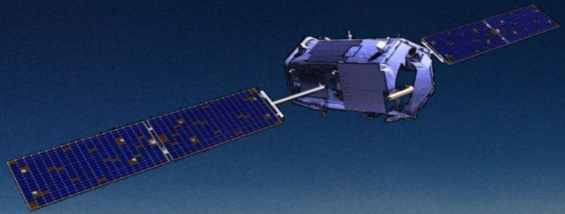


Measuring Carbon Dioxide from Space: Prospects for the Orbiting Carbon Observatory-2

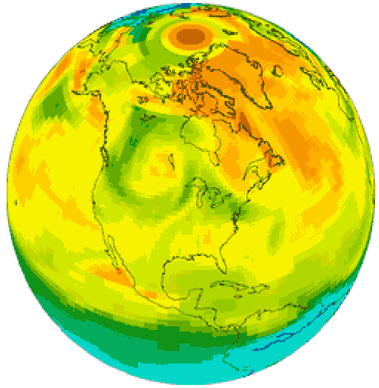
David Crisp, OCO-2 Science Team Leader
for the OCO-2 Science Team

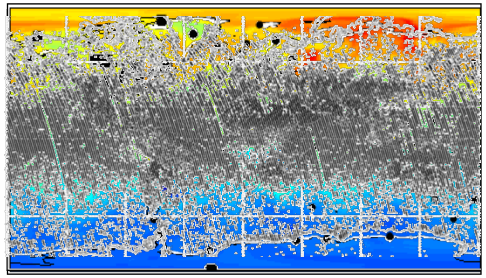
Jet Propulsion Laboratory, California Institute of Technology

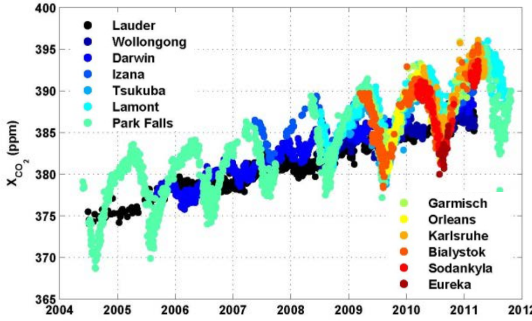
March 2013

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

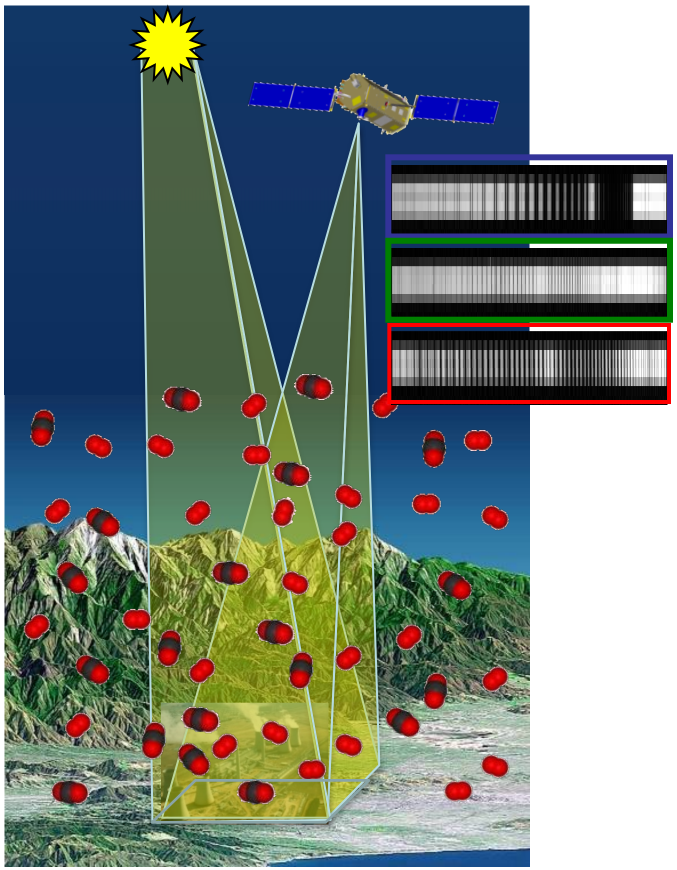




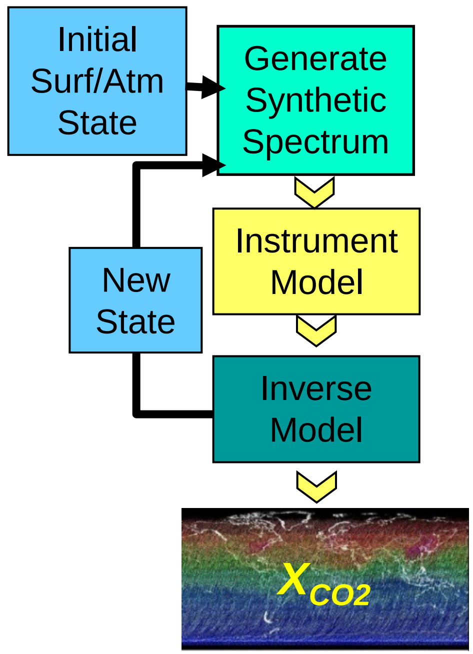


Measuring CO_2 from Space

- **Record** spectra of CO_2 and O_2 absorption in reflected sunlight



- **Retrieve** variations in the *column averaged CO_2 dry air mole fraction, X_{CO2}* over the sunlit hemisphere

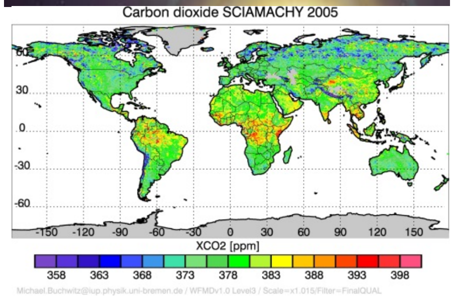


- **Validate** measurements to ensure X_{CO2} accuracy of 1 - 2 ppm (0.3 - 0.5%)

Remote Sensing of CO_2 using Reflected Sunlight: The Pioneers

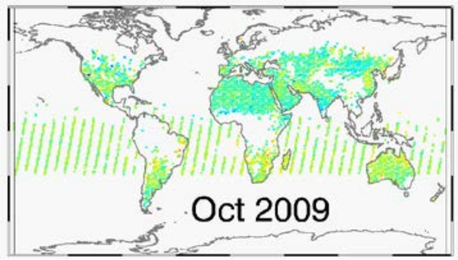
SCIAMACHY (2002 - 2012)

- 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



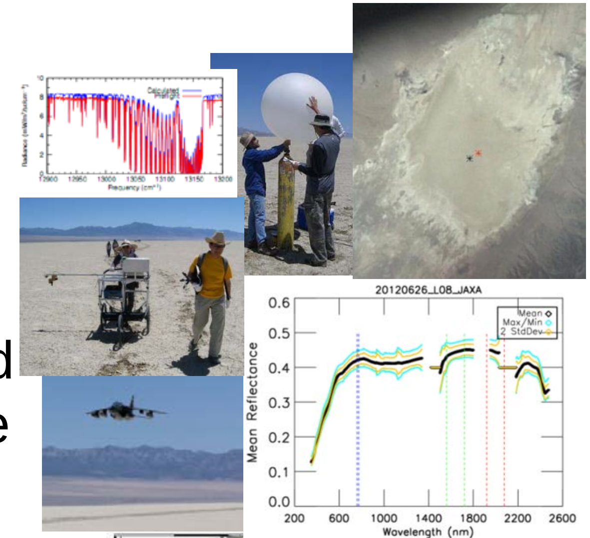
GOSAT (2009 - Present)

- 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/day)
  - Lack of ocean glint at high latitudes limits coverage

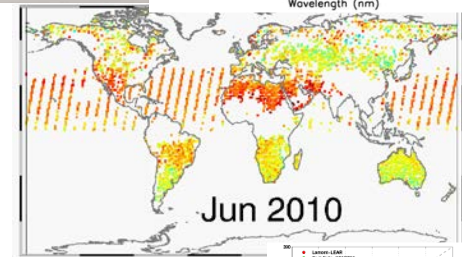


The ACOS/GOSAT Collaboration

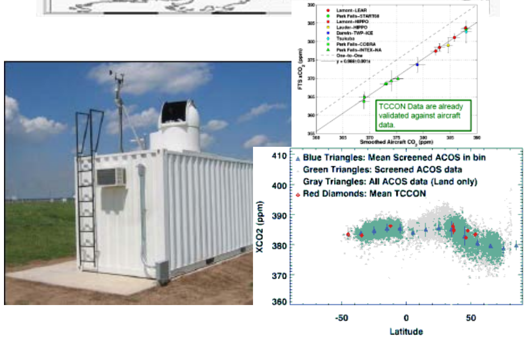
After the loss of OCO, NASA reformulated the OCO Team under the Atmospheric CO_2 Observations from Space (ACOS) task to continue the collaboration with the GOSAT Project Team at JAXA and NIES to:



- Conduct vicarious calibration campaigns in Railroad Valley, Nevada, U.S.A. and analyze results of those campaigns

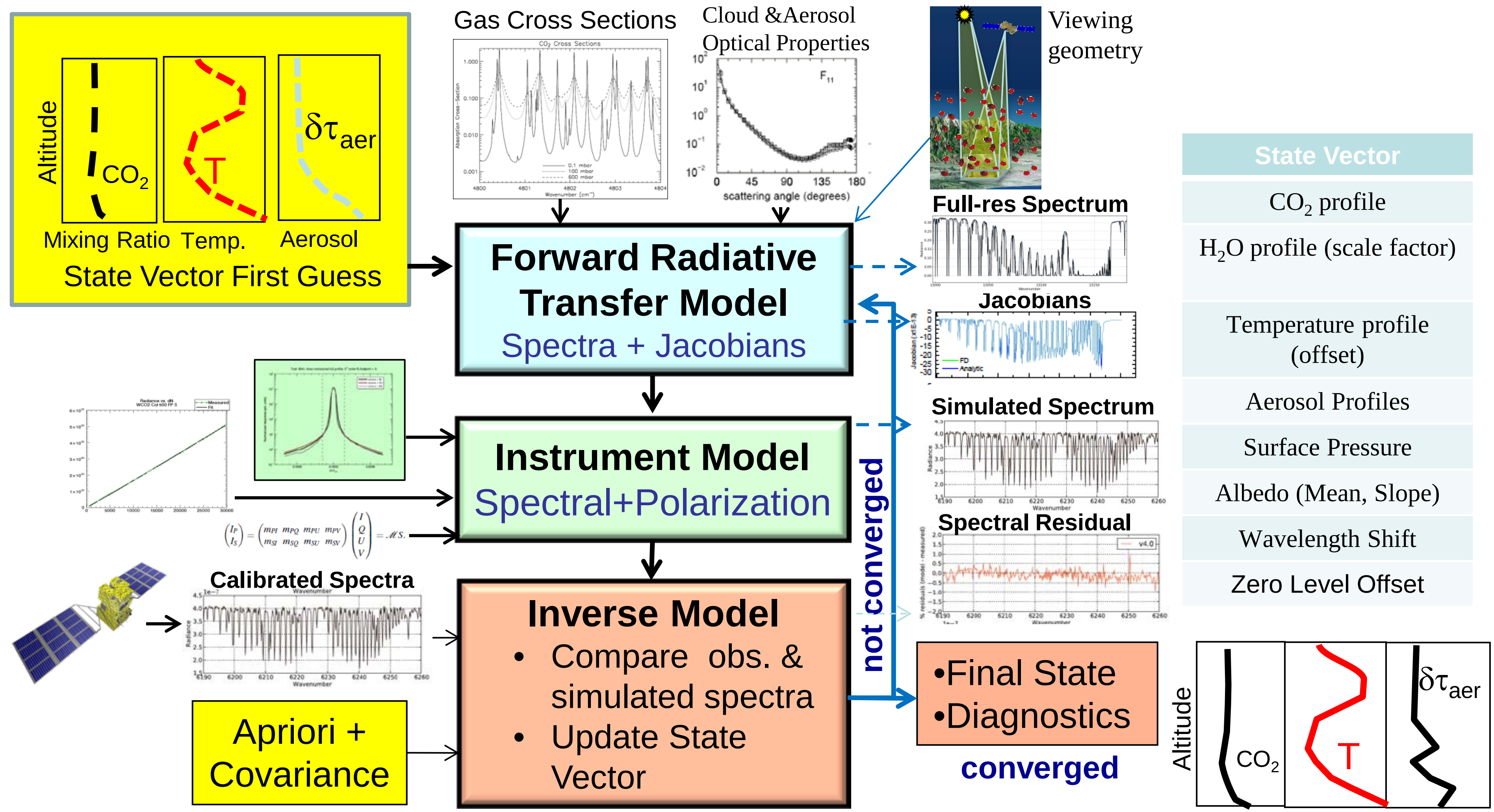


- Retrieve X_{CO2} from GOSAT spectra
  - Model development, and testing
  - Data production and delivery



- Validate GOSAT retrievals by comparing
  - GOSAT retrievals with TCCON measurements
  - 0ther validation standards (surface pressure, aircraft and ground-based CO_2 measurements)

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

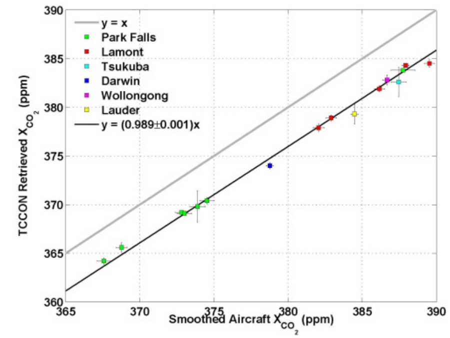


GOSAT Data have provided a critical validation of the OCO Algorithm

Validation against TCCON

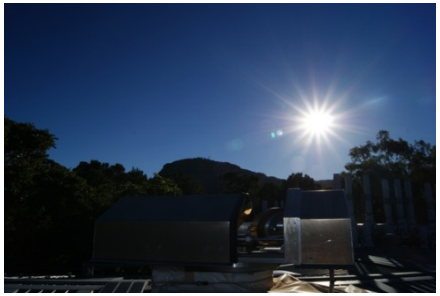
- Ground-based Fourier transform spectrometers
- Remote sensing of total columns of CO_2, CH_4, N_2O, CO, H_2O, HDO, O_2 via solar absorption
- Divide trace gas columns by O_2 column to get dry-air mole fractions: X_{CO_2}, X_{CH_4}, X_{N_2O}, X_{CO}, X_{H_2O}, X_{HDO}

Validated against in situ sensors



Over 20 Operating Sites and Growing

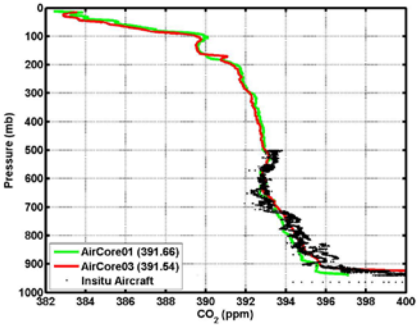
Molecule	Precision	Accuracy
CO_2	~0.8 ppm	~0.8 ppm
CH_4	~5 ppb	~7 ppb
N_2O	~1.5 ppb	~3 ppb
CO	~0.5 ppb	~4 ppb



New Validation Capabilities

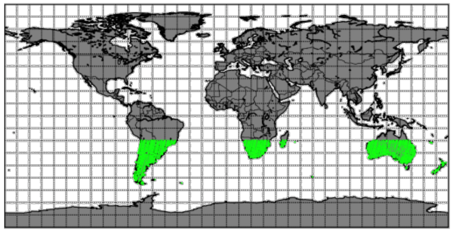
New Column Measurements: AirCore

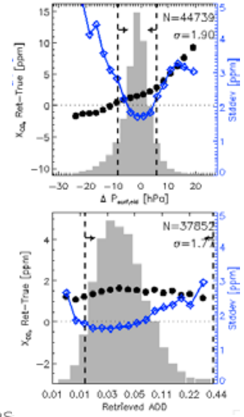
- Contributes to TCCON calibration
- Provides validation at additional locations



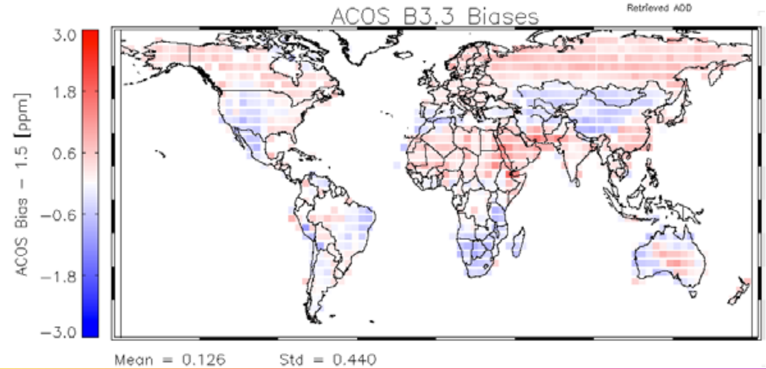
Post Processing Screening

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.

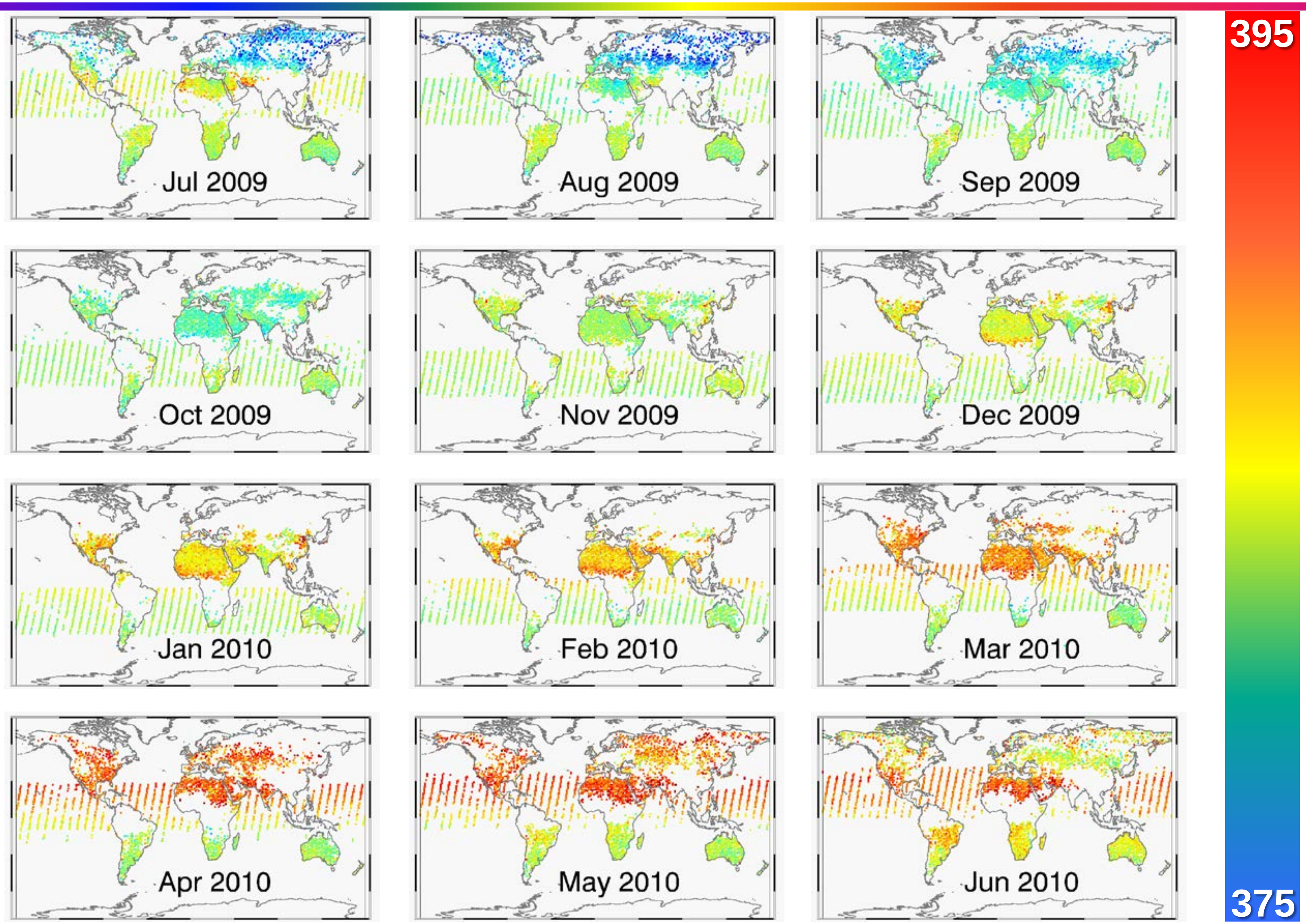




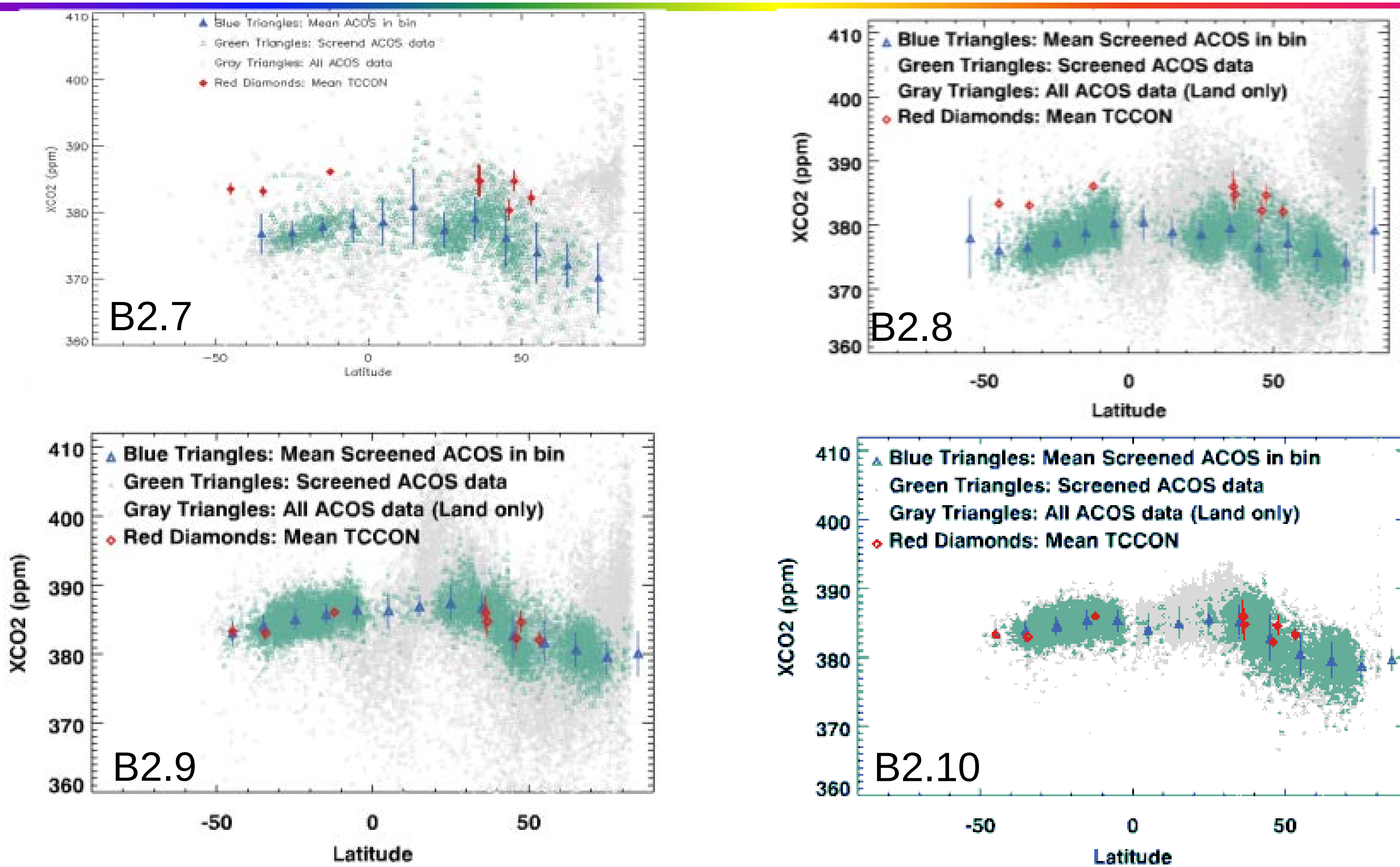
2. Multi-Model Means:
   - Compare ACOS GOSAT X_{CO2} retrievals to the average X_{CO2} fields generated by flux inversion models



ACOS GOSAT B2.10 X_{CO2} Retrievals

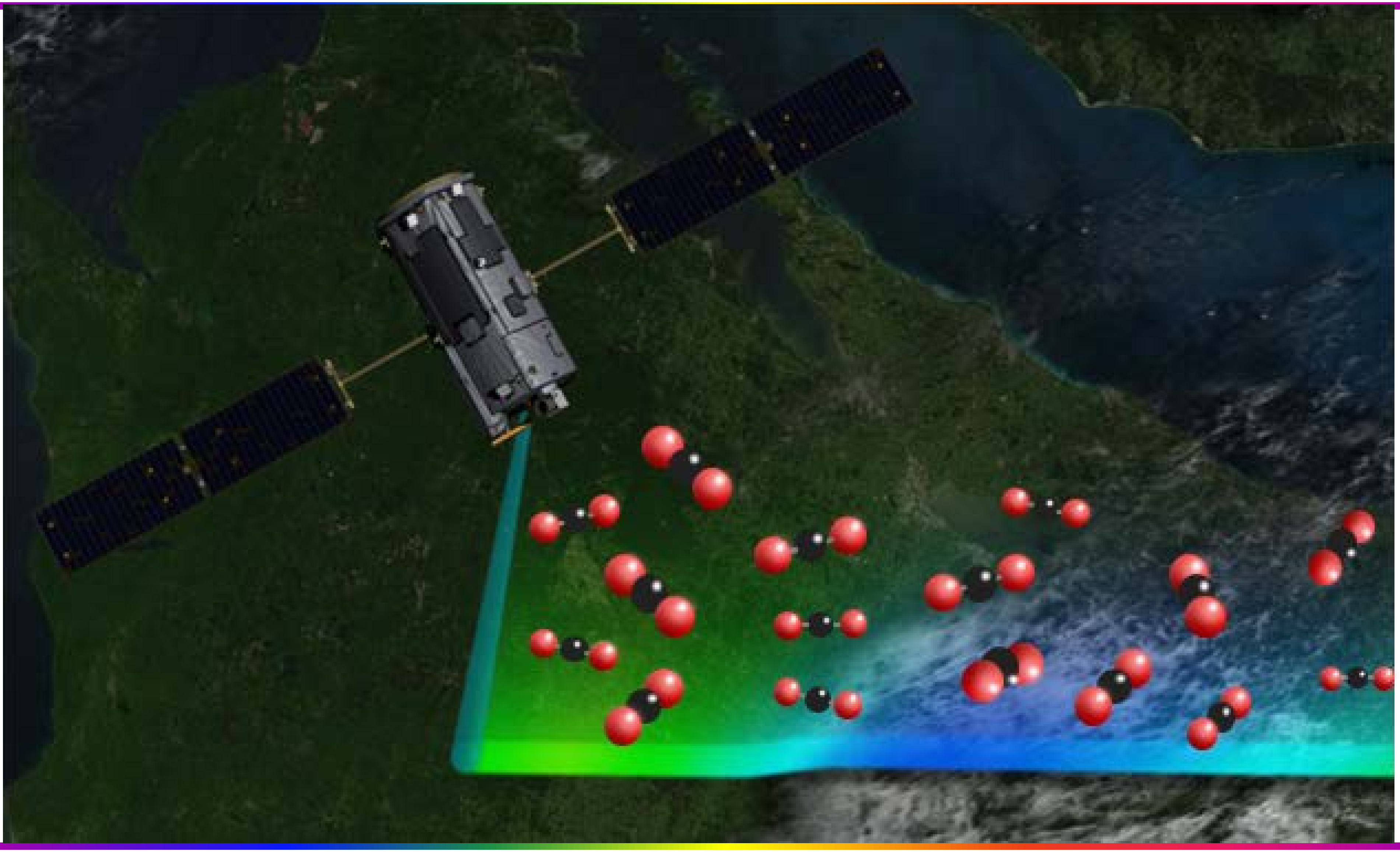


TCCON Comparisons Show Improvements in ACOS GOSAT X_{CO2} Bias and Random Error



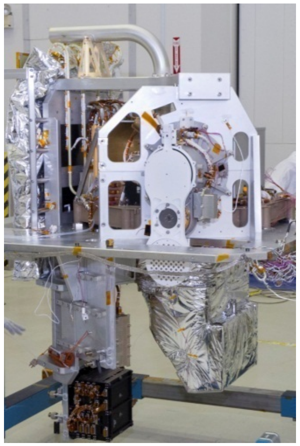
Zonal profiles of ACOS/GOSAT XCO2 estimates (green and grey triangles) are compared to the monthly mean XCO2 estimates from TCCON stations (red diamonds) for July 2009. The precision (scatter), bias, and yield of the ACOS/GOSAT products have improved over time (Crisp et al. 2011).

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

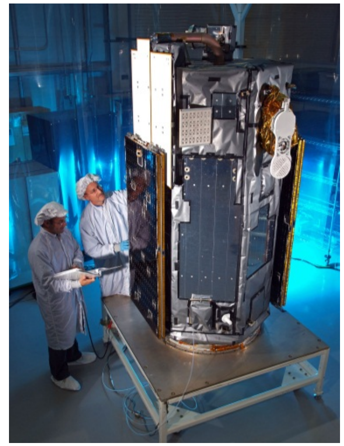


The OCO-2 Mission Overview

3-Channel Grating Spectrometer (JPL)

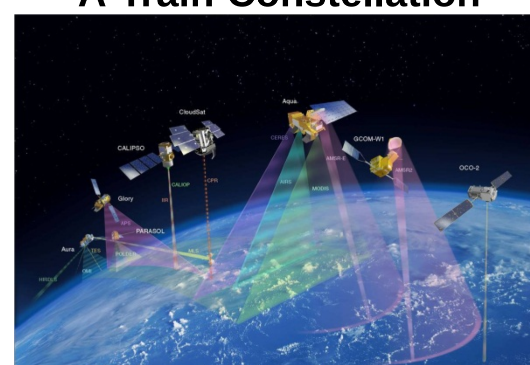


Dedicated Spacecraft Bus (OSC)



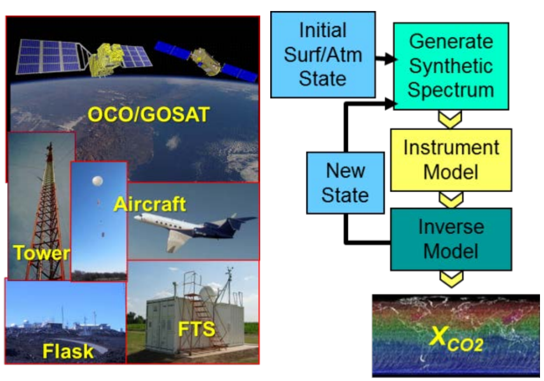
Delta-II Launch Vehicle

Formation Flying in the A-Train Constellation



NASA NEN (GSFC) and SN (TDRSS)

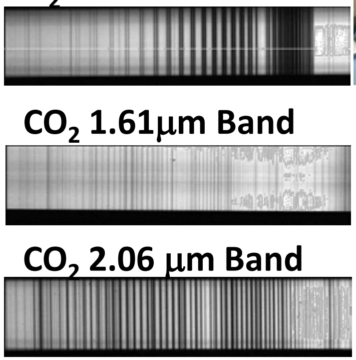
Data Product Generation (JPL)

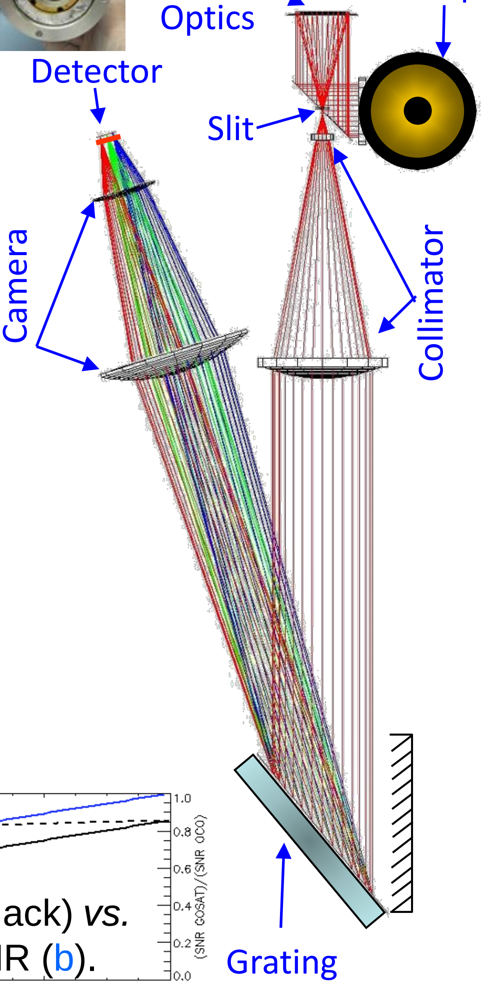


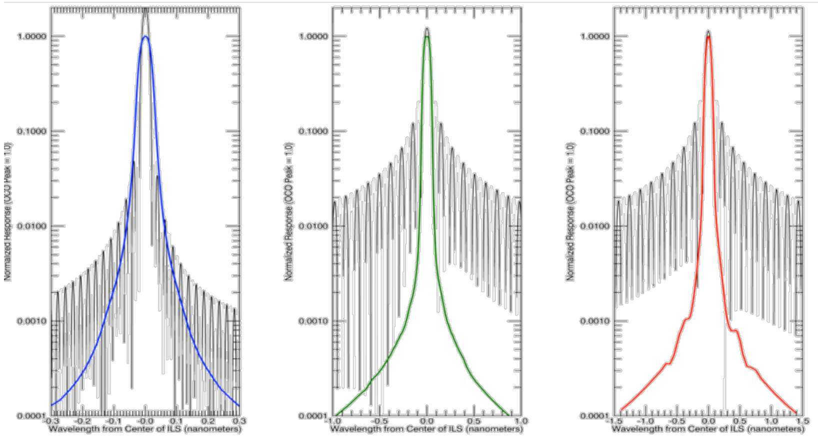
The OCO Instrument – Optimized for Sensitivity

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

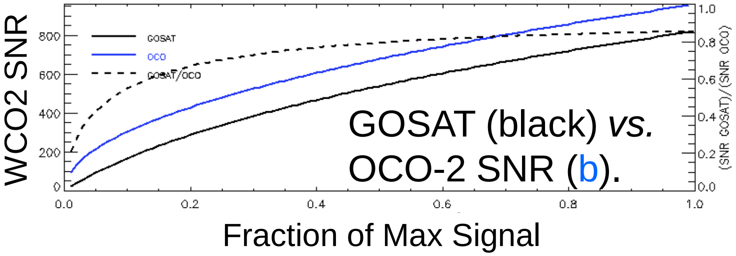
- Resolving Power 17,000 - 20,000
- High Signal-to-Noise Ratio
- Collects 24 soundings / sec
  - 10^6 soundings / day over the sunlit hemisphere







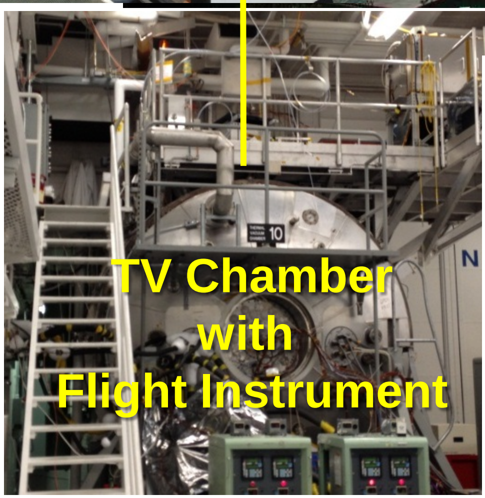
GOSAT (black) *vs.* OCO-2 instrument line shape (ABO2, WCO2, SCO2).

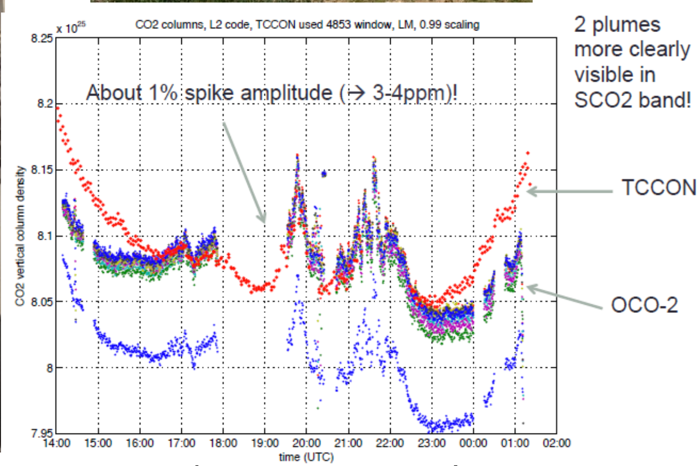


GOSAT (black) *vs.* OCO-2 SNR (b).

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

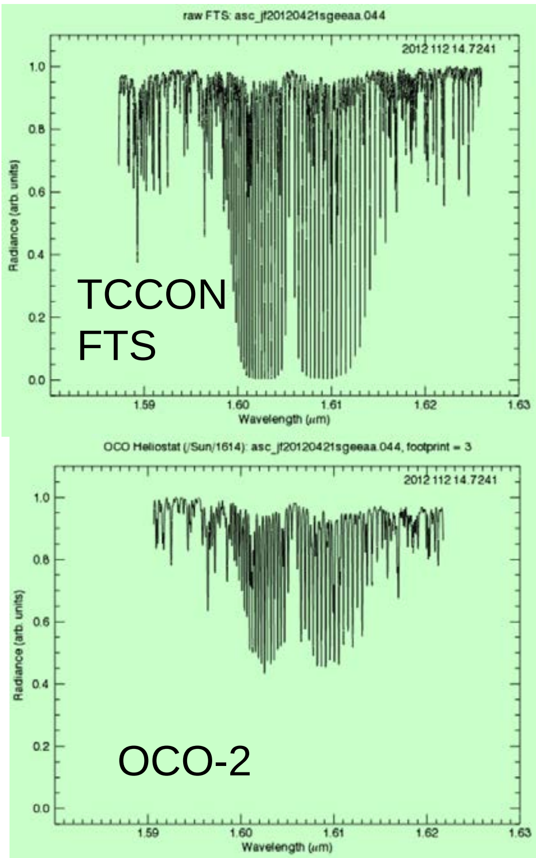
Observations of the sun with the flight instrument taken during TVAC tests provide an end-to-end verification of the instrument performance.





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

1.6 μm CO_2



21 April 2012

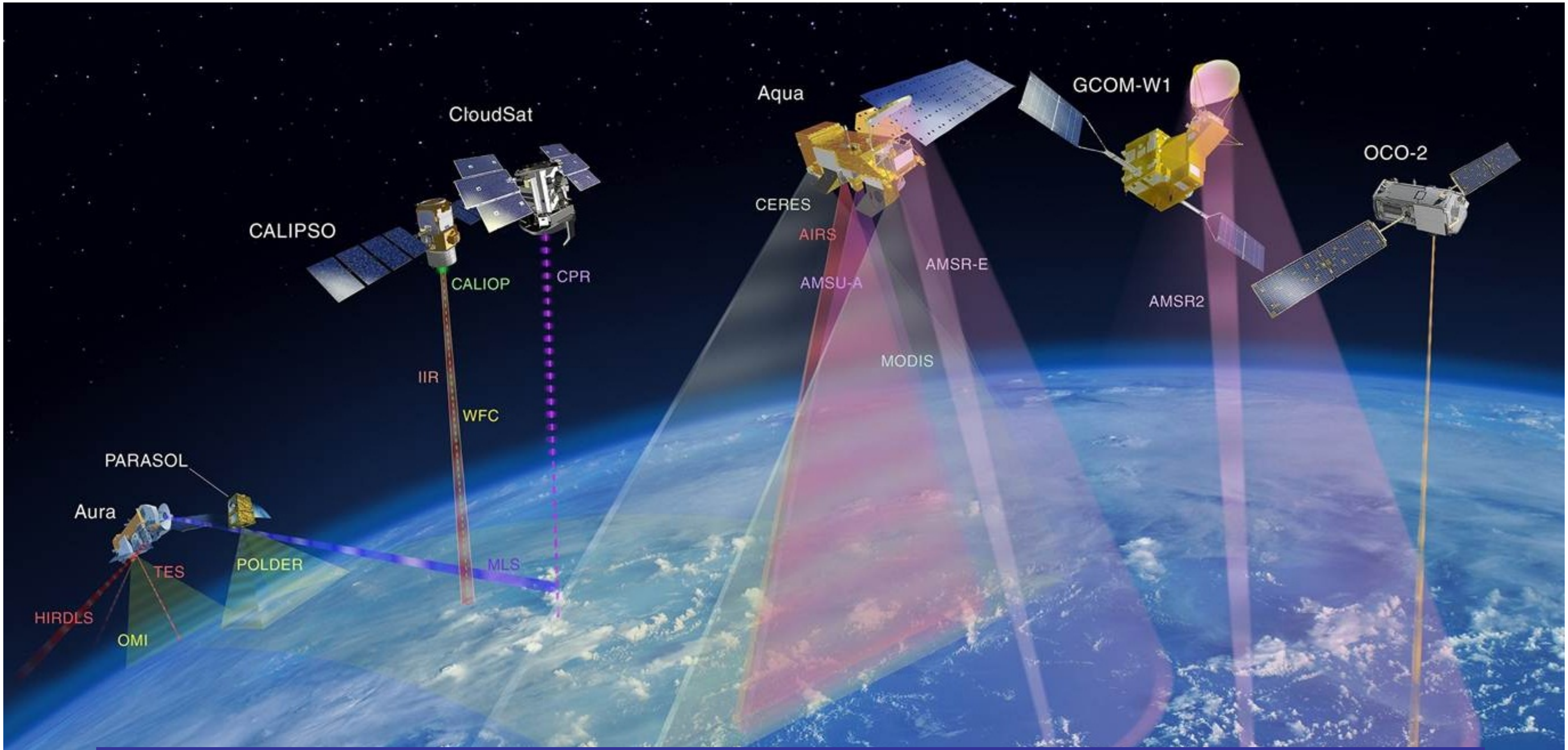
Observatory I&T Activities Ongoing

Launch Date Driven by Launch Service Availability

- 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 nominal OCO-2 launch date is “no earlier than 1 July 2014”

Credit: Steve Greenberg, JPL

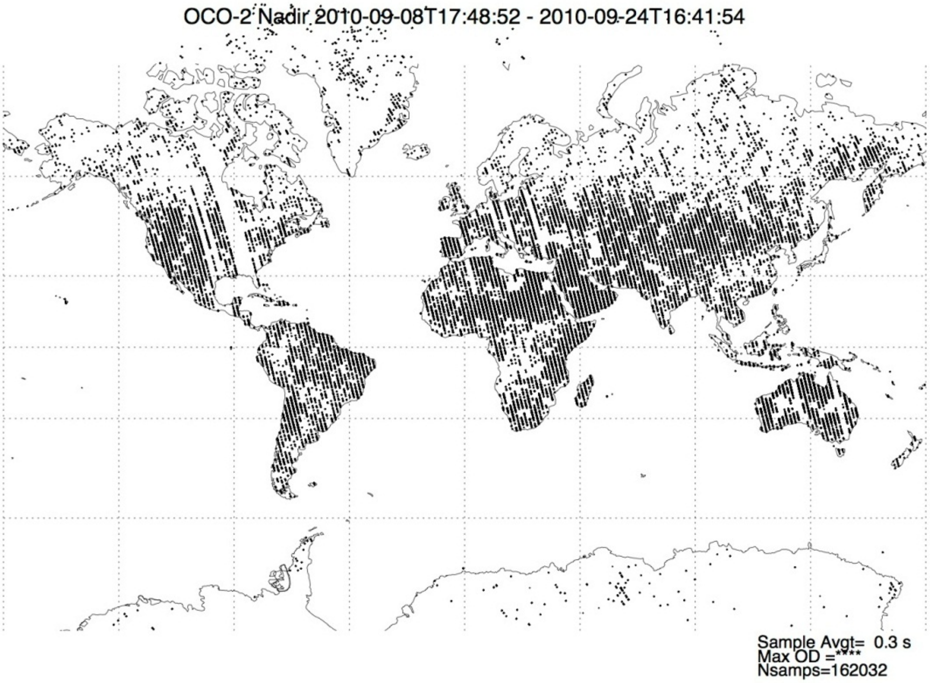
Flying in Formation in the A-Train



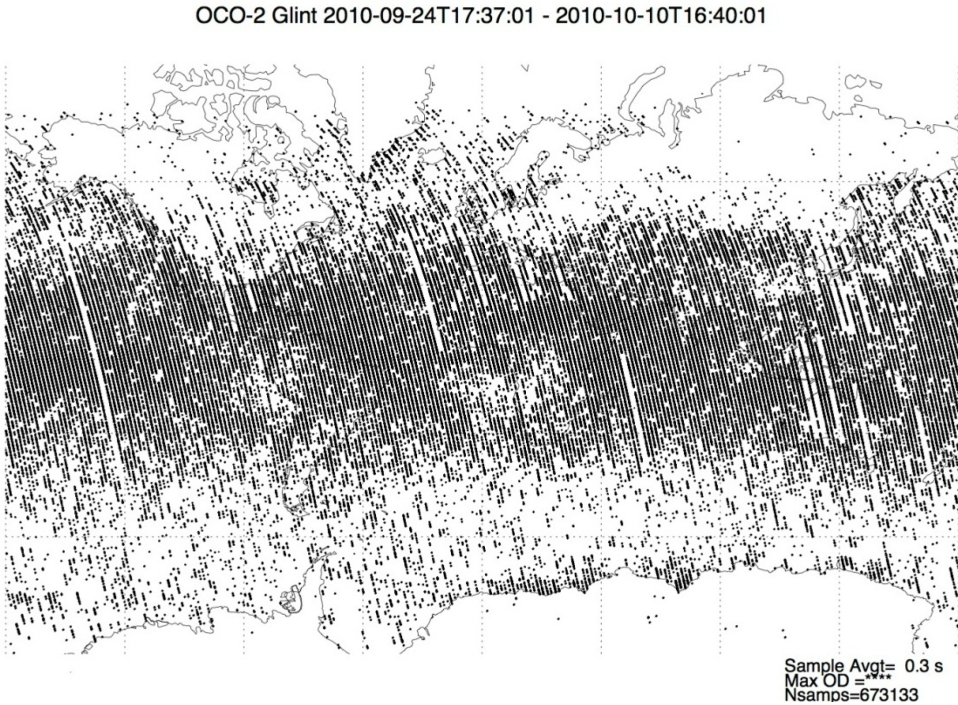
OCO-2 will fly at the head of A-Train (now called the 705-km Constellation), but has changed it flight path to share the ground track with CloudSat and CALIPSO, which is 217 km East of the AQUA (WRS-2 Standard) track.

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

Conclusions

- Space-based remote sensing observations hold substantial promise for future long-term monitoring of CO_2 and other greenhouse gases
  - These measurements will complement those from the existing ground-based greenhouse gas monitoring network with increased: spatial coverage and sampling density

- The principal challenge is the need for high precision (~0.3% or 1 ppm)

- The Japanese GOSAT mission (Nicknamed “Ibuki”) has provided a valuable pathfinder for analysis techniques

- Once it is launched in 2014, the NASA OCO-2 mission will demonstrate the measurement precision, coverage, and resolution needed to:
  - Quantify CO_2 sources on the scale of an average-sized nation
  - Find the natural “sinks” that are absorbing over half of the CO_2 emitted by human activities

Thanks for your Attention

Questions?