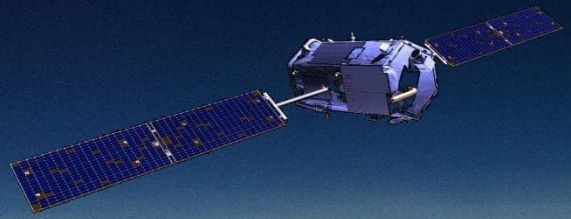

OCO-2: The Next Step in Space-Based CO_2 Measurements

David Crisp, OCO-2 Science Team Leader
Jet Propulsion Laboratory, California Institute of Technology
for the OCO-2 Science Team

October 1, 2013

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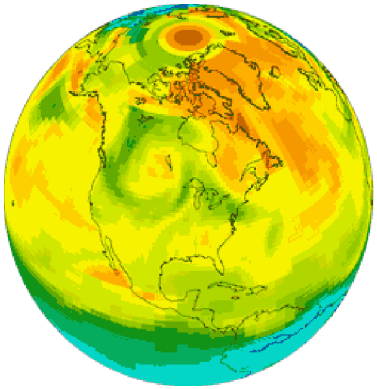
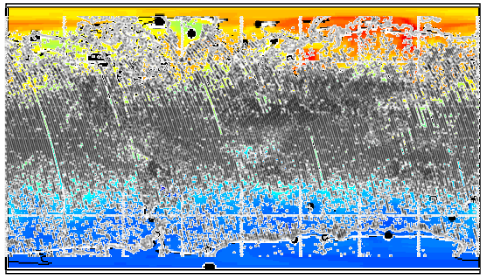
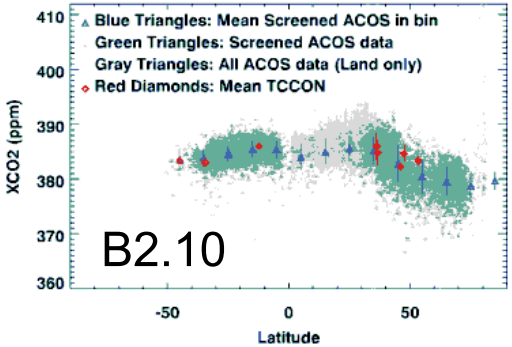
Government sponsorship acknowledged.

The Promise and Challenge for Space Based CO_2 Measurements

- Spatial coverage
  - Observations over both land and ocean
- Temporal resolution and sampling
  - Daily/Weekly sampling needed to resolve CO_2 weather
  - Monthly measurements required over > 1 year to resolve seasonal and inter-annual variability in CO_2
- Spatial resolution and sampling
  - Sensitivity to point sources scales with area of footprint
  - Small measurement footprints enhance sensitivity to point sources and reduce data losses due to clouds
- Primary Challenge: Precision and accuracy
  - High precision required to resolve small (0.2-0.3%) variations in CO_2 associated with sources and sinks
  - High accuracy essential to avoid regional-scale biases



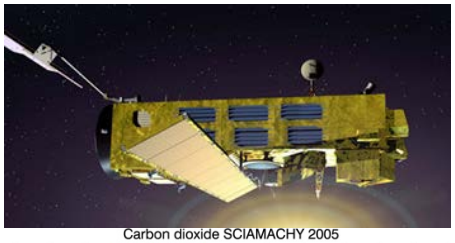


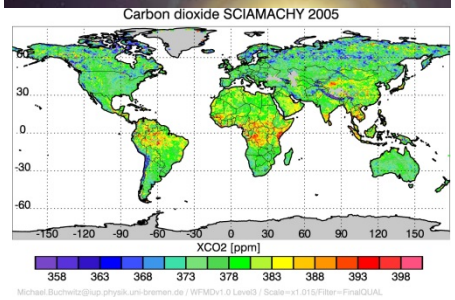


Remote Sensing of CO_2 using Reflected Sunlight: The Pioneers

SCIAMACHY (2002 - 2012)

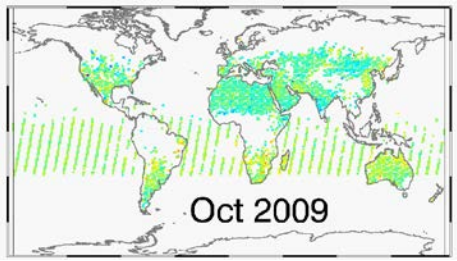
- First solar NIR/SWIR CO_2 / CH_4 sensor
  - Provided regional-scale maps of CO_2 and CH_4 over continents on seasonal time scales
  - Low precision (3-6 ppm) and high probability of cloud bias within large footprint (18,000 km^2) reduced accuracy
  - Lack of ocean glint pointing further limited coverage



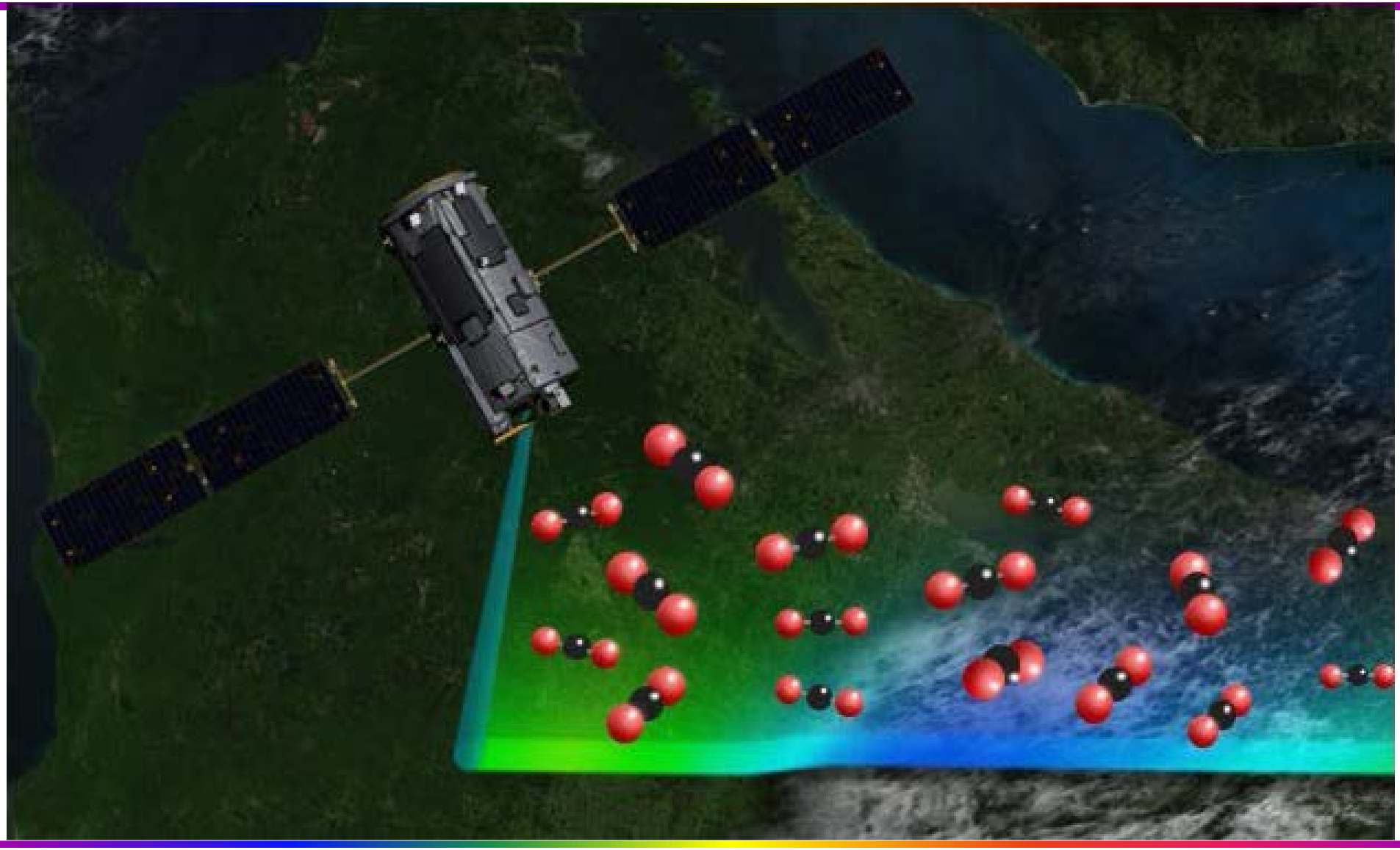


GOSAT (2009 - Present)

- Optimized for spectral coverage and fast repeat cycle
  - Combination of high spectral resolution over broad spectral range yields high sensitivity to CO_2, CH_4, and chlorophyll fluorescence
  - 4-second integration time and 10.5 km diameter footprint limits resolution and number of cloud free soundings (~1000 soundings/day)
  - Lack of ocean glint at high latitudes limits coverage

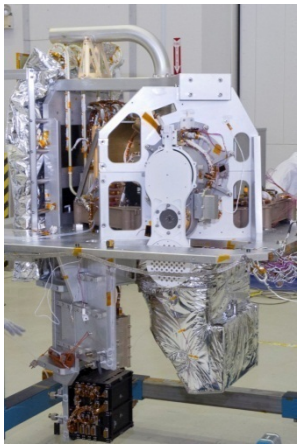


The Next Step - The NASA Orbiting Carbon Observatory-2 (OCO-2) Mission

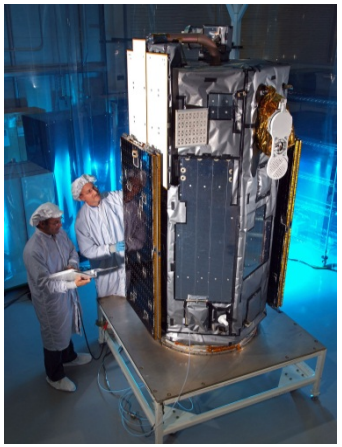


The OCO-2 Mission Overview

3-Channel Grating Spectrometer (JPL)

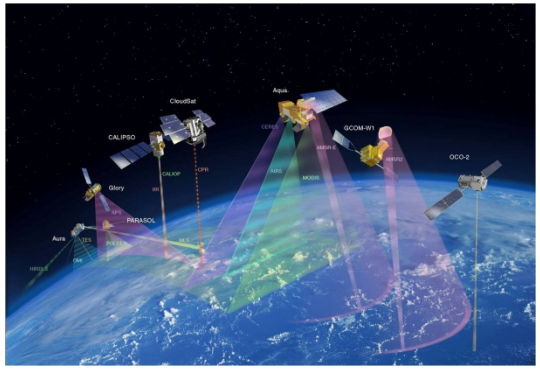


Dedicated Spacecraft Bus (OSC)



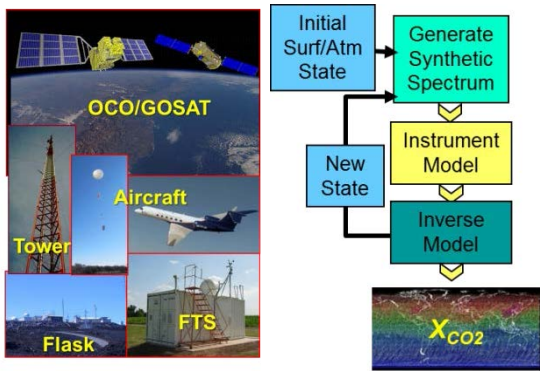
Delta-II Launch Vehicle

Formation Flying in the A-Train Constellation



NASA NEN (GSFC) and SN (TDRSS)

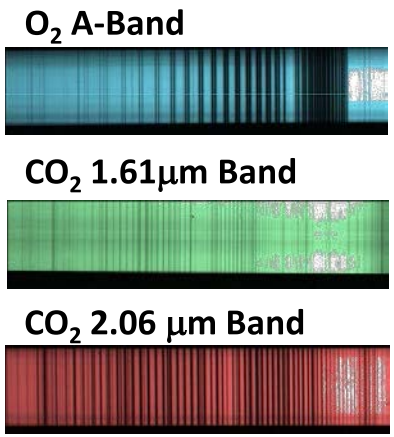
Data Product Generation (JPL)

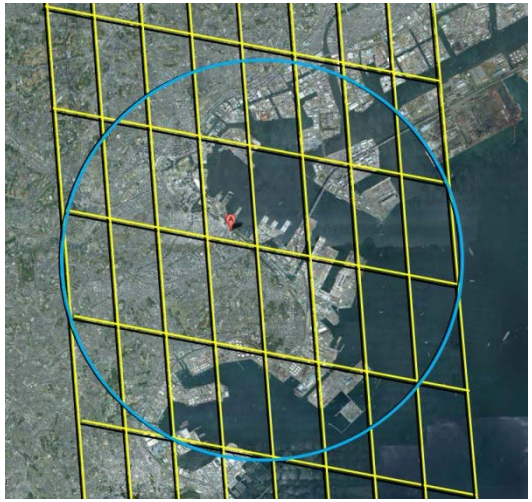


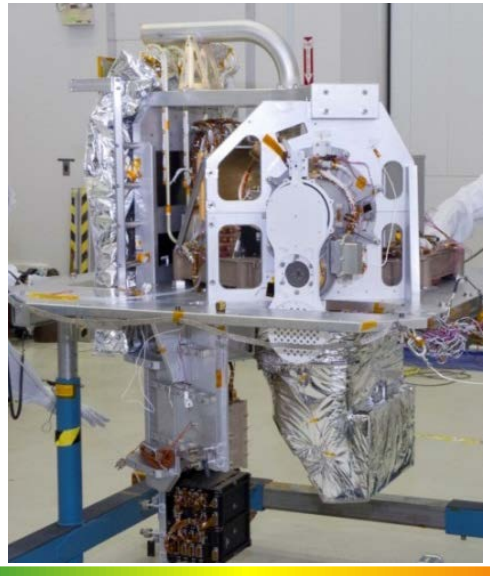
The OCO Instrument – Optimized for Sensitivity

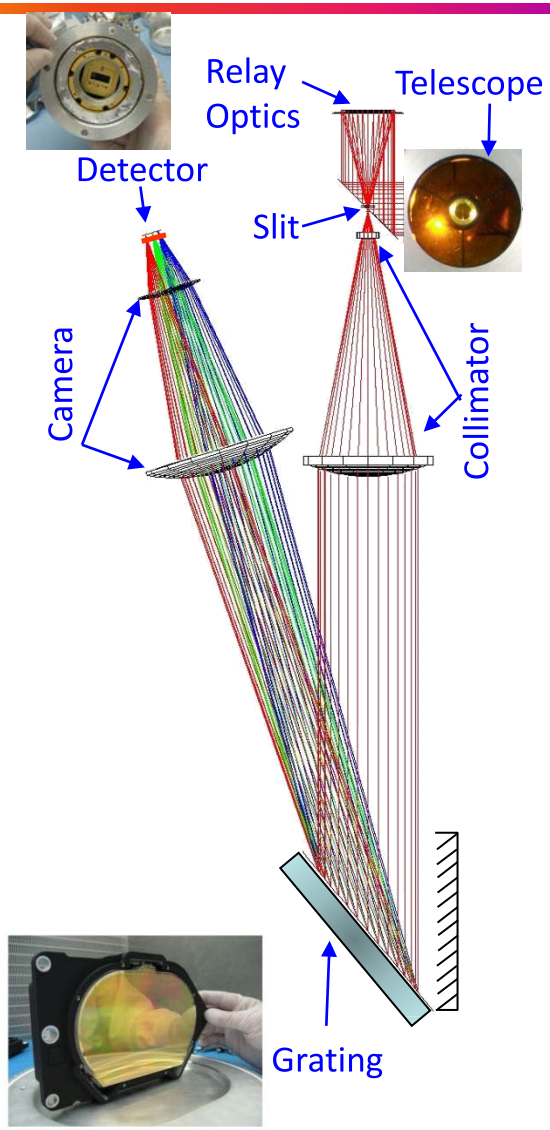
3 co-bore-sighted, high resolution, imaging grating spectrometers

- Resolving Power 17,000 - 20,000
- High Signal-to-Noise Ratio
- Collects 24 soundings / sec over a narrow (0.8º) swath
  - 10^6 soundings / day over the sunlit hemisphere

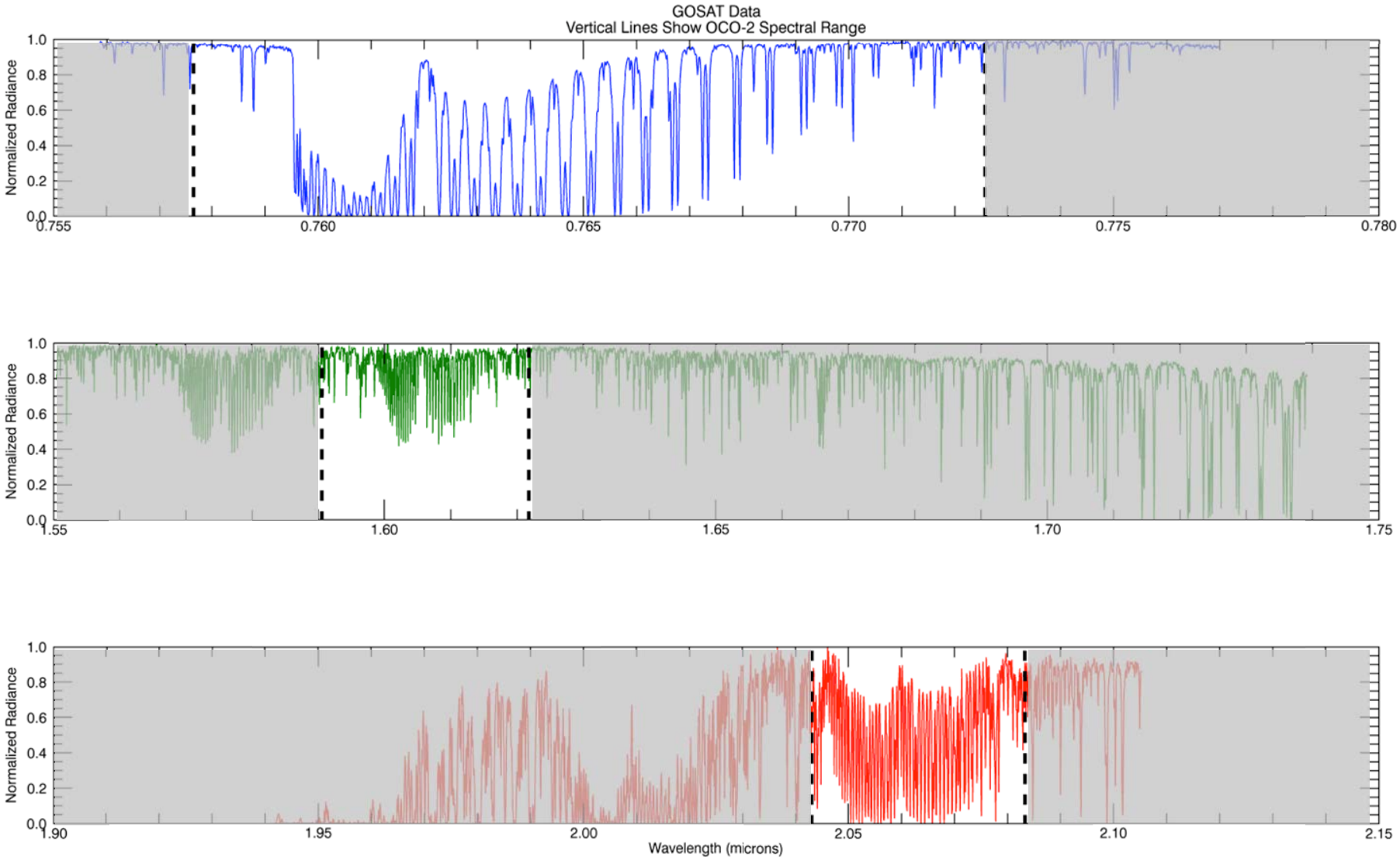






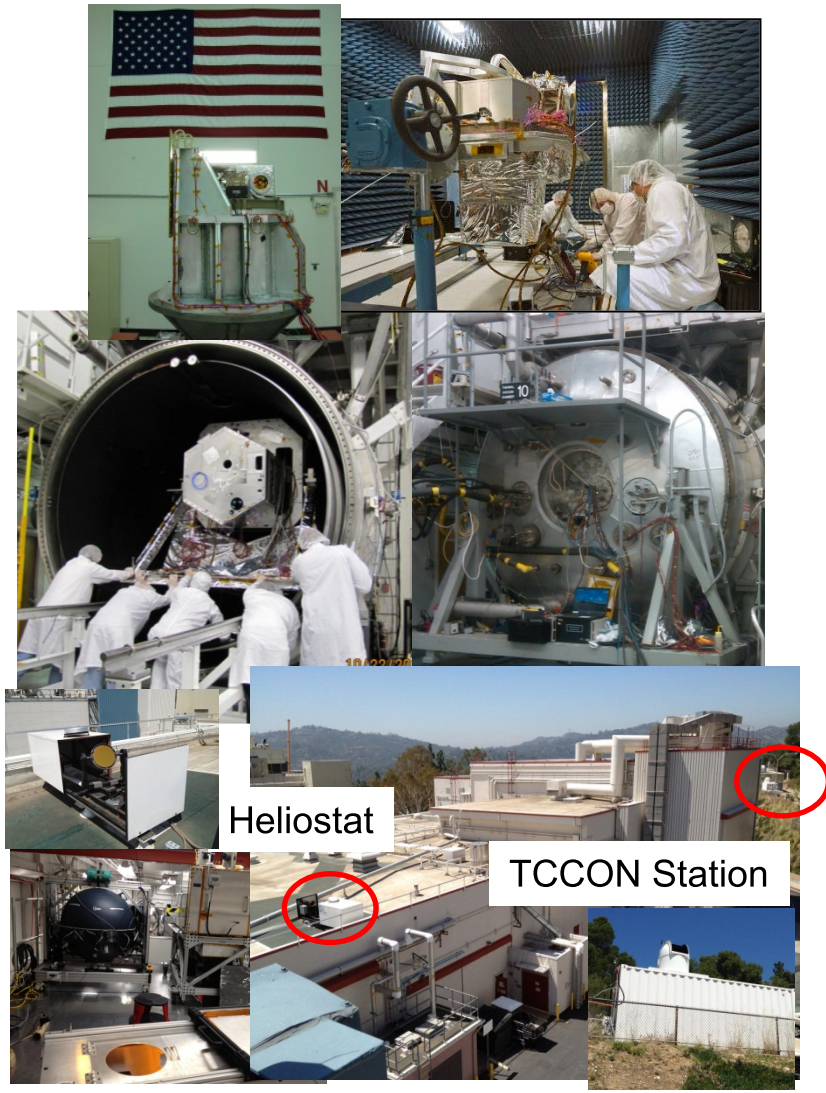


GOSAT Has Wider Spectral Ranges

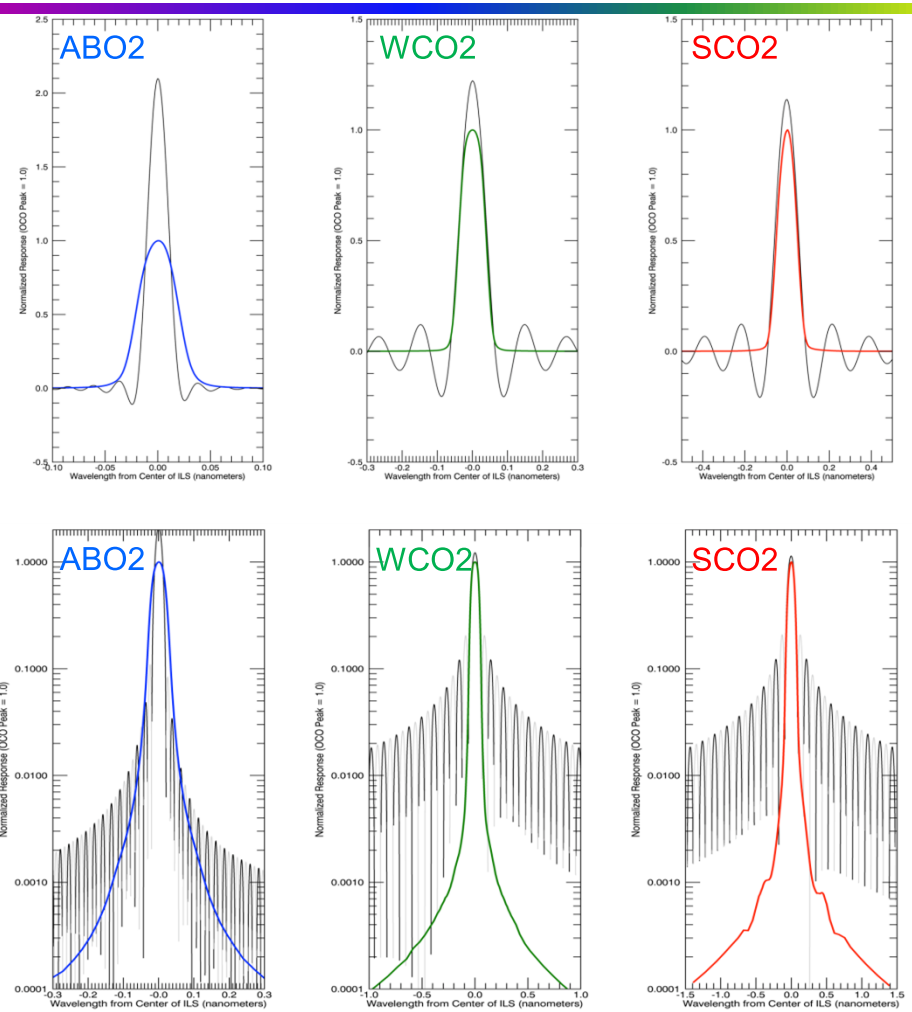


Pre-Flight Instrument Characterization and Calibration

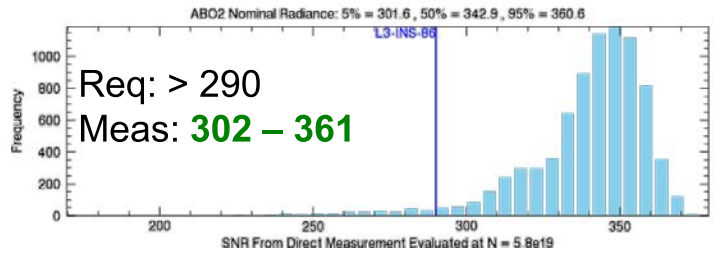
- Pre-flight testing quantifies key Instrument performance and knowledge parameters
  - Geometric
    - Field of view, Bore-sight alignment
  - Radiometric
    - Zero-level offset (bias)
    - Gain, Gain non-linearity
  - Spectroscopic
    - Spectral range, resolution, sampling
    - Instrument Line Shape (ILS)
  - Polarization
  - Instrument stability
- Pre-flight instrument characterization and calibration completed in April 2012

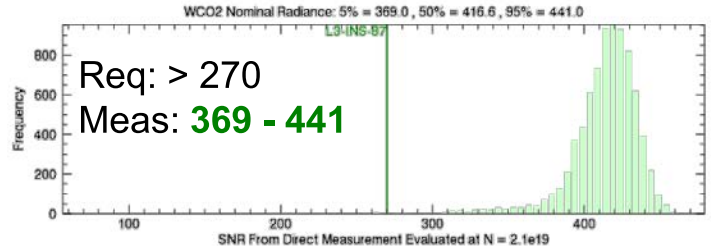


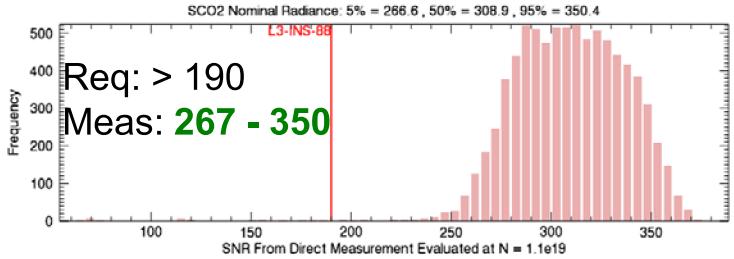
The OCO Instrument – Measured Performance

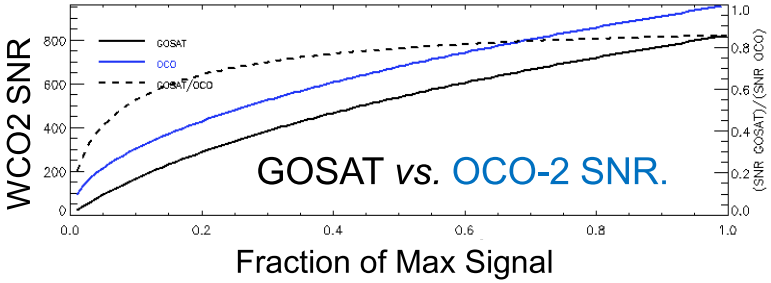


GOSAT (black) *vs.* OCO-2 instrument line shape



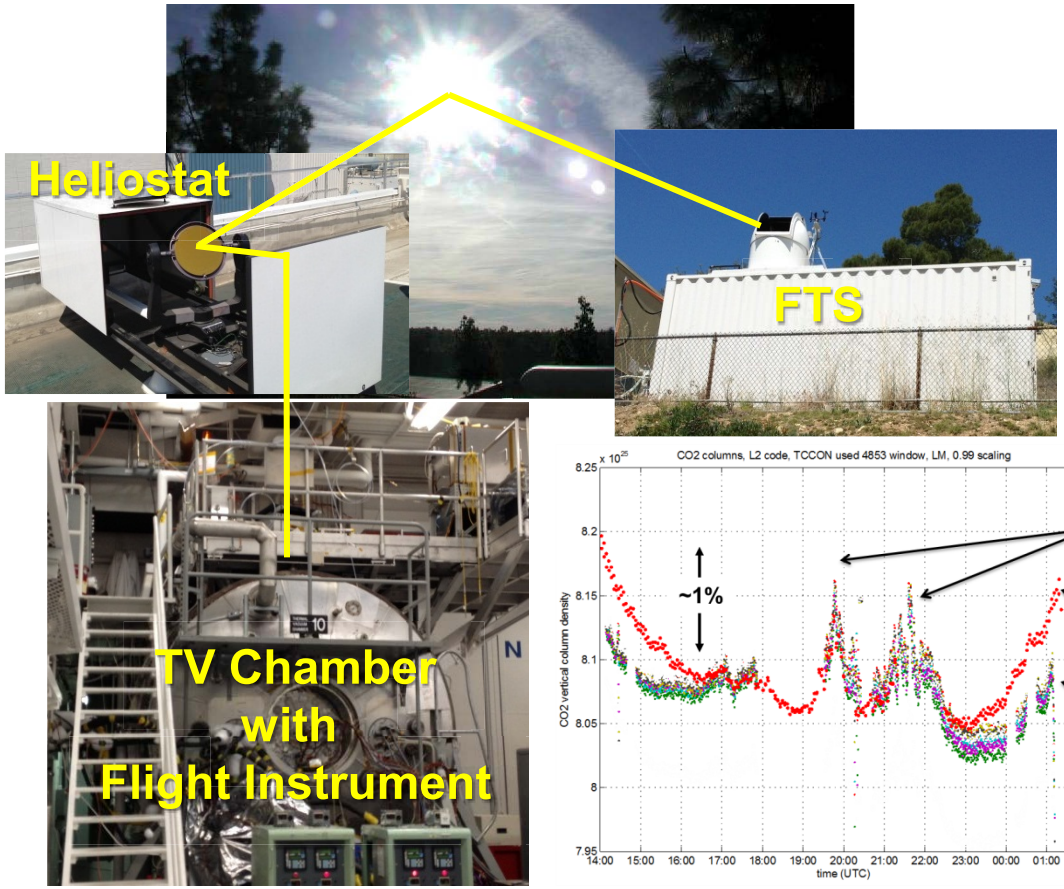


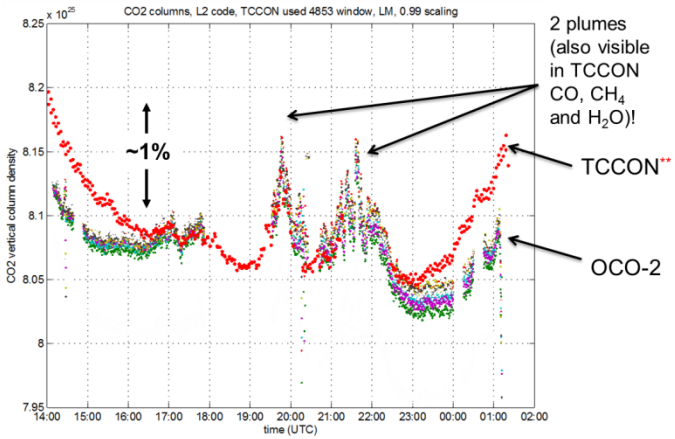




Pre-flight Heliostat/TCCON Observations Verify End-to-End Instrument Performance

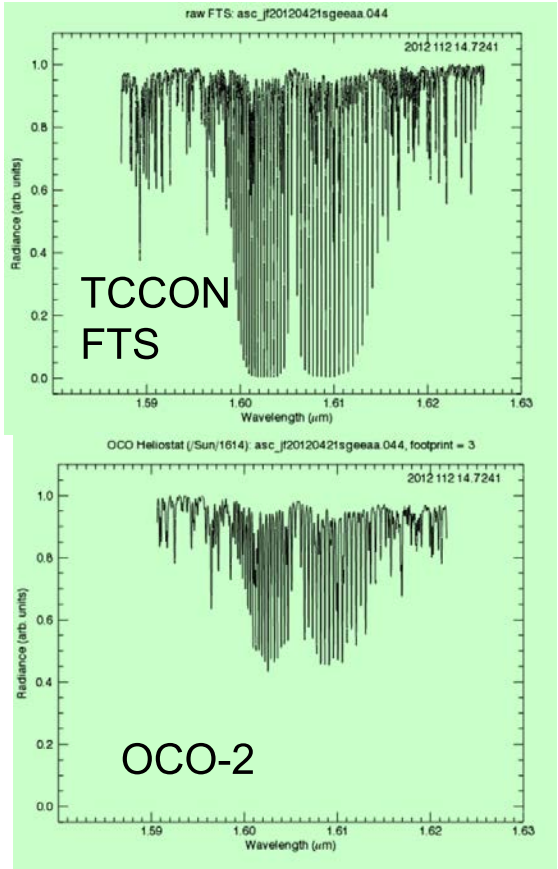
Observations of the sun with the flight instrument taken during TVAC tests provide an end-to-end verification of the instrument performance.





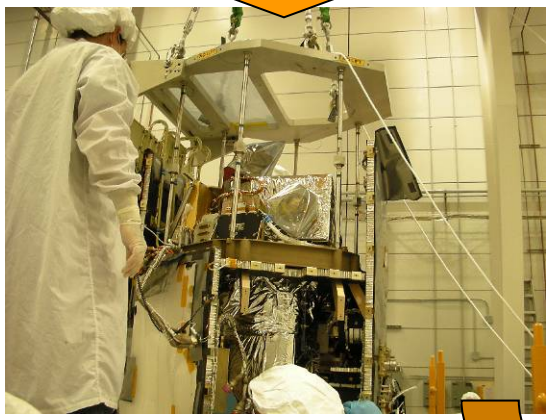
TCCON/OCO-2 comparison – Still a work in progress!!

1.6 μm CO_2



21 April 2012

Observatory I&T Activities Ongoing

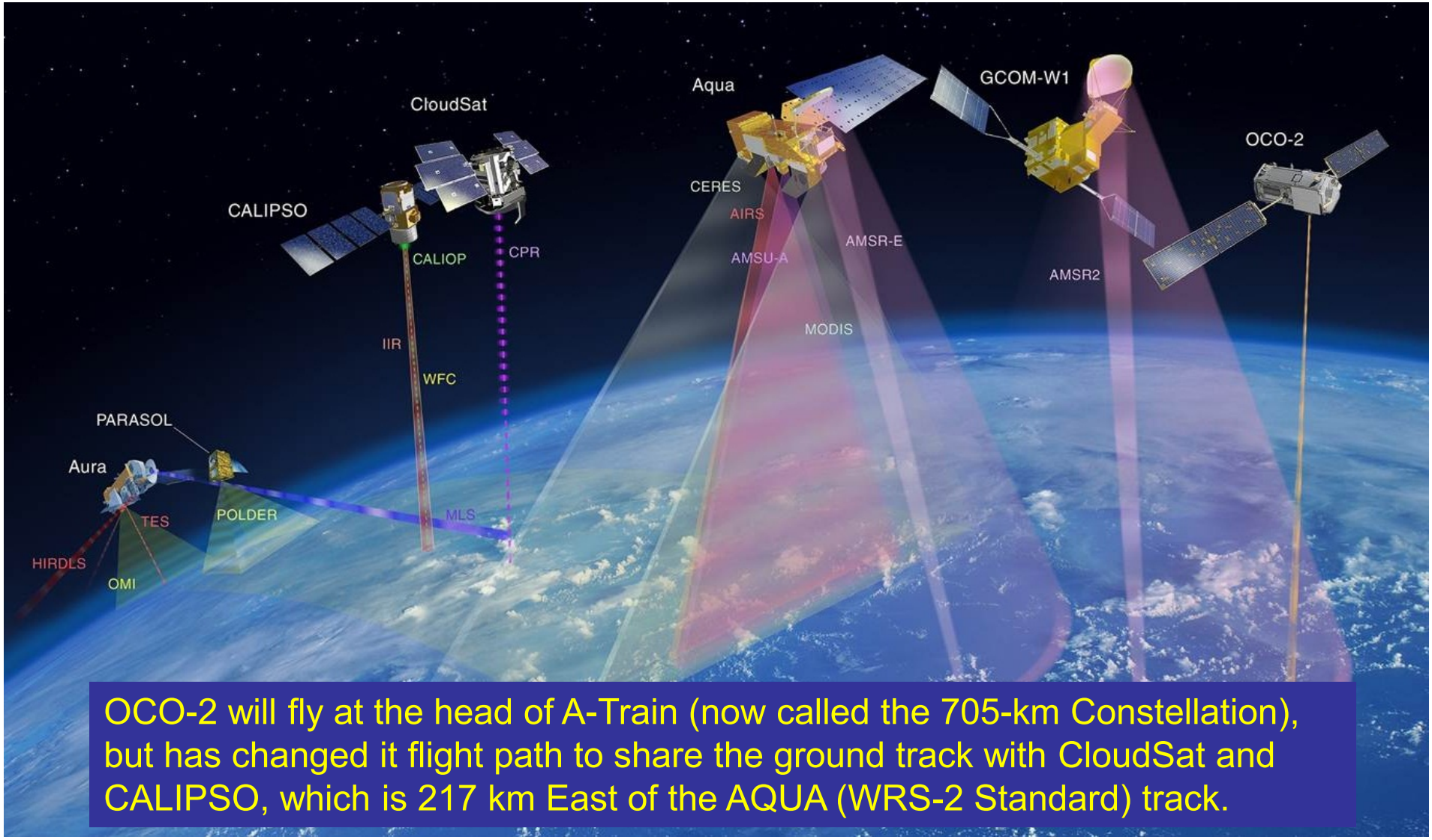


OCO-2 Launch Schedule

- OCO-2 will fly on a United Launch Alliance Delta II 7320
  - Selected by NASA in July 2012, (along with launch vehicles for SMAP, JPSS-1, and Jason-3)
- The OCO-2 Team is currently working closely with Launch Vehicle team to accommodate OCO-2 on the Delta-II
  - Substantially different interface and launch environment
- The OCO-2 launch date is now officially scheduled for 1 July 2014 from Vandenberg Air Force Base, CA

Credit: Steve Greenberg, JPL

Flying in Formation in the A-Train

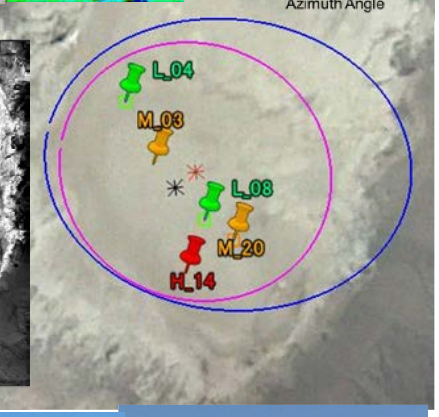


OCO-2 will fly at the head of A-Train (now called the 705-km Constellation), but has changed it flight path to share the ground track with CloudSat and CALIPSO, which is 217 km East of the AQUA (WRS-2 Standard) track.

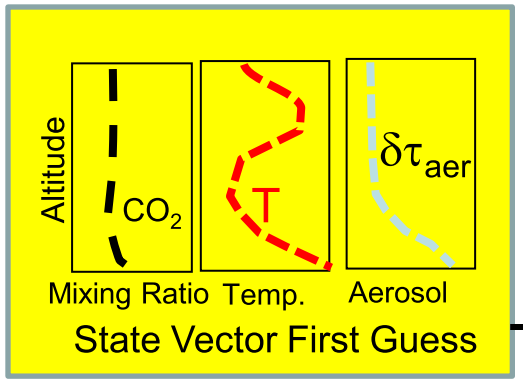
Vicarious Calibration – GOSAT Experience

Site: Railroad Valley, NV, USA (RRV)

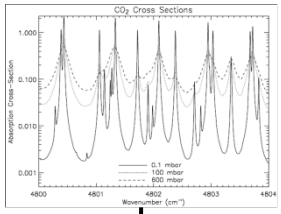
- Spatial variations in surface reflectance were characterized by ground-based measurements form t several sights across the valley floor.
- Aircraft (ER-2 AVIRIS and MASTER) and spacecraft (ASTER, MODIS, CAI) were used to extrapolate these results across the valley.
- Because GOSAT and OCO-2 collect data within atmospheric absorption bands, a comprehensive description of the atmosphere is needed to interpret RRV observations.
  - Surface/Balloon Met observations (p,T,q,v)
  - Aerosol: RRV Aeronet station (U. Arizona)
  - Surface CO_2 (NASA Ames / Picarro)



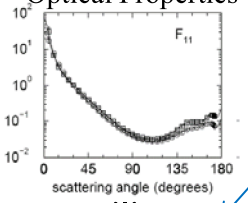
Retrieving X_{CO2} from TANSO-FTS Spectra with the ACOS/OCO-2 Algorithm

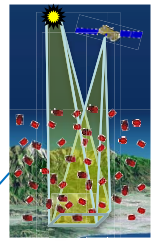


Gas Cross Sections



Cloud &Aerosol Optical Properties

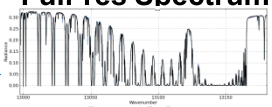




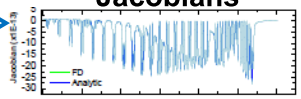
Viewing geometry

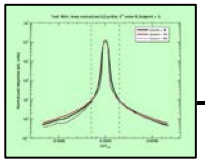
Forward Radiative Transfer Model
Spectra + Jacobians

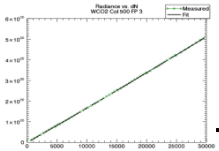
Full-res Spectrum



Jacobians



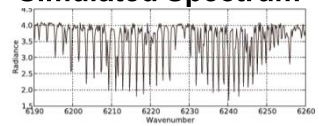




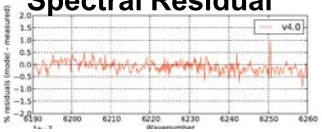
Instrument Model
Spectral+Polarization

$$\begin{pmatrix} I_P \\ I_S \end{pmatrix} = \begin{pmatrix} m_{PI} & m_{PQ} & m_{PU} & m_{PV} \\ m_{SI} & m_{SQ} & m_{SU} & m_{SV} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \mathcal{M}S.$$

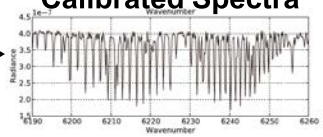
Simulated Spectrum



Spectral Residual



Calibrated Spectra



Apriori + Covariance

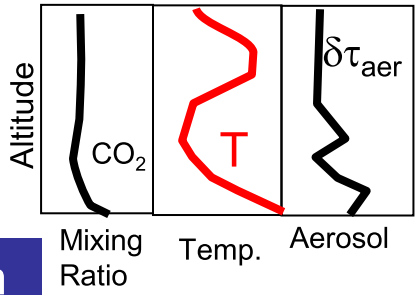
Inverse Model
- Compare obs. & simulated spectra
- Update State Vector

not converged

- Final State
- Diagnostics

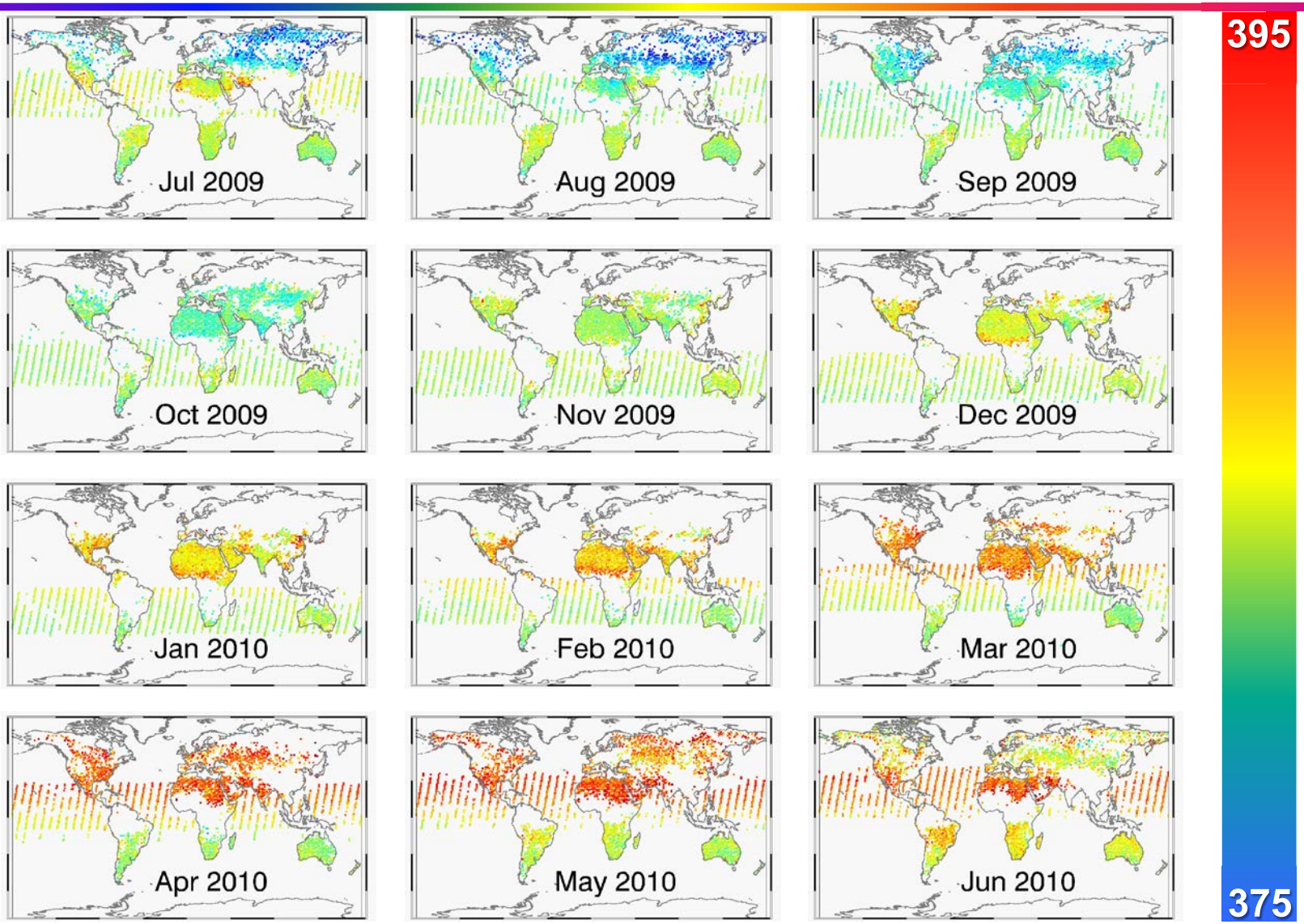
converged

State Vector
CO_2 profile
H_2O profile (scale factor)
Temperature profile (offset)
Aerosol Profiles
Surface Pressure
Albedo (Mean, Slope)
Wavelength Shift
Zero Level Offset



GOSAT Data have provided a critical validation of the OCO Algorithm

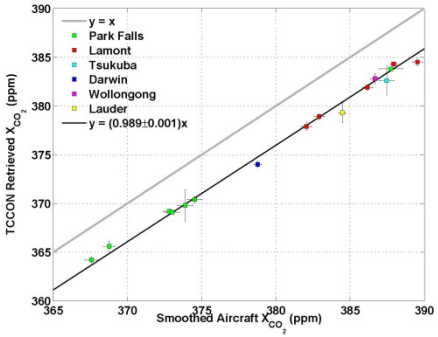
ACOS GOSAT B2.10 X_{CO2} Retrievals

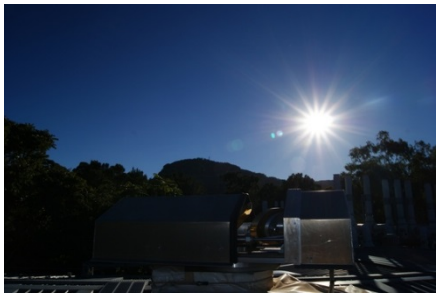


Validation against TCCON

- Solar-tracking, ground-based, Fourier transform spectrometers at over 20 sites around the world
- Retrieve the column average dry air mole fraction of CO_2, CH_4, N_2O, CO, H_2O, HDO, O_2 from solar absorption

Validated against in situ sensors

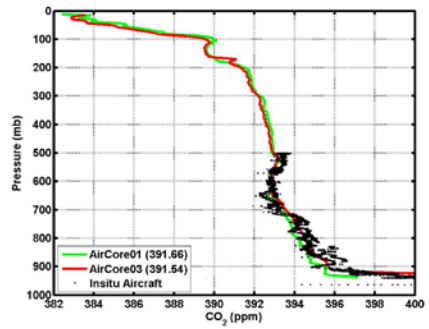




New Validation Capabilities

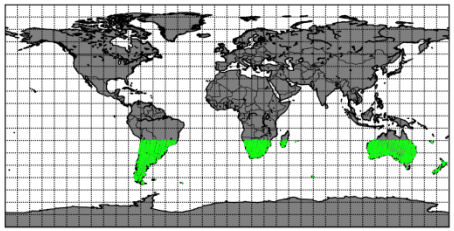
New Column Measurements: AirCore

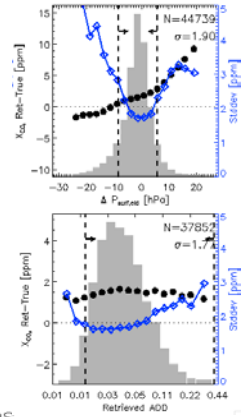
- Contributes to TCCON calibration
- Provides validation at additional locations



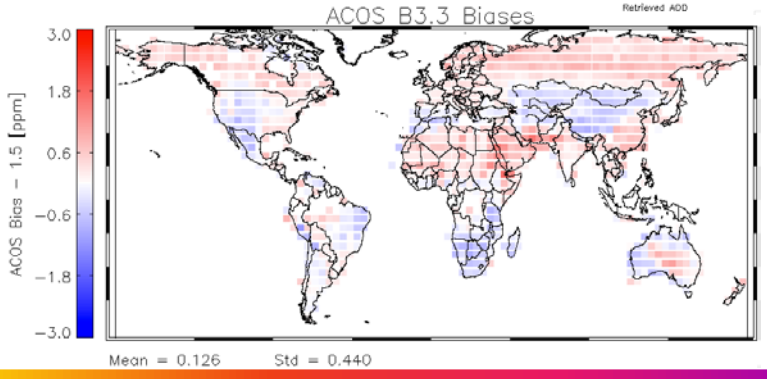
Post Processing Screening

1. 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.



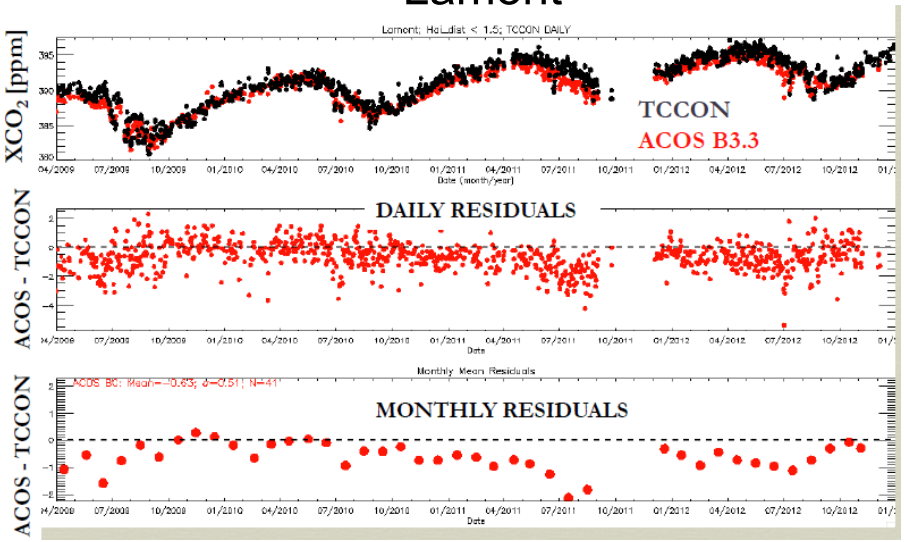


2. Multi-Model Means:
   - Compare ACOS GOSAT X_{CO2} retrievals to the average X_{CO2} fields generated by flux inversion models

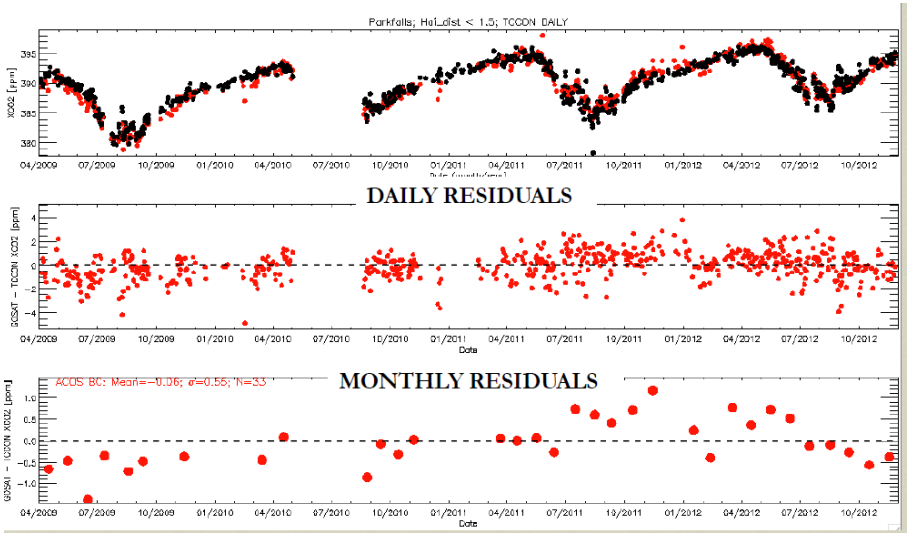


Improved Fits to TCCON (after Bias Correction)

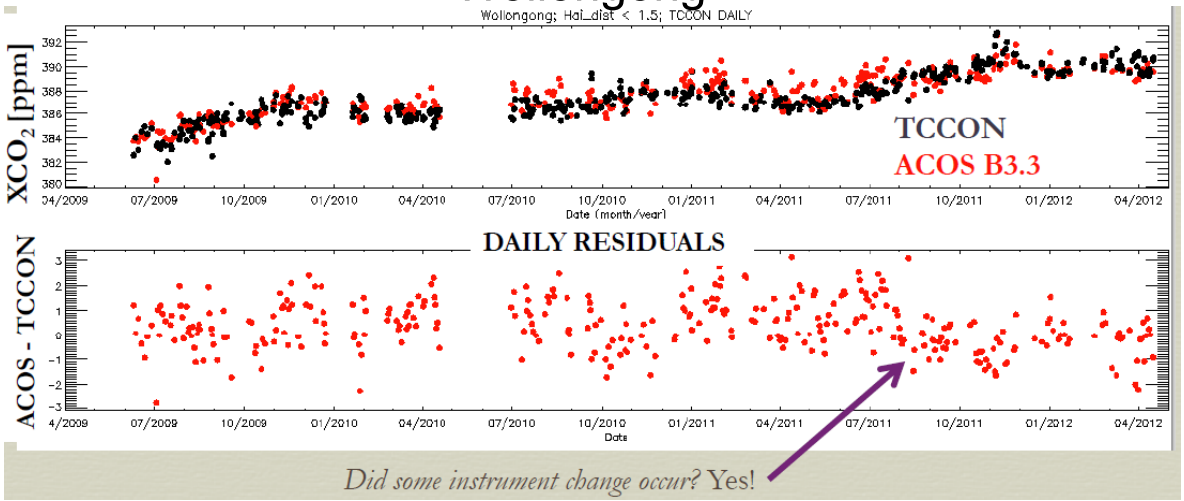
Lamont



Park Falls



Wollongong

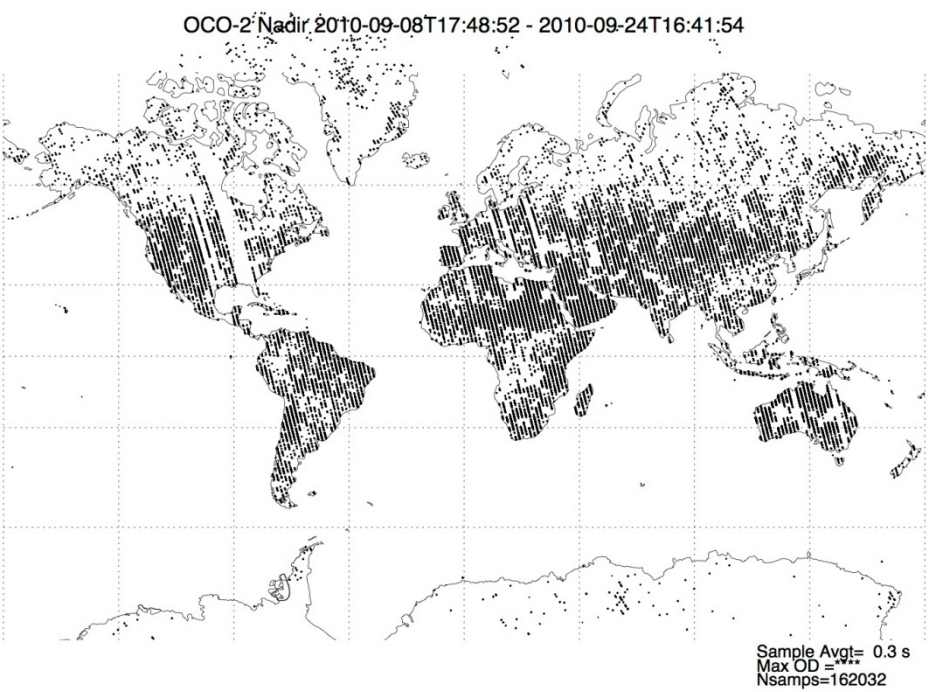


Screening and bias correction techniques substantially reduce the impact of known biases on regional scales.

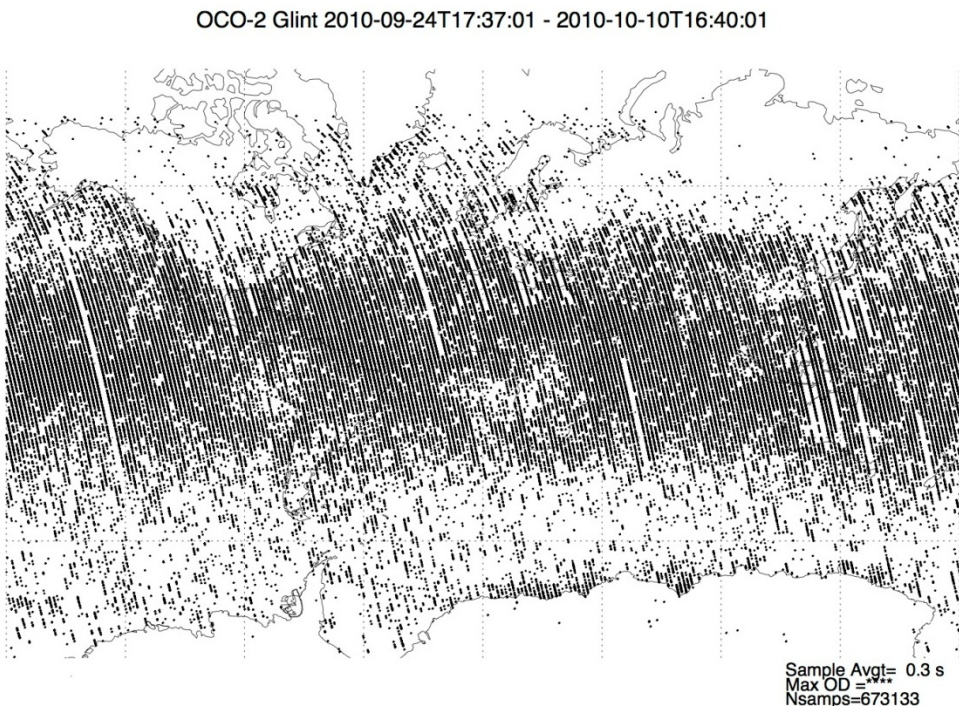
Results from O'Dell et al., IWGGMS-9, 2012

Nadir vs. Glint Coverage

- OCO-2 will collect ~380 Soundings/degree of latitude (>10^6 soundings/day)
- OCO-2 will obtain Nadir and Glint observations of the sunlit hemisphere on alternate 16-day ground track repeat cycles.



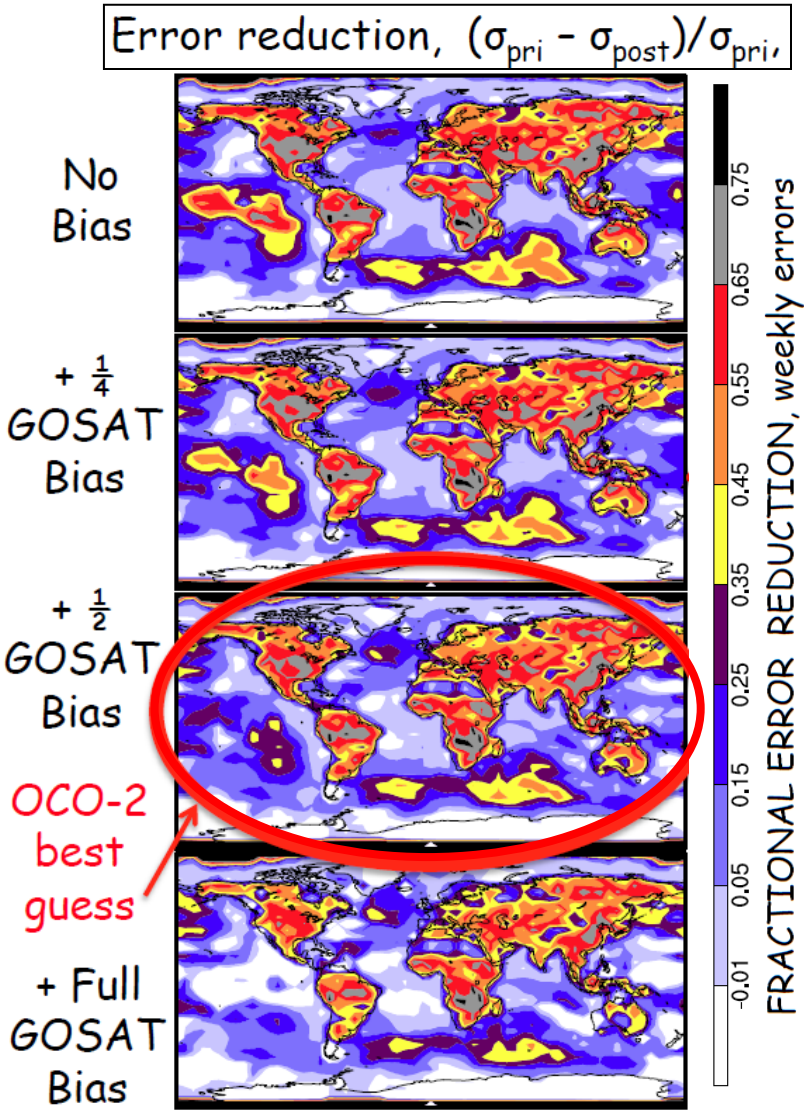
Nadir observations provide better coverage over continents



Glint observations provide better coverage over oceans

Flux Inversion Experiments

- Flux inversion experiments using OCO-2 data are providing new insights into the relative role of random errors and biases
- To assess these errors we used:
  - Conservative estimates of the random errors were obtained by multiplying values in Boesch et al. (2012) by **2**.
  - Spatially-dependent biases estimated by scaling observed errors in the ACOS/GOSATB2.10 product
- Flux inversion experiments performed by David Baker (CIRA/CSU)
  - Parameterized Chemical Transport Model (PCTM; Kawa, et al, 2004)
  - 4.5º x 6º (lat/lon), 40 σ layers, $\Delta t \approx 2$ hrs
- Significant error reductions expected on time scales as short as 1 week



Conclusions

- The OCO-2 implementation is progressing on course, 9 months before its scheduled 1 July 2014 launch date.
  - The OCO-2 flight instrument performance exceeds (most) requirements
  - Observatory and Launch Vehicle I&T are underway

- The OCO-2 Retrieval Algorithm performance continues to improve
  - ACOS/OCO-2 GOSAT B3.3 delivered to the DAAC
    - Improvements in variance for Gain H over land, but poor glint coverage and baised ~2 ppm high
  - The “Launch” version of the algorithm (B3.5) is currently in testing

- Simulations of OCO-2 products are promising
  - Indicate substantial improvements in sensitivity and coverage
  - Flux inversion experiments indicate that OCO-2 data will yield substantial reductions in CO_2 flux uncertainty on regional scales

Thank You for Your Attention

Questions?