# Laser Sounder for Measurements of Atmospheric CO2 Concentrations for the ASCENDS Mission

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# Outline

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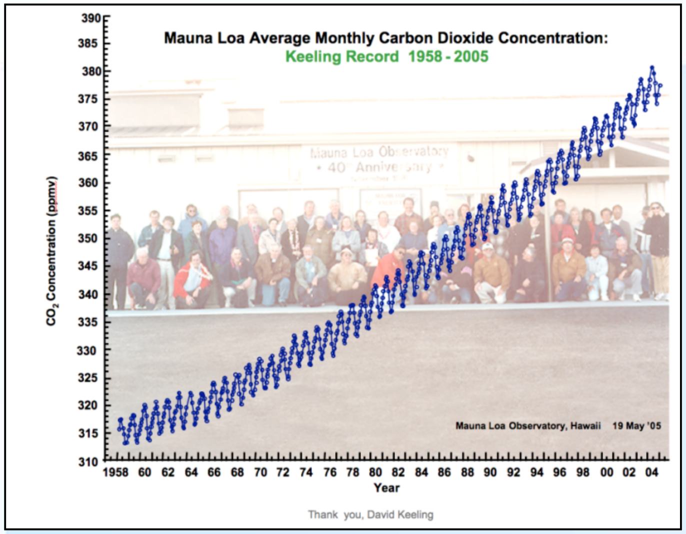
- Carbon Cycle and $CO_2$
- $CO_2$ Measurements from space: Passive and Active measurements
- $CO_2$ measurement requirements
- Laser Sounder approach and error sources
- Field measurements with breadboard sounder
- Airborne demonstration
- Oxygen measurements
- Technology development
- ASCENDS precursor and Space instrument

# Atmospheric $CO_2$ & Earth's Carbon Cycle

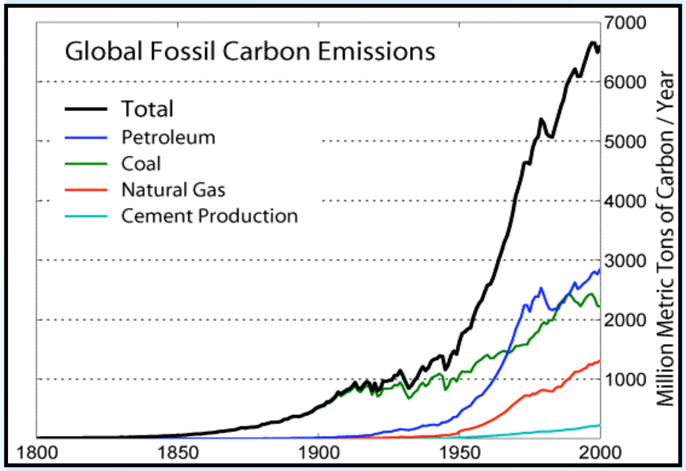


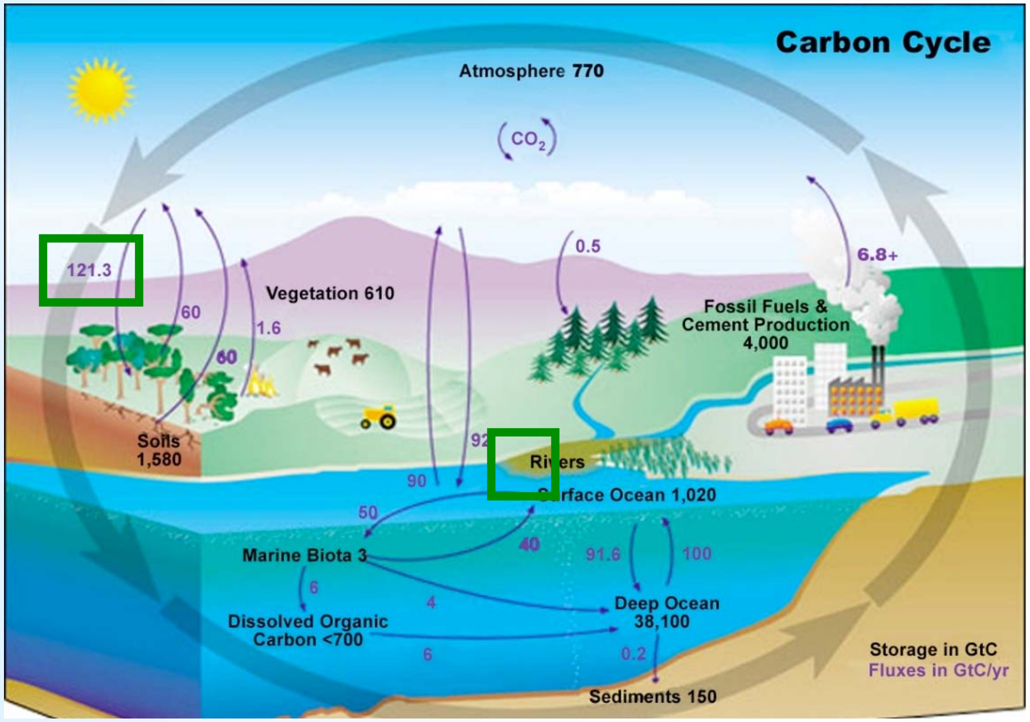



Understanding the Carbon Cycle: Observations from Space

Passive: Orbiting Carbon Observatory (OCO-2009)

Active: Active Sensing of $CO_2$ Emissions over Nights, Days and Season Space Observations (ASCENDS)



# CO2 Concentration from Ice Cores

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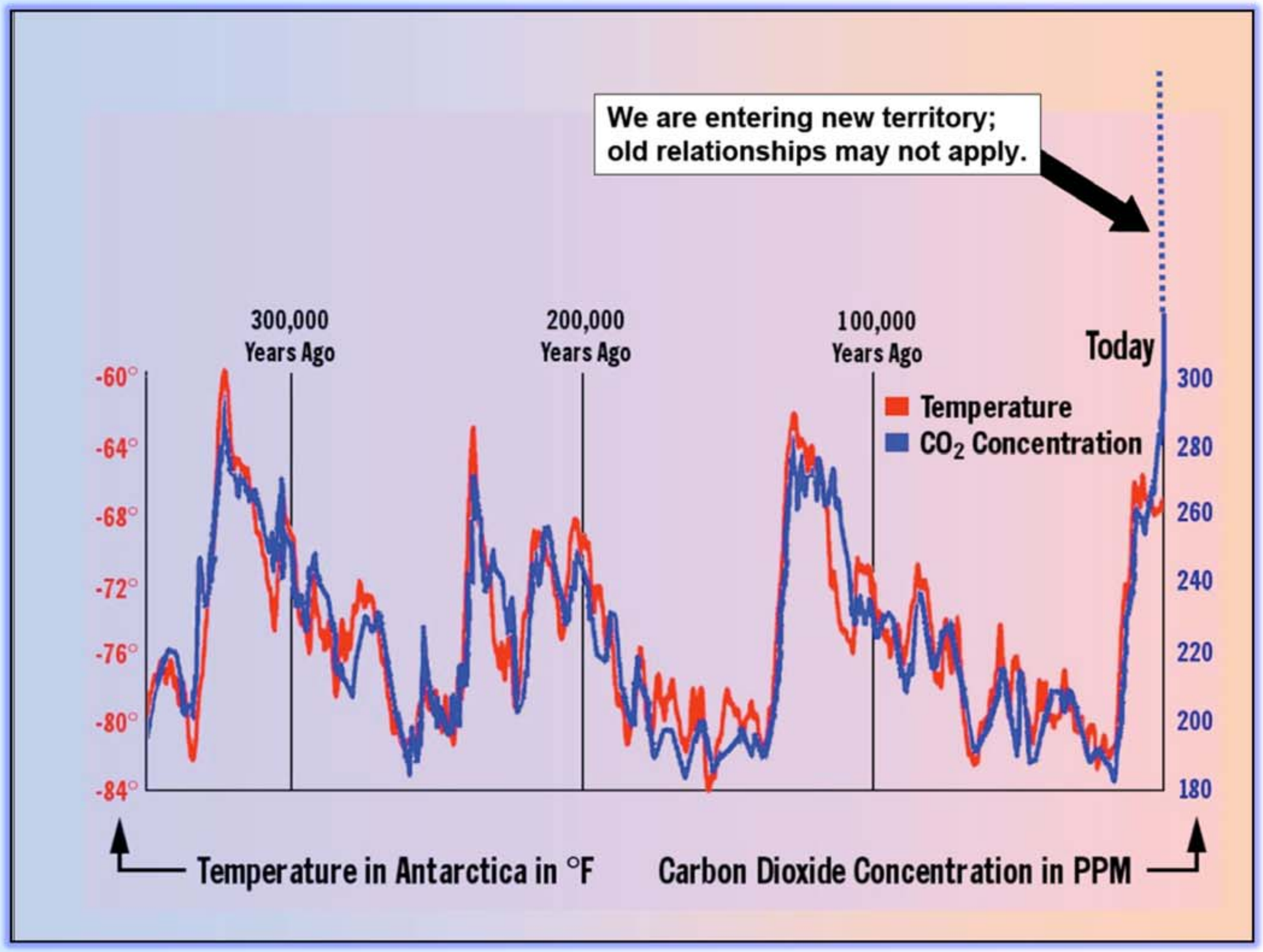

# $CO_2$ from space with passive spectrometers

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*Benefits:*

Global column measurements

Much higher coverage than ground networks

Improve our understanding of carbon cycle

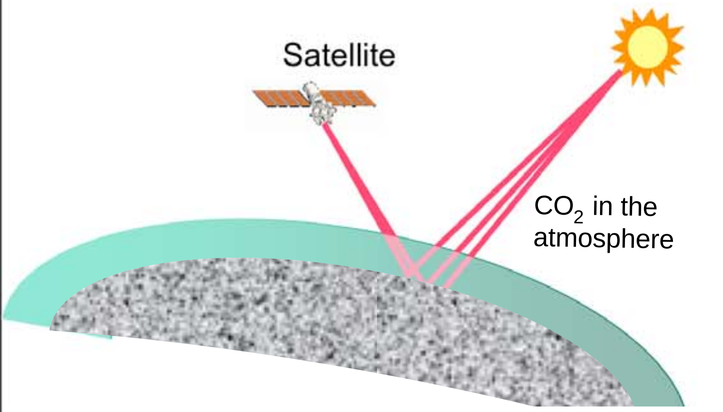
No active components (lasers)

*Unavoidable Limitations:*

Susceptible to biases from scattering of sunlight from aerosols & thin clouds

Sunlit areas only (no day/night observations)

Optical path can vary during orbit




Measures $CO_2$ absorption bands

# $CO_2$ from Space: ASCENDS Mission

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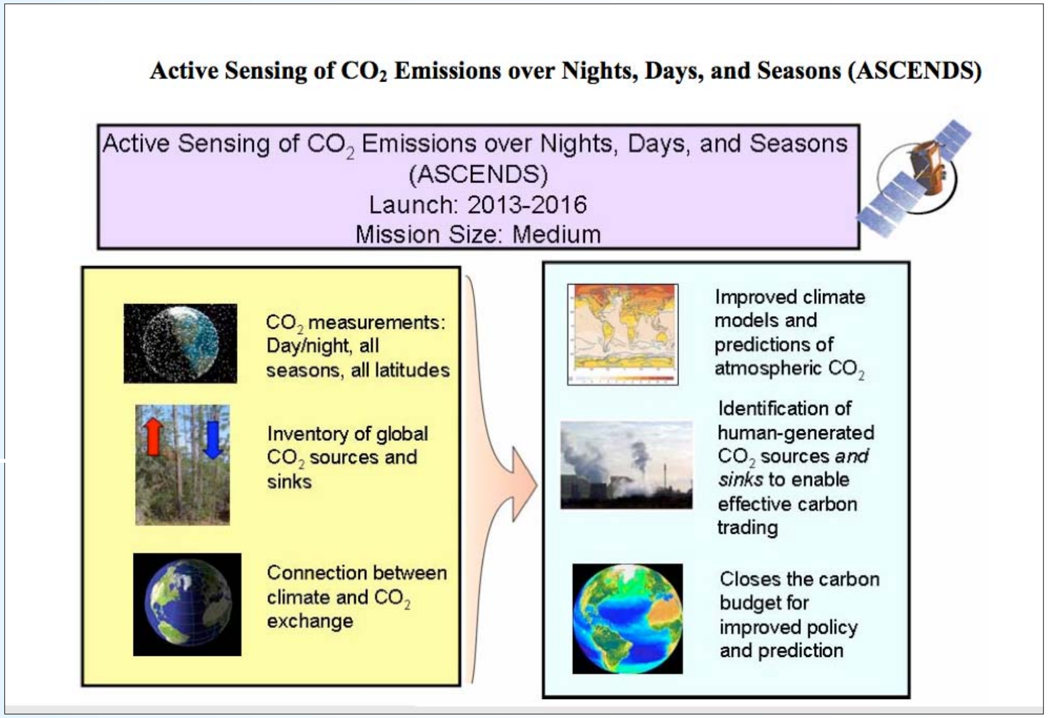
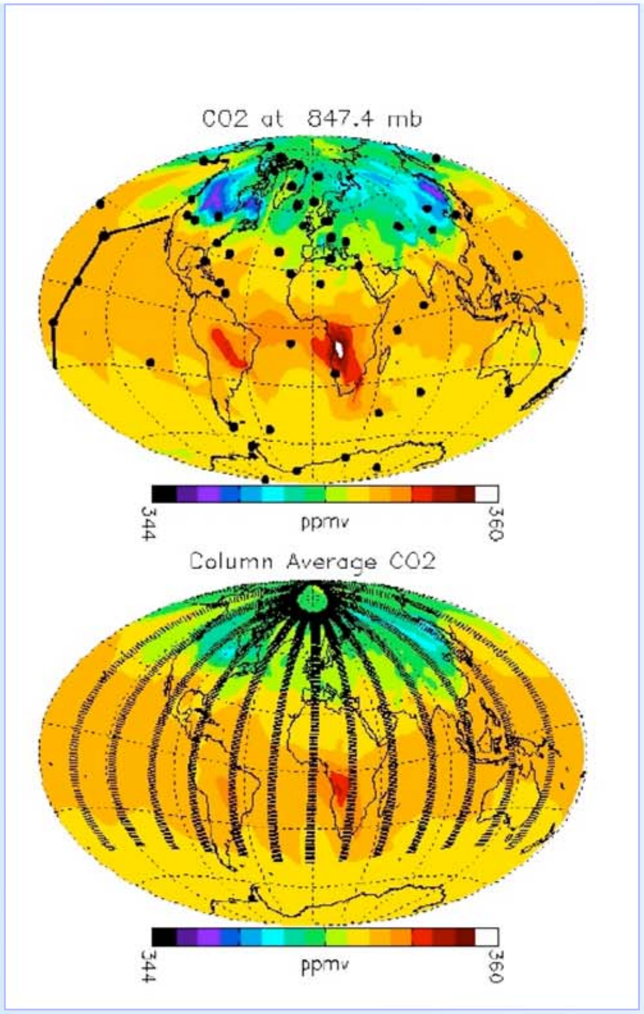
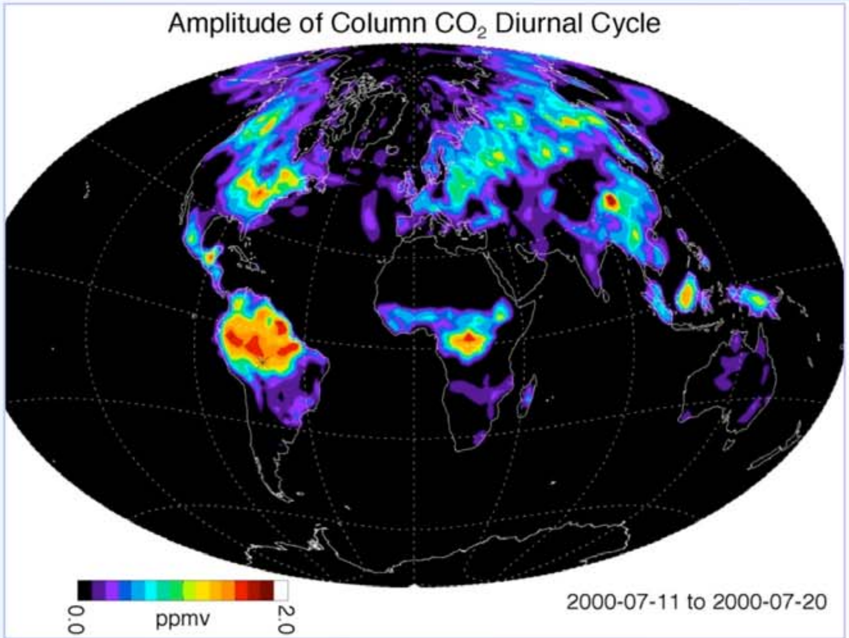
"The goal of the ASCENDS mission is to enhance understanding of the role of $CO_2$ in the global carbon cycle. The three science objectives are to:
(1) quantify global spatial distribution of atmospheric $CO_2$ on scales of weather models in the 2010–2020 era
(2) quantify current global spatial distribution of terrestrial and oceanic sources and sinks of $CO_2$ on 1-degree grids at weekly resolution; and
(3) provide a scientific basis for future projections of $CO_2$ sources and sinks through data-driven enhancements of Earth-system process modeling."
*(NASA Decadal Survey)*



# CO2 Measurement Needs





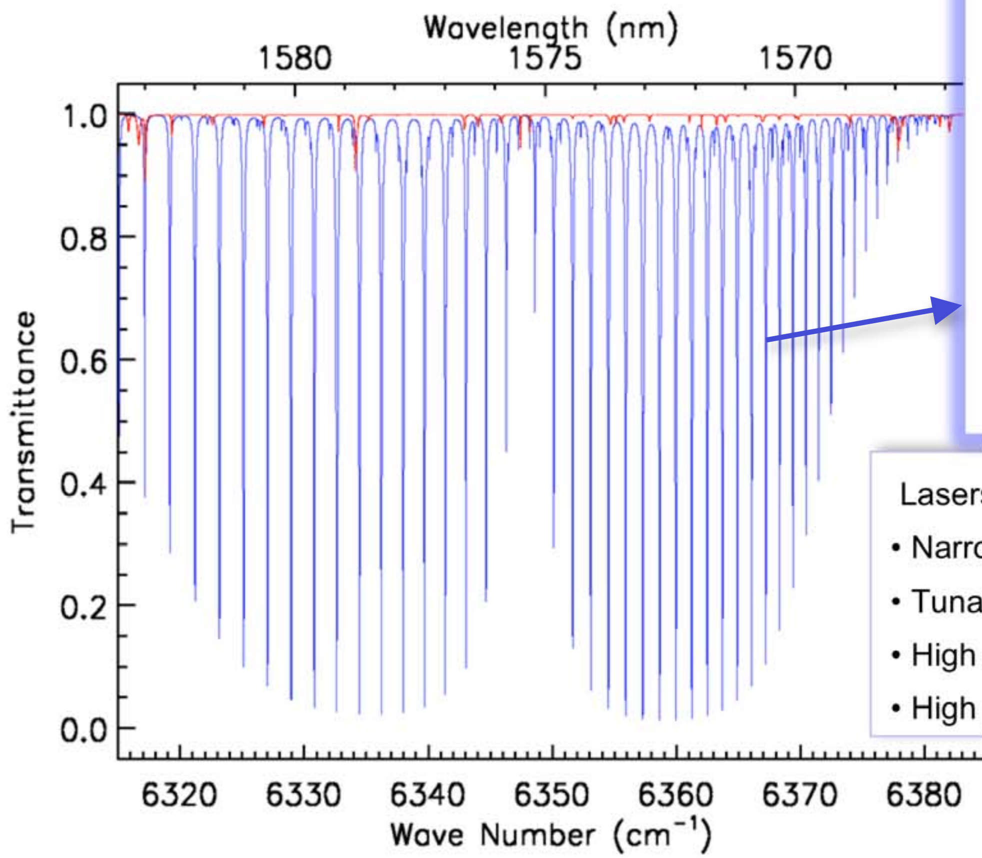




$CO_2$ measurement for ASCENDS requires both ***accuracy*** and *long term* ***precision*** *(~ 0.1% to measure 1 ppm)*.

Sensitivity (i.e. minimum detectable absorption) should not be an issue (absorption from space > 50%)

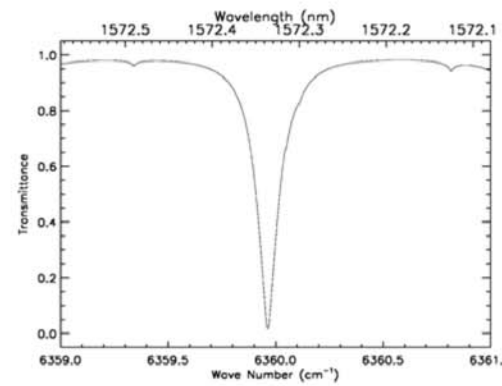
# Laser Spectroscopy Measurements






1570 nm CO2 Absorption Band from Space

Selected CO2 Line




Lasers Provide:

- Narrow measurement line widths (MHz)
- Tunable wavelengths
- High spectral brightness
- High peak power

# ASCENDS Mission - Laser Sounder Approach

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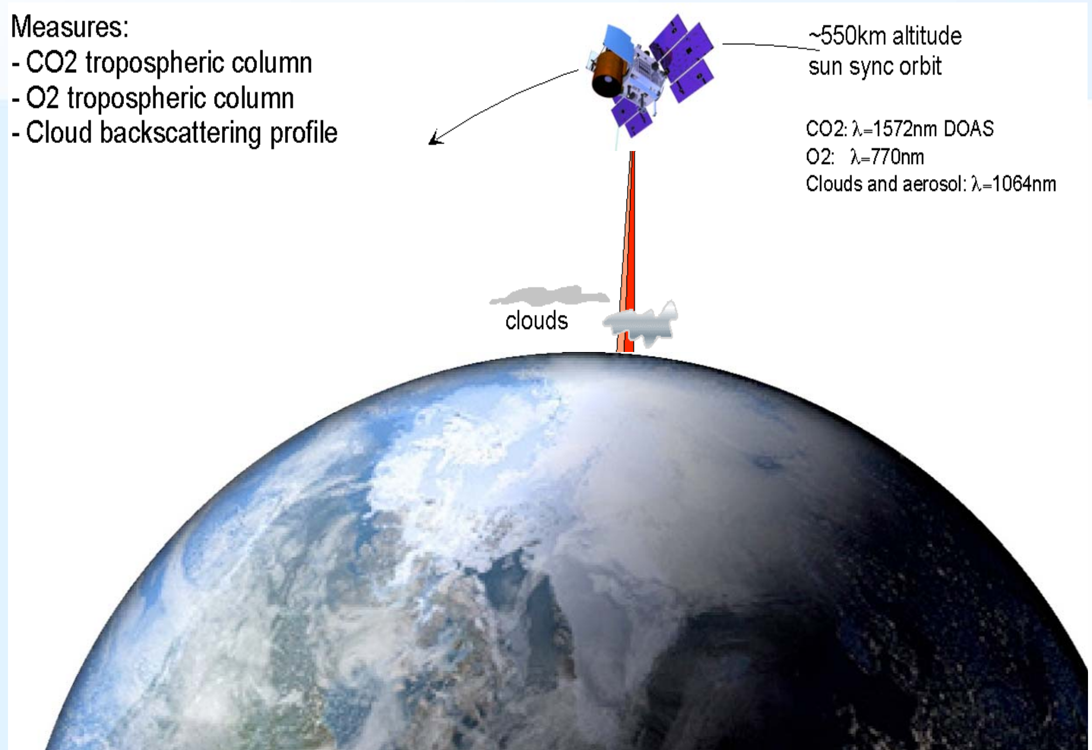
## Three simultaneous laser measurements

1. $CO_2$ lower tropospheric column
   One line near 1572 nm
2. $O_2$ total column
   Measured between 2 lines near 765 nm
3. Altimetry & atmospheric backscatter profile:
   Surface height and atmospheric scattering profile

## Measurements use:

- Pulsed EDFA lasers
- kHz pulse rates
- 6 or more laser wavelengths
- Time gated Photon counting receiver




**Pulsed (time gated) signals :**

- Isolates full column signal from surface
- Reduces noise from detector & solar background

**Goal:**

- Monthly “grid”, 1 deg spatial resolution, ~1 ppmV

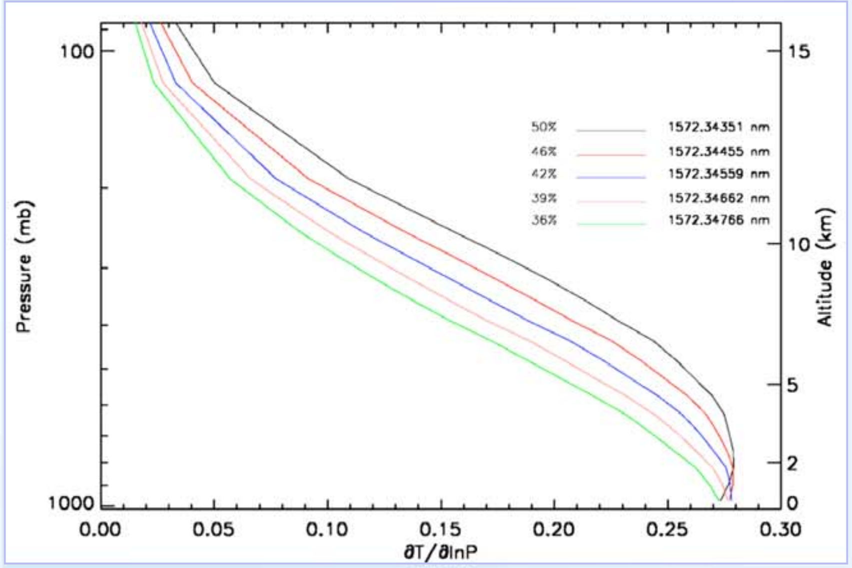
# Measurement Approach

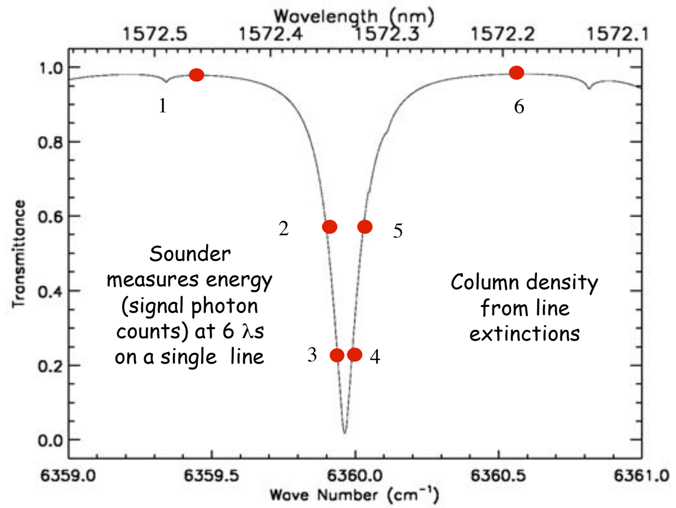
## Laser Sounder Approach

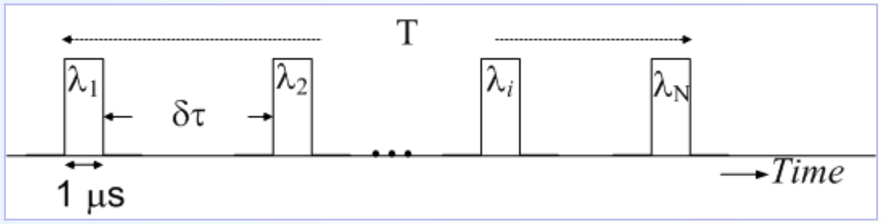
- Use 6 or more pulsed lasers to “trace” $CO_2$ line
- Use time gating to isolate ground returns
- Lock Laser wavelengths (~ 2 – 34 MHz)
- Wavelengths are flexible
- Common nadir-zenith measurement path
- Need < 1 ppm error in CO2 mixing ratio

$$\frac{E_r(\lambda_{on})}{E_r(\lambda_{off})} = \frac{E_{tr}(\lambda_{on})}{E_{tr}(\lambda_{off})}\frac{\tau_{sys}(\lambda_{on})}{\tau_{sys}(\lambda_{off})}\exp(-\sigma N_g z)$$

$$N_g = \frac{1}{\sigma z}\ln\left\{\frac{E_r(\lambda_{off})}{E_r(\lambda_{on})}\frac{E_{tr}(\lambda_{on})}{E_{tr}(\lambda_{off})}\frac{\tau_{sys}(\lambda_{on})}{\tau_{sys}(\lambda_{off})}\right\}$$



# Partial Error Source List

- Atmospheric and Spectroscopy Error Sources:
  - Temperature dependence (line parameters)
  - Pressure (broadening, shift)
  - $H_2O$ mixing ratio and spectral interference
  - Aerosol/Cloud Scattering
- Random Instrument Error Sources:
  - Shot noise
  - Laser noise
  - Johnson Noise
  - Amplifier noise
  - Detector Noise
  - Digitizer Noise
- Systematic Instrument Error Sources:
  - Laser wavelength drift
  - Opto-mechanical (alignment) drifts
  - Polarization Drifts
  - Fiber coupling/transmission drifts
  - Detector responsivity drifts
  - Pointing
  - Etalon Fringes

# Impact of Atmospheric Scattering

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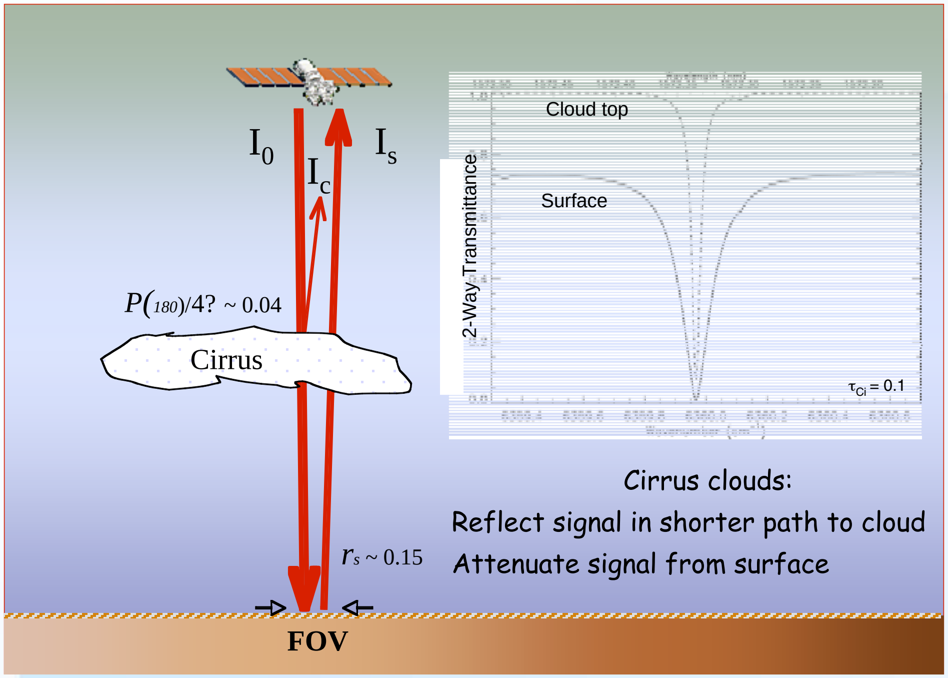
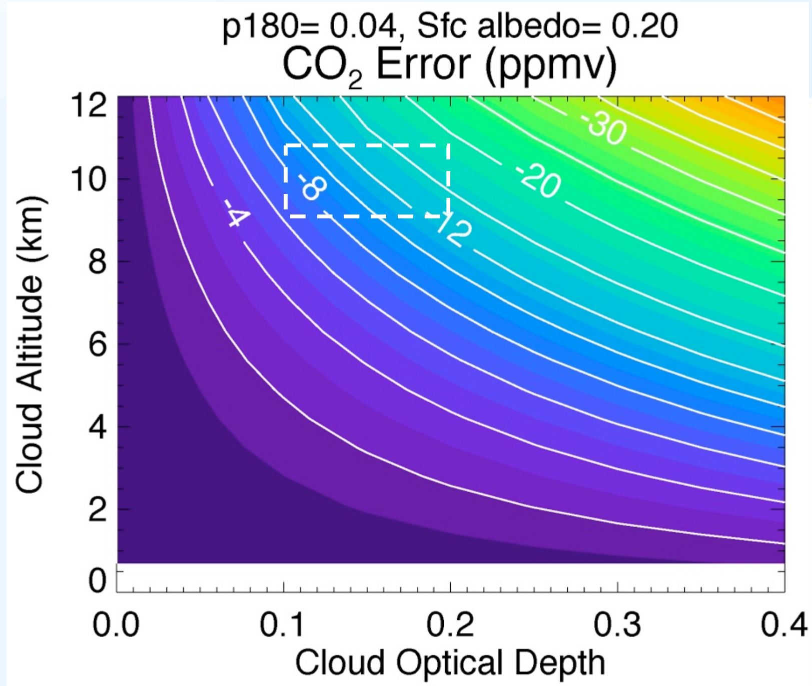
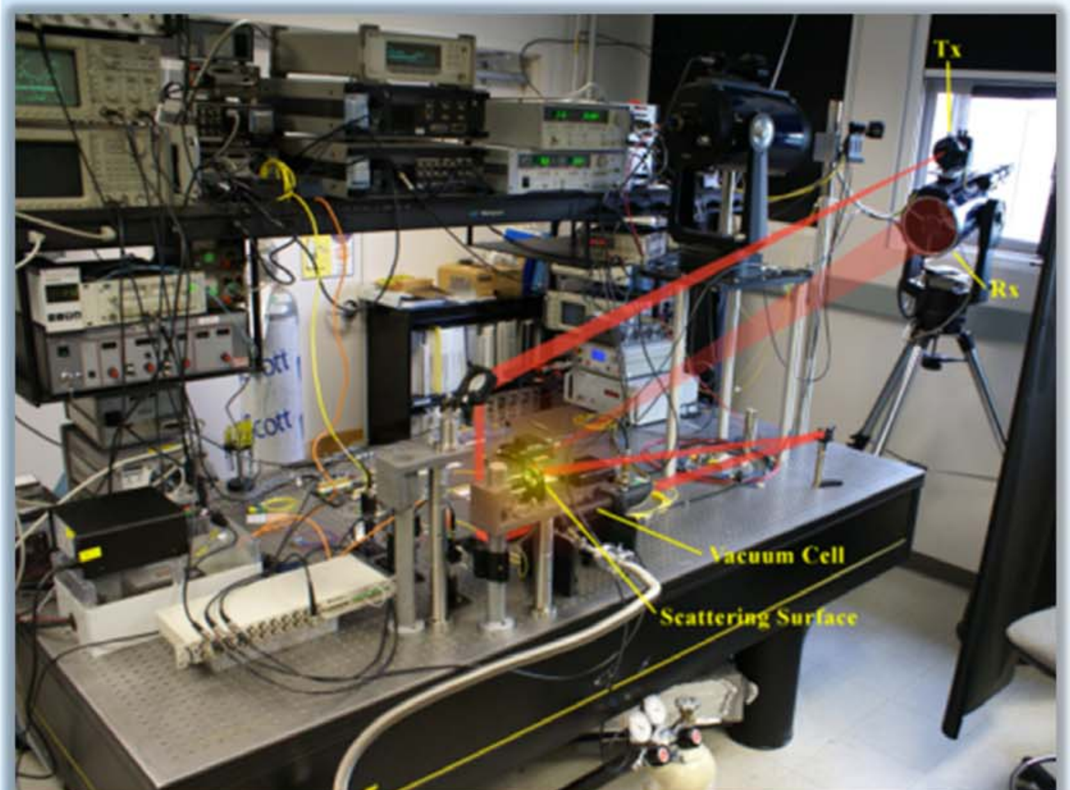
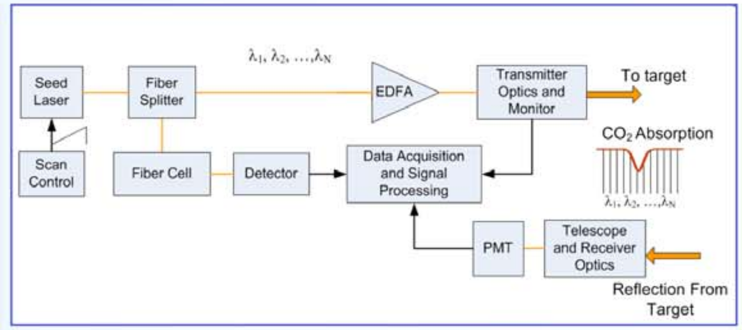


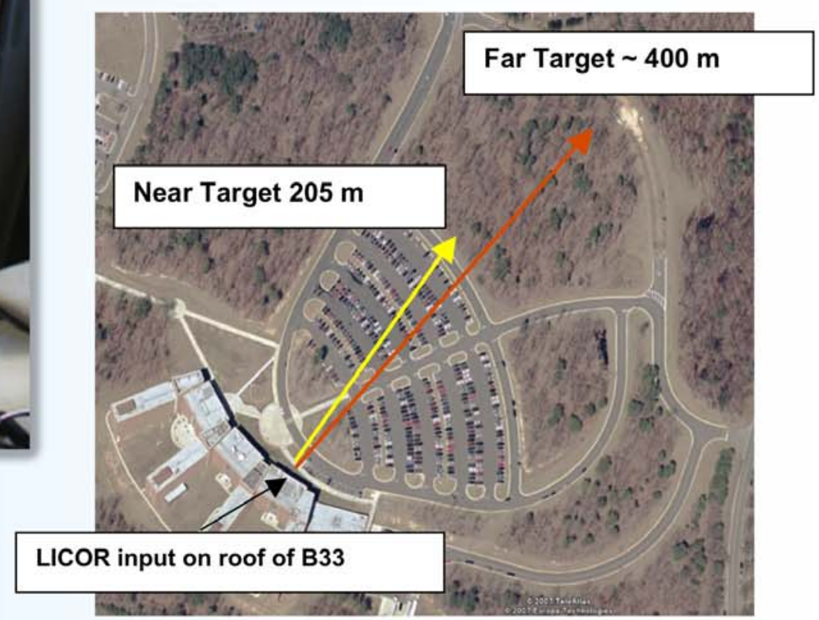




- Cirrus clouds are quite prevalent
- Cloud reflections shorten average optical path -> bias CW (non-gated) column estimates
- Cirrus cloud scattering -> 8-14 ppm errors in non-range gated measurements
- Errors led our team to use a pulsed (& range gated) approach
- Range gating eliminates cloud scattering errors (except for ground fogs)

# GSFC CO2 Breadboard Sounder



# Breadboard Sounder Measurements

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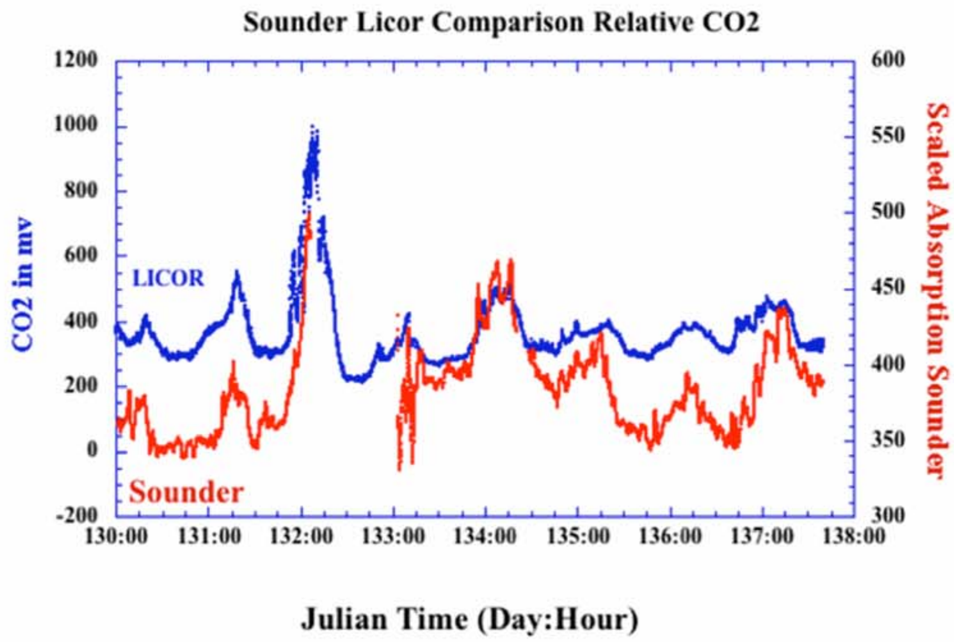


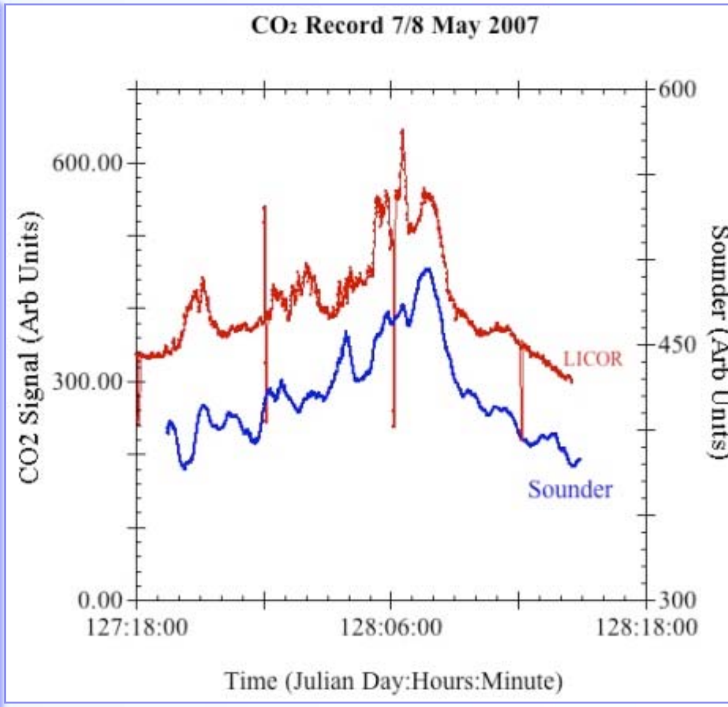

# Breadboard long term precision and accuracy

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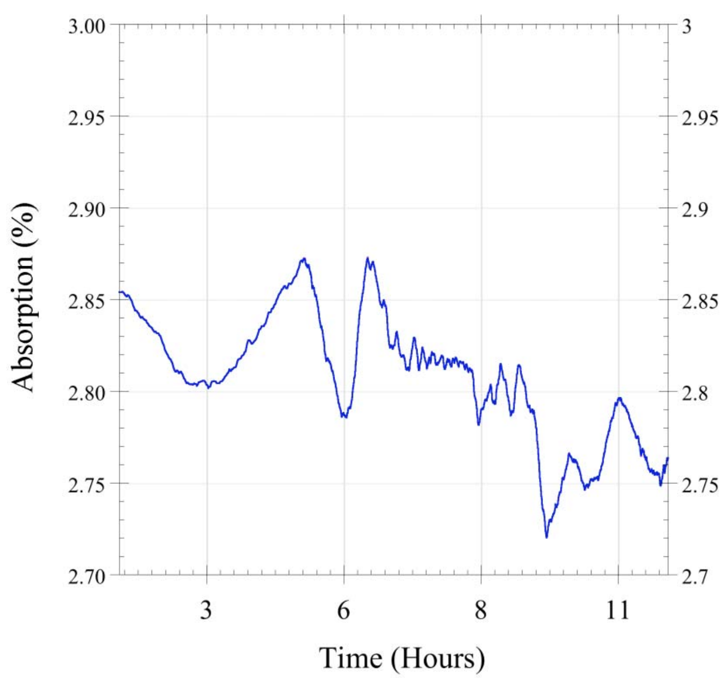
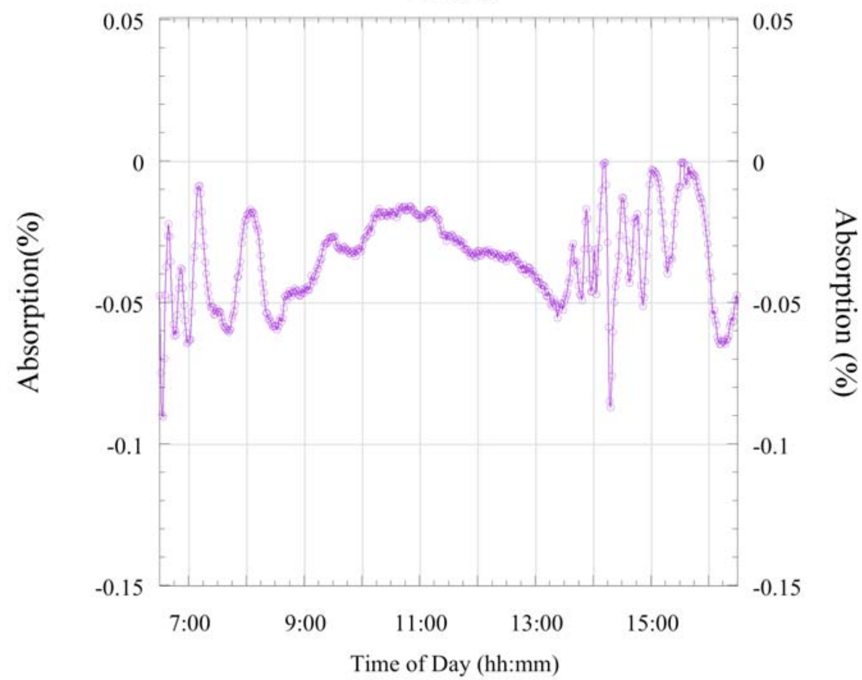
**Stability assessment in Lab**
**Measurements of Peak Absorption vs Time**
**in the lab through a 30 cm long Reference Cell**
**with ~10 mbar Co2**




**Stability of offset (Zero point)**
**Measurement in a 30 cm absorption cell**
**in the lab with no Co2**
**2/28/07**



# Integration into mobile platform

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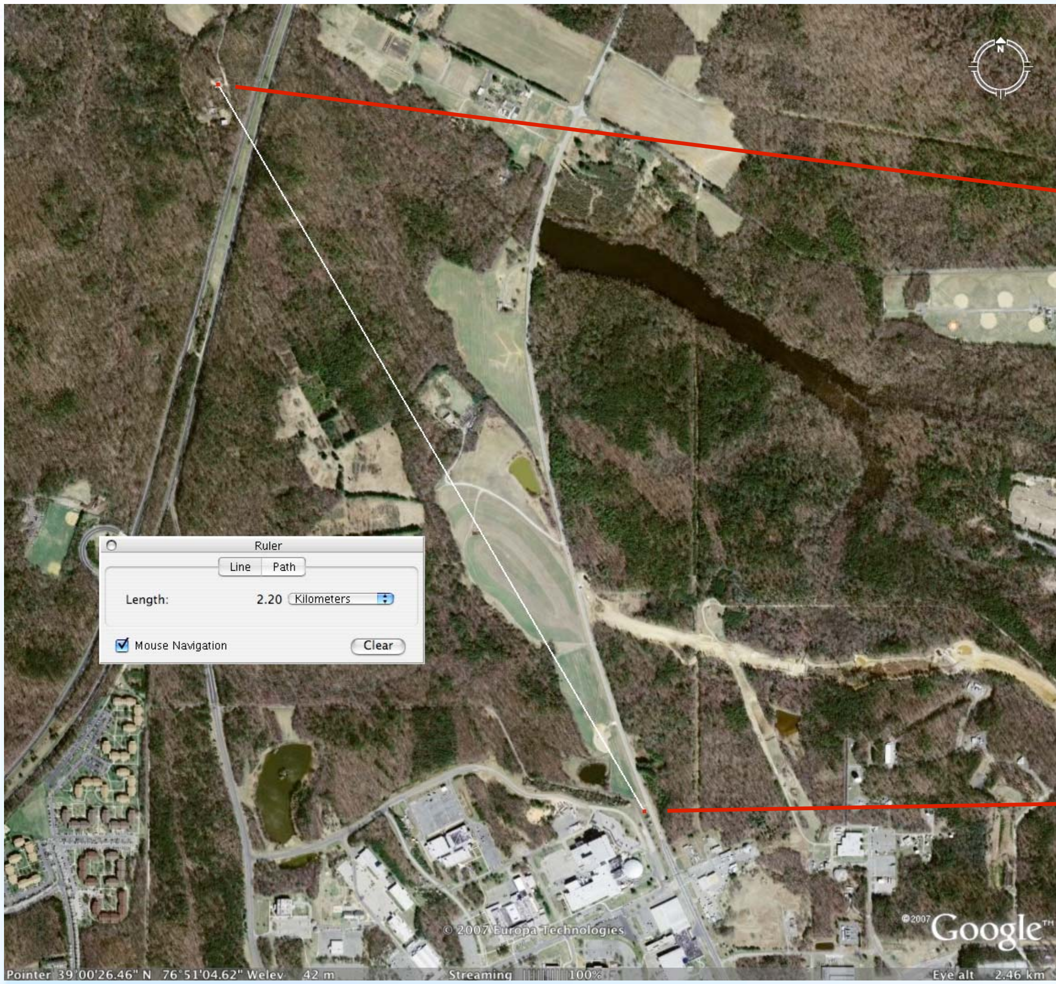


# CO2 Measurements at NOAA tower, Erie CO

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## CO2 Tower - Erie Colorado: NOAA BAO Tower

- CO2 sampled with LICORs at 20, 200 and 300 meters.
- ~1.2 km long slant path measurements to near top of tower.

# NOAA Tower Measurements

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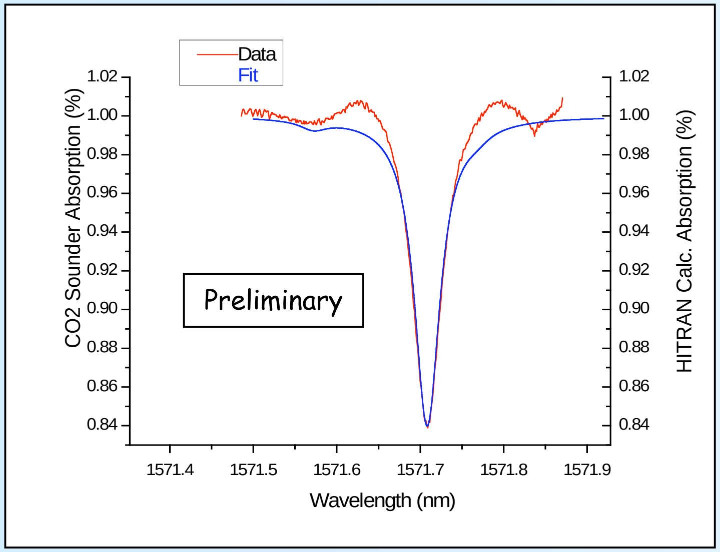
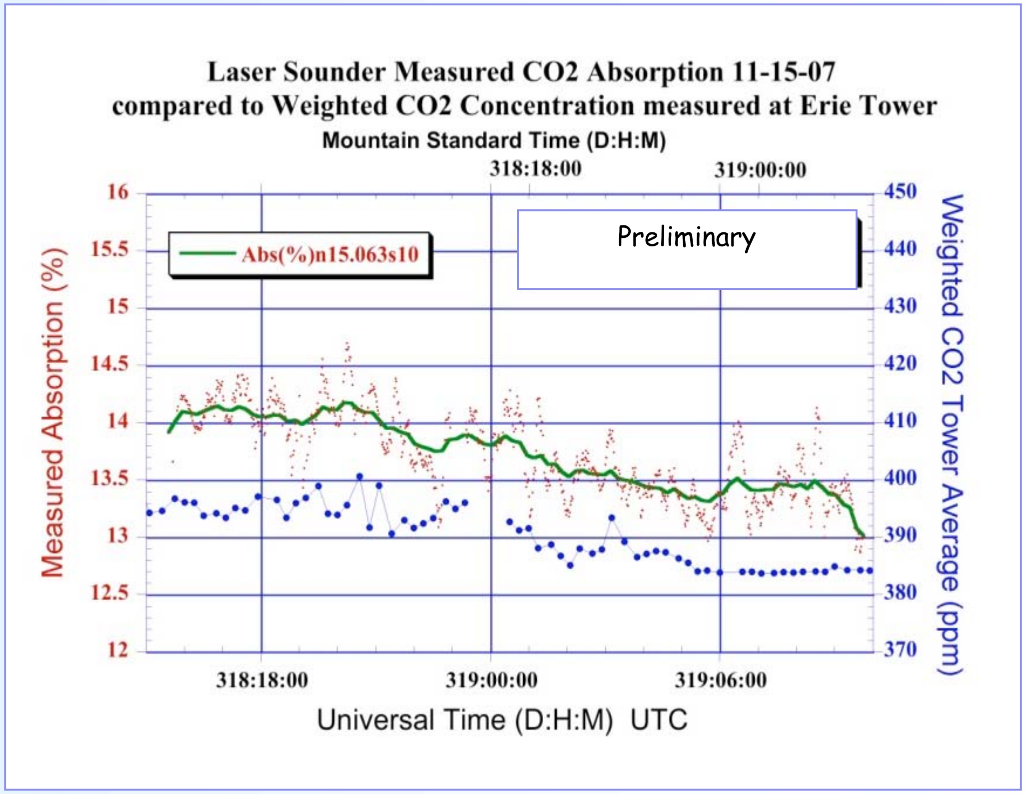



Comparison of measured CO2 line scan with HITRAN Prediction based on the Tower LICOR




Comparison of measured CO2 absorption with LICOR

# Retrieval Algorithm

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**OBSERVABLE**

$\frac{\text{Detector signal, returning}}{\text{Monitor signal, outgoing}}$

(in terms of time index)

200 Hz \ 10 sec

**Fixed quantities**

Temperature BAO tower($T_{10m}$, $T_{100m}$, $T_{300m}$)
Pressure ($P_{10m}$)
Path length (2.47 Km)
HITRAN absorption spectra

**Iterative Retrieval Algorithm**

**Analysis (variables)**

$CO_2$ concentration (column mean)
Linear coefficients converting time index to wavelength
Polynomial coefficients for baseline

# Laser Sounder and LICOR Comparison

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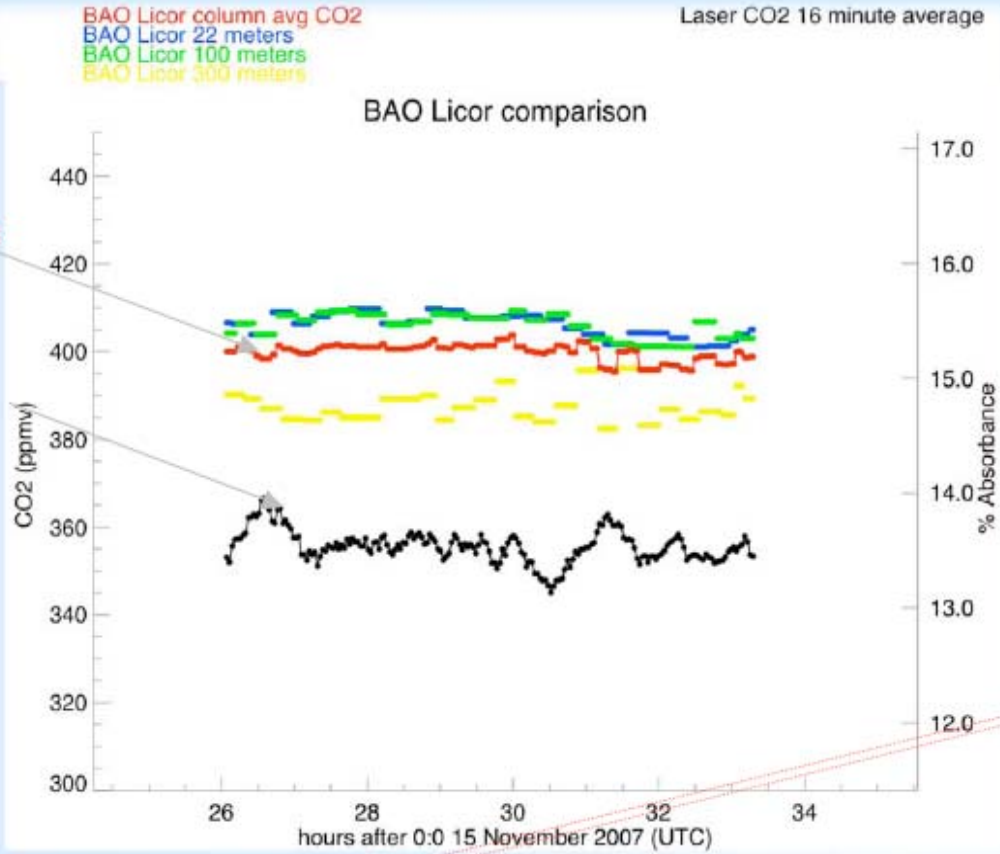
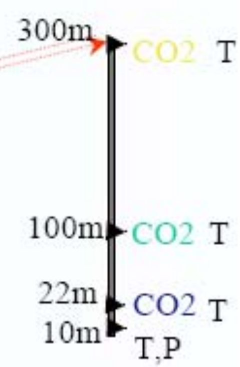
BAO LICOR column average

Laser Sounder




| | Mean | Sigma |
|---|---|---|
| Laser | 355.7 | 3.67 |
| Licor Column | 399.9 | 1.93 |
| Licor 22 m | 406.1 | 2.67 |
| Licor 100m | 406.0 | 2.71 |
| Licor 300m | 387.5 | 3.54 |




1.236 km

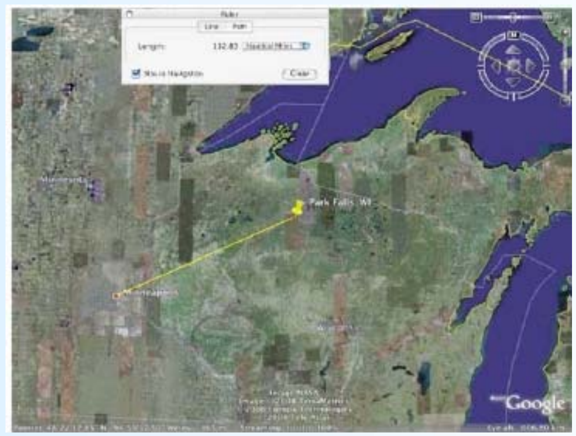
- Stability over 8 hour period
- Low bias with respect to LICOR

# Airborne Demonstration



Airborne Demonstration of Laser Sounder:
Aircraft: Lear Jet 25 operated by Glenn Research Center at Lewis Field, Cleveland, OH
Max Altitude: 45,000 ft. (13.7 km)
Range: 1436 Nmi

Overfly WLEF Tower in Park Falls, WI




# Airborne Instrument Design

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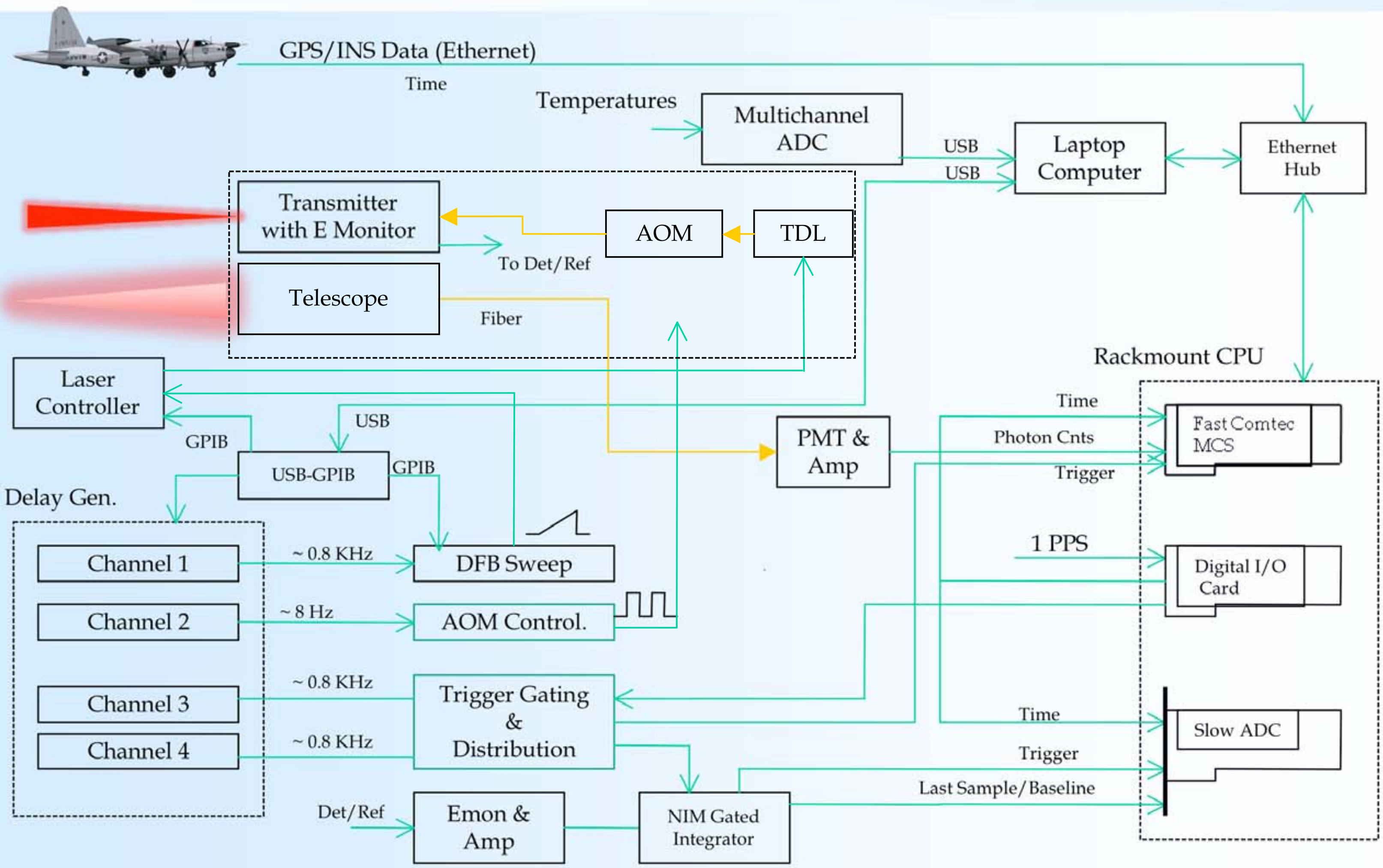

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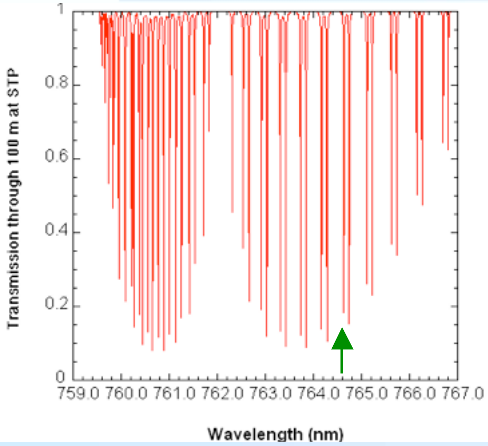
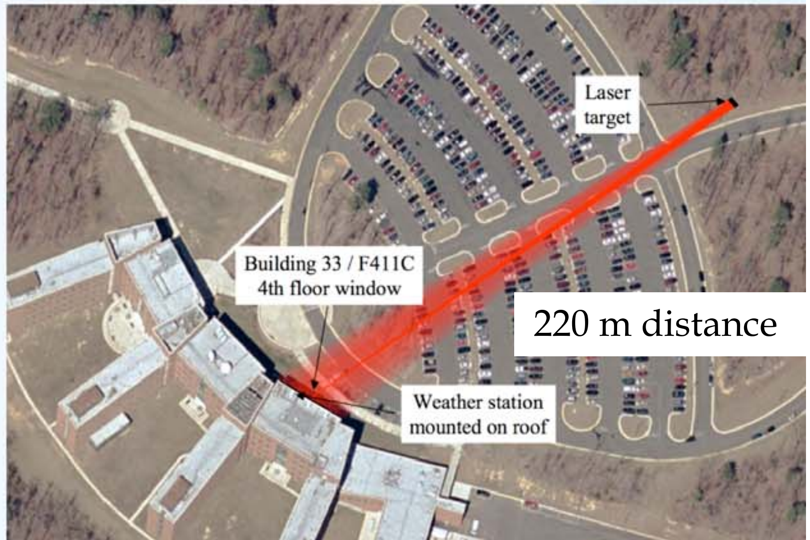
# Oxygen Measurements

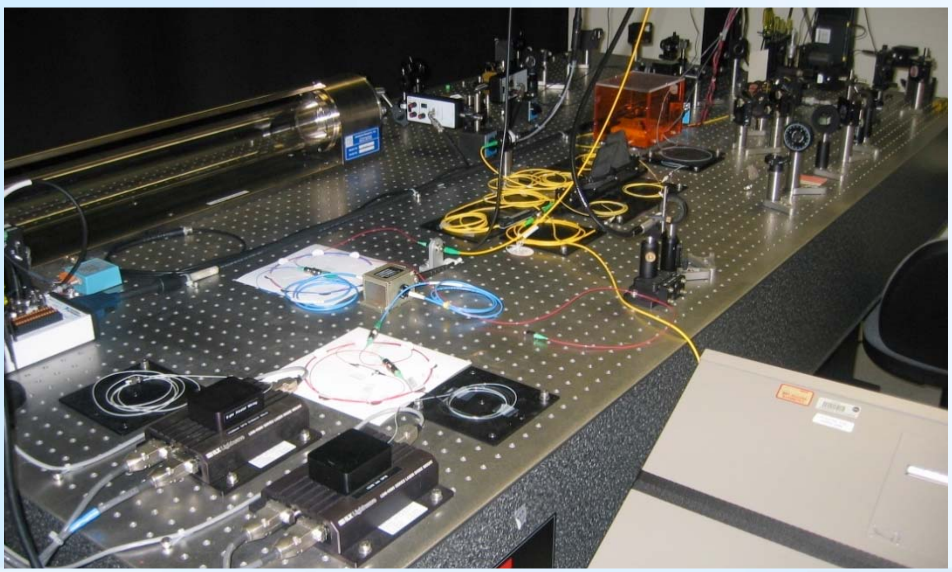


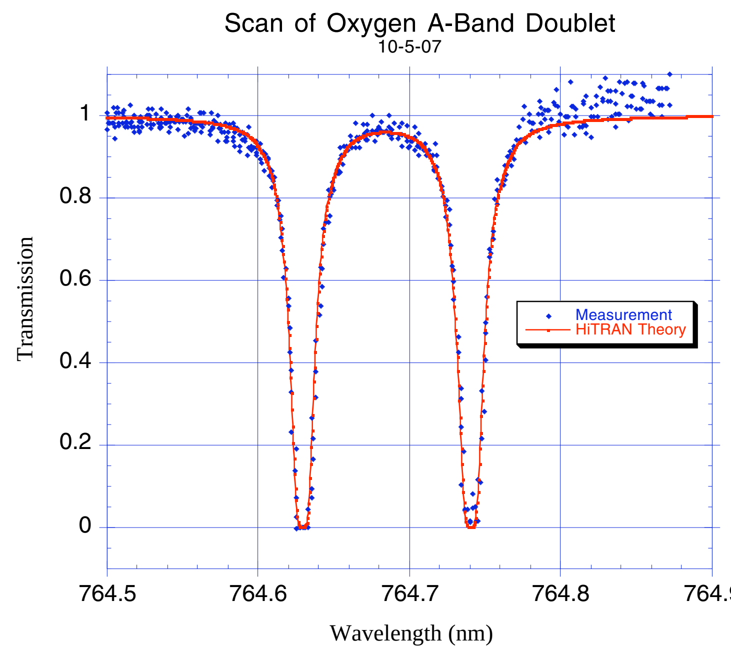

Oxygen A band: Calculated atmospheric transmission for 100 m path at STP

Telescope viewing target


Peak optical power ~ 50 mW
Attenuation for round trip was ~$10^6$

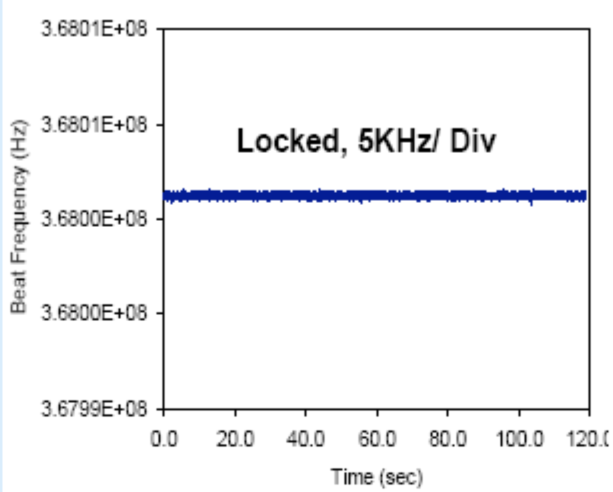


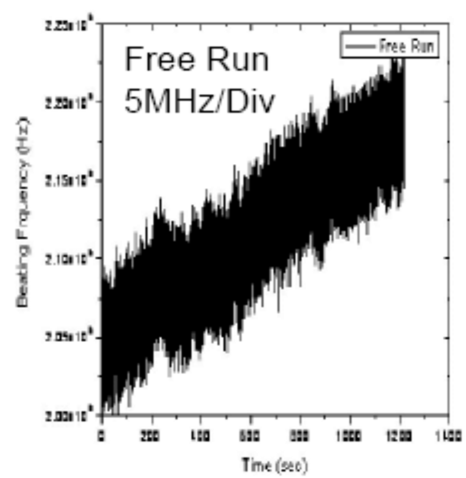





# Technology Development - Transmitter

- Working with several vendors to achieve high peak power and leverage DoD work for space qualification of fiber amplifiers.
- Demonstrated locking of diode lasers to 1 kHz

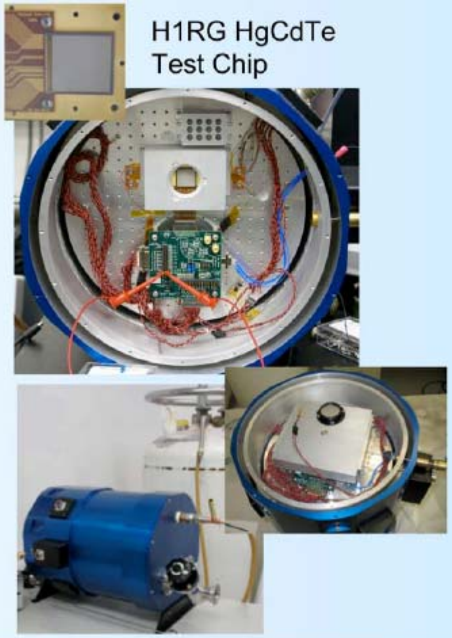


# Technology Development - Detector

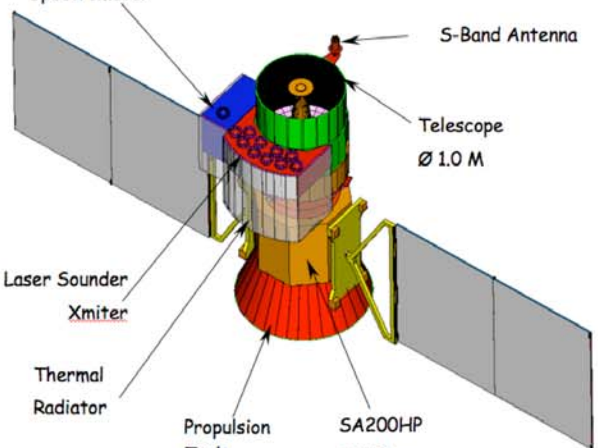
- Continue to test several detectors
- Commercial PMTs continue to improve
- Modify JWST HgCdTe detector for lidar application

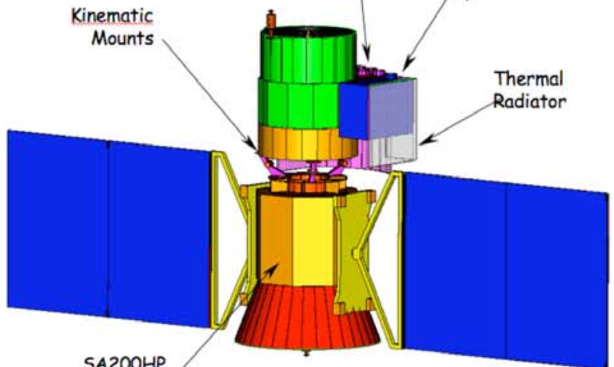
H10330-75
TEC cooled with no vacuum pump
QE~9%



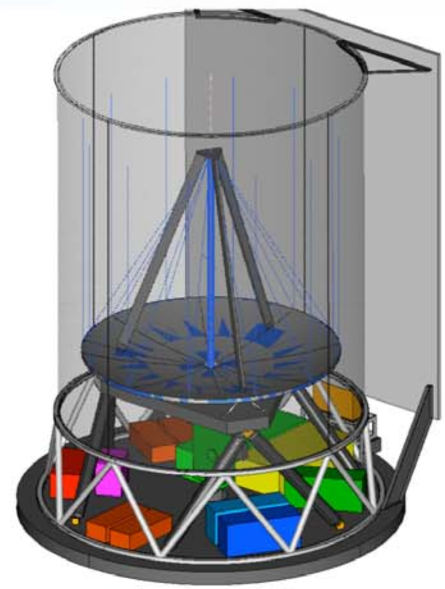
# Moving to Space



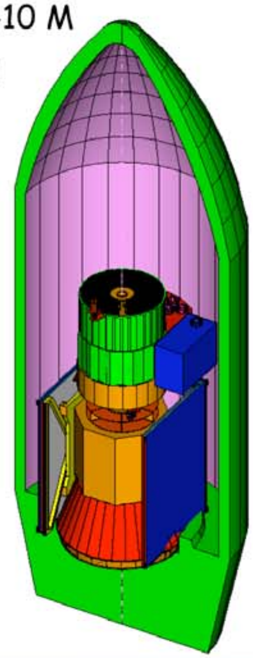



Instrument Configuration Concept from 4/08 Study (using 1.5 m ADM ALADIN Telescope)



Delta 2320-10 M Shroud



**Carbon Cycle Initiative, CO2/Lidar**

**System Overview**

**David Everett**

*Initial Space Mission Study showed space mission concept practical*

*To be updated in 2008 with improved estimates for measurement , orbit, and components*

# Summary

- Demonstrated concept of laser sounder in a laboratory setting
- Demonstrated that achieving 1 ppm measurement accuracy and precision is possible with a laser sounder.
- Demonstrated oxygen detection at 765 nm.
- Performed field experiments at GSFC and at Erie, CO.
- Currently addressing technology needs of fiber amplifiers and detectors.
- Plan airborne CO2 measurement demo - fall 2008.
- Develop ASCENDS Precursor (ESTO IIP)
- Moving to Space – ISAL study