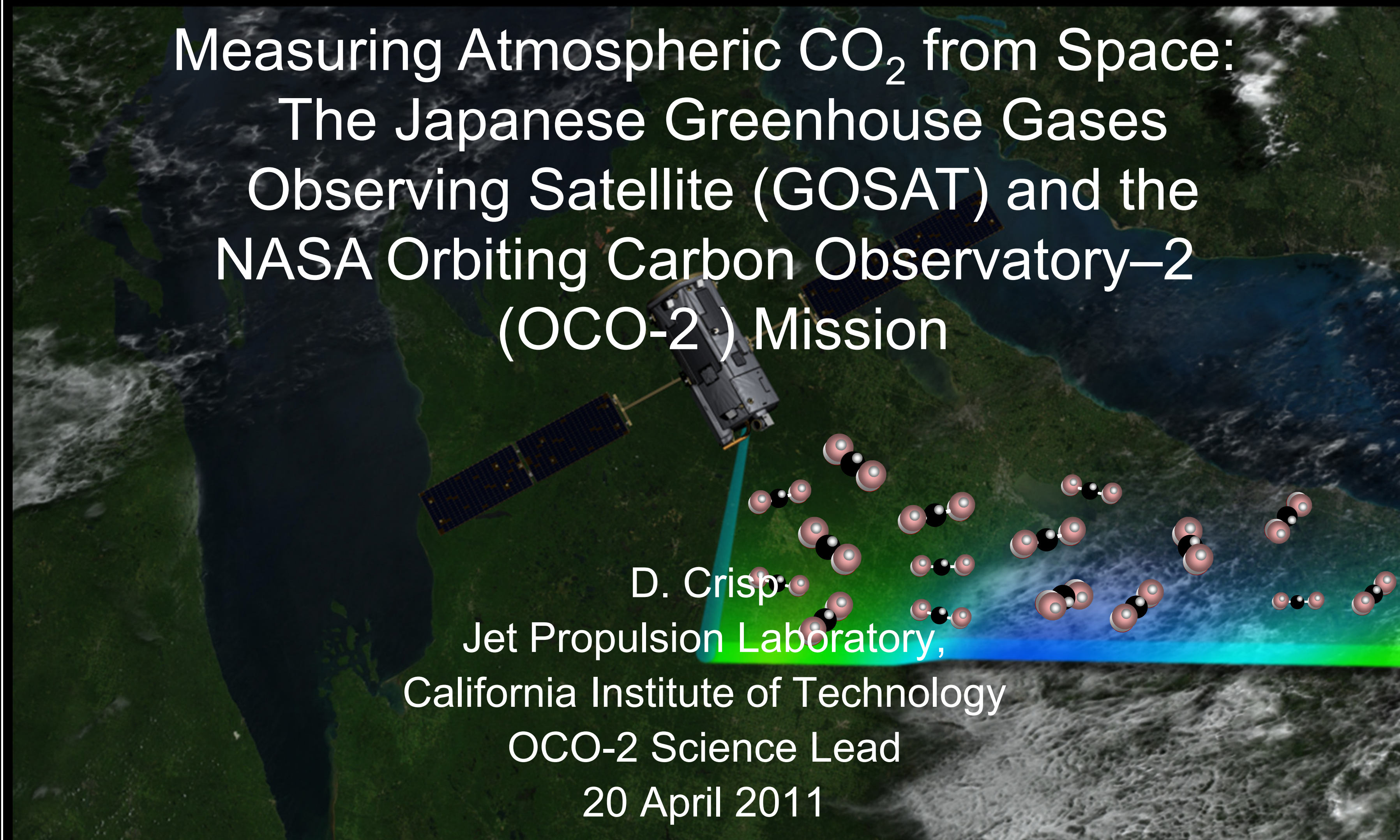

Measuring Atmospheric CO_2 from Space: The Japanese Greenhouse Gases Observing Satellite (GOSAT) and the NASA Orbiting Carbon Observatory–2 (OCO-2) Mission

D. Crisp
Jet Propulsion Laboratory,
California Institute of Technology
OCO-2 Science Lead

20 April 2011

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Government sponsorship acknowledged.

Capabilities vs Expectations for OCO-2

- A decade ago, when the OCO mission was proposed, the primary objective was to acquire global, space-based observations of CO_2 with the precision, coverage, and resolution needed to characterize regional scale natural CO_2 sinks, which are now absorbing more than half of the CO_2 that is being emitted by human activities
- More recently, the interest in global, space-based observations of greenhouse has intensified, but the focus has shifted, emphasizing the need to quantify emissions from human activities
  - The current emphasis is on monitoring treaty compliance and the efficacy of greenhouse gas mitigation strategies
- This change in focus, combined with new insight into the carbon cycle has introduced new challenges for remote sensing observations of greenhouse gases
- While OCO-2 is not optimized for that mission, it will provide opportunities to validate observation strategies for future CO_2 monitoring missions

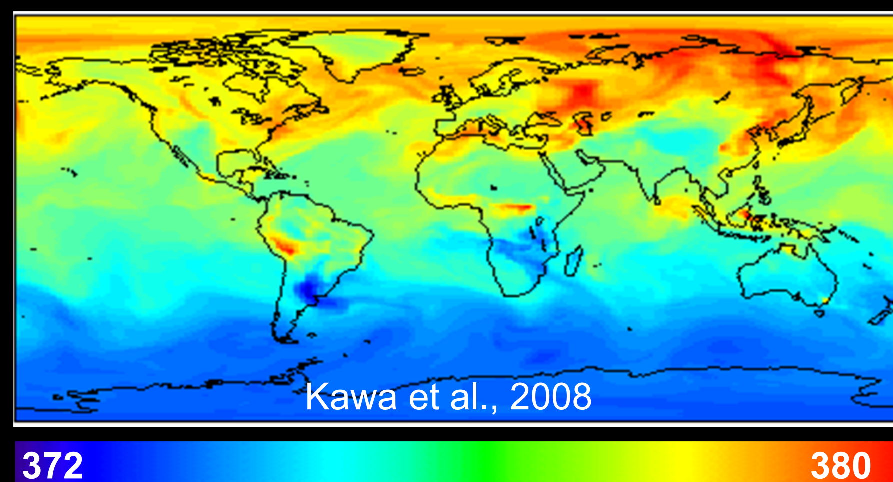
Global Measurements are Essential

- To limit the rate of atmospheric carbon dioxide buildup, we must
  - Control emissions associated with human activities
  - Understand & exploit natural processes that absorb carbon dioxide

We cannot manage what we cannot measure

- Identifying sources and sinks of atmospheric carbon dioxide from atmospheric measurements is intrinsically challenging

Plumes from medium-sized power plants (4 MtC/yr) elevate X_{CO2} levels by ~0.5% (2ppm) for 10's of km downwind [Yang and Fung, 2010].



Variations of CO_2 are rarely larger than 1-2% on 100 – 1000 km scales

Is 1 ppm Good Enough?

Large metropolitan areas with strong, discrete sources are easier to detect, but also rarely produce full column X_{CO2} perturbations larger than 1 ppm

TABLE B.3 Expected CO_2 Signals for Selected Metropolitan Areas

City	Area (km^2)[a]	Emissions (Mton CO_2 yr^{-1})	Emissions ($\mu mol\ m^{-2}\ s^{-1}$)	Total Column (ppm)	PBL (1 km) (ppm)
Los Angeles	3,700	73.2	14.2	0.49	4.3
Chicago	2,800	79.1	20.3	0.60	5.4
Houston	3,300	101.8	22.2	0.72	6.4
Indianapolis	900	20.1	16.1	0.27	2.4
Tokyo	1,700	64	27	0.63	5.6
Seoul	600	43	52	0.71	6.3
Beijing	800	74	67	1.1	9.4
Shanghai	700	112	116	1.8	15

(1) Committee on Methods for Estimating Greenhouse Gas Emissions Board on Atmospheric Sciences and Climate Division on Earth and Life Studies, National Research Council of the National Academy of Science, National Academies Press, 2010.

A satellite instrument with a 1 ppm sensitivity over a ~100 km down-track segment of its orbit might not detect Los Angeles, Chicago, Houston, or Tokyo.

The Minimum Measurable Point Source Flux

- For a satellite like OCO, designed to measure the column averaged dry air mole fraction, X_{CO2}, the minimum measurable flux can be approximated as follows:
  - Assume the minimum detectable change in X_{CO2} is $\Delta XCO2_{min}$ (e.g. 1 ppm)
  - If the CO2 flux, ***F***, is constant over an accumulation time interval, ***t***, the change in XCO2 is given by: $\Delta XCO2 = F \cdot t$
  - If we have an average horizontal wind speed, $u(\theta)$, in direction, θ, over time, ***t***, and a footprint has a horizontal dimension, $x(\theta)$, then the residence time, $t = x/u$
  - The minimum increase in the vertical column is therefore related to the minimum detectable flux as follows

$$\Delta XCO2_{min} = F_{min} \cdot x / u$$

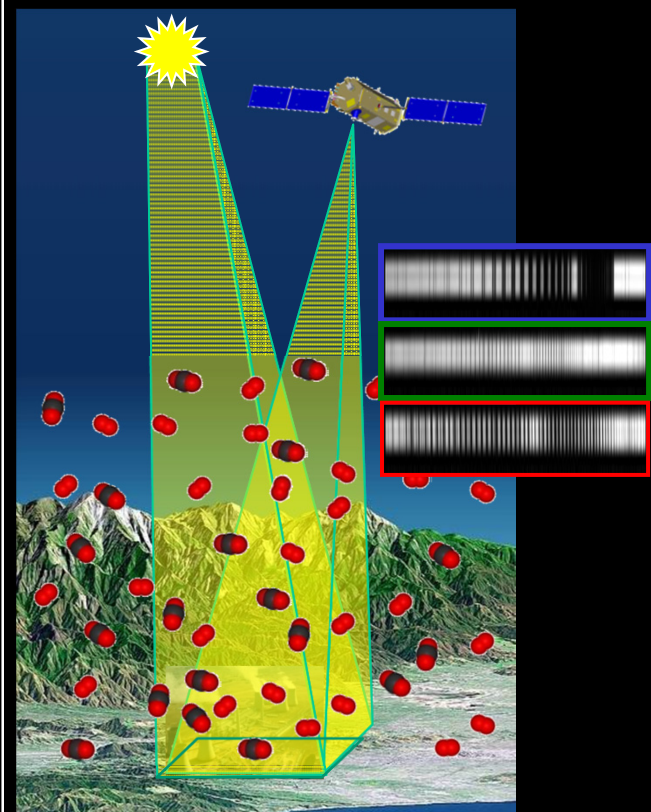
Rearranging, gives

$$F_{min} = u \cdot \Delta XCO2_{min} / x$$

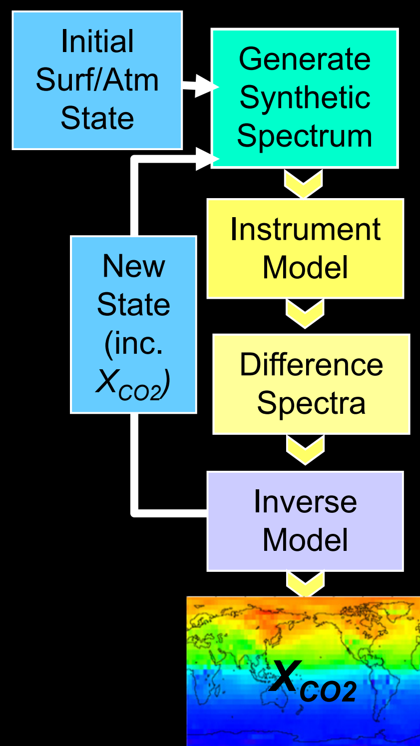
For a given X_{CO2} sensitivity, the minimum measureable CO_2 flux is proportional to wind speed and inversely proportional to footprint size

Measuring CO_2 from Space

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



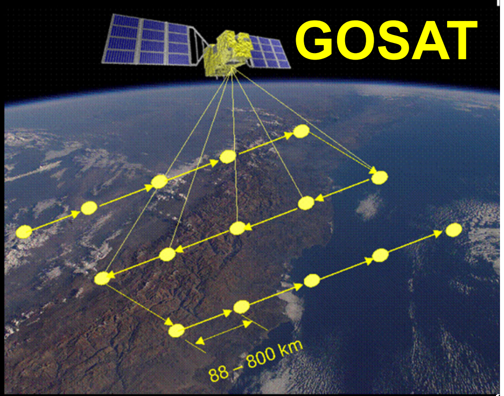
- **Retrieve** variations in the *column averaged CO_2 dry air mole fraction, X_{CO2}* over the sunlit hemisphere



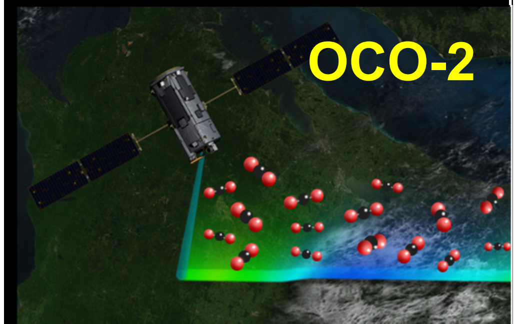
- **Validate** measurements to ensure X_{CO2} accuracy of 1 - 2 ppm (0.3 - 0.5%)

OCO-2 and GOSAT

	GOSAT	OCO
Gases Measured	CO_2, CH_4, O_2, O_3, H_2O	CO_2, O_2
Instruments	SWIR/TIR FTS, CAI	Grating Spectrometer
IFOV / Swath (km)	FTS: 10.5 / 80-790 (160) CAI: 0.5 / 1000	1.29 x 2.25 / 5.2-10.4
Spectral Ranges (µm)	0.758-0.775, 1.56-1.72, 1.92-2.08, 5.56-14.3	0.757-0.772, 1.59-1.62, 2.04-2.08
Soundings/Day	10,000	500,000 to 1,000,000
Sampling Rate	0.25 Hz	12 to 25 Hz
Orbit Altitude	666 km	705 km
Local Time	12:48	13:30
Revisit Time/Orbits	3 Days/72 Orbits	16 Days/233 Orbits
Launch Vehicle	H-IIA	Taurus 3110 (TBD)
Launch Date	January 2009	February 2013
Nominal Life	5 Years	2 Years



GOSAT was optimized for spectral & spatial coverage



OCO-2 was optimized for sensitivity and resolution

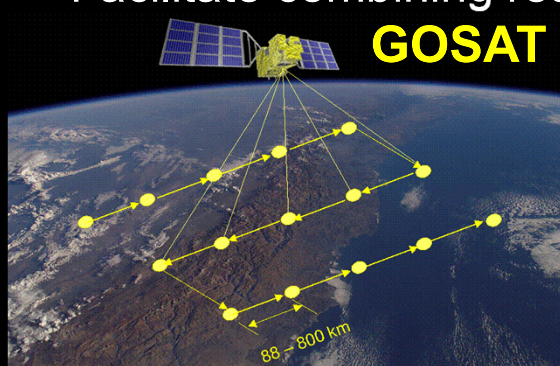
OCO and GOSAT Collaboration

The OCO and GOSAT teams formed a close partnership during the implementation phases of these missions to:

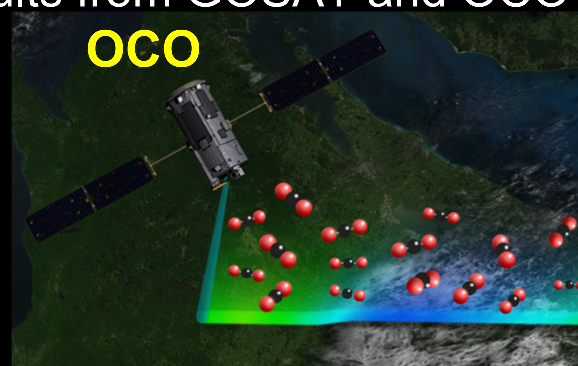
- Cross calibrate the OCO instrument and TANSO-FTS
- Cross validate OCO and GOSAT X_{CO2} retrievals against a common standard

The primary objectives of this partnership were to:

- Accelerate understanding of this new data source
- Facilitate combining results from GOSAT and OCO



3-day ground track repeat cycle resolves weather



Continuous high resolution measurements along track

The Launch of GOSAT & Loss of OCO

GOSAT launched successfully on 23 January 2009

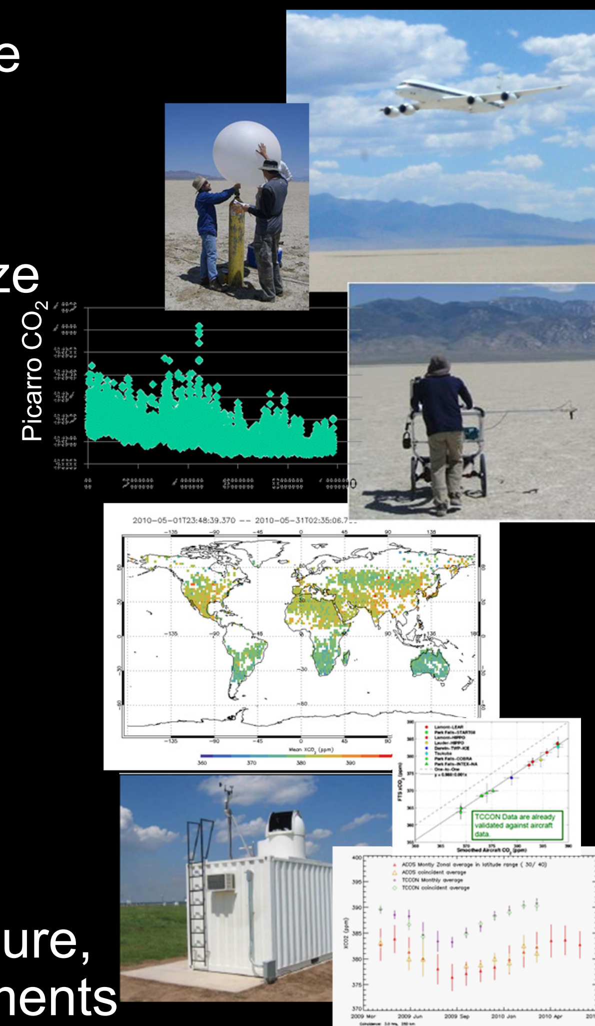
OCO was lost a month later when its launch system failed

Working with the GOSAT Team

- Immediately after the loss of OCO, the GOSAT Project manager invited the OCO Team to participate in GOSAT data analysis
- NASA reformulated the OCO team as the "Atmospheric CO_2 Observations from Space" (ACOS) team
- This collaboration benefits the GOSAT team by:
  - Combining the ground based calibration and validation resources of both teams to maximize the accuracy of the GOSAT data
  - Combining the scientific expertise from both teams to accelerate our understanding of this new, space-based data source
- This collaboration benefits the NASA OCO by
  - Providing direct experience with the analysis of space based CO_2 measurements
  - Accelerating the delivery of precise CO_2 measurements from future NASA carbon dioxide monitoring missions

Scope of the ACOS/GOSAT Collaboration

- The ACOS team is collaborating closely with the GOSAT teams 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, implementation, & testing
    - Data production and delivery
  - Validate GOSAT retrievals by comparing
    - GOSAT retrievals with TCCON measurements
    - Other validation standards (surface pressure, aircraft and ground-based CO_2 measurements

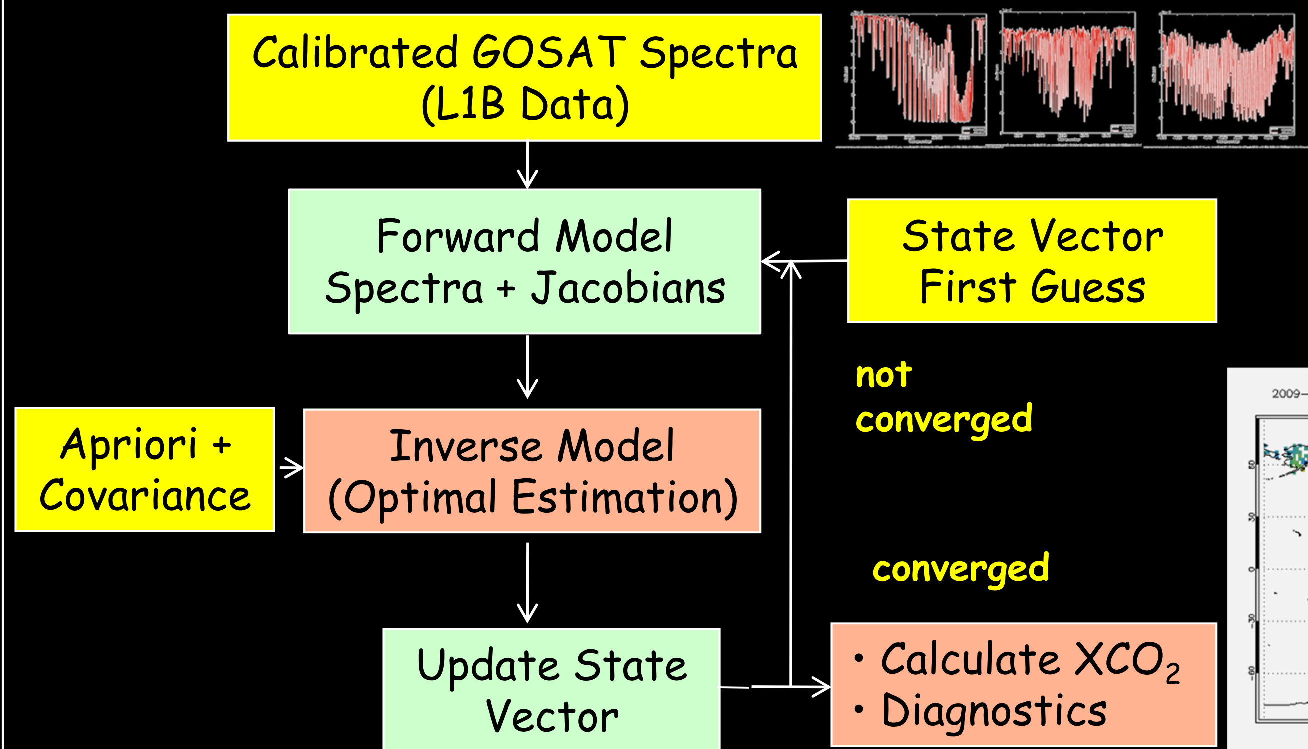


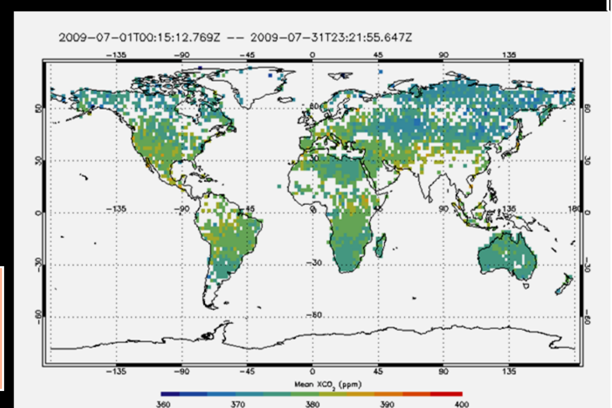
Retrieving X_{CO2} from GOSAT Data

The OCO Retrieval Algorithm was modified to retrieve X_{CO2} from GOSAT measurements

- "Full-physics" forward model
- Inverse model based on optimal estimation

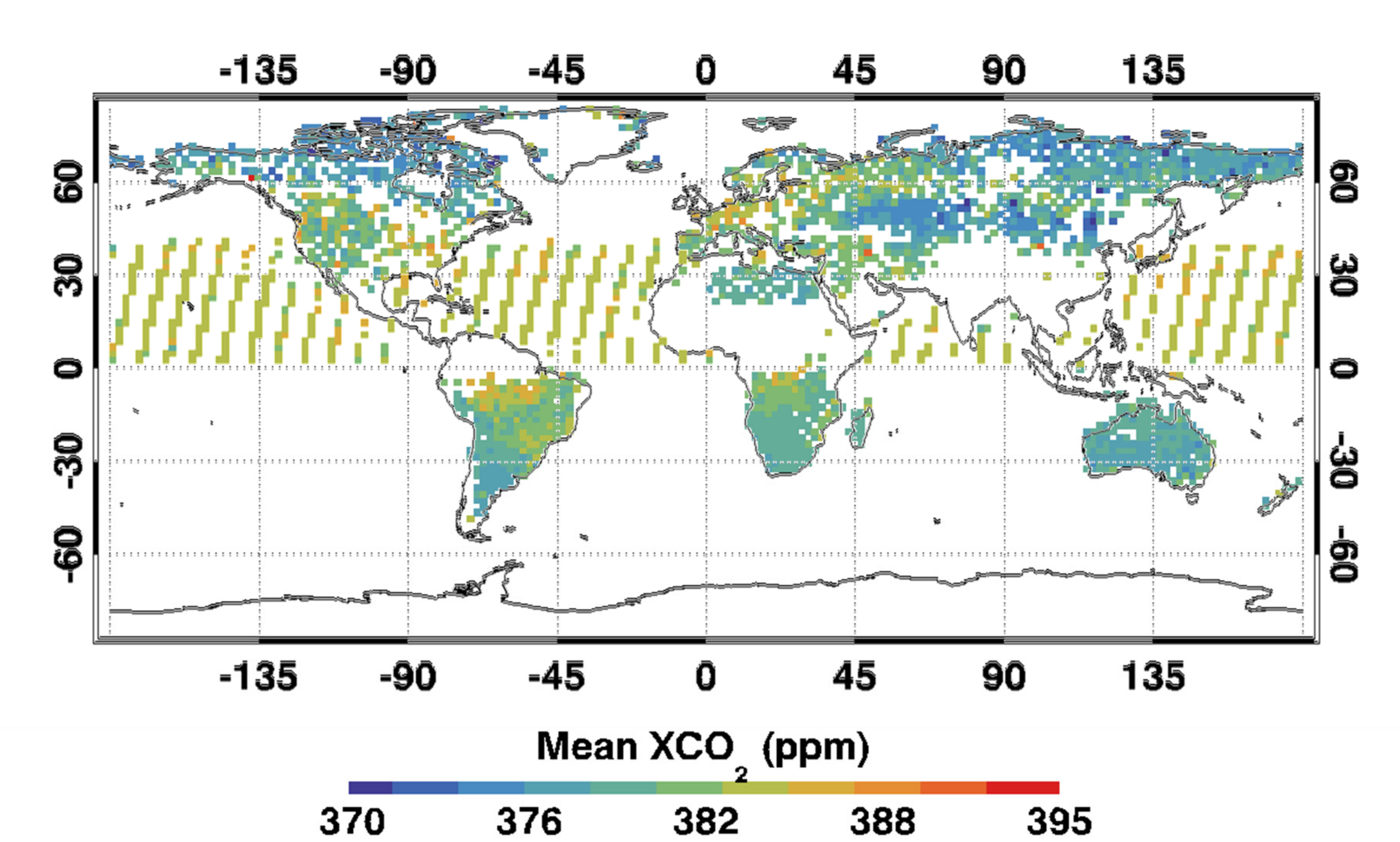
State Vector
CO_2 profile (full)
H_2O profile (scale factor)
Temperature profile (offset)
Aerosol Profiles
Surface Pressure
Albedo (Mean, Slope)
Wavelength Shift (+ stretch)





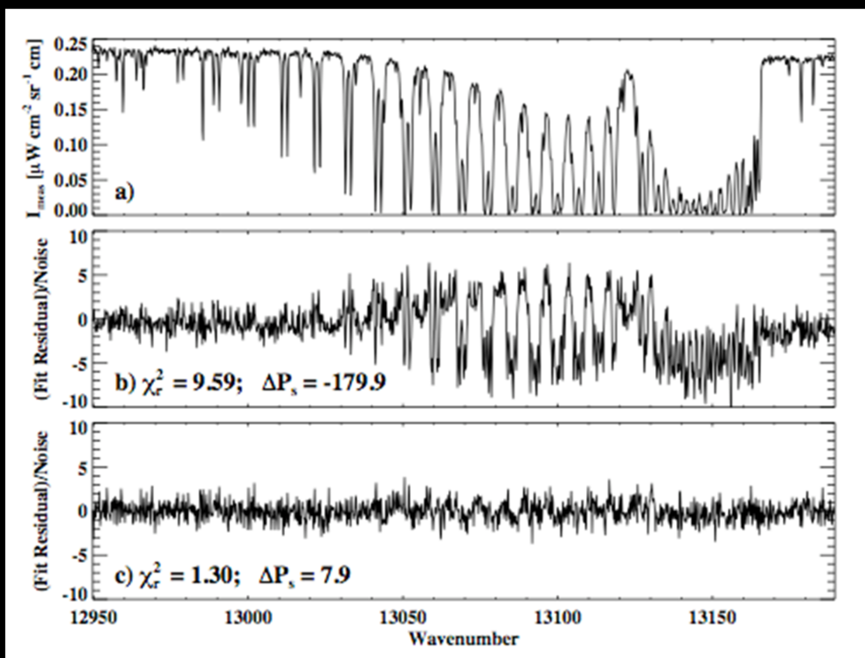
ACOS/GOSAT Data Products: X_{CO2} Retrievals

X_{CO2} Retrievals for July 2010



The ACOS Cloud Screen

- A Spectroscopic cloud screening algorithm based on the O_2 A-band is currently being used for GOSAT retrievals
  - Fits a clear sky atmosphere to every sounding in the O_2 A band.
  - High values of χ^2 and large differences between the retrieved surface pressure and the ECMWF prior indicate the presence of clouds
  - Over non-glint ocean, a simple albedo test is also used.



Example A-Band fit

Poor fit (χ^2 = 9.6) indicates presence of cloud

Small residuals and good agreement between retrieved and ECMWF surface pressure indicates cloud free

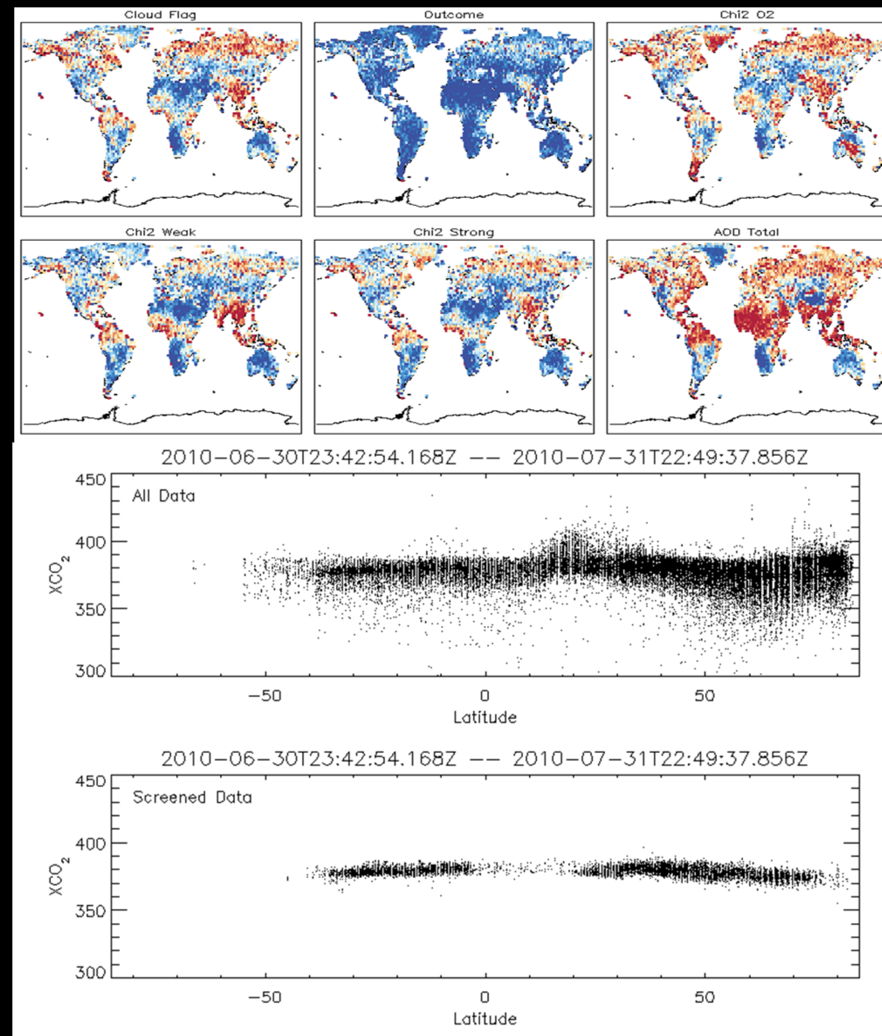
Post Screening Improves Accuracy

Errors can be further reduced by post-screening retrievals, based on a series of criteria, including:

- Measurement SNR
- Convergence
- Goodness of spectral fit
- Surface pressure error
- Evidence for clouds or optically thick aerosols
- *A postiori* retrieval error
- Evidence of known biases

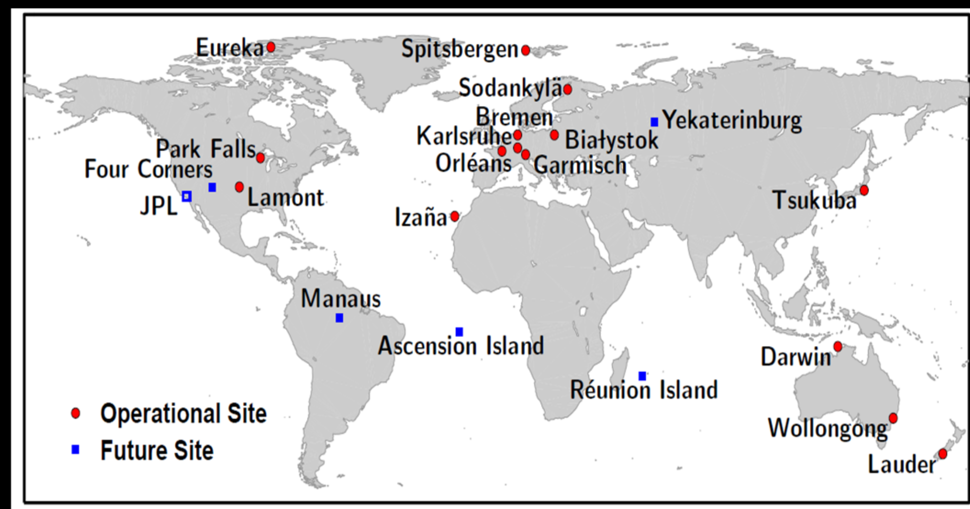
The cloud screen is responsible for the largest data reductions.

- Improved cloud screening algorithms are a major focus of our development effort



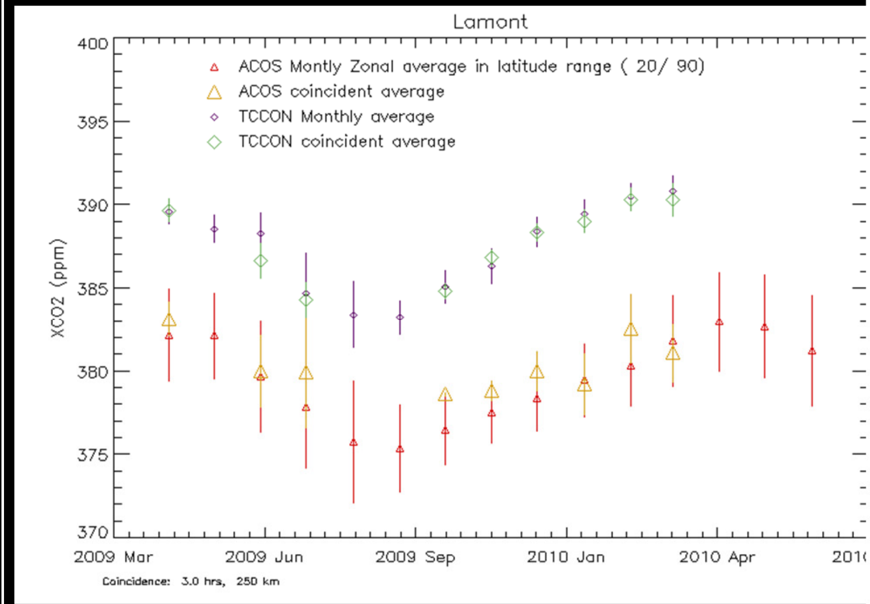
Validation of GOSAT Products

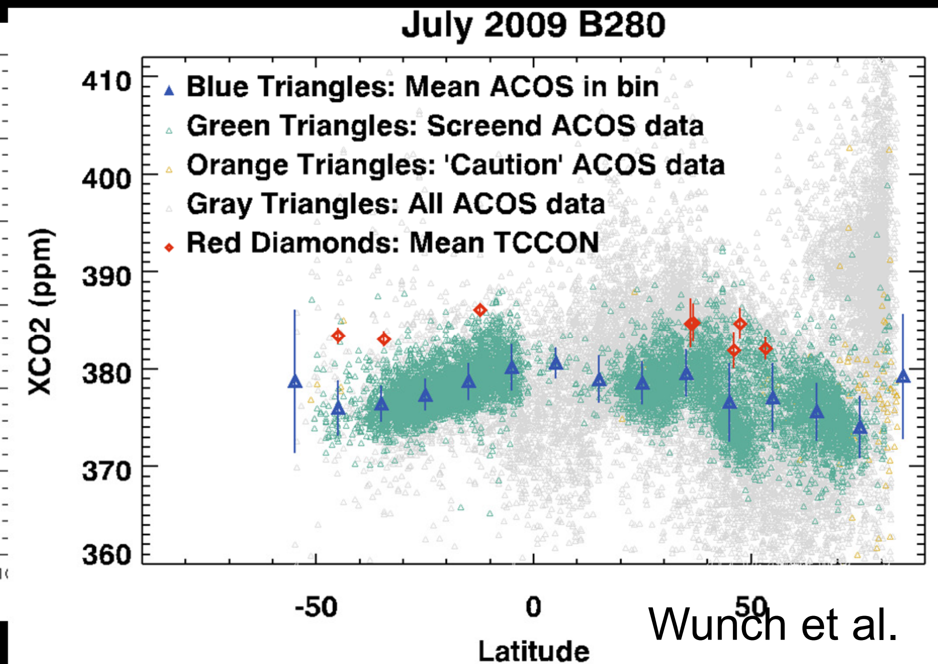
Current and Planned TCCON Stations



GOSAT X_{CO2} retrievals are being compared with those from the ground based Total Carbon Column Observing Network to very their accuracy

Comparisons of GOSAT and TCCON

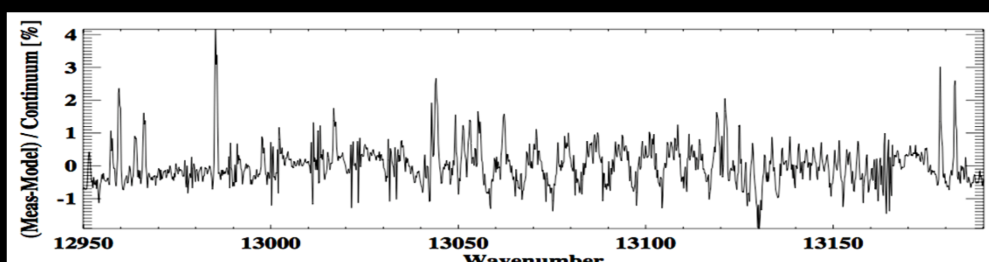




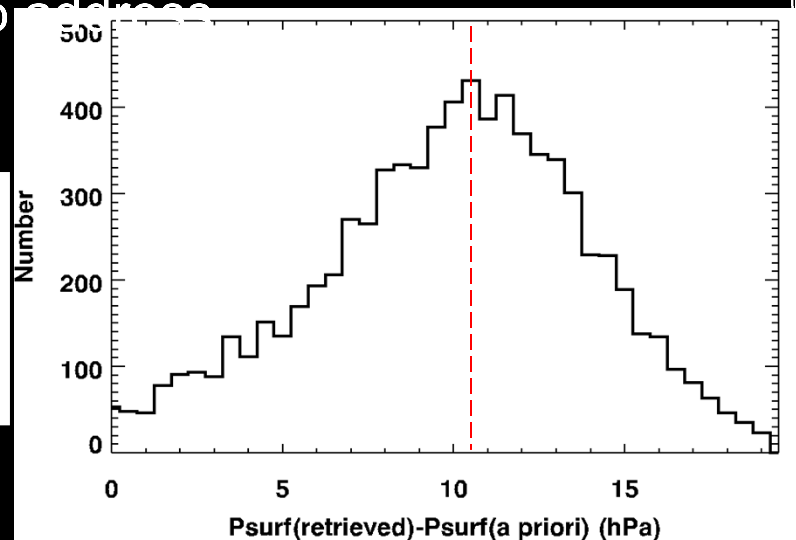
- ACOS GOSAT retrievals show
  - A consistent global bias of ~2% (7 ppm) in X_{CO2} when compared with TCCON and aircraft measurements.
  - X_{CO2} variations that are a factor of 2 to 3 larger than that measured by TCCON.

Sources of Bias in the X_{CO2} Maps

- About half of the global 2% bias is caused by a ~10 hPa (1%) high surface pressure bias associated with:
  - Radiometric and spectroscopic calibration errors
    - Non linearity and ILS corrections currently being implemented
  - Uncertainties in the O_2 A-band absorption cross sections
    - Oversimplified treatment of line mixing and line shape
- Improvements in the CO_2 spectroscopy and aerosol retrieval approach are also being implemented to address remaining bias



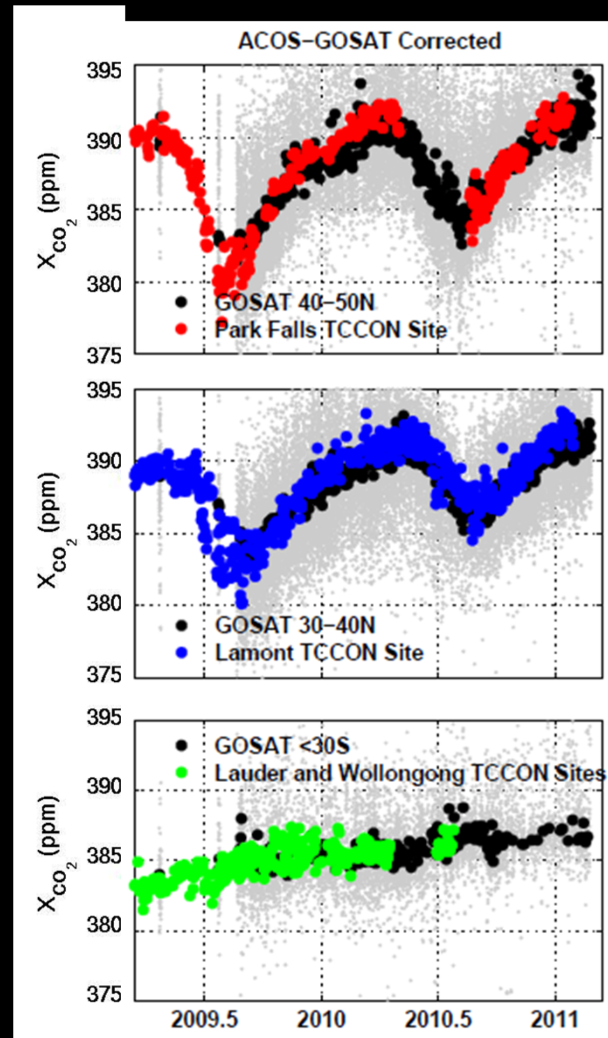
Typical O_2 A-band retrieval residuals.



Validation of X_{CO2} at TCCON Sites

Once the known biases are removed, retrievals of X_{CO2} compare well against "ground truth" from the TCCON (Total Carbon Column Observing Network).

Both the hemispheric gradients and the seasonal cycles are captured in the bias-corrected GOSAT X_{CO2} retrievals.

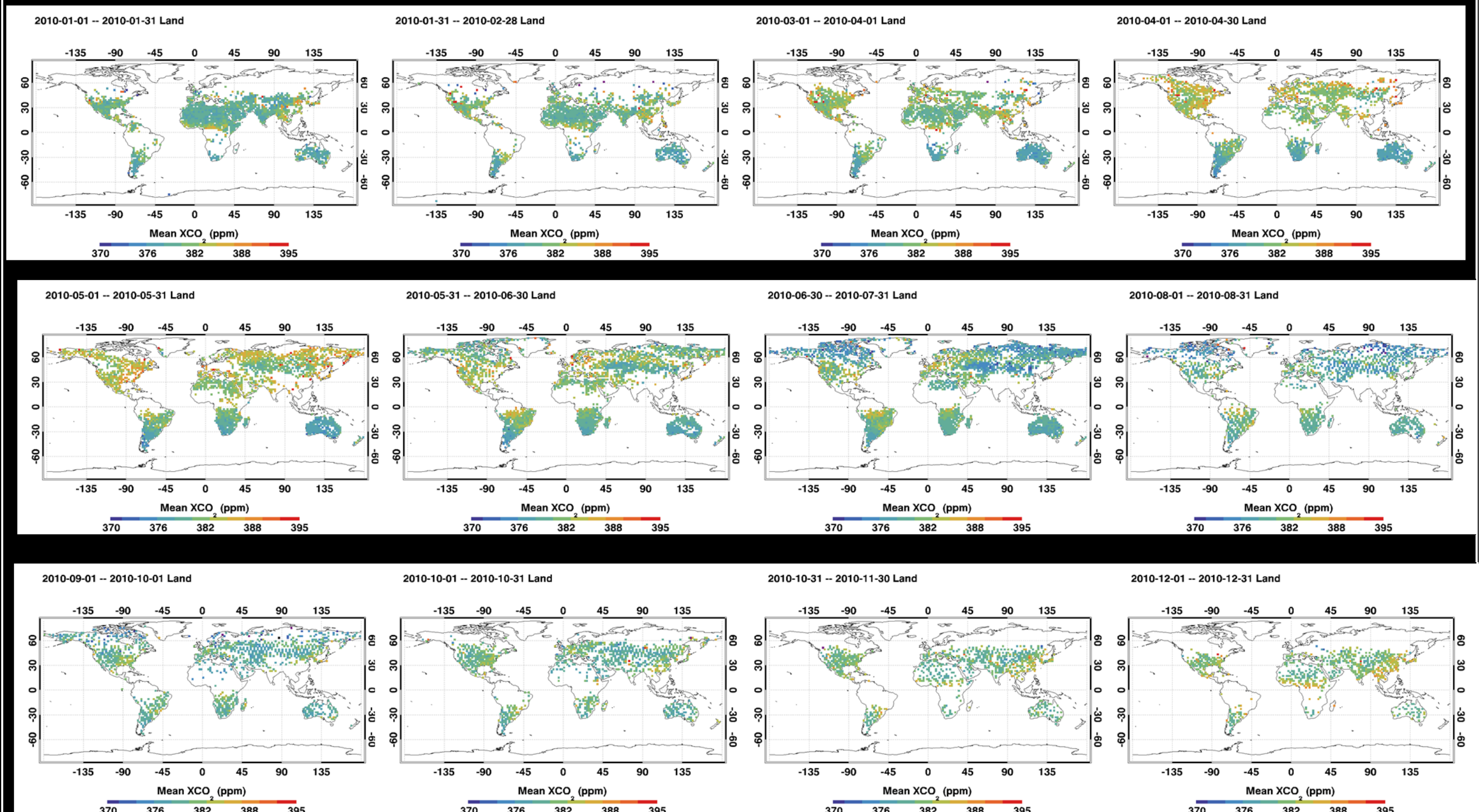


Park Falls, WI

Lamont, OK

Lauder, NZ

Experiences with its operations: A Year of ACOS/GOSAT X_{CO2}



ACOS GOSAT Data Release

- The ACOS L2 Standard Products are now being distributed on the GSFC Mirador site.

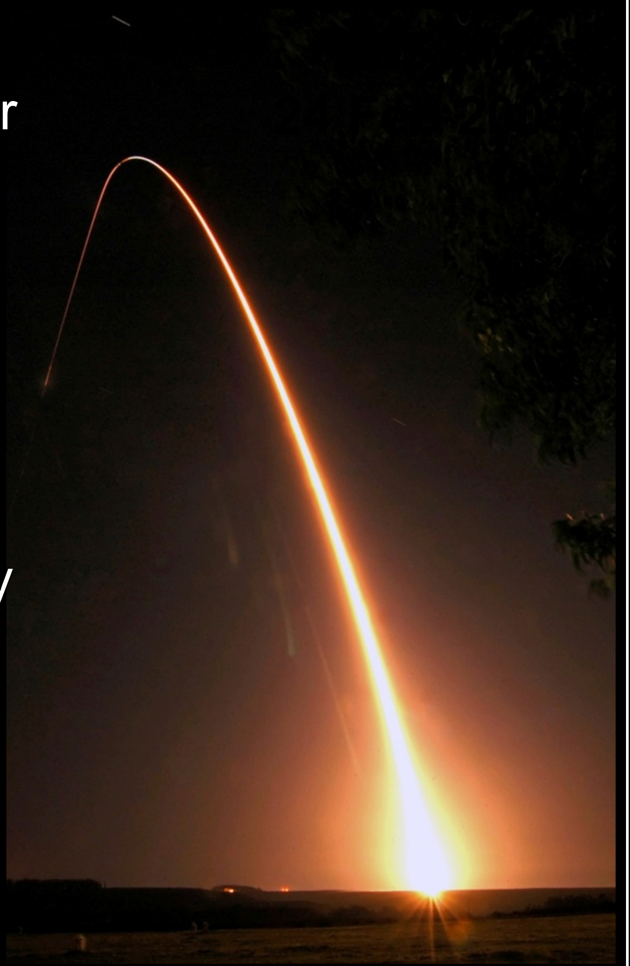
http://mirador.gsfc.nasa.gov/

- You can find the data, along with a README and a Data Quality Statement at the site:

http://disc.sci.gsfc.nasa.gov/acdisc/documentation/ACOS.shtml

The Loss of OCO and the Birth of OCO-2

- NASA's Orbiting Carbon Observatory (OCO) was designed to provide the measurements needed to estimate the atmospheric CO_2 dry air mole fraction (X_{CO2}) with the sensitivity, accuracy, and sampling density needed to quantify regional scale carbon sources and sinks over the globe and characterize their behavior over the annual cycle.
- February 2009: The OCO spacecraft was lost when its launch vehicle's fairing failed to deploy
- December 2009: The U.S. Congress added funding to the NASA FY2010 budget to restart the OCO Mission
- The OCO-2 spacecraft bus and instrument are currently on track for a February 2013 launch

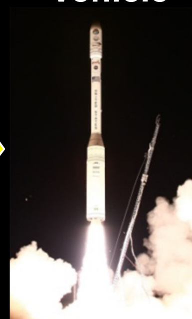


OCO Mission Overview

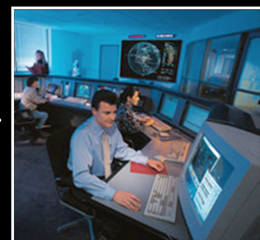
3-Channel Spectrometer

Dedicated Spacecraft bus

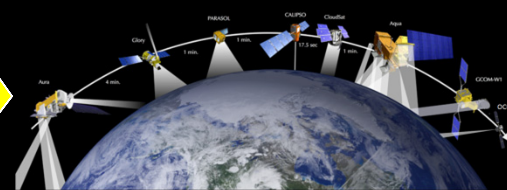
Dedicated Launch Vehicle



"Routine" Mission Operations



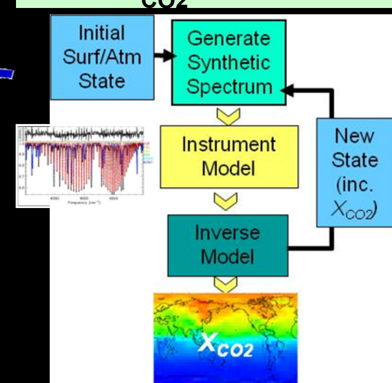
Formation Flying as part of the A-Train Constellation



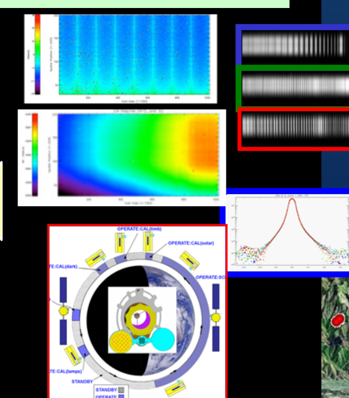
NASA NEN (GSFC) and SN (TDRSS)

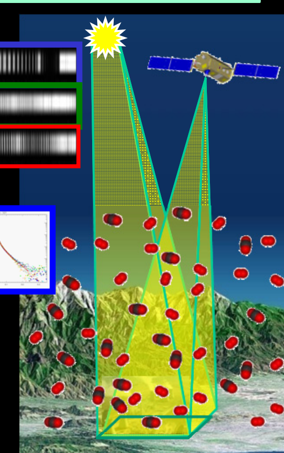
Science Data Operations Center (JPL)

L2 X_{CO2} Retrieval

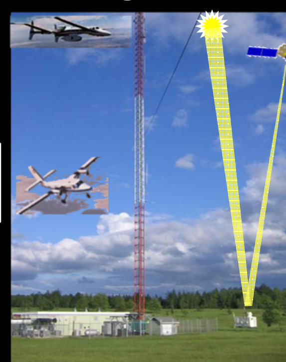


Calibrate Data

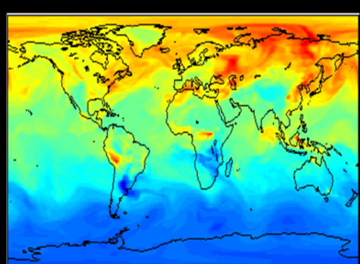




Validation Program



Products Delivered to a NASA Archive



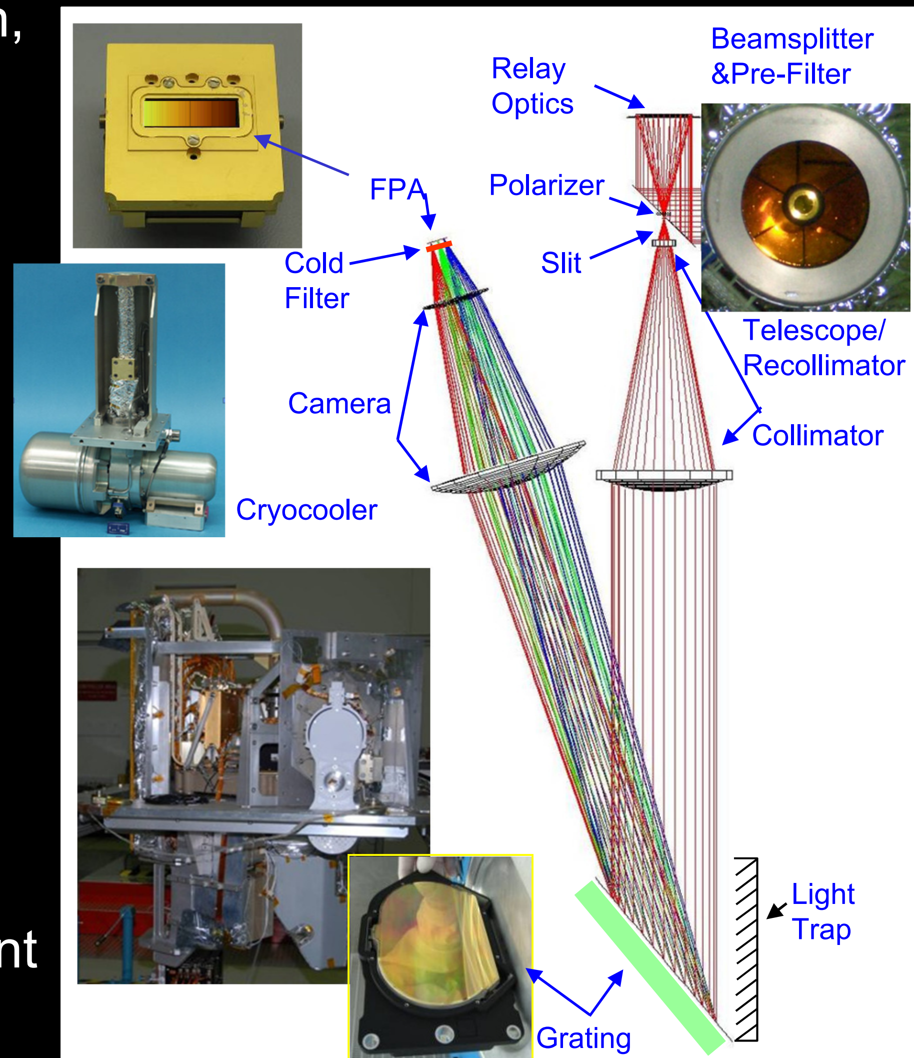
Please visit http://oco.jpl.nasa.gov for more information

The OCO-2 Instrument

- 3 co-bore-sighted, high resolution, imaging grating spectrometers
  - O_2 0.765 μm A-band
  - CO_2 1.61 μm band
  - CO_2 2.06 μm band
- Resolving Power > 20,000
- Optically fast: f/1.8 (high SNR)
- Swath: < 0.8° (10.6 km at nadir)
  - 8 cross-track footprints
  - 1.29 x 2.25 km at nadir
- Mass: 140 kg, Power: ~105 W

Changes from OCO

- Design modified to mitigate residual image & slit alignment anomalies found in testing
- New cryocooler



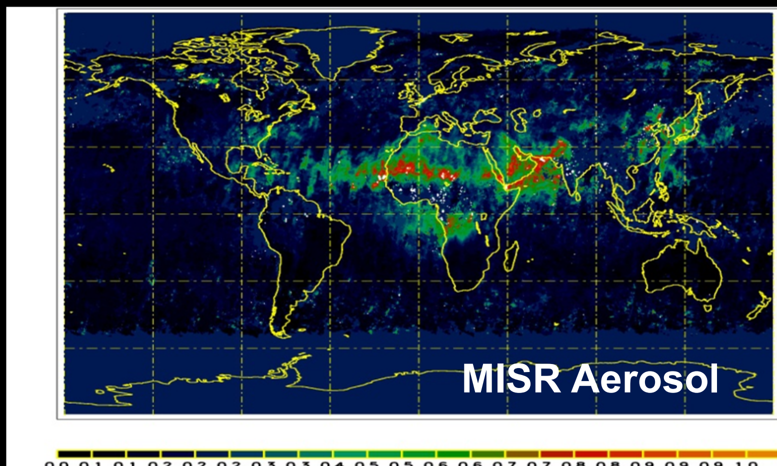
OCO-2 Spacecraft

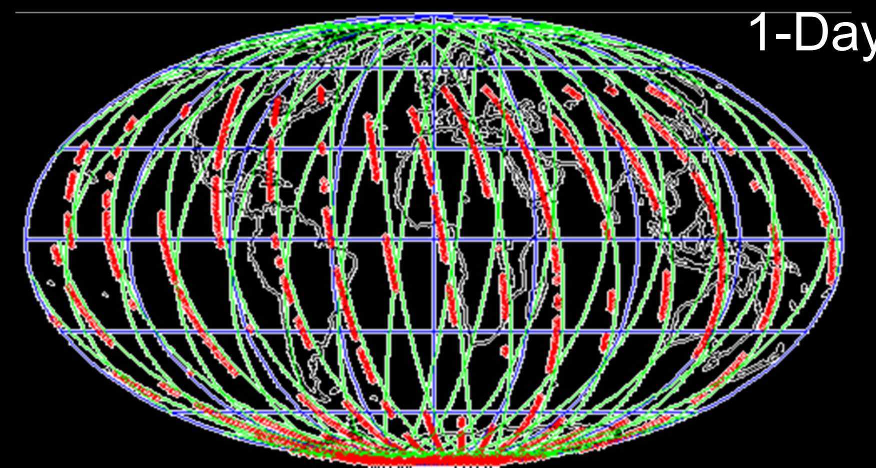
Orbital Sciences LEOStar-2 Bus

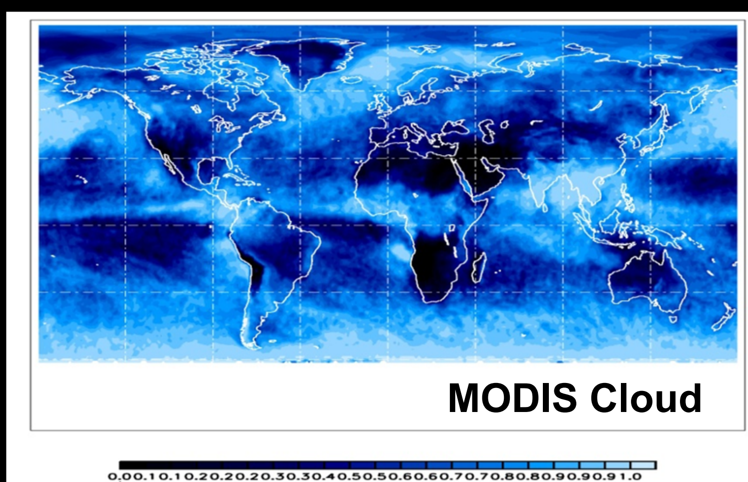
- 0.94 m x 2.1 m hexagonal structure
- 128 Gb of data storage
- 150 Mb/s X-band + 2 Mb/s S-band
- 3-axis stabilized: 4 Reaction wheels + 3 torque bars
- Articulated solar arrays
- Propulsion system for orbit maintenance

- Minimal changes to replace obsolete parts
    - RAD6000 modified to replace the static read-only memory (SRAM)
    - S-band updated from analog to digital
    - Reaction wheels modified to address lifetime issues
    - Star tracker replaced with new model
    - Obsolete Si course sun sensors replaced with GaAs sensors

Spatial/Temporal Sampling Constraints





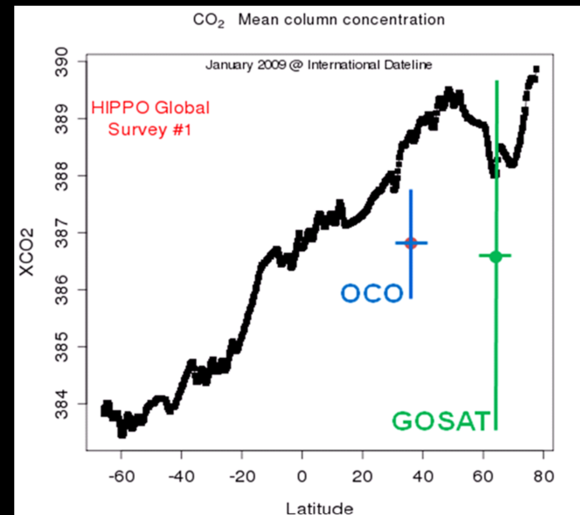


Factors Limiting Sampling Density

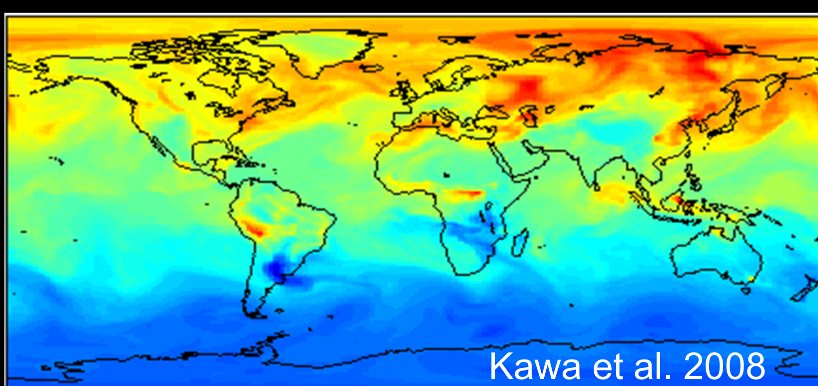
- Orbit ground track
- Clouds and Aerosols
  - OCO can collect usable samples only in regions where the cloud and aerosol optical depth < 0.3
- Low surface reflectance
- Very rough surfaces

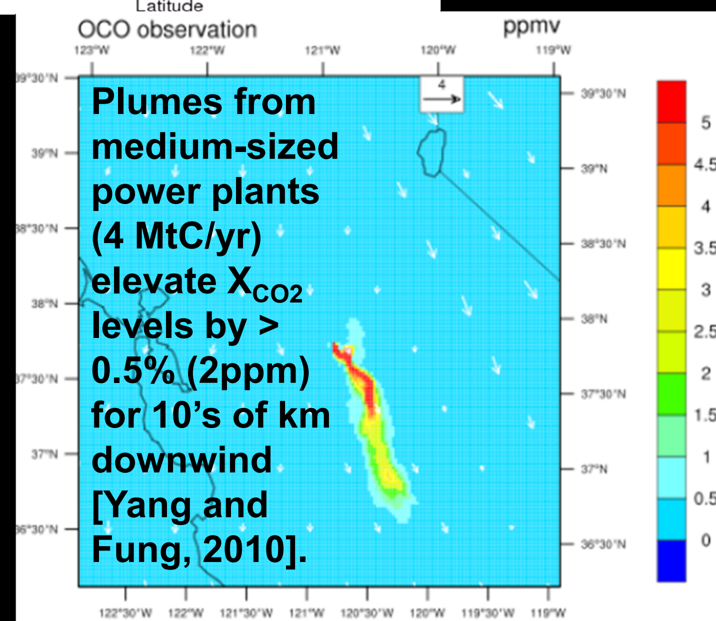
OCO-2 Is Optimized for High Precision

- CO_2 sources and sinks must be inferred from small (<2%) spatial variations in the (387 ±5 ppm) background CO_2 distribution
  - Space based NIR measurements constrain the column averaged CO_2
  - Largest variations near the surface
- High precision is essential to resolve small spatial variations in X_{CO2}
  - OCO-2 yields single-sounding random errors < 1 ppm over most of the sunlit hemisphere



Small spatial gradients in X_{CO2} verified by HIPPO flights [Wofsy et al. 2010]

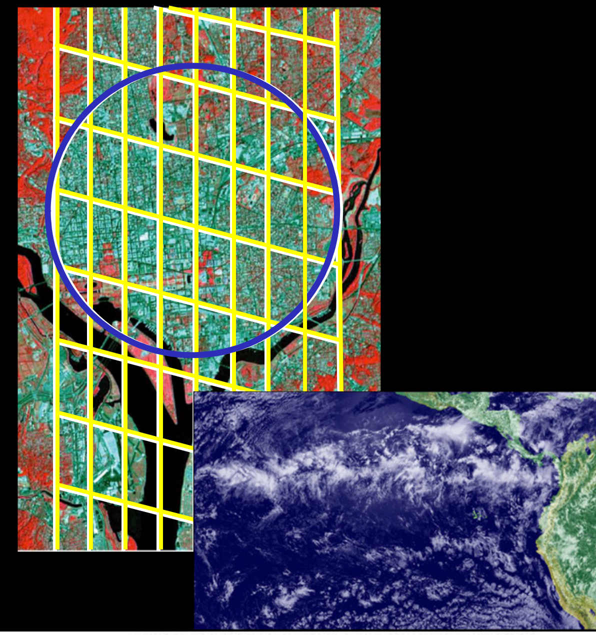




OCO-2 Optimized for High Spatial Resolution

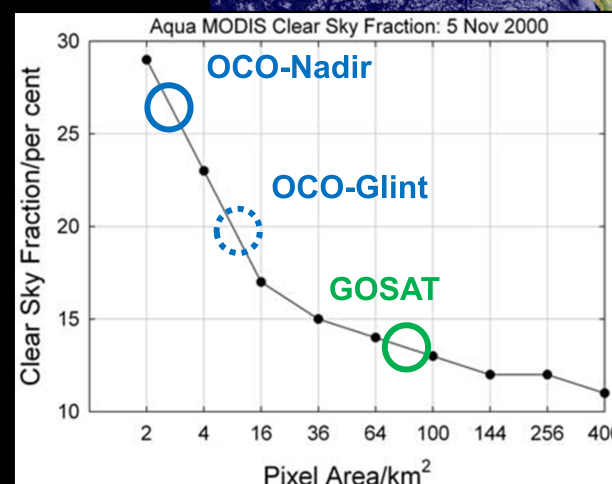
High Sampling Rate:

- OCO-2 collects up to up to 8 soundings @ 3 Hz along a narrow swath (<10.6 km at nadir)
  - Yields 200 – 400 soundings per degree of latitude over sunlit hemisphere
  - Soundings that can be averaged along the track to increase precision



Small footprint (<3 km^2 at nadir) :

- Increases sensitivity to CO_2 point sources
  - The minimum measureable CO_2 flux is inversely proportional to footprint size
- Increases probability of recording cloud free soundings in partially cloudy regions
  - OCO: 27% @ Nadir, 19% for Glint
  - GOSAT (85 km^2): ~10%

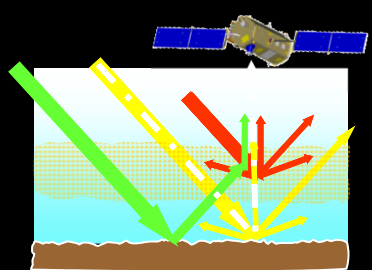


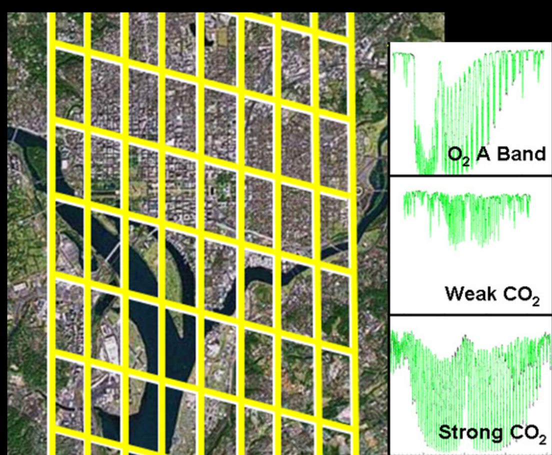
Observation Modes Optimize Sensitivity and Accuracy

Nadir Observations:

\+ Small footprint (< 3 km^2)

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

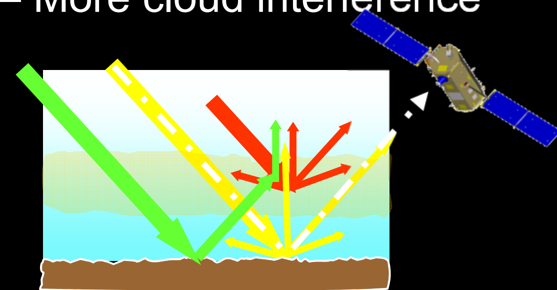


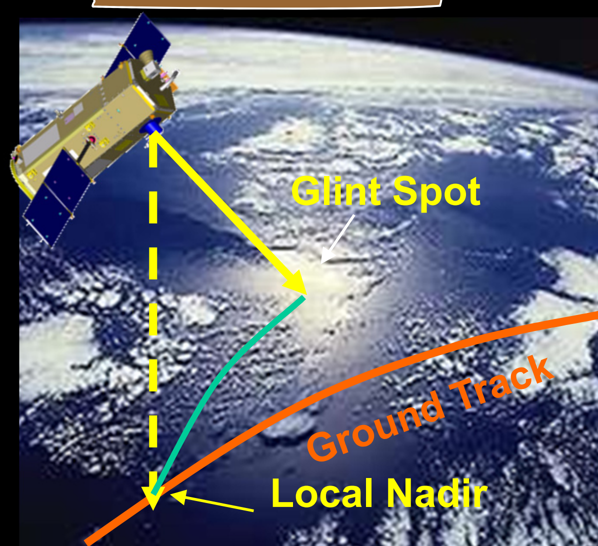


Glint Observations:

\+ Improves Signal/Noise over oceans

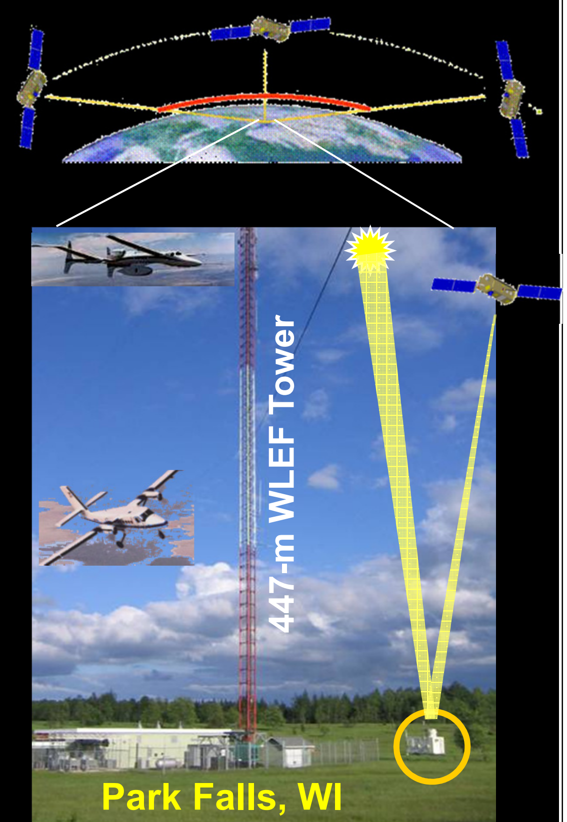
– More cloud interference





Target Observations:

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



OCO-2 Provides High SNR over both Continents and Oceans

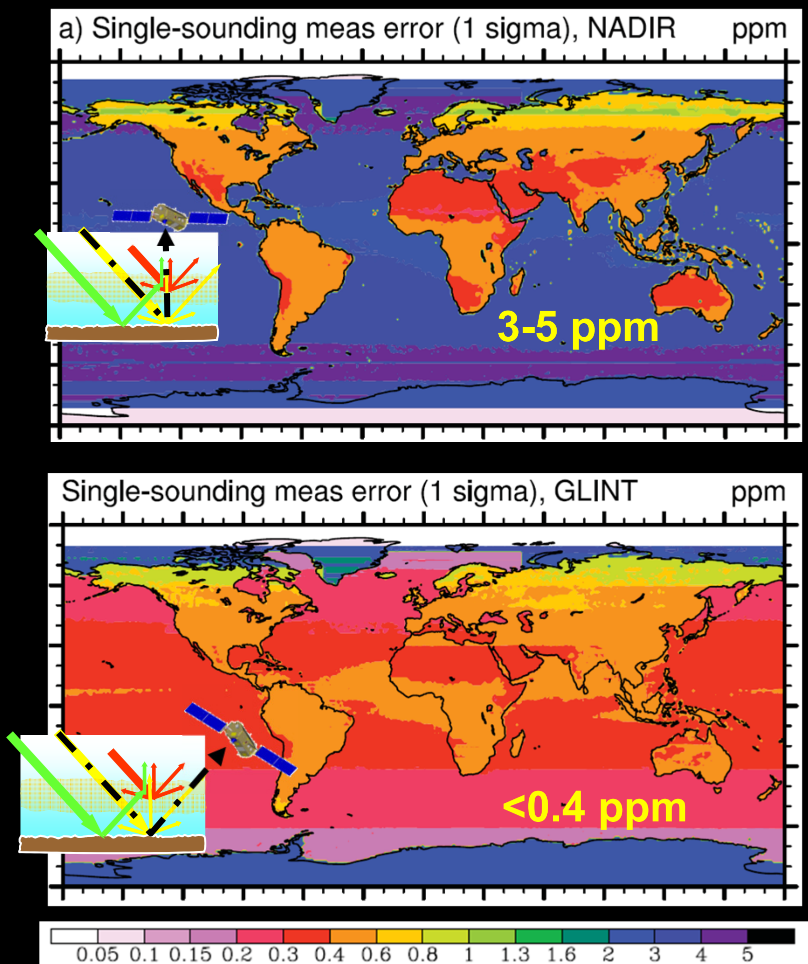
Full global coverage is needed to:

- Resolve X_{CO2} over land and ocean for the full range of latitudes,
- Minimize errors from CO_2 transport in and out of the observed domain

Near IR solar measurements of CO_2 over the ocean are challenging

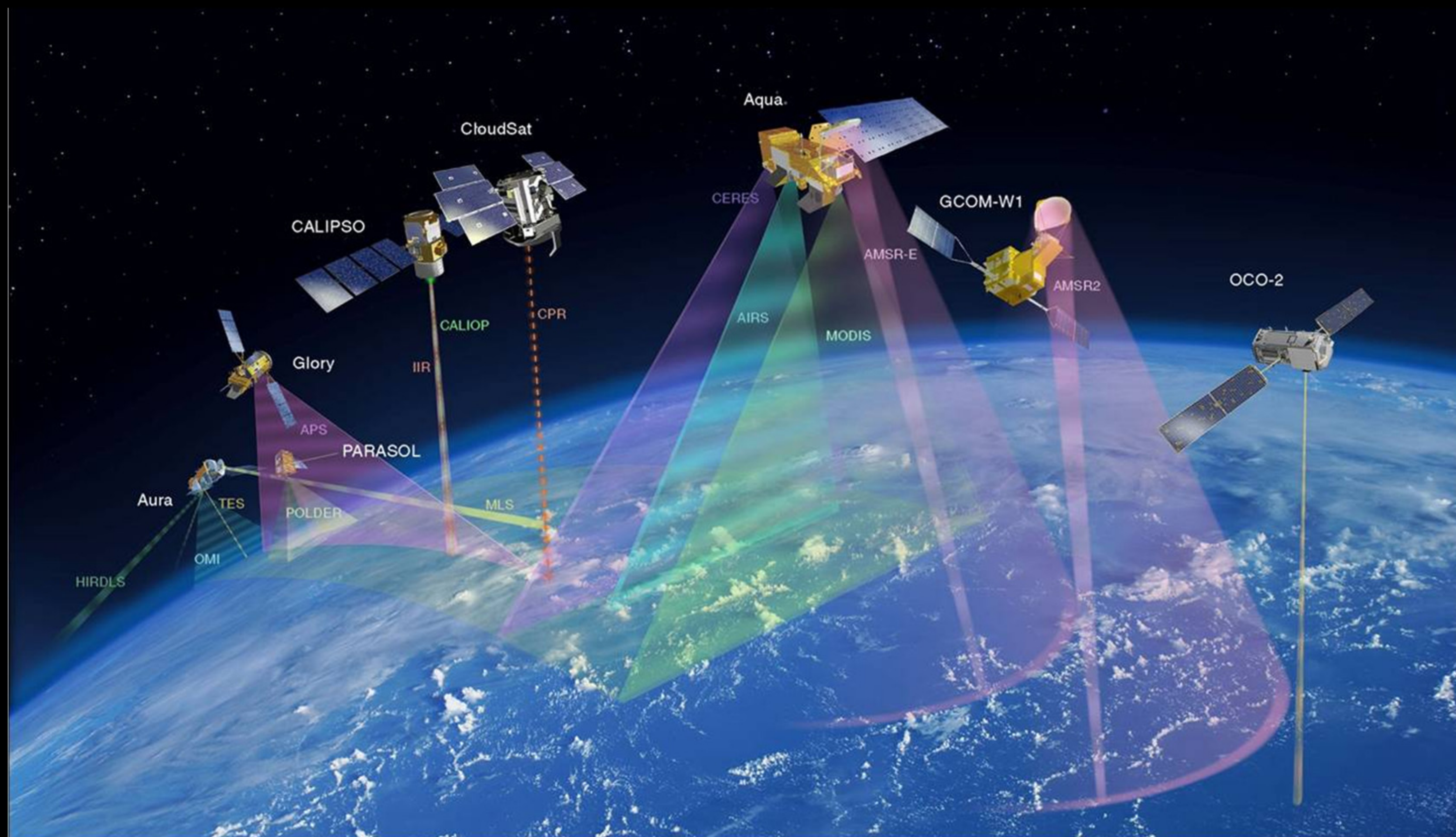
- Typical nadir reflectances: 0.5 to 1%
- Most of the sunlight is reflected into a narrow range of angles, producing the familiar “glint” spot

OCO-2 combines glint and nadir measurements to optimize sensitivity



OCO single sounding random errors for nadir and glint [Baker et al. ACPD, 2008].

OCO-2 Flies at the Head of the A-Train

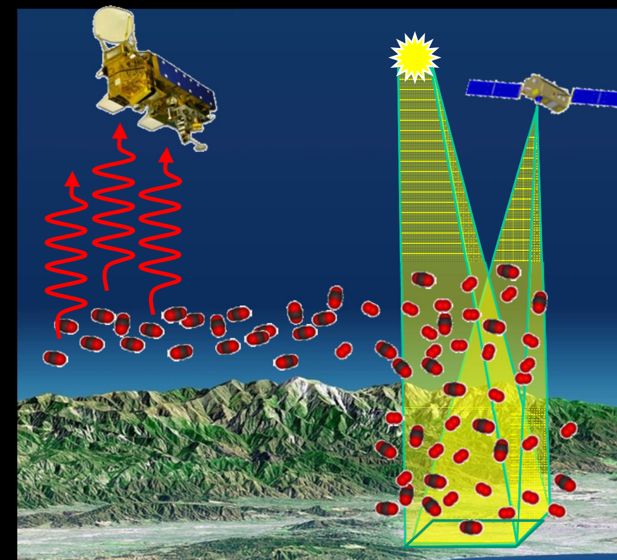


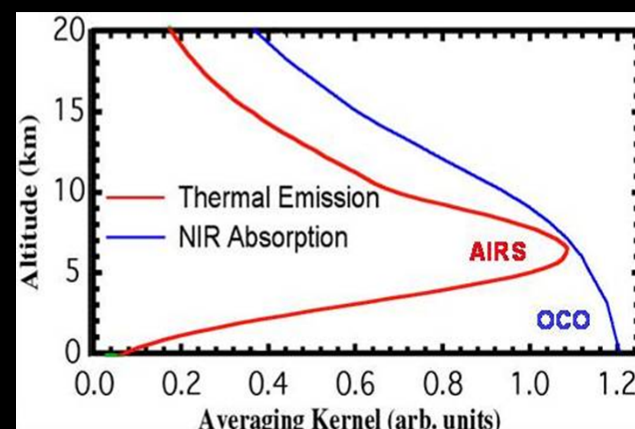
Like OCO, OCO-2 will fly at the head of the A-Train. However, OCO-2 may fly along the CloudSat/CALIPSO path, rather than the Aqua path to maximize synergy with CloudSat/CALIPSO/MODIS products.

Measuring CO_2: Synergy with AIRS and TES

Atmospheric CO_2 can be inferred from both thermal IR or solar remote sensing data

- Thermal IR instruments (AIRS,TES , IASI) measure CO_2 above the mid-troposphere
  - Directly measure the greenhouse forcing by CO_2 in the present climate
  - Provides limited information on sources/sinks
- Solar NIR instruments (GOSAT, OCO-2) measure the total CO_2 column
  - Most sensitive to surface fluxes
  - Provides insight needed to predict future rates of CO_2 buildup and climate impacts
- Combining solar NIR and thermal IR measurements could provide insight into vertical atmospheric transport of CO_2





Operational Uses by NOAA: OCO-2 Surface Pressure Measurements

- **OCO-2 will collect 0.5 to 1 million soundings over the sunlit hemisphere each day**
  - **Over 100,000 of these soundings were expected to be sufficiently cloud free to enable surface pressure (and X_{CO2}) retrievals**
  - **For each X_{CO2} retrieval, the O_2 A-Band measurement yields an surface pressure retrieval, with typical accuracies of ± 1 hPa**
- **OCO-2 surface pressure measurements can be combined with AIRS temperature and moisture measurements in meteorological data assimilation models to assess their impact on weather forecasts.**
  - **Largest impacts expected in data sparse regions– such as over oceans**
- **OCO-2 would demonstrate this capability, but is not (currently) designed to deliver measurements on NWP time scales (2.75 hr)**

Looking ahead

- **OCO-2:** Launch may be delayed due to launch vehicle problems
- 2-year nominal mission
  - The only life limiting consumable is fuel for orbit maintenance (> 5 years)
- **OCO-3*:** NASA's Architecture for Earth Science (June 2010) and the Presidents 2012 NASA budget proposal include funds to assemble the OCO-2 instrument spares to produce a follow-on instrument
  - Available for a flight of opportunity as early as 2015
  - Currently assessing a wide range of host missions
    - ISS, conventional nadir pointing platforms (JPSS), as well as agile (OCO-like) spacecraft in sun-sync & non sun-sync orbits
    - A pointing mechanism is under development to preserve glint and target capabilities on nadir-pointing platforms
- **ASCENDS*:** NASA's next step in CO_2 measurements
  - Uses LIDAR to provide day/night measurements for all seasons and latitudes
  - Baselined for a launch in the 2020 time frame

*Proposed Mission Only – Pre-decisional for planning and discussion purposes only

Summary

- OCO-2 is currently on track for a 2013 - 2014 Launch
- The OCO-2 Instrument will collect over 500,000 to 1,000,000 soundings/day along a narrow swath, either along the ground track, or in the direction of the local "glint" spot
- Integration with ground and airborne networks is essential for validating, interpreting, and maximizing the benefit of remote sensing observations
- OCO-2 surface pressure measurements can be used to assess the value of future space-based surface pressure measurements in weather prediction models
- Need a long-term vision to establish and address community priorities
  - Must incorporate ground, air, and space-based assets
  - Must balance calls for new observations with need to maintain climate data records