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Laser Sounder for Measurements of Atmospheric CO2 Concentrations - *Overview*

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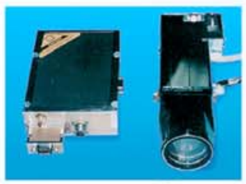
An operational Space Lidar History
(LITE and SLA experiments not shown)

Apollo, - Moon
NASA (1971-1972)
Ruby lasers,
5,000 shots

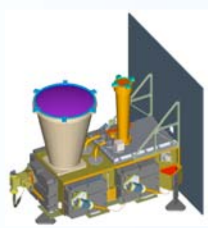
Clementine - Moon
LLNL/NRL (1994)
Nd:YAG laser,
~72,000 shots



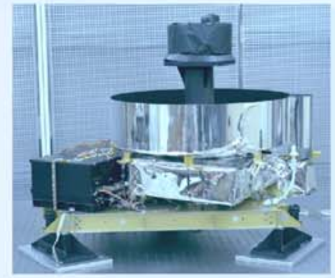
SELENE/LALT - Moon
Japan (2007-present)
Nd:YAG laser,

Chang'E - Moon
China (2007-present)
Nd:YAG laser

LRO/LOLA - Moon
NASA GSFC (2008-2010)
Nd:YAG laser,
>1 Billion shots (planned)



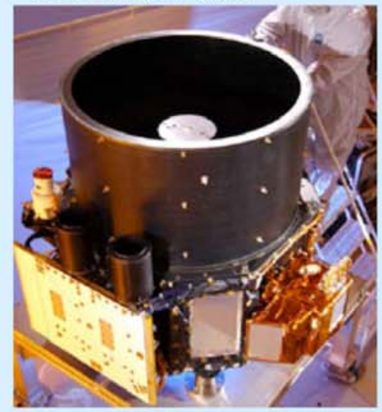
MGS/MOLA - Mars
NASA GSFC (1996 - 2000)
Nd:YAG laser,
670 million shots



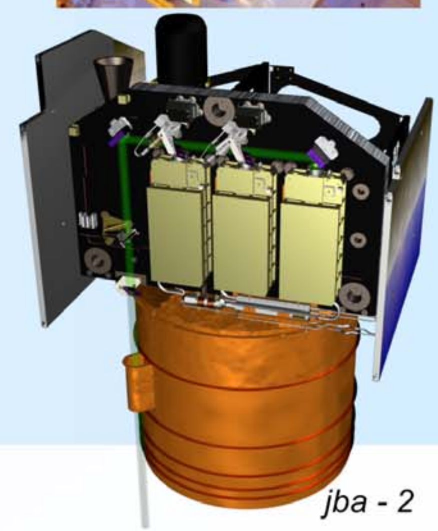
NEAR/NLR - Eros
JHU/APL (96-2001)
Nd:YAG laser,
11 million shots

MESSENGER/MLA - Mercury
NASA GSFC (2004-2012)
Nd:YAG laser,
12M shots (planned)

CALIOP/CALIPSO - Earth
NASA LaRC/ Ball Aerospace
(2006-present)
Nd:YAG laser,
> 1B shots to date



ICESat/GLAS - Earth
NASA GSFC (2003-present)
Nd:YAG laser
>1.7 billion shots to date



Laser Sounder for ASCENDS Mission

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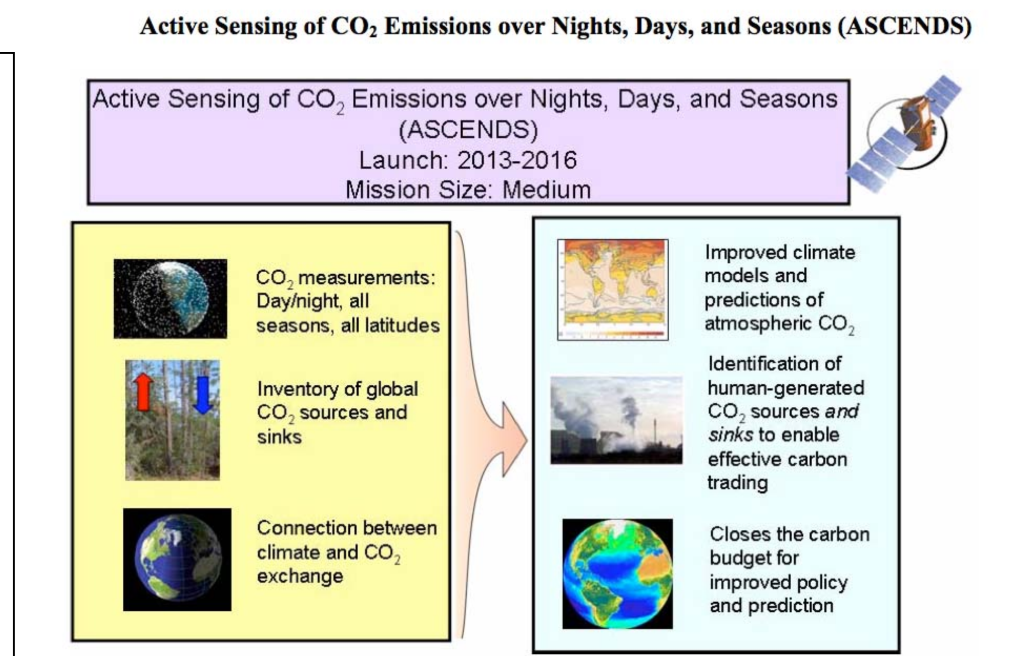


Why lasers ?

- Measures at night & all times of day
- Constant nadir/zenith path
  - Illumination = observation path
  - Continuous "glint" measurements over oceans
- Measurements at high latitudes
- Small measurement footprint
- Measure through broken clouds
- Measure to cloud tops
- Very high spectral resolution and accuracy

Lidar approaches for CO2 column:

Broadband laser - 1570 nm band - λ tuned receiver

1 line - 2 um band - pulsed - direct detection

1 line - 2 um band - CW heterodyne detection

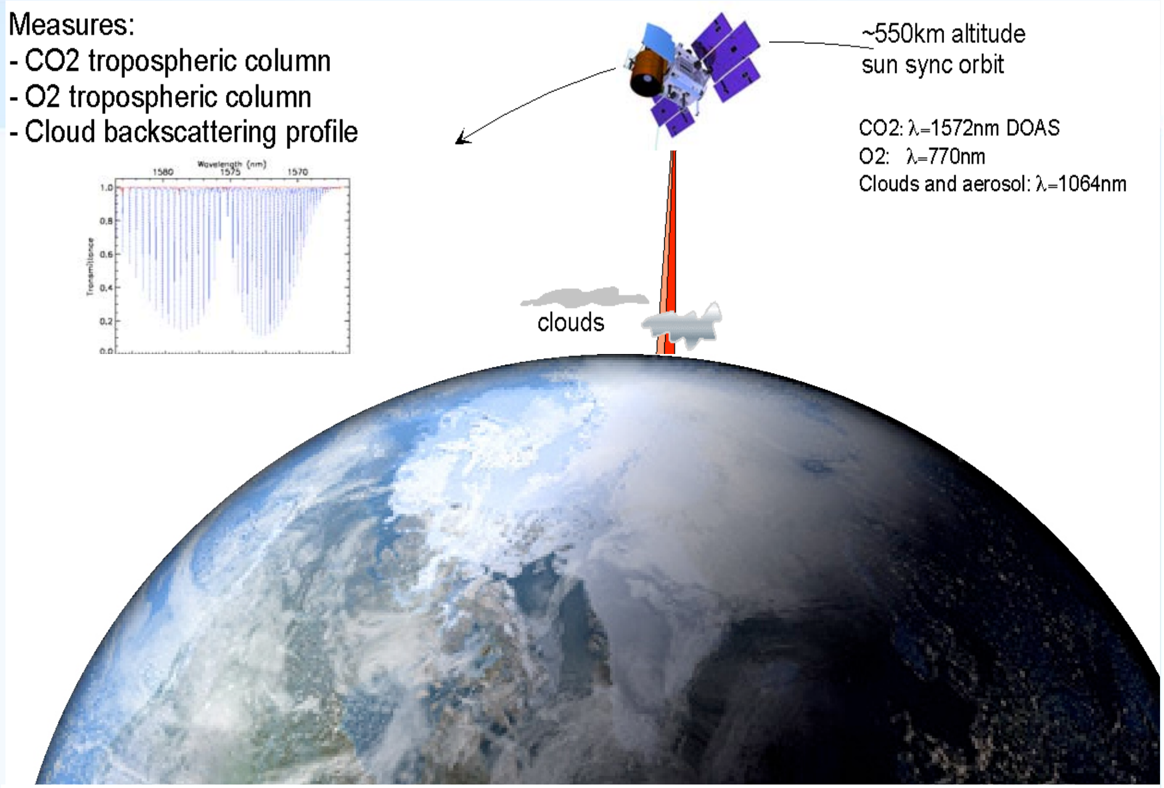
1 line - 1570 nm band - synchronous direct detection

This talk → 1 line - 1570 nm band - pulsed direct detection

ASCENDS Mission - Laser Sounder Approach

3 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 at ~ 1064 nm



Measurements use:

- Pulsed EDFA lasers
- KHZ pulse rates
- 6 laser wavelengths/ gas line
- Time gated Photon counting receiver

CO_2 & O_2 column measurements:

- 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

For more information - see Poster by Abshire et al.

CO_2 Band & Line Measurement Approach

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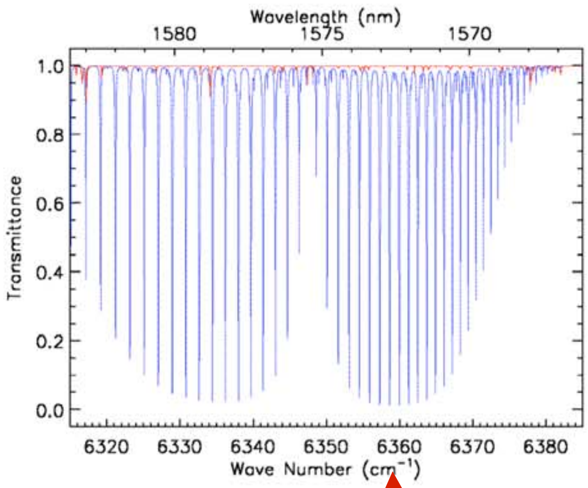
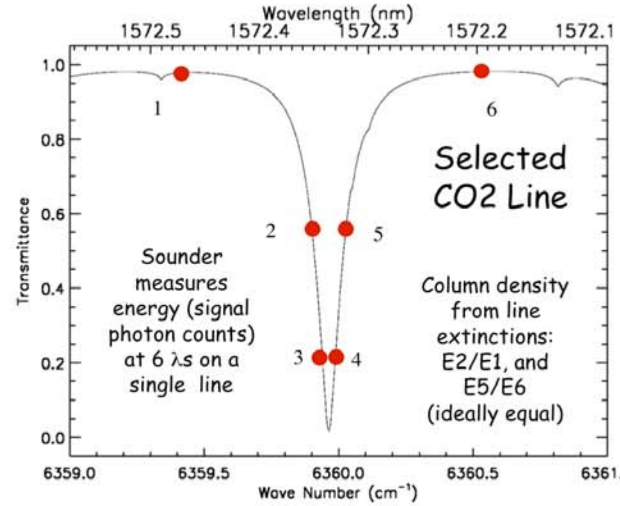


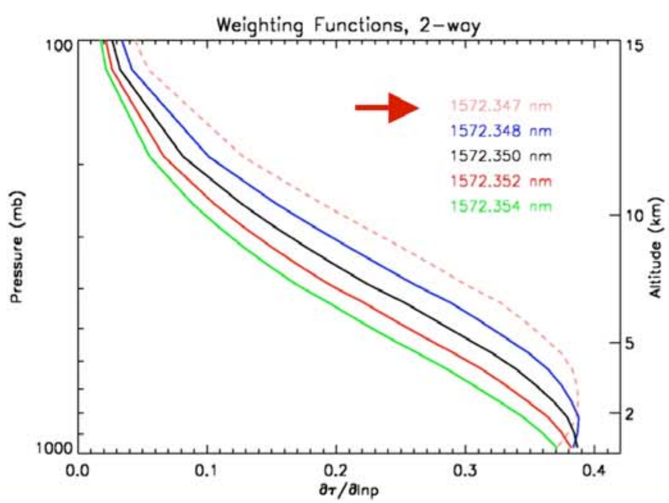
1570 nm CO2 Absorption Band from Space (HITRAN)

Extinction of lines vary with # of CO2 molecules in column



Sequentially step through the λ's in time

Column Altitude Weighting Function (pts 2 & 5)



Using laser tuned to sides of Absorption line provides Column Measurement weighted to lower trop., via CO_2 Line Broadening

Lasers Provide:

- Narrow measurement line widths (MHz)
- Tunable Stable frequencies (MHz)

Energy Measurement Resolution:

- Need ~ 1000:1 SNR for online energies (E2, E5)
- With similar errors for O2 gas measurement, results in ~ 1 ppm error in CO2 mixing ratio

CO2 & O2 spectroscopy - see Poster by J. Mao, et al

Gas column retrievals from measurements

Accurate estimates of N depend on knowledge of :

- σ - line cross section
- "z" effective path length
- λ - laser wavelengths
- Pref : Transmitted laser power (λ)
- Tsys: System transmission (λ)
- E_r (high SNRs)

Some error sources:

- σ - temp effects in line cross section
- z - atmospheric scattering, topo height change
- System changes; small λ–dependences in:

  E_{tr}, $\tau_{sys}(\lambda_{on})/\tau_{sys}(\lambda_{off})$
- Noise (signal & background shot noise, detector noise) in detected echo signal

Goal :

- Maximize received SNR
- Minimize all other error sources

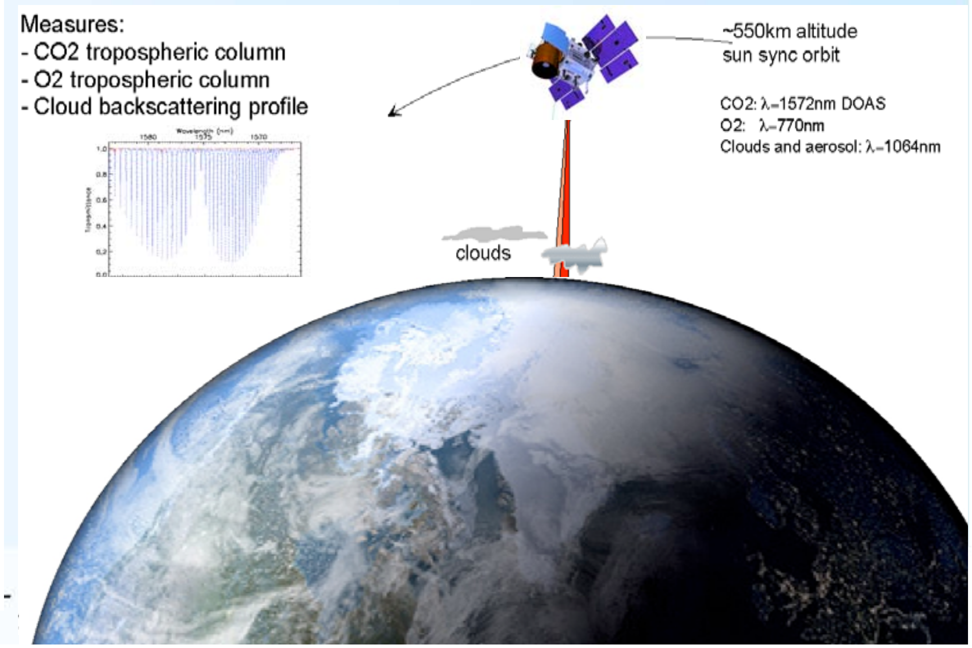
General form of DIAL equation for uniform horizontal path (Beer-Lambert Law):

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

Estimated CO2 number density:

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

SNR *"Stability"*

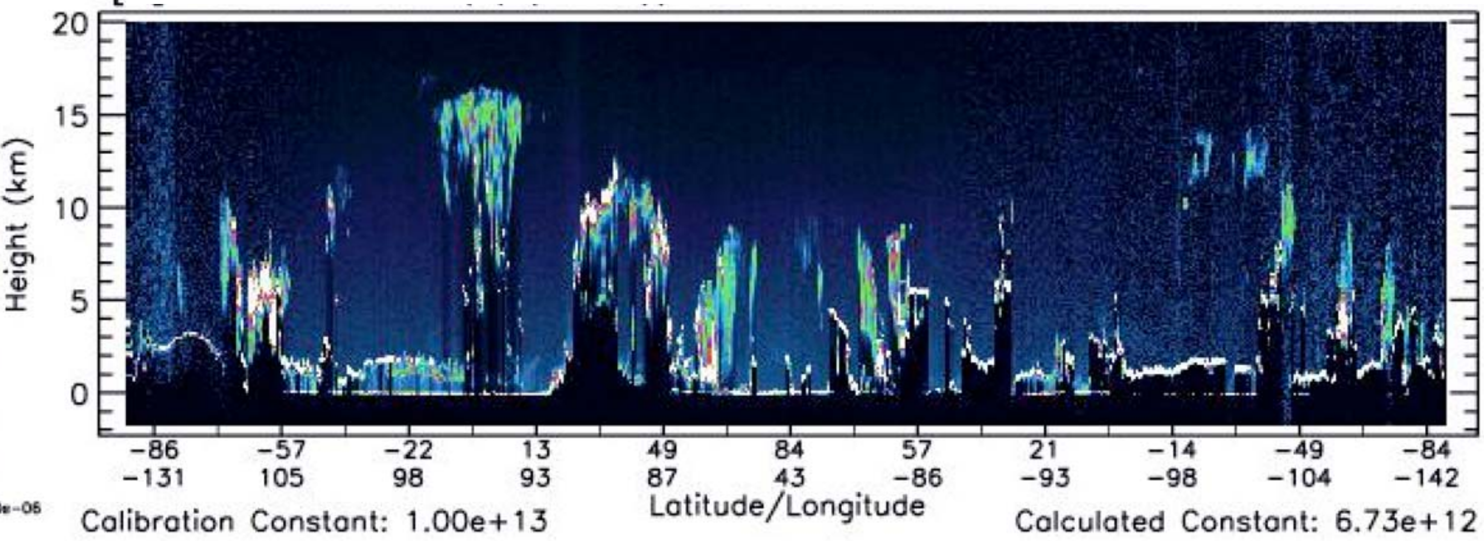


Atmospheric Scattering & measurement approach

Atmospheric Backscatter:

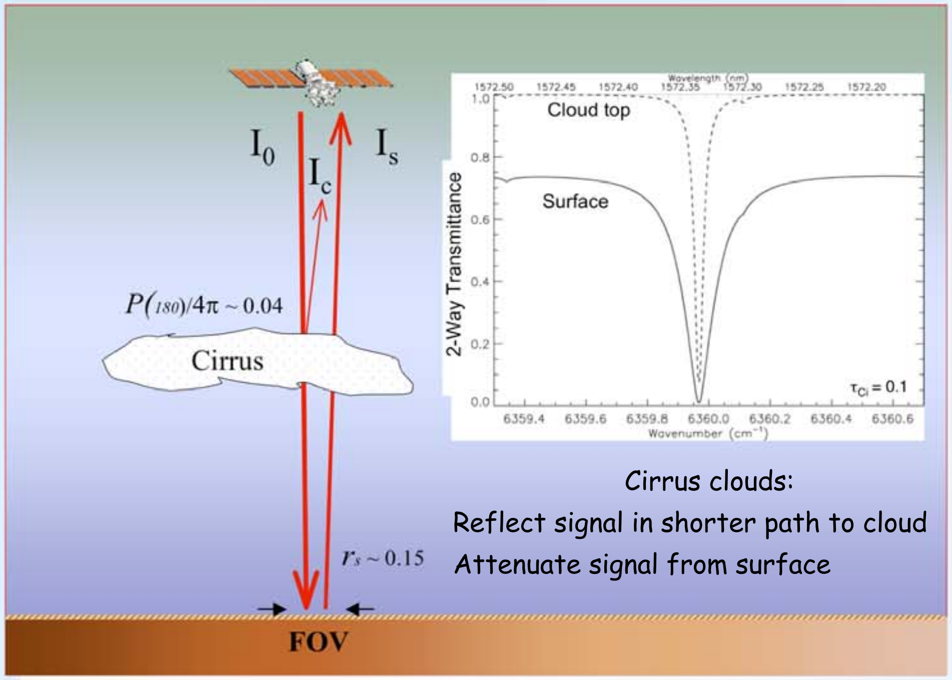
- Scattering structure is complex & variable
- Most nadir-zenith paths have some scattering above surface
- Many instances of thin cirrus clouds & aerosols
- Thin cirrus clouds can cause errors 8-14 ppm in non-pulsed systems
- Some thick clouds
- "Target Depth" with clouds ~15 km => leave ~133 usec in travel time

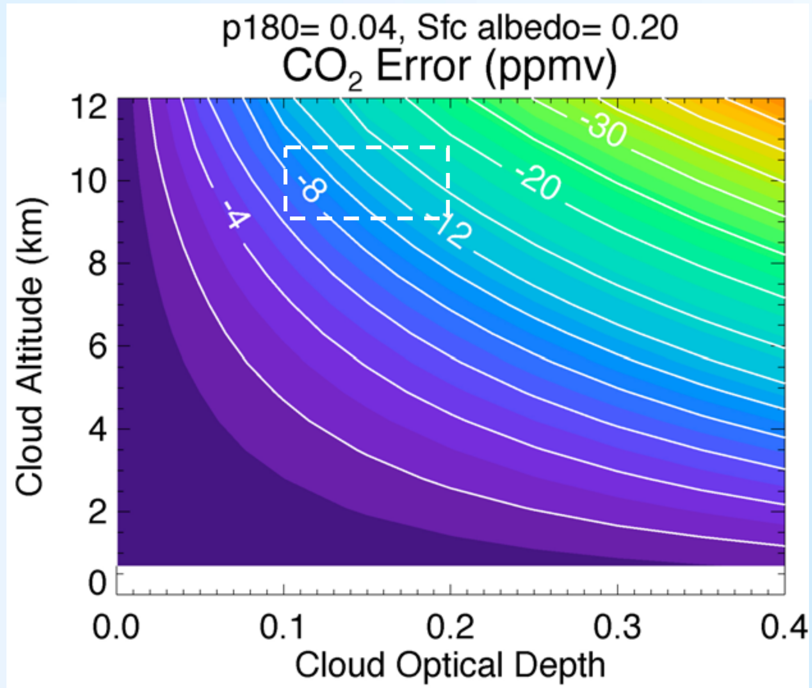
Atmospheric Profile measured by GLAS/ ICESat (from campaign L2a)



One orbit sample measured by GLAS 532 nm photon counting receiver (J. Spinhirne)

Atmospheric Scattering - Impact on Non-range gated measurements





- 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)

Laser transmitters (CO2 and O2): Diode Seed Lasers -> Fiber Amplifiers

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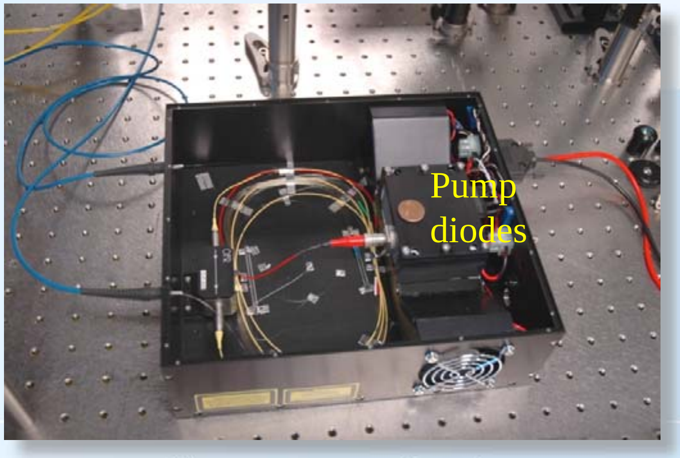
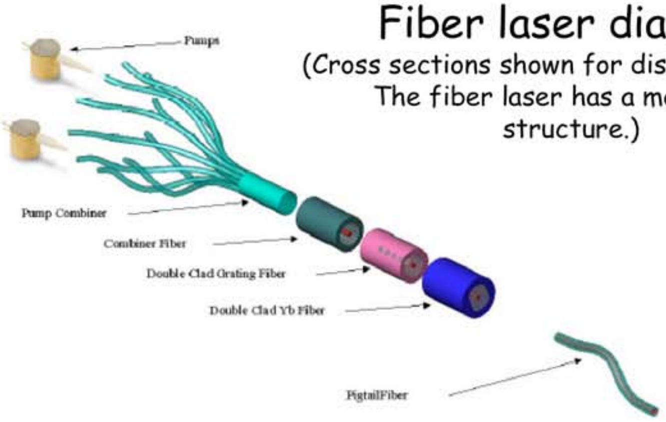
Tunable diode seed lasers

An example of commercial EDFA





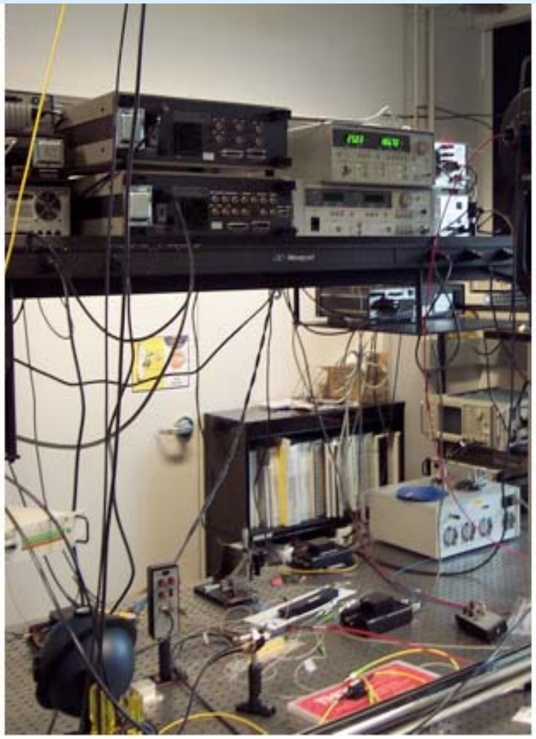
Fiber laser diagram

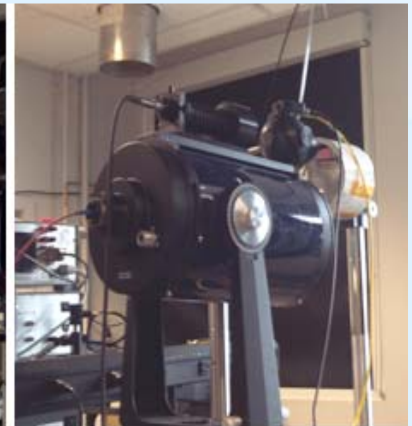
(Cross sections shown for display purposes. The fiber laser has a monolithic structure.)

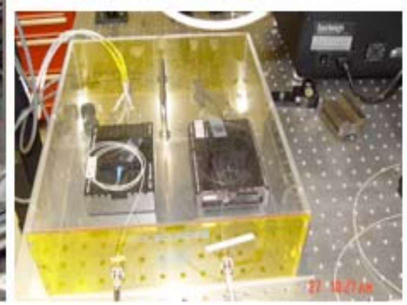
Characteristics:

- Fiber architecture - permanently aligned
- Closed laser cavity - free from contamination
- Large investments from industry
- Components built to Telcordia standards
- Diode pump technology is very reliable (undersea fiber optic repeaters)
- Distributed thermal load
- Electrical efficiencies: 8- 15%
- Ongoing work for use on satellites
- Wide availability of highly engineered parts
- Wavelength flexibility

CO2 - Breadboard Instrument (2006)







CO_2 measured over 206 & 405 m open paths

Comparison to samples from end point in-situ sensor

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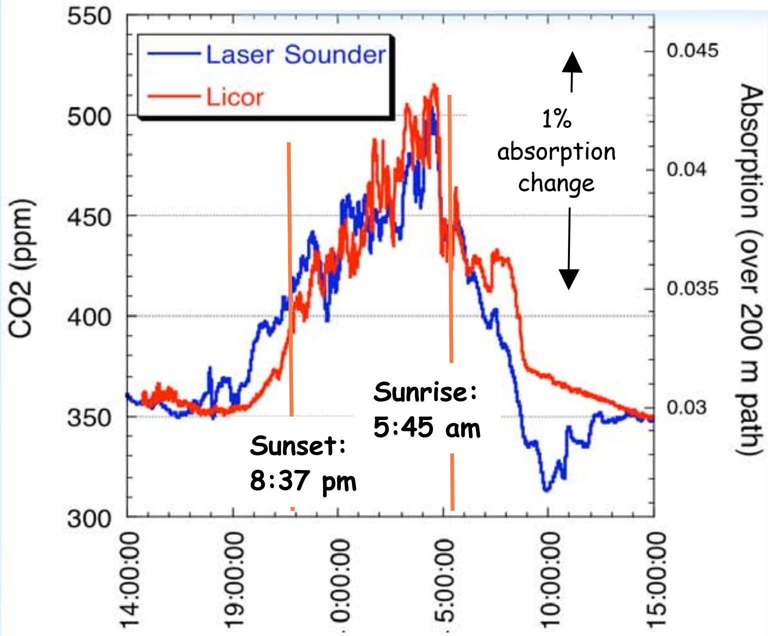
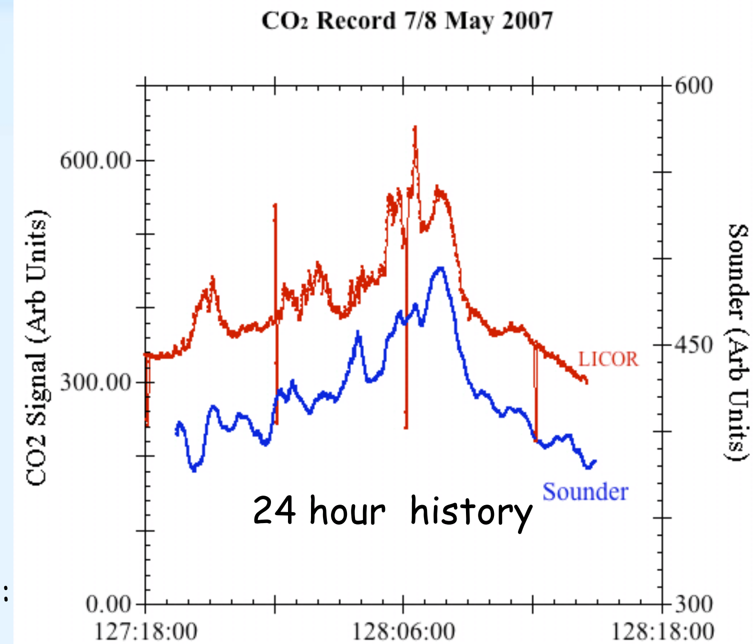


25 hour history



Earlier Summer Measurements: 206 m path (vegetation active)

- Breadboard measurements offset and scaled
- Show diurnal change in Co2 near surface
- Agreement to 1: 500 in absorption over 1st 16 hrs
- Close to performance needed for space mission
- Improvements later improved reproducibility

In-situ samples: Single-point measurements (Licor) from air intake on B33 rooftop

CO2 Absorption Measurements from van over 2.2 km path near GSFC using PMT detector

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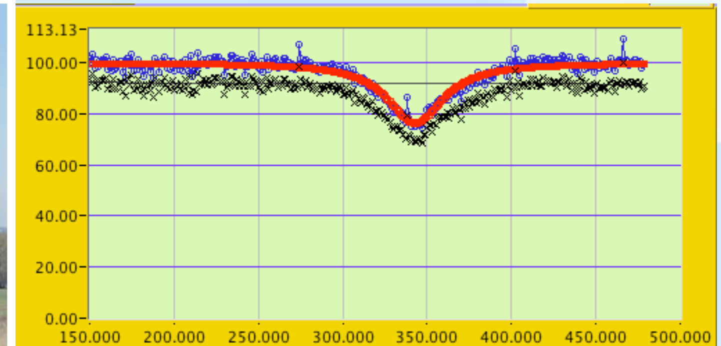
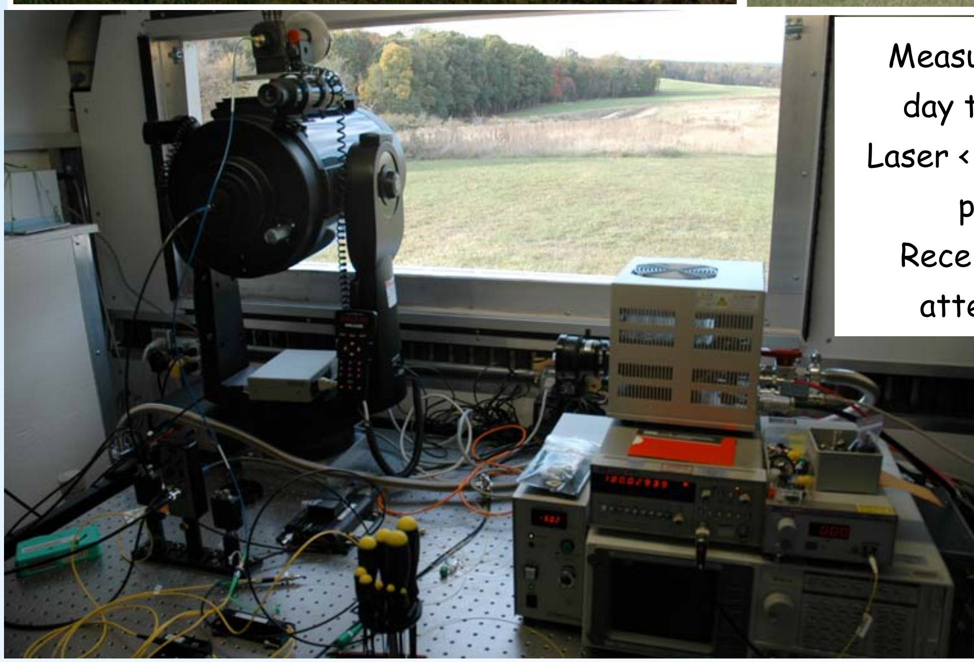
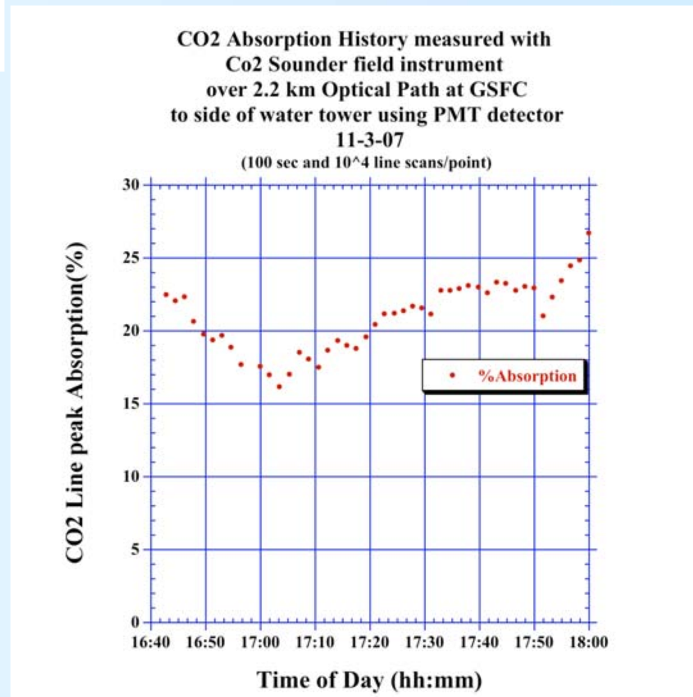


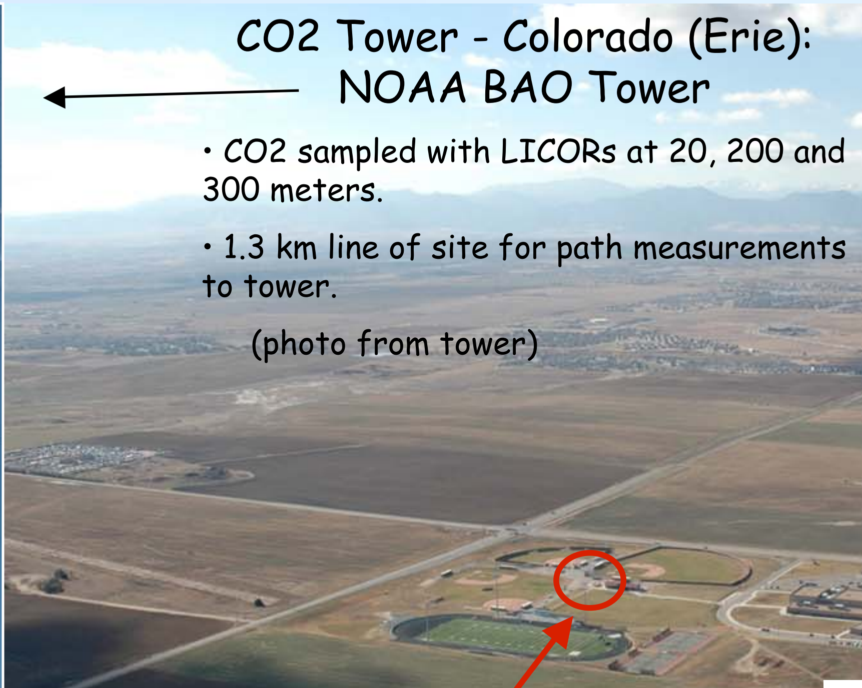
CO2 Line scan using PMT receiver



Measurements - day to sunset
Laser < 0.4W peak power
Receiver PMT attenuated



CO2 Measurements at NOAA tower, Erie CO

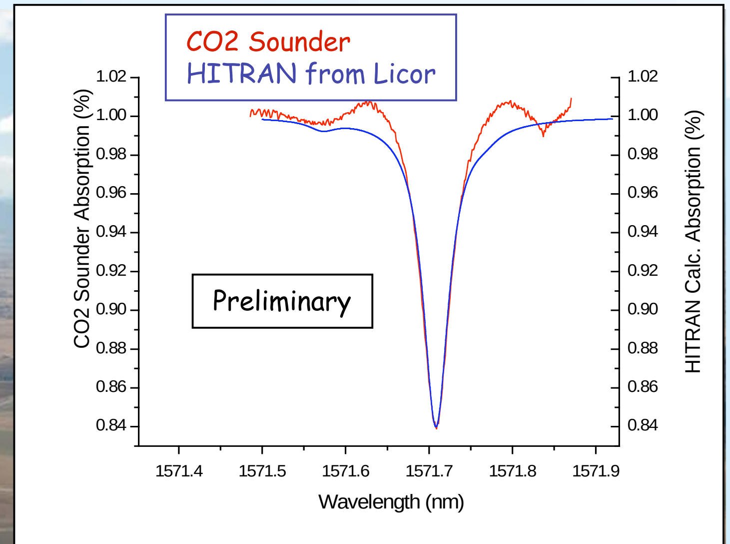


CO2 Tower - Colorado (Erie):
NOAA BAO Tower

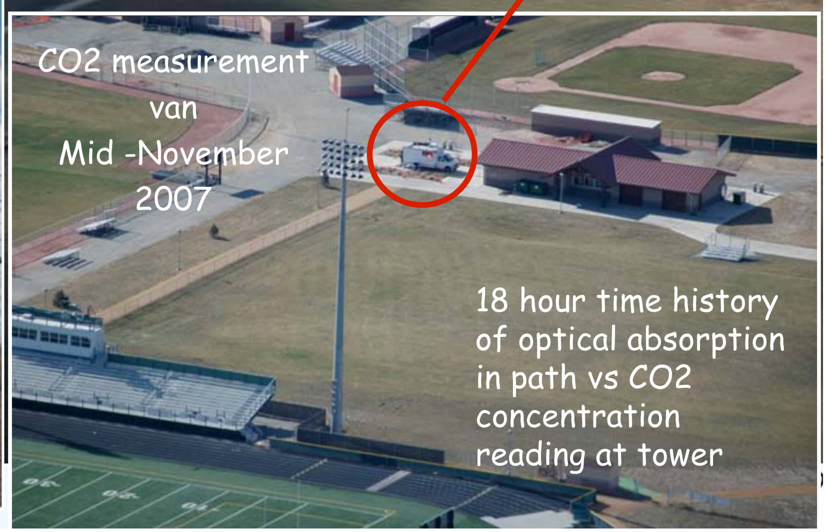
• CO2 sampled with LICORs at 20, 200 and 300 meters.

• 1.3 km line of site for path measurements to tower.

(photo from tower)

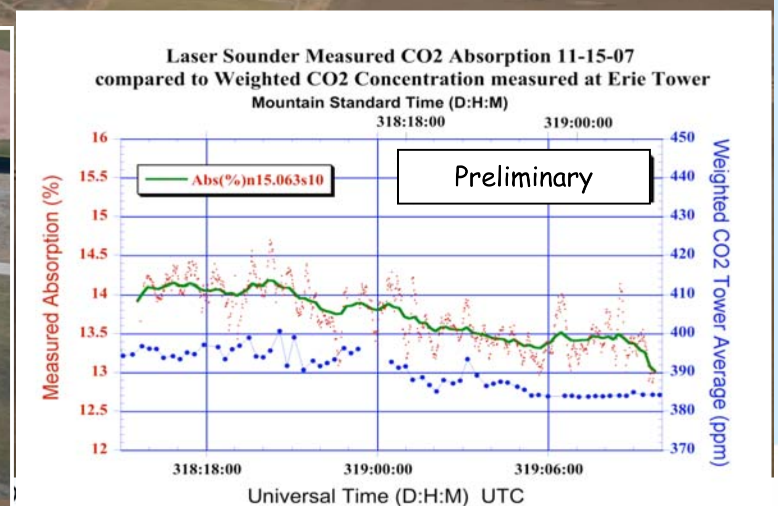


Comparison of measured CO2 line scan with HITRAN Prediction based on the Tower LICOR

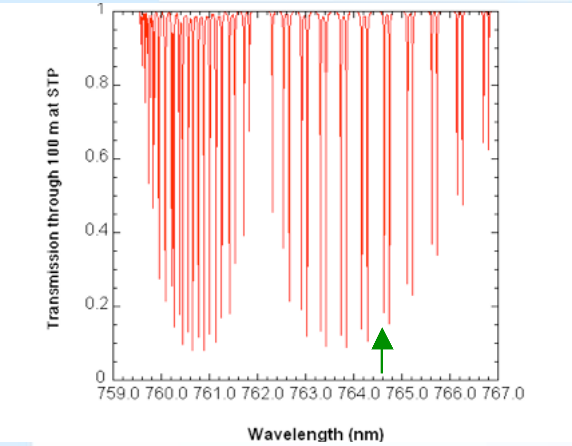


CO2 measurement van
Mid -November 2007

18 hour time history of optical absorption in path vs CO2 concentration reading at tower



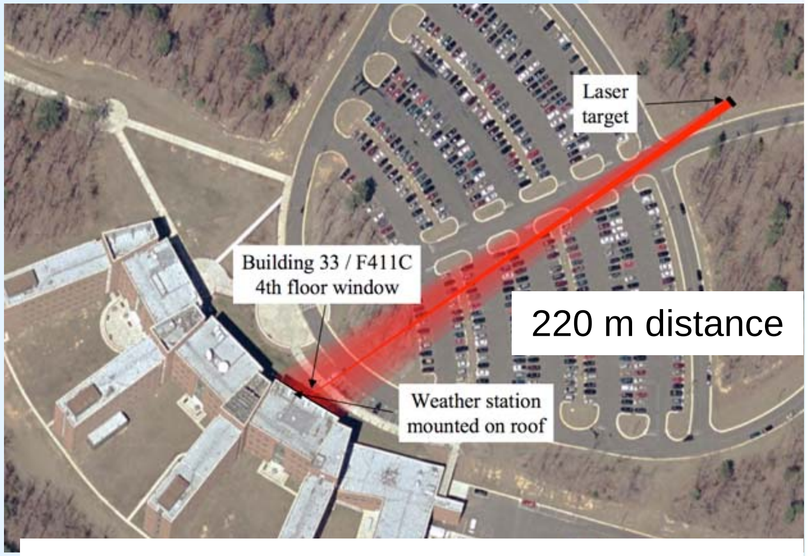
Oxygen - Open path measurement of absorption lines near 765 nm (M. Stephen)

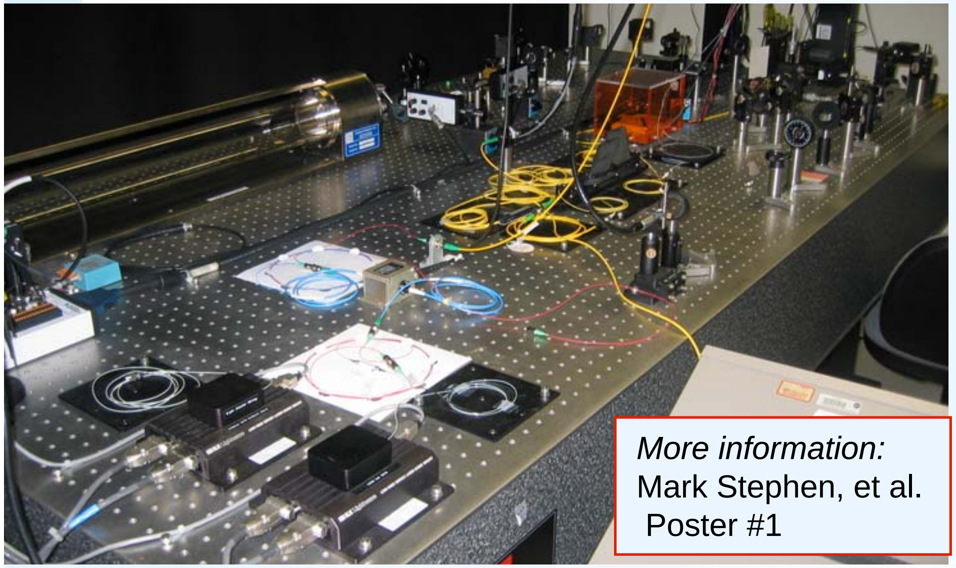


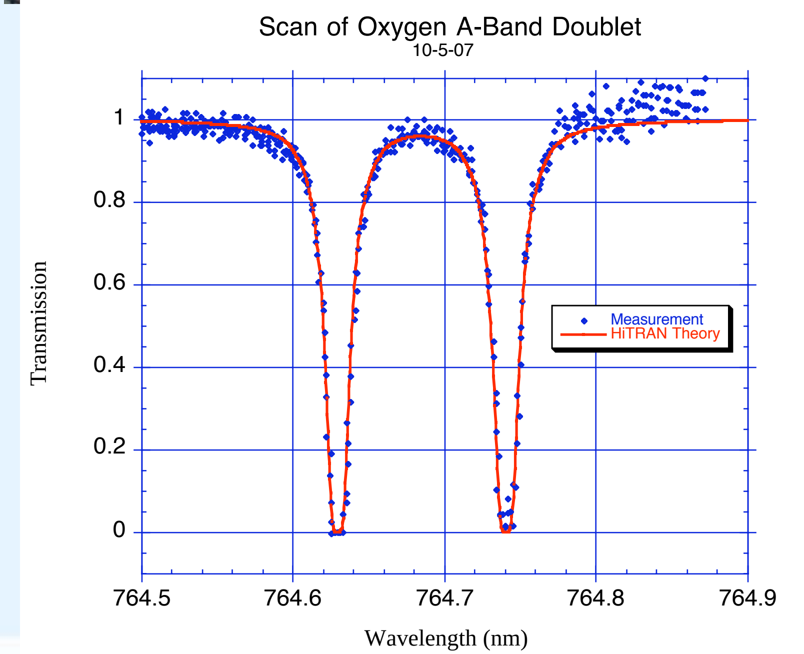
Oxygen A band: Calculated atmospheric transmission for 100 m path at STP

Telescope viewing target

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

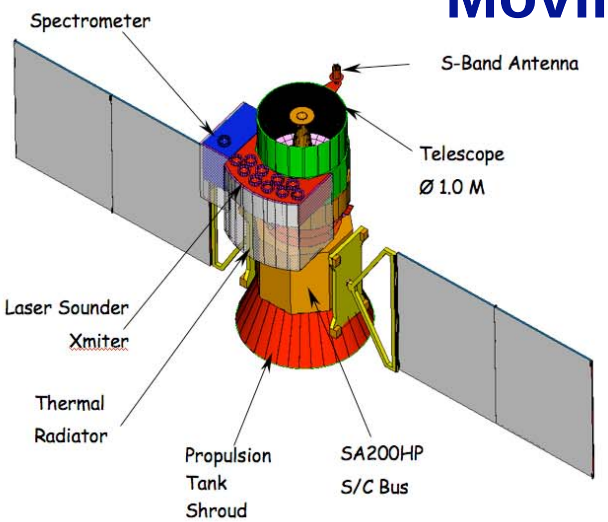


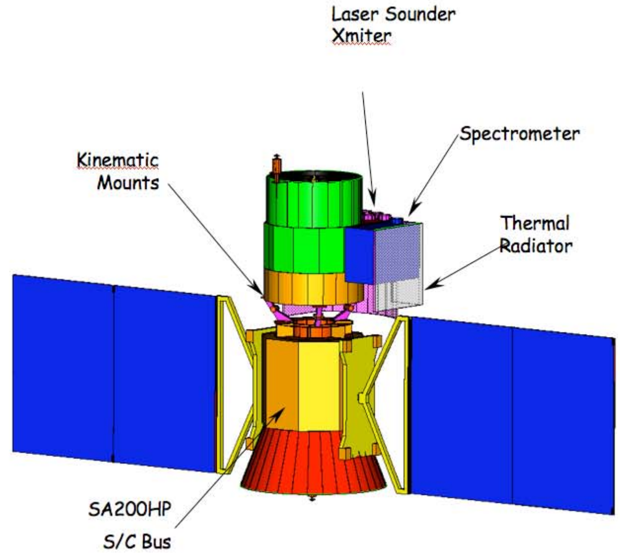




More information:
Mark Stephen, et al.
Poster #1

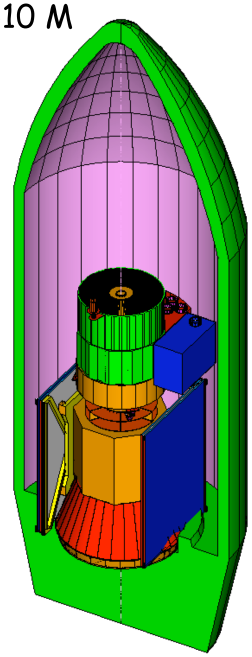
Moving to Space



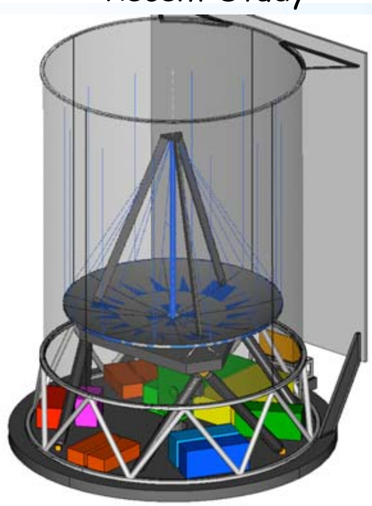


Initial Space Mission Study showed space mission concept practical

Delta 2320-10 M Shroud



Instrument configuration from Recent Study



Overview of new instrument study in Posters

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Carbon Cycle Initiative, CO2/Lidar

System Overview

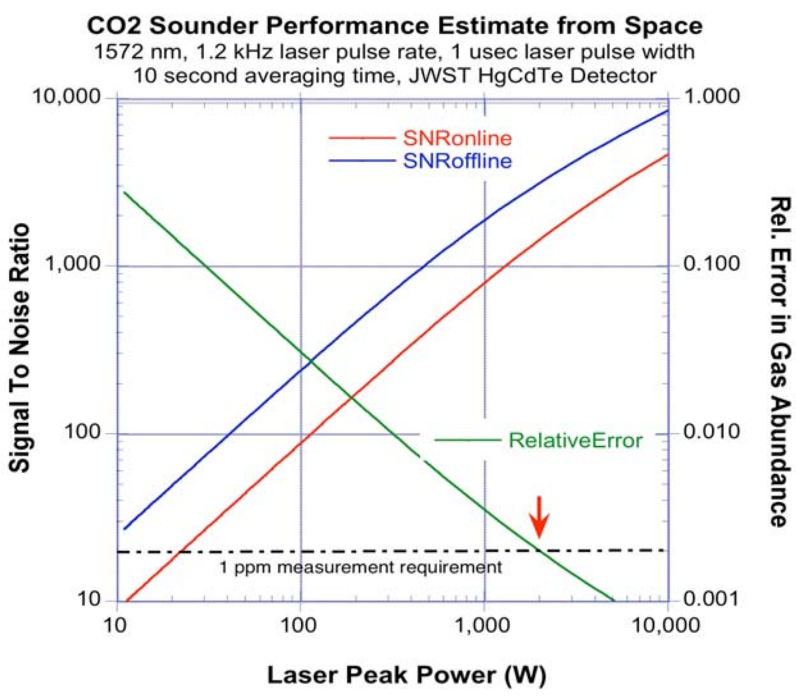
David Everett

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

Space: SNR & Relative Measurement Errors

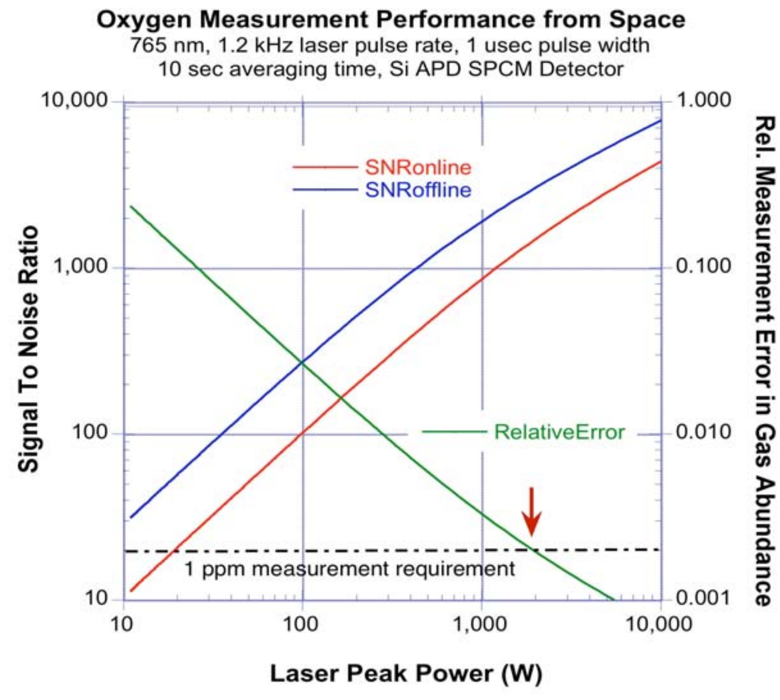
(10 seconds observing time, 500 km orbit, 1.5m telescope)

CO2 column measurement



4 EDFA's, 500W pk power

O2 column measurement



8 EDFAs, 500W pk power, 50% doubling

Rel Measurement Errors scale as (laser pulse energy)$^{-1}$ *(T) $^{-1/2}$

Next steps: 1. Airborne demo - fall 2008
2. ASCENDS Precursor for ESTO IIP - start 10/08

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CO_2 Laser Sounder for ASCENDS Mission – Technology development and airborne demonstrations

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December 12, 2007

Submitted in response to NNH07ZDA001N-IIP

Summary:

We propose to advance measurement technology and reduce the risk and cost for the ASCENDS mission. The measurements from our targeted laser instrument for space will measure CO_2 column abundance and fluxes with a spatial resolution of ~100 km, and will meet or exceed the science needs as summarized in the mission description.

Our pulsed laser approach measures the energies of laser pulses reflected from the Earth's surface. Laser transmitters for CO_2 and O_2 are rapidly tuned on and off selected atmospheric CO_2 and O_2 absorption lines near 1572 nm and 765 nm. A laser at 1064 nm is used to measure surface height and aerosol backscatter profile. Time gating is used to isolate the echo pulses from the surface and to minimize errors from atmospheric scattering and solar background.

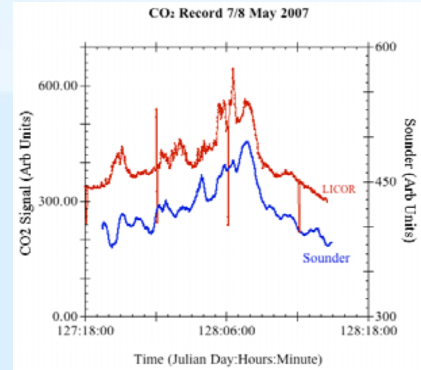
Our proposal leverages strong understanding and capabilities developed over the past 7 years with support from the ESTO ACT and IIP programs. This work addressed many aspects of the measurement, improved the technique and technologies, and successfully addressed a number of significant error sources. We have demonstrated both CO_2 and O_2 measurements in open path tests, and made precise measurements of CO_2 absorptions over many days. Our understanding of CO_2 fluxes is enhanced by co-investigators who conduct research on atmospheric CO_2.

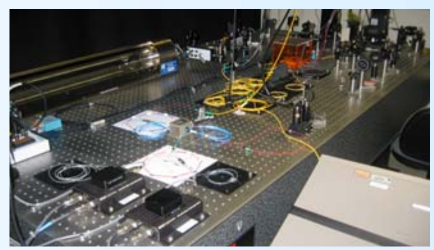
We propose to advance the readiness of the instrument technologies. We will demonstrate these in an airborne precursor instrument for the ASCENDS mission, to use as a simulator for a space mission, as a test bed for improving components, and for airborne science campaigns. We will also optimize the calibration approaches and flux recovery and improve the fidelity of the space instrument definitions. Our proposed work will advance the technology TRL > 5, to allow an instrument baseline that can be developed for space mission in a ~3-year period.

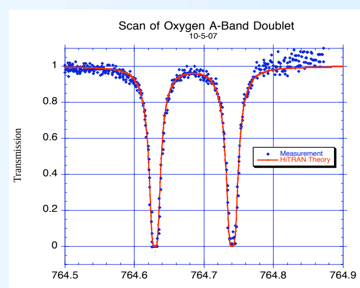
Airborne Precursor for ASCENDS Mission:
Calibrated mixing ratio measurements

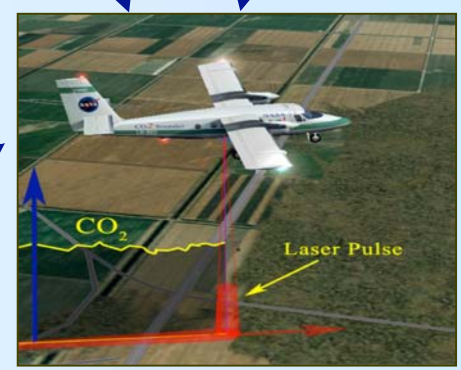
Why ?

- Simulator for Space
- Test bed for evolving components
- Airborne science campaigns









ASCENDS Airborne Precursor Instrument