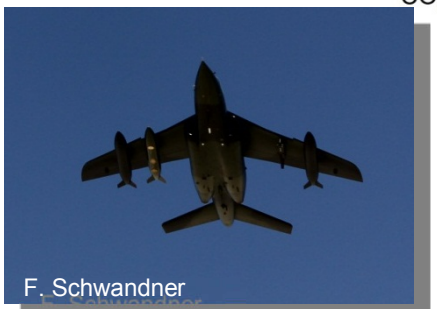
Meteorological data were collected by the surface weather station and by balloons.

Comparison of Vertical Profiles to Columns

- Pressure-weighted average of in-situ data (NASA Ames), compared to satellite retrievals



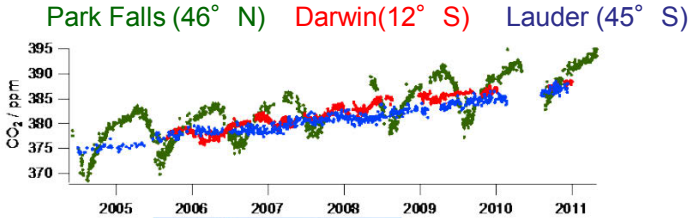




The RRV Field Team

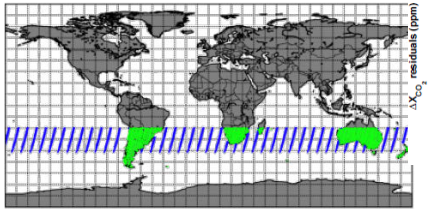
Validation: Identifying and Correcting Regional Scale Biases in X_{CO2}

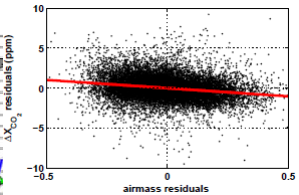
- The ACOS task developed three approaches for identifying and correcting regional scale biases



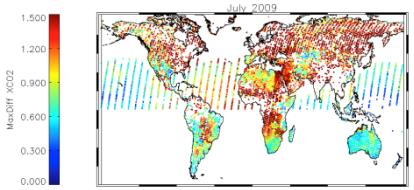
TCCON
total carbon column observing network

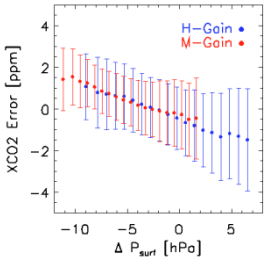
1. **TCCON Validation**: Uses direct comparisons between nearly coincident ACOS GOSAT and TCCON X_{CO2} retrievals





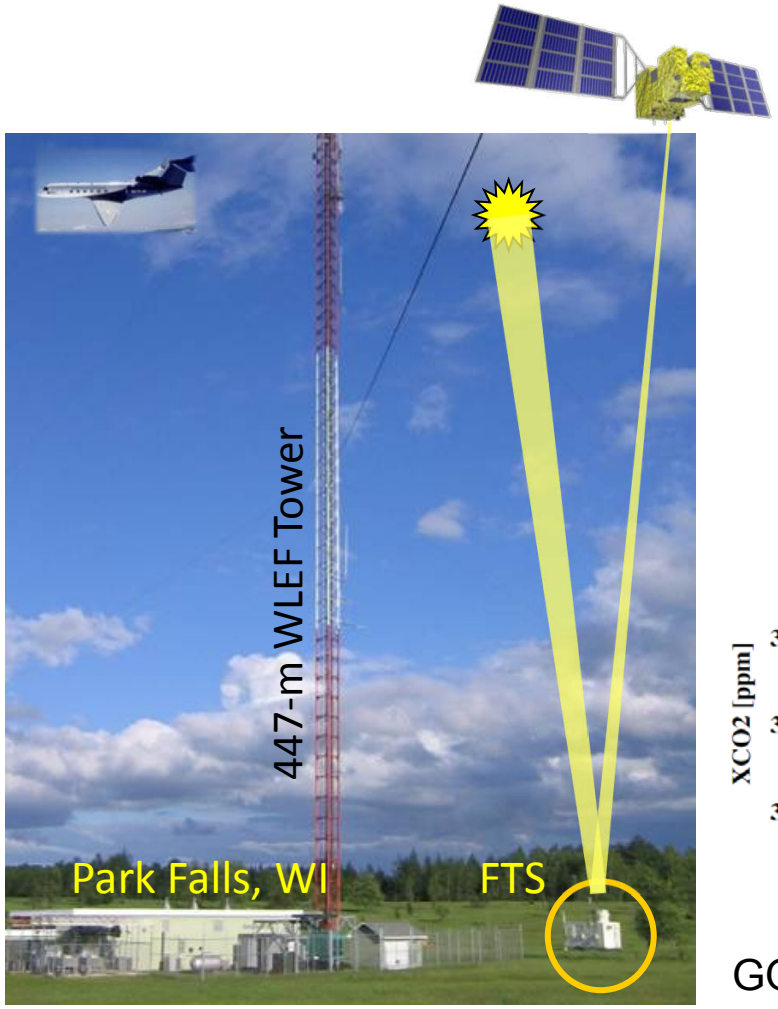
2. **Southern Hemisphere Approximation:** Identifies spurious correlations between X_{CO2} retrievals and other environment parameters at mid latitudes in the southern hemisphere, where X_{CO2} variations are known to be small.



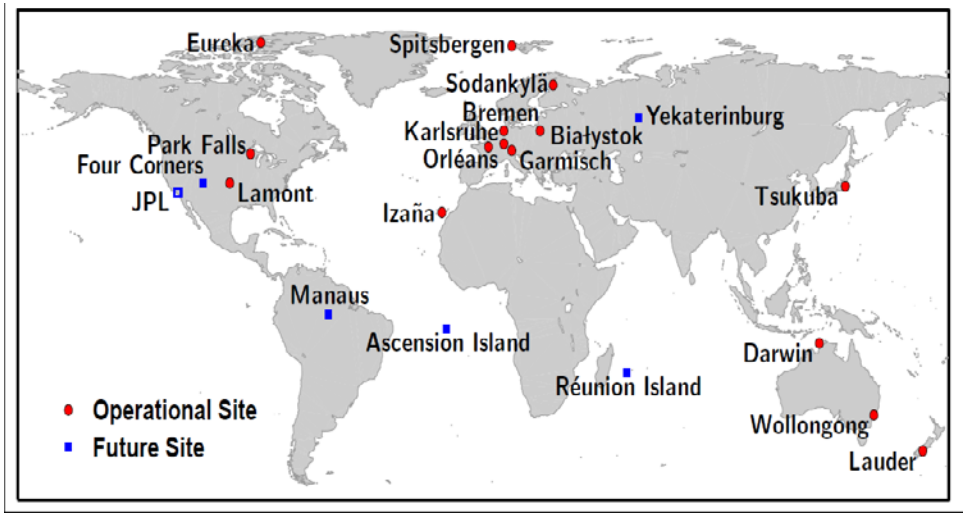


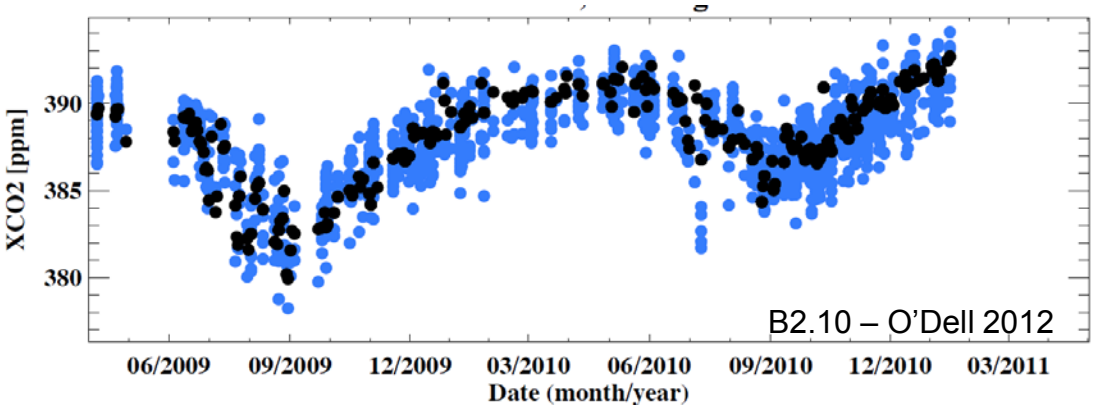
3. **Multi-Model Means**: Compare ACOS GOSAT XCO2 retrievals to the average XCO2 fields generated by flux inversion models

Validation of GOSAT Products against TCCON Reduces Regional Scale Bias



Near-simultaneous observations are acquired over TCCON station.

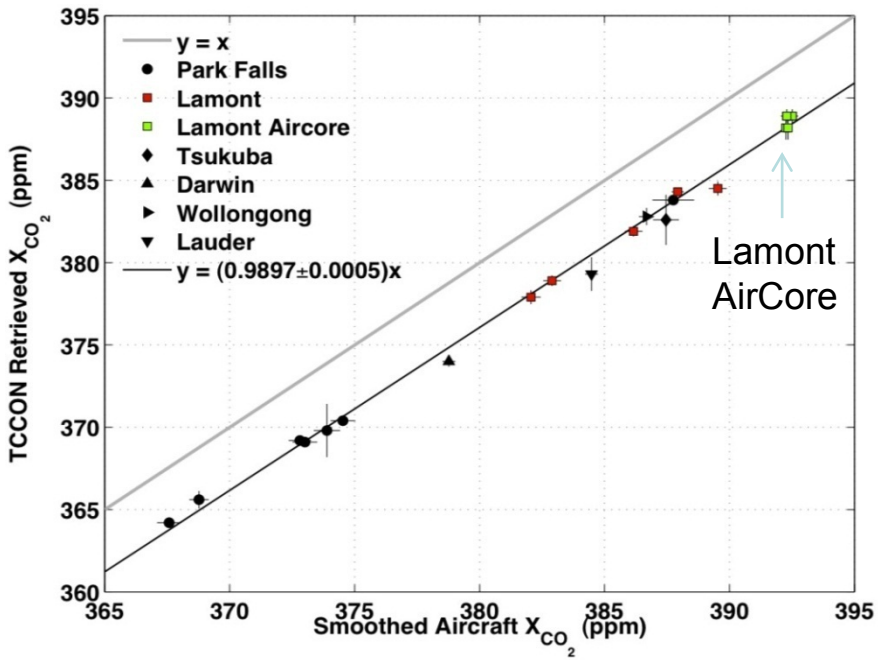




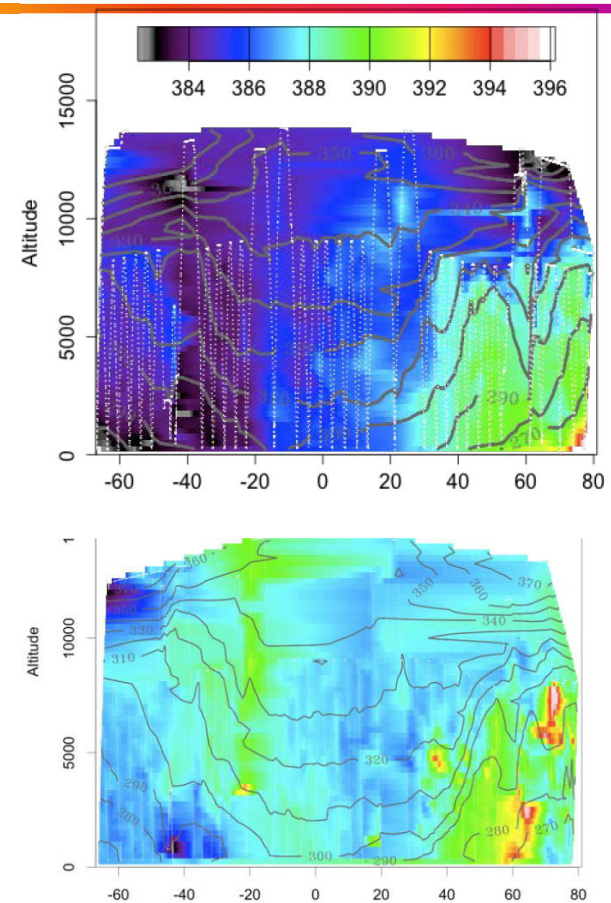
GOSAT X_{CO2} retrievals are compared with those from the ground based Total Carbon Column Observing Network (TCCON) to verify their accuracy

Traceability of the TCCON FTS X_{CO2} data to the WMO CO_2 Standard

TCCON FTS observations are related to the WMO in situ CO_2 standard by acquiring in situ measurements of CO_2 with high altitude aircraft over TCCON sites.



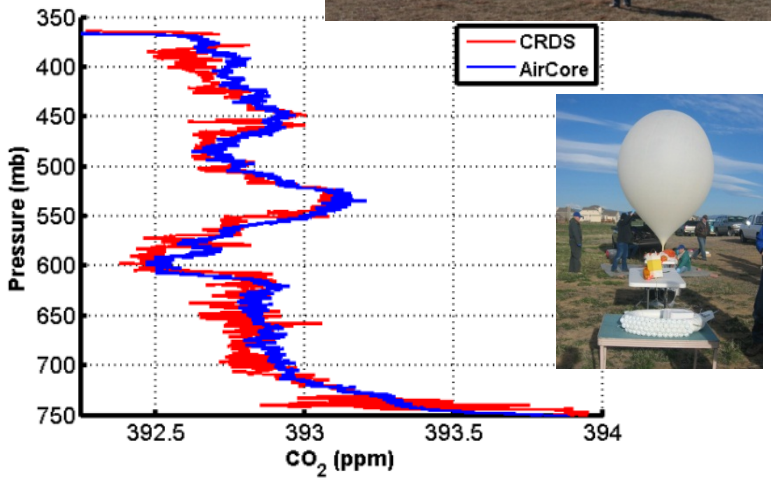
Comparisons of results from TCCON retrievals and aircraft over flights indicates a TCCON X_{CO2} uncertainty of ~0.8 ppm (2 σ); after scaling for a ~1% bias attributed to errors in O2 and CO2 spectroscopy. (*Wunch, D., et al. The Total Carbon Column Observing Network (TCCON), Phil. Trans. Roy. Soc. A, 369, 2087-2112, 2011.)*



In situ CO_2 measurements were acquired over TCCON sites in January (top) and November (bottom) 2009 during the HIAPER Pole-to-Pole Observations (**HIPPO**) campaigns.

AIRCORE – A New Tool for Tracing TCCON observations to the WMO Standard

- The ACOS activity provided an opportunity to test a new CO_2 profiling system – the AirCore
- An AirCore is a passive CO_2 profiling system, consisting of a 48 – 150 m long, narrow (3-6 mm diameter) tube, with one end open and one end closed, that is coiled into a ring.
- The AirCore is carried aloft by a balloon.
- As the balloon rises, the fill gas in the tube evacuates from the open end.
- The AirCore is then released and falls back to Earth on parachute, capturing a "profile" of the atmospheric gas traversed on descent.
- It is recovered, returned to the lab, and the column of atmospheric gas is pumped out and analyzed using the same instruments used to analyze CO_2 flask samples (WMO reference).
- The AirCore is ideal for acquiring high altitude (24 km) CO_2 profiles over TCCON stations.

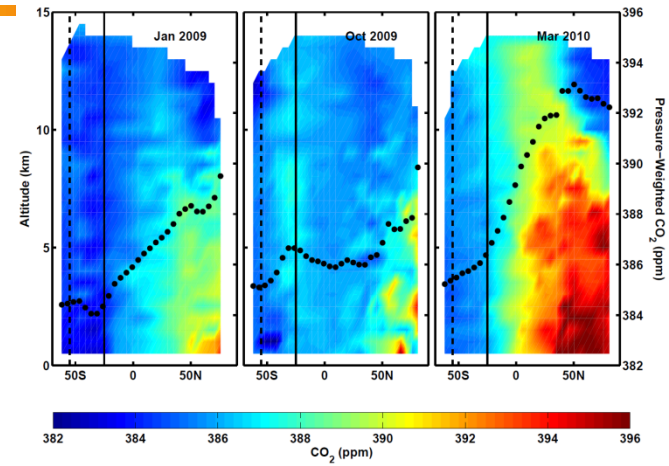


Side-by-side tests with reference instruments verify the accuracy and resolution of the AirCore. High altitude AirCore measurements have been collected over the Lamont TCCON site.

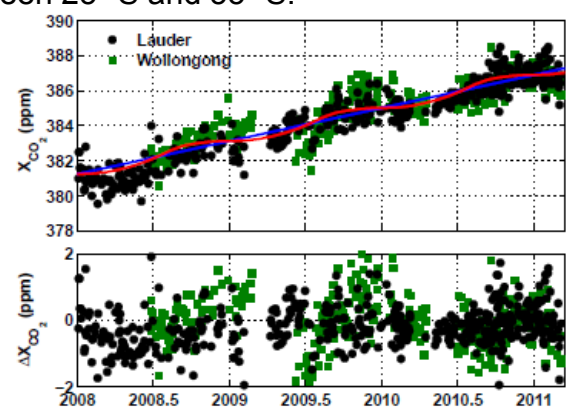
Karion et al., J. Atmos. Ocean Tech., 2010.

Validation Using the Southern Hemisphere Approximation

- CO_2 observations of mid latitudes in the southern hemisphere (25° to 55° S) indicate little variability (c.f. Wunch et al. 2011).
  - XCO2 estimates from TCCON stations at Lauder, NZ and Wollongong, AZ, show typical variations of ~ 1 ppm, after correcting for a 1.89 ppm/year trend
- ACOS GOSAT X_{CO2} retrievals from this region with values that differ substantially from the mean assumed to be spurious
- Differences between X_{CO2} estimates and the southern hemisphere (SH) mean, ΔX_{CO2}, have been analyzed with respect to a number observational and environmental factors to diagnose and correct these biases



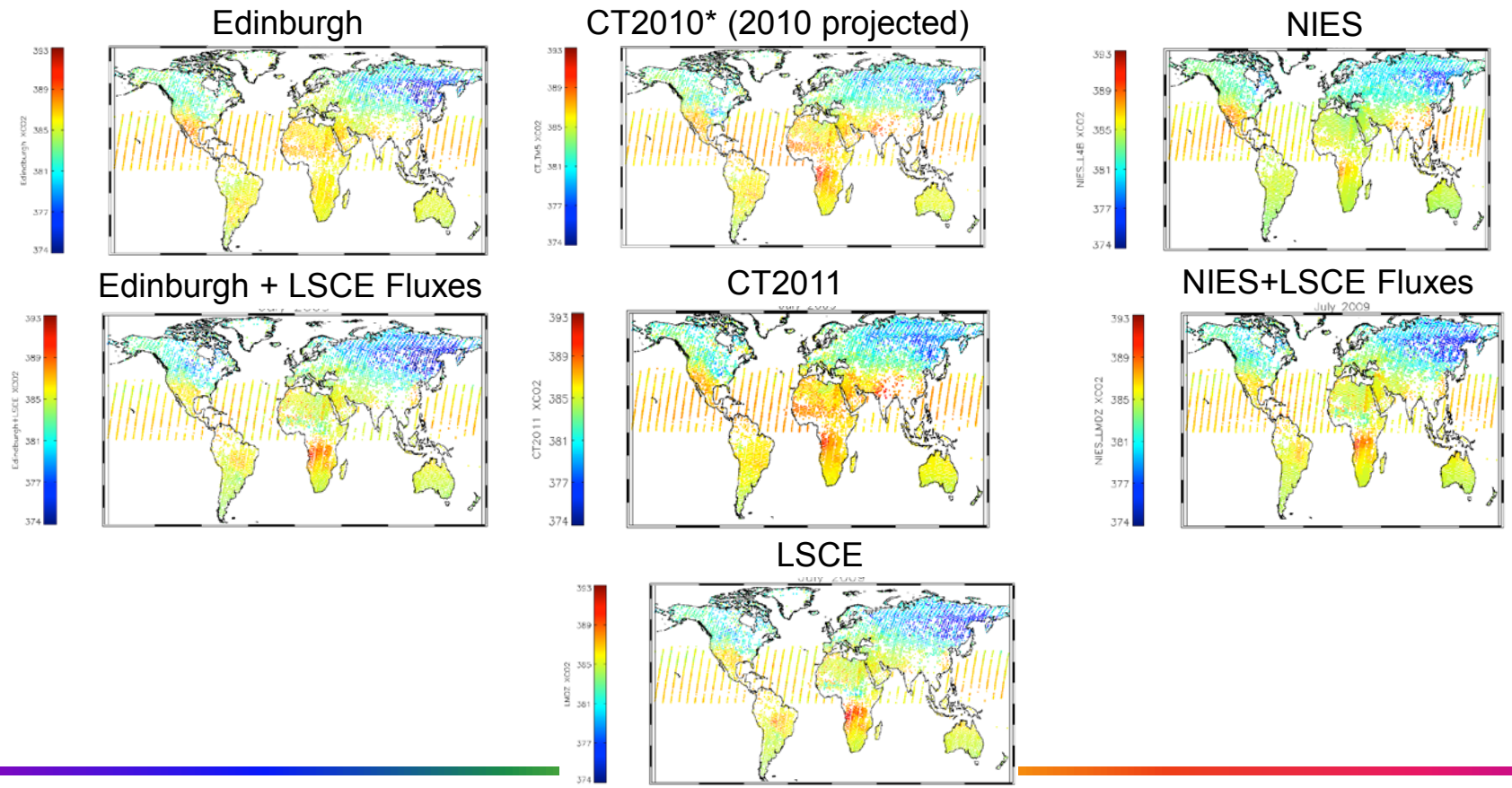
CO_2 observations collected by the HIPPO campaign show little variability at latitudes between 25º S and 55º S.



X_{CO2} retrievals from the Lauder NZ and Wollongong Aus. TCCON stations are used to identify and remove the 1.89 ppm/year CO_2 trend. (D. Wunch et al. 2011.)

Validation Using a Multi-Model Mean

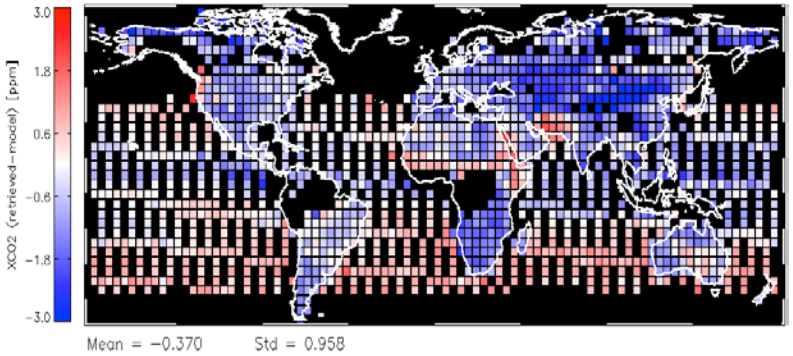
- Existing flux inversion models include a number of limitations (transport errors, sensitivity to priors, etc.), but mean results from ensembles of models still provide a tool for identifying and characterizing X_{CO2} biases.
- So far, 7 models have been used to define a multi-model mean



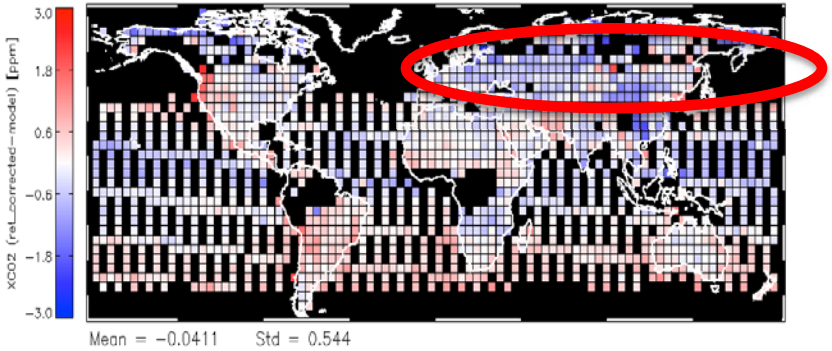
Error Assessment vs. Models

- Multiple Inverse models XCO_2 sampled at GOSAT sounding locations/times
- All models use fluxes optimized against surface observations
- Use **model mean** as truth
- All models run with their own optimized fluxes through 2010, and optionally with those from LSCE.
- Reject soundings that have greater than 1 ppm difference between any model and the multi-model mean for that sounding (~30% of soundings)
- Limitation: Places where all models are wrong in the same way!

Raw B2.10



Corrected B2.10



Summary

- The overall performance of the OCO-2 instrument is similar to that of the original OCO instrument, with improvements in three areas:
  - The residual image, scattered light, and slit misalignment anomalies that compromised the performance of the OCO instrument have been substantially mitigated.
- The instrument and spacecraft bus have now been integrated, and observatory testing has commenced
- A launch vehicle has been selected – Delta II 7320
- The earliest launch date would be July 2014.
  - At this point, there are no plans to recalibrate the instrument prior to launch
- OCO-2 will be launched into the Afternoon Constellation (A-Train), beginning a 2-year nominal mission.