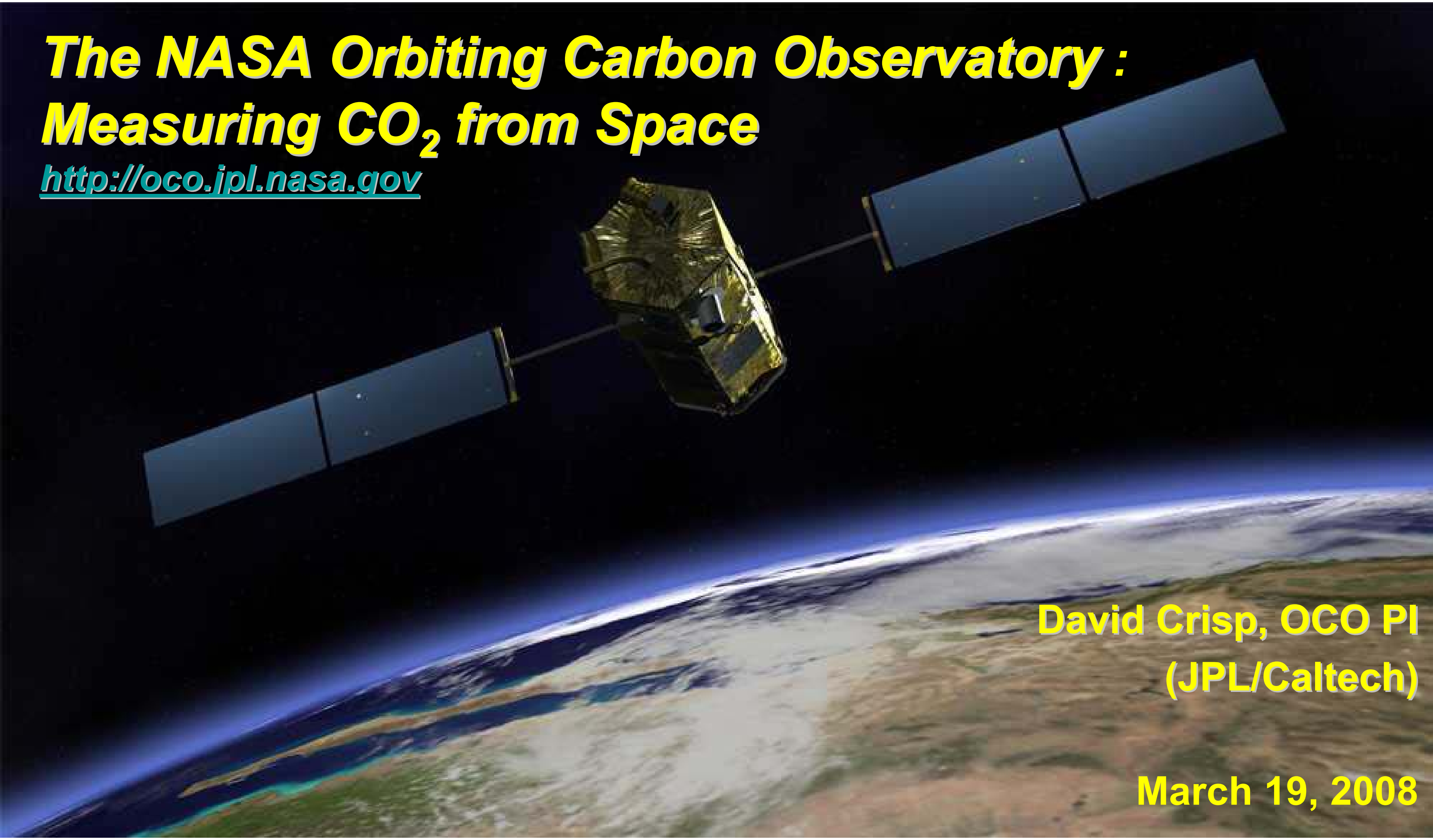
The NASA Orbiting Carbon Observatory : Measuring CO_2 from Space

http://oco.jpl.nasa.gov



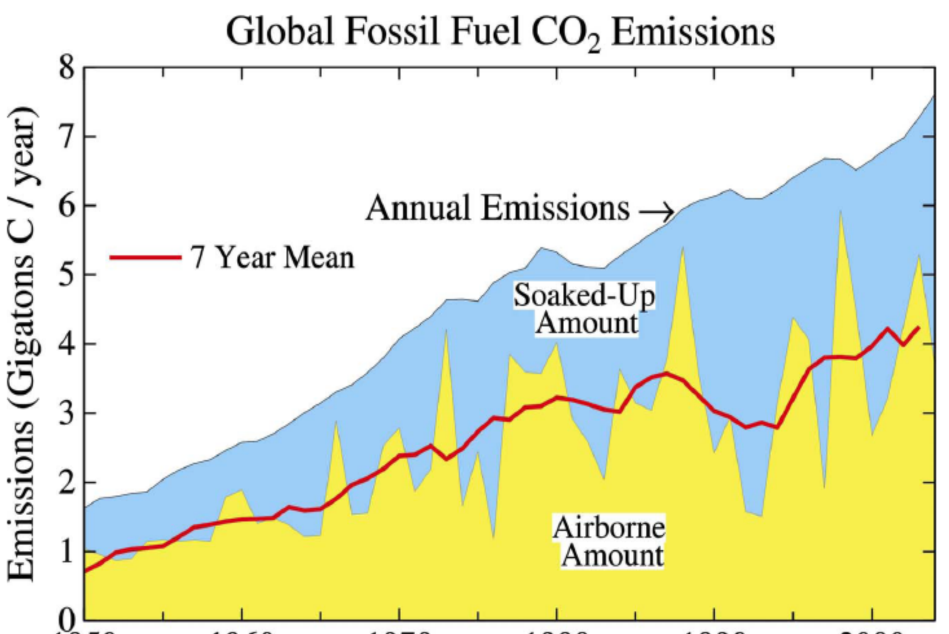
David Crisp, OCO PI
(JPL/Caltech)

March 19, 2008

JPL Orbital Hamilton Sundstrand A United Technologies Company

Outstanding Questions

- Humans have added >200 Gt C to the atmosphere since 1958
- Only ~58% of this CO_2 is staying in the atmosphere
- Where are the ***sinks*** that are absorbing over 40% of the CO_2?
  - Land or ocean?
  - Eurasia/North America?
- Why does the CO_2 buildup vary from year to year with nearly uniform emission rates?
- How will these CO_2 sinks respond to climate change?



Global fossil fuel CO_2 emissions with division into portions that remain airborne or are soaked up by the ocean and land.

Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

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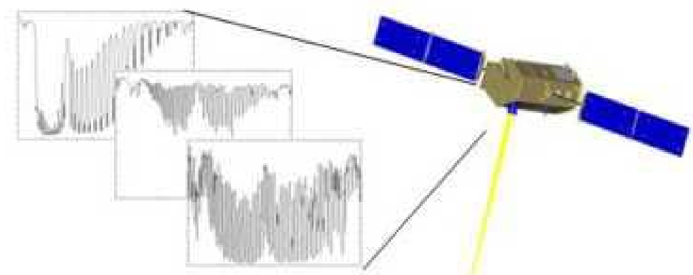
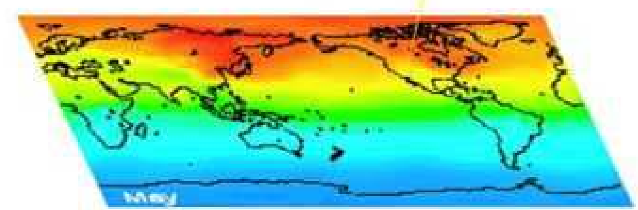
?

The Orbiting Carbon Observatory (OCO)

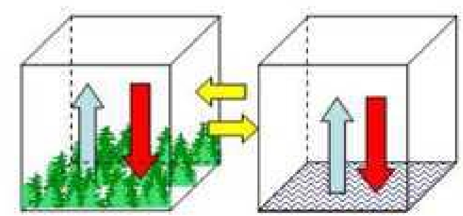
OCO will acquire the space-based data needed to identify CO_2 sources and sinks on regional scales over the globe and quantify their variability over the seasonal cycle





Approach:

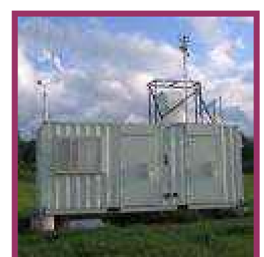
- Collect spectra of CO_2 and O_2 absorption in reflected sunlight

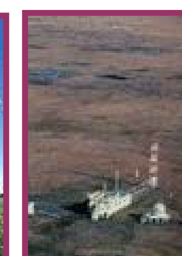


- Use these data to resolve variations in the ***column averaged CO_2 dry air mole fraction, X_{CO2}*** over the sunlit hemisphere

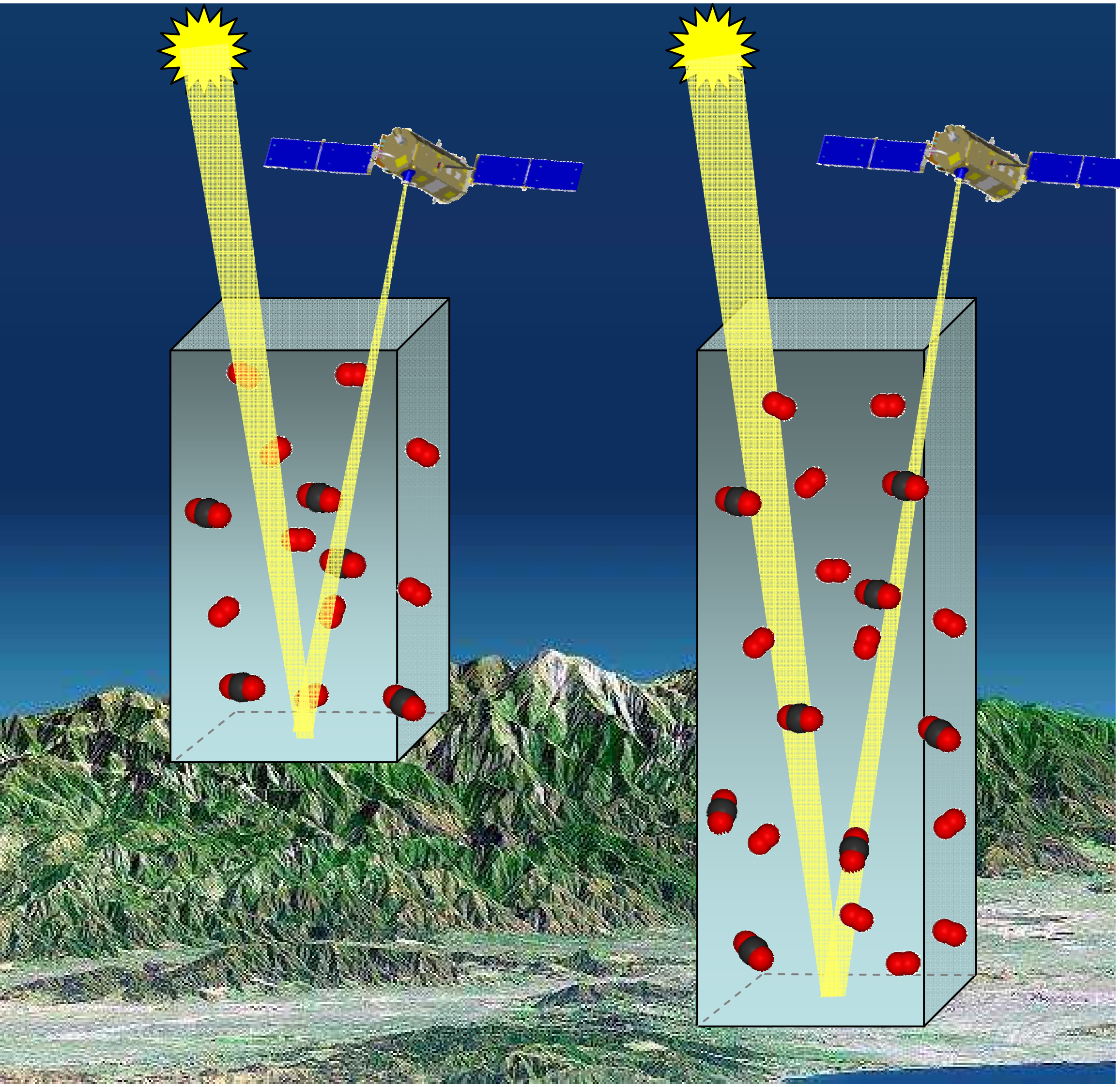
$$X_{CO2} = 0.20995 \times [CO_2] / [O_2]$$

- Validate measurements to ensure X_{CO2} accuracies of 1 - 2 ppm (0.3 - 0.5%) on regional scales at monthly intervals

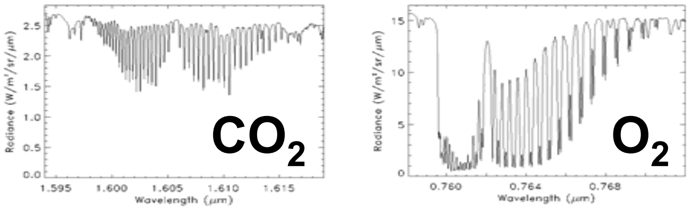




What is X_{CO2}?

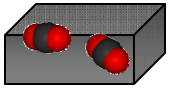


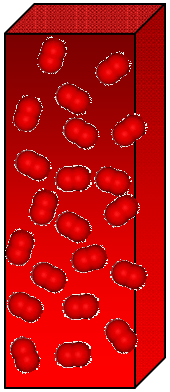
Measured Spectra



Column Abundance

Path Dependent



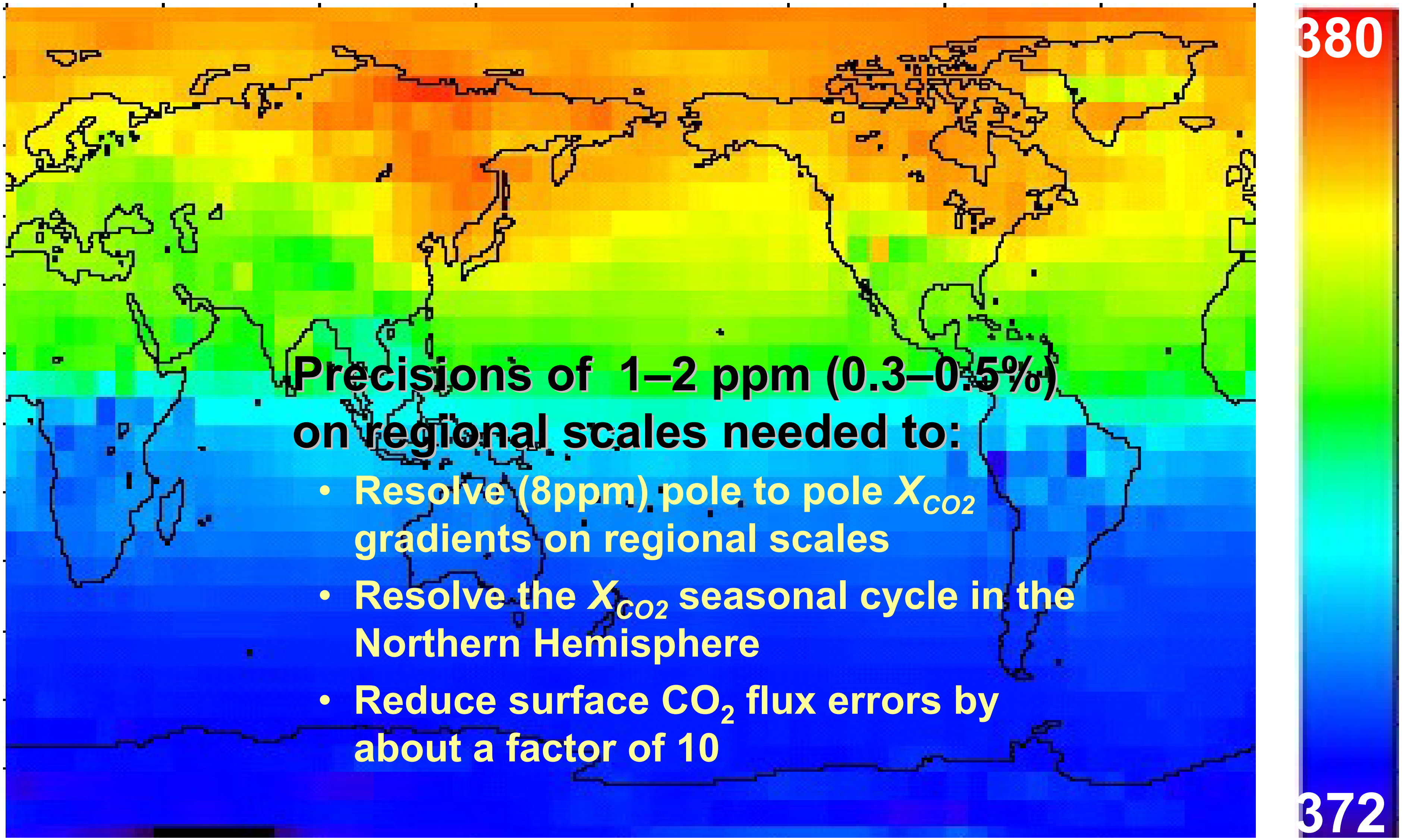


Ratio

$$X_{CO2} = 0.20995 \times [CO_2] / [O_2]$$

Path Independent Mixing Ratio

Precise Measurements are Needed to Resolve X_{CO2} Variations

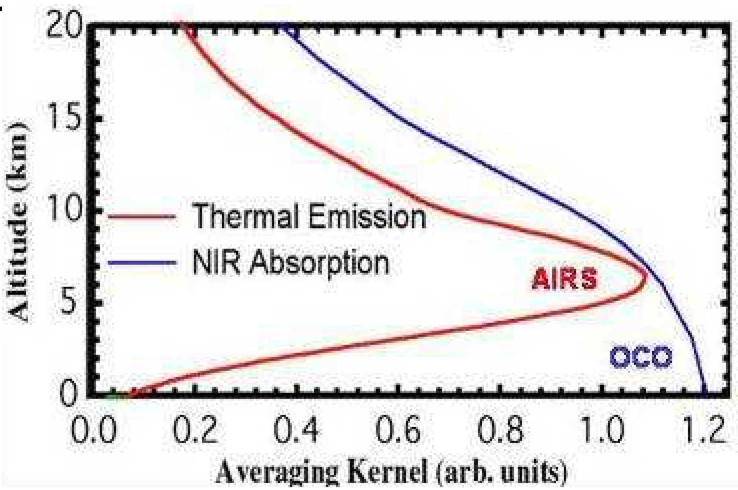


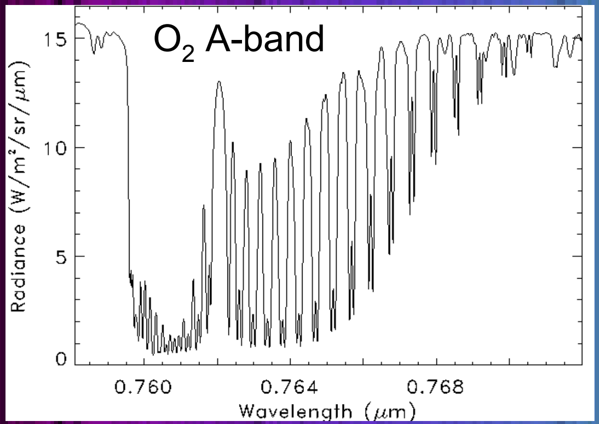
Precisions of 1–2 ppm (0.3–0.5%) on regional scales needed to:

- Resolve (8ppm) pole to pole X_{CO2} gradients on regional scales
- Resolve the X_{CO2} seasonal cycle in the Northern Hemisphere
- Reduce surface CO_2 flux errors by about a factor of 10

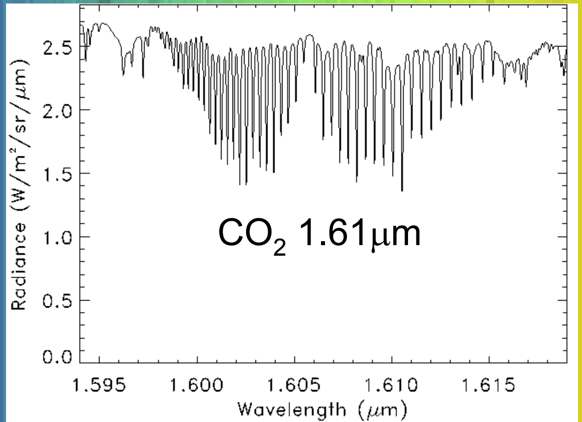
Making Precise X_{CO2} Measurements from Space

- High resolution spectra of reflected sunlight in near IR CO_2 and O_2 bands used to retrieve the column average CO_2 dry air mole fraction, X_{CO2}
  - 1.61 μm CO_2 band: Column CO_2
  - 2.06 μm CO_2 band: Column CO_2, Aerosols
  - 0.76 μm O_2 A-band: Surface pressure, clouds, aerosols
- Why high spectral resolution?
  - Enhances sensitivity, minimizes biases

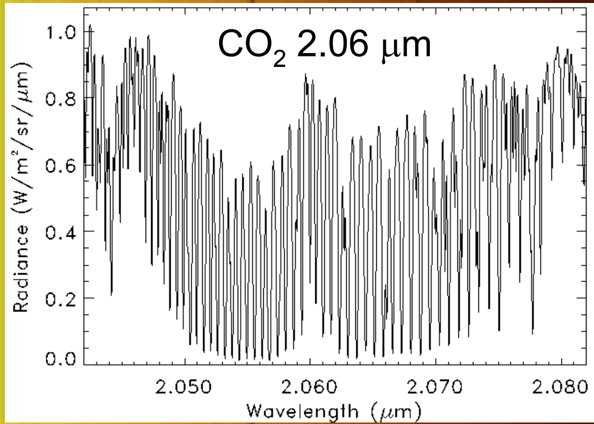




Clouds/Aerosols, Surface Pressure

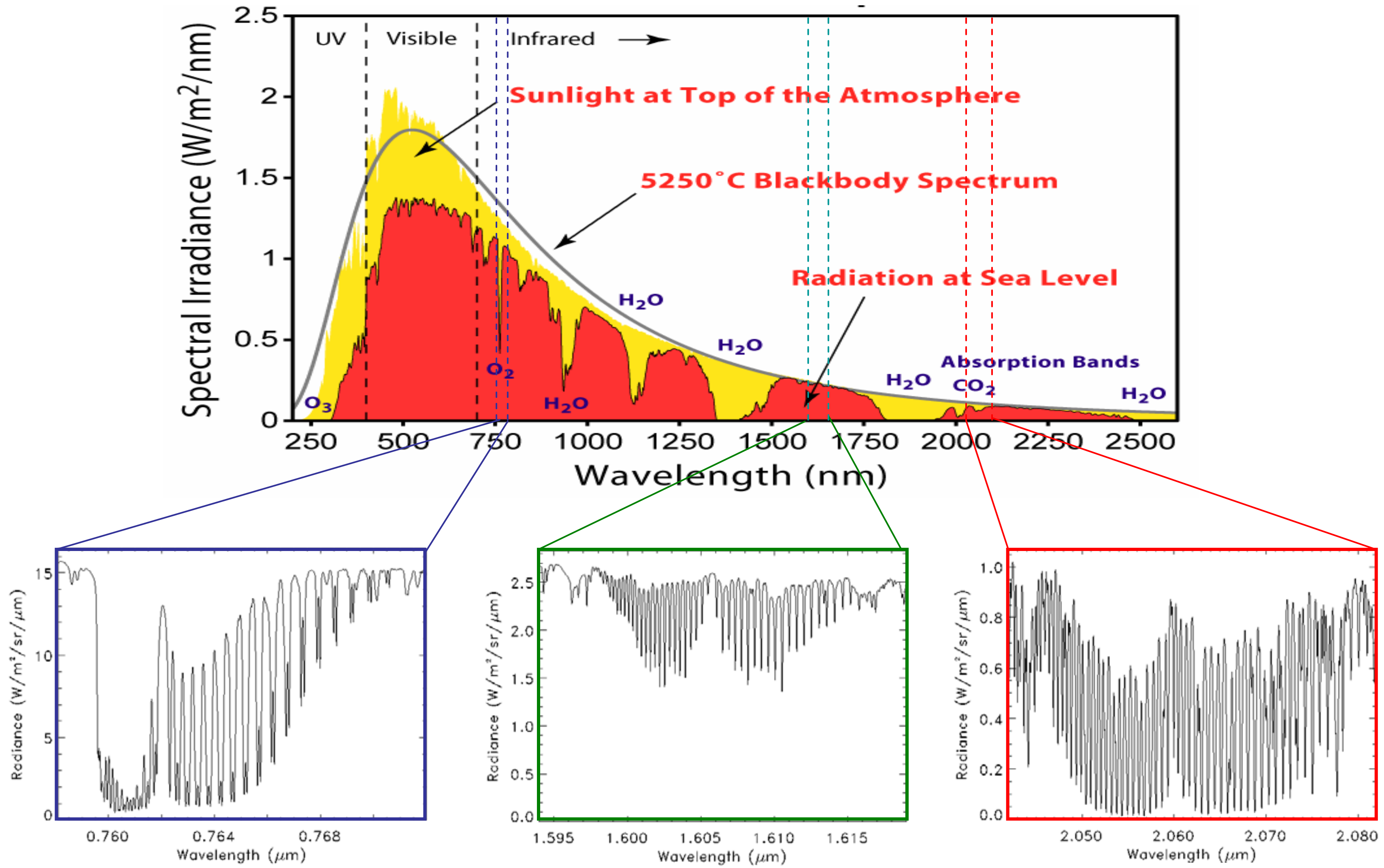


Column CO_2



Clouds/Aerosols, H_2O, Temperature

Putting the OCO Bands into Context



Clouds/Aerosols, Surface Pressure

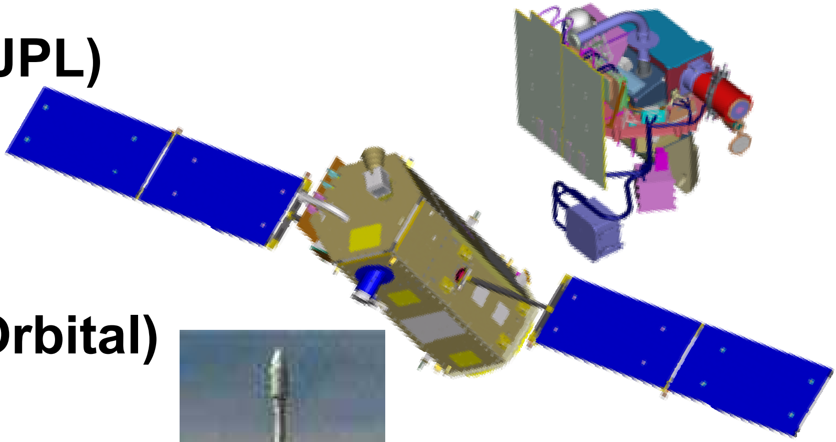
Column CO_2

Clouds/Aerosols, H_2O, Temperature

OCO Mission Implementation Approach

Project Management (JPL)

International Science Team



Single Instrument (Hamilton Sundstrand/JPL)

Dedicated Spacecraft (Orbital Sciences)

Dedicated Taurus 3110 Launch Vehicle (Orbital)

Mission Operations (JPL/Orbital/NGN)

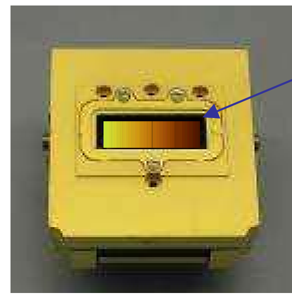
December 2008 Launch from Vandenberg AFB

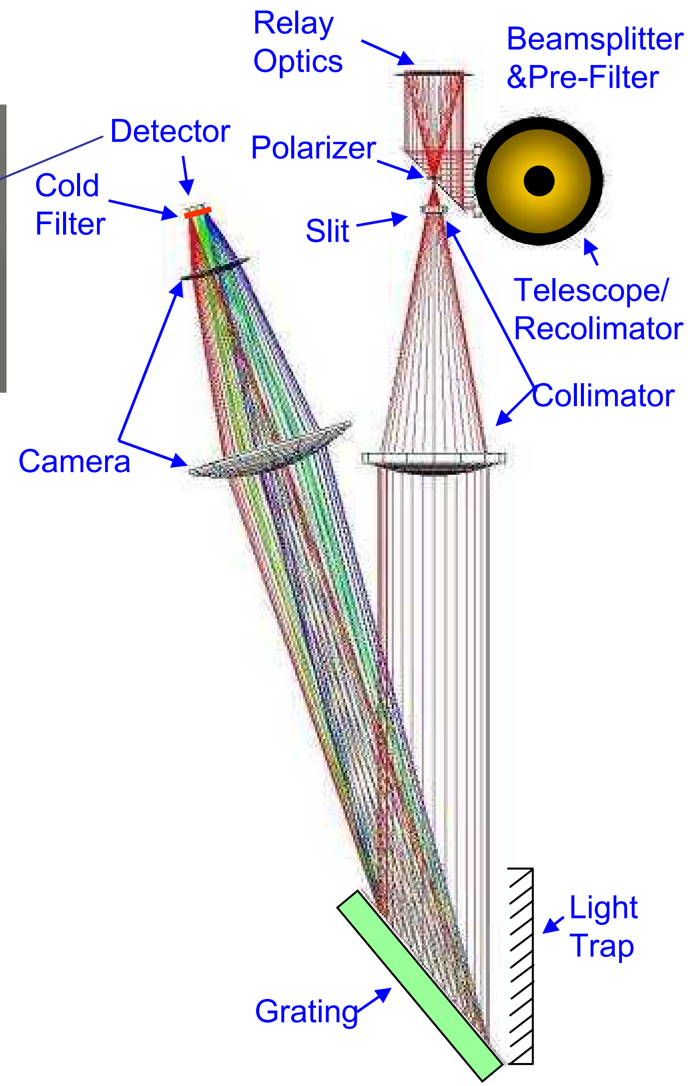
2-Year Nominal Mission

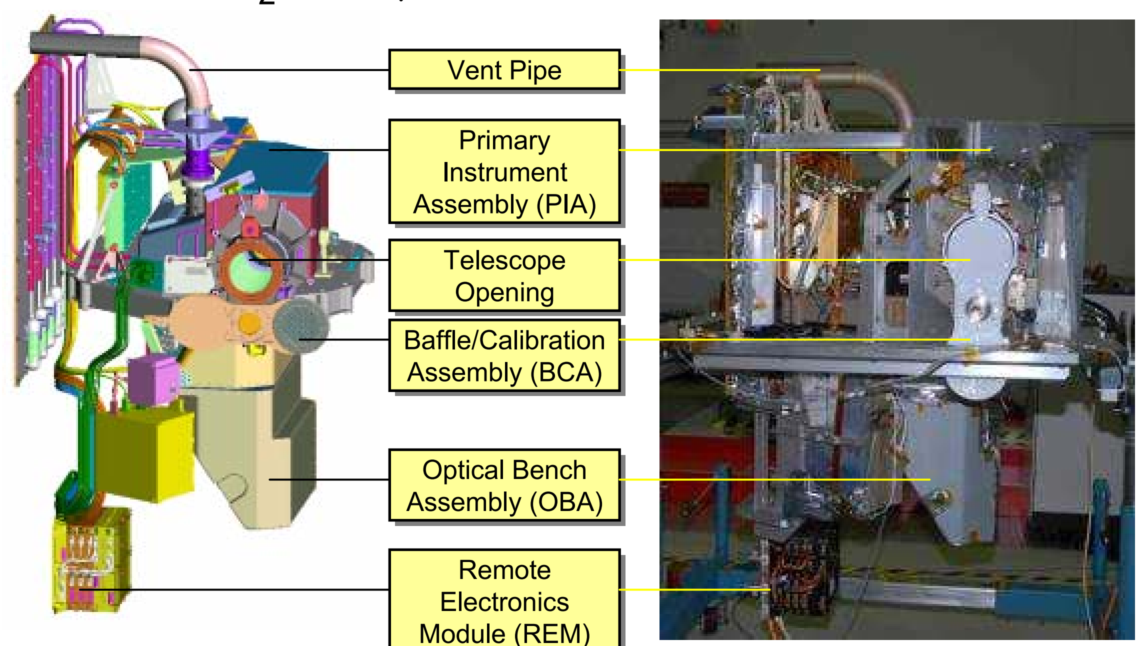
The OCO Instrument

Single instrument:

- **3 bore-sighted, high resolution, grating spectrometers**
  - O_2 0.765 μm A-band
  - CO_2 1.61 μm band
  - CO_2 2.06 μm band

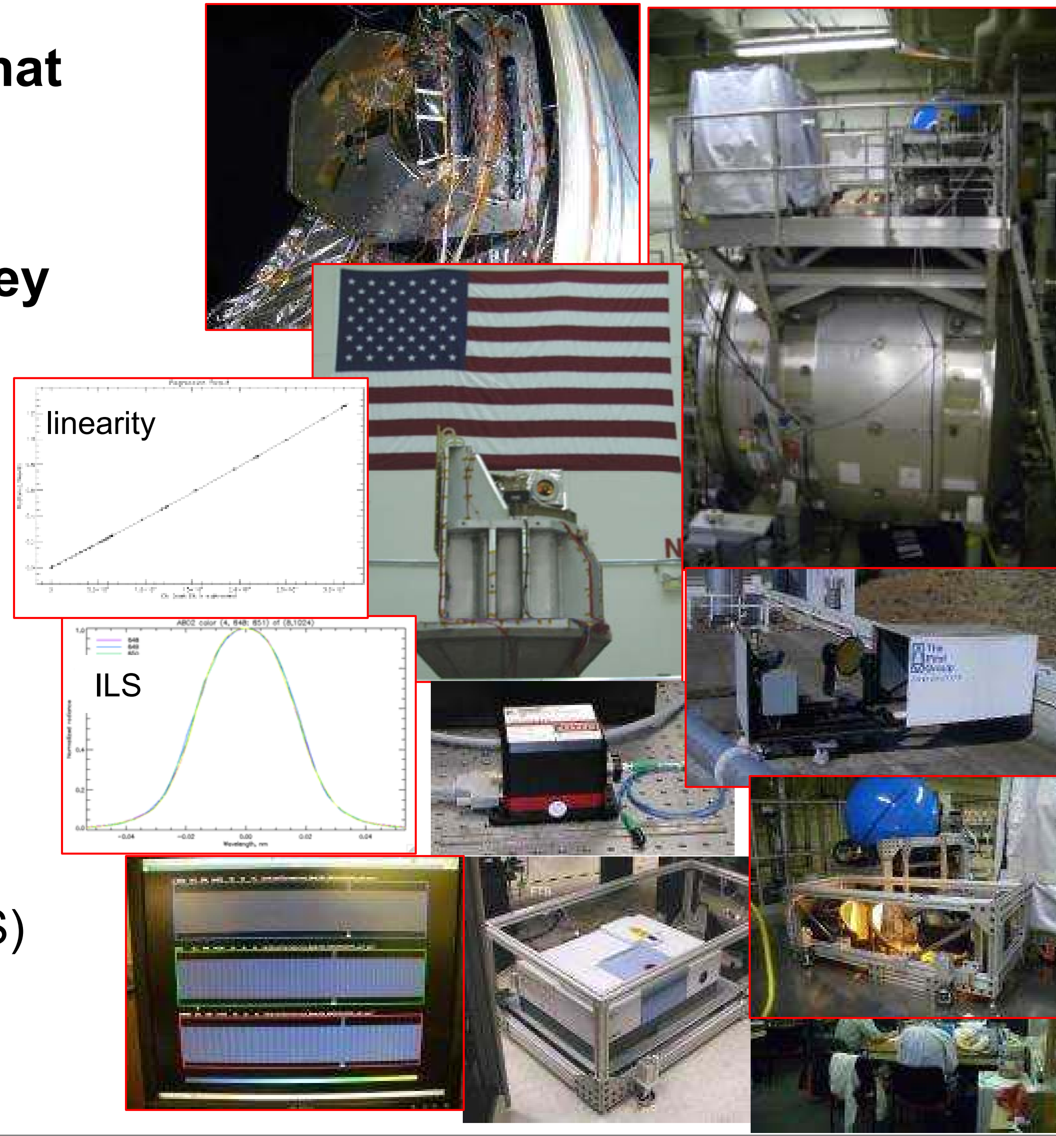






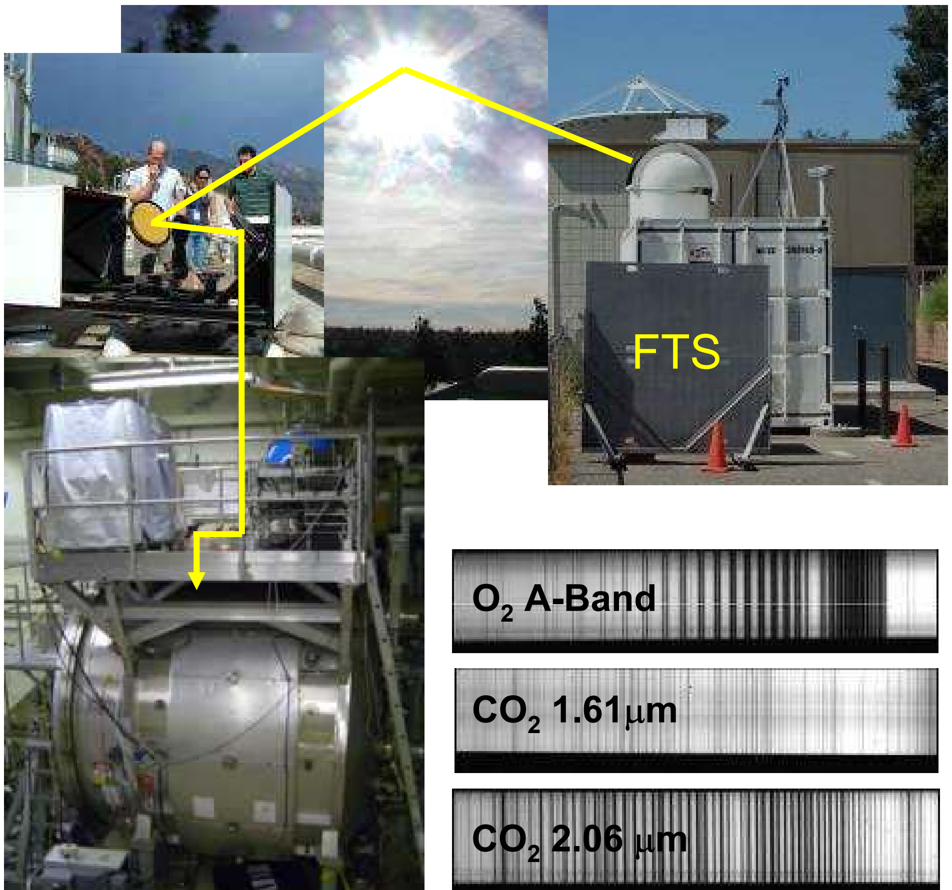
Pre-Flight Instrument Calibration and Characterization

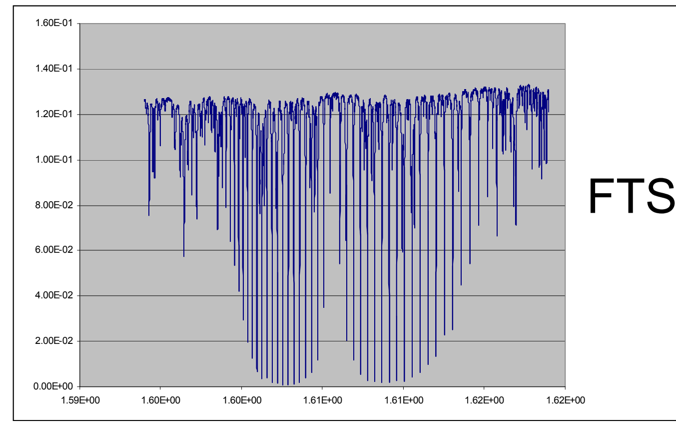
- **Flight qualification ensures that instrument survives**
  - **Thermal, vacuum, vibration**
- **Pre-flight testing quantifies key Instrument performance and knowledge parameters**
  - **Geometric**
    - Bore-sight alignment
  - **Radiometric**
    - Zero-level offset (bias)
    - Gain, Gain non-linearity
  - **Spectroscopic**
    - Spectral range, resolution, sampling
    - Instrument Line Shape (ILS)
  - **Polarization**
  - **Instrument stability**

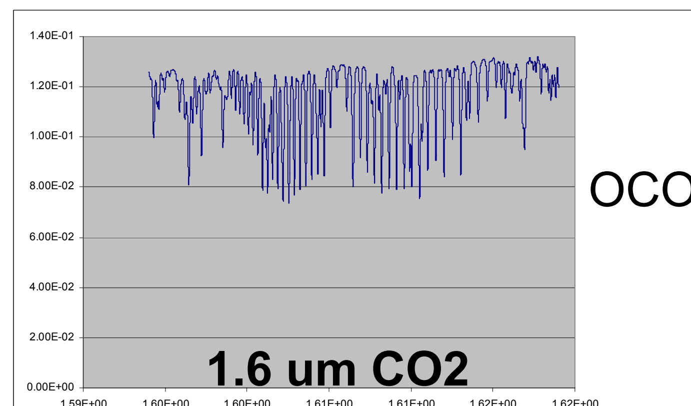


Pre-Launch Atmospheric Spectra

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

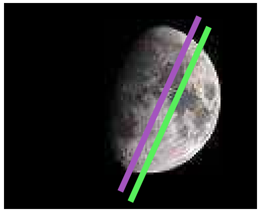


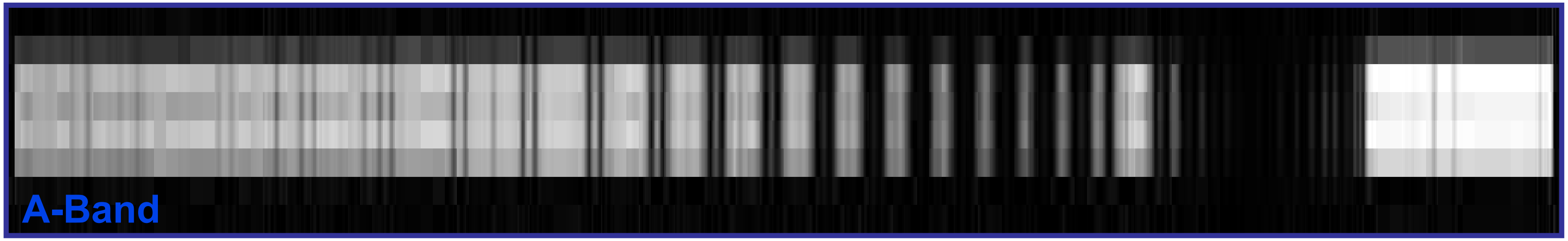


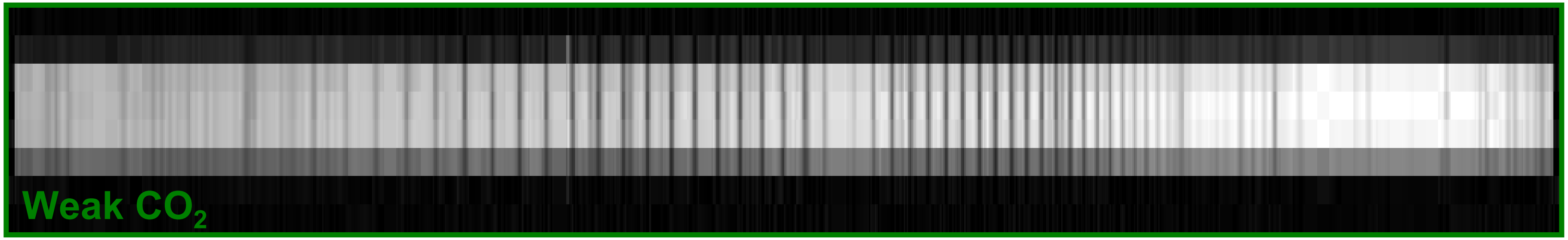


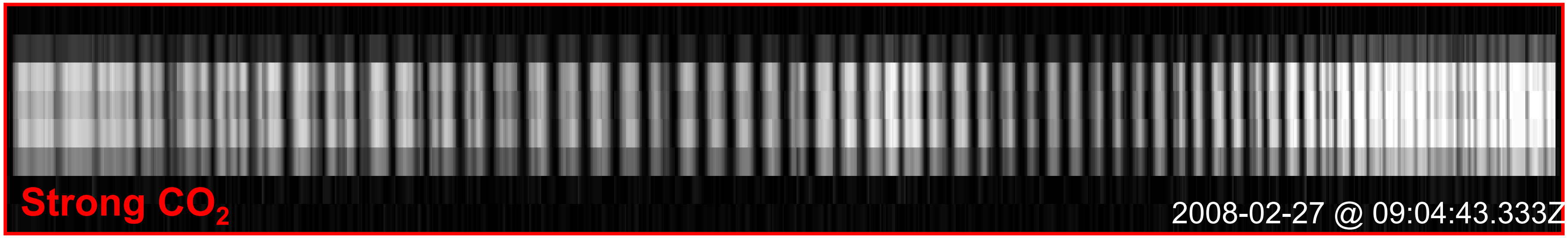
Instrument is a Very Sensitive Imaging Spectrometer

<u>Single Frame</u> of Data using the Moon
- High SNR (given low illumination levels)
- High spectral resolution (absorption bands are clearly visible)
- Imaging works (moon is ~0.5° wide - just as expected)

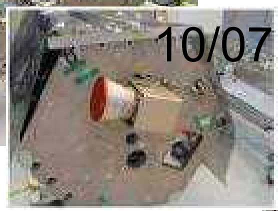


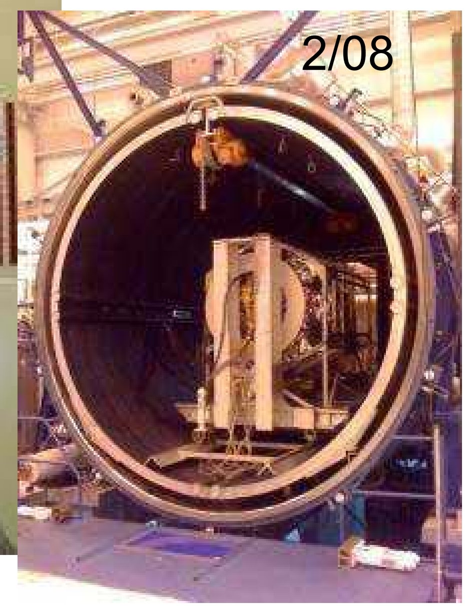




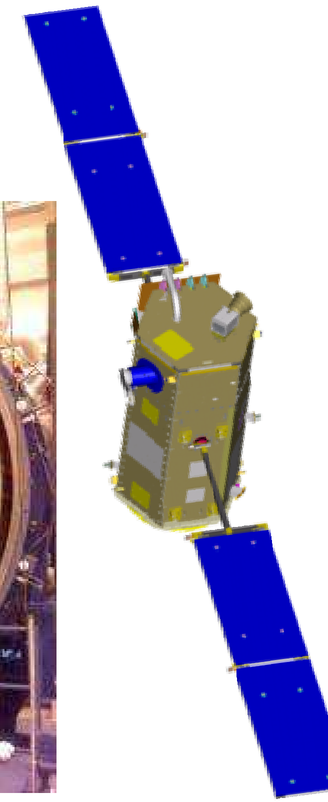


The OCO Spacecraft Bus





- Orbital Sciences LEOStar-2 Bus
  - 0.94 m x 2.1 m
  - 3-axis stabilized
  - Includes propulsion system for orbit maintenance



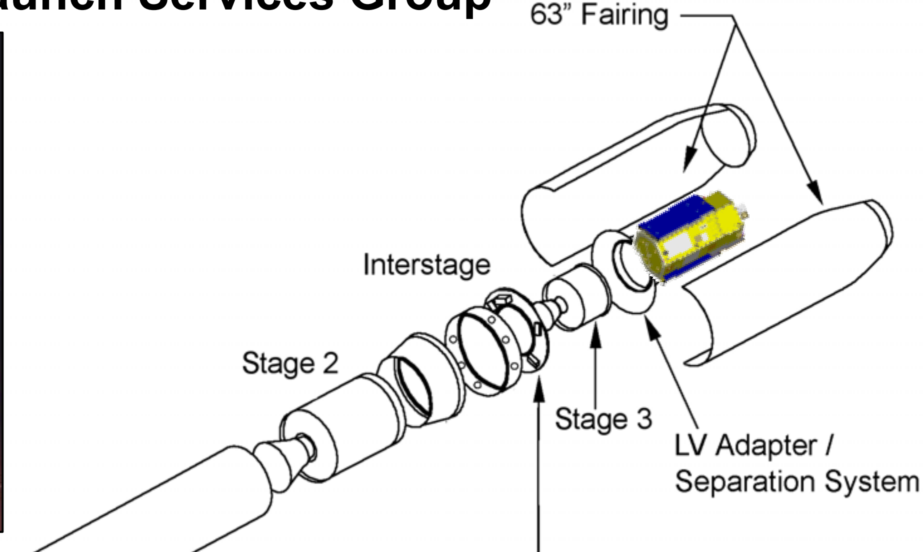
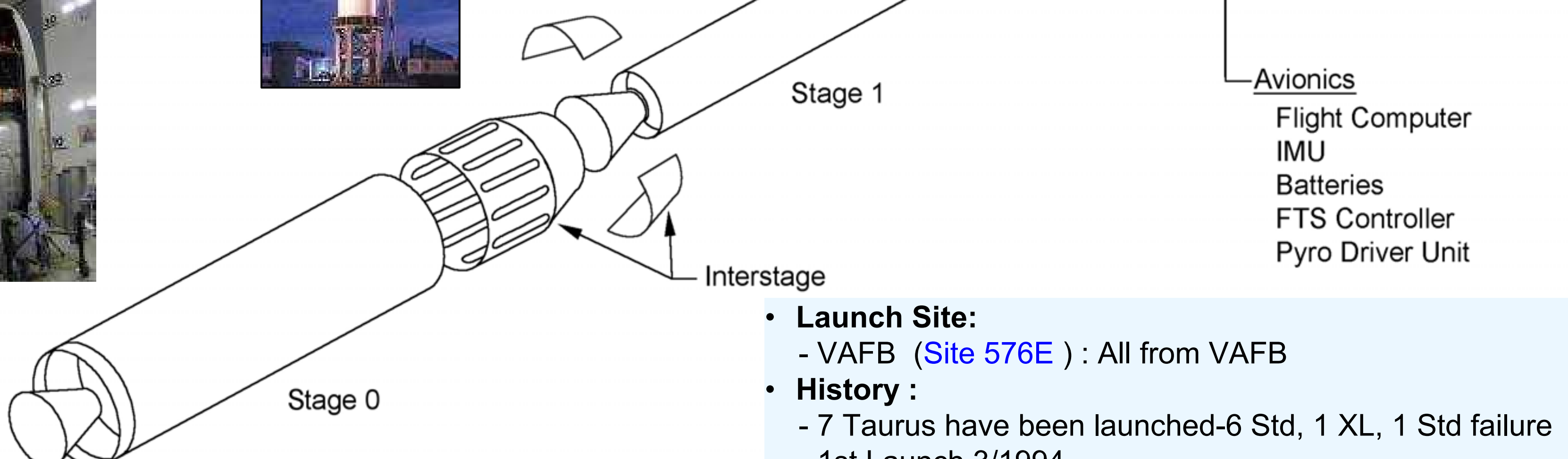
- Spacecraft bus development and flight qualification testing completed
- Integration with instrument started in late March

Our Ride: Taurus 3110 Launch Vehicle

- **Manufactured by the Orbital Sciences Launch Services Group**
- **Integration on Schedule**

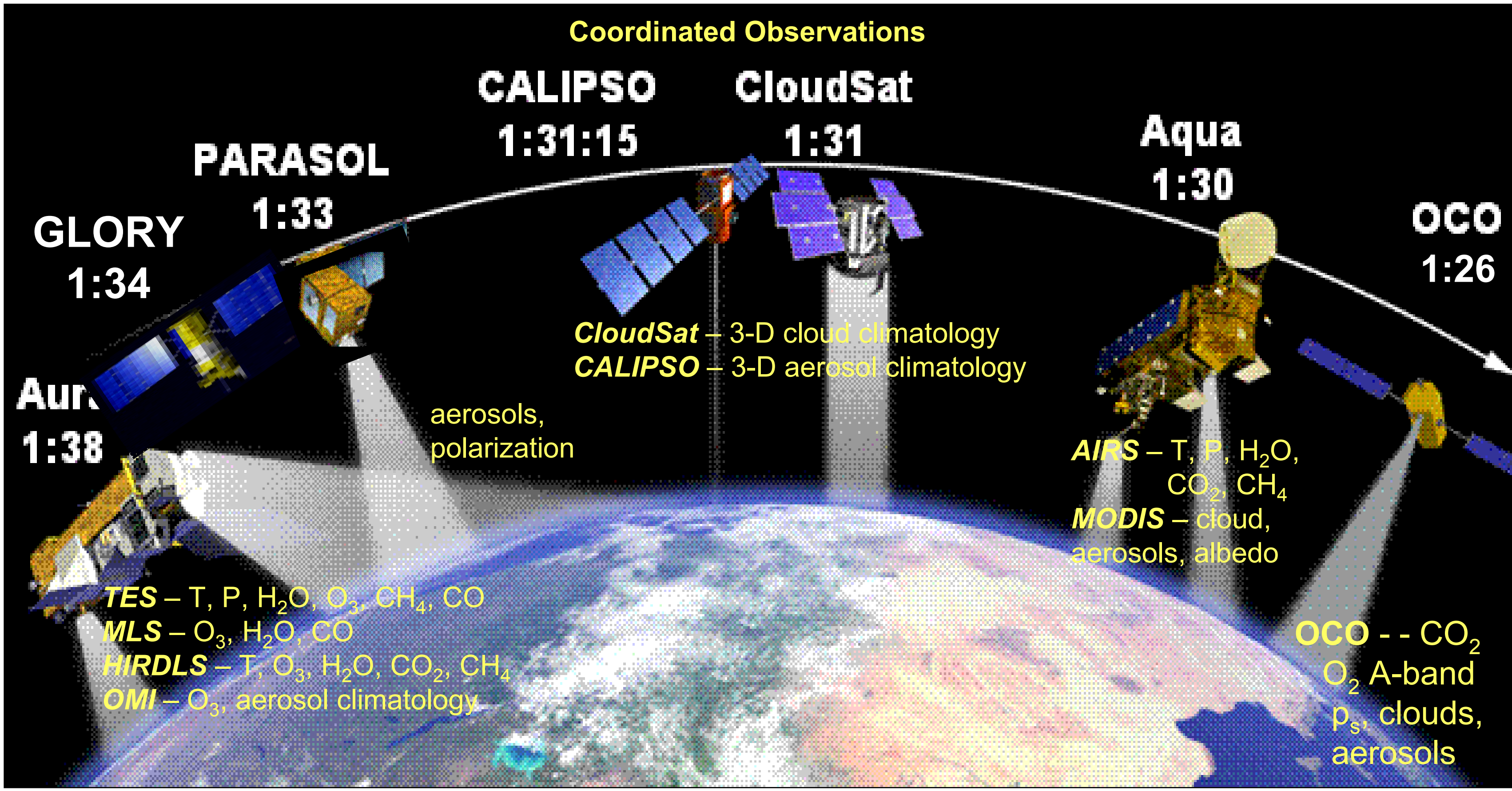




- **Launch Site:**
  - VAFB (Site 576E) : All from VAFB
- **History :**
  - 7 Taurus have been launched-6 Std, 1 XL, 1 Std failure
  - 1st Launch 3/1994

OCO Will Fly in the A-Train



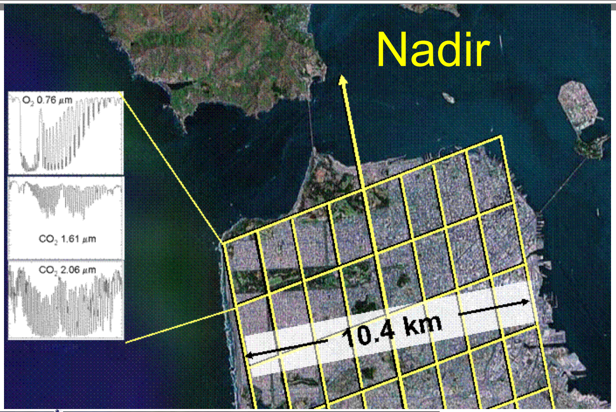
OCO files at the head of the A-Train, 4 minutes ahead of the Aqua platform

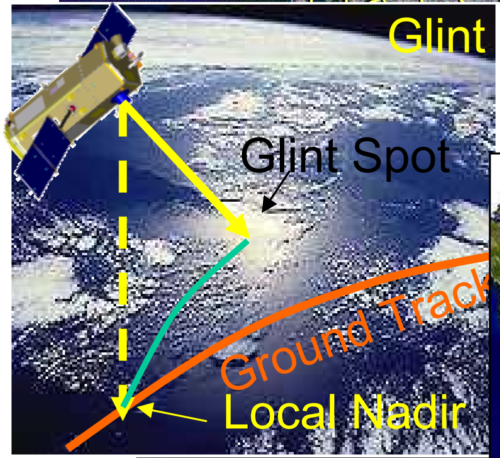
- 705 km altitude sun synchronous, 98.2° inclination, 98.8 minute period
  - Global coverage with a 16-day(233 orbit) ground track repeat cycle

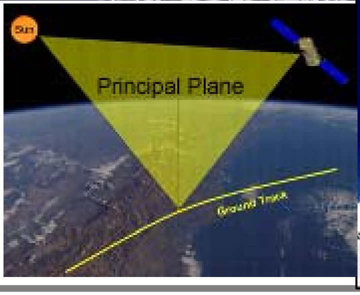
On-orbit Measurement Strategy

- Optimized to minimize bias and yield high Signal/Noise observations of X_{CO2} over the globe
- Nadir Observations: tracks local nadir
  - \+ Small footprint (< 3 km^2) isolates cloud-free scenes and reduces biases from spatial inhomogeneities over land
  - – Low Signal/Noise over dark ocean
- Glint Observations: views "glint" spot
  - \+ Improves Signal/Noise over oceans
  - – More interference from clouds
- Data acquisition schedule:
  - alternate between Nadir and Glint on 16-day intervals

Glint and Nadir observations are taken with the spectrometer slit oriented perpendicular to the principle plane to minimize biases associated with polarization of the scene

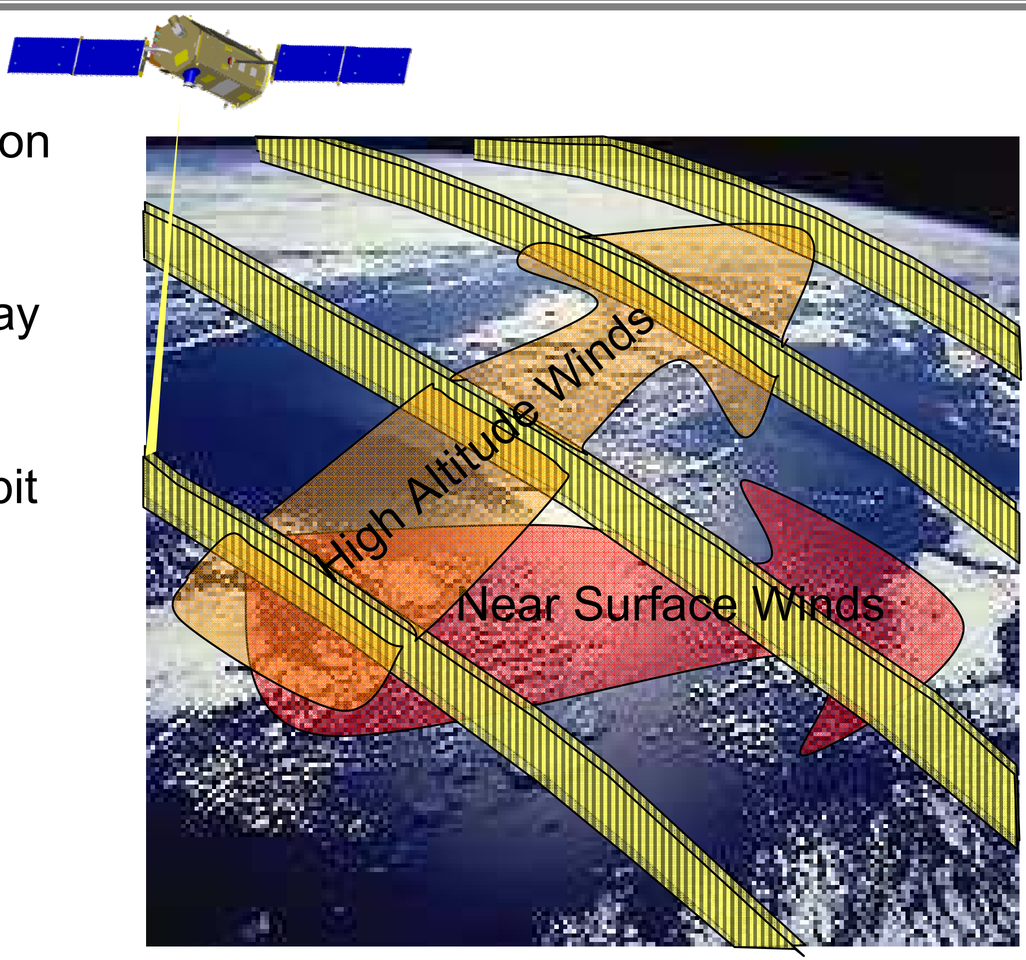






Spatial Sampling Approach

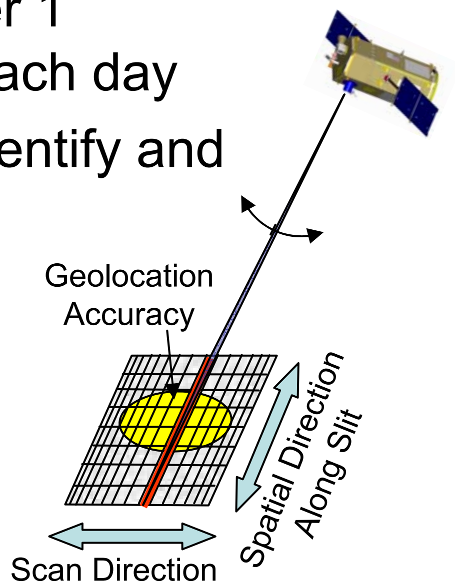
- OCO Orbit Constraints
  - The 705 km altitude ,98.2° inclination
    - global coverage with a 16-day ground repeat cycle
  - 98.8 minute period: 14.57 Orbits/day
    - ~25° longitude offset between consecutive orbits
    - 1.5° longitude offset between orbit tracks over 16-day repeat cycle
- OCO Sampling Rate/Coverage
  - Glint: ±75° SZA, Nadir: ±85° SZA
  - 12-24 samples/second collected along track over land and ocean
    - 200 to 400 samples/degree of latitude along orbit track on day side of the Earth
    - 7 and 14 million soundings over the globe once every 16 days.

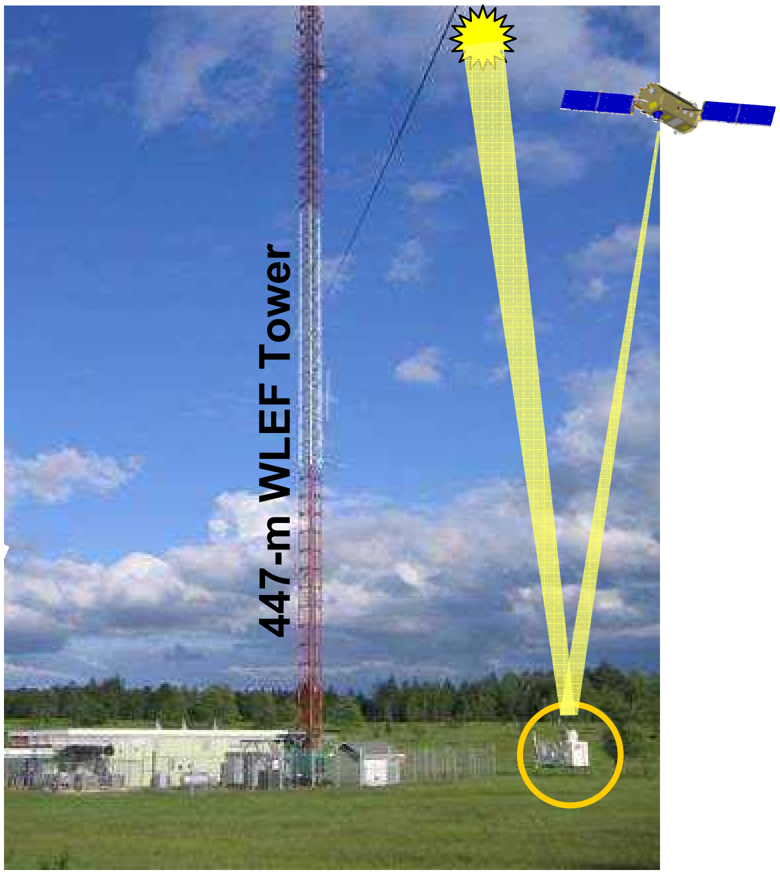


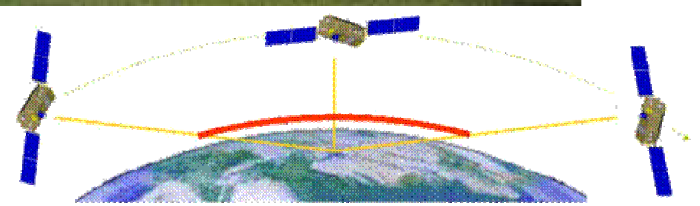
OCO provides dense sampling along track and coarser sampling from track-to-track. Plumes of CO_2 rich/poor air are captured by the column measurements.

Target Observations

- Tracks a stationary surface calibration site to collect large numbers of soundings
- Uplooking ground-based FTS data acquired simultaneously through same slant column
- Acquire Target data over 1 surface validation site each day
- Comparisons used to identify and remove biases





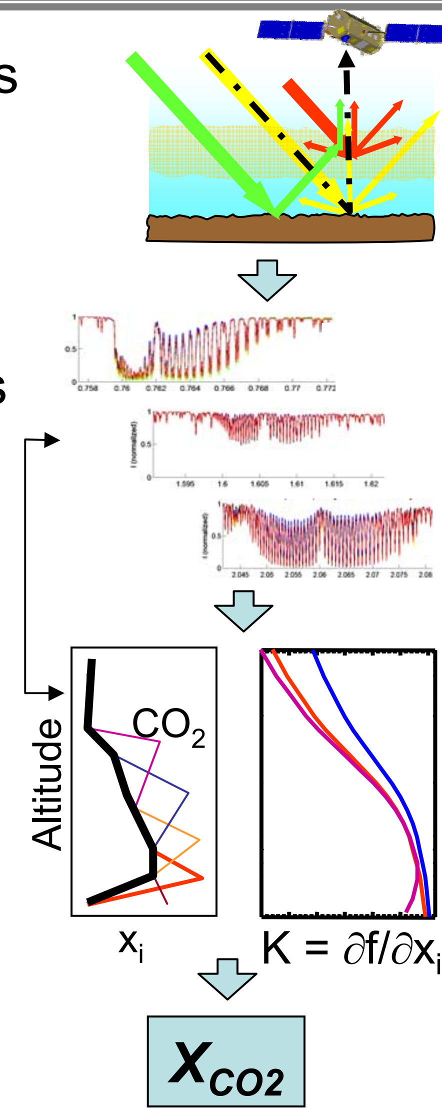


Estimating X_{CO2} from OCO Spectra: The OCO L2 Retrieval Algorithm

Purpose: To derive X_{CO2} from calibrated spectral radiances

Approach: A hybrid approach has been adopted:

- A “Full Physics” algorithm that incorporates everything known about atmospheric and surface optical properties that affect observed radiances
  - Should be reliable over a wide range of conditions, providing an absolute standard
  - Too slow to process all data
- A “Semi-Analytical” method based on correlations between correlated Apparent Optical Path Differences (AOPD’s) in the O_2 and CO_2 bands
  - Fast and accurate over “training” range
  - Provides good initial guess for full physics algorithm



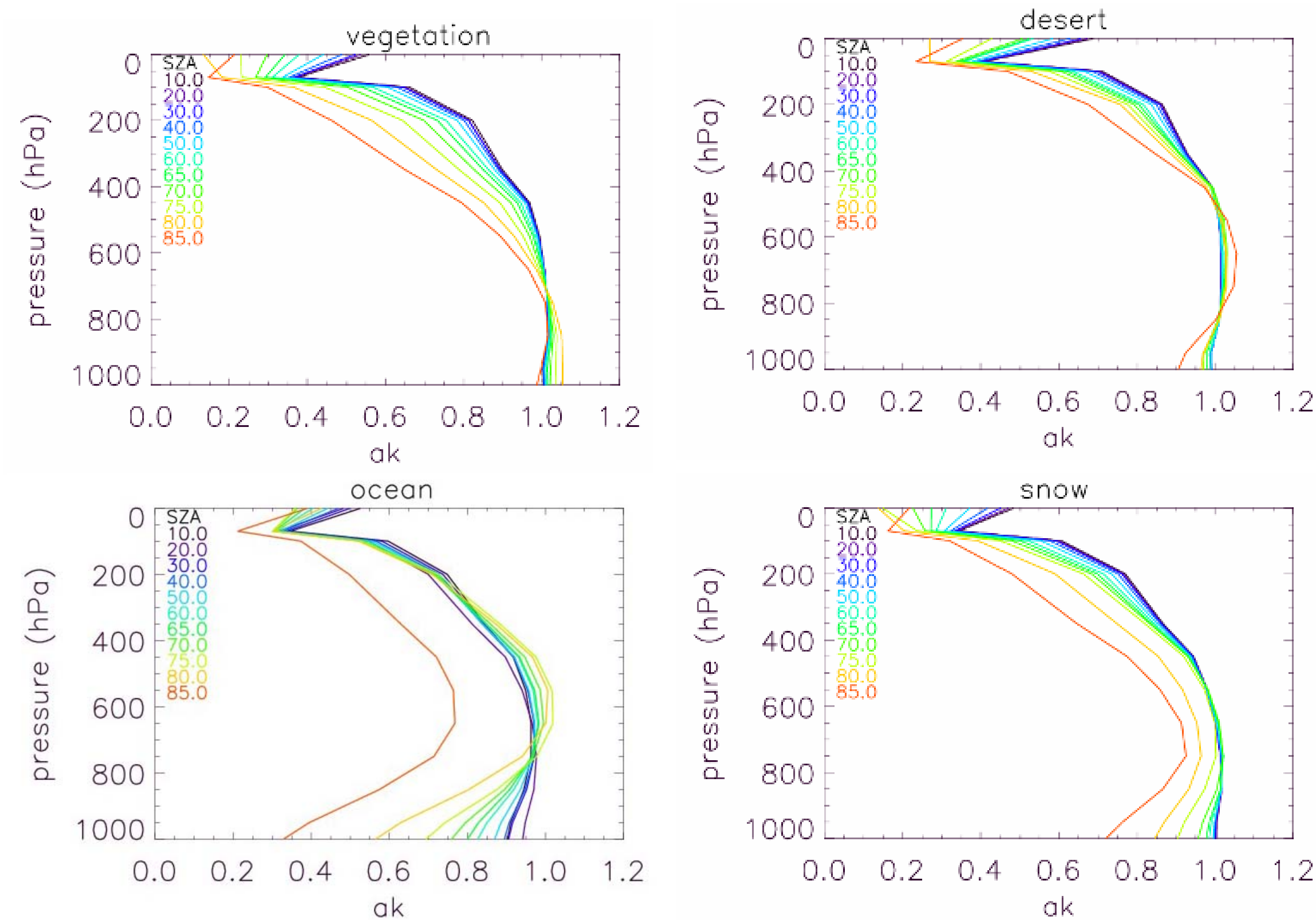
Characterization of Sensitivity and X_{CO2} Errors

- OCO spectra depend on large number of parameters, but by far dominating are:
  - Aerosol loading
  - Solar zenith angles
  - Surface types
- Lin. Error analysis has been used to calculate errors and averaging kernels for range of the 3 dominating parameters:
  - Aerosol: $0 < AOD < 0.3$
  - Surface types: Lambert: vegetation, ocean, snow, desert, soil-vegetation mix
CoxMunk surface for ocean sunglint
  - Solar zenith angle: $0^{o} < SZA < 85^{o}$ for nadir
$0^{o} < SZA < 75^{o}$ for sunglint
  - SNR and FWHM: current best estimate
- Main assumptions:
  - Retrieval has converged to the correct solution
  - Retrieval errors are small
  - No systematic errors included here (i.e. perfect Forward Model)

Averaging Kernels for Nadir Observations

'Bright Surfaces'
(AOD = 0.1)

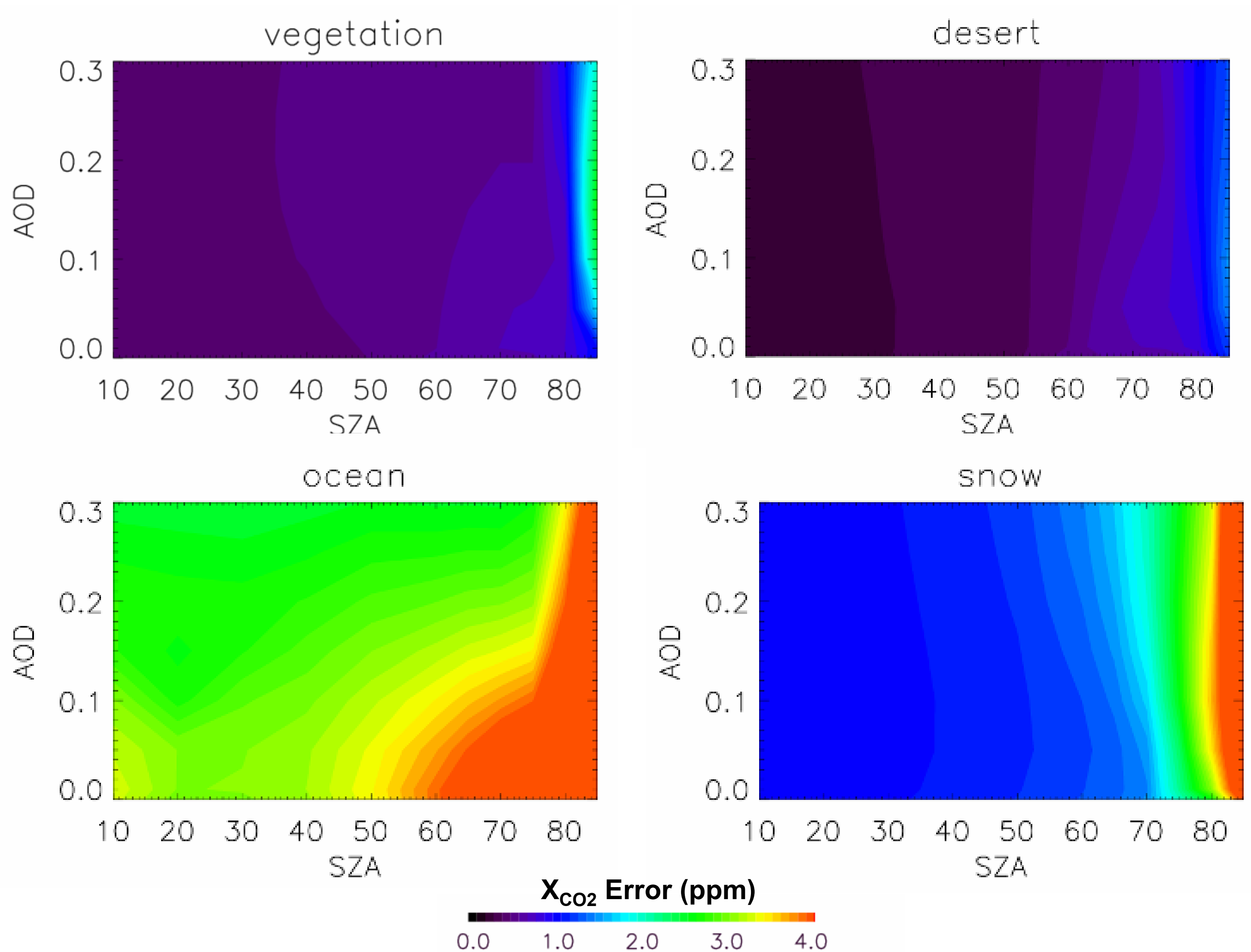
'Dark Surfaces'
(AOD = 0.1)



Simulated Single Sounding X_{CO2} Retrieval Errors for Nadir Observation

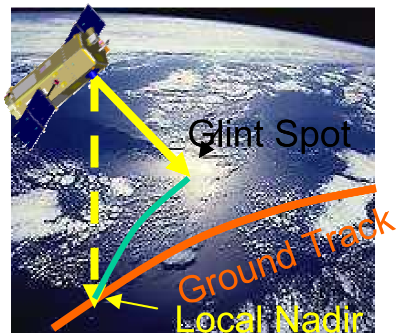
'Bright Surfaces'

'Dark Surfaces'

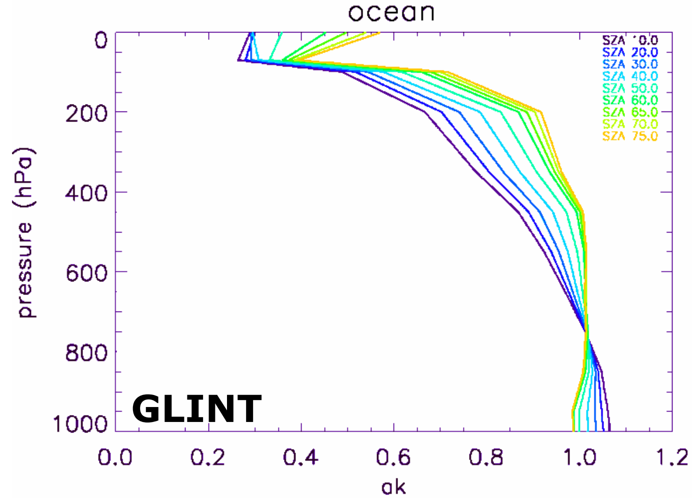


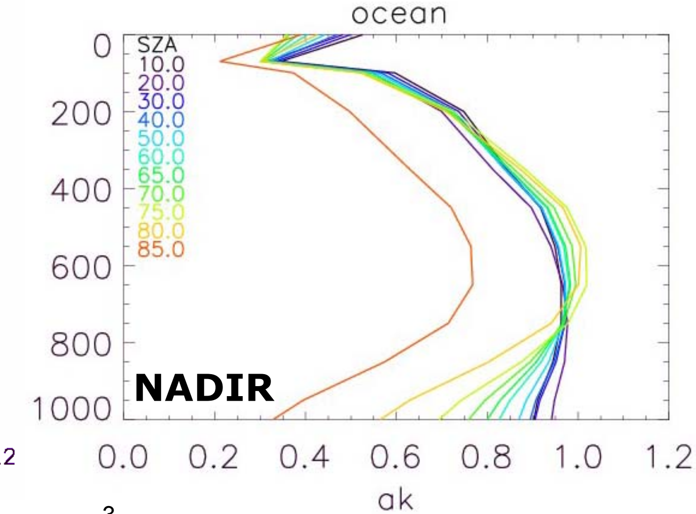
Sun Glint Observations

Sun glint observations provide high Signal-to-noise for ocean (and snow) which are dark in nadir

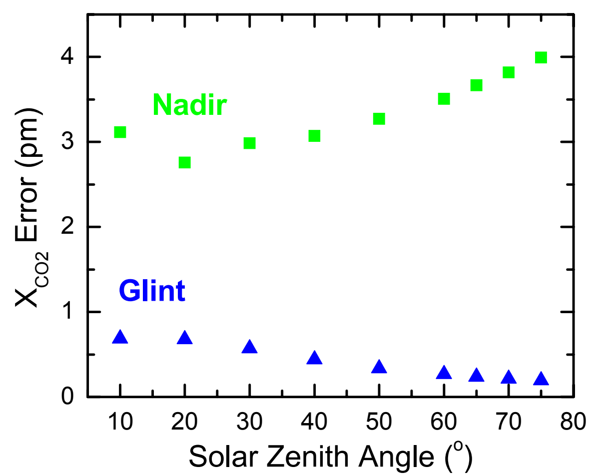


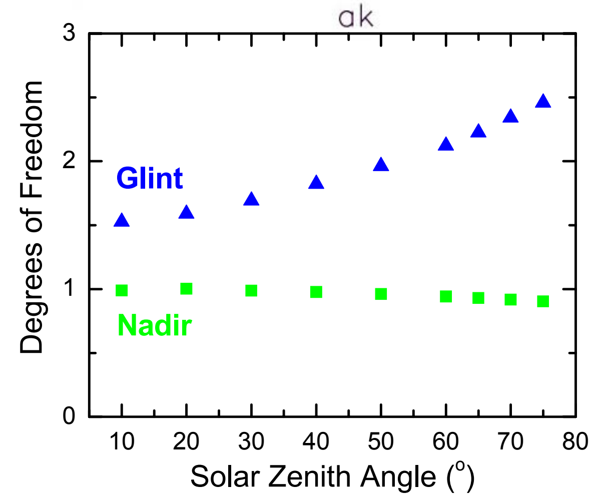
Column averaging kernel (AOD = 0.1)





Retrieval error and degrees of freedom for CO_2 (AOD = 0.1)





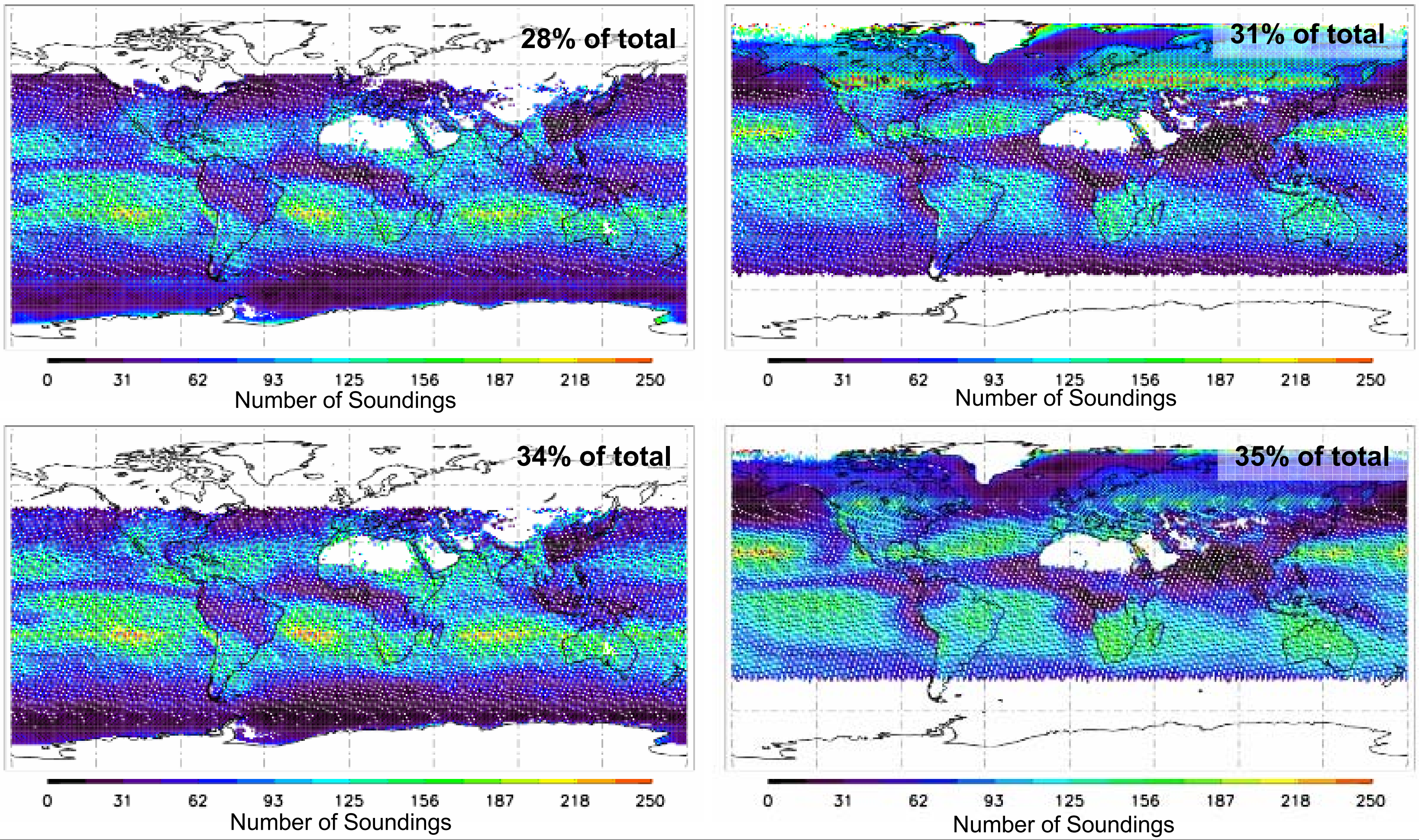
Number of OCO Soundings for 16 Day Repeat Cycle per 1°x1° Bin

Based on OCO orbit geometry + MODIS cloud and AOD maps + OCO pixel size

January **July**

Nadir (SZA < 85°)

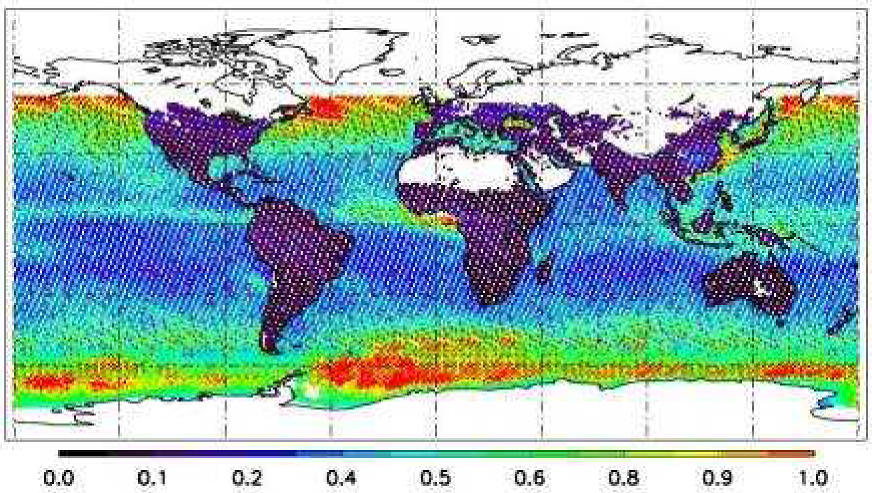
Glint (SZA < 75°)



Averaged 16 Day Ensemble X_{CO2} Retrieval Error for Nadir Observations

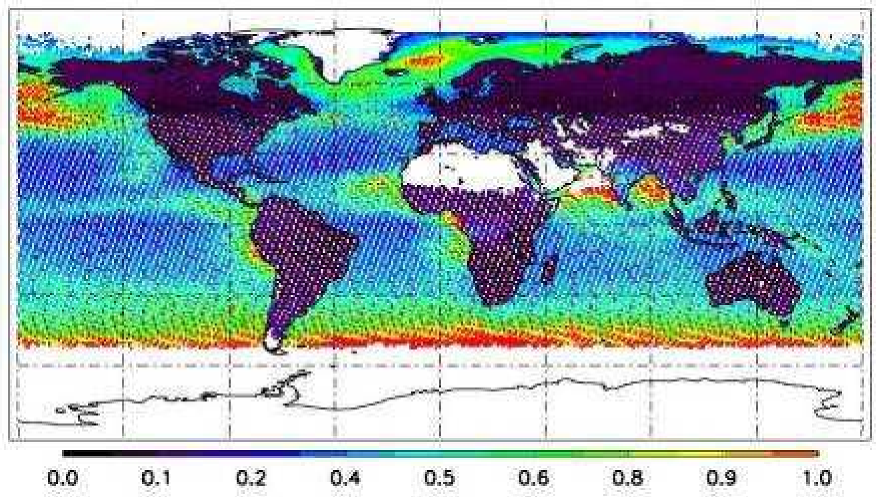
- Based on land type climatology + AOD histogram (for AOD < 0.3) + number of cloud-free OCO pixels from effective OCO pixel size
- SZA < 85°
- No MODIS aerosol data available over ice and desert regions

January



X_{CO2} Error (ppm)

July



X_{CO2} Error (ppm)

sunglint observations will significantly reduce errors over ocean at high latitudes

Space-based X_{CO2} Validation Strategy Ensures Accuracy and Early Acceptance

A rigorous validation approach will speed acceptance of OCO data by the Science Community

- The space-based measurements must be validated against the surface CO_2 standard