Pulsed Lidar for Measurement of CO2 Concentrations for the ASCENDS Mission: *Progress*

James B. Abshire

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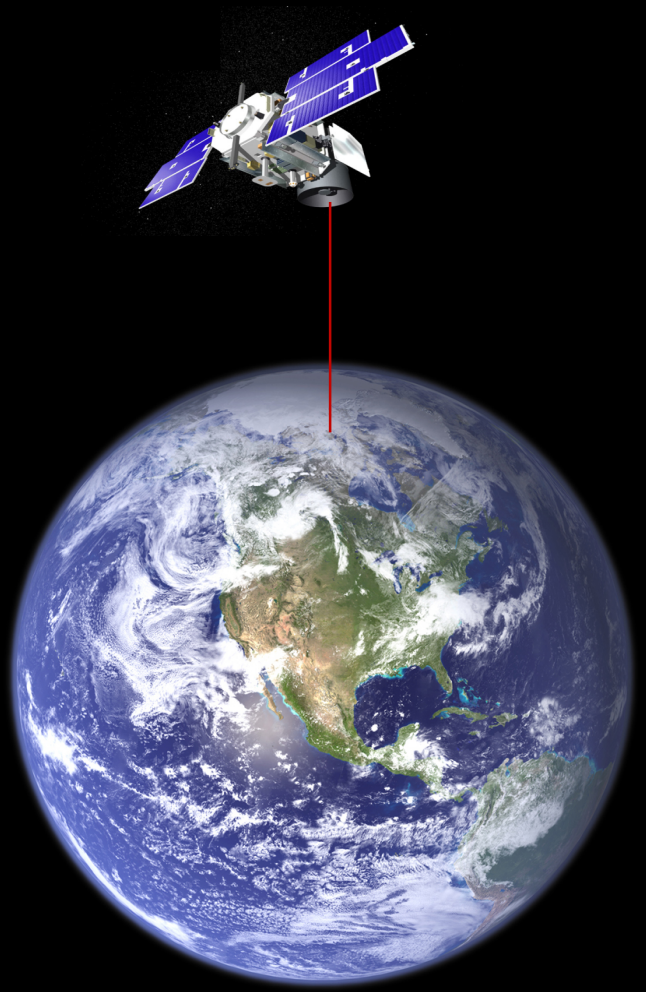

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ESTO Task Manager: Joe Famiglietti

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NASA ESTO IIP , Goddard IRAD, ASCENDS Definition programs

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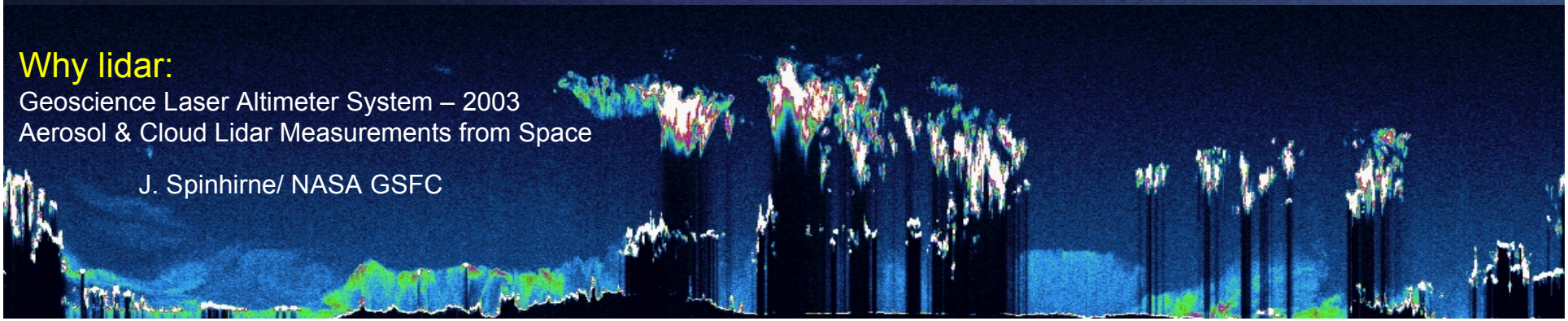
Outline

- ASCENDS Mission
- Lidar measurement environment
- O2 Measurement approach
- CO2 Measurement approach
- Airborne CO2 measurements
- Space Mission simulations
- Scaling to space & technologies
- Summary



NASA's ASCENDS Mission

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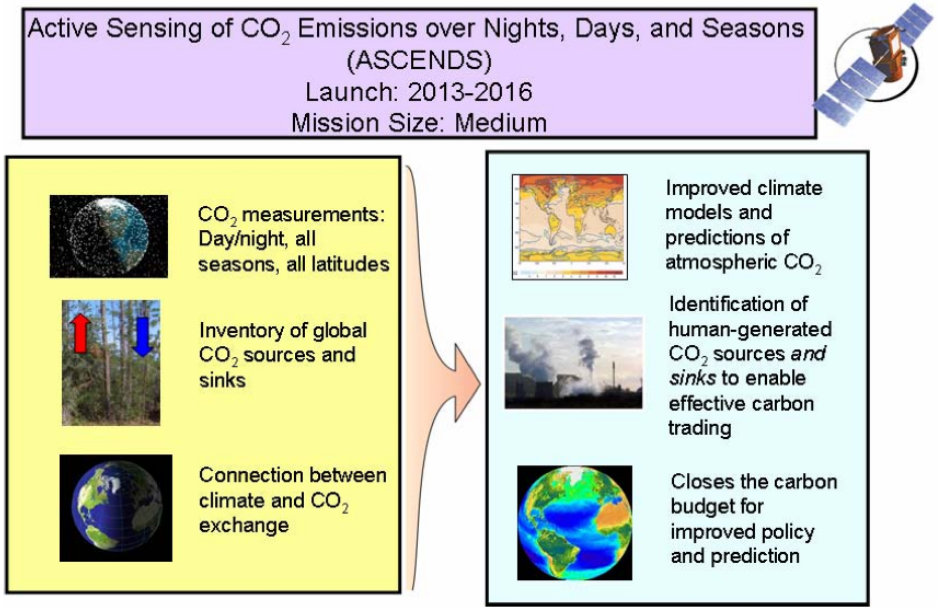
Why lasers ?

- 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

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS)



Are several 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

1 line - 1570 nm band - pulsed direct detection

This approach →

Laser Sounder Approach for ASCENDS Mission

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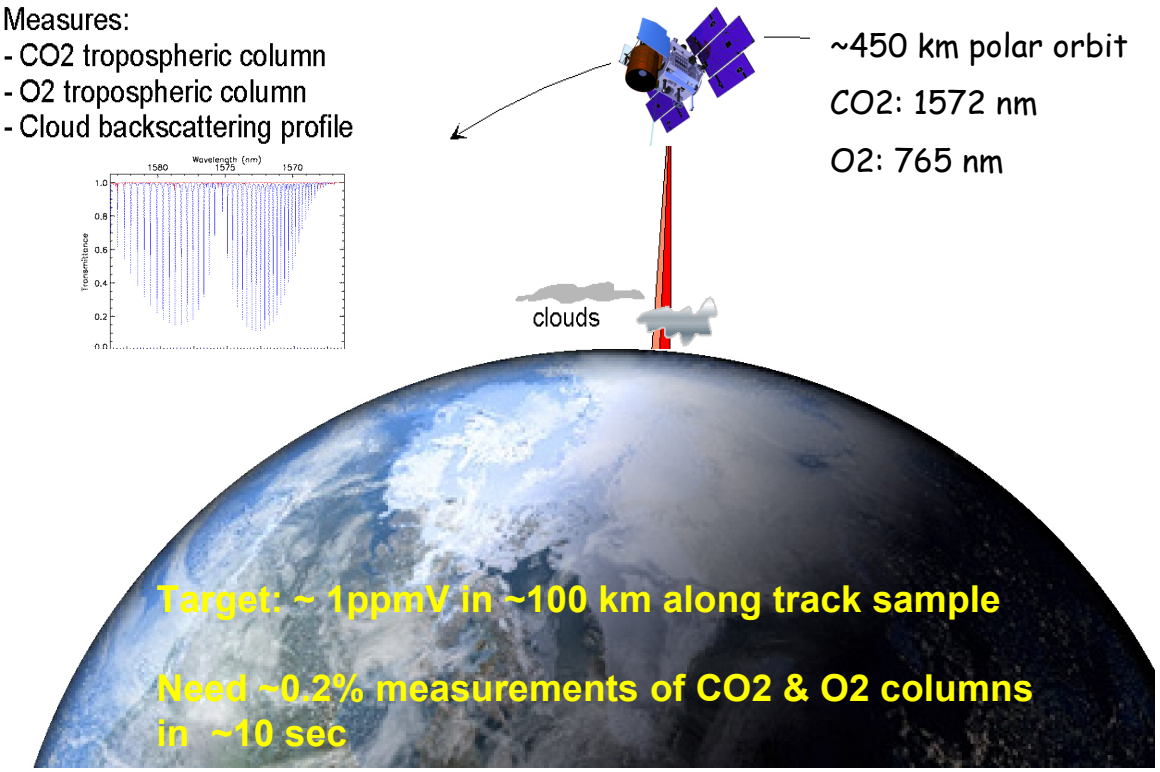
Simultaneous laser measurements:

1. CO2 lower tropospheric column
   One line near 1572 nm
2. O2 total column (surface pressure)
   Measure 2 lines near 765 nm
3. Altimetry & atmospheric backscatter profile from CO2 signal:

Measures:
- CO2 tropospheric column
- O2 tropospheric column
- Cloud backscattering profile



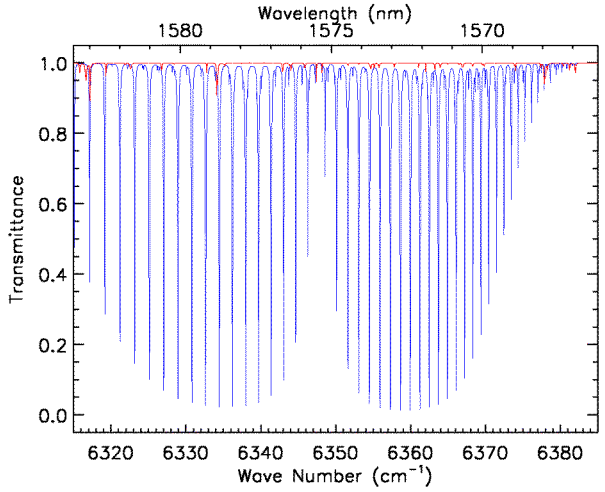
Measurements use:

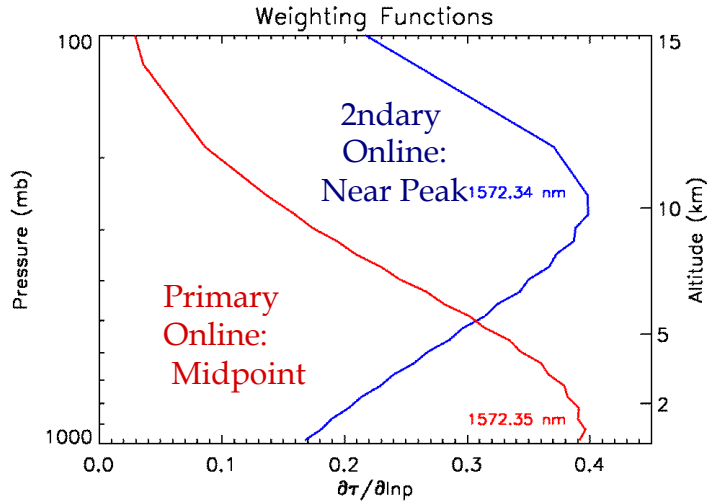
- Pulsed lasers
- ~10 KHZ pulse rates
- 8 laser wavelengths for CO2 line
- Time gated Photon counting receiver

CO2 & O2 column measurements:

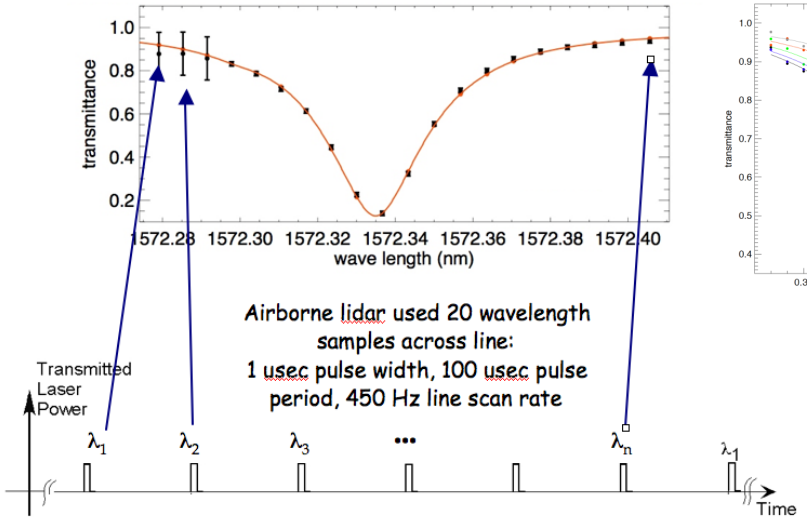
- Pulsed (time gated) signals :
  - Isolate full column signal from surface
  - Reduces noise from detector & solar background
  - Time of flight provides column length

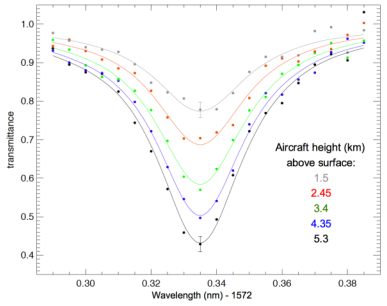
CO2 Band, Line Sampling & Vertical Weighting Functions





Total Column from area of line





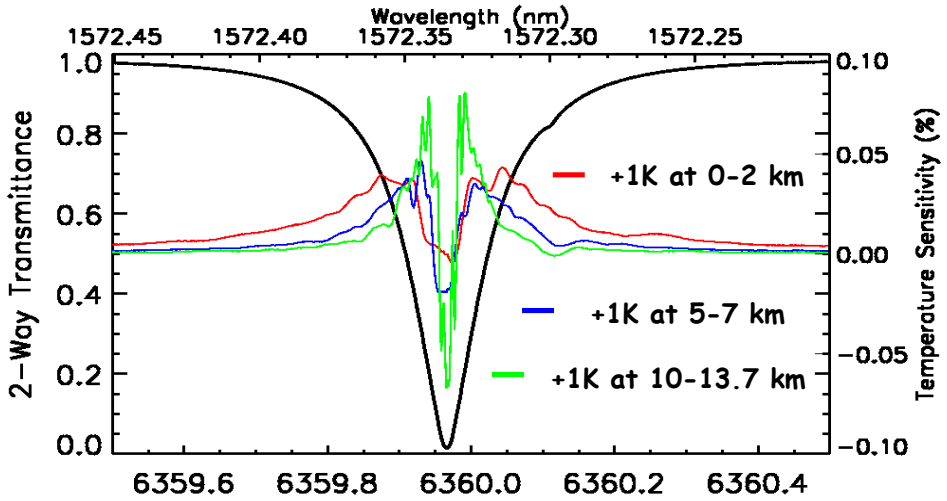
Increasing CO2 Column Density

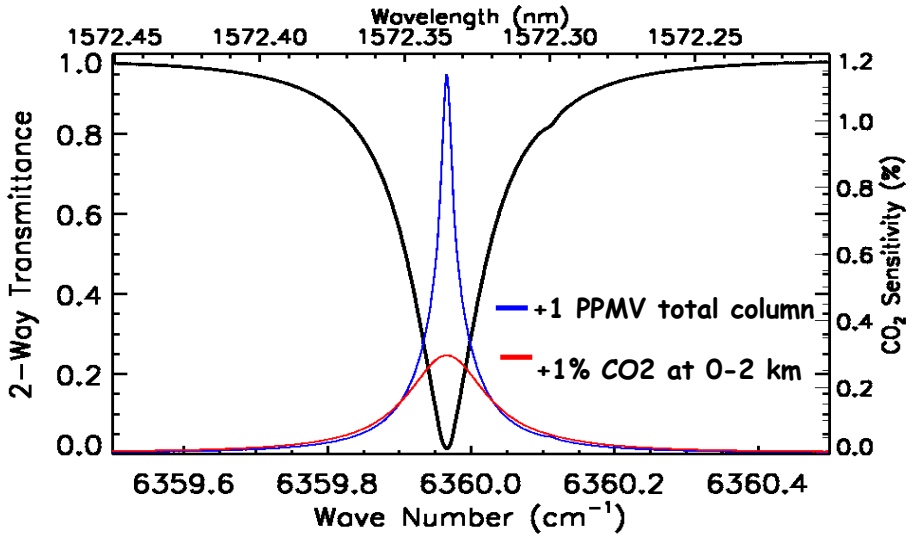
Space lidar plans: 8 wavelength samples across line

Multi-wavelength Line Sampling allows:

- Detection & correction of Doppler & λ errors
- Modeling & reducing errors from varying λ response
- CO2 retrievals for lower & upper troposphere
- Line shape information

Temperature Sensitivity of 1572.33 nm line



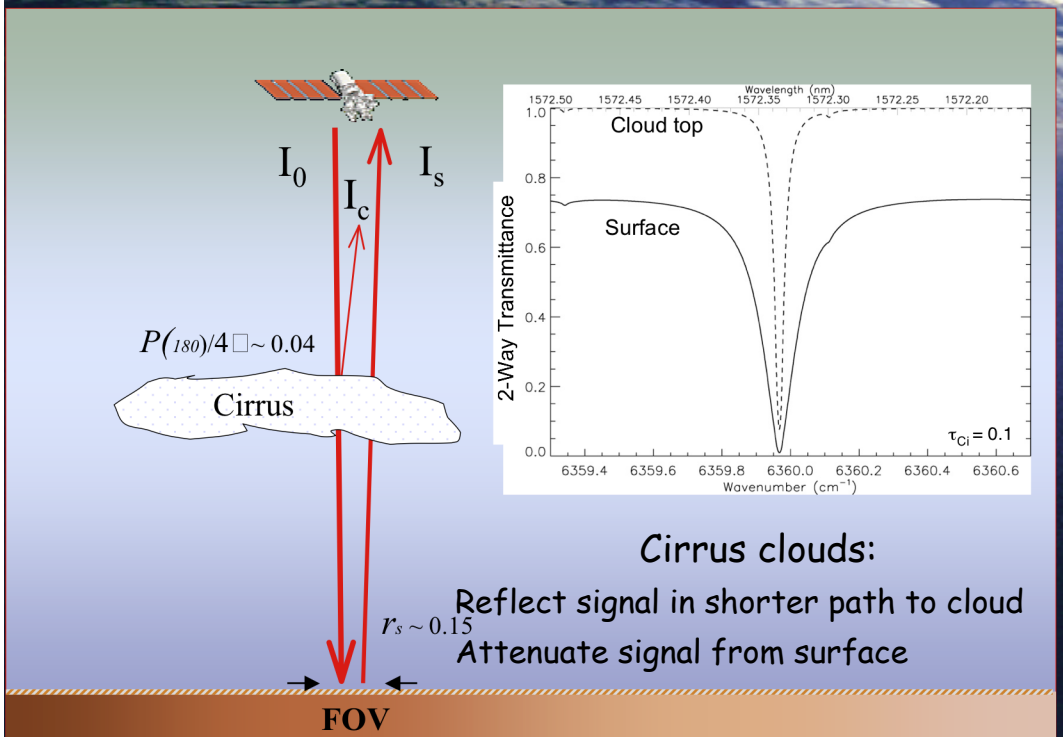


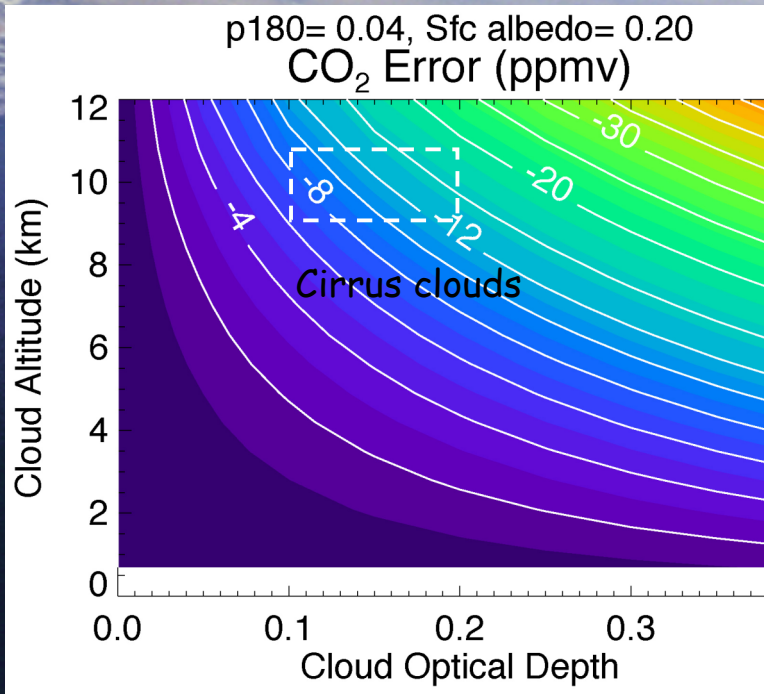
- ✓ Less sensitivity to atmospheric temperature
- ✓ Greater sensitivity to atmospheric CO2 amount

Why use pulsed lasers & ranging gating ?

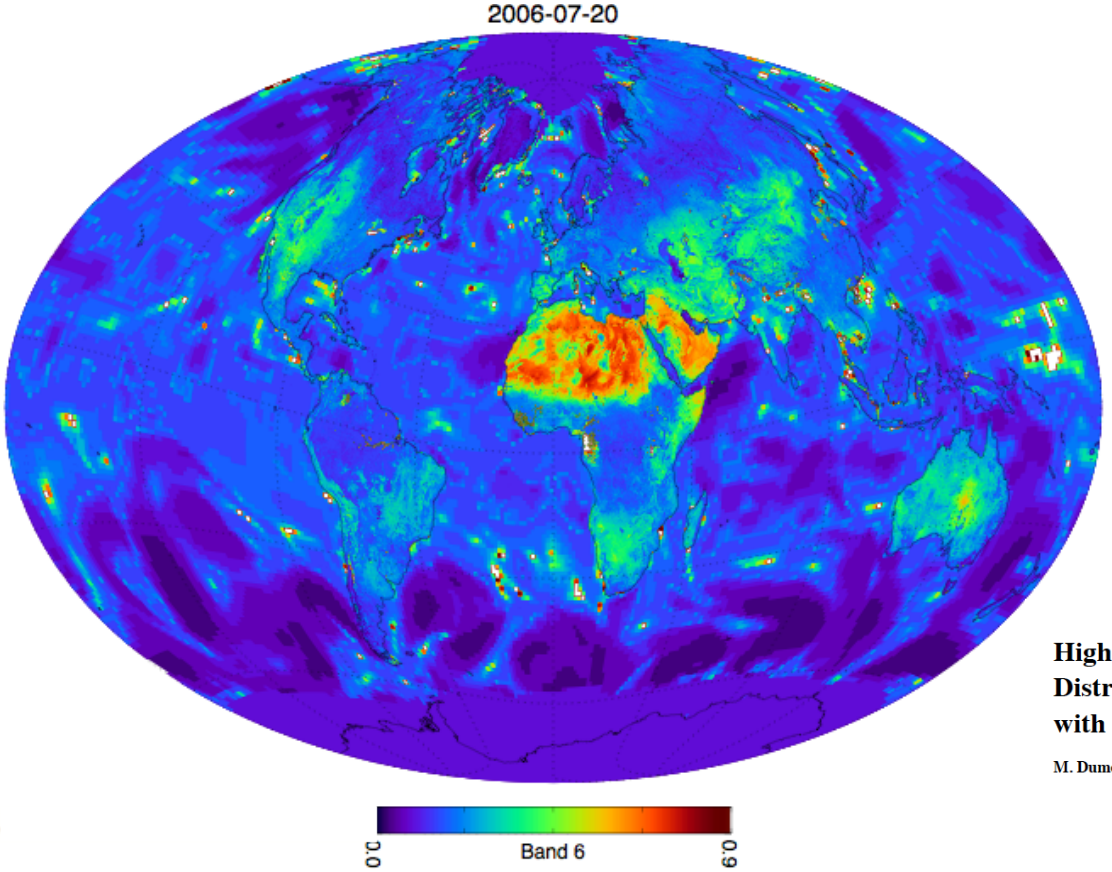
Atmospheric Scattering

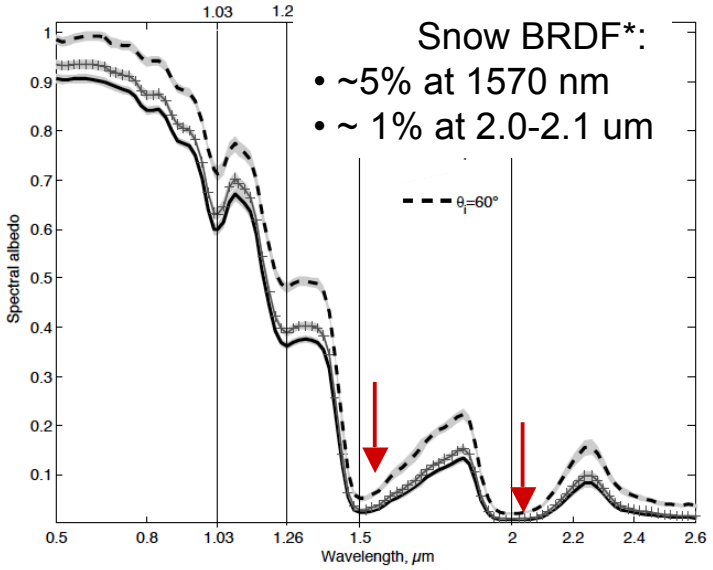
- Thin cirrus clouds are quite prevalent, β_π varies with λ
- Cloud reflections shorten average optical path -> bias non-gated column estimates
- Cirrus cloud scattering -> 4-10 ppm errors in non-range gated measurements
- **Pulsed lasers & range gating eliminate these errors**





Global Surface Reflectance Estimates



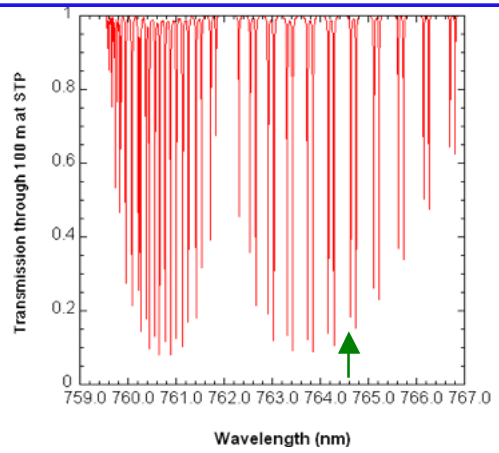


High-accuracy measurements of snow Bidirectional Reflectance Distribution Function at visible and NIR wavelengths – comparison with modelling results

M. Dumont[1], O. Brissaud[2], G. Picard[1], B. Schmitt[2], J.-C. Gallet[1], and Y. Arnaud[3]

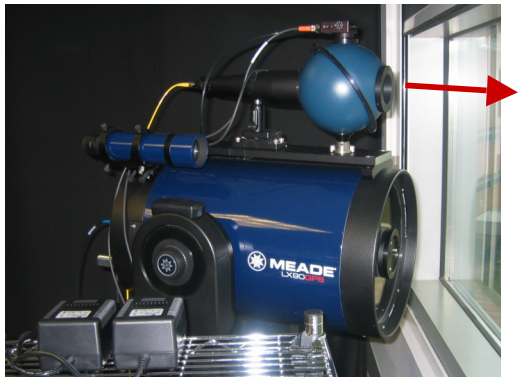
- Reflectance over land from MODIS 16-d composite BRDF-adjusted nadir reflectance. Missing data =0.2.
- Over water, Fresnel reflectance is calculated at nadir using 10-m wind speed from the meteorological analysis.
- Reflectance over ice that is not available from MODIS (e.g., in the polar dark) is assumed to be 0.1.
- Ice cover extent is determined from the GEOS-4 analysis.

Oxygen - Open path measurement of absorption lines near 765 nm

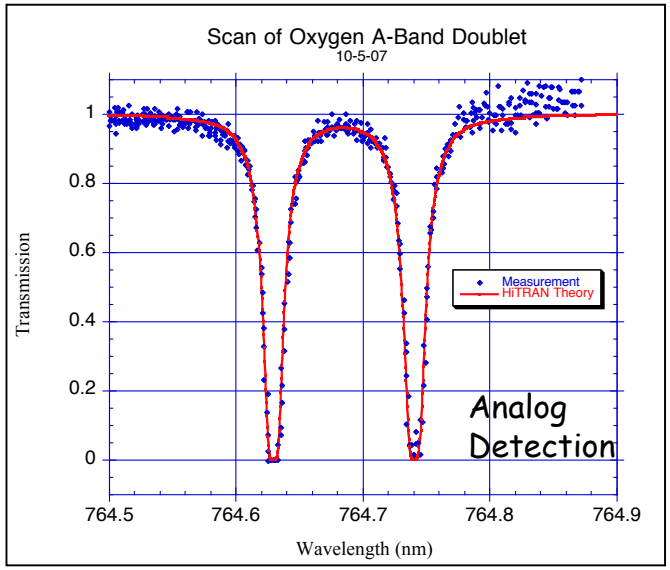


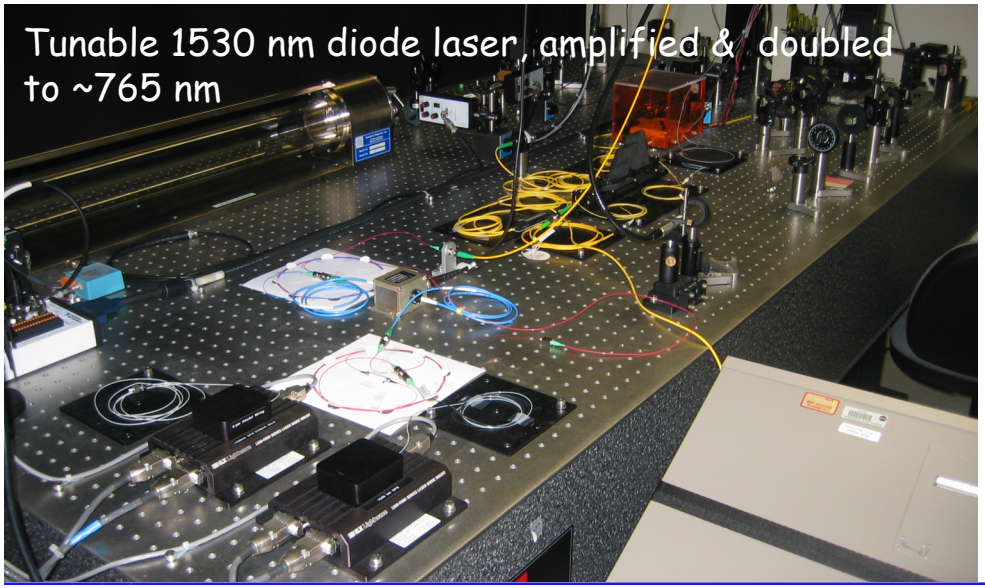
Oxygen A band: Atmospheric transmission for 100 m path at STP

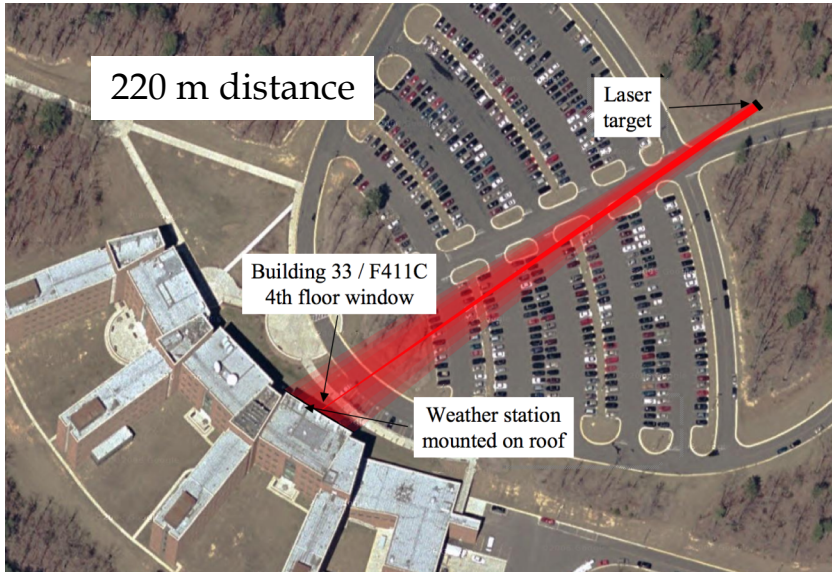
Telescope viewing target



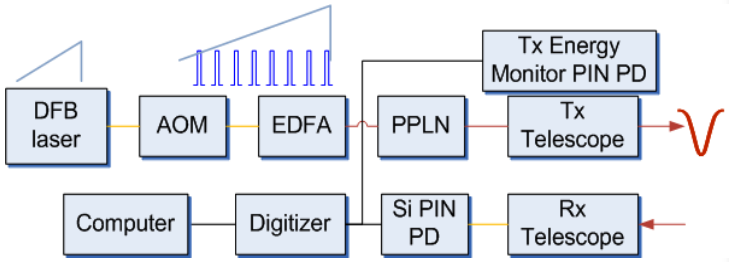
Peak optical power ~ 50 mW
Attenuation for round trip was ~10^6

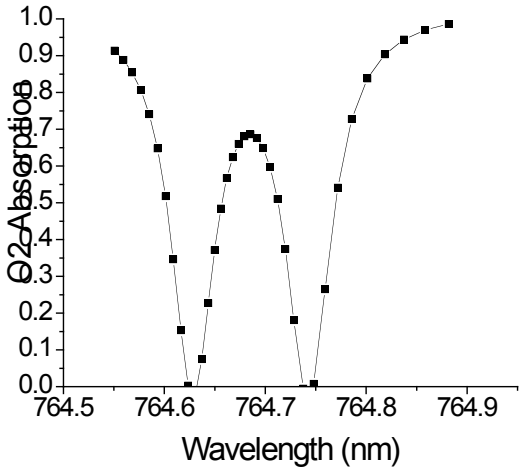






O2 absorption measurements from laboratory





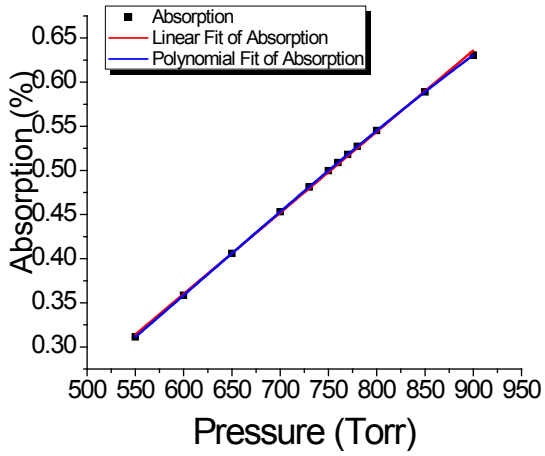
Airborne O2 Lidar Parameters:

- Diode laser Wavelength: 1529 nm
- Amplifier: NP Photonics EDFA
- Output Wavelength: 764.5 nm
- Output Energy: ~1 uJ/pulse
- Detector: SPCM
- Scan over the absorption with 20-40 Pulses (selectable) at 450 Hz

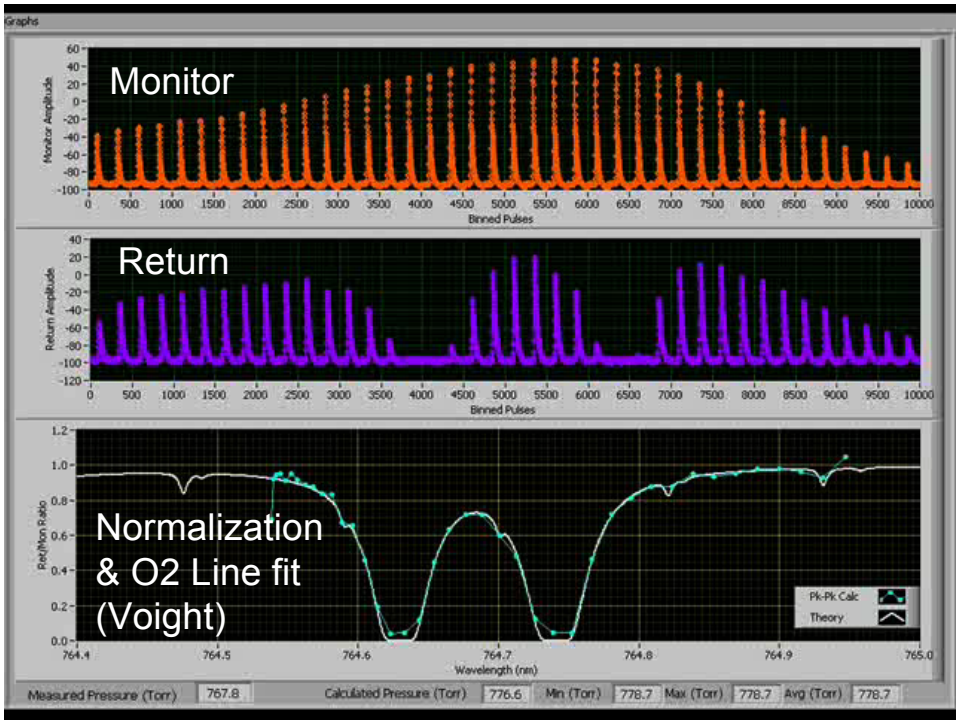
Distance to target: 1.5 km
Target illuminated by green alignment laser

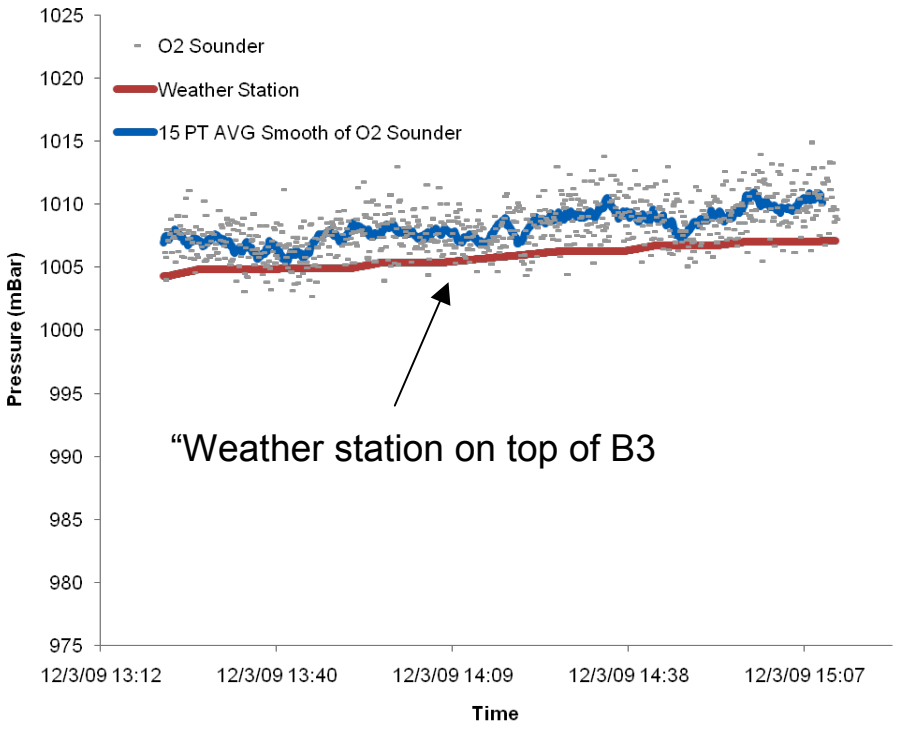
B33 Room F411
"Truth:" Weather station on top of B33

Calculated



Sample O2 Measurement made over 1.5 km horizontal path using photon counting detector

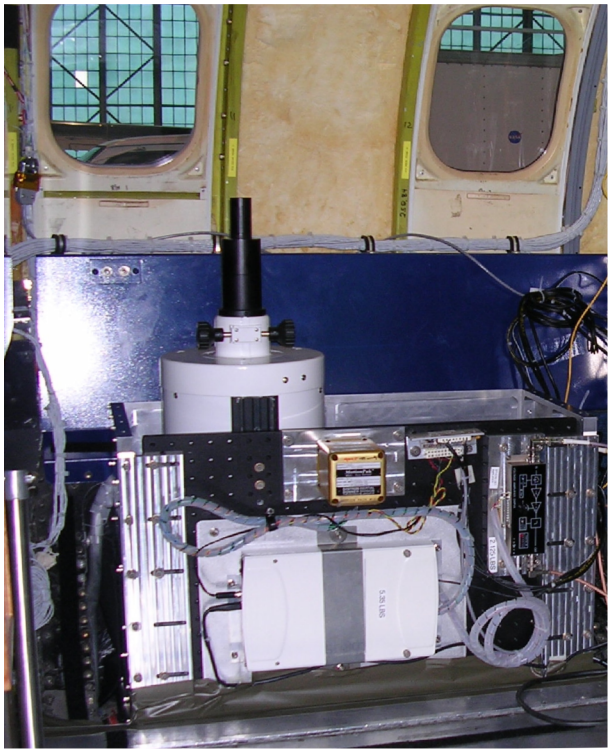


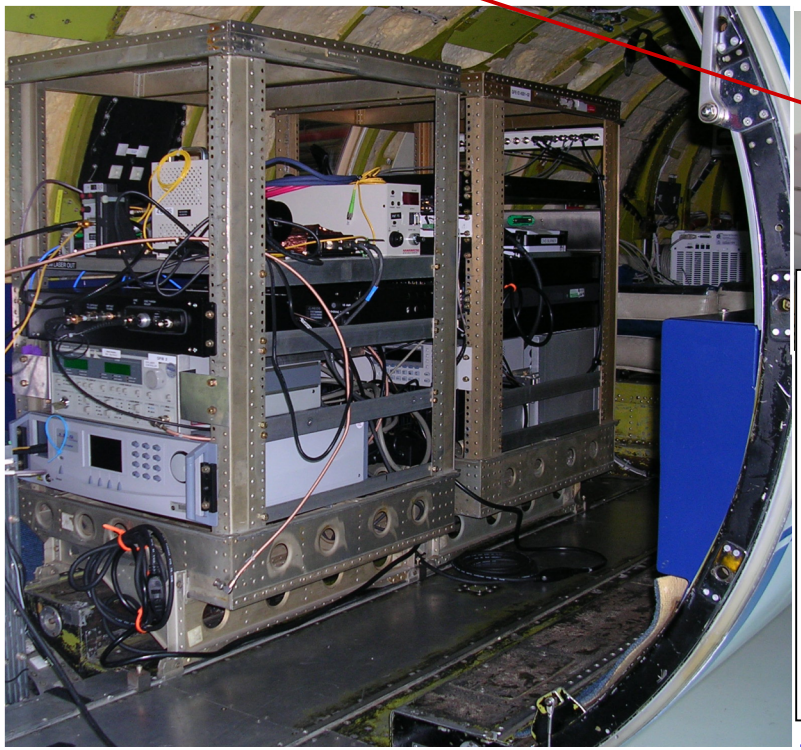


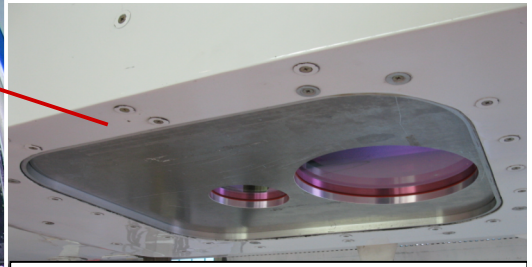
Pulsed Airborne CO2 Sounder Lidar on the NASA Glenn Lear-25

Experiment Team in Ponca City OK, USA

Nadir port showing transmit and receiver windows





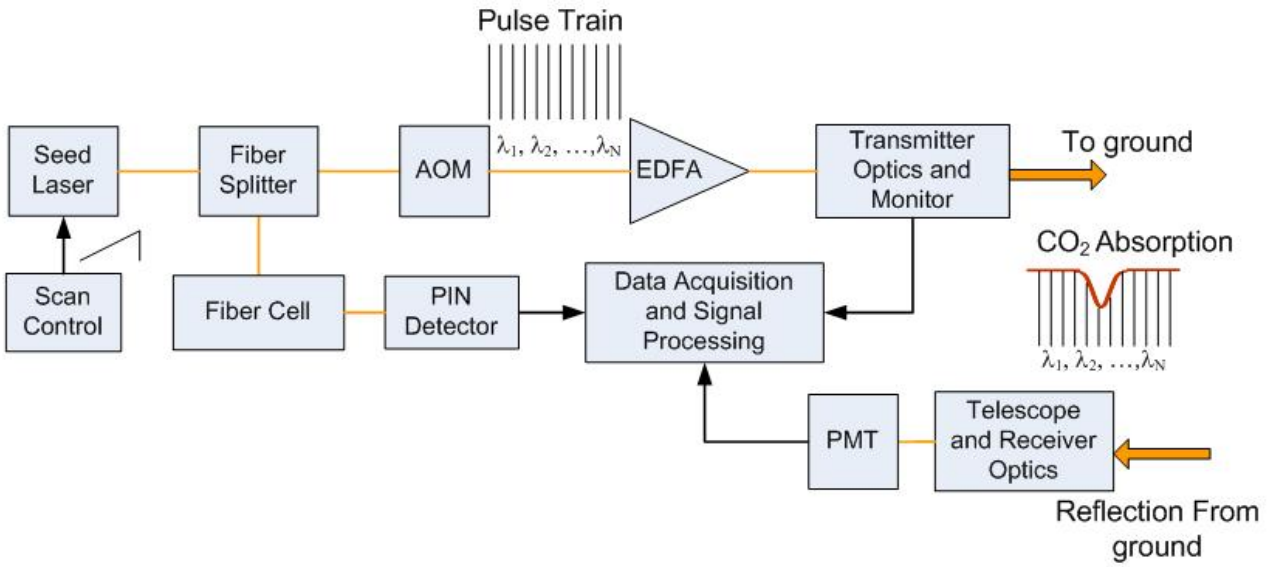


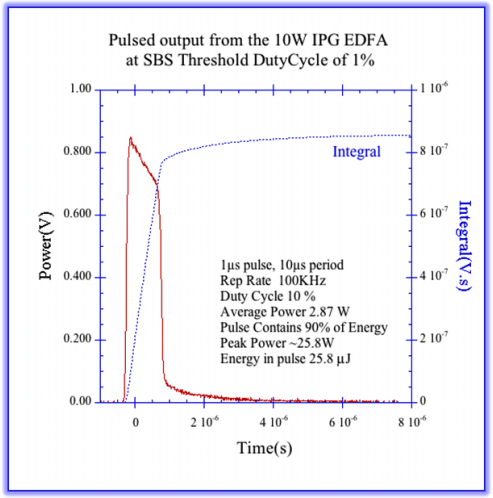
Paper on 2008 flights :

J. B. Abshire, H. Riris, G.R. Allan, J. Mao, C. Weaver, S. Biraud and S.R. Kawa " Airborne Lidar measurements of Atmospheric CO_2 line shape and Column Absorption," *Accepted for publication, Tellus-B,* 2010.

Pulsed Airborne CO2 Lidar

GSFC



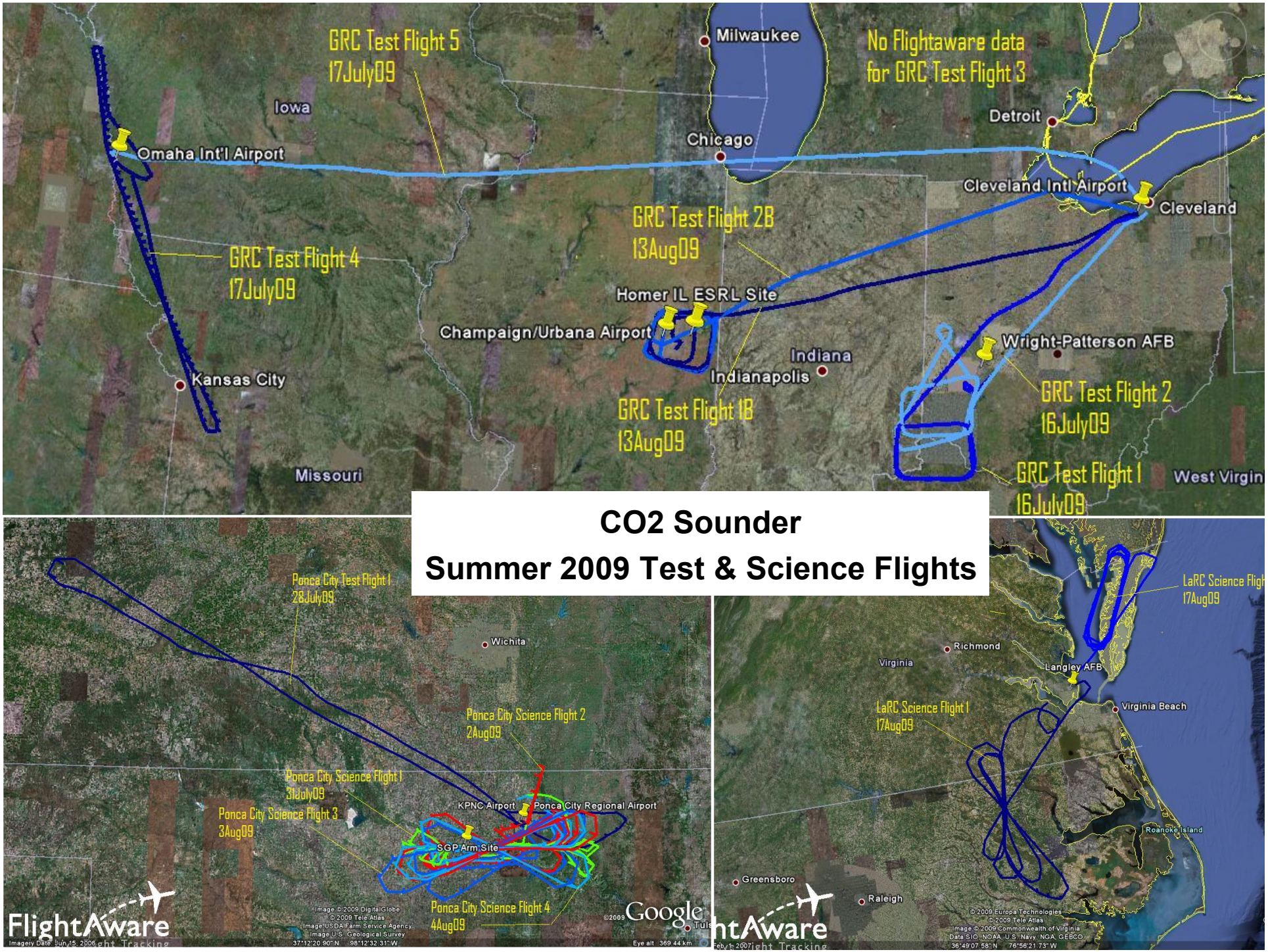


Parameters:

Laser peak power: 24 watts (24 uJ/pulse)
Laser: DFB diode laser, AOM, Fiber amplifier
Wavelength scans: 20 wavelengths, 450 Hz
Telescope diameter: 20 cm
Receiver transmission: 65%*
PMT dark count rate: ~ 550 kHz

Laser divergence angle: 100 urad
CO2 line: 1572.33 nm
Receiver FOV: 200 urad
Receiver optical bandwidth: 0.8 nm
Detector quantum efficiency: 1-5%
Receiver range bin size: 8 nsec*

* Were 470 urad, 16% and 64 nsec, respectively, during 2008 flights


GRC Test Flight 5
17July09
Milwaukee
No Flightaware data
for GRC Test Flight 3
Iowa
Detroit
Chicago
Omaha Int'l Airport
Cleveland Intl Airport
Cleveland
GRC Test Flight 2B
13Aug09
GRC Test Flight 4
17July09
Homer IL ESRL Site
Champaign/Urbana Airport
Wright-Patterson AFB
Indiana
Indianapolis
Kansas City
GRC Test Flight 2
16July09
GRC Test Flight 1B
13Aug09
Missouri
GRC Test Flight 1
16July09
West Virgin
CO2 Sounder
Summer 2009 Test & Science Flights
Ponca City Test Flight 1
28July09
Wichita
Ponca City Science Flight 2
2Aug09
Ponca City Science Flight 1
31July09
Ponca City Science Flight 3
3Aug09
KPNC Airport
Ponca City Regional Airport
SGP Arm Site
Ponca City Science Flight 4
4Aug09
FlightAware
Google
LaRC Science Flight
17Aug09
Richmond
Virginia
Langley AFB
LaRC Science Flight 1
17Aug09
Virginia Beach
Roanoke Island
Greensboro
Raleigh

1. Cessna Takeoff
(DOE in-situ CO2 sensor)

2. Twin Otter Takeoff
(JPL 2 um lidar)

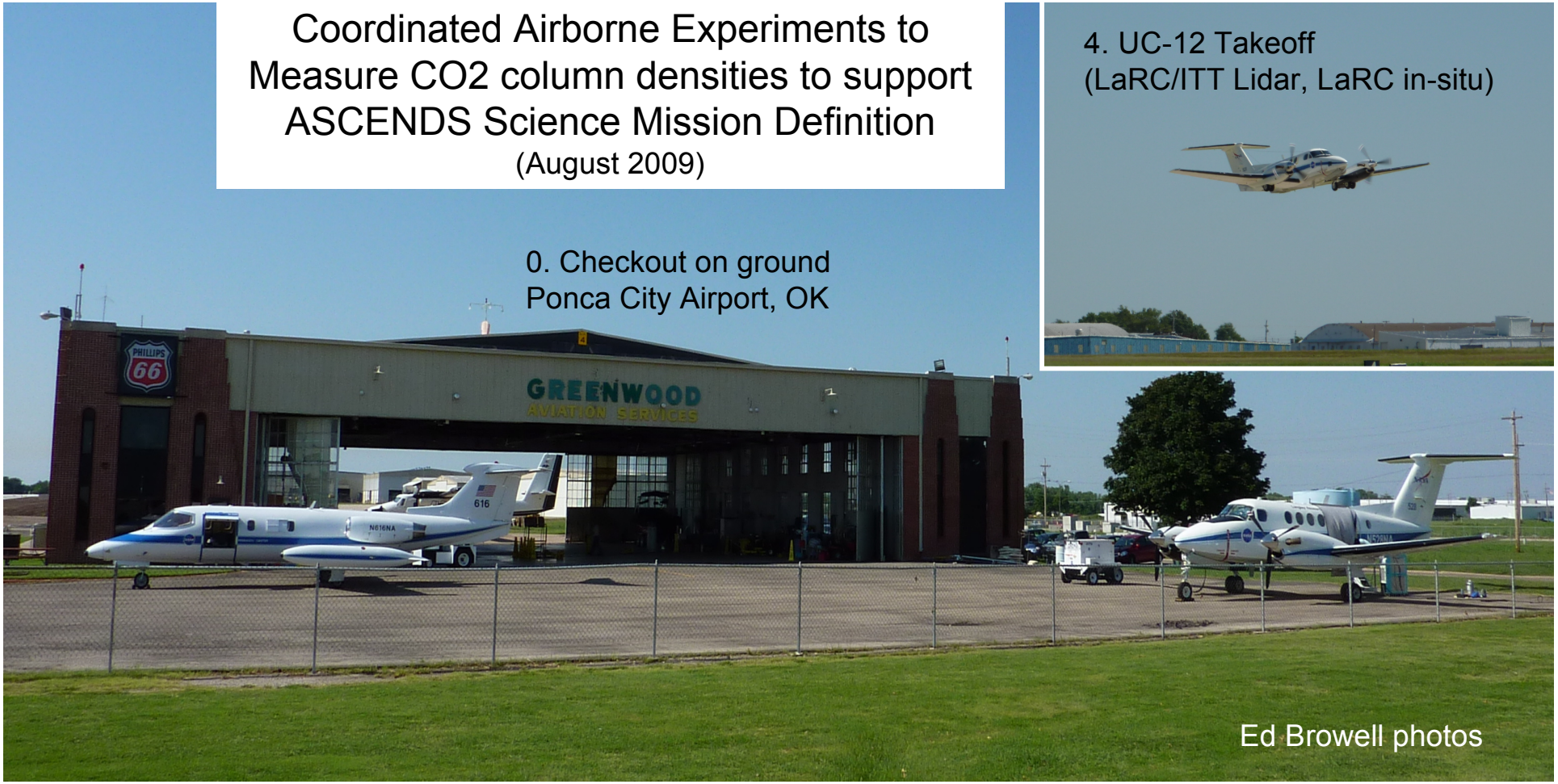
3. Lear Takeoff
(GSFC CO2 Sounder lidar)

Coordinated Airborne Experiments to Measure CO2 column densities to support ASCENDS Science Mission Definition

(August 2009)

4. UC-12 Takeoff
(LaRC/ITT Lidar, LaRC in-situ)

0. Checkout on ground
Ponca City Airport, OK

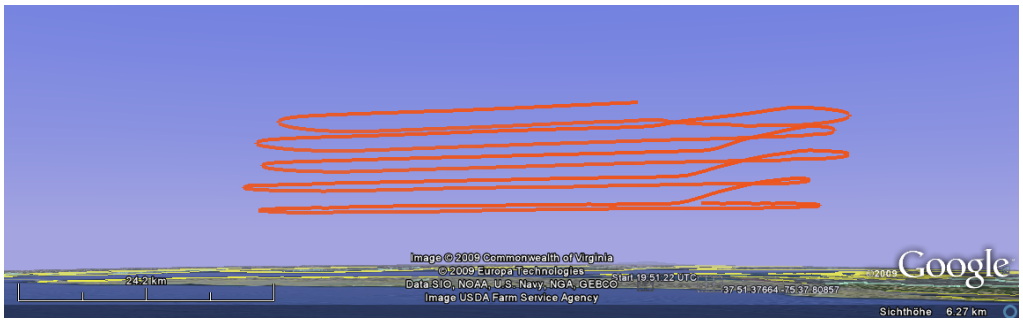


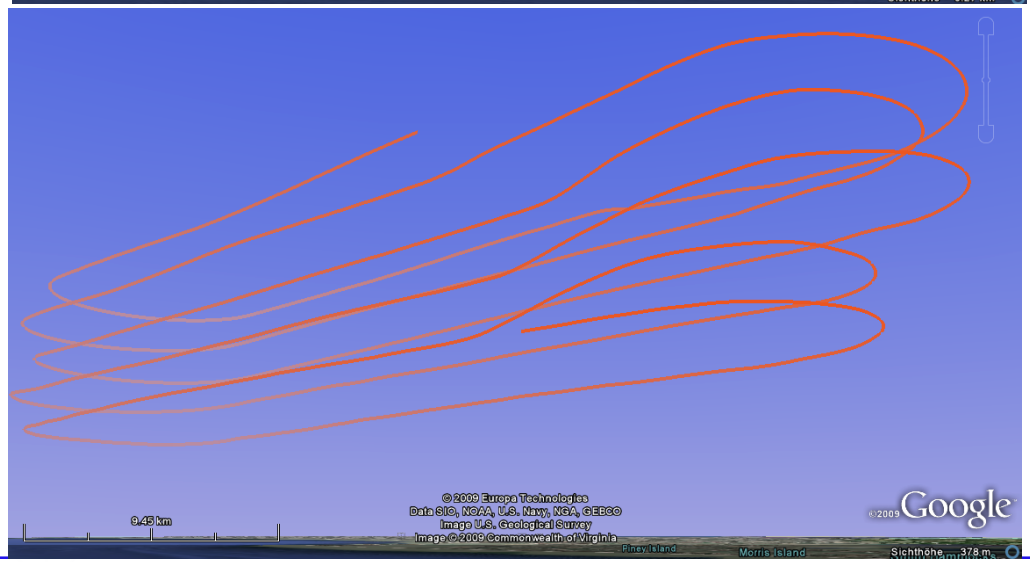
Ed Browell photos

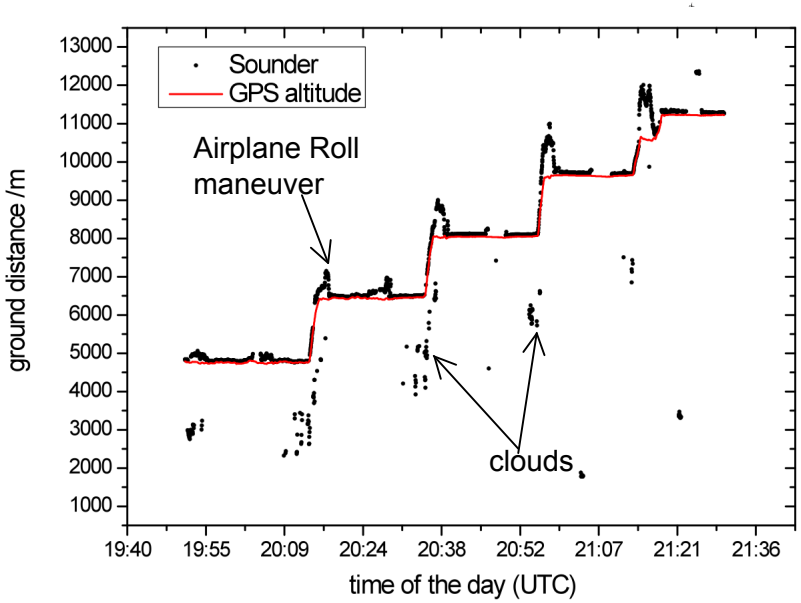
CO_2 Column Height Analysis

Eastern Shore, VA Flight
Aug. 17, 2009
4-5:30 pm local time, Ground speed 150 to 200 m/s

Axel Amediek, DLR



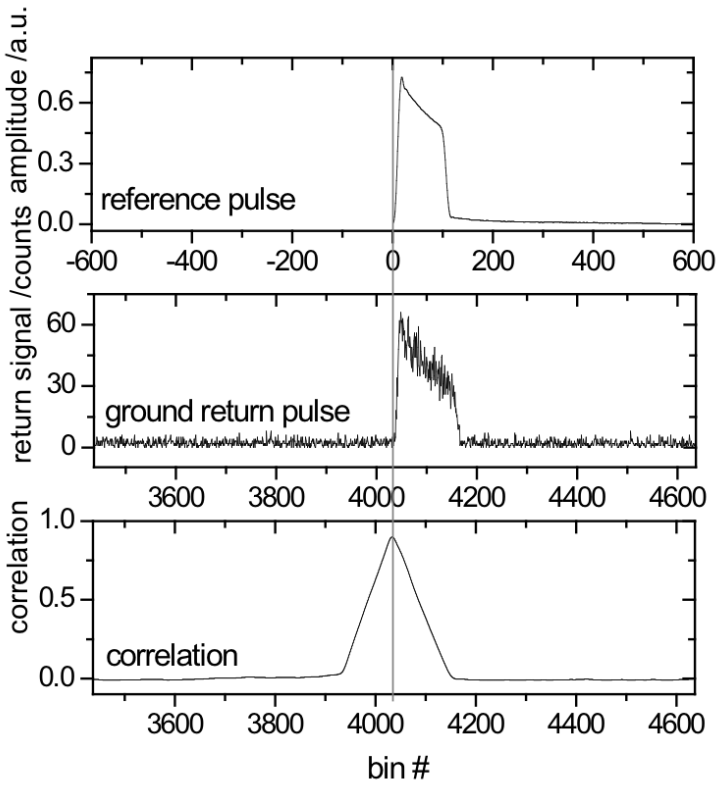


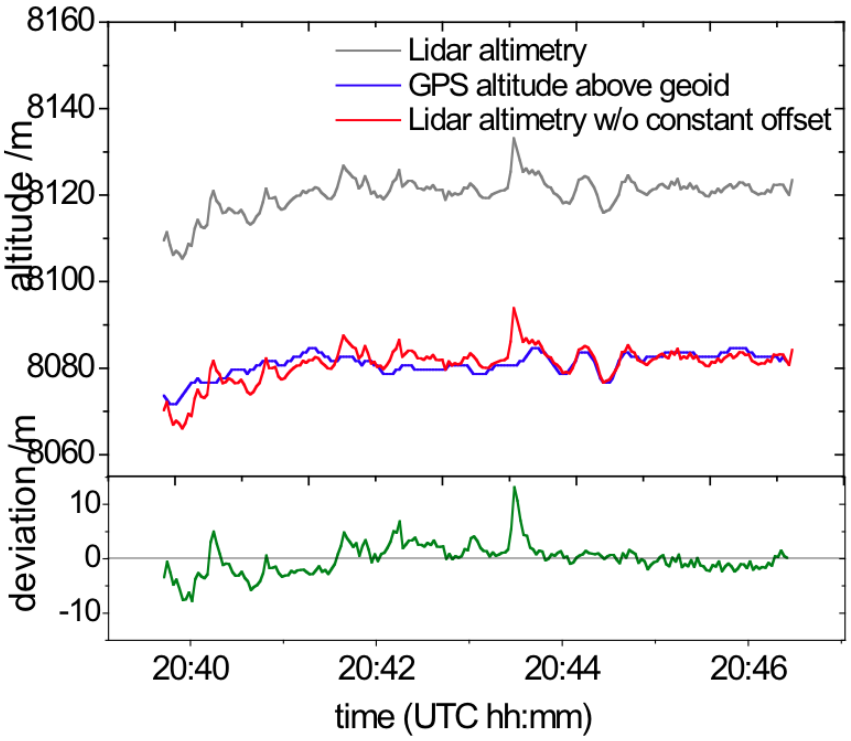


Column Height (Altimetry) Measurements

Approach: Cross correlate the received signal with transmit laser pulse shape

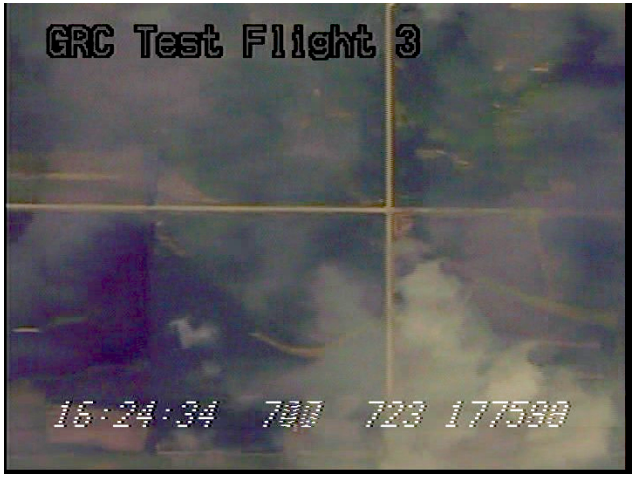
- Use peak of correlation function as laser pulse time of flight.
- Robust & well suited for detecting multiple targets (ground & cloud returns)
- Range was resolved by flight measurements to ~3m accuracy & <1 m from laboratory



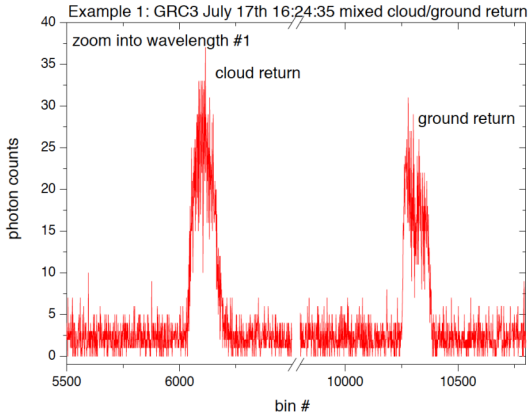


Examples of Measurements through 2 Cloud layers (cloud, cloud, ground echo pulses)

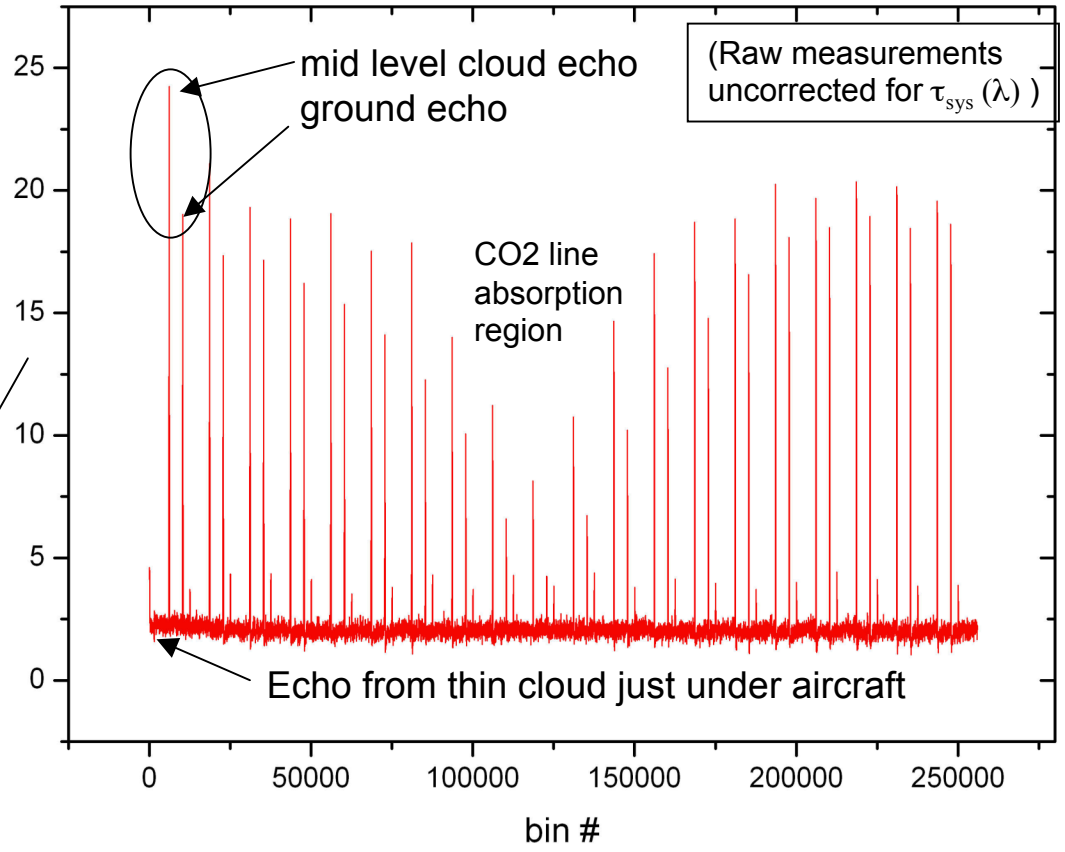
Nadir Camera Image for Measurement



Expanded view of 1st echo pulse group in sequence



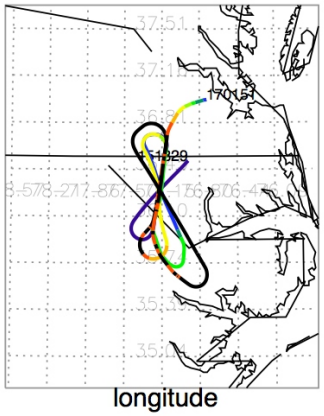
Example 1: GRC3 July 17th 16:24:35 mixed cloud/ground return

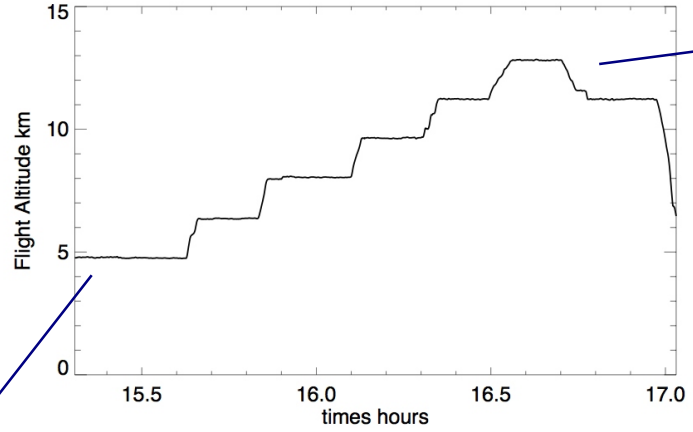


Absorption line shapes:
- to clouds - thinner, less deep
- to ground - broader & deeper

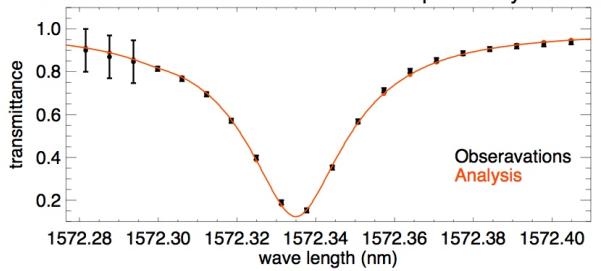
Examples of Line shapes vs Altitude
North Carolina Flight - August 17, 2009

GSFC

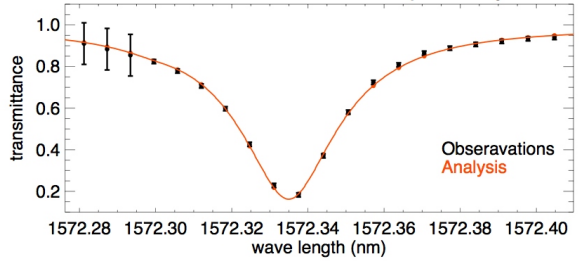




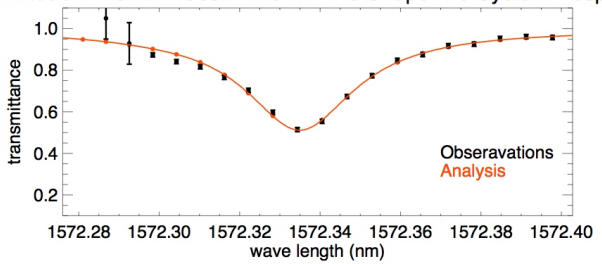
Altitude= 12.9 km Cost= 0.156 Line Shape w/o System Response



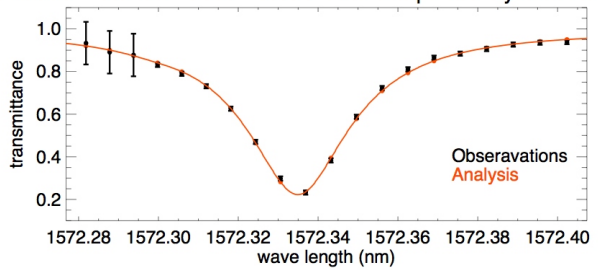
Altitude= 11.5 km Cost= 0.155 Line Shape w/o System Response



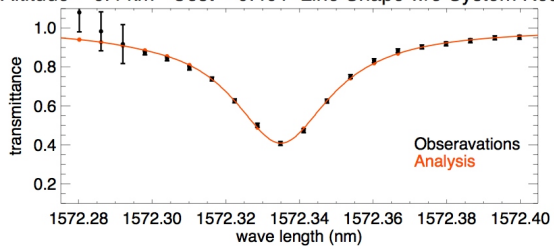
Altitude= 4.9 km Cost= 2.614 Line Shape w/o System Response



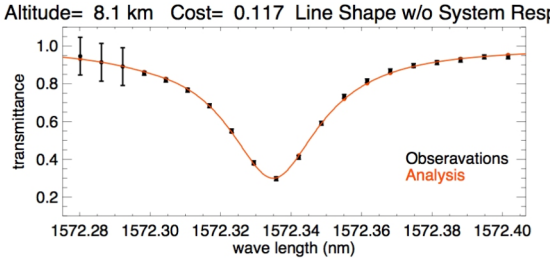
Altitude= 9.8 km Cost= 0.181 Line Shape w/o System Response



Altitude= 6.4 km Cost= 0.401 Line Shape w/o System Response



Altitude= 8.1 km Cost= 0.117 Line Shape w/o System Response

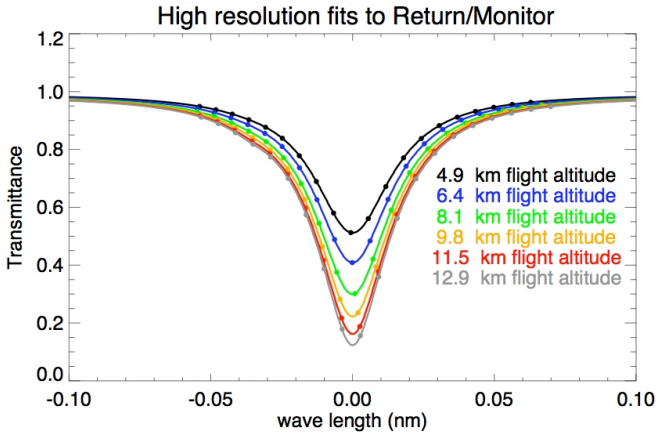


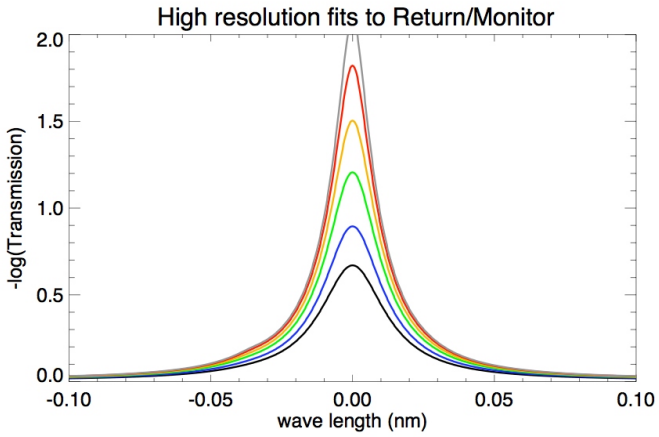
ESTO
Earth Science Technology Office

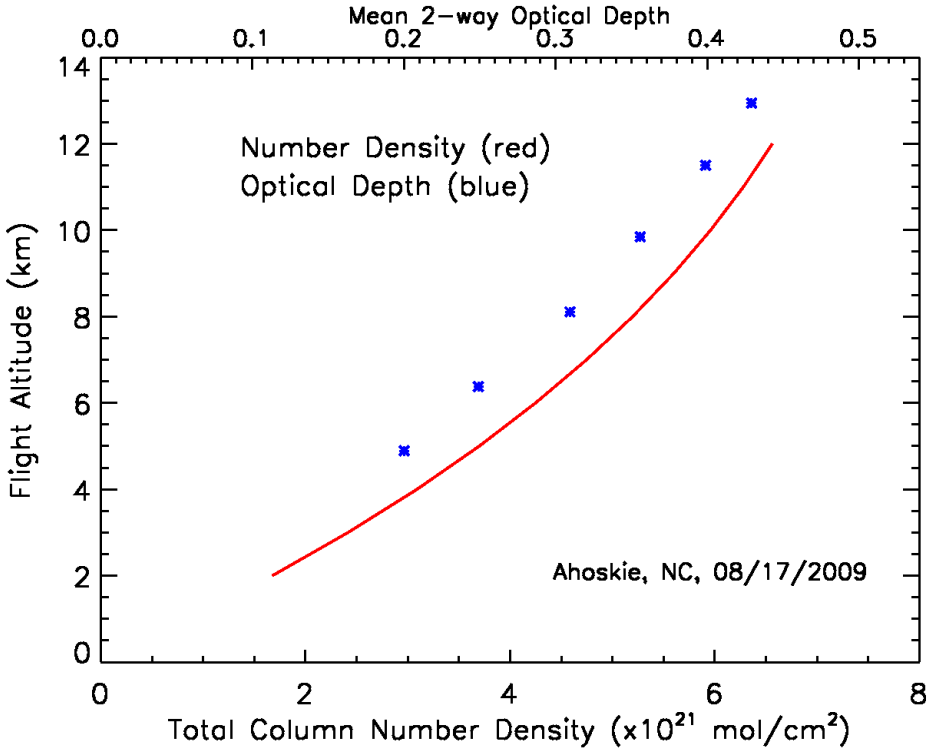
- Depth increases with altitude
- Smooth line shapes at all altitudes !

Line Optical Density & # Density vs Altitude
North Carolina Flight - August 17, 2009

GSFC







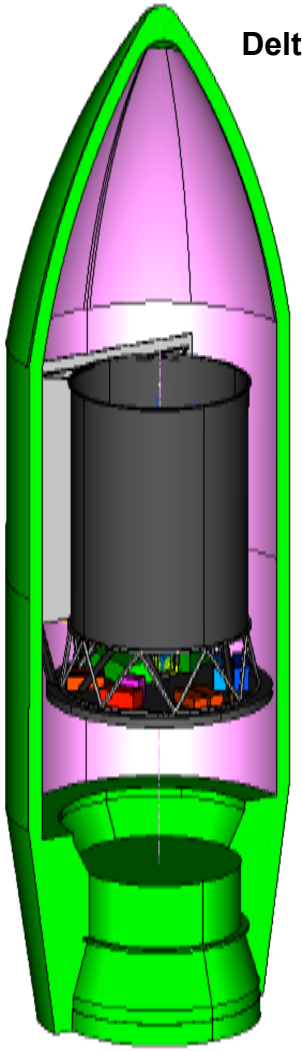
• 4 papers on 2009 CO2 & O2 measurements at 25th ILRC conference, St. Petersburg, Russia, July 2010.

• Mean Optical Depths from line fits to CO2 Sounder measurements

• # Densities calculated from LaRC in-situ sensor and radiosonde readings

Space Instrument Studies (2008 & 2009)

- Sun synchronous orbit
  - Altitude 500, 450 km
  - Sun-sync inclination, 1:30 pm crossing time
- Mission Risk Class B
  - 5 year mission life
  - 85% mission reliability
  - Mitigate single point failures with redundancy or high reliability parts
- Traditional S/C bus orbit and attitude knowledge sufficient for mission requirements (i.e., no on-instrument attitude processing required)

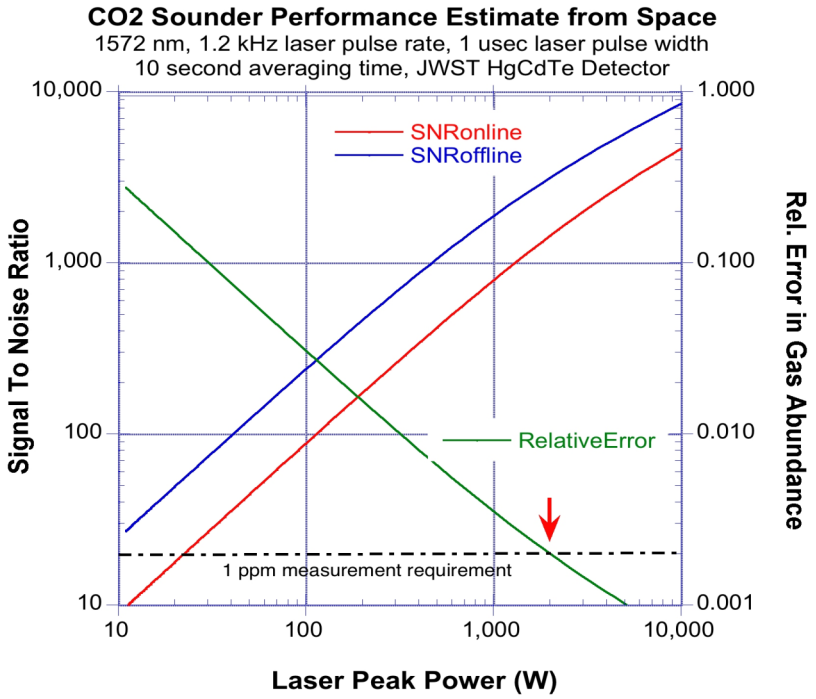


Space: SNR & Relative Measurement Errors

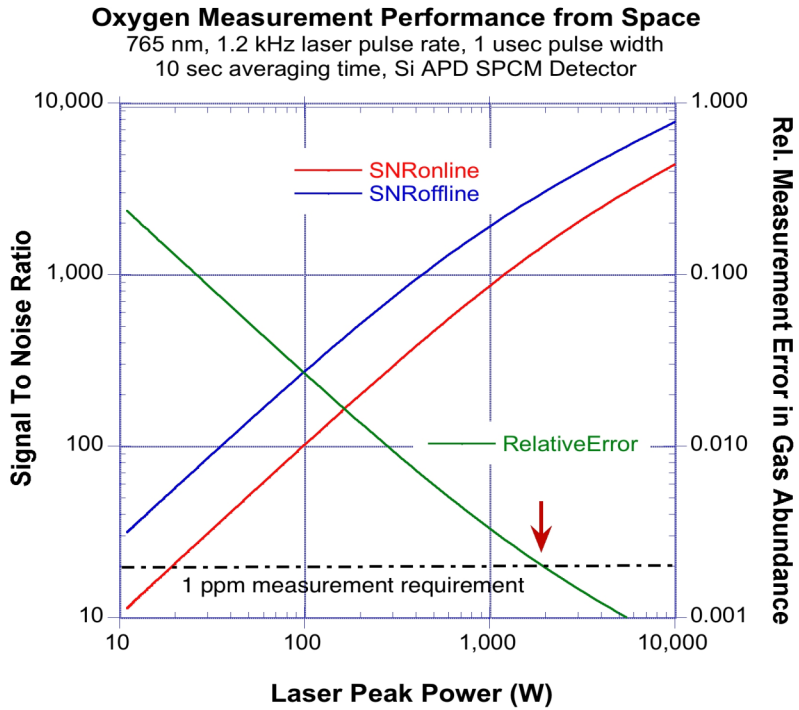
(10 seconds observing time, 500* km orbit, 1.5m telescope)

GSFC

CO2 column measurement



O2 column measurement



~ 3 mJ/pulse energy (HgCdTe detector*)

Ave optical power ~25-30W

~ 3 mJ/pulse energy (SPCM detector)

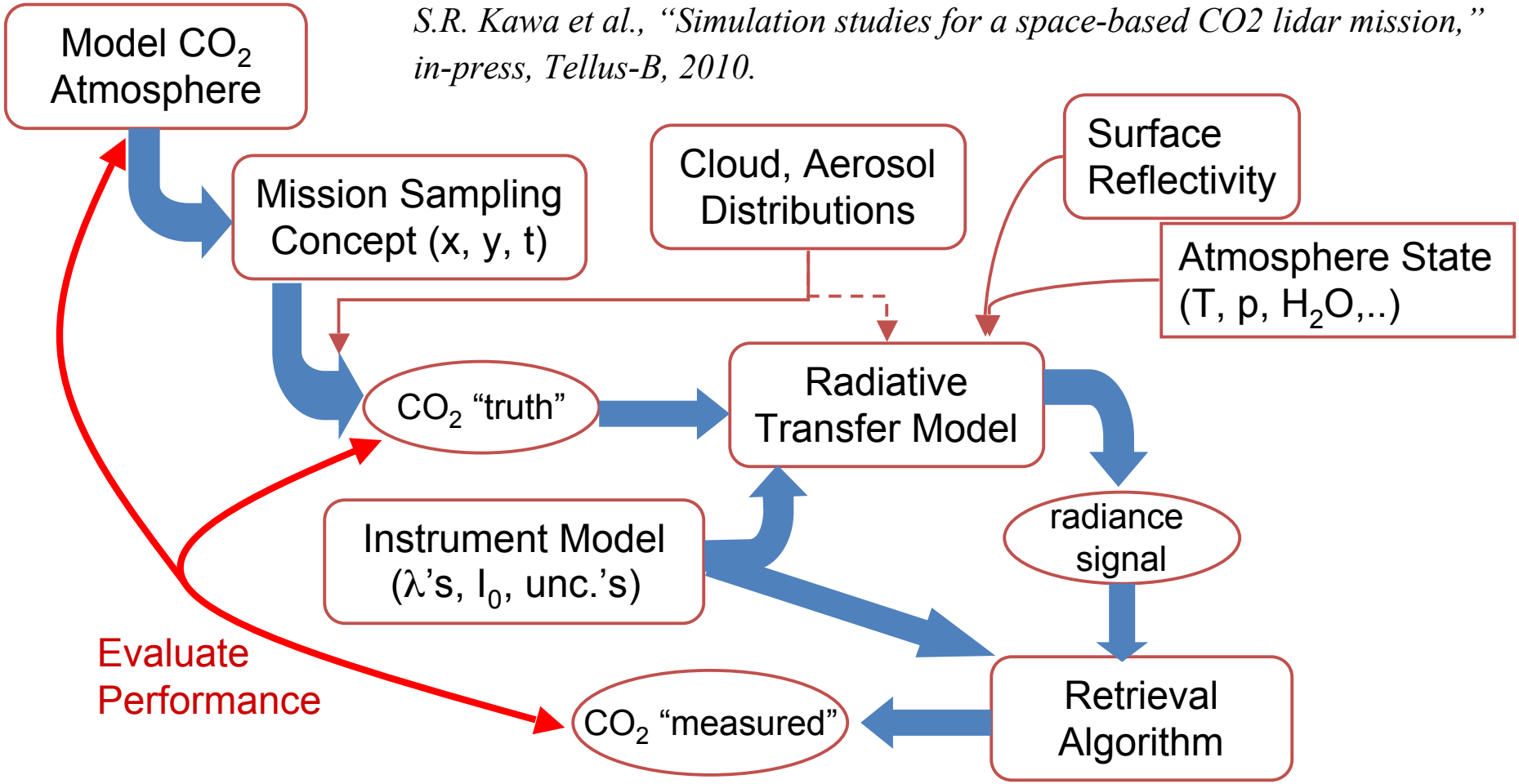
6 mJ energy from 1530 nm amp, 50% doubling

Ave optical power ~25-30 W

* - Same performance at 3 mJ/pulse with PMTs at 400 km orbit

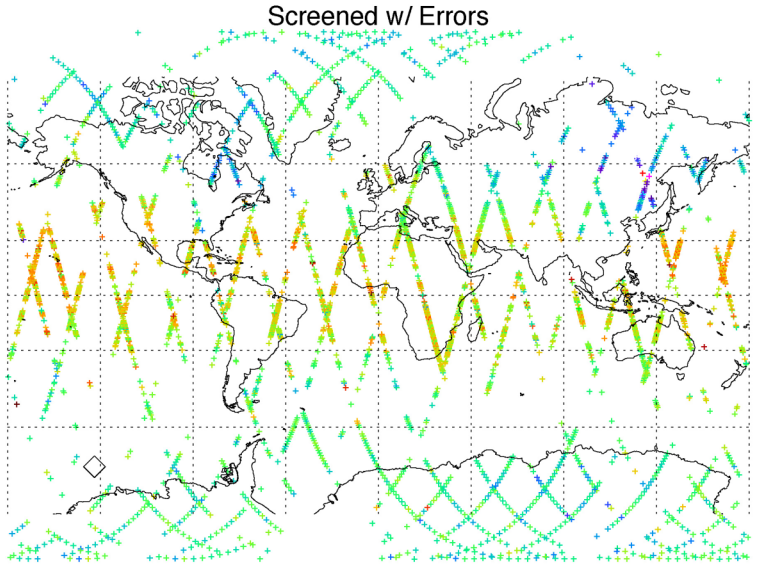
Measurement Model & Mission Performance Simulation

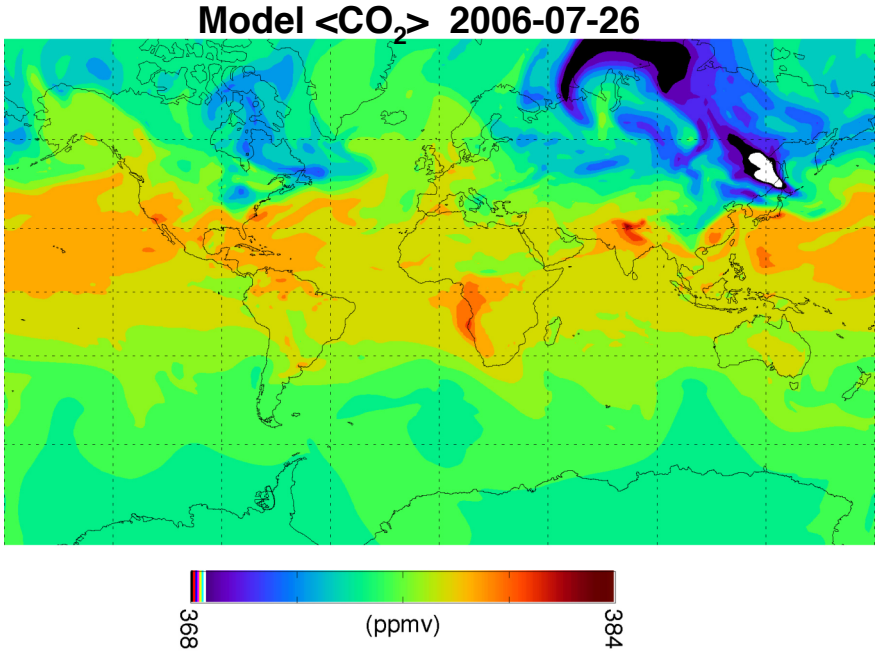
S.R. Kawa et al., "Simulation studies for a space-based CO2 lidar mission," in-press, Tellus-B, 2010.

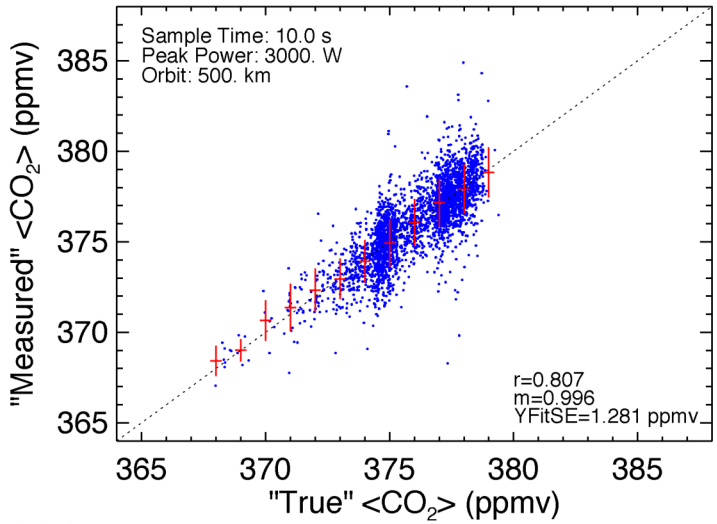


➔ Test sensitivity of inferred CO_2 distributions to varying mission & instrument design parameters.

Nominal Design Point Error Estimate







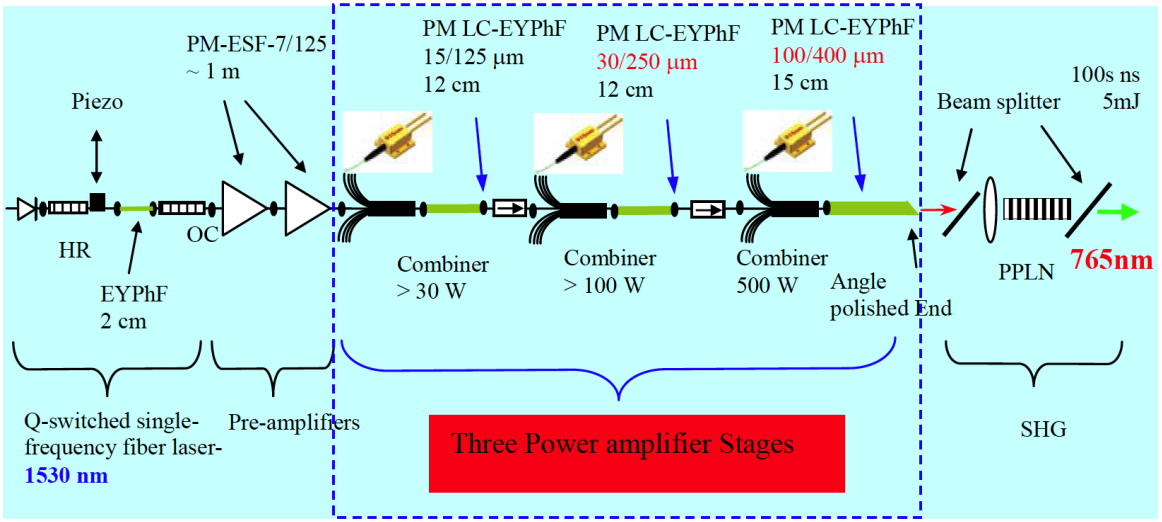
Initial results (CO2 only), 3 mJ/pulse:

- Single-sample (10 sec) errors average ~1.3 ppmv for this instrument configuration.
- Consistent with ASCENDS requirements.
- Work is ongoing

Laser Power Scaling: Amplifier R&D

High SBS-threshold Er/Yb co-doped phosphate glass fiber amplifier

- Develop high SBS-threshold, SM, PM, high power amplifiers for the 100s ns pulses using NP's proprietary patented large core SINGLE-MODE PM highly Er/Yb codoped phosphate fibers and patented Q-switched single frequency fiber laser seed.
- Develop amplifier prototypes/products: 50μJ, 100s μJ and mJ. Push the SBS threshold to 100s kW.



SBIR (-1 & -2) with NP Photonics (Wei Shi,PI) COTR: Mark Stephen

Near-term Raytheon applications of fiber lasers have been in various versions of laser sensors, including a state-of-the-art coherent laser radar system. In the commercial world, fiber lasers are becoming the laser of choice in a number of laser processing applications, most significantly in the marking area where they essentially dominate all other options.

Planar Waveguide Lasers (PWGs), are high aspect ratio sandwich-type structures consisting of a high-index active core surrounded by lower index claddings. A PWG is essentially a one-dimensional fiber in which the thin transverse axis is guided and the wide transverse axis is unguided. The core, typically 5 to 200 μm thick, may be single-mode or multimode and may be

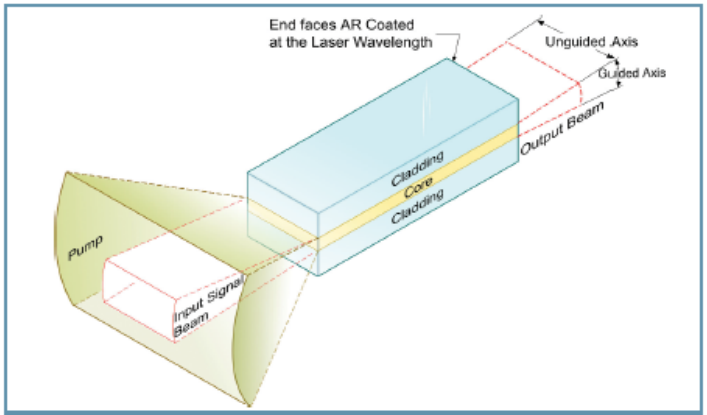


Figure 2. Planar waveguide gain medium showing pump insertion and output beam

Raytheon

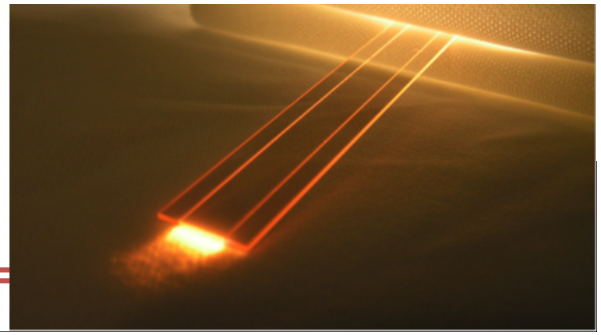
Customer Success Is Our Mission

Amplifier R&D

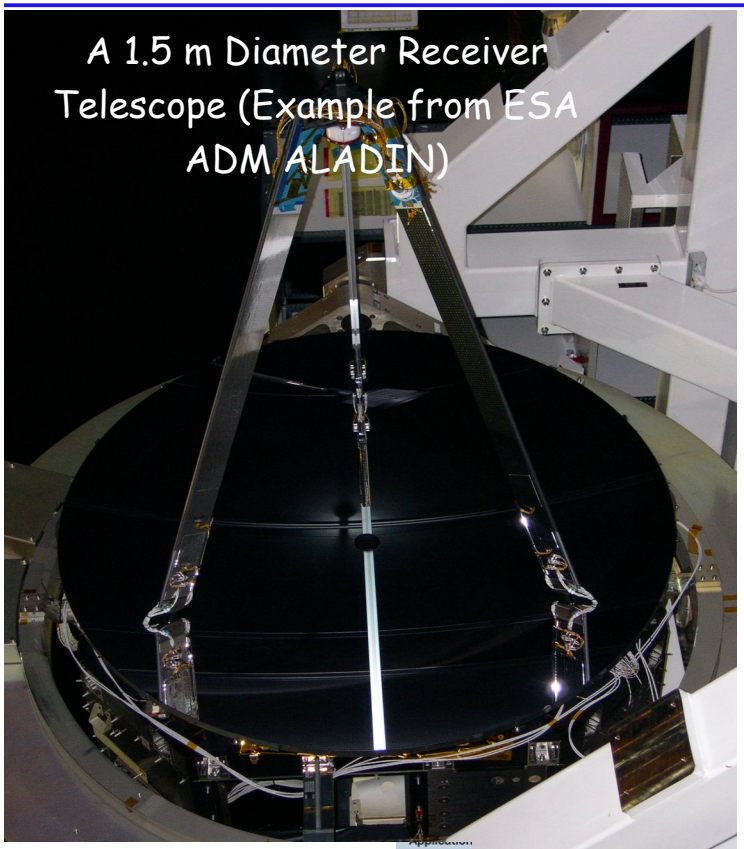
Planar Waveguide Amplifier

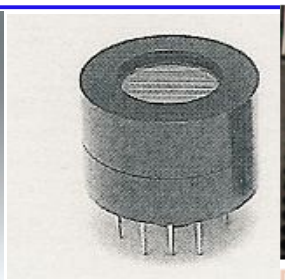
Planar waveguides allow guided mode amplification with larger areas

=> higher peak powers & energies



Other key elements of space lidar:





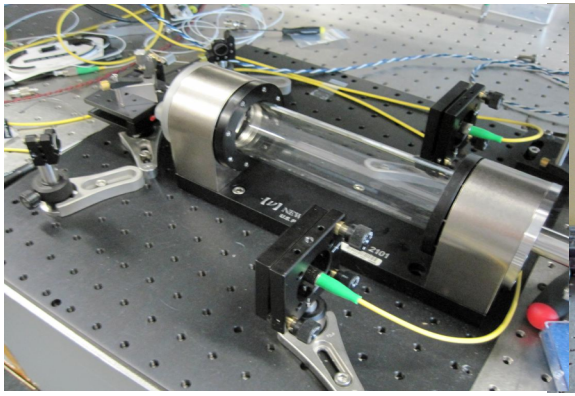
CO2 detectors:

Left: Hamamatsu H9170-75 PMT: 12% QE used in airborne lidar

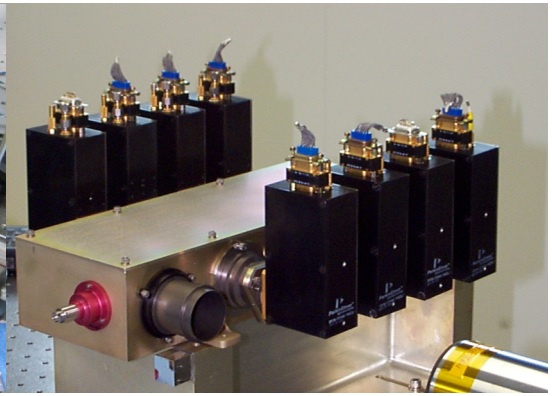
Right: ~70% QE HgCdTe detector (under evaluation)

DBR tunable seed lasers:
5MHz linewidth, > 30nm tuning

18m compact Herriott cell



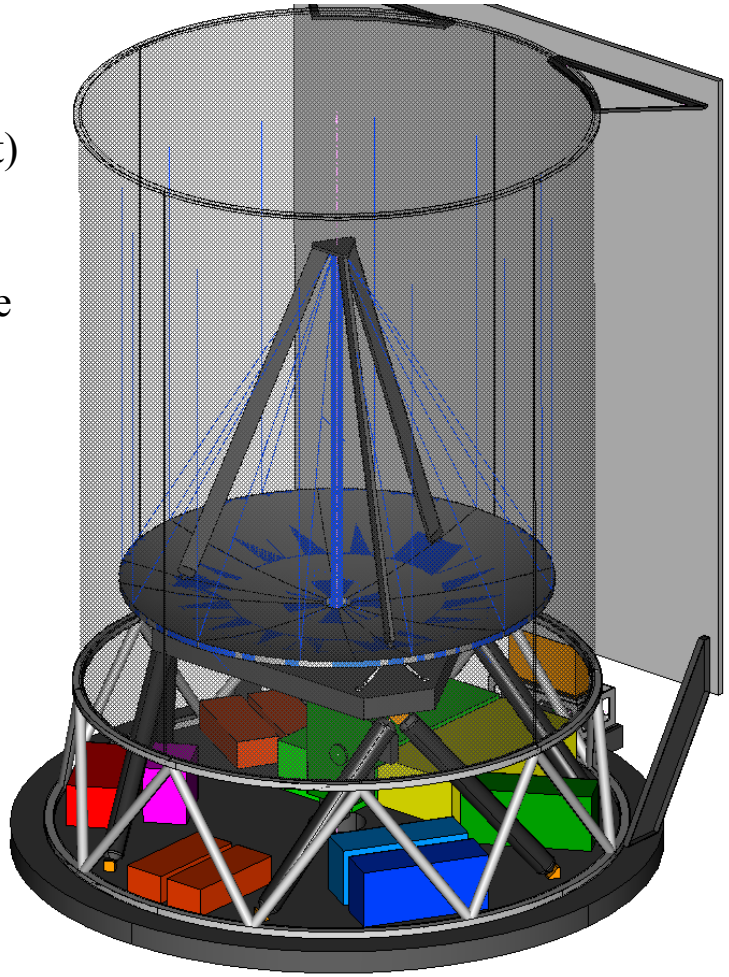
O2 Lidar detectors:
SPCM detectors flown on ICESat/GLAS



Summary of 2 Space Lidar Studies

- Conducted studies of this approach for ASCENDS space lidar: 4/08 & 9/09
- Several aspects can be further optimized in design studies
- Straightforward space lidar design:
  - Mass: ~ 400 Kg (can be reduced via more efficient layout)
  - Power: ~ 850W (3dB margin); driven by SNR needs
  - Data rate: ~1.9 Mbit/sec; high latitude comm. ground site
- Low risk: Space qualified telescope, O2 detectors
- Detectors: reliability via multiple detectors & spares.
- Primary power draw: lasers
- Lasers: high efficiency & reliability & spares
- Mission compatible with medium class rocket

(Taurus-II or equivalent), with considerable margin



Layout concept from 1st study

Summary

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

NASA Science Definition and Planning Workshop Report

July 23-25, 2008
University of Michigan in Ann Arbor, Michigan

Workshop report:
http://cce.nasa.gov/ascends/index.htm

Developing CO2 Sounder approach for ASCENDS:

- CO2 and O2 (pressure) measurements
  - Line shape & Column height measurements
  - 2 altitude wieghting functions
  - Robust against atmospheric scattering
  - Ground-based O2 measurements
- Airborne demonstrations:

  CO2 measurements in 2008 & 2009

  CO2 & O2 in prep. for 2010
- Studies show lasers & lidar for space are feasible
- 1st mission simulations show can meet science needs, but more are needed.

We appreciate the ESTO support !

Thank you !

Backup

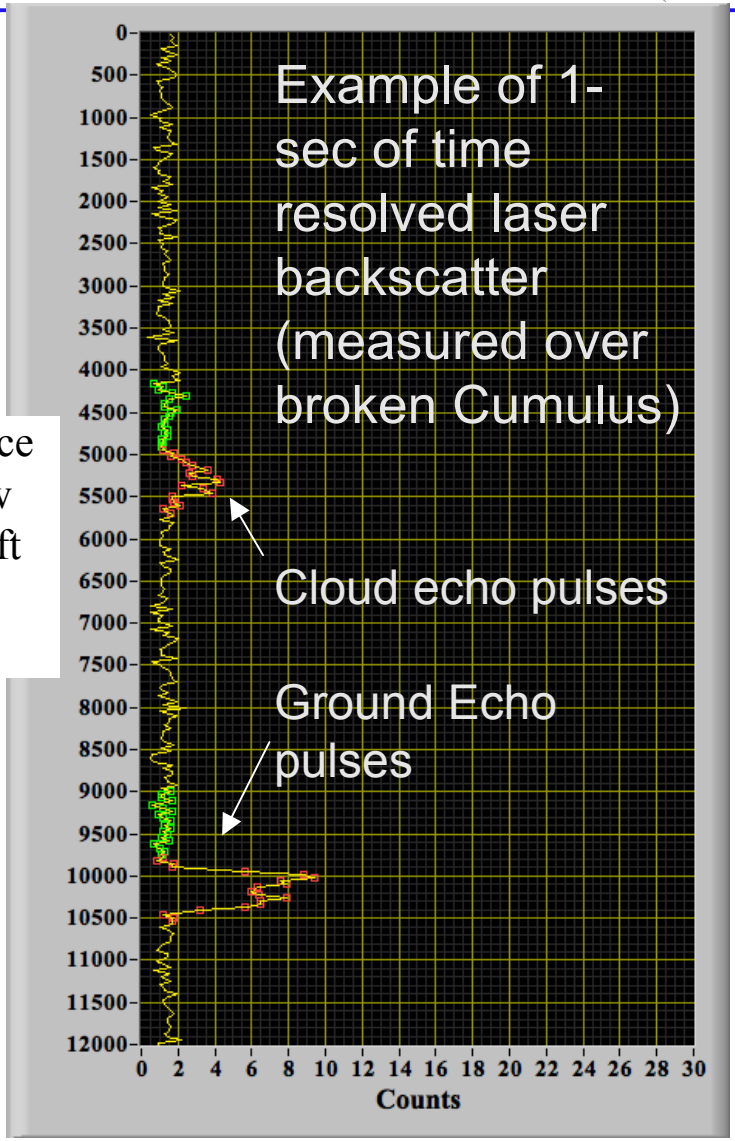
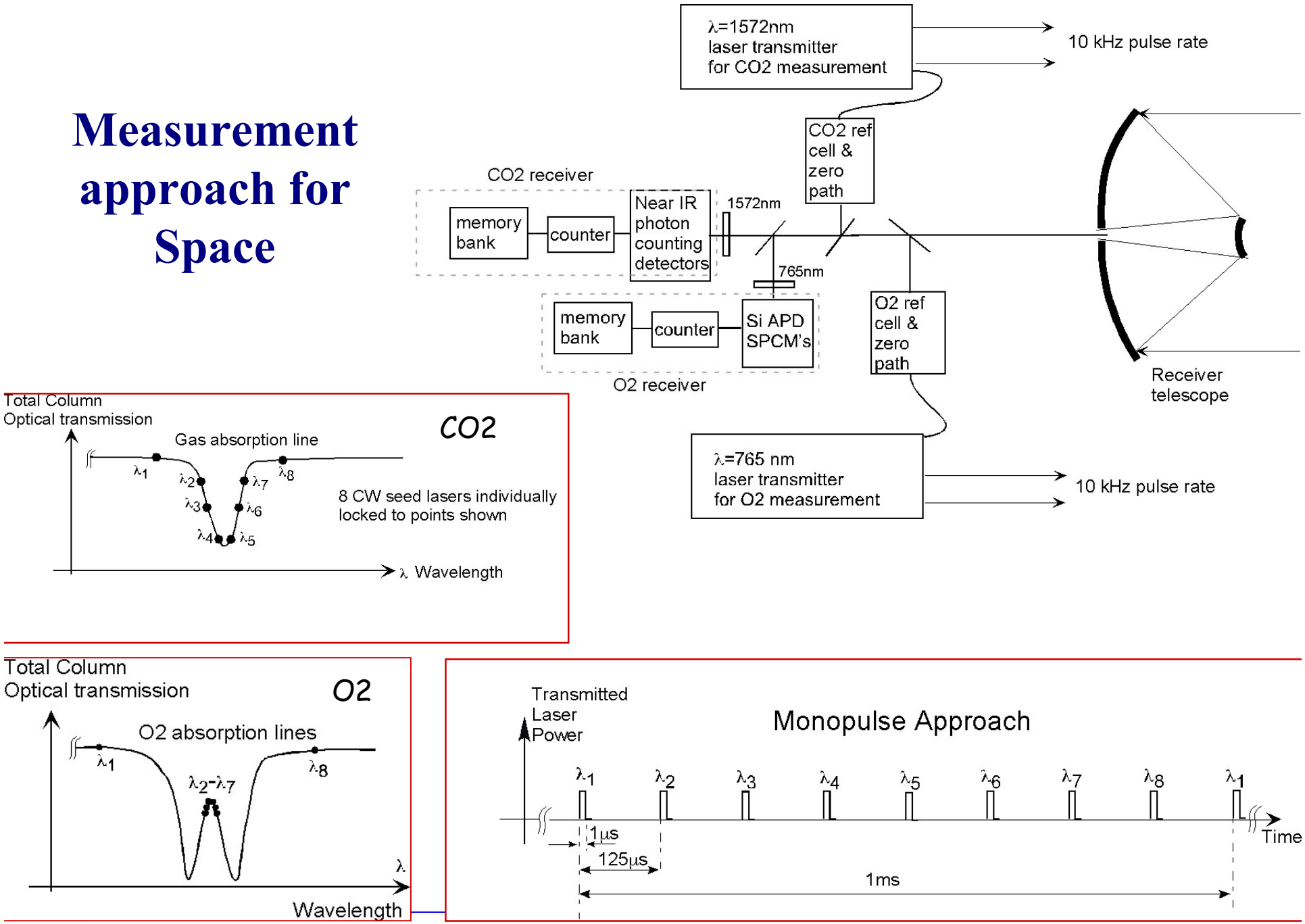
2009 Flight Example: Measuring though Cloud deck over Homer IL

GSFC

Cirrus at ~32000 ft

Broken Cumulus ~5000'

Distance below aircraft (ft)



Measurement approach for Space