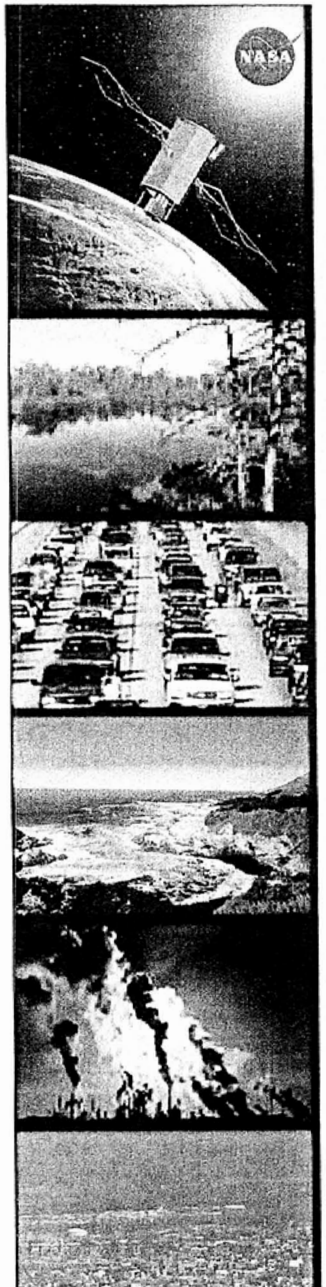


IGARSS 2003

The Earth System Science Pathfinder Orbiting Carbon Observatory (OCO) Mission

David Crisp (JPL)

OCO Principal Investigator

and the OCO Team

HERITAGE • LOW RISK • AMPLE MARGINS • ALL US MISSION • SINGLE PASSIVE INSTRUMENT • COST RESILIENCY

Why CO_2?

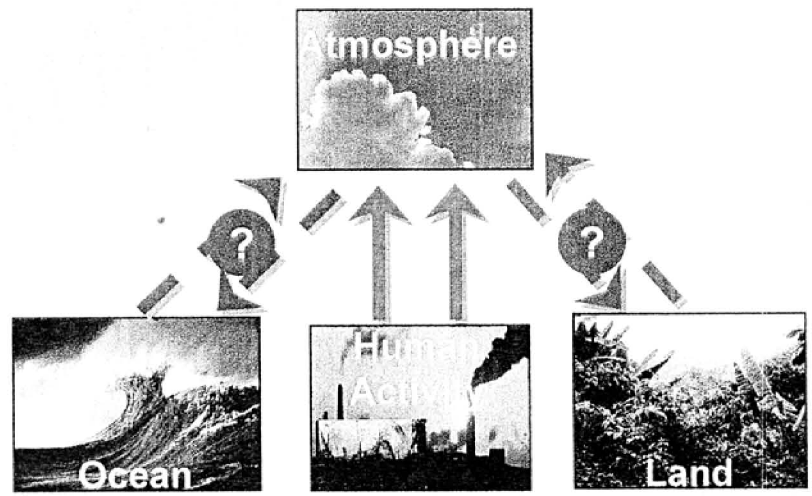
Carbon dioxide (CO_2) is the

Primary atmospheric component of the global carbon cycle

Primary anthropogenic driver of climate change

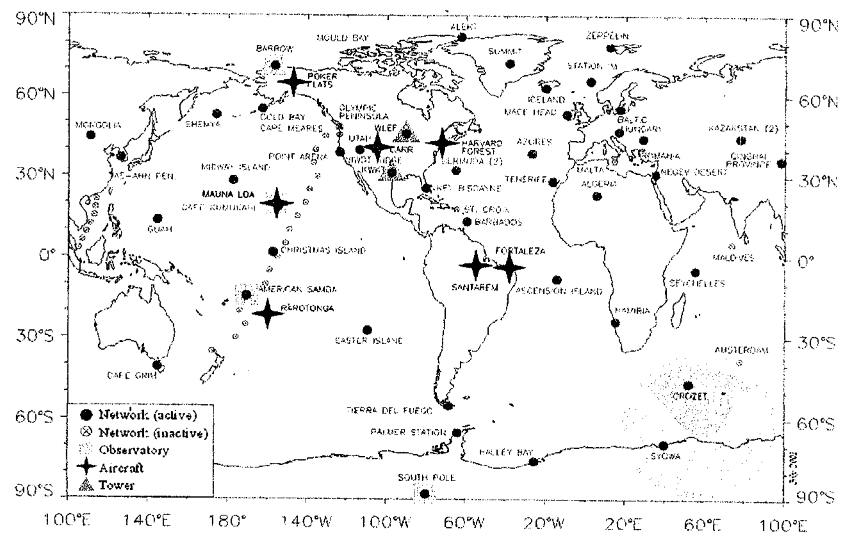
Only half of CO_2 produced by human activities over the past 30 years has remained in the atmosphere.

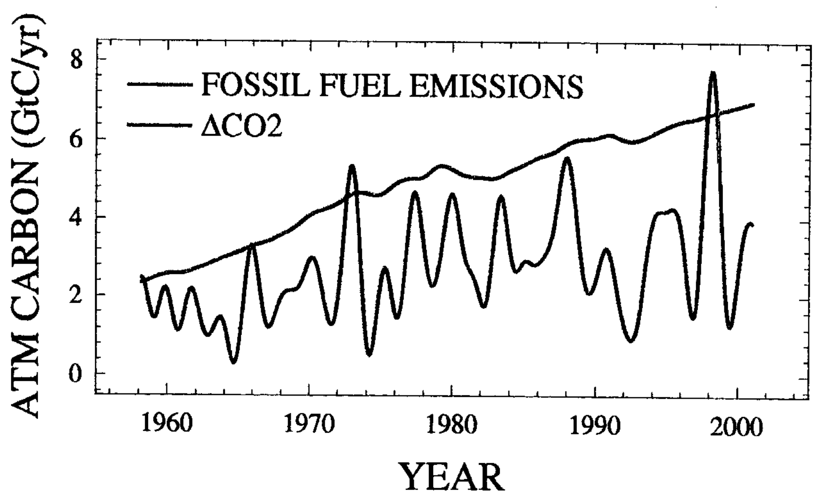
- Where are the sinks?
- Will this process continue?



What Processes Control CO_2 Sinks?

- **Our current understanding of atmospheric CO_2 is based primarily on**
  - Measurements from ~120 surface stations
  - Coupled carbon-cycle/chemical transport models that derive CO_2 sources and sinks from spatial and temporal gradients in the CO_2 abundance
- **Outstanding Issues:**
  - Why does the atmospheric buildup vary substantially with uniform emission rates?
  - What are the relative roles of the oceans and land ecosystems in absorbing CO_2?
  - What are the relative roles of North America and Eurasia?
  - How will sinks respond to climate change?
- **Improved measurements are needed for**
  - Reliable predictions of future CO_2 concentrations and their climate impacts





OCO Science Team

David Crisp, PI
Charles Miller, Deputy PI

Education

Retrieval Algorithms
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Z. Kuang
G. Stephens
G. Toon
Y. Yung

Cal/Val
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L. Brown
J. Burrows
P. Ciais
B. Connor
C. Miller
R. Salawitch
S. Sander
P. Tans
P. Wennberg
S. Wofsy

Source/Sink Modeling
R. Atlas
S. Doney
I. Fung
D. Jacob
S. Pawson
J. Randerson
P. Rayner

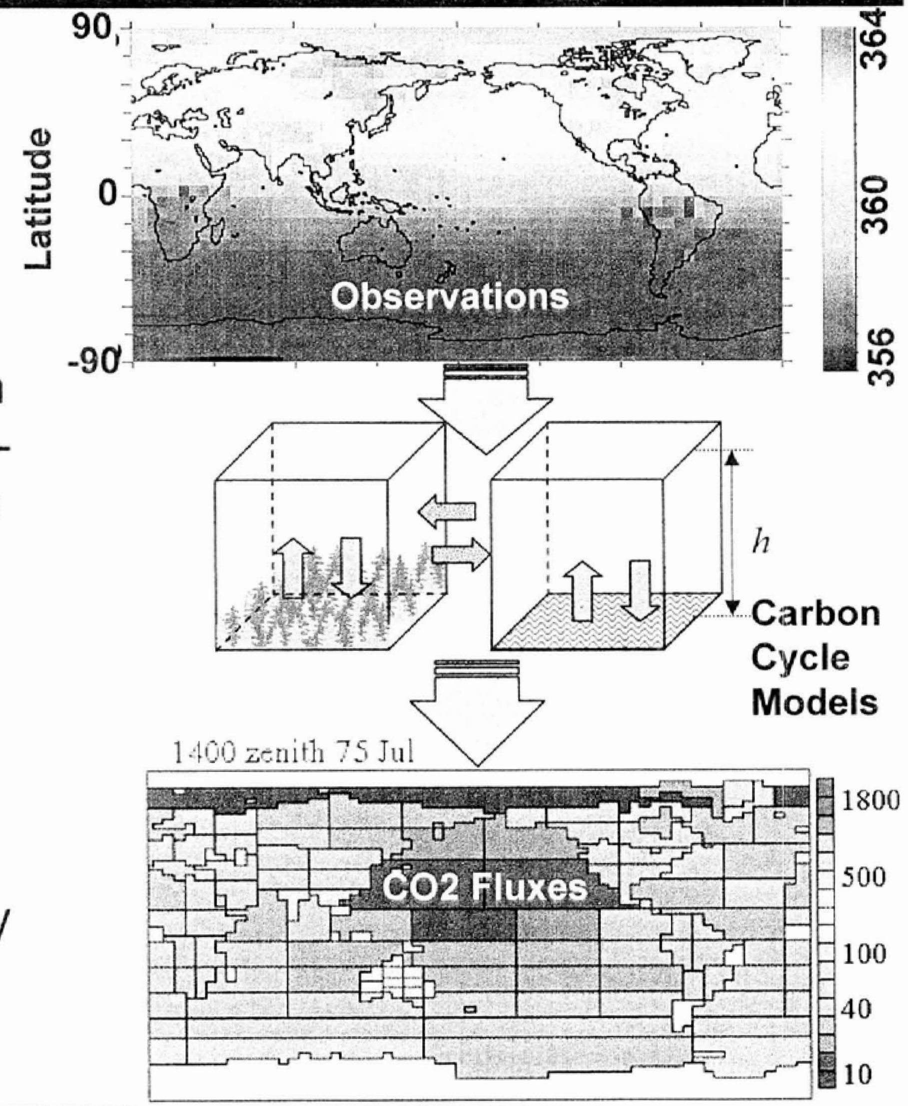
Ground Data System Interface
B. Sen

Universität Bremen
CSIRO
NIWA
Colorado State University
UMBC
JPL

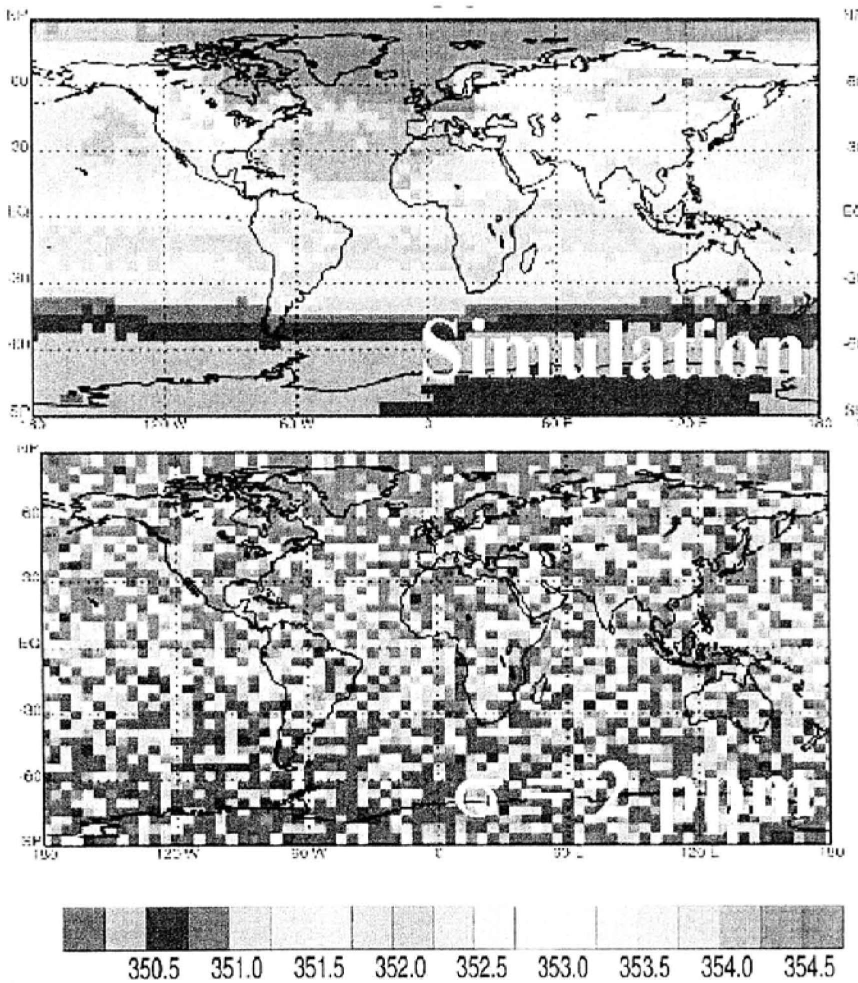
Space-Based Measurements of CO_2

The Orbiting Carbon Observatory will:

- Collect precise, spatially-resolved global measurements of the CO_2 column averaged dry air mole fraction, X_{CO2}
- Use independent calibration and validation approaches to identify and correct regional-scale systematic biases and random errors in the X_{CO2} product.
- Combine the space-based X_{CO2} measurements with other environmental measurements in carbon cycle models to characterize the geographic distribution and magnitude of CO_2 sources and sinks on regional to continental scales at monthly intervals



Driving Requirement: Precise, Bias-Free Global Measurements

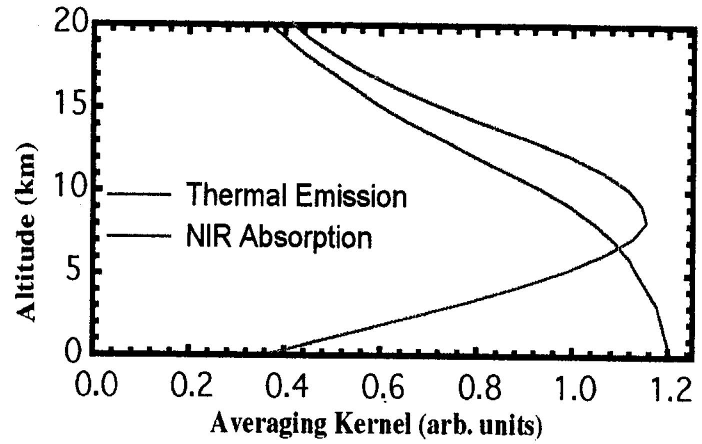


Space-based X_{CO2} measurements could revolutionize our understanding of the geographic distribution of CO_2 sources and sinks if these measurements

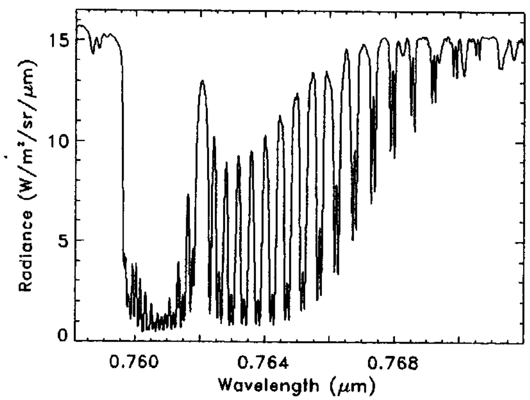
- are acquired globally (land and ocean)
- have random errors <0.3% (~1 ppm out of 370 ppm)
- have no significant systematic bias on regional to continental scales

Making Precise CO_2 Measurements from Space

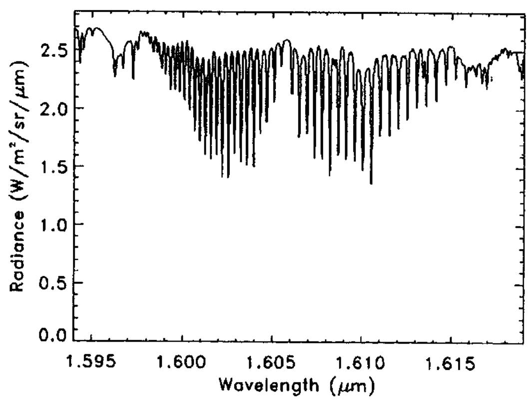
- **High resolution spectra of reflected sunlight in near IR CO_2 and O_2 bands used to retrieve the column average CO_2 dry air mole fraction, X_{CO2}**
  - Column-integrated CO_2 abundance
    - Maximum contribution from surface
  - Other data needed (provided by OCO)
    - Surface pressure, albedo, atmospheric temperature, water vapor, clouds, aerosols



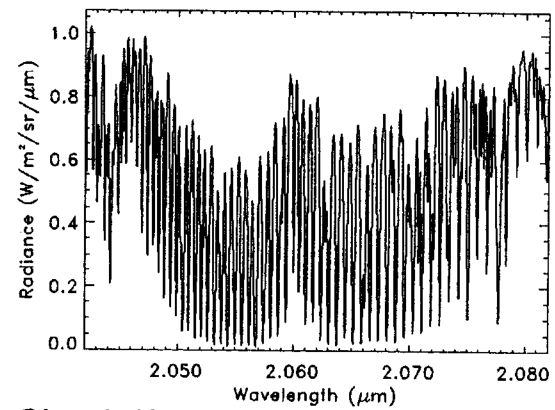
- **Why high spectral resolution?**
  - Lines must be resolved from the continuum to minimize systematic errors



Clouds/Aerosols, Surface Pressure



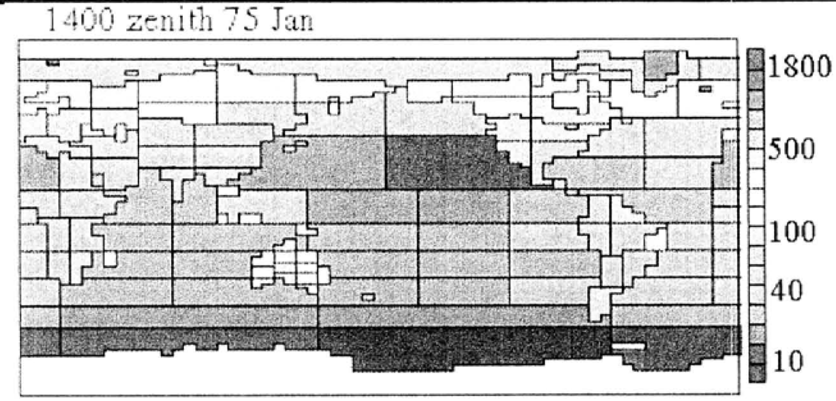
Column CO_2

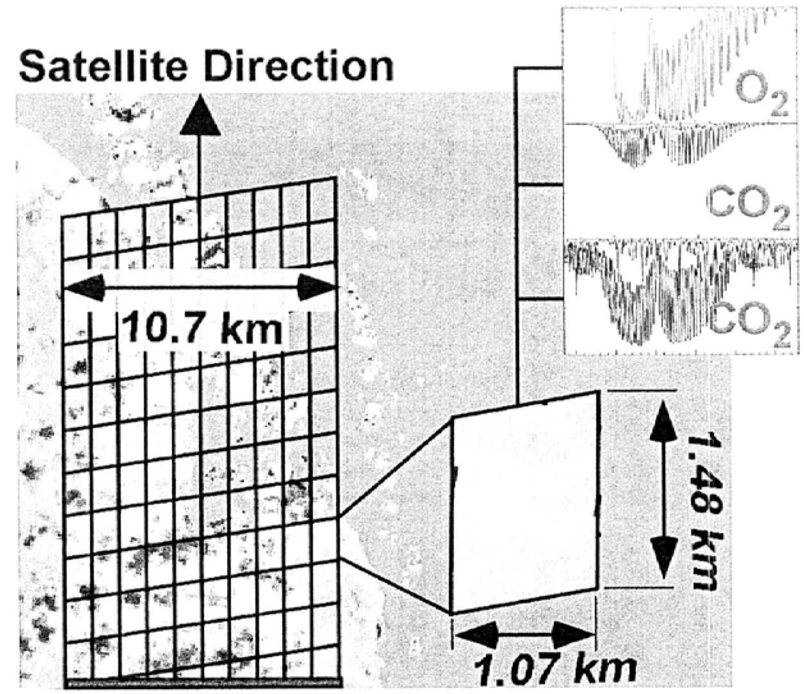


Clouds/Aerosols, H_2O, Temperature

OCO Spatial Sampling Strategy

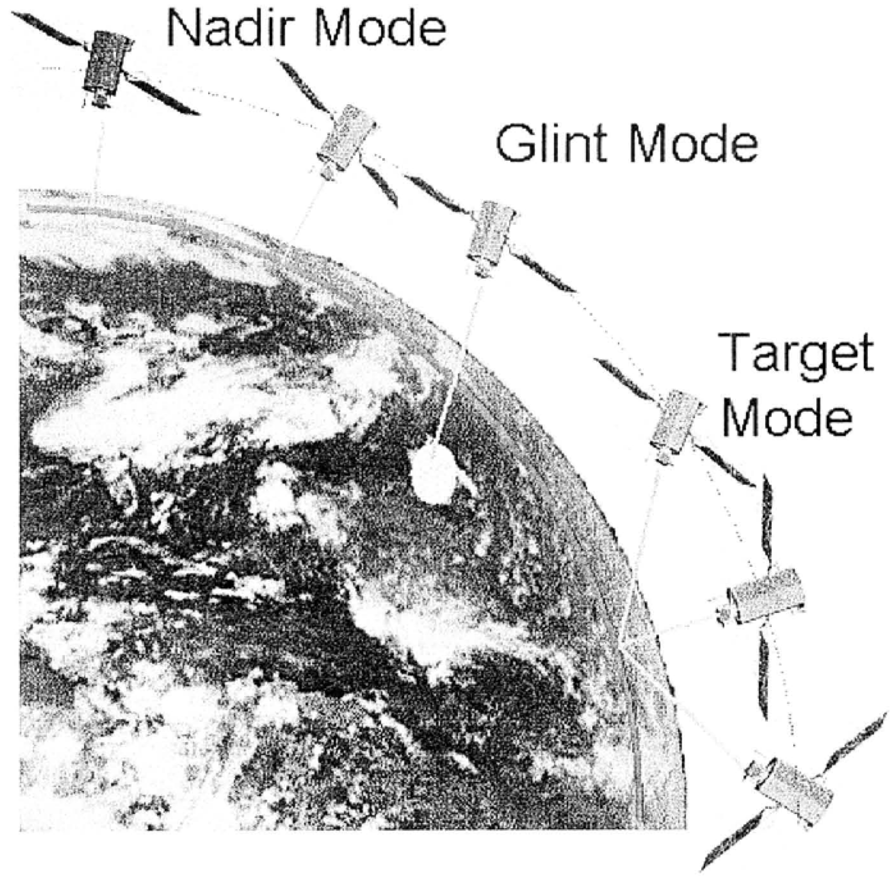
- **The spatial sampling strategy is designed to provide precise, bias-free estimates of X_{CO2} on regional scales at monthly intervals**
  - Chemical Transport Models infer sources and sinks from spatial and temporal gradients in X_{CO2}
  - Atmospheric motions mix CO_2 over large areas as it is distributed through the column
- **OCO collects X_{CO2} soundings at high spatial resolution**
  - Maximizes the number of cloud-free samples in partly cloudy regions
  - Minimizes systematic errors due to spatial inhomogeneities within each measurement footprint



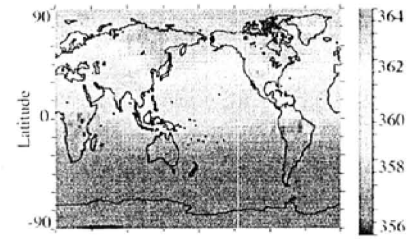


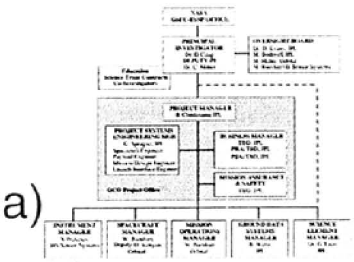
OCO Observing Modes

- **OCO employs independent measurement approaches to**
  - Maximize signal to noise
  - Minimize systematic biases
- **Three observing modes:**
  - Nadir mode
    - Footprint area < 3 km^2 to isolate cloud-free scenes and minimize other spatial inhomogeneities
    - Provides thousands of samples on regional scales
  - Glint Mode
    - Improved Signal/Noise over oceans
  - Target Mode
    - Large numbers of observations over surface calibration sites

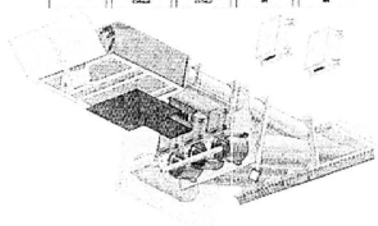


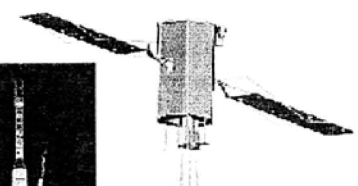
Implementation Approach

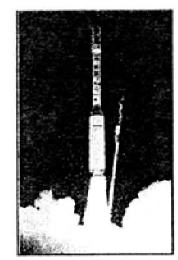




- **International Science Team**
  - Atmospheric remote sensing and spectroscopy
    - JPL, Bremen, CSU, CSIRO, NIWA
  - Carbon Cycle Science
    - NOAA CMDL, GSFC, CSIRO, LSCE, UC Berkeley, Harvard, Woods Hole, UMBC, Caltech
- **JPL Management oversight**
  - Project Management and Mission Assurance (Bharat Chudasama)
  - System Engineering and Mission Planning (George Sprague)
- **Industry Team Members Provide Spacecraft and Instrument**
  - –Ensures rapid infusion of capabilities into US industry
    - Essential to enable future operational missions (NOAA/IPO)
  - –Instrument Provider: UTC Hamilton Sundstrand Sensor Systems
    - –Delivered the last 4 TOMS instruments
    - –Experience with CloudSat O_2 A-Band spectrometer design
  - –Spacecraft Provider: Orbital Sciences Corporation
    - Based on LEOStar-2 Bus

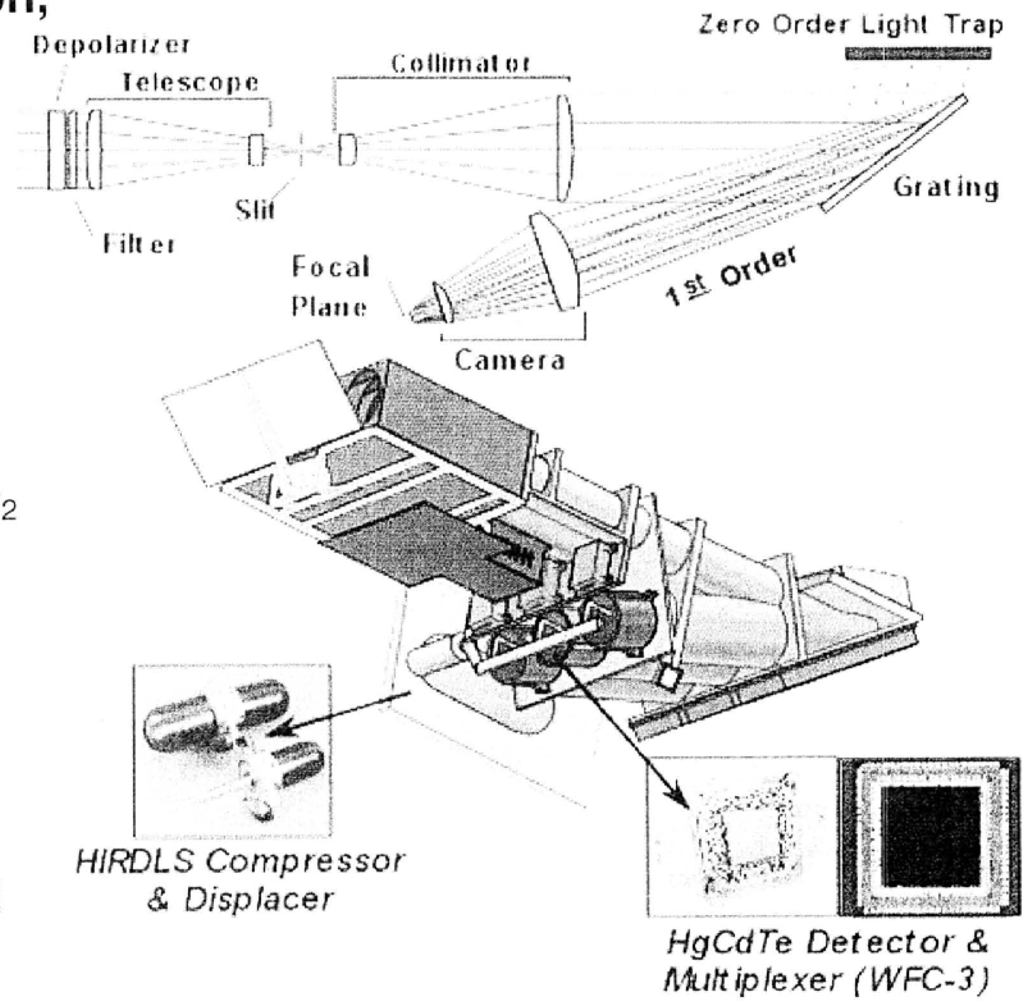






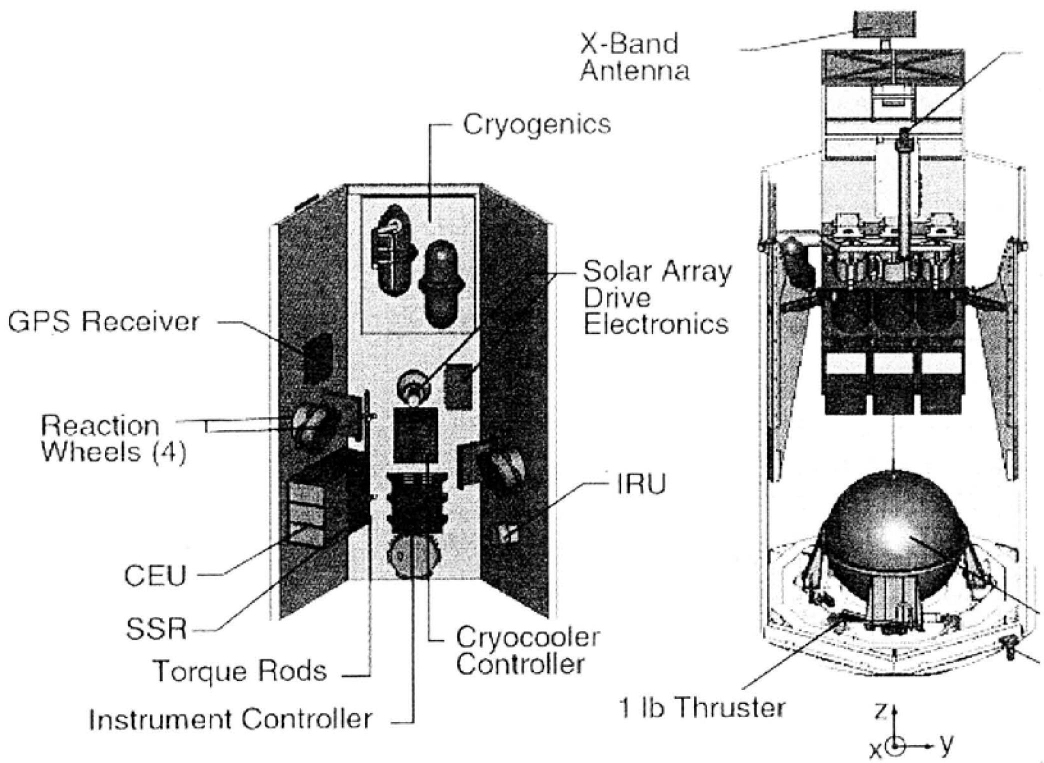
The OCO Instrument

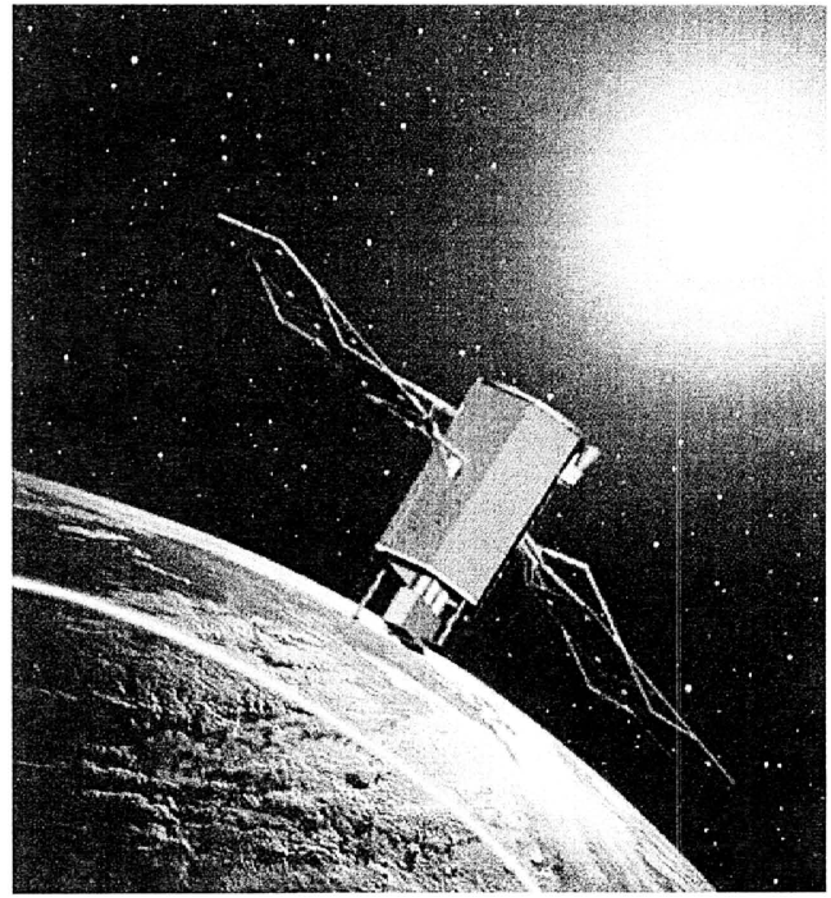
- **Three bore-sighted, high resolution, grating spectrometers**
  - CO_2 1.61 μm band
  - CO_2 2.06 μm band
  - O_2 0.765 μm A-band
- **Similar optics and electronics**
  - 200 mm f/2 refractive optics
  - Spectral Resolution ~20,000
  - RSC Hawaii HgCdTe FPAs for CO_2 channels
  - RSC HyViSI FPA for O_2 channel
- **Existing Designs For Critical Components**
  - Hubble WFC-3 detectors
  - Build-to-Print Aura HIRDLS cooler
- **Provided by Hamilton Sundstrand Sensor Systems (Pomona CA)**
  - Provided last 4 TOMS instruments



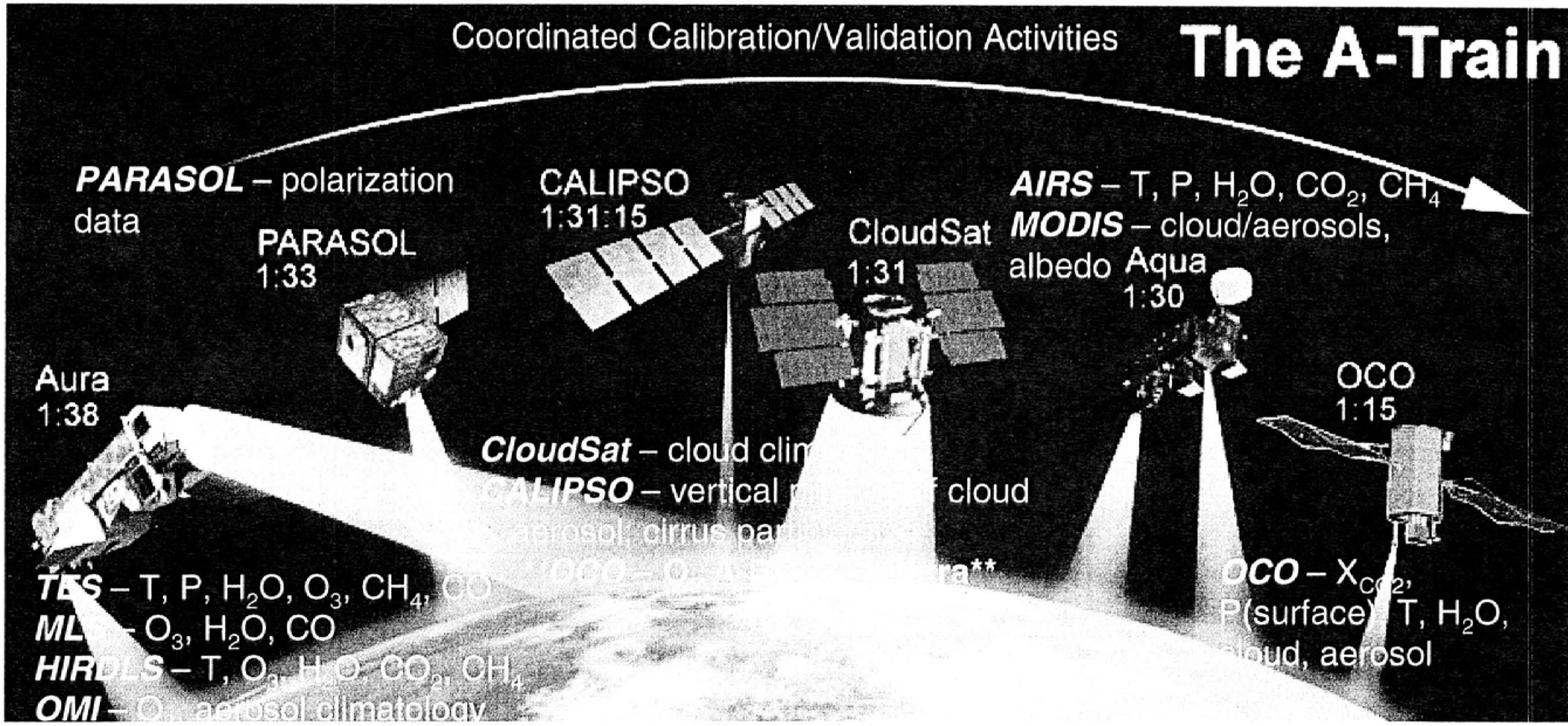
The OCO Spacecraft

- **4th build of Orbital LEOStar-2 Bus**
  - Orbview 4, GALEX, SORCE
  - Now in NASA's RSDO Catalog
- **Satisfies all OCO Requirements with large margins**





OCO Will Fly in the A-Train

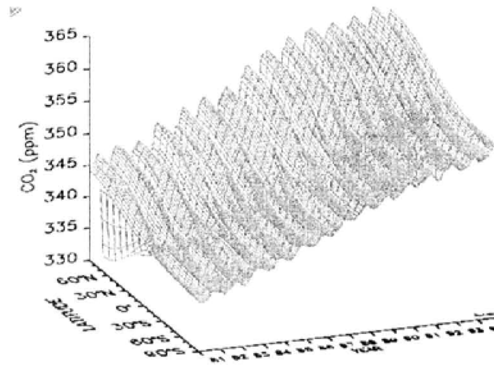


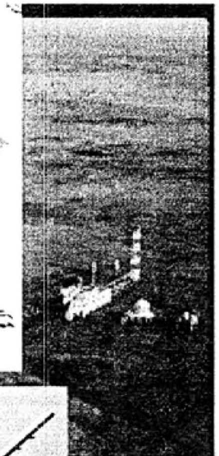
OCO files at the head of the A-Train, 15 minutes ahead of the Aqua platform

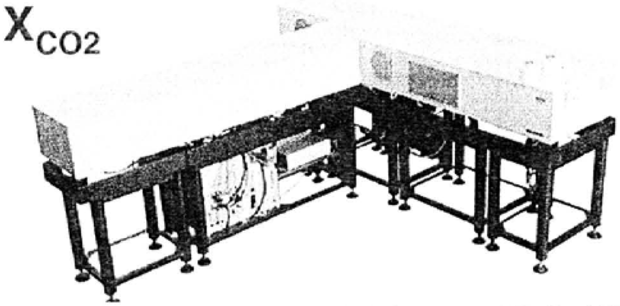
- 1:15 PM equator crossing time yields same ground track as AQUA
- Near noon orbit yields high SNR CO_2 and O_2 measurements in reflected sunlight
- CO_2 concentrations are near their diurnally-averaged values near noon
- Maximizes opportunities of coordinated science and calibration activities

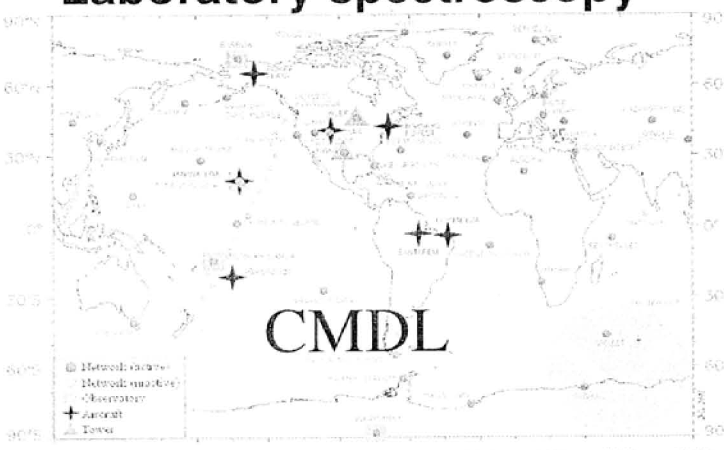
Validation Program Ensures Accuracy and Minimizes Spatially Coherent Biases

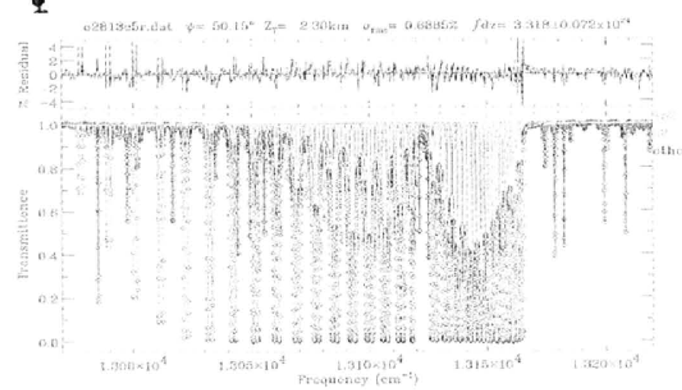
- **Ground-based in-situ measurements**
  - NOAA CMDL Flask Network + Tower Data
    - Typical errors <<0.1%
- **Aircraft measurements of CO_2 profile**
  - Wofsy (US), Ciais (CNRS Aerocarb)
    - Typical errors << 0.1%
- **Uplooking FTS measurements of X_{CO2}**
  - 3 funded by OCO
  - 4 upgraded NDSC
- **Laboratory spectroscopy**

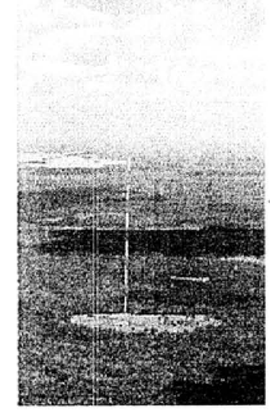






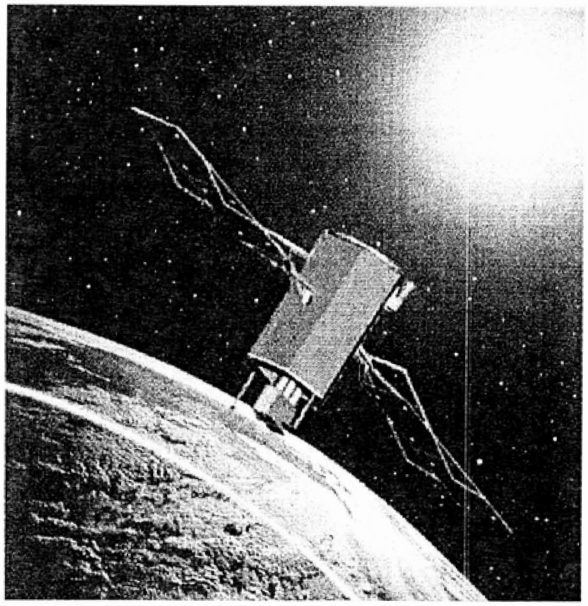






Can OCO Provide the Required Precision?

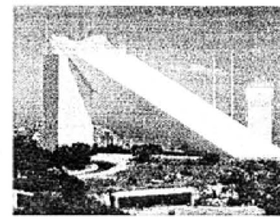
- **A comprehensive series of measurements and modeling studies are being conducted to ensure that OCO will provide the needed precision**
  - Acquisition and analysis of ground-based uplooking Fourier Transform Spectrometer observations of O_2 and CO_2 from Kitt Peak and Table Mountain
  - Aircraft measurements of the O_2 A-band
  - Observational System Simulation Experiments
    - Prototype OCO retrieval algorithm
    - Carbon Cycle Models
      - Seasonal Cycle of X_{CO2}
      - North-South X_{CO2} gradient
      - Diurnal variations in X_{CO2}

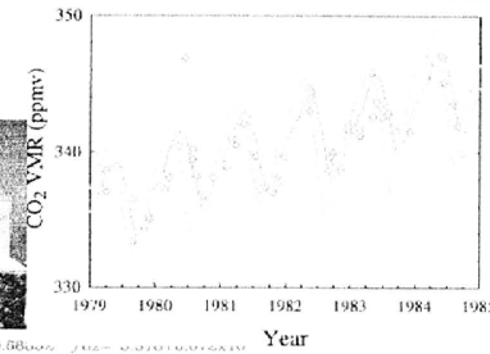


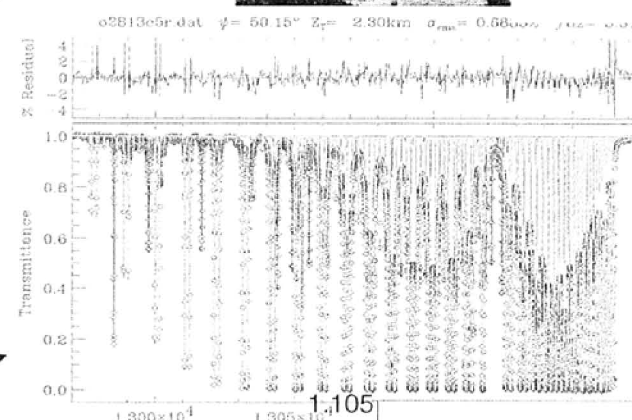
O_2 Column Retrievals with Ground-based FTS

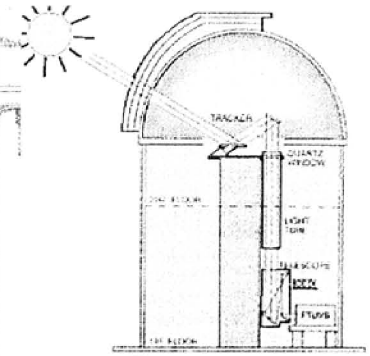
Ground-based spectroscopy is being used to demonstrate the feasibility of column abundance measurements with precisions near 0.3%

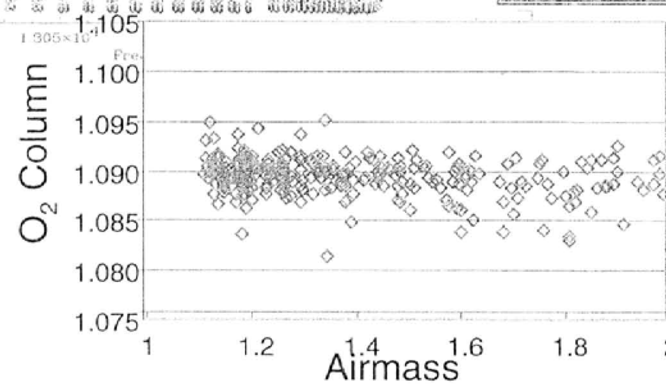
- Two sets of measurements have been acquired and analyzed
  - FTS data from Kitt Peak
    - precisions close to those required by OCO for column O_2 and CO_2 (0.5%) even though the observations were not optimized
  - FTS observations of O_2 from FTUVS at Table Mountain
    - Indicate that accuracies near 0.2% are achievable for O_2
    - Have provided new insight into O_2 A-band spectroscopy











Z. Yang, P. Wennberg, G. Toon, R. Cageao, T. Pongetti, S. Sander

X_{CO2} Retrieval Simulations

Retrieval Modeling Studies:

- X_{CO2} precision of 1ppm (0.3%) needed to characterize CO_2 fluxes

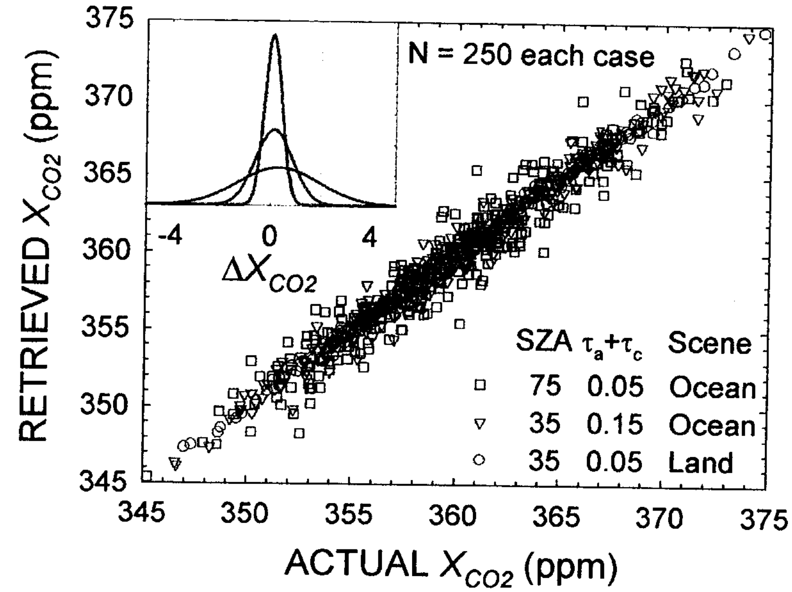
Approach:

- Realistic, end-to-end, Observational System Simulation Experiments
  - Reflected radiances for a range of atmospheric/surface conditions
  - Comprehensive description of
    - Measurement scenario
    - Instrument characteristics

Results:

- The OCO payload will meet or exceed the requirements for measuring X_{CO2}

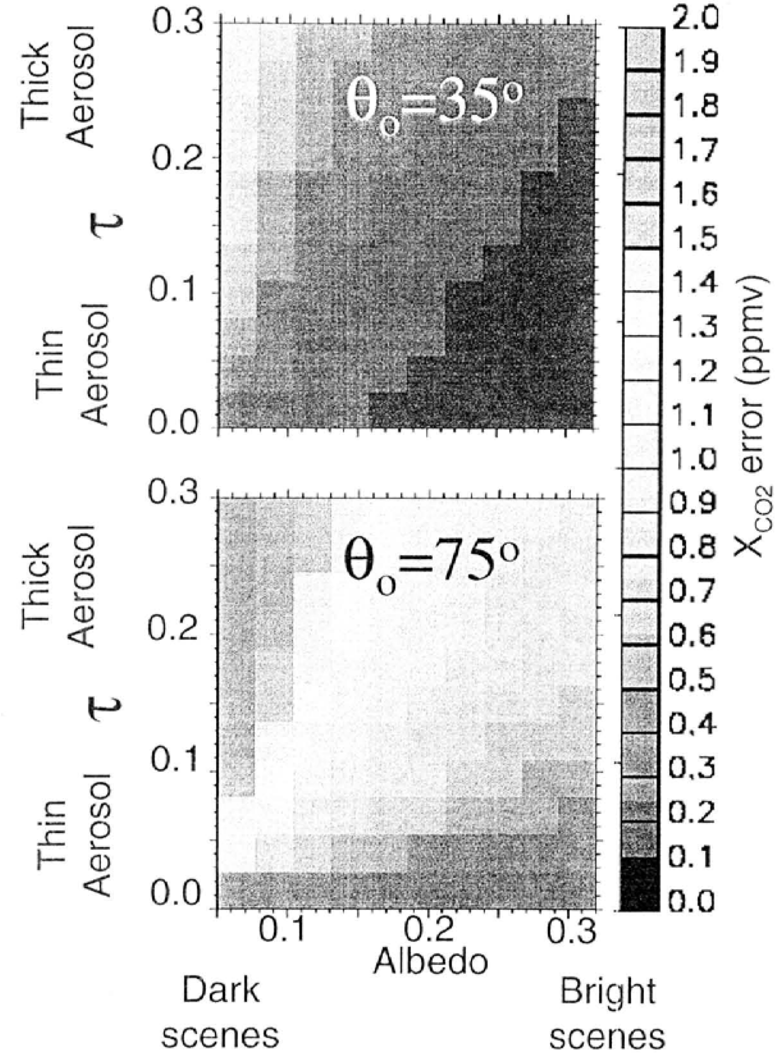
Z. Kuang - Univ. Washington, Y. Yung - Caltech



End-to-end retrievals of X_{CO2} from individual simulated nadir soundings at SZAs of 35^o and 75^o. The model atmospheres include sub-visual cirrus clouds ($0.02 \leq \tau_c \leq 0.05$), light to moderate aerosol loadings ($0.05 \leq \tau_a \leq 0.15$), over ocean and land surfaces. INSET: Distribution of X_{CO2} errors (ppm) for each case

Impact of Albedo and Aerosol Uncertainty on X_{CO2} Retrievals

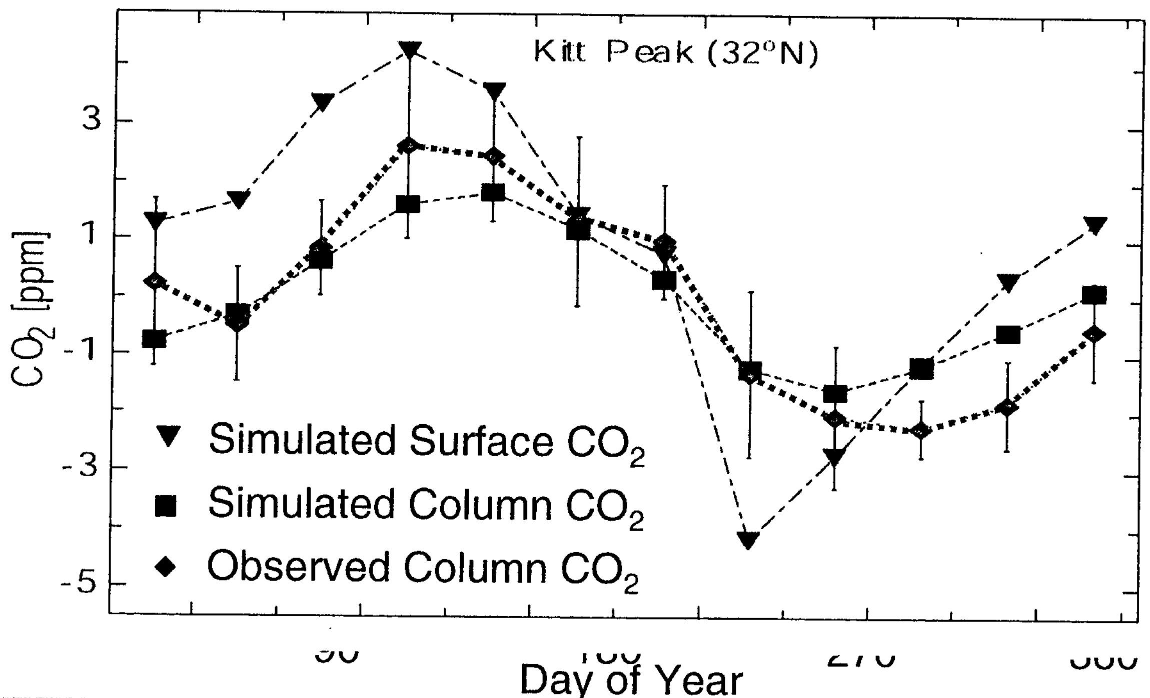
- Retrieval studies have been used to estimate X_{CO2} retrieval error (ppmv) as a combined function of albedo and aerosol optical depth (τ).
  - *At high albedos and/or low aerosol optical depths, the X_{CO2} retrieval errors are much less than 1 ppmv.*
  - **At low albedos (<0.05) and high aerosol optical depths (τ > 0.15), the X_{CO2} retrieval errors exceed 1 ppmv**
- ***Summary:*** *OCO can retrieve X_{CO2} with errors less than 1 ppm even under sounding conditions that are far from ideal.*



Z. Kuang - Univ. Washington, Y. Yung - Caltech

Carbon Cycle Modeling Studies: Seasonal Cycle

- **Seasonal cycle:** *How well does OCO need to measure X_{CO2}?*
- Amplitude of Northern hemisphere seasonal cycle in X_{CO2} is reduced by 40% to 50% as compared to surface amplitude
- Phase delay of 20-40 days in the column as compared to surface
- Seasonal cycle can be resolved from space if 1-2 ppm precision were obtained in column CO_2

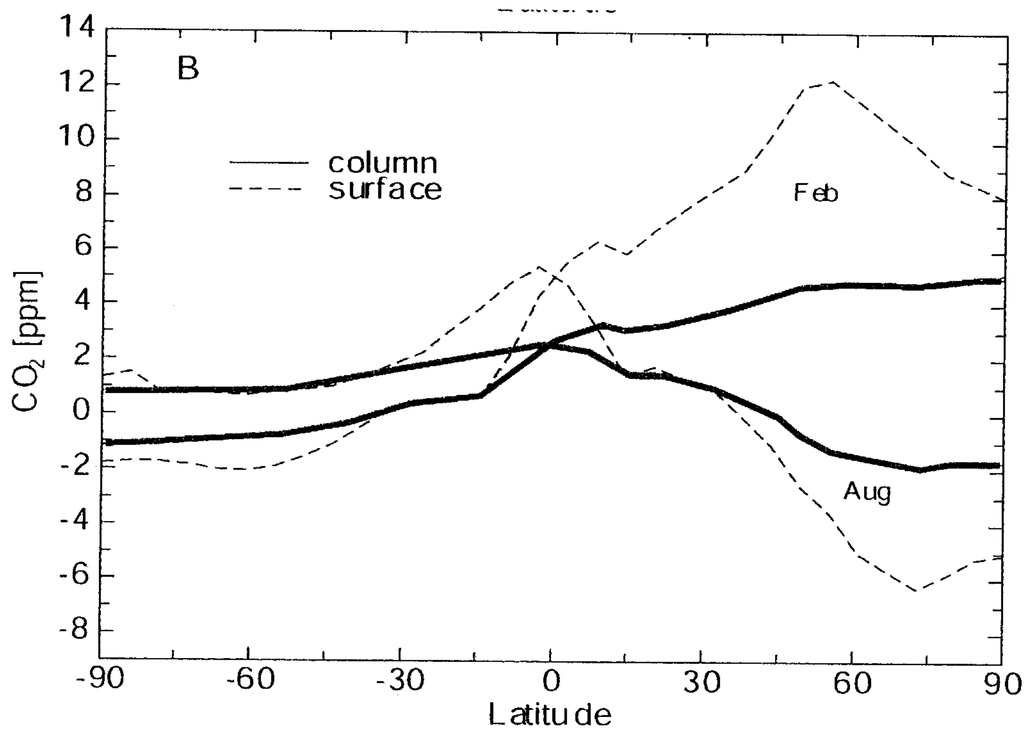


Comparison of column CO_2 retrieved from Kitt Peak FTS (red) to simulated column and surface *in situ* CO_2 results

Carbon Cycle Modeling Studies: The North-South Gradient in CO_2

North-South Gradient: *How well does OCO need to measure X_{CO2}?*

- North-South gradient in column CO_2 is only half as large as the CO_2 gradient at the surface
- Northern Hemisphere-Southern Hemisphere gradients can be resolved from space by 1-2 ppm precision X_{CO2} measurements

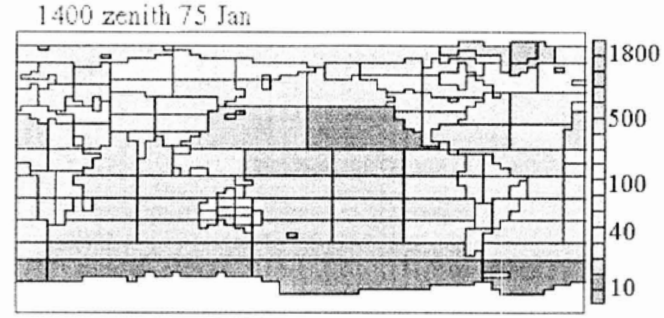


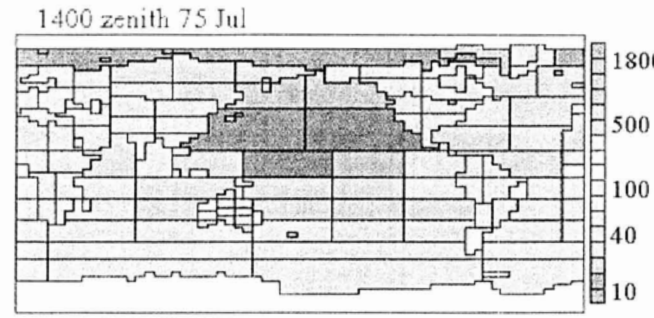
Simulated latitude dependence of the surface CO_2 concentrations for February and August (dashed lines) are compared to the corresponding latitude dependence for the column-integrated dry air mole fraction, X_{CO2} (solid blue and red lines. Typical pole to pole gradients in X_{CO2}. are ~6 ppm.

Carbon Cycle Modeling Studies: Effect of Diurnal Biases

Diurnal cycle: *How well can OCO measure X_{CO2}?*

- **Approach:**
  - "True" source estimates generated from two orbits, each sampling twice per day
    - 0600h & 1800h (sunrise/sunset)
    - 1100h & 2300h (mid-day/midnight)
- These results were compared to 1400h orbit (approx. OCO orbit) with 75 degree SZA cut-off
- **Results:**
  - Differences between the sources are smaller than the uncertainties on the 1400h orbit source estimates.
  - Where larger differences occur, they are not solely due to diurnal biases.
    - Example Biases occur in the winter high latitudes due to the lack of data in the 1400h orbit and these overwhelm any diurnal effect
  - Uncertainties in 24-hr average column CO_2 after correcting for diurnal effects is < 0.1 ppm
  - Diurnal cycle may be greatest over the Amazon (~0.7 ppm diurnal cycle in July vs ~0.4 ppm over Wisconsin)





Estimated regional CO_2 diurnal flux bias ($gC/m^2/yr$) from nadir soundings acquired a 1400 for January and July. The current uncertainties are around 2000 $gC/m^2/yr$. The largest errors are seen at high latitudes during the winter, where there is too little sunlight for OCO retrievals (P. Rayner, R. Law – CSIRO).

Project Status and Schedule

Contract Start	October 2, 2002
Project Kick-Off Meeting	October 10, 2002
Risk Mitigation Phase begins	October 10, 2002
System Requirement Review (SRR)	June 25, 2003
Risk Mitigation Phase Final Review	July 29, 2003
Preliminary Design Review (PDR)	June, 2004
Critical Design Review (CDR)	July, 2005
Launch	August, 2007
Mission Check out (PLSR)	One Month After Launch
Mission Operations	24 Months

Summary

- **OCO will provide critical data for**
  - Understanding the carbon cycle
    - Essential for developing carbon management strategies
  - Predicting weather and climate
    - Understanding sources/sinks essential for predicting CO_2 buildup
    - O_2 A-Band will provide global surface pressure measurements
- **OCO validates technologies critically needed for future operational CO_2 monitoring missions**
  - Satisfies an unaccommodated measurement need identified by NPOESS

Climate Forcing/Response

•$T/H_2O/O_3$	☑	AIRS/TES/MLS
•Clouds	☑	CloudSat
•Aerosols	☑	CALIPSO
•CO_2	☑	OCO