The Orbiting Carbon Observatory (OCO) Mission

Watching The Earth Breathe…Mapping CO_2 From Space.

OCO Project and Science Status

Charles Miller, *JPL*

3rd International Workshop on Greenhouse Gas Measurements from Space

30 May, 2006 Tsukuba, Japan

Watching the Earth breathe.... mapping CO2 from space.

Orbiting Carbon Observatory

The Orbiting Carbon Observatory (OCO)

Watching The Earth Breathe…Mapping CO2 From Space

Salient Features

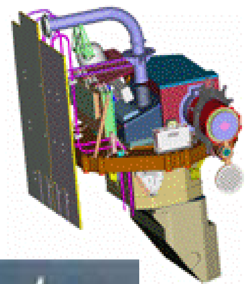
- High Resolution, three Channel Grating Spectrometer
- Partnership with HS (Instrument) and OSC (Spacecraft)
- High Heritage Spacecraft, Flies in Formation with the A-Train
- Launch date: September 2008 on Taurus XL
- Operational life: 2 years
- PI: Dr. David Crisp
- Deputy PI: Dr. Charles Miller
- Project Manager: Rod Zieger, Deputy: Bharat Chudasama
- JPL Program Manager: Dr. Steven Bard
- Program Scientist: Dr. Philip DeCola, NASA HQ
- Program Manager: Eric Ianson, NASA HQ

Science

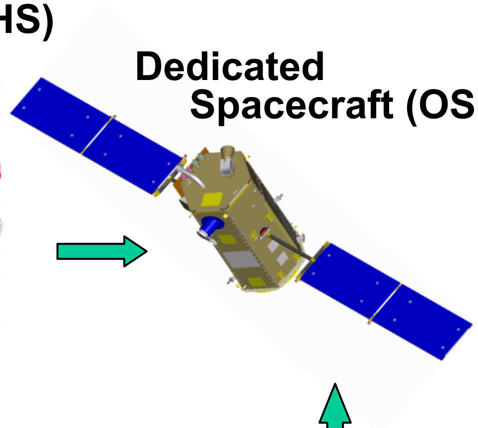
- Collect the first space-based measurements of atmospheric CO_2 with the precision, resolution, and coverage needed to characterize its sources and sinks on regional scales and quantify their variability over the seasonal cycle.
- Use independent data validation approaches to ensure high accuracy (1-2 ppm, 0.3% - 0.5%)
- Reliable climate predictions require an improved understanding of CO_2 sinks
  - What human and natural processes are controlling atmospheric CO_2?
  - What are the relative roles of the oceans and land ecosystems in absorbing CO_2?

Mission Overview

3-channel Spectrometer (HS)



Dedicated Spacecraft (OSC)

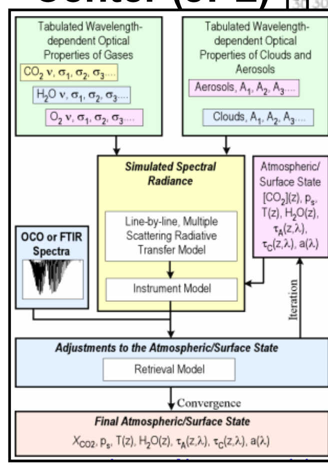


Taurus 3110 (KSC)

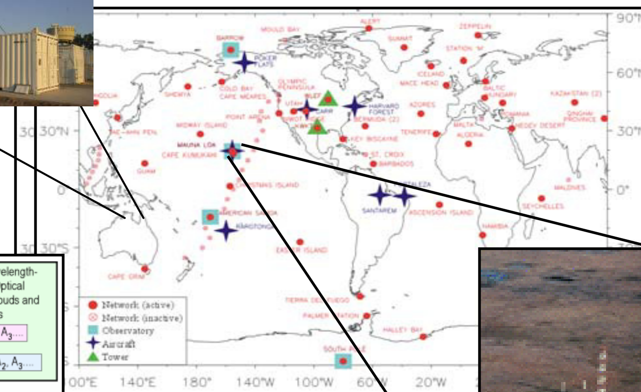
Mission Ops (OSC)

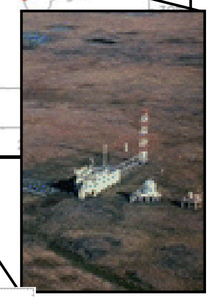
Ground Stations (GSFC/NASA)

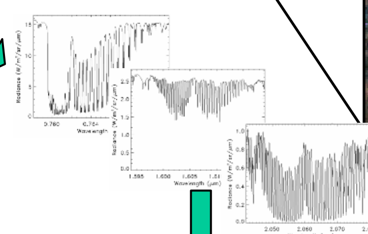
Data Processing Center (JPL)

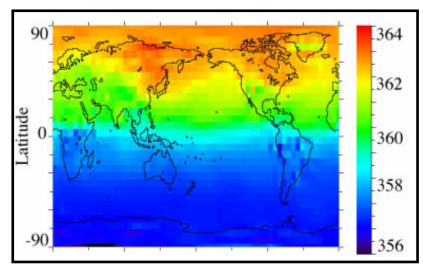


Ground Validation Sites









Data Products

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

Mission Architecture

Project Management (JPL)

- **Science & Project Team**
- **Systems Engineering, Mission Assurance**
- **Ground Data System**

Single Instrument (Hamilton Sundstrand)

- **3 high resolution grating spectrometers**

Dedicated Bus (Orbital Sciences)

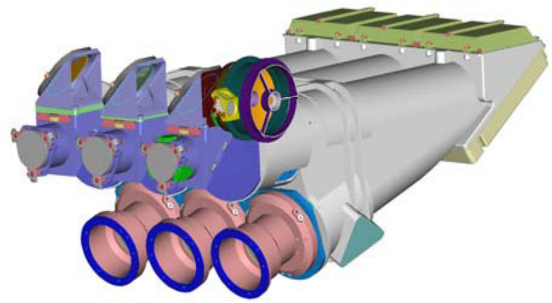
- **LEOstar2: GALEX, SORCE, AIM**

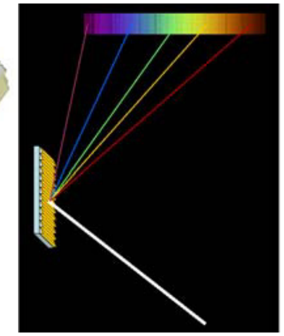
Dedicated Launch Vehicle (Orbital Taurus 3110)

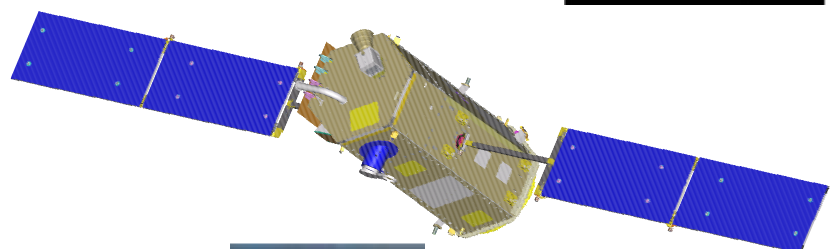
- **September 2008 Launch from Vandenberg AFB**

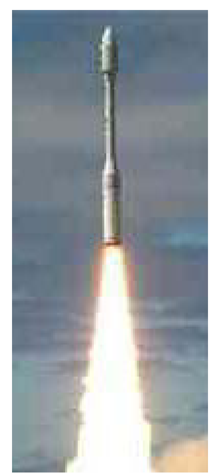
Mission Operations (JPL/Orbital Sciences)

- **NASA Ground Network, Poker Flats, Alaska**

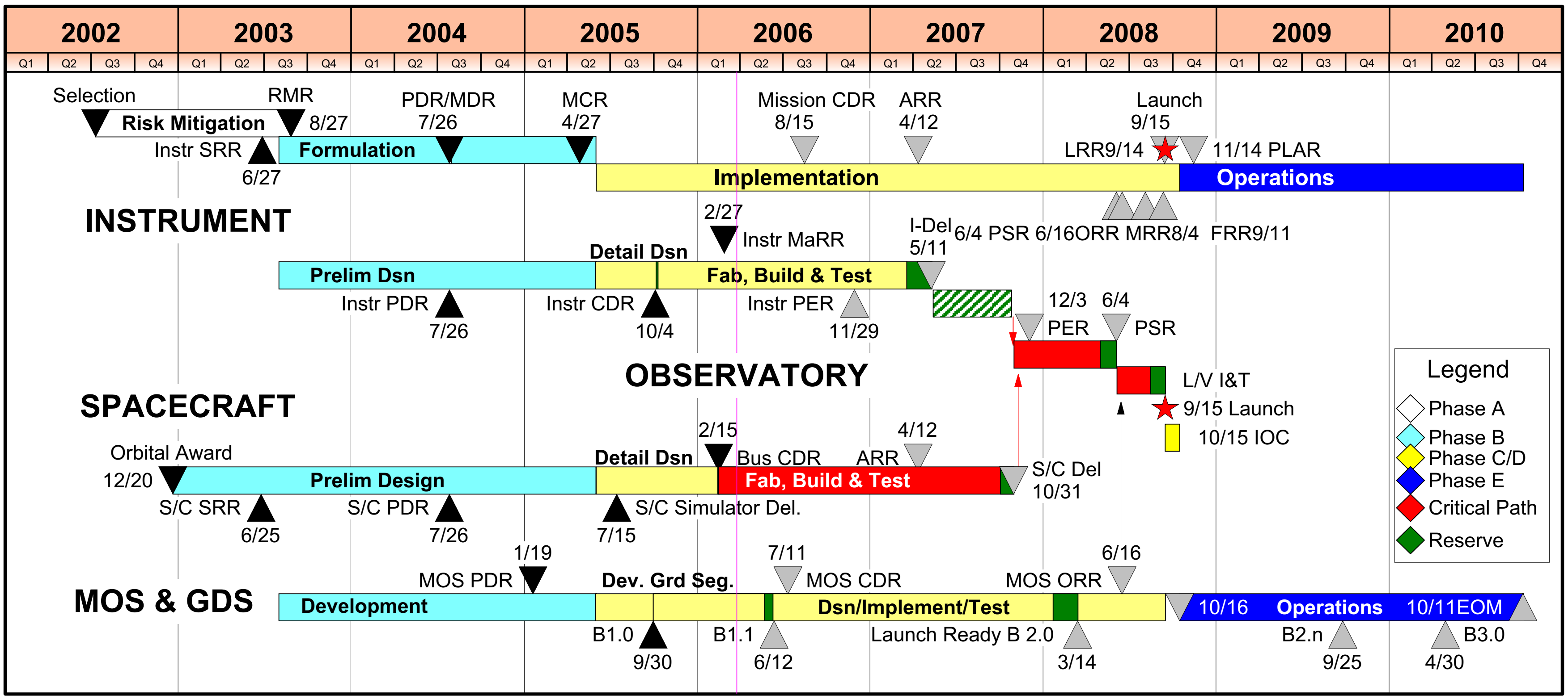








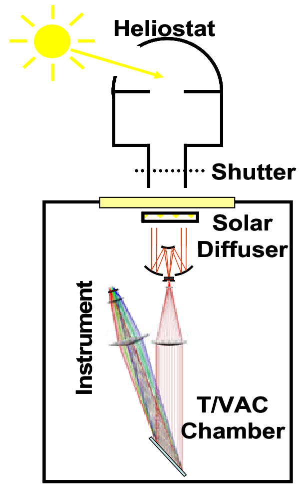
OCO Project MCR Schedule 9/15/08 Launch

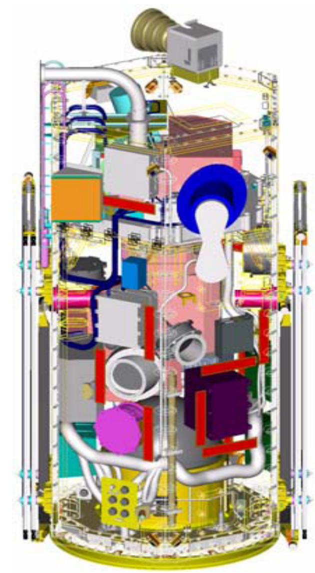


- ARR - ATLO Readiness Review
- CDR - Critical Design Review
- EOM - End Of Mission
- FRR - Flight Readiness Review
- GDS - Ground Data System
- I-Del - Instrument-Delivery
- PER - Pre-Environmental Review
- LRR - Launch Readiness Review
- L/V I&T - Launch Vehicle Integration & Test
- MCR - Mission Confirmation Review
- MDR - Mission Design Review
- MOS - Mission Operations System
- MRR - Mission Readiness Review
- MaRR - Manufacturing Readiness Review
- ORR - Operational Readiness Review
- PSR - Pre Ship Review
- PDR - Preliminary Design Review
- RMR - Risk Mitigation Review
- RTR - Risk Termination Review
- SRR - System Requirements Review

OCO Schedule

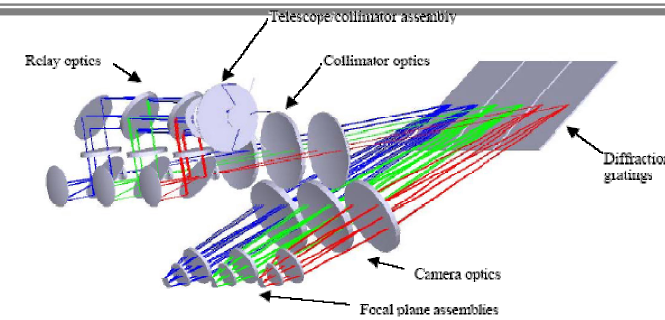
- 7/2001: Step-1 Proposal Submitted
- 2/2002: Step-2 Proposal Submitted
- 7/2003: Selected for Formulation
- 7/2004: System PDR
- 5/2005: Mission Confirmed for Implementation
- 10/2005: Instrument CDR
- 12/2005: OCO selected as ESA 3rd Party Mission
- 2/2006: Spacecraft CDR
- 3/2006: 4th OCO Science Team Meeting
- **7/2006: MOS/GDS CDR**
- **8/2006: System CDR**
- **2-4/2007: Instrument Testing**
- **5/2007: Instrument Delivery to SC**
- **10/2007: Observatory Integration begins**
- **6/2008: Launch Vehicle Integration begins**
- **9/2008: Launch from VAFB**
- **10/2010: End of Nominal Mission**

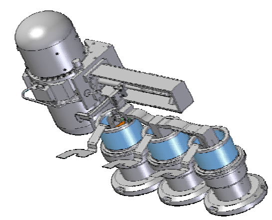


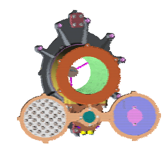


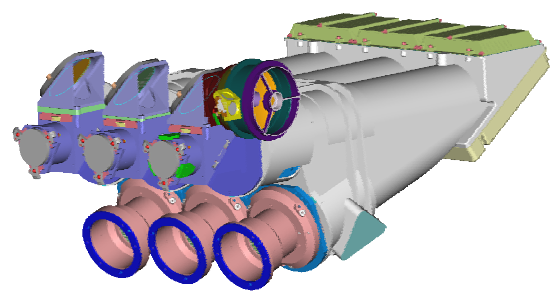
OCO Instrument Status

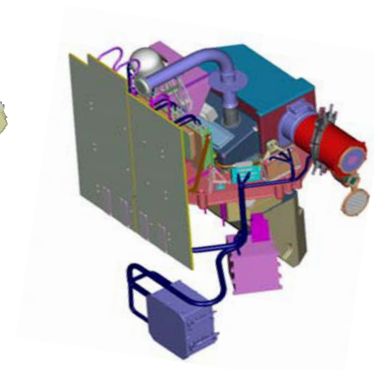
- Instrument Design Complete
  - Instrument CDR October 2005
- Electronics boards testing – March – May 2006
- OBA casting delivered – March 2006
- Detector tests – May 2006
- Cryosystem delivery – May 2006
- Gratings delivery – Summer 2006
- Detector delivery – Summer 2006
- Instrument integration – Summer/Fall 2006
- Instrument delivery to JPL – Nov 2006
- Final alignment – Dec 2006
- Engineering tests – Jan 2007
- CPT 1 (calibration)– Feb 2007
- Environmental tests – March 2007
- CPT 2 (calibration) – April 2007
- Instrument Delivery – May 11 2007











OCO Science Team Meeting #4
21 – 23 March 2006

Jet Propulsion Laboratory
California Institute of Technology

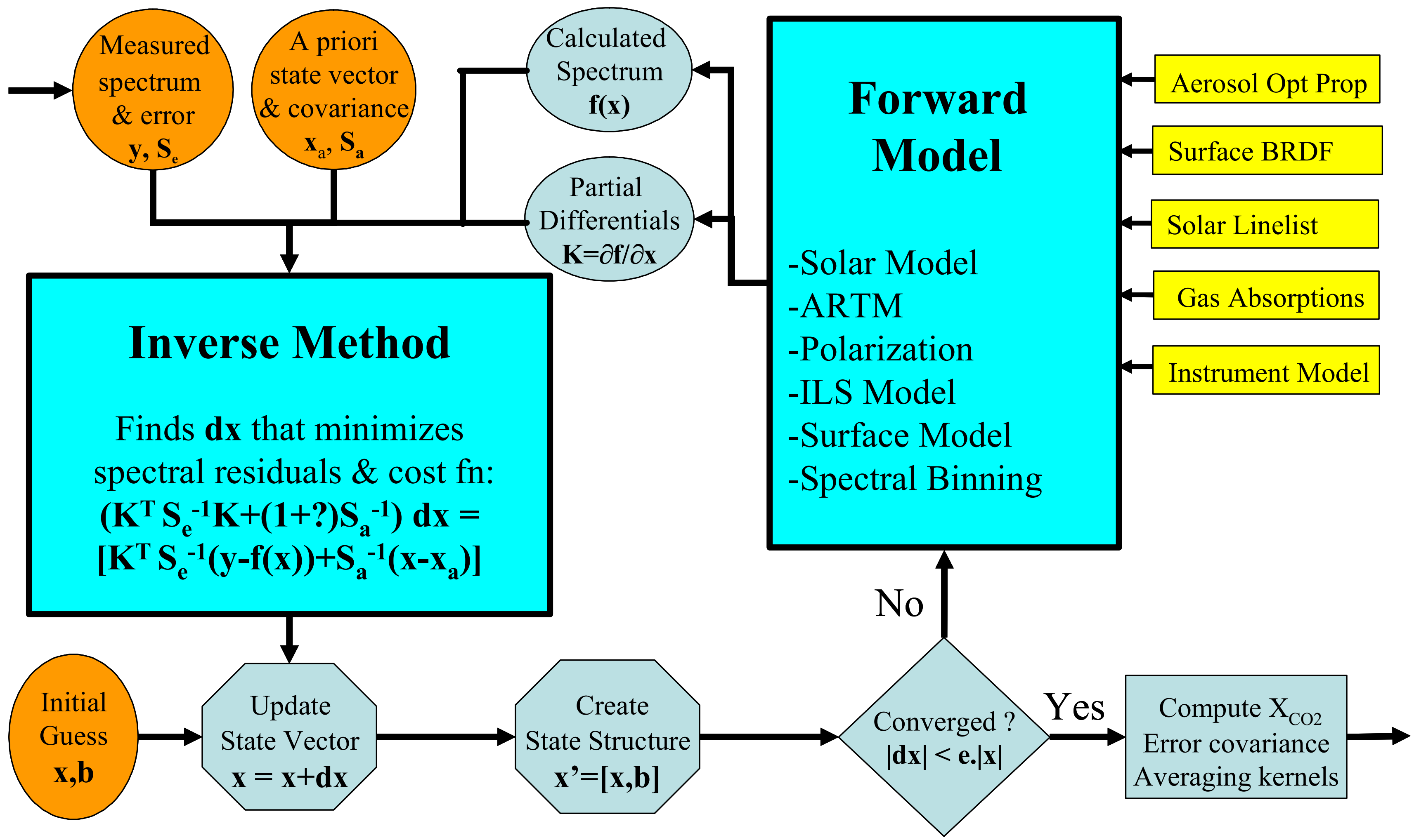




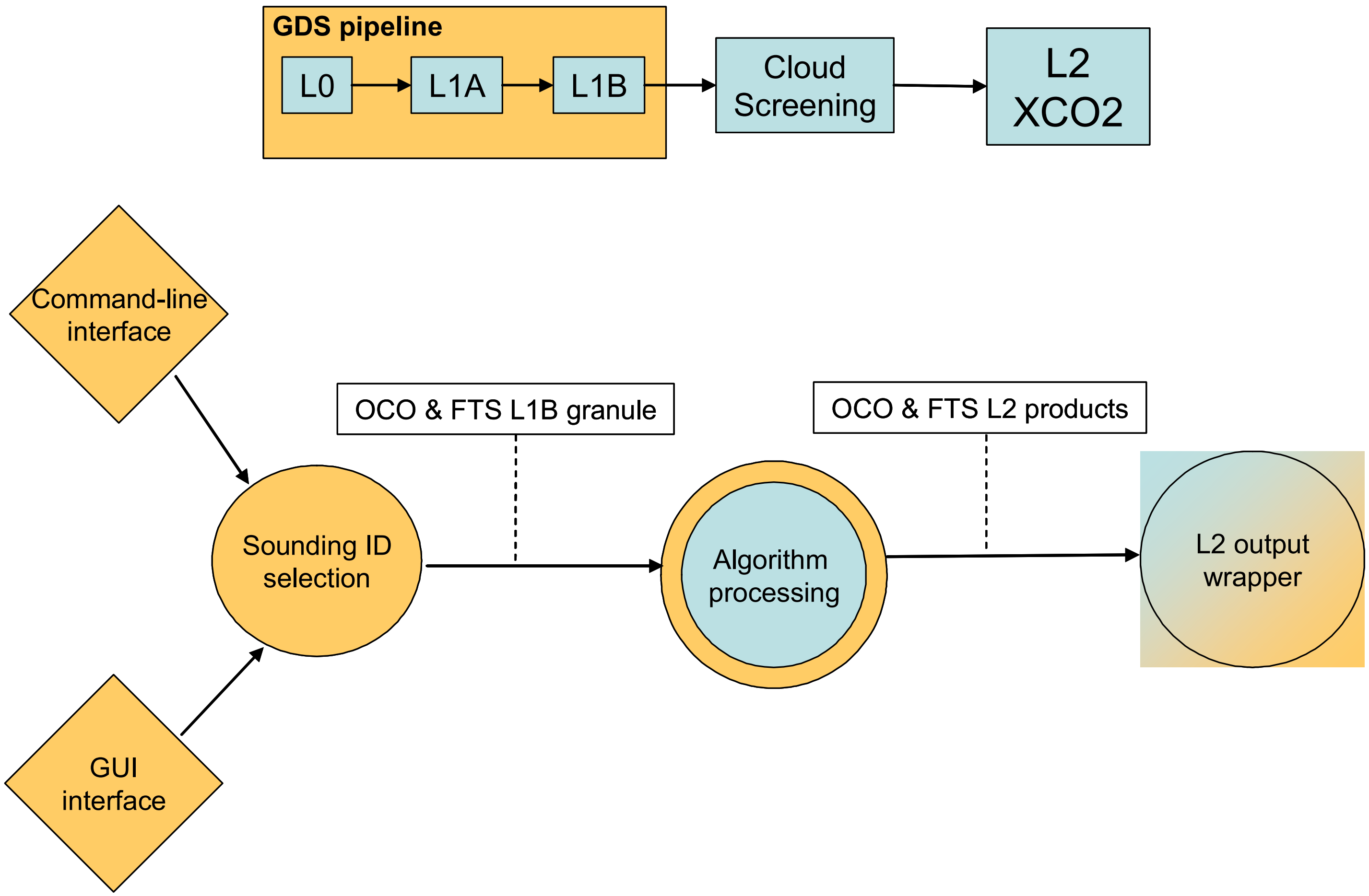




Retrieval Algorithm Design



X_{CO2} Retrieval Processing Flow

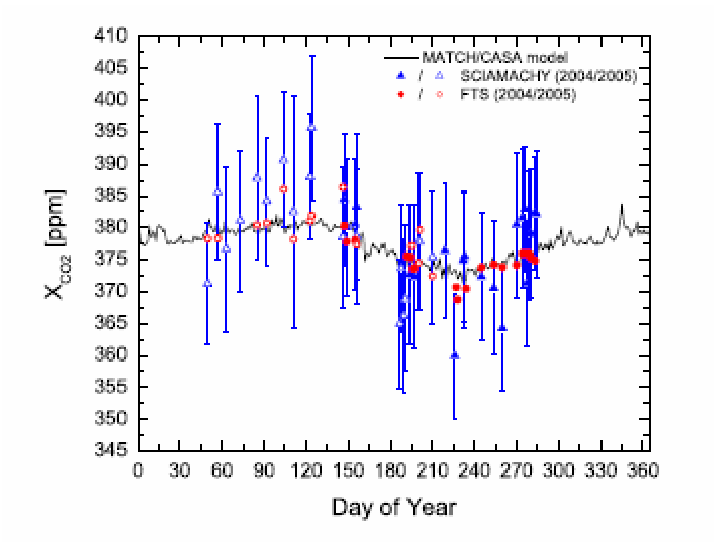


Early Testing and Validation with SCIAMACHY and FTS Data Reduce Algorithm Risks

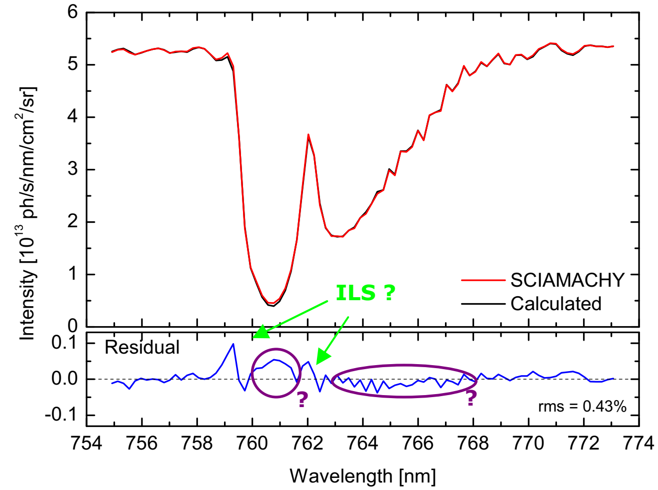
Space-based Near-infrared CO_2 Retrievals: Testing the OCO Retrieval and Validation Concept Using SCIAMACHY Measurements over Park Falls, Wisconsin

H. Bösch[1], G. C. Toon[1], B. Sen[1], R. Washenfelder[2], P. O. Wennberg[2], M. Buchwitz[3], R. de Beek[3], J. P. Burrows[3], D. Crisp[1], M. Christi[4], B. J. Connor[5], V. Natraj[2], and Y. L. Yung[2]

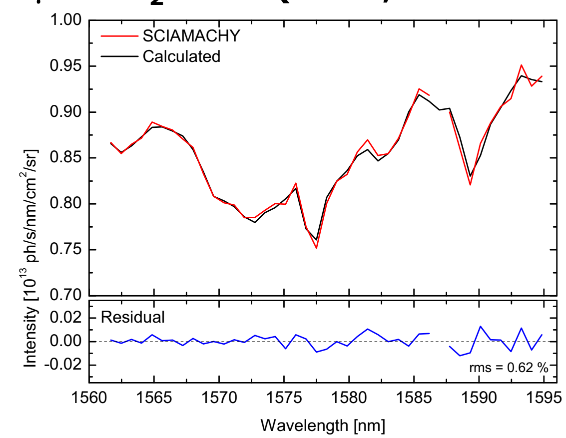
Submitted to *J. Geophys. Res.*, Feb 2006



O_2 A-band (Ch. 4, FWHM = 0.5 nm)



1.58 µm CO_2 band (Ch. 6, FWHM = 1.5 nm)

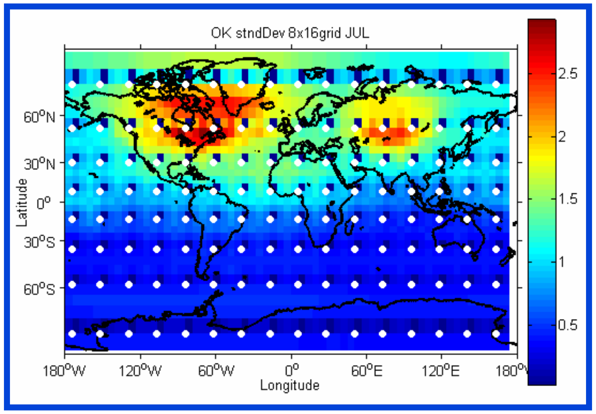


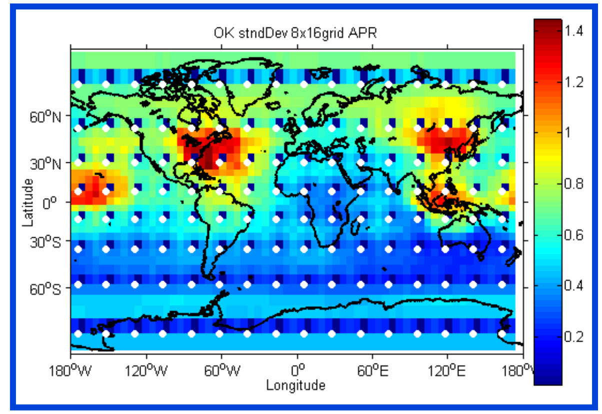
X_{CO2} Sampling Strategy
A. Michalak, University of Michigan

Jet Propulsion Laboratory
California Institute of Technology

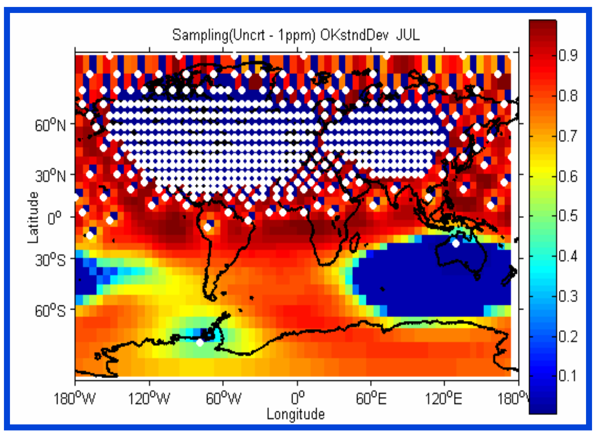
Clever sampling strategies will improve the XCO2 product and require the processing of fewer soundings

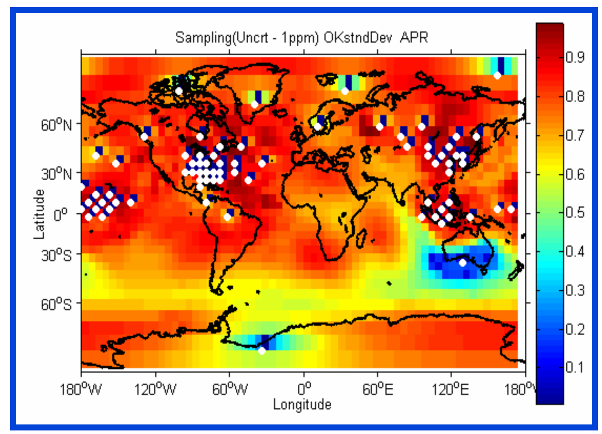
Naïve sampling strategy leaves large regional X_{CO2} errors



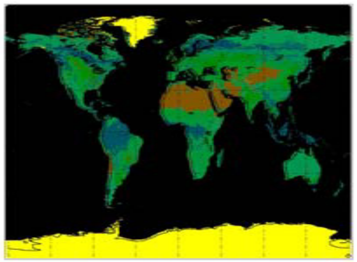


Statistically driven sampling strategy reduces regional X_{CO2} errors below 1 ppm





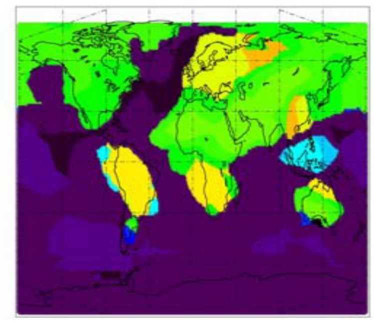
Global Simulations of OCO Data
H. Boesch, JPL

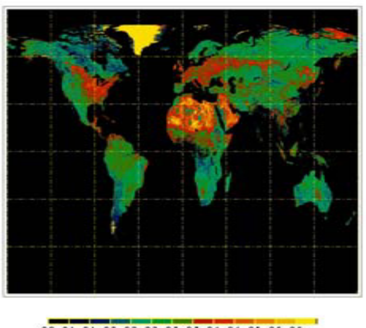


Surface Type: MODIS L3 product (annual average)

AIRS Orbit:
- Lat/Lon/Time
- **Temperature** profile
- **H_2O** profile
- **Surface pressure**

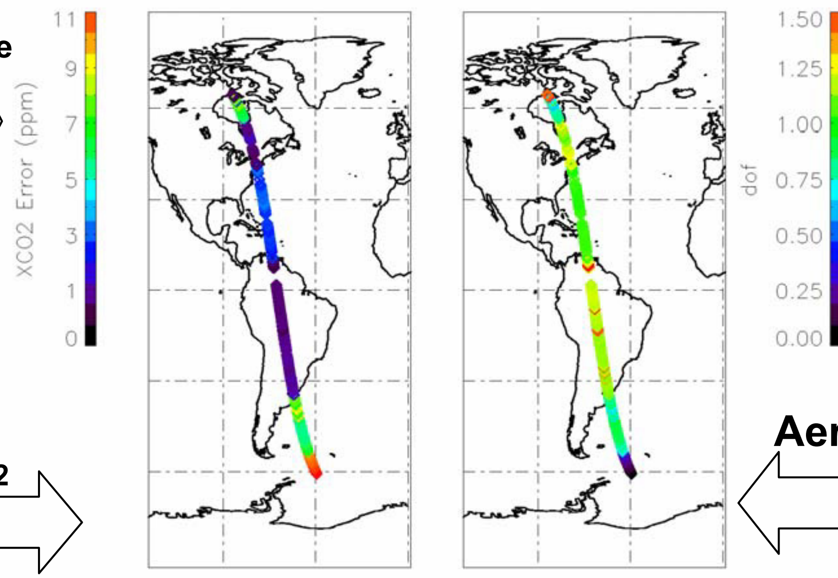
Optical Properties: MISR Aerosol Type Climatology

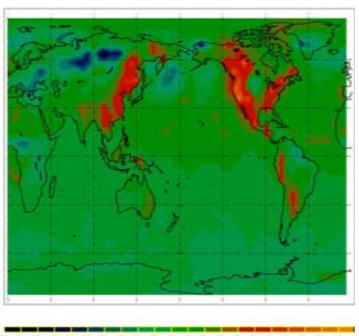




Surface

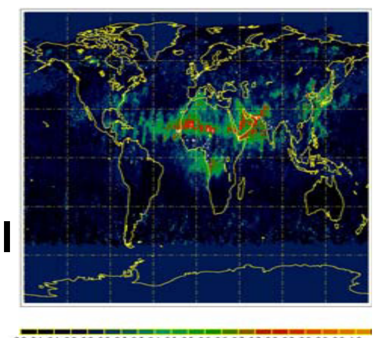
Surface Albedo: MODIS L3 product (16 day average)





CO_2

Aerosol

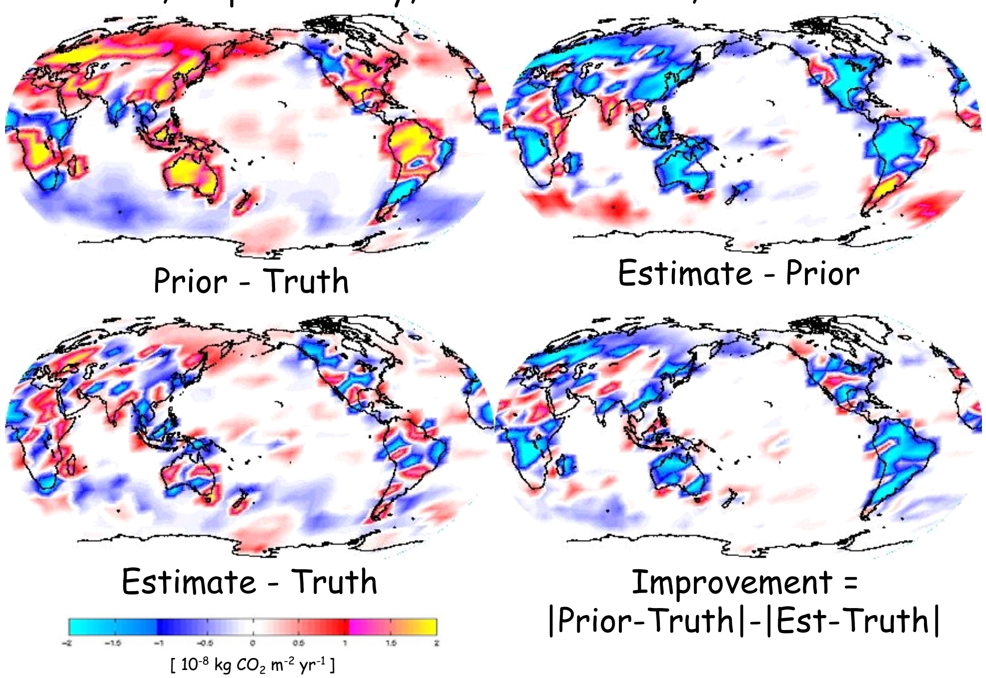


OD: MISR L3 Product (monthly average)

July 1 , 2005

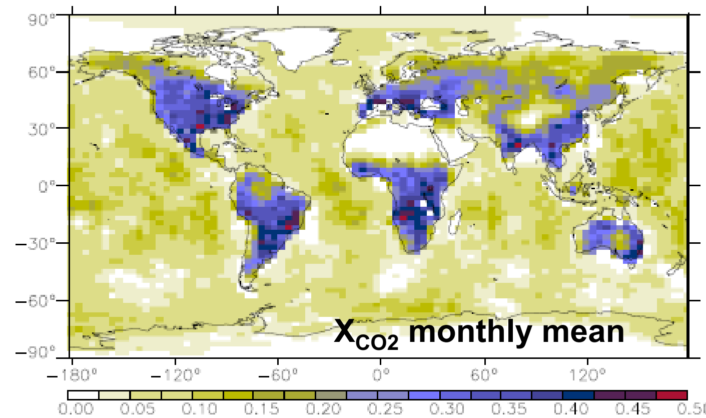
Impact of OCO X_{CO2} Data on Source/Sink Modeling

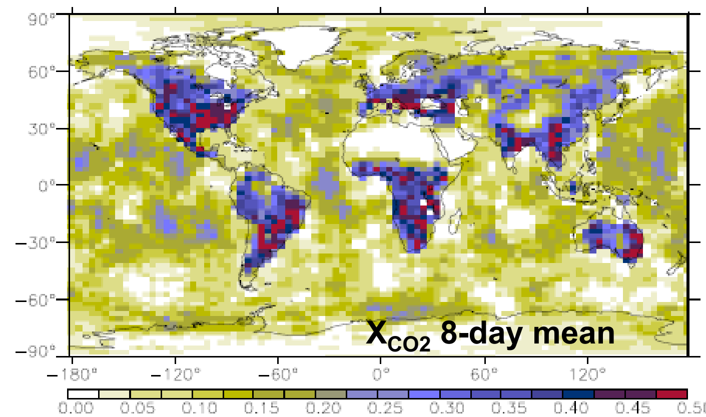
W/ noise, w/ prior: 5-day, 6°x10° resolution, reduced error



Significant improvement in CO_2 flux estimates can be achieved with OCO X_{CO2} data accumulated over 5-day periods.

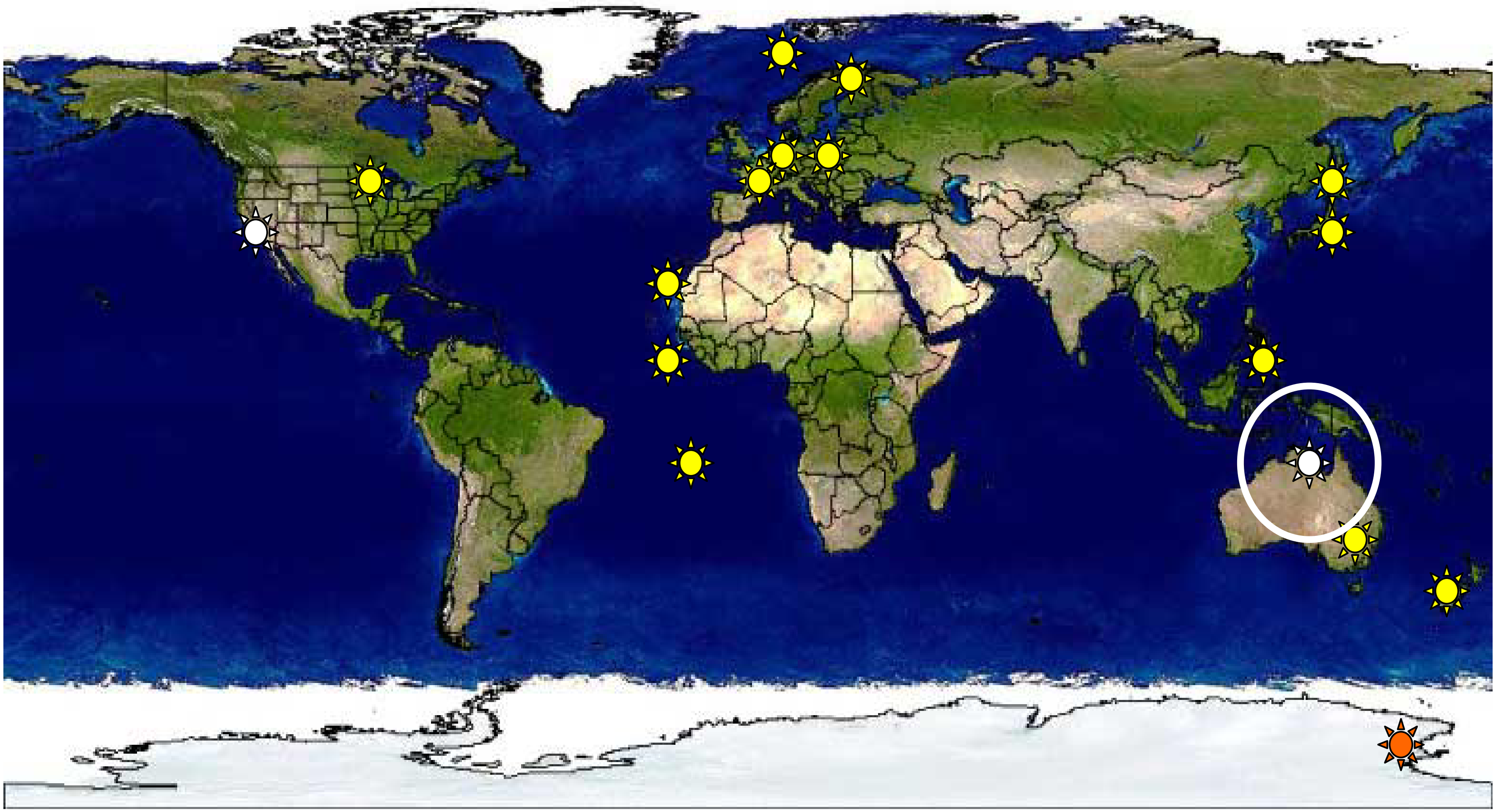
D. Baker (NCAR), S. Doney (WHOI)



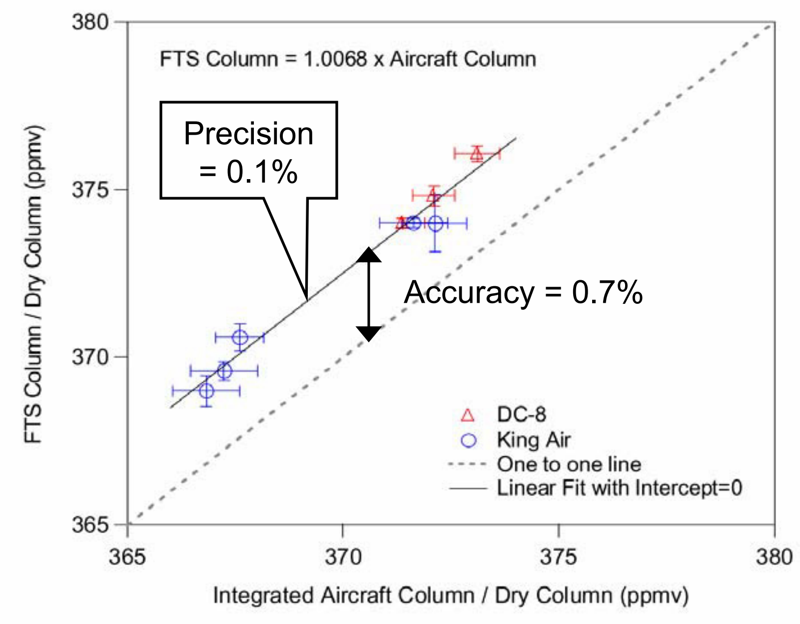


Up to 40% error reduction in CO_2 fluxes.
Chevallier, Rayner and Breon, LSCE

Establishing a Global FTS Network to Link Space-based X_{CO2} to WMO Standards



Pre-launch FTS X_{CO2} Validation
Park Falls, USA

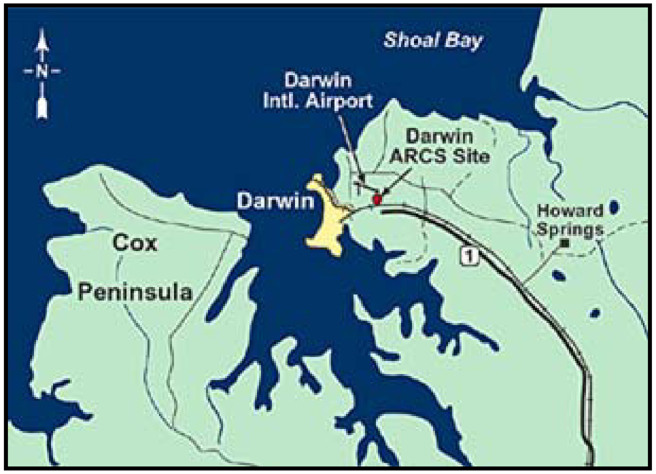


Validate FTS X_{CO2} by aircraft overflights

Required Precision = 0.3%

Mission	Date	Site	Precision	Accuracy
INTEX	**Jul 2004**	**Park Falls**	**0.1%**	**0.68%**
COBRA	**Aug 2004**	**Park Falls**	**0.1%**	**0.68%**
TWP ICE	**Jan 2006**	**Darwin**	**13 profiles on 12 days!**	

OCO FTS Mobile Laboratory
Deployed @ Darwin TWP ARM Site

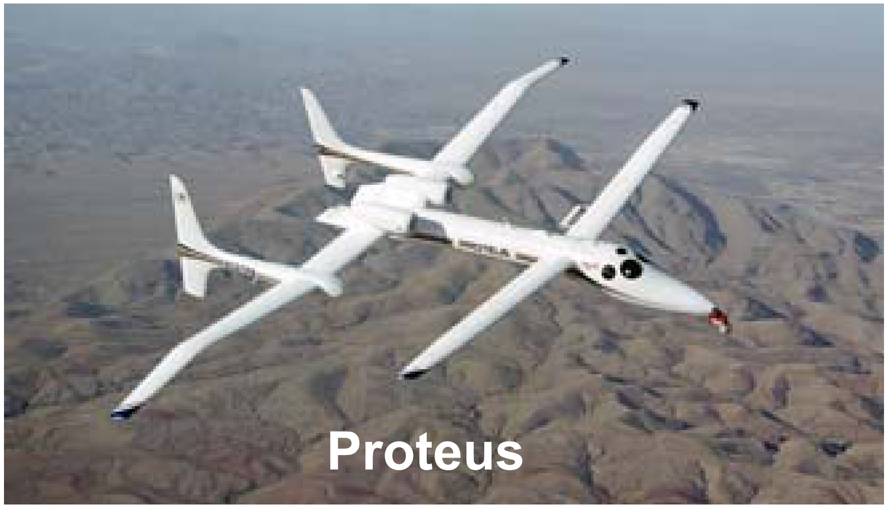


OCO FTS Mobile Laboratory
Deployed @ Darwin TWP ARM Site

FTS Mobile Lab installation at the Darwin ARM-TWP site

- Rebecca Washenfelder, Yael Yavin (Caltech) and Nick Deutscher, David Griffith (Wollongong)
- Testing: Sep – Dec 2005
- Aircraft in situ validation overflights during Jan 2006
- Operations: Feb 2006 - EOM

Pre-launch FTS Validation - Darwin



Jan/Feb 2006: TWP/ICE Campaign

Proteus aircraft (ceiling >15 km) carrying COBRA in situ CO_2 sensor over Darwin TWP site

Comparison against FTS X_{CO2} retrievals will validate this station

In situ CO_2 measured over Darwin FTS

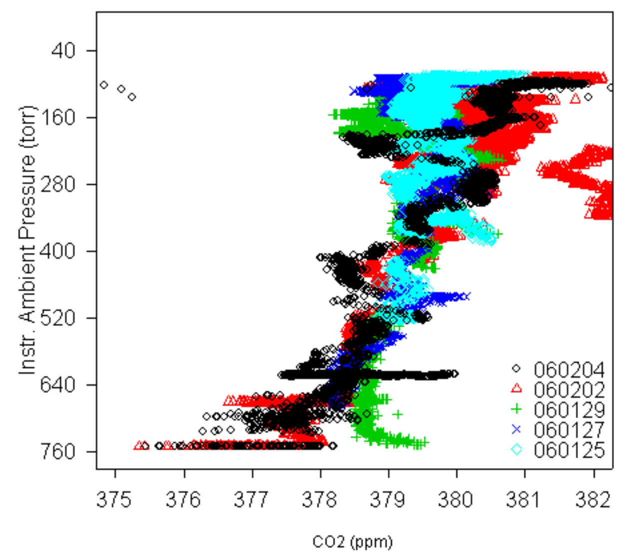
Wofsy instrument (DOE Proteus):

- 2 flights dedicated to FTS validation
  - 2 and 4 Feb 2006
- 3 flights of opportunity
  - 27, 29, and 31 Jan 2006

Volk instrument (ESA Geophysica):

- 8 flights of opportunity
  - 12, 19, 23, 25, 29, 30 (two flights) Nov 2005 and 6 Dec 2005

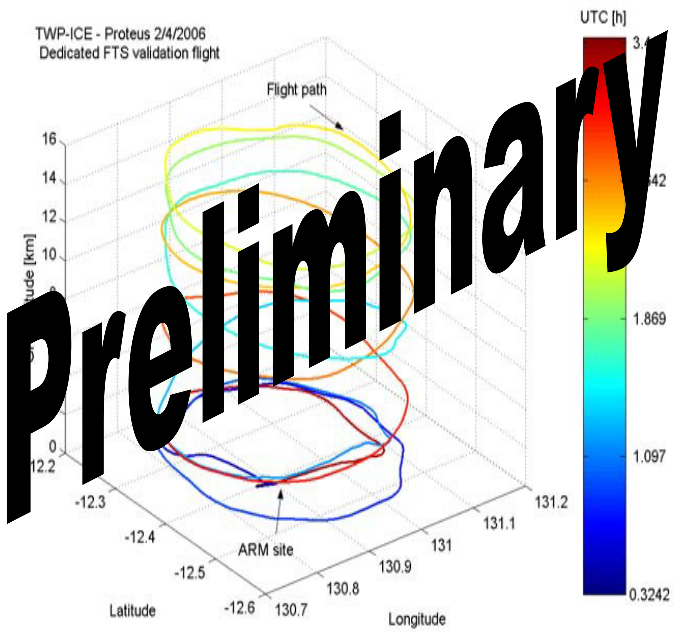
Wofsy et al. in situ CO_2 profiles

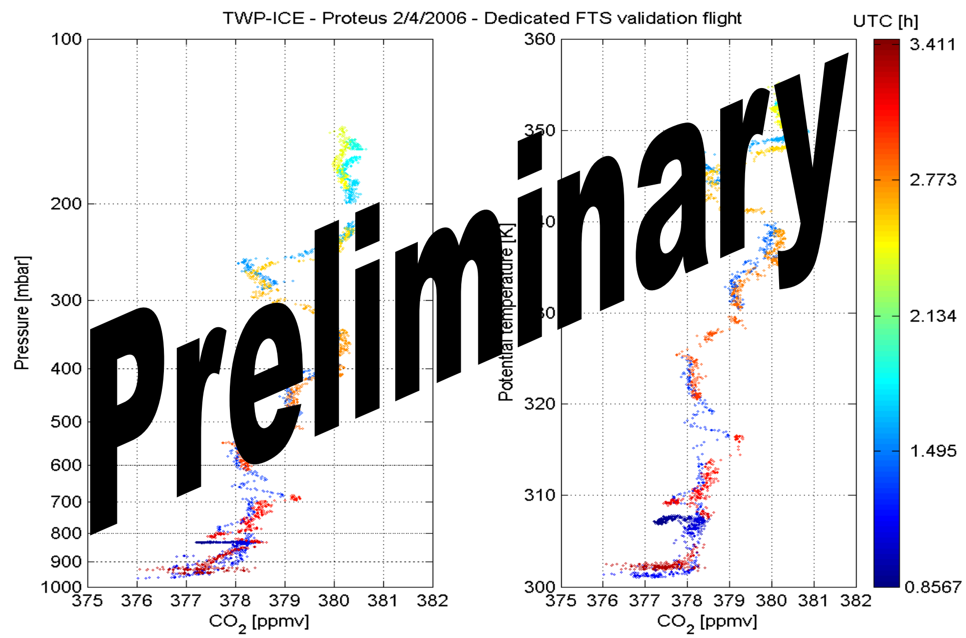


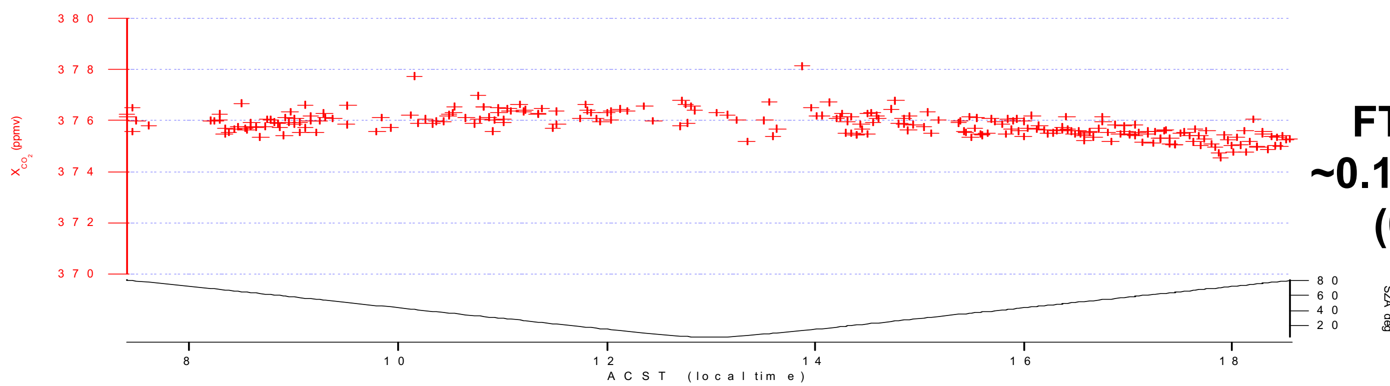
These in situ CO_2 profiles will yield excellent inter comparisons with ground based FTS measurements of X_{CO2}

The OCO validation team is very pleased with the results of the Darwin overflight campaign, and looks forward to showing results at an upcoming MMR

Darwin FTS Pre-launch Validation
4 Feb 2006







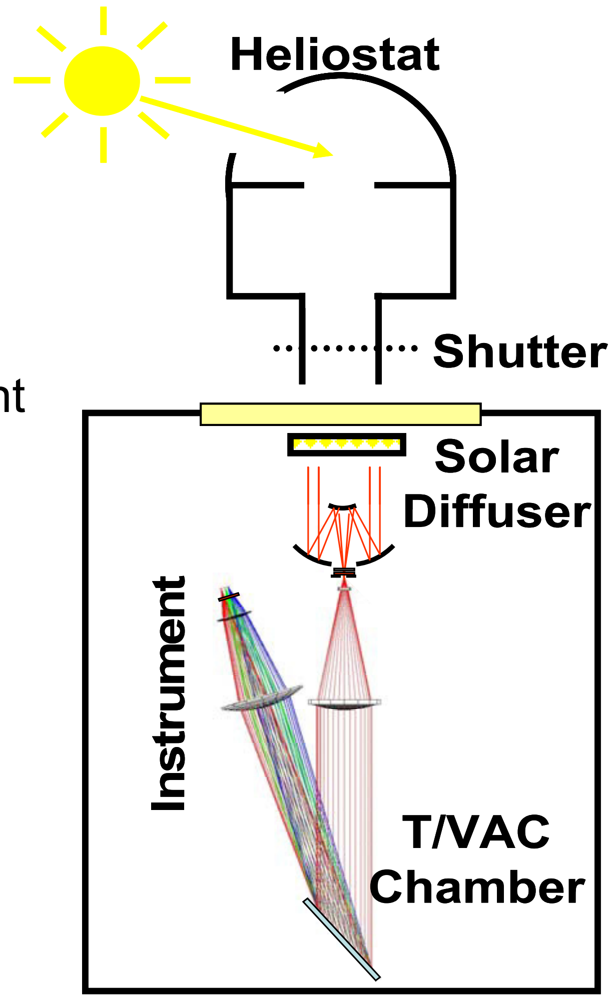
FTS X_{CO2}
~0.1 ppm rms
(0.03%)

Side-by-Side FTS/Flight Instrument Testing Establishes a Calibration Transfer Standard

Acquire solar spectra simultaneously with the OCO flight instrument and one of the FTS

Validate flight instrument performance for real atmospheric data

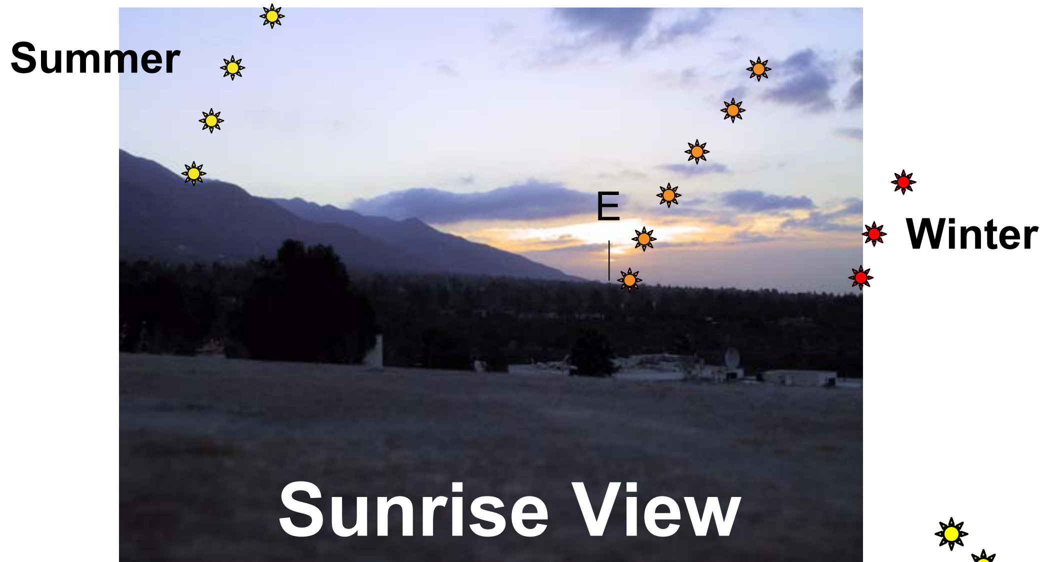
Verify that the OCO retrieval algorithm contains an accurate instrument model

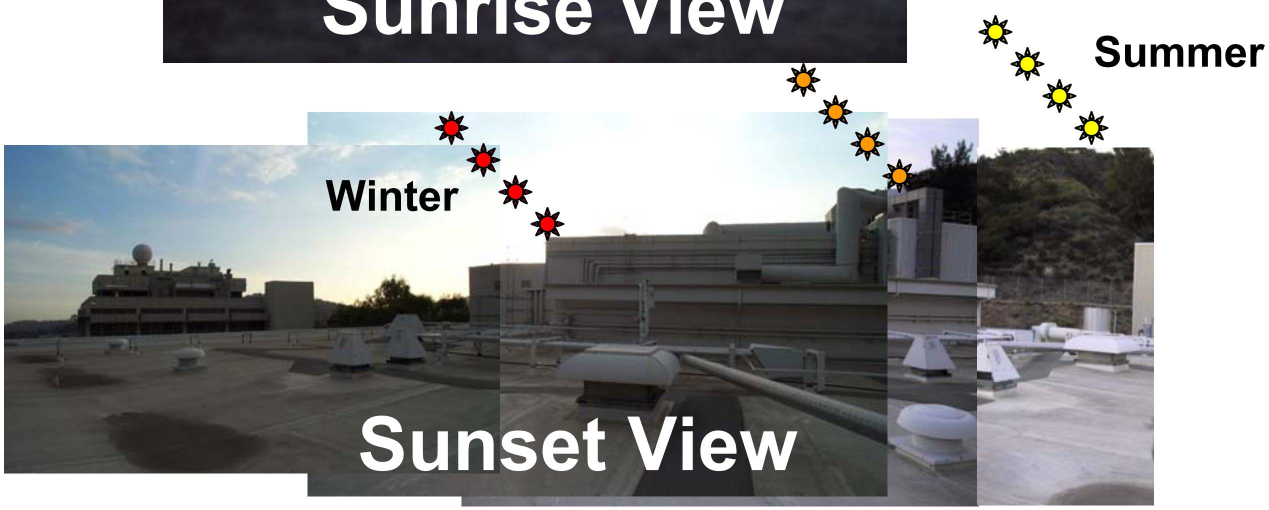


View towards East from #1 FTS site; from roof of container, none of the buildings will obscure view. We will be able to measure during sunrise in February, during April, the mountains will obscure early morning sun.

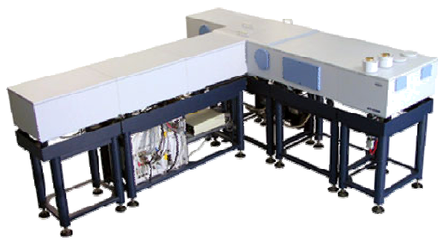
View to the North from #1 FTS site. The tops of neighboring containers/buildings will not be an obstruction to the suntracker on the roof. We are told that the sun sets between the storage tank and the building to its left.

Heliostat Sunrise and Sunset Views

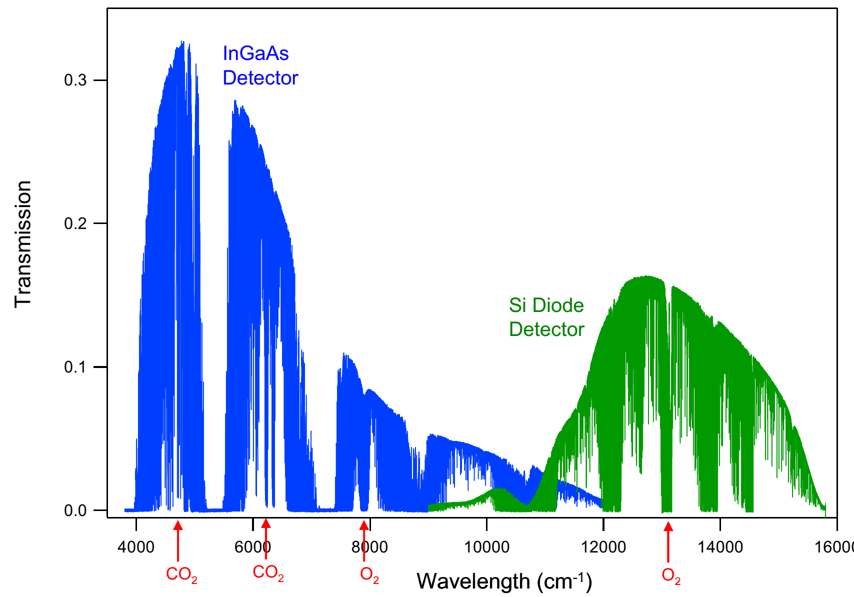




Rigorous Spectroscopy Testing Using Atmospheric Remote Sensing Data



Bruker 125 HR deployed in a solar-viewing mobile laboratory, Park Falls WI



Single spectrum, 9:30 am, 9 Sept 2004.
Resolution = 0.02 cm^{-1}.

Spectroscopic Parameter Requirements for CO_2 Atmospheric Remote Sensing

Parameter	Mid-IR Remote Sensing Precision Requirement	OCO Remote Sensing Precision Requirement
Column CO_2 uncertainty	Best Effort	< 0.3%
Range	600 – 2500 cm^{-1}	4000 – 6500 cm^{-1}
Line position unceretainty	0.0003 cm^{-1}	<0.0002 cm^{-1}
E" uncertainty	0.5%	<0.1%
Line Intensity uncertainty	< 3%	0.3%
Lorentz Width uncertainty	< 3%	0.6%
Pressure Shift uncertainty	< 0.0003 cm^{-1} atm^{-1}	< 0.0002 cm^{-1} atm^{-1}
Line Mixing	Q-branches only	P-, Q- and R-branches

Existing Spectral Databases Do Not Provide Sufficient Accuracy for CO_2 Remote Sensing

3 retrievals of the same CO_2 spectrum using the most recent versions of the HITRAN database

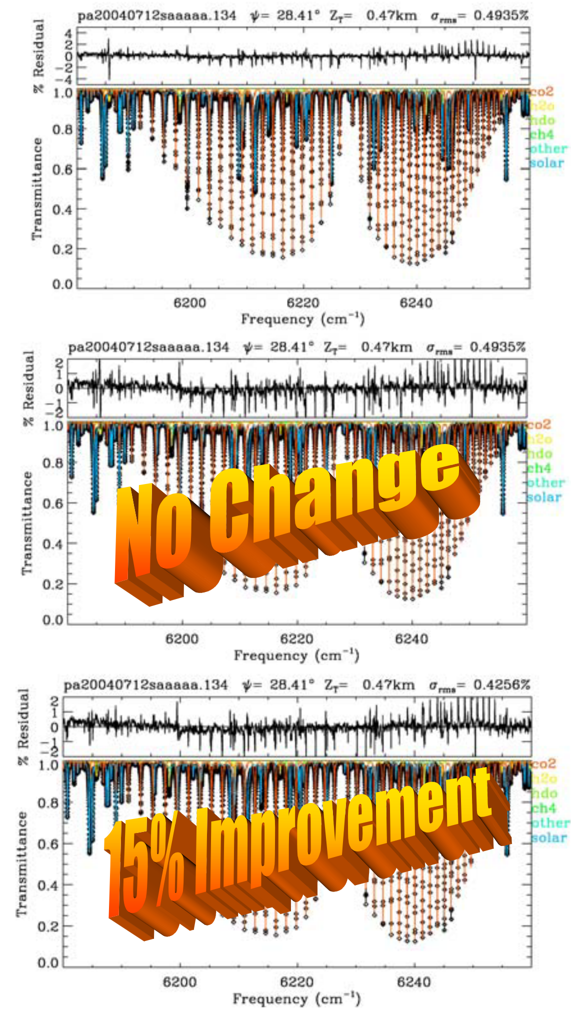
- HITRAN 1996 provides the benchmark
- No Change found using HITRAN 2000
- 15% improvement in the rms residual when using HITRAN 2004

Fit using HITRAN 2004 still exhibits persistent systematic errors in intensities throughout the band

HITRAN 1996

HITRAN 2000

HITRAN 2004



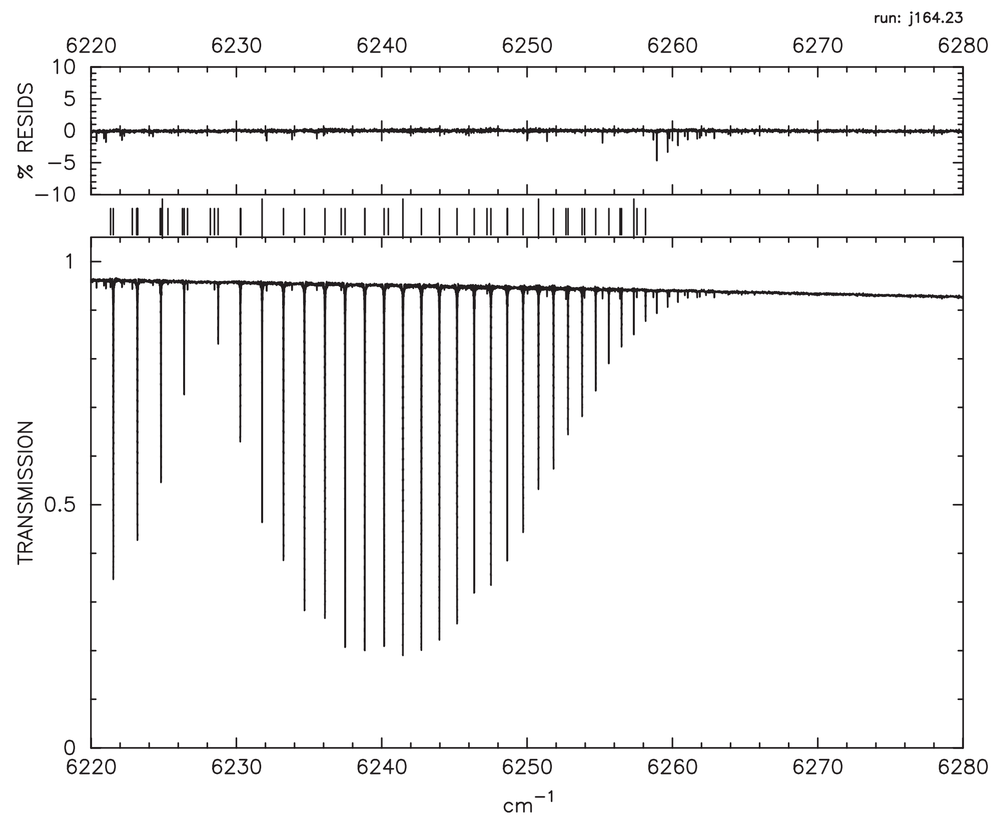
New CO_2 Spectroscopic Database Developed from New Laboratory Data

New data acquired with excellent knowledge and control of the experimental state

- Temperature
- Pressure
- Composition
- Path length

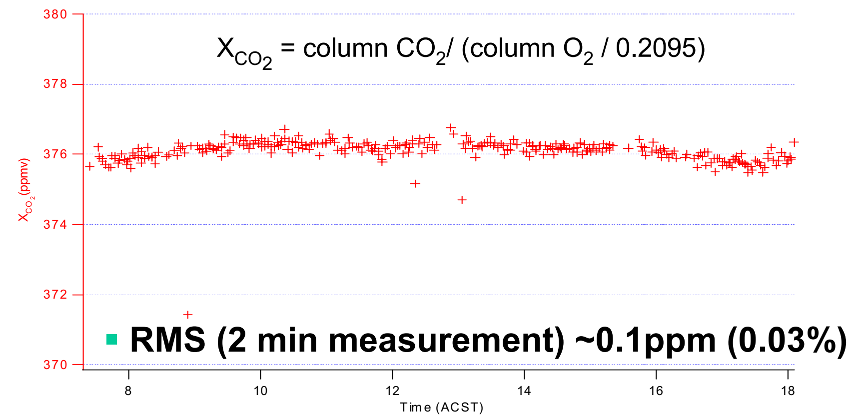
Spectroscopic parameters determined using standard fitting methods (Toth et al.)

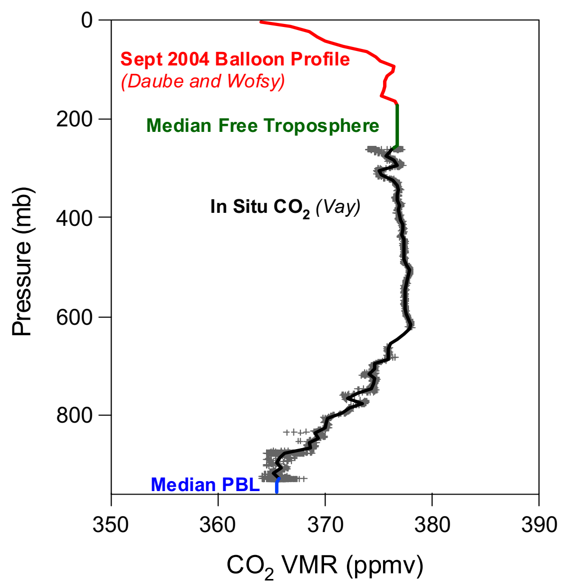
Small residuals from unfit lines due to weak CO_2 hot bands and isotopologues ($^{13}CO_2$)

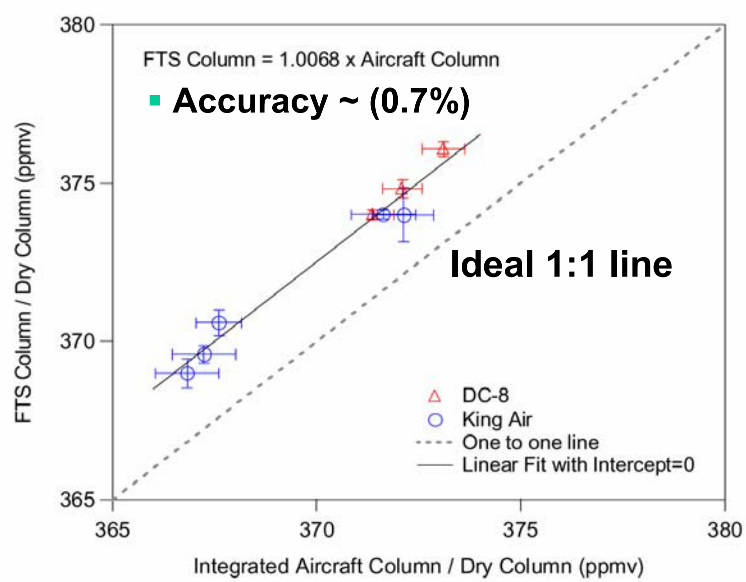


Atmospheric Remote Sensing Retrievals Show Excellent Precision and Accuracy

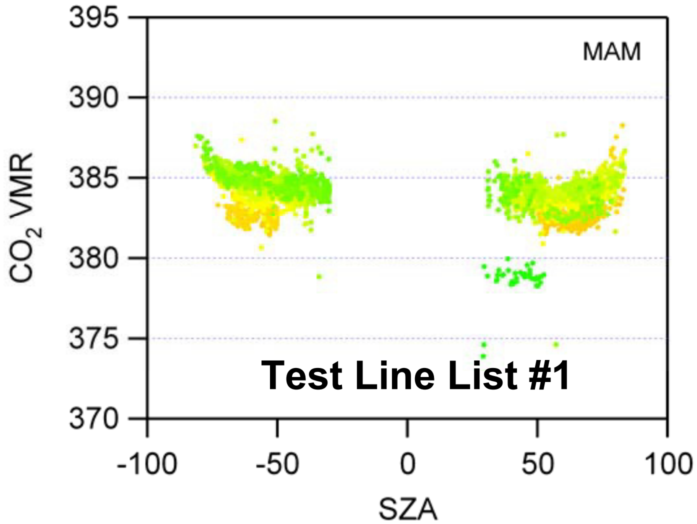
- Precision and accuracy demonstrate spectroscopic parameters are high quality
- FTS X_{CO2} retrievals validated against integrated CO_2 column obtained from in situ CO_2 sampling during aircraft over flights of the FTS site

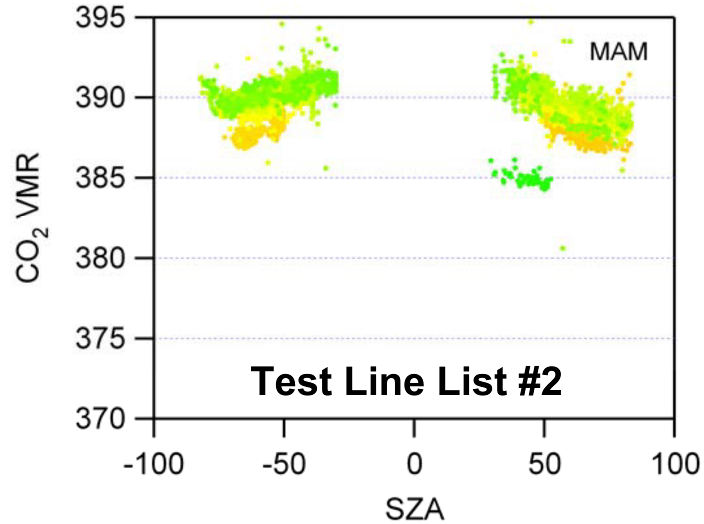




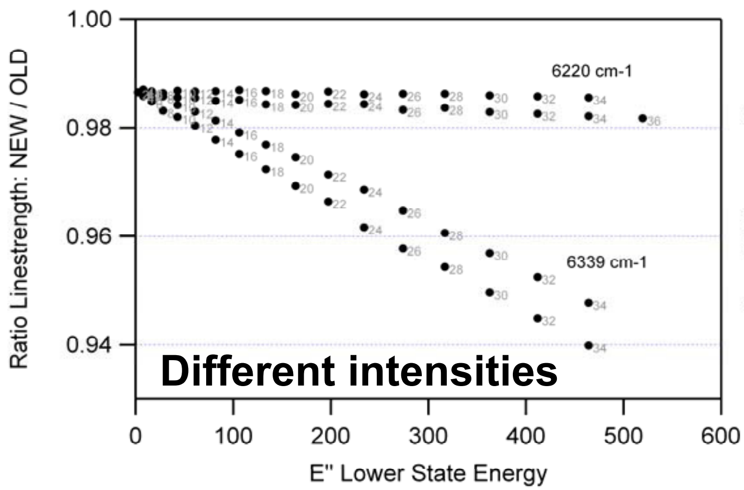


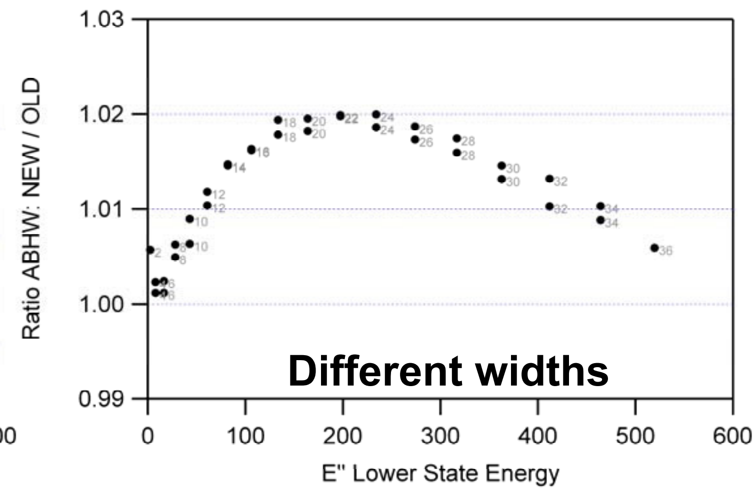
Airmass-dependent Effects Observed for Small Changes in Strengths & Widths





MAM = March April May (2005)





Non-Voigt Line Shapes Yield Different Width Parameters for Same Spectral Data

Compare retrievals from two methods

Constrained Multispectrum vs unconstrained

(Line Mixing + non-Voigt) (Voigt)

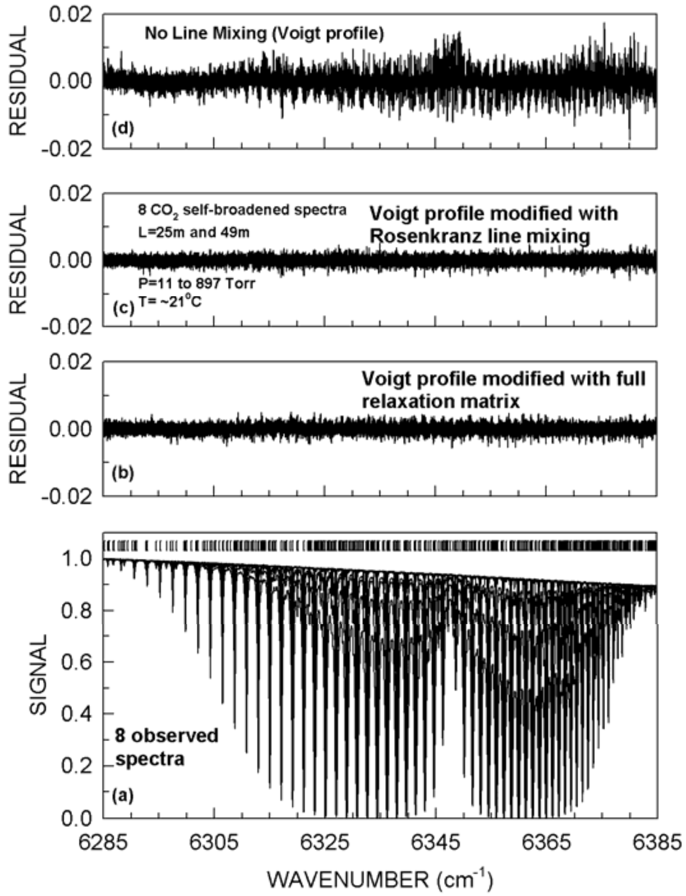
Average Differences in Retrievals

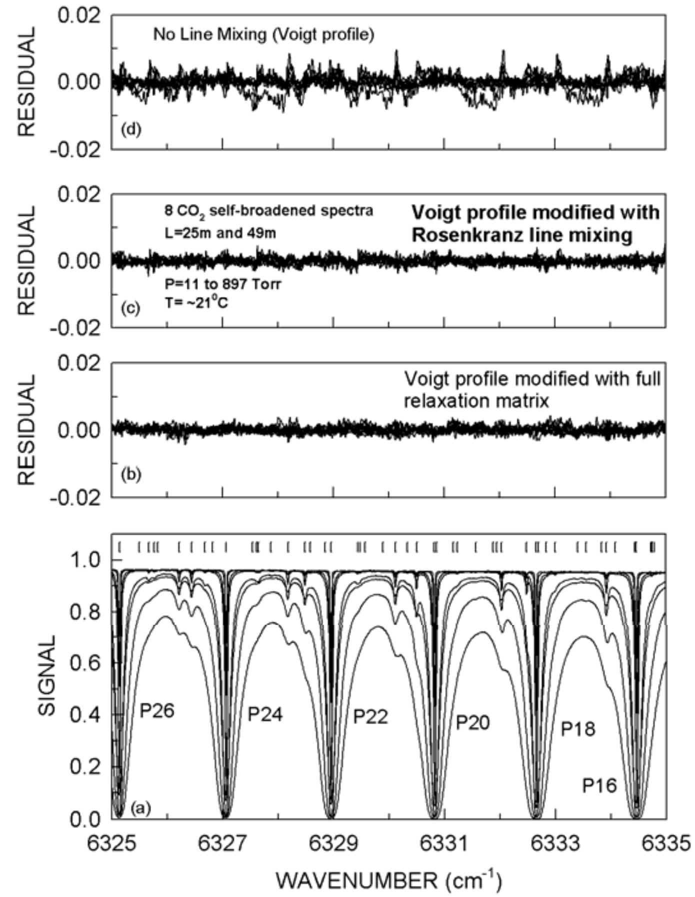
Intensities	(self-) widths
0.25%	1.52%

Miller et al., manuscript in preparation

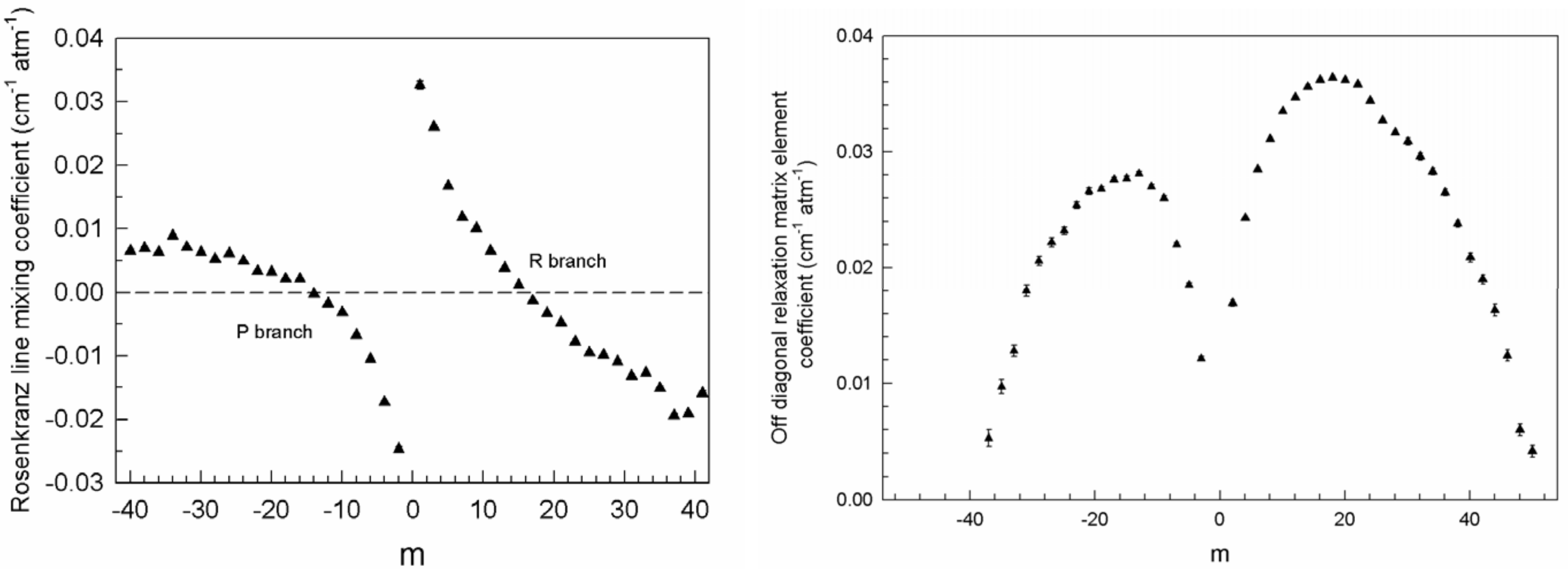
Devi et al., manuscript in preparation

Line Shape Choice Affects Simulations of Laboratory Data





CO_2 Line Mixing Coefficients



- Line mixing observed in the 6220 even though this band has no Q-branch, no perturbations and adjacent lines are spaced by ~ 1 cm^{-1}

Multispectrum Fitting
Benner et al., *JQSRT* 53, 705 (1995)

- Fit all lines and spectra simultaneously
- Use physical constraints for positions and intensities
- Increases sensitivity to subtle effects in line shapes
- Updated capabilities include non-Voigt line shapes, line mixing, speed dependence (Benner et al., in preparation)

Line Positions:

$n_i = n_0 + B(J(J+1)) + D(J(J+1))^2 + H(J(J+1))^3 + \ldots$

n_i resonant frequency

n_0 band origin

B, D, H rotational constants

J rotational quantum number

Line Shape Parameters:

$\gamma i = a_1 + a_2 m + a_3 m^2 + a_4 m^3 + \ldots$

Measured half-width at half-max at each line position

Line Intensities:

$S_i = (\nu_i/\nu_0)(S_v/L_i) \exp(-hcE_i''/kT)[1-\exp(hc\nu_i/kT)].F$

S_i, observed individual line intensity

S_v vibrational band intensity,

L_i Hönl-London factor, where $l_i = (m^2 - l''^2)/|m|$ for CO_2

$m = J''+1$ for the R branch, $m = -J''$ for the P branch

J'' lower-state rotational quantum number.

l angular momentum quantum number.

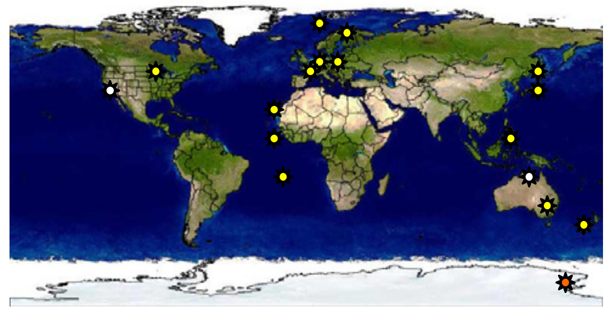
Q_r lower state rotational partition function at T0=296 K

E_i'' lower state rotational energy

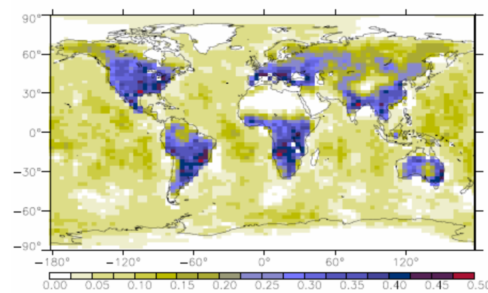
F Herman-Wallis factor $= [1+A_1 m+A_2 m^2+A_3 m^3]$

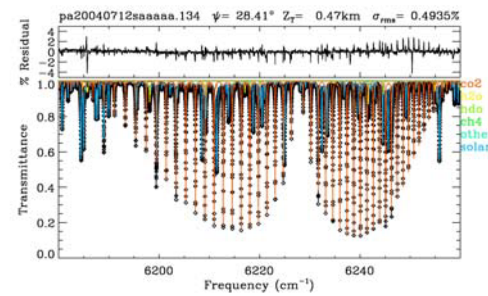
Opportunities for Cooperation

- Sub-orbital calibration of space-based data



- Simulation and modeling of space-based X_{CO2} data





- Spectral line databases

- Data archive and distribution