Laser Sounder for Measuring Atmospheric CO2 Concentrations for the ASCENDS Mission - Progress

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Abstract

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Accurate global measurements of tropospheric CO2 concentrations with diurnal coverage and monthly temporal resolution are needed to better quantify the processes that exchange atmospheric CO2 with the land and oceans. The National Research Council's 2007 Decadal Survey for Earth Science recommended following the OCO and GOSAT CO2 measuring missions with a laser-based mission called ASCENDS.

We have been developing and analyzing the laser technique and technologies for the remote measurement of tropospheric CO2 concentrations from space. Our initial goals are to develop and demonstrate the lidar techniques and technologies that permit measurements of the CO2 column abundance over horizontal paths and from aircraft at the few-ppmv level. Our longer-term goal is to demonstrate the needed capabilities of the technique and technologies, and develop a space mission approach and the instrument design for the ASCENDS mission. This work in ongoing and has been supported by the NASA ESTO ACT and IIP programs.

Our approach is to use the 1570-nm CO2 band and a pulsed dual channel laser absorption spectrometer. This uses differential lidar absorption measurement in an altimeter mode, and continuously measures at nadir from a near-polar circular orbit. It uses several tunable fiber laser transmitters allowing simultaneous measurement of the absorption from a CO2 absorption line in the 1570 nm band, O2 extinction in the oxygen A-band, as well as surface height and aerosol backscatter in the same measurement path. It directs the narrow co-aligned laser beams toward nadir, and measures the energy of the pulsed laser echoes reflected from land and water surfaces. During the measurement, the lasers are tuned across a selected CO2 line and a region between two O2 lines near 765 nm. The lasers have spectral widths much narrower than the gas absorption lines and are wavelength tuned at kHz rates. The receiver uses a telescope and photon counting detectors, and measures the background light and energies of the laser echoes from the surface, along with scattering from any clouds and aerosols in the path. The gas extinction and column densities for the CO2 and O2 gases are estimated from the ratios of the on and off line signals. We use pulsed laser signals and time gating to isolate the laser echo signals from the surface, and to reject photons scattered from thin clouds and aerosols in the path, which can otherwise bias retrievals. High signal-to-noise ratios are required and the gas column absorption estimates need to be quite stable for hours.

We have constructed breadboard versions of the CO2 and O2 sensors, which use fiber lasers and a 20 cm diameter telescopes. We have used them to make measurements of CO2 and O2 absorption in the laboratory and over 206, 400-m 1.3 and 2.2 km long open horizontal paths. These have been in several sessions extending over multiple days, and have allowed us to compare its estimates to readings from external CO2 sensors. We have also calculated several characteristics of the technique for space, including its expected measurement performance, selected some key technologies for space and have performed a space mission accommodation study. We will show these results in the paper.

Atmospheric CO_2 - Cycle, Sources, Sinks

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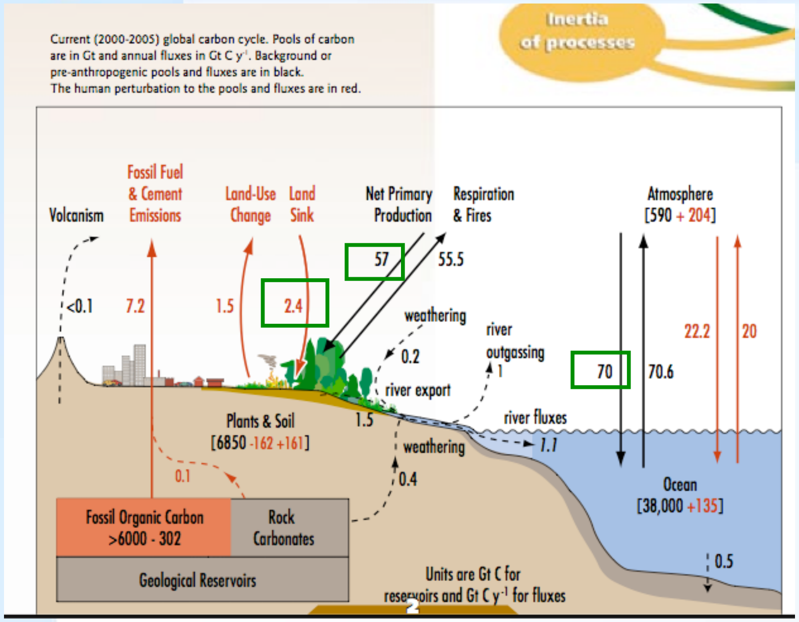
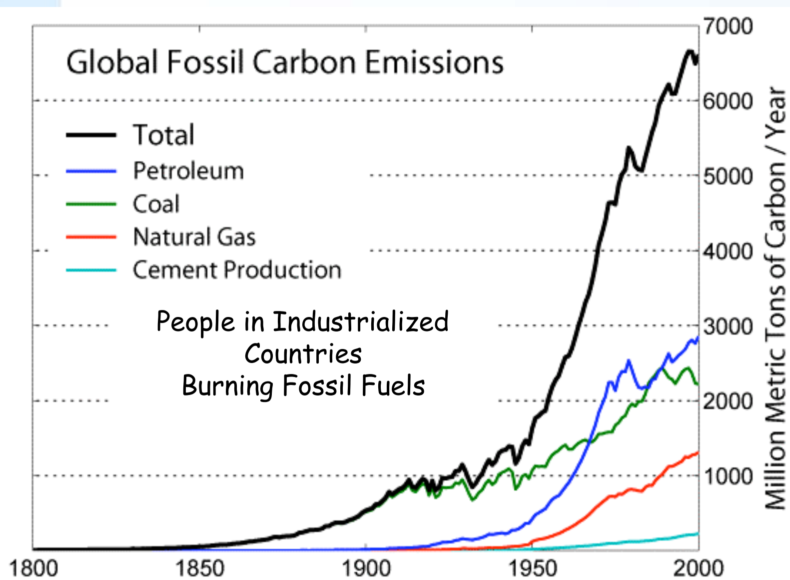
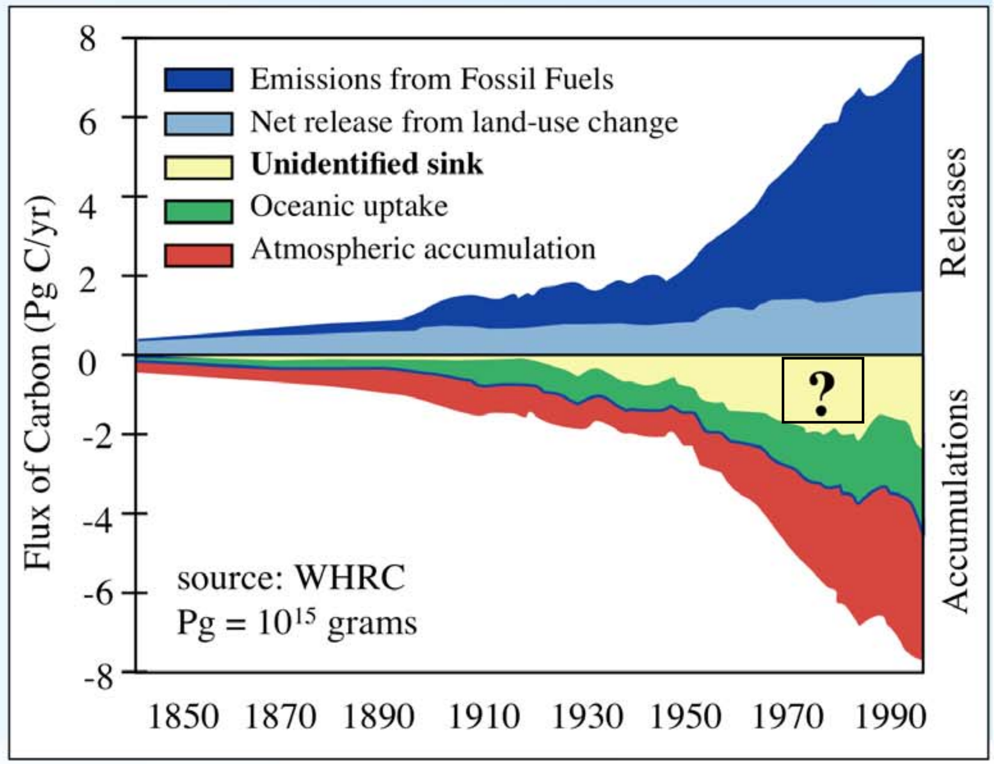


- Of anthropogenic CO_2 emitted to date, ~ 30% can not be accounted for - the "unknown sink"
  - The "unknown sink" may be Northern Hemisphere forests.
  - Will this sink continue to operate in the future?
- How will CO_2 fluxes in polar regions respond to warming ?





Laser Sounder for ASCENDS Mission

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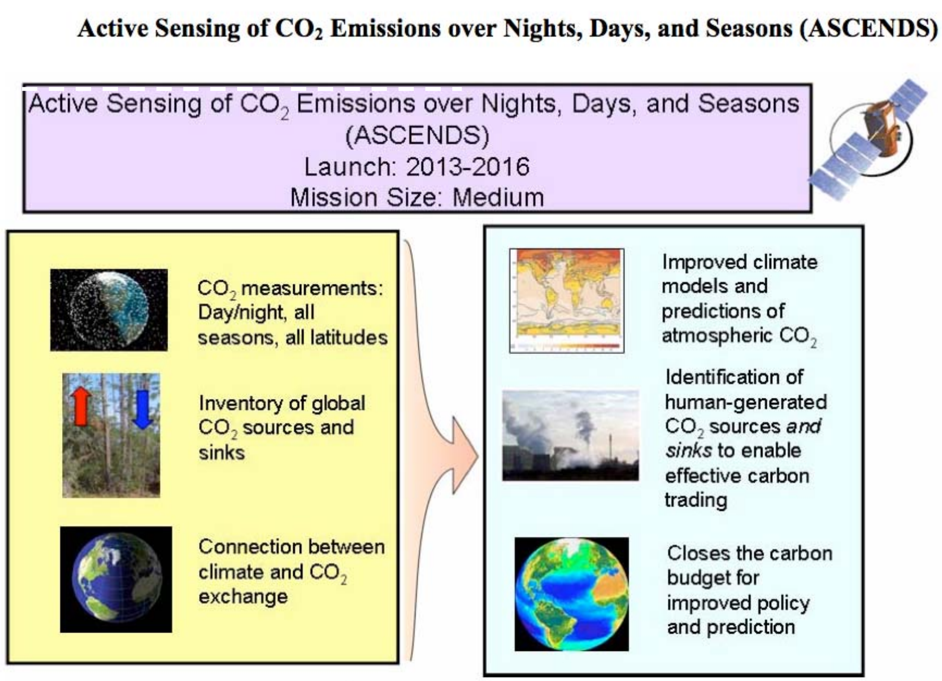
Why lasers ?

- Measures at night & at all times of day
- Continuous "glint" measurements over oceans
- Measures at high latitudes
- Illumination path = observation path
- Smaller measurement footprint
- Measures through broken clouds

Why CO2 Sounder approach ?

- Excellent CO2 & O2 lines at 1572 & 765 nm
- Weight column ~ uniformly in lower troposphere
- Time gating isolates the full column signal
- Surface height & aerosol backscatter profiles
- Multi-wavelengths minimize instrumental errors
- Strong laser & detector technology bases

Ascends Mission from US NRC Decadal Survey

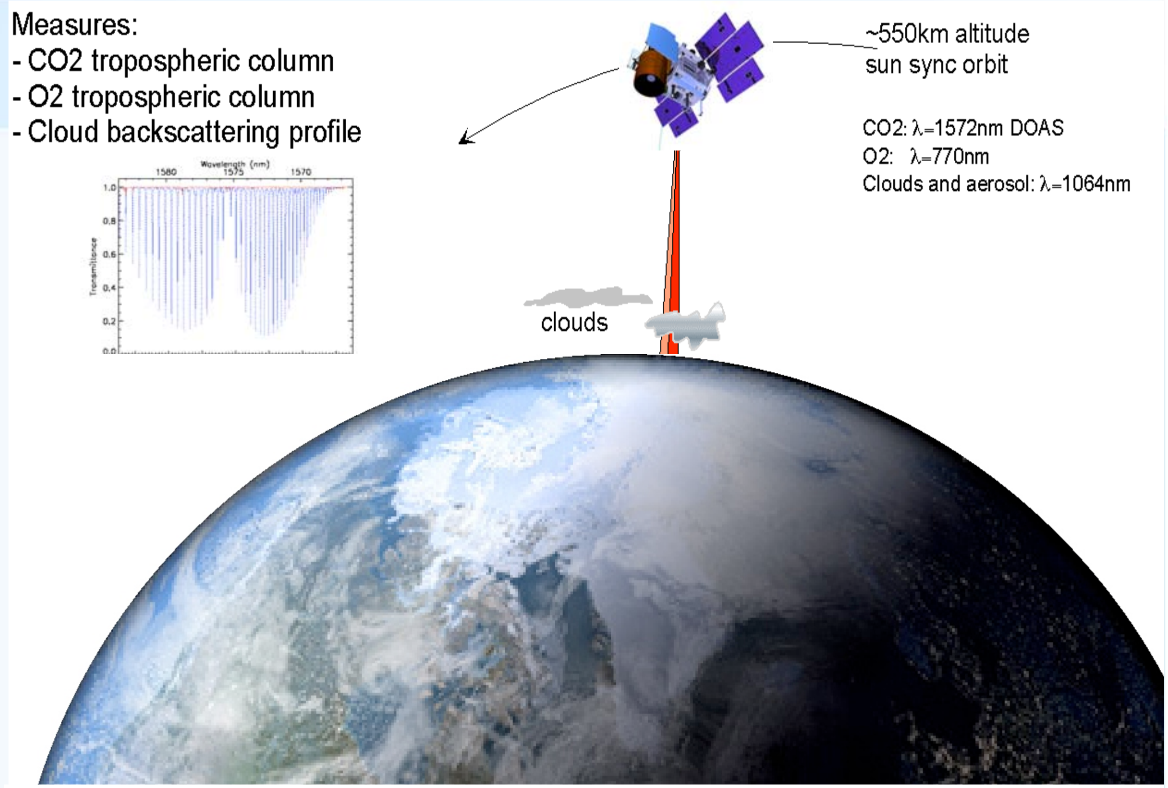


Need CO2 & O2 Lower tropospheric column measurements

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
- Target: ~ 1ppmV in ~100 km along track sample

Dynamic CO_2 concentrations & Orbital Sampling

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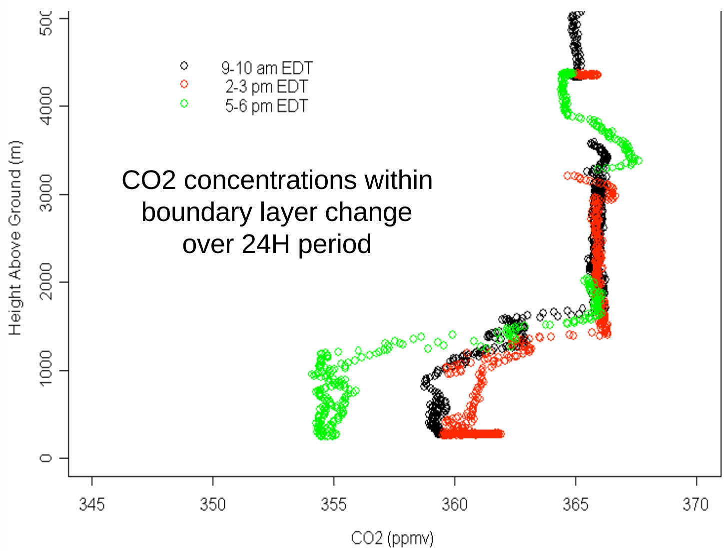
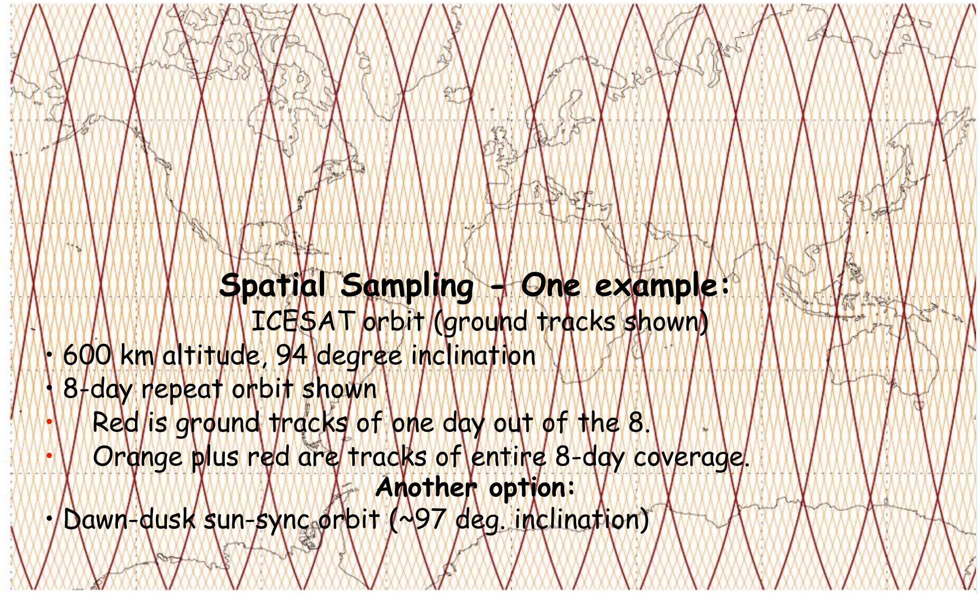
Vertical (diurnal) variability

Daytime example:
CO2 at WLEF tower 8-24-2000





Spatial (x,y) variability

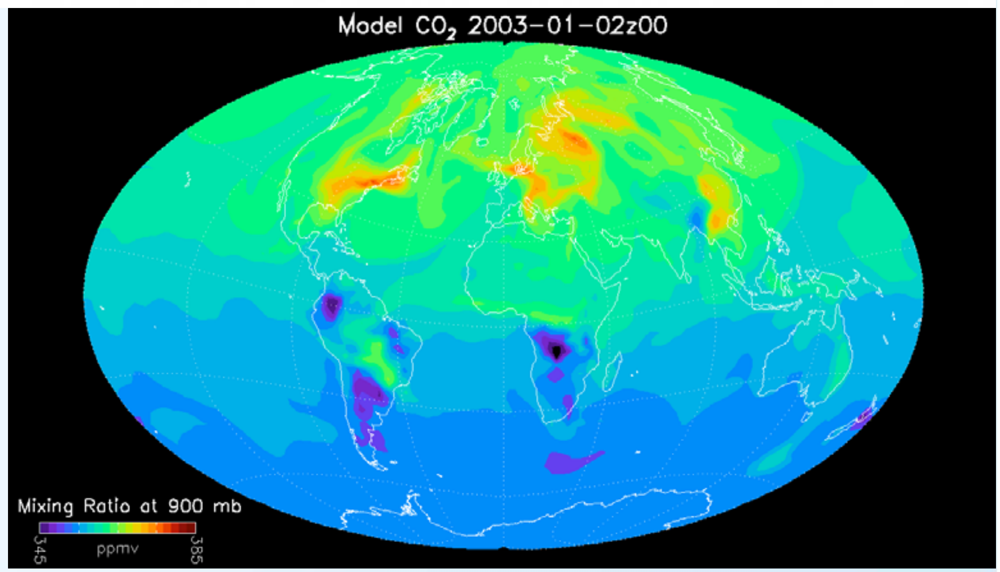
Global CO2 Concentration Simulation

at 900 mbar pressure altitude

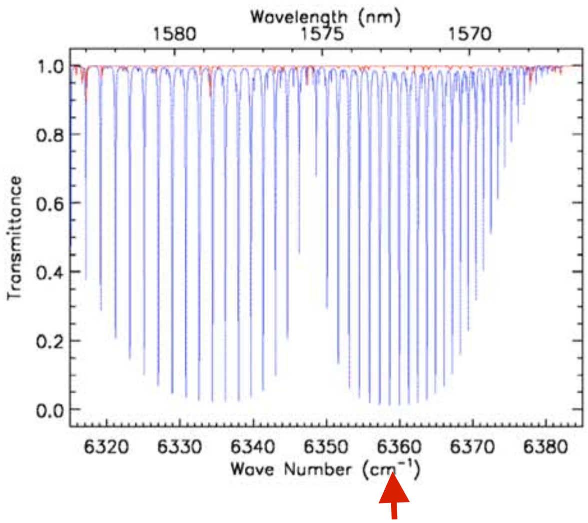
(Kawa et al., JGR, 2004)

The output step of the movie is 6 hrs, i.e., 4/day.

The Simulation runs on a 15-min time step.

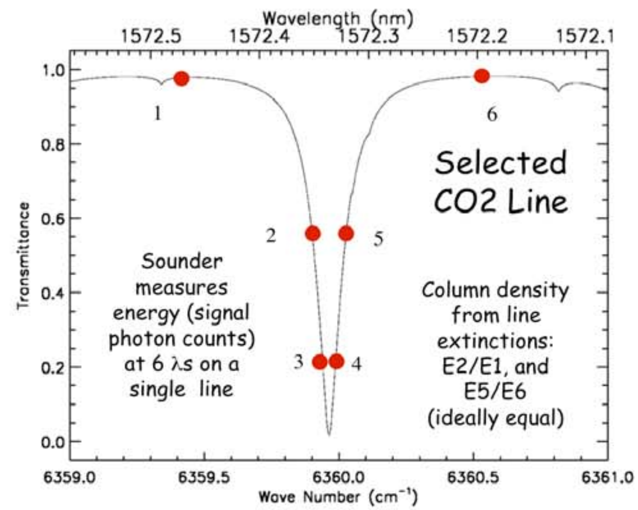


CO_2 Band & Line Measurement Approach



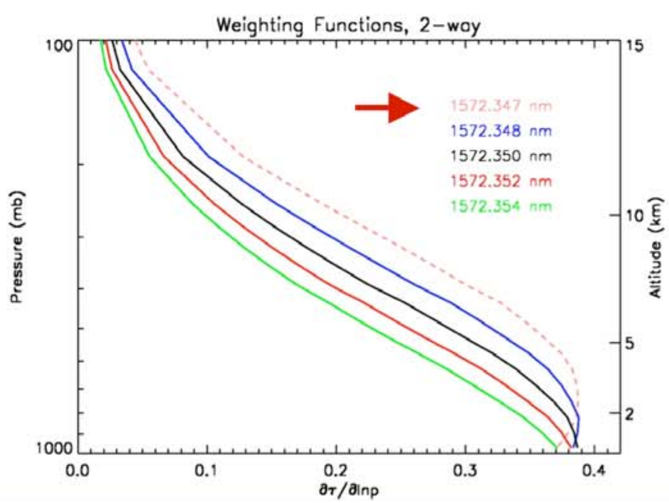
1570 nm CO2 Absorption Band from Space (HITRAN)

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

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, from atmospheric scattering
- 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

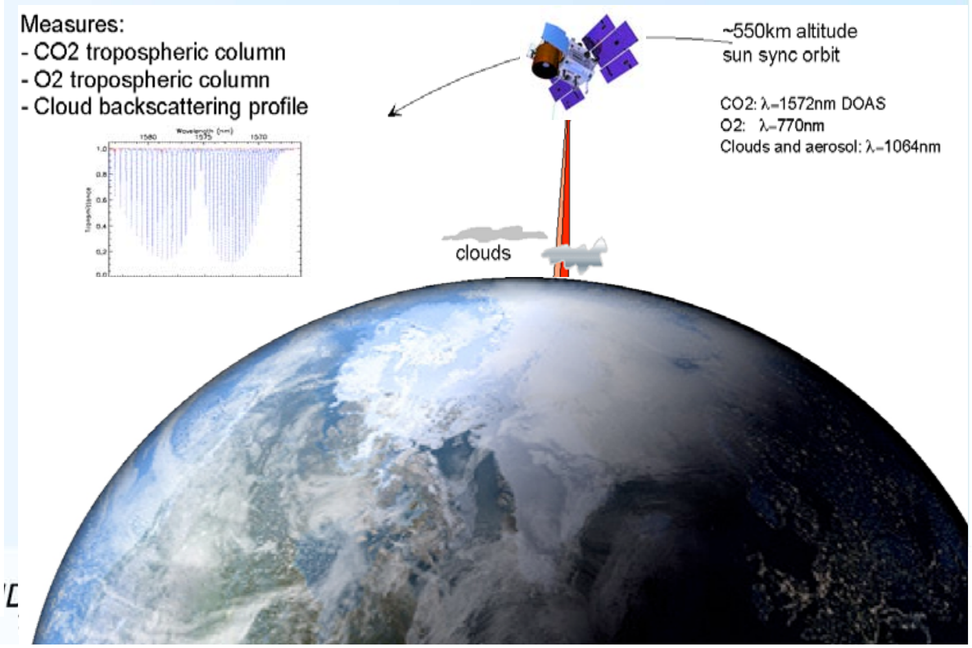
General form of DIAL equation for uniform horizontal path (Beer's Law):

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

Estimated CO2 number density:

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

SNR *"Stability"*



Atmospheric Scattering - Impact on Non-range gated measurements

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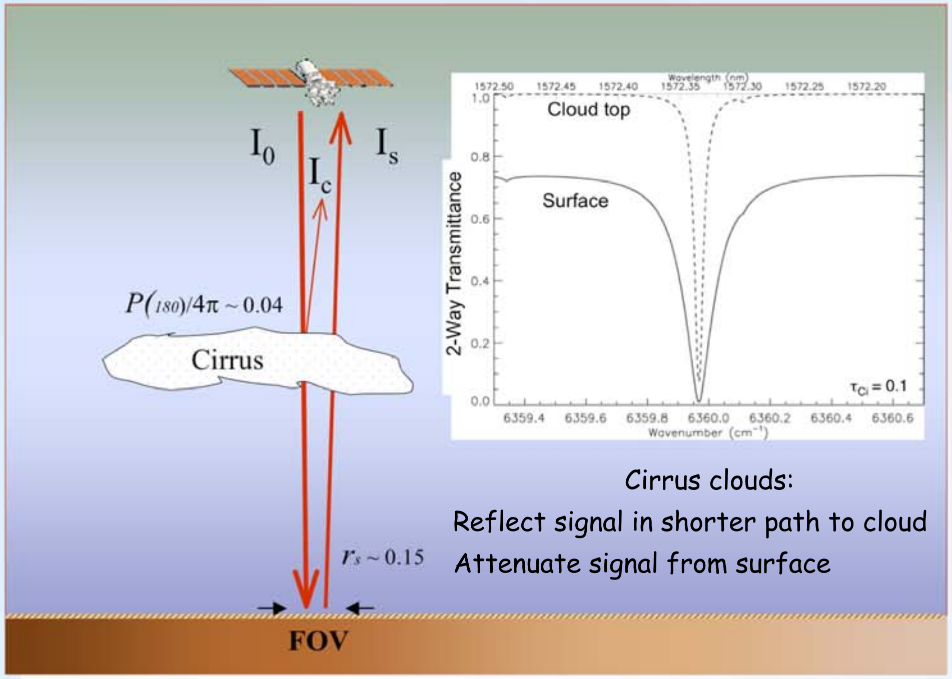
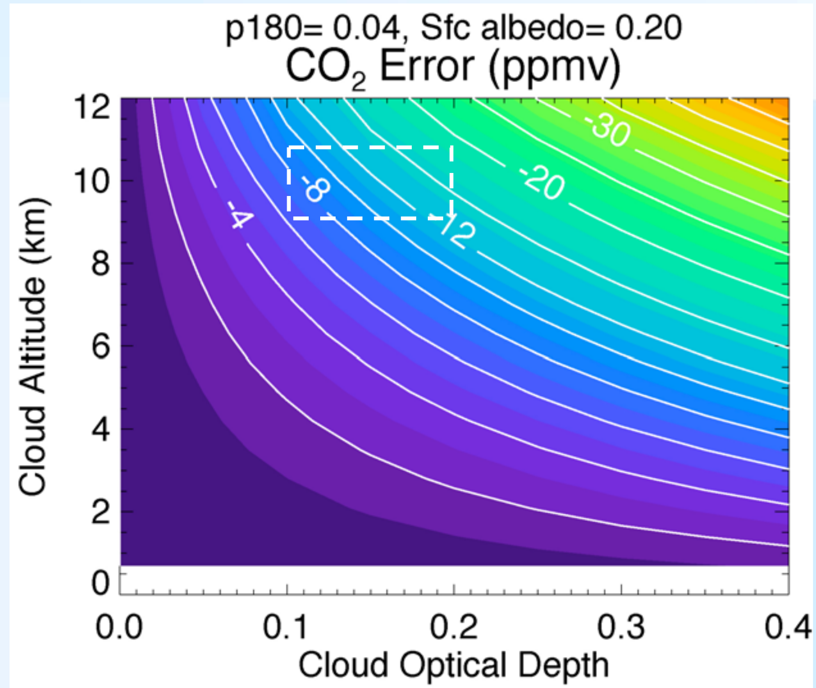




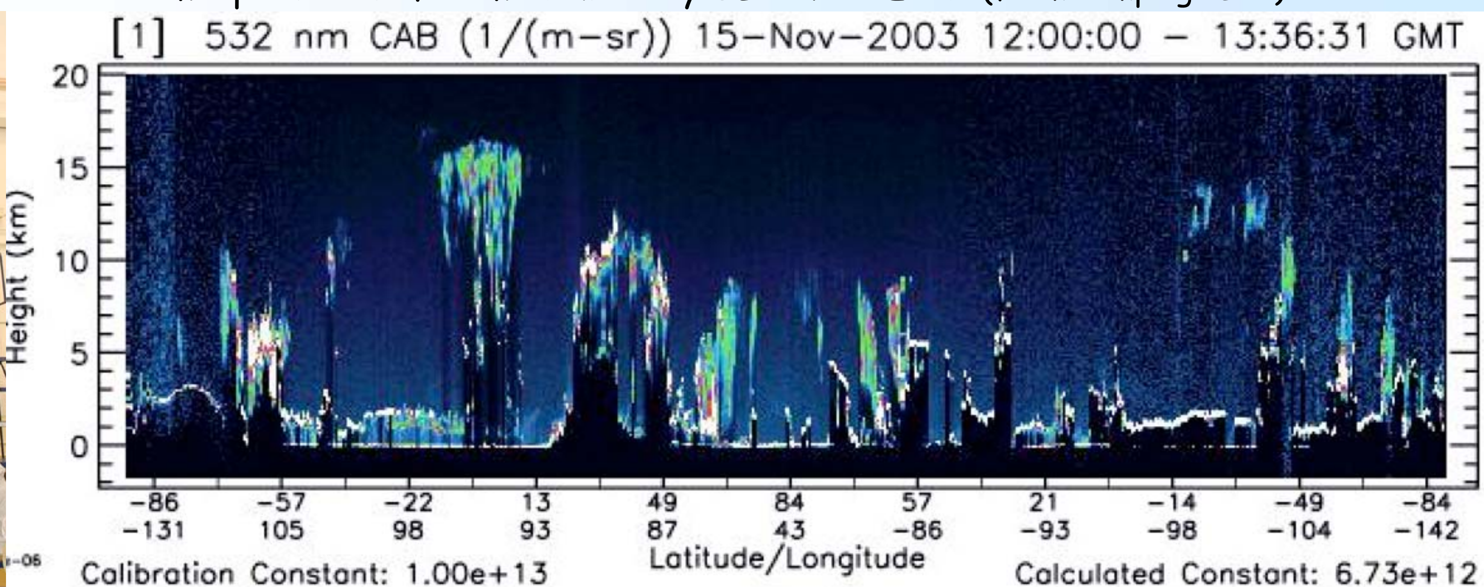
- Cirrus clouds are quite prevalent
- Cloud reflections shorten average optical path -> bias CW (non-gated) column estimates
- Cirrus cloud scattering -> 8-14 ppm errors in non-range gated measurements
- Errors led our team to use a pulsed (& range gated) approach
- Range gating eliminates cloud scattering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

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
- Some thick clouds
- "Target Depth" with clouds ~15 km => ~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)

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

Tunable diode seed lasers

An example of EDFA technology (Lucent)

High Reliability 49 dB Gain, 13W PM Fiber Amplifier at 1550 nm with 30 dB PER and Record Efficiency

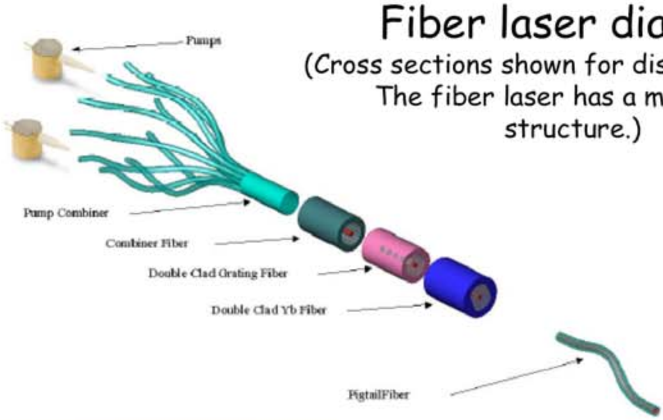
P. Wysocki, T. Wood, A. Grant, D. Holcomb, K. Chang, M. Santo, L. Braun, G. Johnson
Lucent Technologies, Bell Laboratories ,600 Mountain Avenue, Murray Hill, NJ 07974

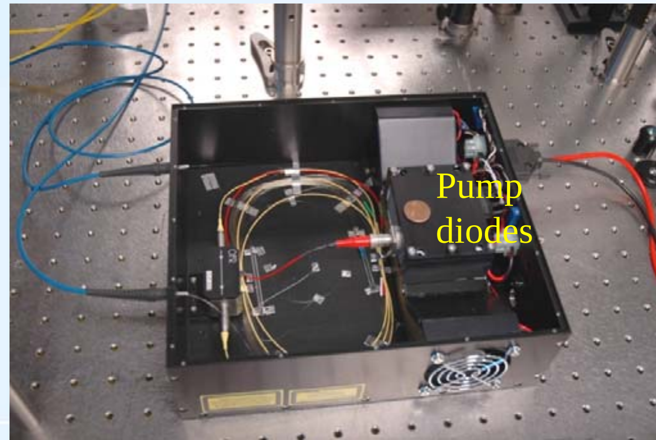
Abstract: We present a single-mode, polarization-maintaining, Er/Yb-codoped cladding-pumped amplifier with up to 49 dB of gain, 13W output power, a 30 dB polarization-extinction ratio, 12.9% electrical to optical conversion efficiency, and 42% optical-optical power-stage fiber slope efficiency. This is the most efficient highest PER HPOA ever reported near 1550 nm. The HPOA was built using all fiber-based components qualifiable for long missions in harsh environments.

OCIS codes: 060.2320, 060.2420, 140.4480

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

Example - Pulsed operation of Large Mode Area EDFA

- Aculight developed an EDFA fiber amplifier using a large mode area (LMA) fiber
- Single frequency measurements (to date) show:
  - 360 watts pulsed peak power at 1540 nm with no SBS
  - Beam quality: M2 < 1.1
  - Frequency doubling to 770 nm with 56% efficiency

Calculations show > 500W peak is feasible (space need).

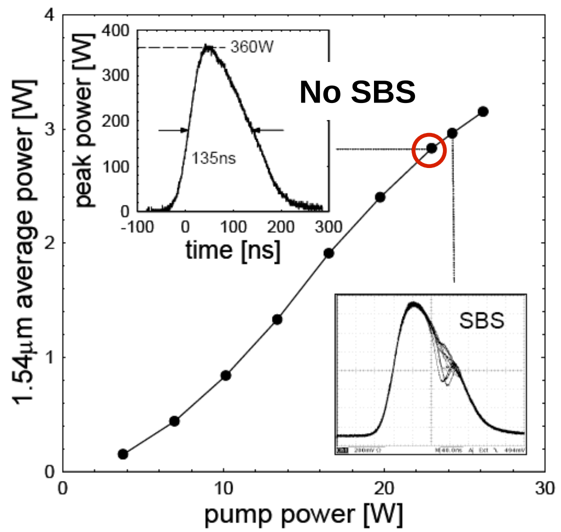


Fig. 3 - 1.54 µm output power at 55 kHz as a function of applied pump power. Additionally, a temporal trace (upper left) with the maximum SBS free peak power and a (long persistence) oscilloscope trace (lower right) showing the onset of SBS are displayed in two separate inserts. The time base of the oscilloscope display was set to 40ns/div.

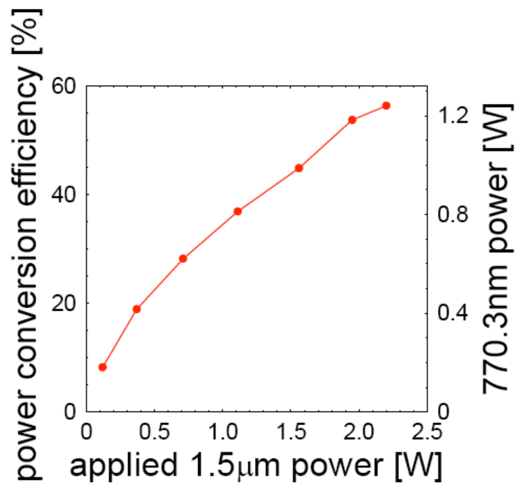


Figure 2-11 Power conversion efficiency to 770.3nm as a function of applied 1540.6nm power.

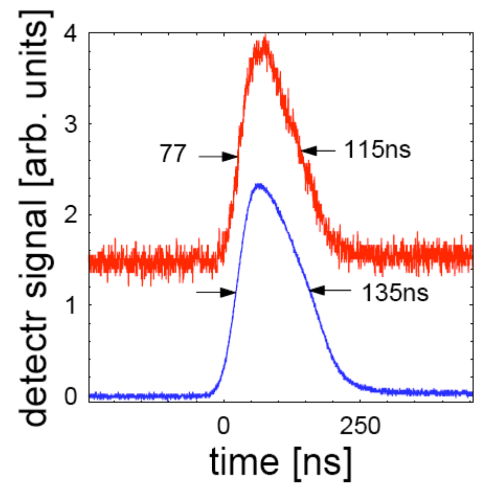
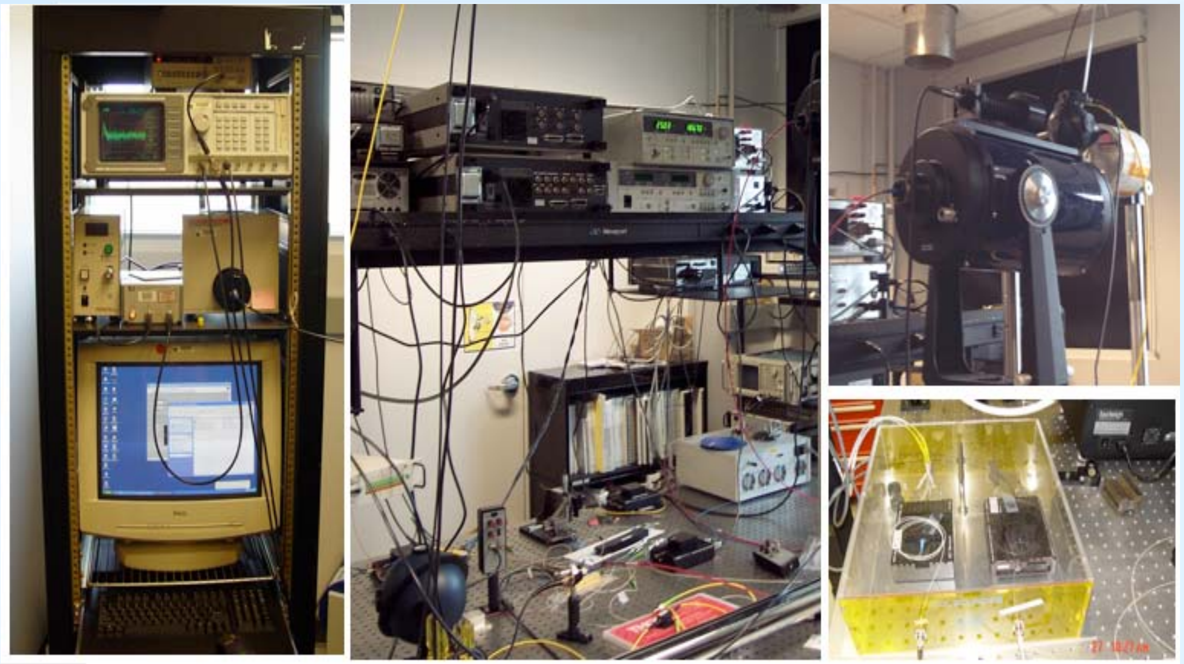


Figure 2-12 Temporal trace of maximum SBS free pulse at 1540.6nm (lower trace) and corresponding frequency doubled pulse at 770.3nm (upper trace).

CO2 - Breadboard & Open Path Atmospheric Measurements across Outdoor paths (206 & 400 m one-way)



Breadboard Co2 laser sounder Charactertistics for March/April 2007

Parameter	Value
CO2 Line wavelength	1572.33 nm
Measurement Approach	FM-CW (chopped)
Wavelength Scan width	3 Co2 lines: 650 pm 80 GHz
Receiver Measurements/freq scan	1024
Wavelength scan resolution	0.6 pm, 80 MHz
Wavelength scan rate	0.3 - 1 KHz (varies)
Laser beam divergence	2.5 mrad
Laser beam power	300 mW
Laser Chopping Duty cycle	50%
Laser Chopping Cycle Rate	207 Hz
Test Path length	405 m
Telescope Diameter	20 cm
Detector type (presently)	InGaAs PIN
Detector Bandwidth	300 KHz
Receiver sample rate	400 & 200 KHz
Receiver recording duty cycle	10%
Number of scans/measurement	2000
Dwell Time/measurement	65 seconds
Signal processing approach	Sample, normalize, equalize, line fit

CO2 Measurement - Stability Demonstration

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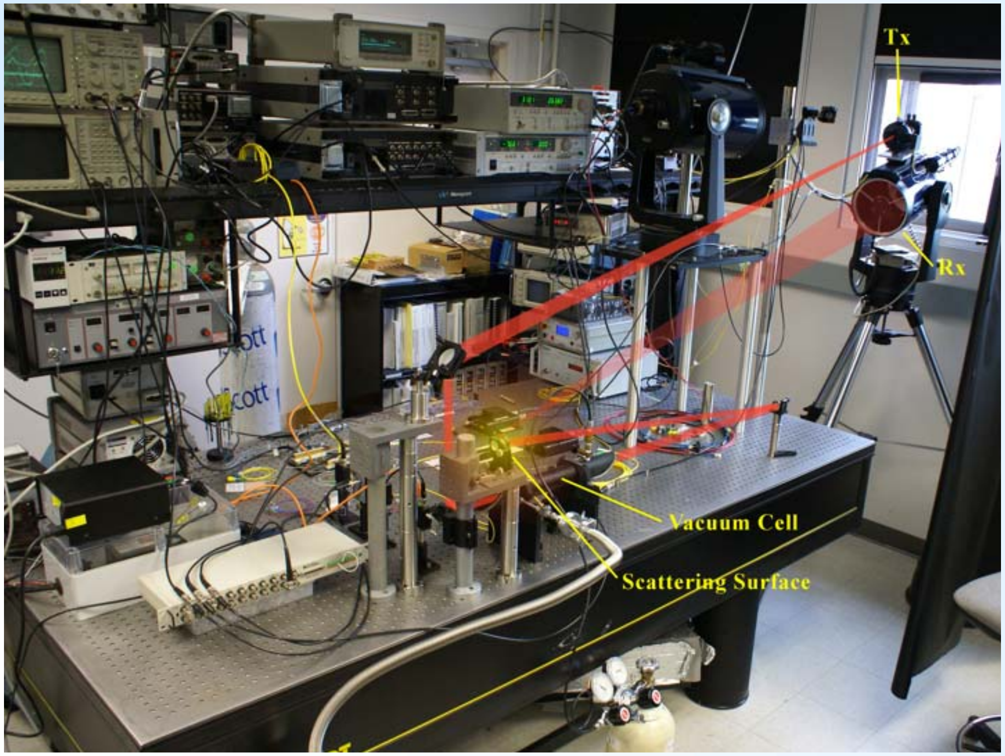
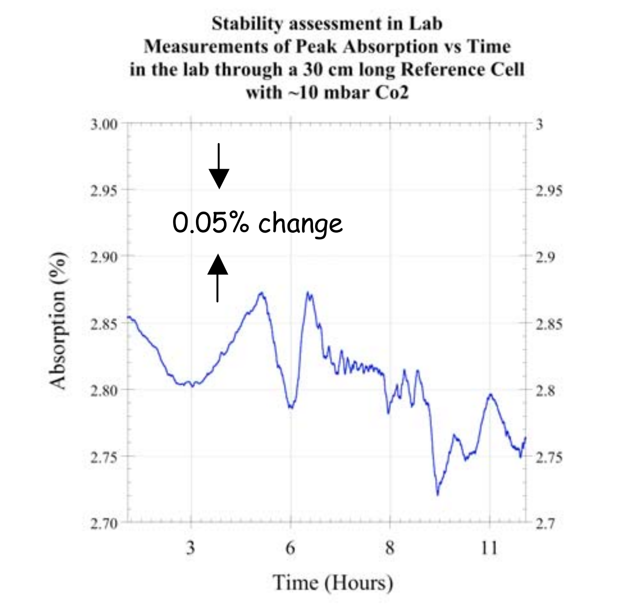
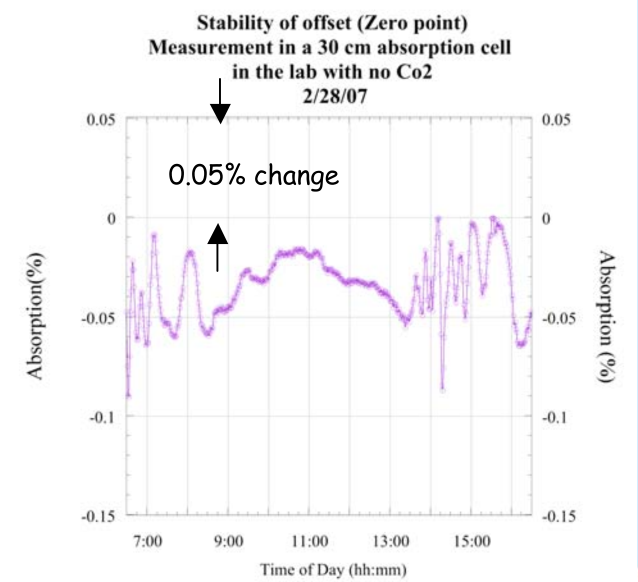


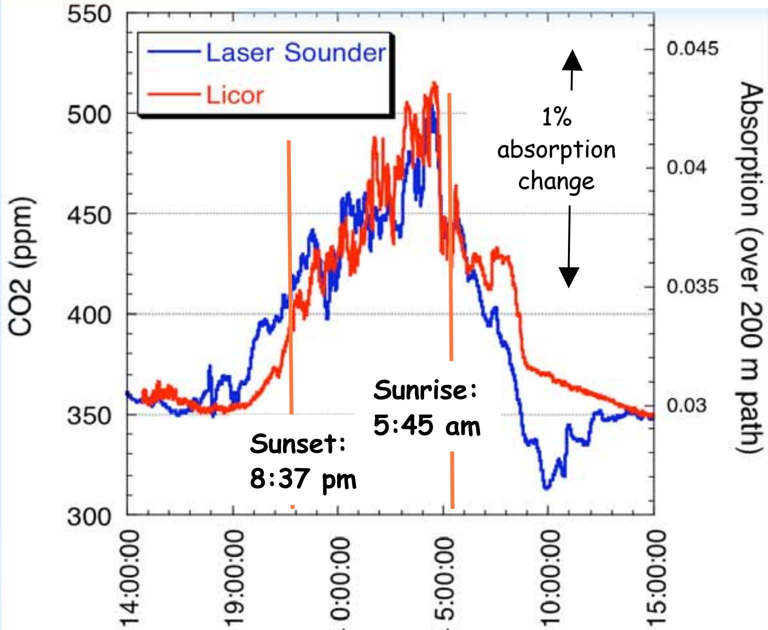




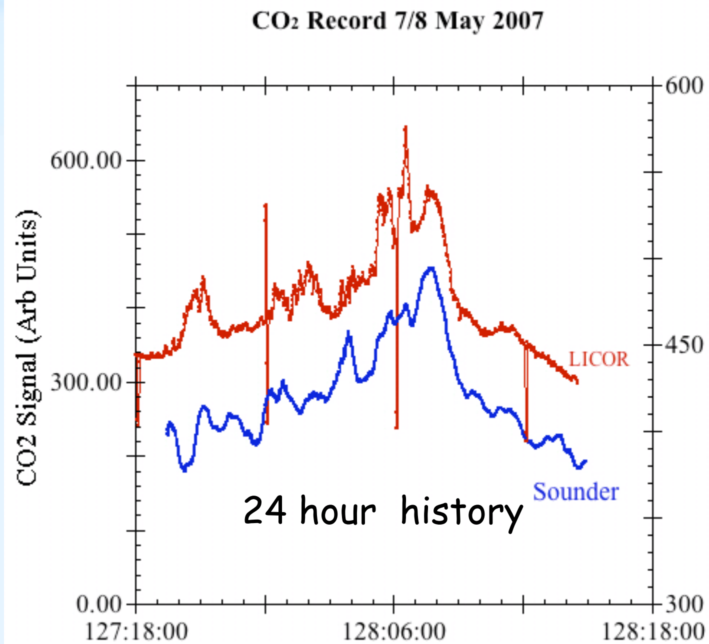
- Must maintain stability between calibrations.
- For space , many hours between calibrations to ground sensors
- Changing etalon fringes can cause drifts in Laser spectrometers
- Goal: keep breadboard drifts to < 10^{-3} * expected absorption.
- For 50% absorption => drift errors < 0.05%

\- measurements with 30 cm absorption cell show ~ 0.05% stability for hours

CO_2 measured over 206 & 405 m open paths
Comparison to samples from end point in-situ sensor



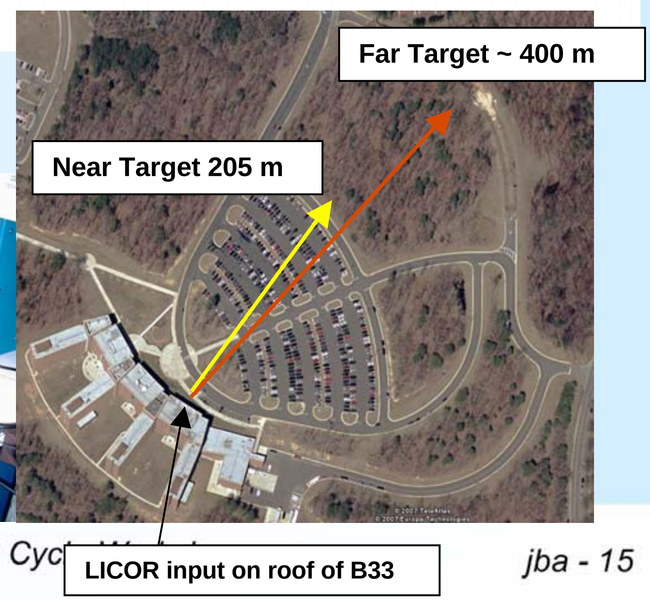
25 hour history



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



CO_2 Receiver - Photon Counting Detectors

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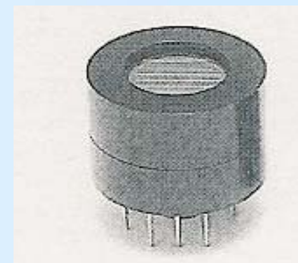
Now:

Hamamatsu H9170-75 PMT

-Detector used in breadboard receiver

HV supply and PMT housing

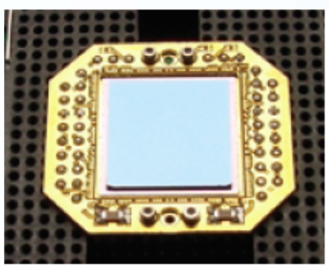
- Turn-key operation
- QE = 9% at 1572 nm
- InP/InGaAs photocathode
- Photocathode: ~5 mm diameter
- Dark count rate ~200 KHz at -80 C (TEC cooled)
- PMT power consumption ~150mW



TO-8 PMT package with transmissive photocathode

Under Development:

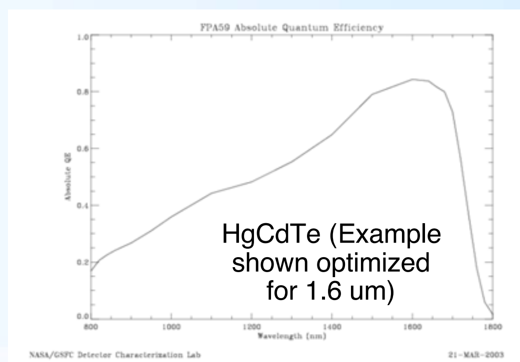
Adapting HgCdTe Photon Counting Detectors



The Infrared Detectors for the Wide Field Camera 3 on HST

ABSTRACT

We present the performance of the IR detectors developed for the WFC3 project. These are HgCdTe 1K×1K devices with cutoff wavelength at 1.7μm and 150K operating temperature. The two selected flight parts, FPA#64 (prime) and FPA#59 (spare) show quantum efficiency higher than 80% at λ=1.6μm and greater than 40% at λ>1.1μm, readout noise of ~25 e⁻ rms with double correlated sampling, and mean dark current of ~0.04 e/s/pix at 150K. We also report the results obtained at NASA GSFC/DCL on these and other similar devices in what concerns the QE long-term stability, intra-pixel response, and dark current variation following illumination or reset.



80% photon detection/accumulation efficiency at 1550 nm with ~0.04 dark counts/sec at 150K

Present read-out configured for photon accumulation

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

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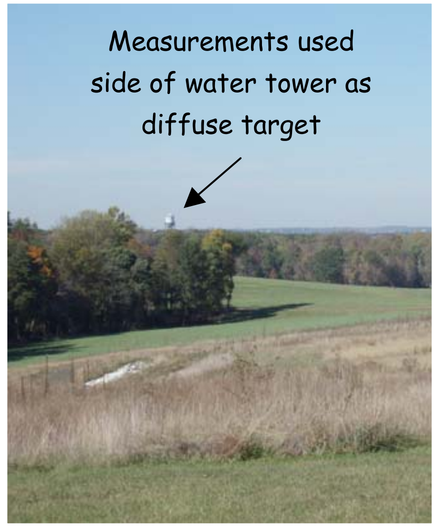
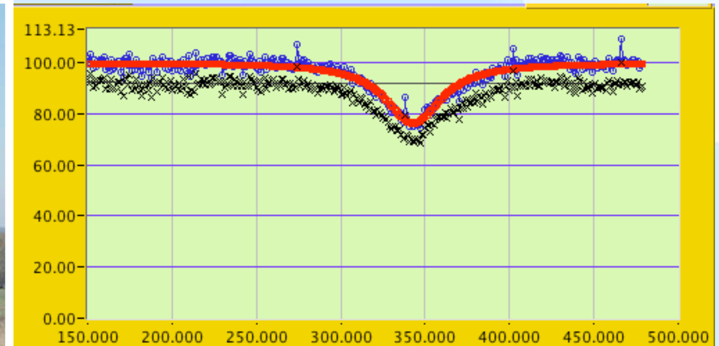
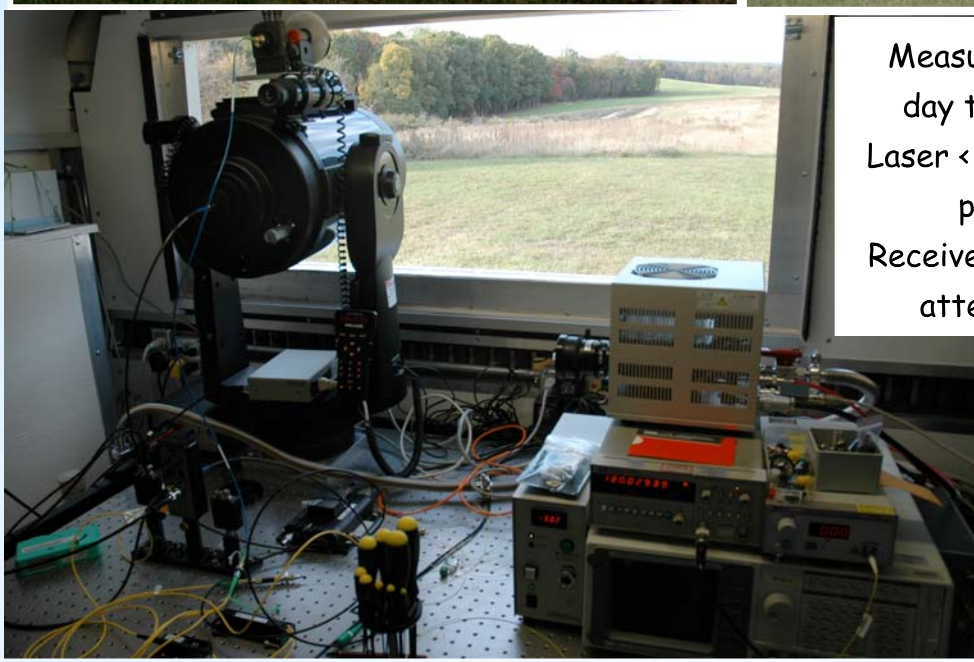


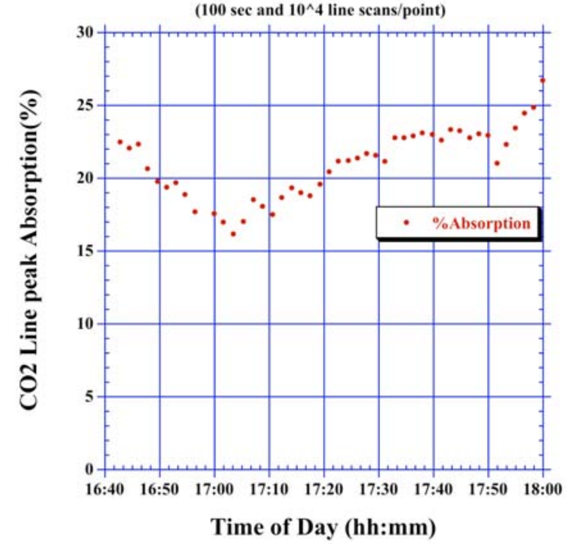
Measurements used side of water tower as diffuse target



CO2 Line scan using PMT receiver



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



CO2 Measurements at NOAA tower, Erie CO
(G. Allan, E. Wilson, H. Riris)

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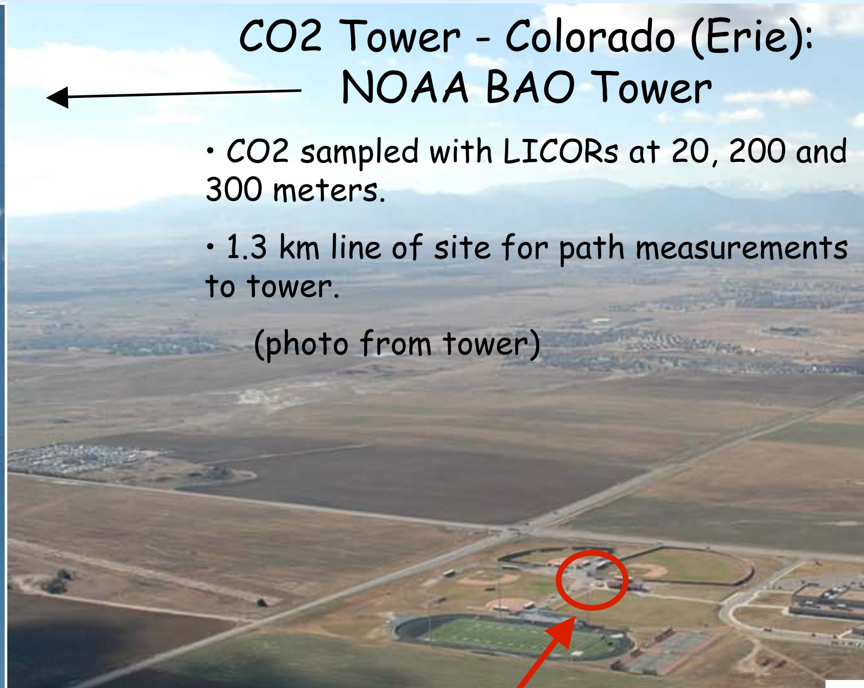
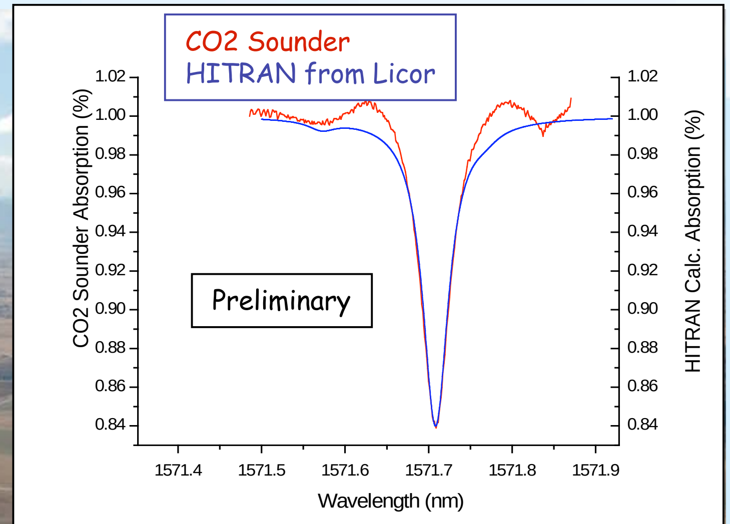


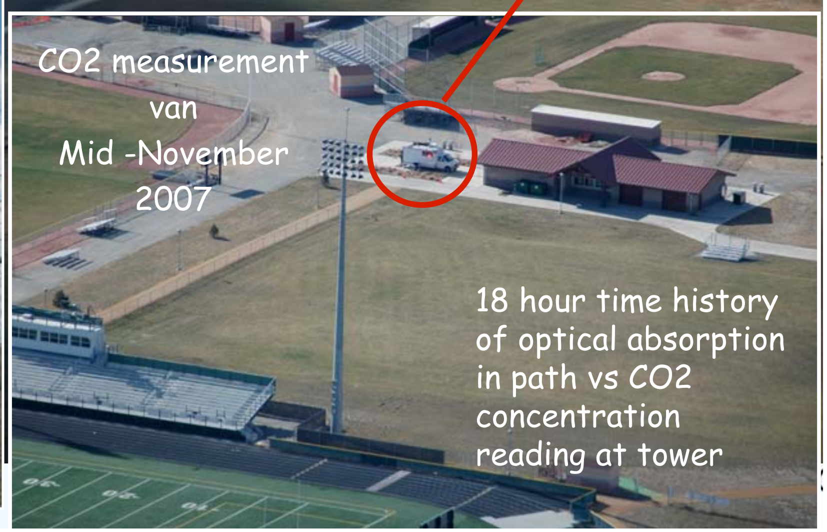
CO2 Tower - Colorado (Erie):
NOAA BAO Tower

- CO2 sampled with LICORs at 20, 200 and 300 meters.
- 1.3 km line of site for path measurements to tower.

(photo from tower)

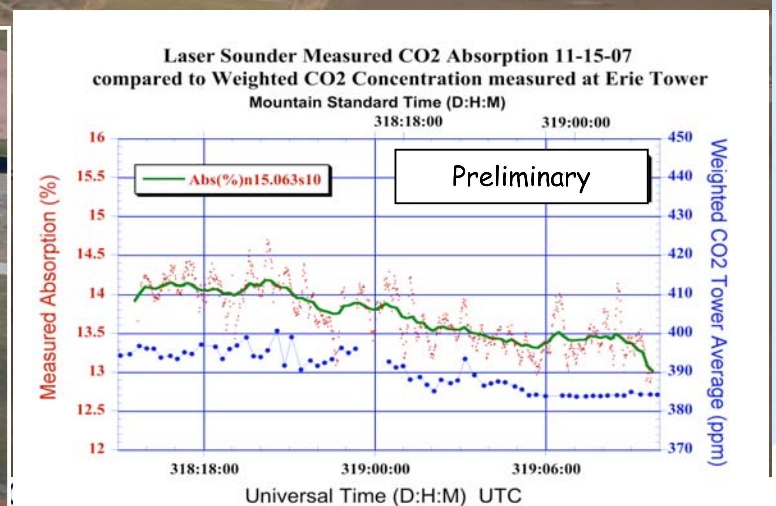


Comparison of measured CO2 line scan with HITRAN Prediction based on the Tower LICOR



CO2 measurement van
Mid -November 2007

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



Measurement approach for Aircraft & Space

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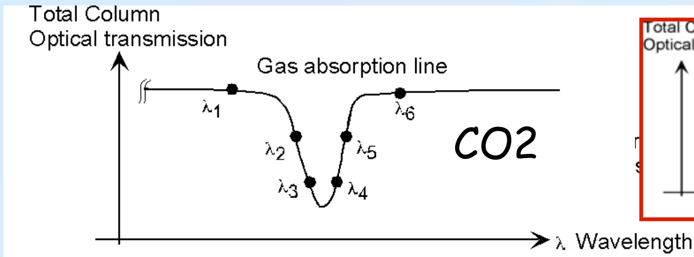
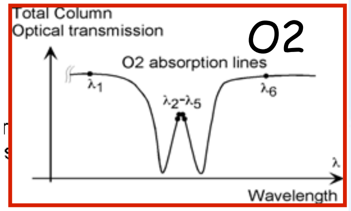
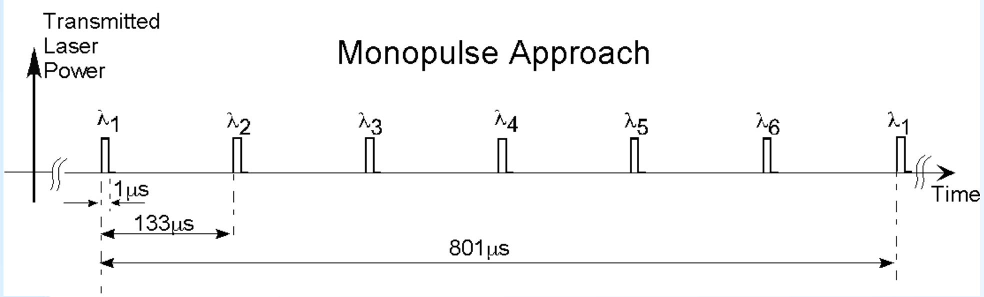
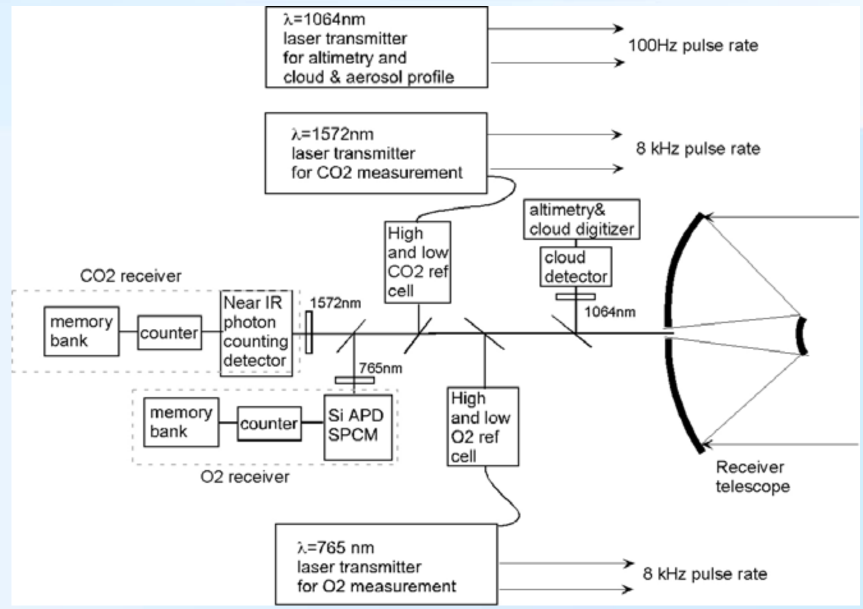
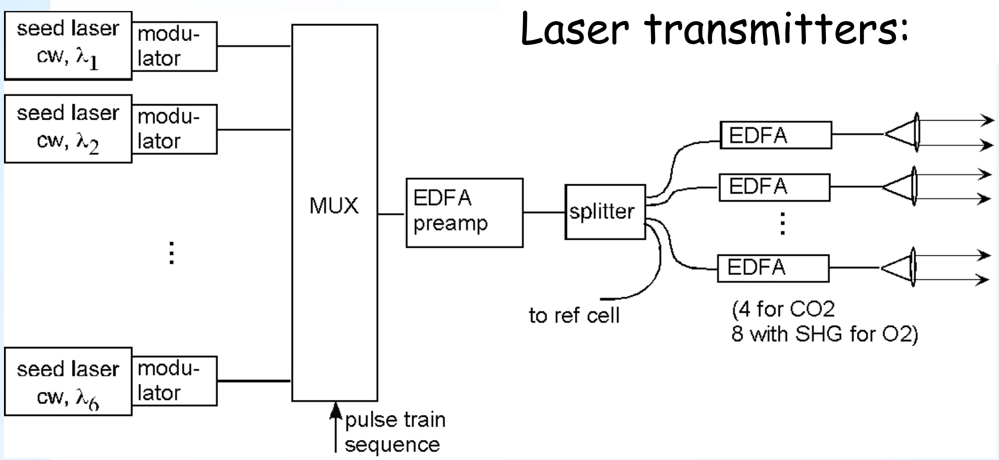




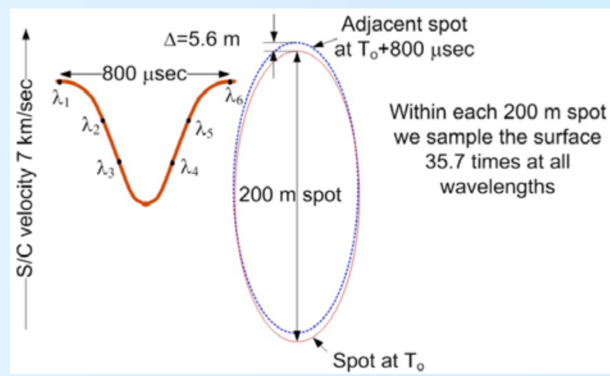






(Each laser spot contains illumination from 35 cycles through the 6 laser wavelengths)

Co-aligned and Overlapped spots on ground



Space: SNR & Relative Measurement Errors

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

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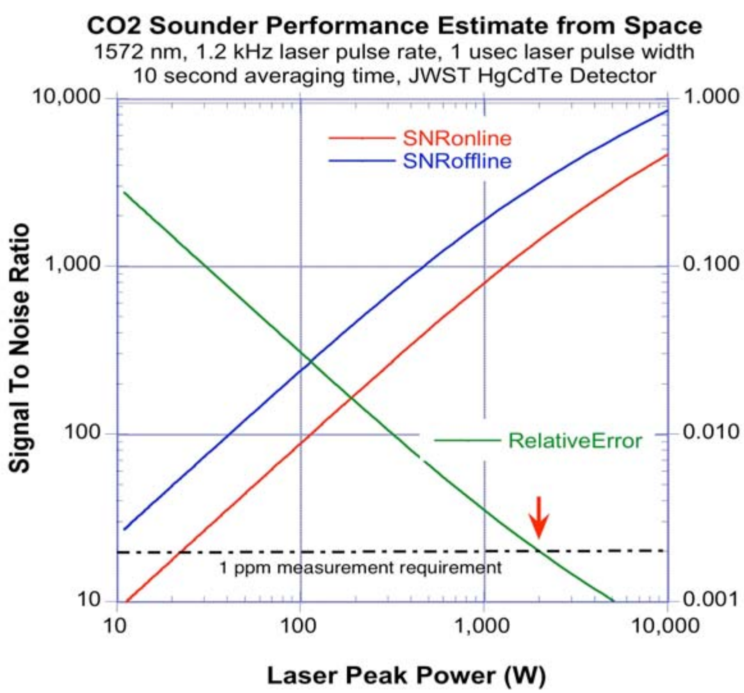
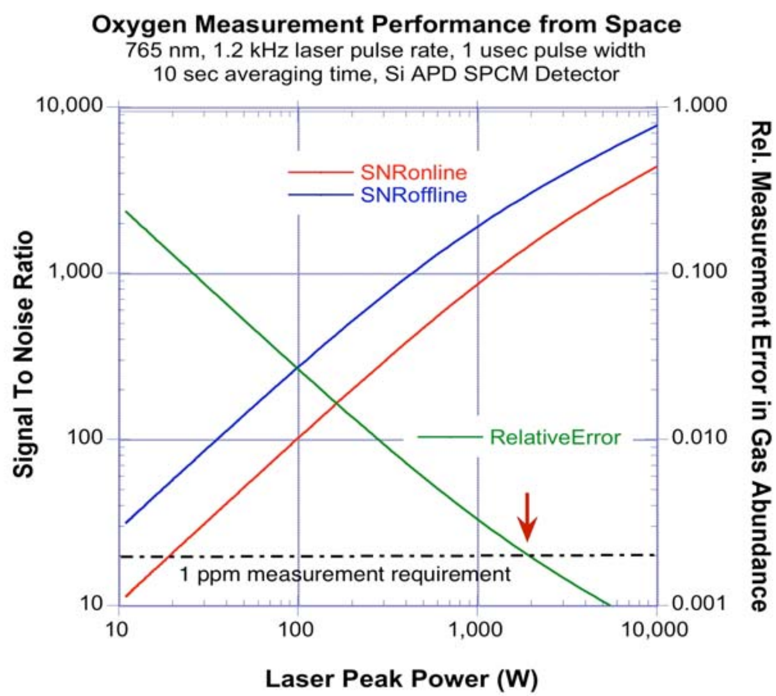
CO2 column measurement



4 EDFA's, 500W pk power

O2 column measurement



8 EDFAs, 500W pk power, 50% doubling

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

Next steps - Airborne ASCENDS Precursor for NASA ESTO IIP Program (start in FY09)

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

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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.

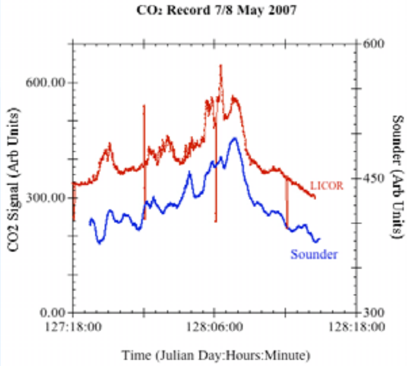
Our proposal leverages strong understanding and capabilities developed over the past 7 years with support from the ESTO ACT and IIP programs. This work addressed many aspects of the measurement, improved the technique and technologies, and successfully addressed a number of significant error sources. 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.

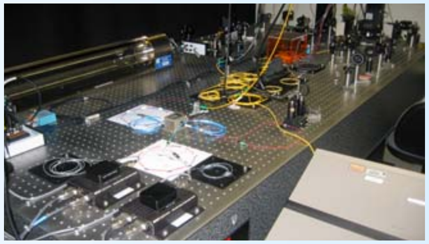
We propose to advance the readiness of the instrument technologies. We will demonstrate these in an airborne precursor instrument for the ASCENDS mission, to use as a simulator for a space mission, as a test bed for improving components, and for airborne science campaigns. We will also optimize the calibration 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.

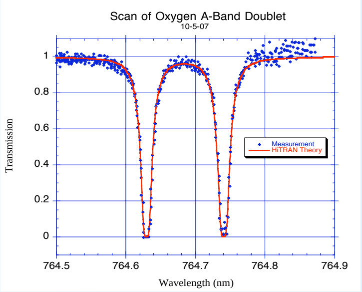
Airborne Precursor for ASCENDS Mission:
Calibrated mixing ratio measurements
Why ?

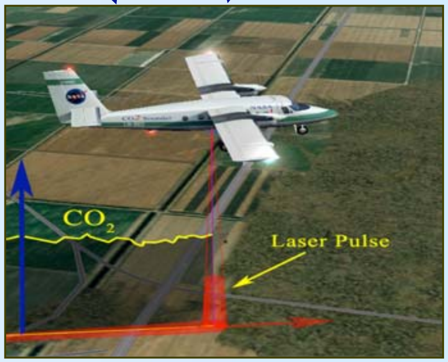
- Simulator for Space
- Test bed for evolving components
- Airborne science campaigns

CO_2 Laser Sounder for ASCENDS Mission – Technology development and airborne demonstration ii



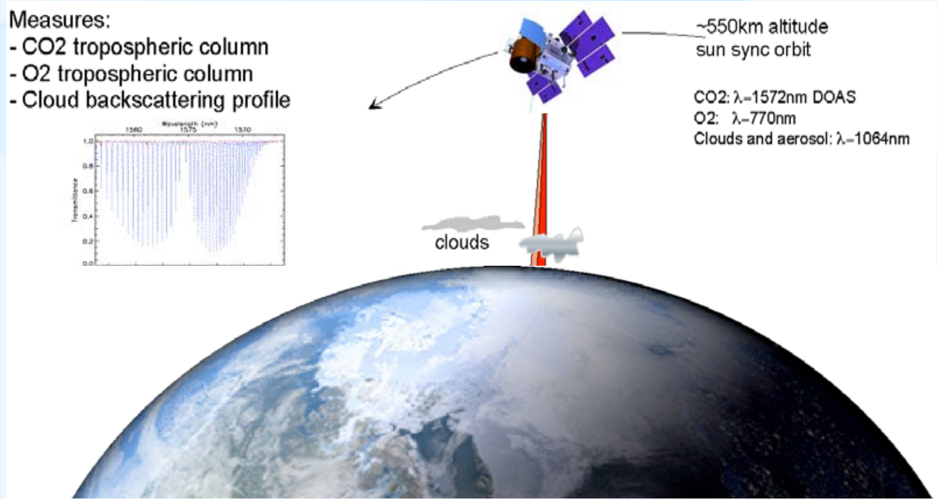






ASCENDS Airborne Precursor Instrument

Summary



A needed & challenging space measurement:

- Complex measurement environment
- Many potential error sources
- Need high precision & accuracy

Our measurement approach:

- CO2 at 1572 nm, O2 at 765 nm
- CO2 lower tropospheric column
- O2 total column (surface pressure)
- Altimetry & atmos. backscatter profile
- Temperature & WV from atmospheric models
- Pulsed EDFA lasers
- Direct detection in all channels
- Time gated Photon-counting receiver

Evolution:

- ✔ Initial concept (2001) & lab measurements
- ✔ Breadboard instrument development
- ✔ Space instrument component need analysis
- ✔ White paper submitted to NRC RFI
- ✔ CO2 & O2 spectroscopy & error analysis
- ✔ Field measurements at CO2 tower (2007)
- CO2 Airborne demonstrations (fall 2008)
- CO2& O2 airborne precursor (2009-11)