DESIGN, DEVELOPMENT AND EVALUATION OF A 2-MICRON DIFFERENTIAL ABSORPTION LIDAR FOR PROFILING CO_2

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2005-2008

Development of a Pulsed Direct Detection DIAL CO_2 Profiling System

Goals and Objectives

Objectives:

- Develop and evaluate a ground-based CO_2 DIAL profiling system.
- Advance system level TRL from 3 to 5.

Features:

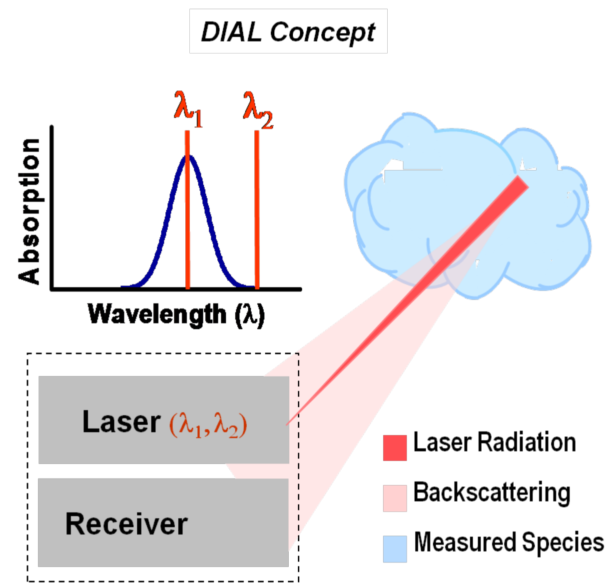
- Use 2-µm pulsed laser developed under LRRP Program.
- Characterize and use IR phototransistors as detectors.
- Use direct detection technique with 16" telescope.

Goal:

- DIAL precision 1-2 ppm (<0.5%), with 0.5 to 1 km vertical resolution, near surface to free troposphere (4-5 km), and ~30 min time resolution data needed for ground-based DIAL systems.
- 1% (3 ppm) absolute accuracy for 30 min, 1 km resolution mixing ratio profile from 0.5 km to free troposphere (4-5 km).

Introduction

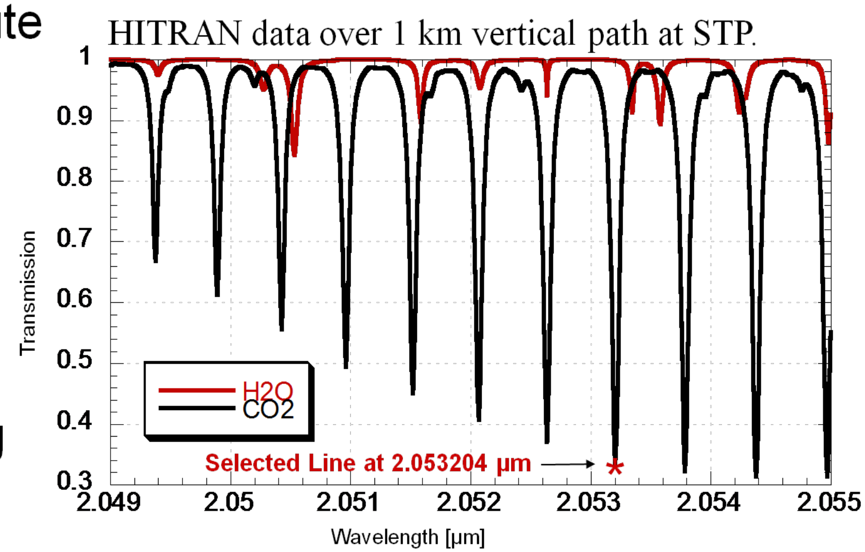
- DIAL technique for atmospheric CO_2 measurement requires suitable absorption lines; narrow-band, tunable, and line-locked lasers; high efficiency and low noise detectors.
- Pulsed laser provides built-in ranging and avoids cloud/aerosol influences.



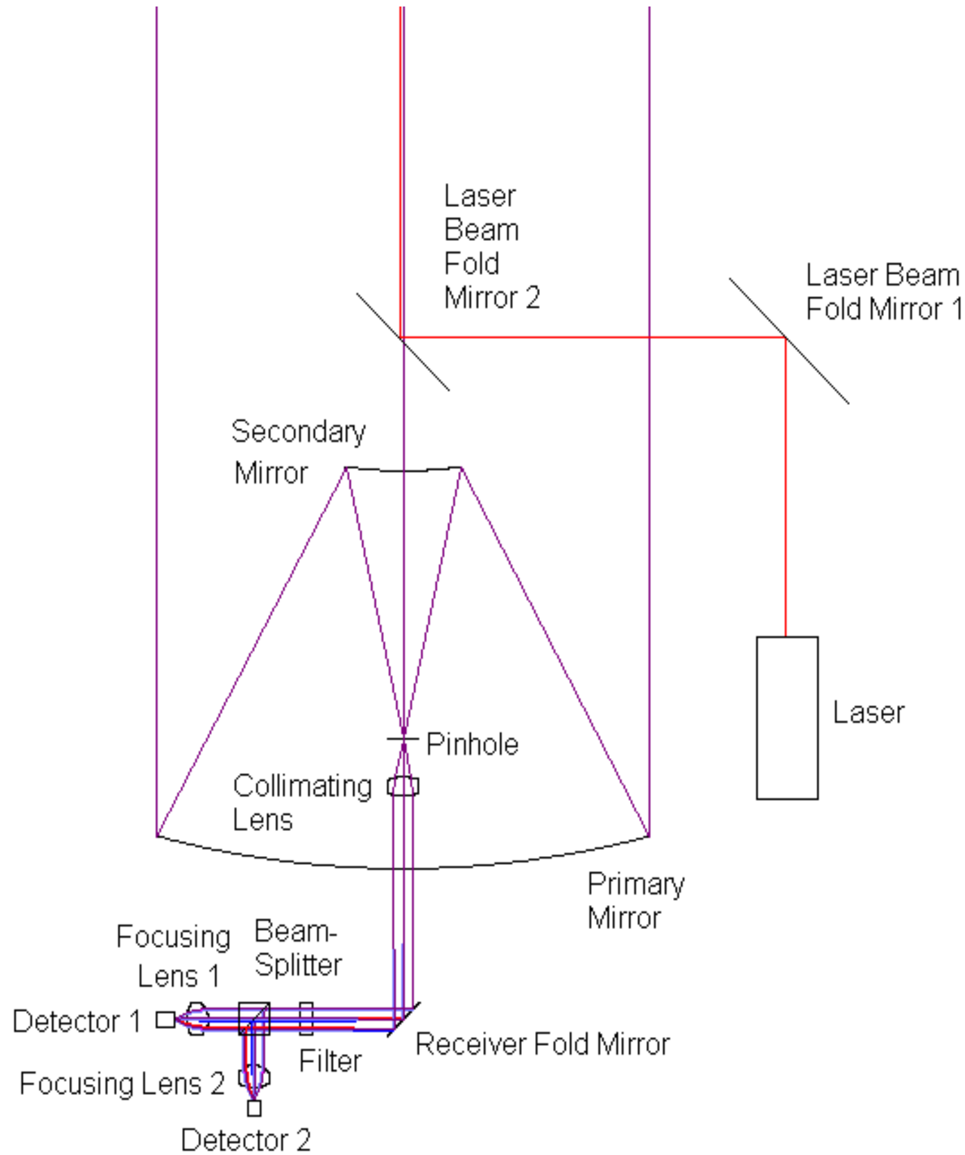
Advantages:

- High vertical and horizontal resolution.
- DIAL data permit direct inversion and absolute concentration measurements.
- Simultaneous species, aerosol and cloud distribution profiles.
- Day and night coverage independent on external radiation.

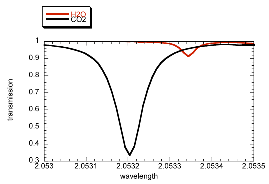
2.053 µm CO_2 absorption line allows optimum sampling of low troposphere, low temperature sensitivity and have minimum interference from other species.

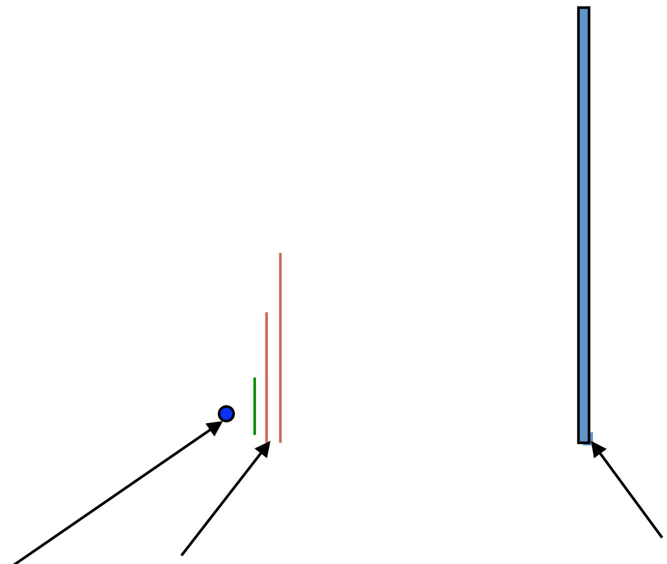


Instrument Concept



Side-Line Operation





center line (locked):
2053.204 nm

side line (locked):
1) 2053.220 nm
2) 2053.227 nm
3) 2053.233 nm

off line (drifting):
2053.403—2053.410

Lidar parameters of a direct detection CO_2 DIAL with Phototransistor and large 16" telescope

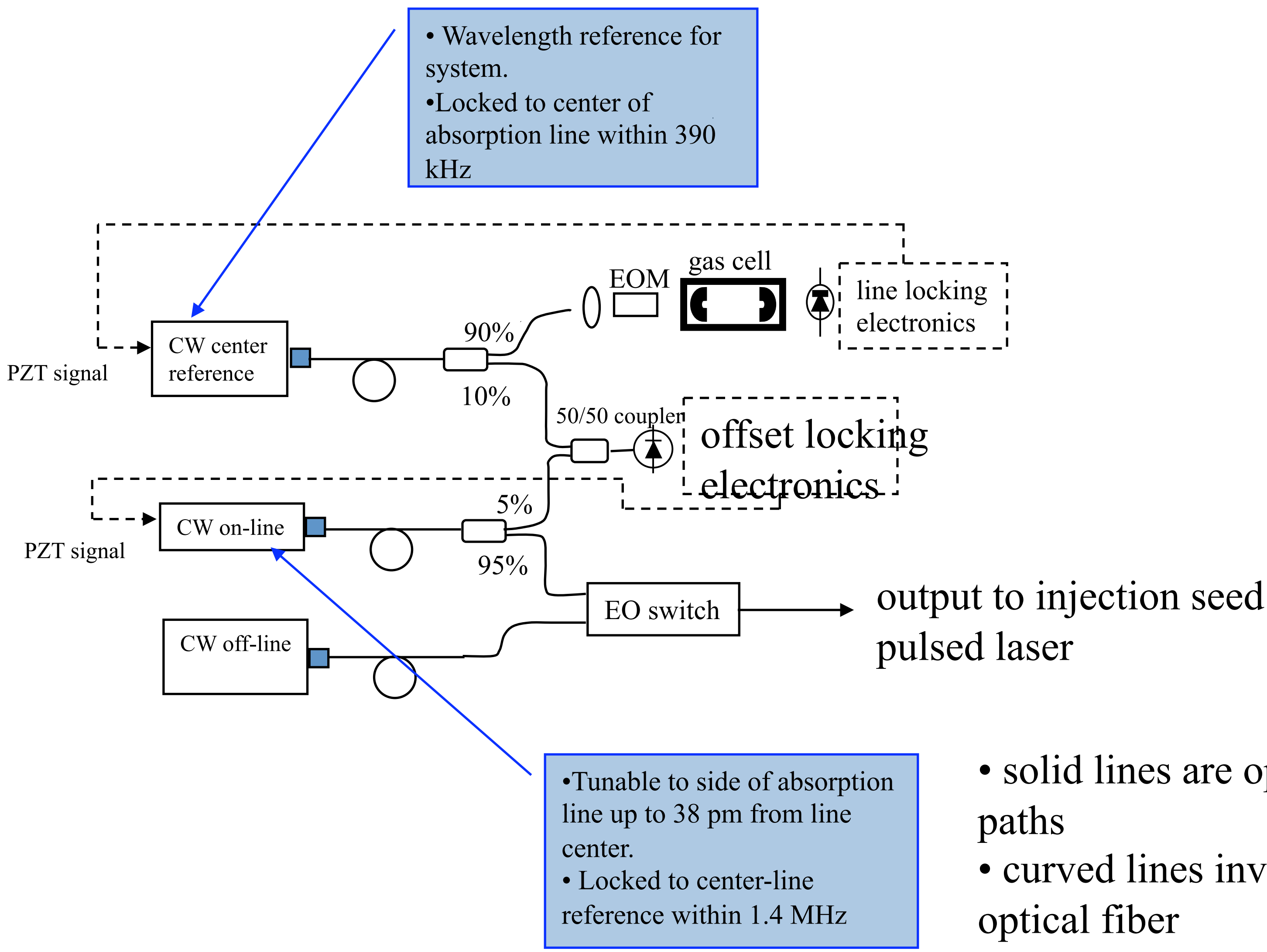
Baseline DIAL system parameters

Pulse energy = 80 mJ single pulsed (Operated); 40/30 mJ double pulsed demonstrated; 80 mJ double Pulsed Proposed
Pulse width = 180 ns
Pulse repetition rate = 5 Hz
Spectrum = single frequency
On-line wavelength = 2053.204 nm
Off-line wavelength = 2053.240 nm
Beam quality < 1.3 time diffraction limit
Long term (one hour) wavelength stability < 2 MHz
Wavelength accuracy < 0.5 MHz
Detector AlGaAsSb/InGaAsSb phototransistor
Quantum efficiency = 70%
Optical efficiency 60%
NEP = 5.0E-14 W/sqrt(Hz)
Telescope aperture = 16 inches

Specifications

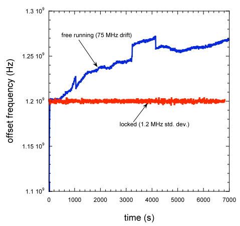
PARAMETER	STATUS in Oct 2005	STATUS in Oct 2006
• pulse energy	100 mJ[1]	100 mJ
• pulse repetition rate	5 Hz	5 Hz
• frequency spectrum	single freq.	single freq.
• wavelength locking	within +/- 13.5 MHz	within +/- 1.35 MHz[2]
• seeded double pulsing	basic principle demonstrated	done
• rapid l switching	done	done
• side-line offset locking	not demonstrated	done

Schematics of Laser & Wavelength Control Architecture



- solid lines are optical paths
- curved lines involve optical fiber
- dashed lines are electronic paths

Side Line Offset Locking Characterization

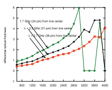


- Electronic control holds an offset from center-line locked laser.

- Offset can be electronically programmed.

- Test here assesses quality of offset lock set for 1.2 GHz (37.3 pm).

Atmospheric test: changing side-line tuning, continued

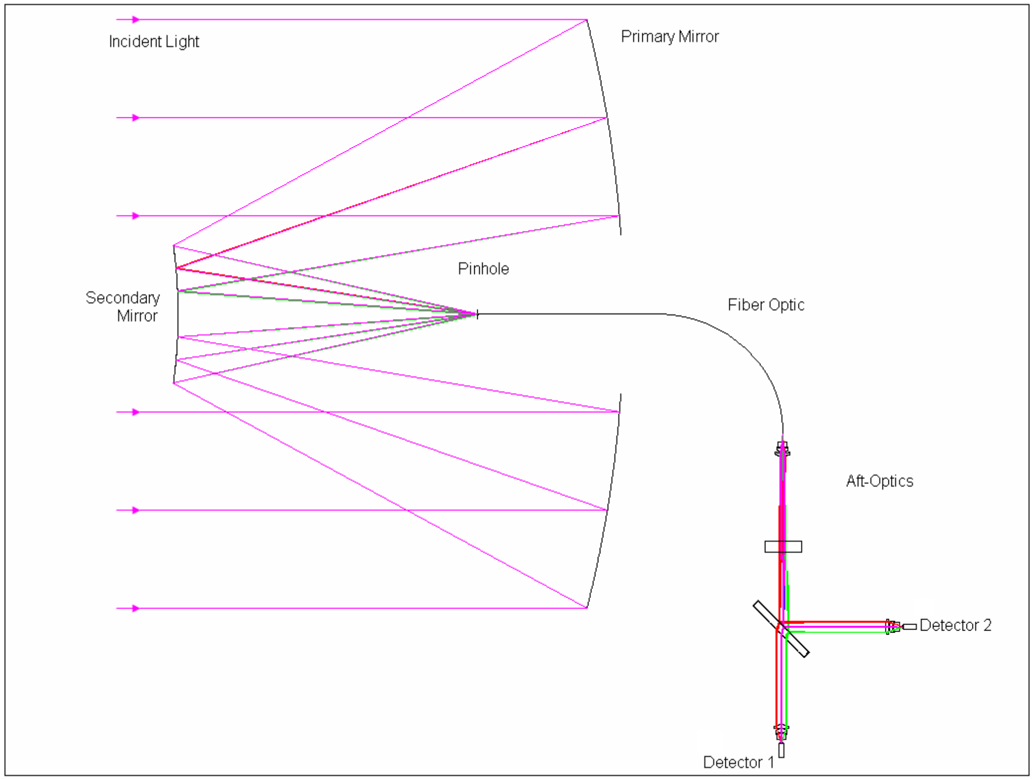


$$\text{diff. opt. thick.} = \ln (S_{off}/S_{on})$$

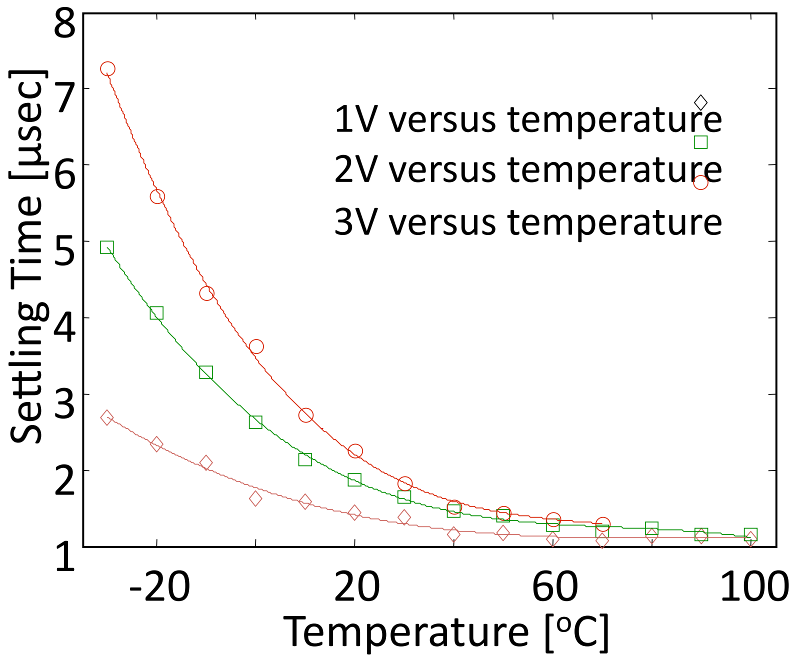
• beam vertically pointing
• processed on 200-m range bins.
•2000 pulse pairs.
• three sets of data
• optical depth changes with wavelength, demonstrating the usefulness of this technique.

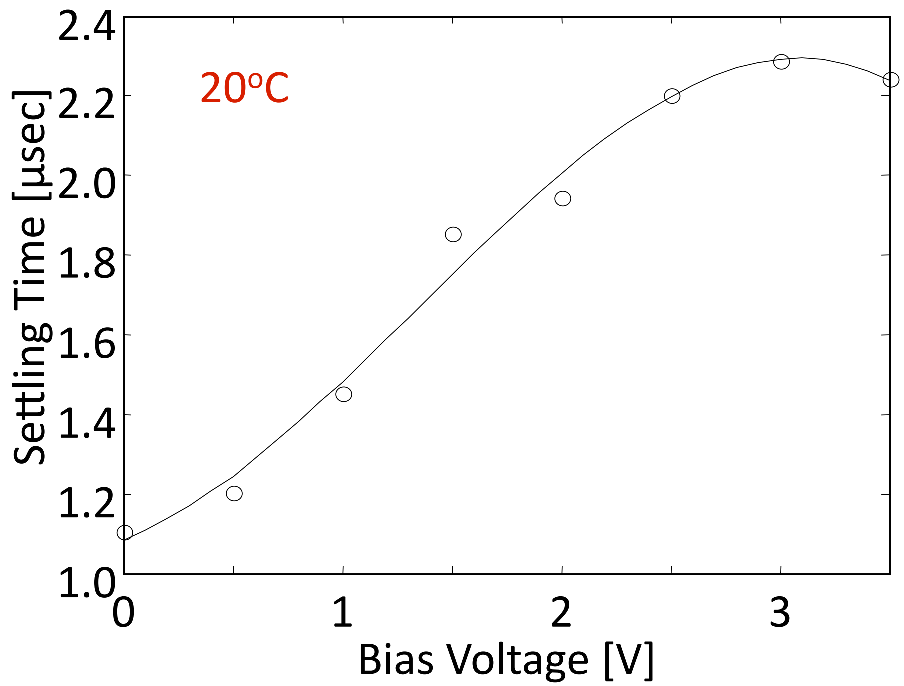
CO_2 DIAL Receiver Optical Design

Below shows the optical layout for the CO2 DIAL receiver. The incident light is focused through the pinhole by the primary and secondary mirrors. A fiber optic cable is used to transmit the light from the pinhole to the focus of the collimating lens. The light propagates through the collimating lens and interference filter. The light is divided into two beams by the beamsplitter. The transmitted light is focused onto detector 1 by focusing lens 1. The reflected light is focused onto detector 2 by focusing lens 2.



Phototransistor Settling Time Vs T and V



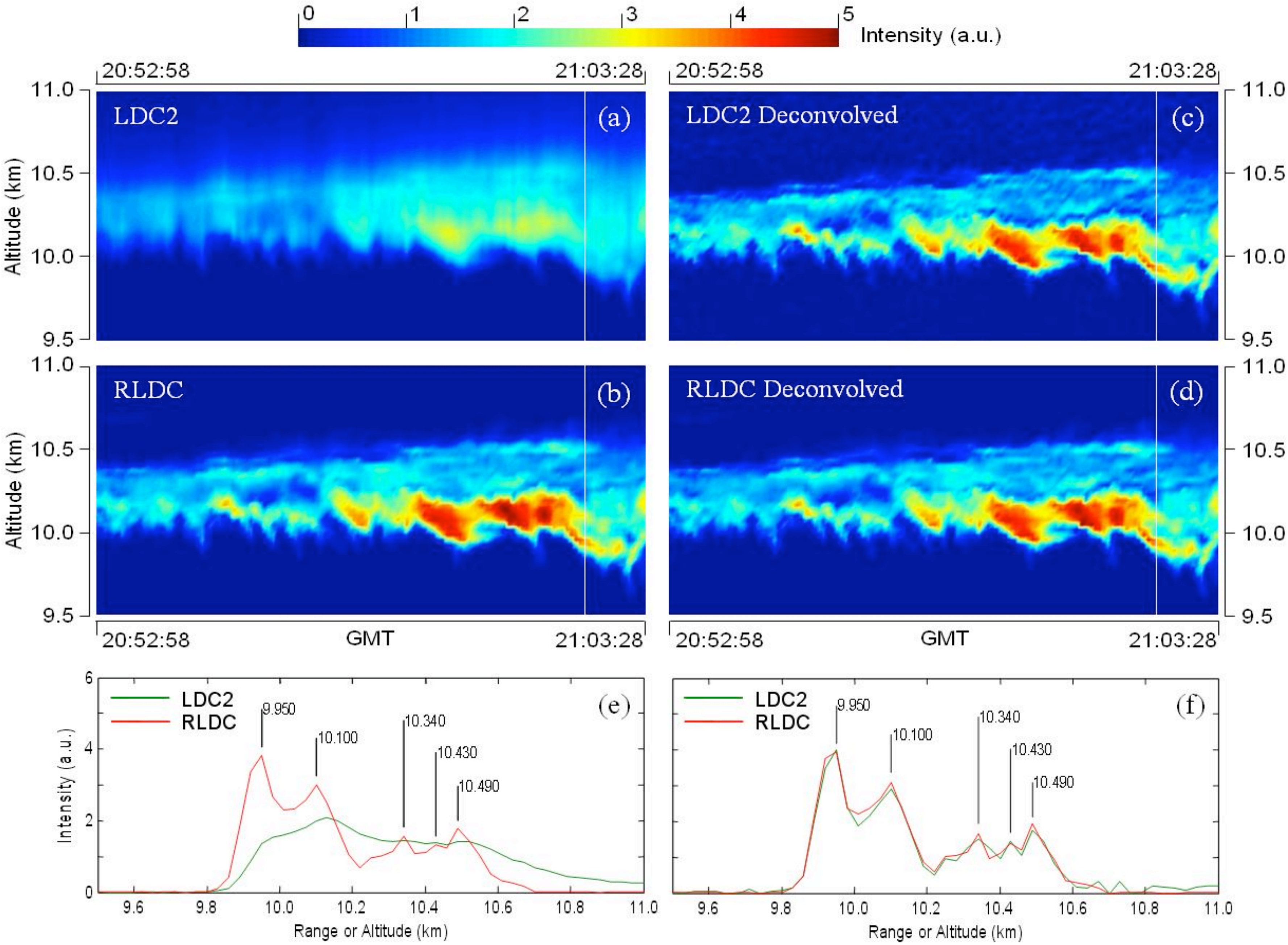


Results of detector atmospheric tests

AlGaAsSb/InGaAsSb (LPE type) Phototransistor
Wavelength: 2050 nm
Area 200 micron
Quantum Efficiency:55-75%
NEP 5.0E-14 to 1.0E-13 w/sqrt(Hz)
Excess Noise Factor: 1.0
Gain 20-3000 (1V/20C-3V/20C)
Bandwidth 1.5-3.0 MHz
Settling time <3 micro sec to <1%

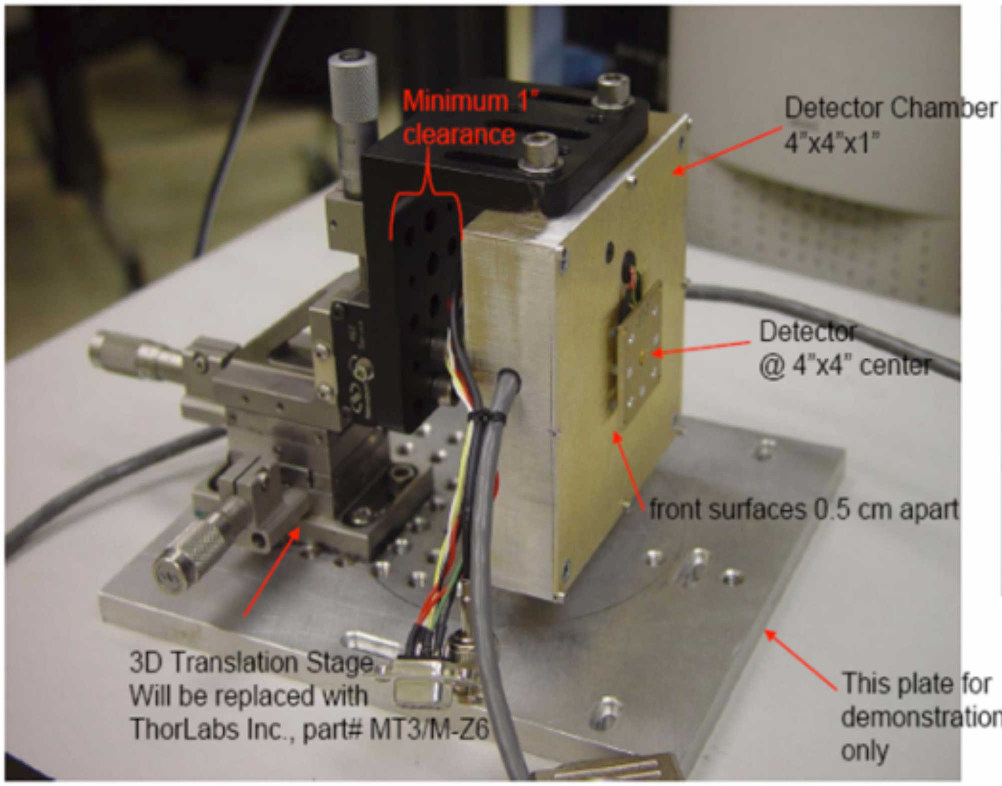
Atmospheric tests using a lidar system at NCAR, Boulder were conducted using a 1.6 micron laser, 16" telescope, focusing light onto the 200 micron detector. The phototransistor showed high sensitivity to detect aerosol layers with a resolution of 100 m.

- Phototransistor was used for the first time in lidar
- It showed longer settling time than an APD that required further analysis



0 1 2 3 4 5 Intensity (a.u.)
20:52:58 21:03:28
Altitude (km)
11.0 10.5 10.0 9.5
LDC2 (a)
LDC2 Deconvolved (c)
RLDC (b)
RLDC Deconvolved (d)
GMT
LDC2
RLDC
(e)
(f)
9.950
10.100
10.340
10.430
10.490
Intensity (a.u.)
Range or Altitude (km)
9.6 9.8 10.0 10.2 10.4 10.6 10.8 11.0

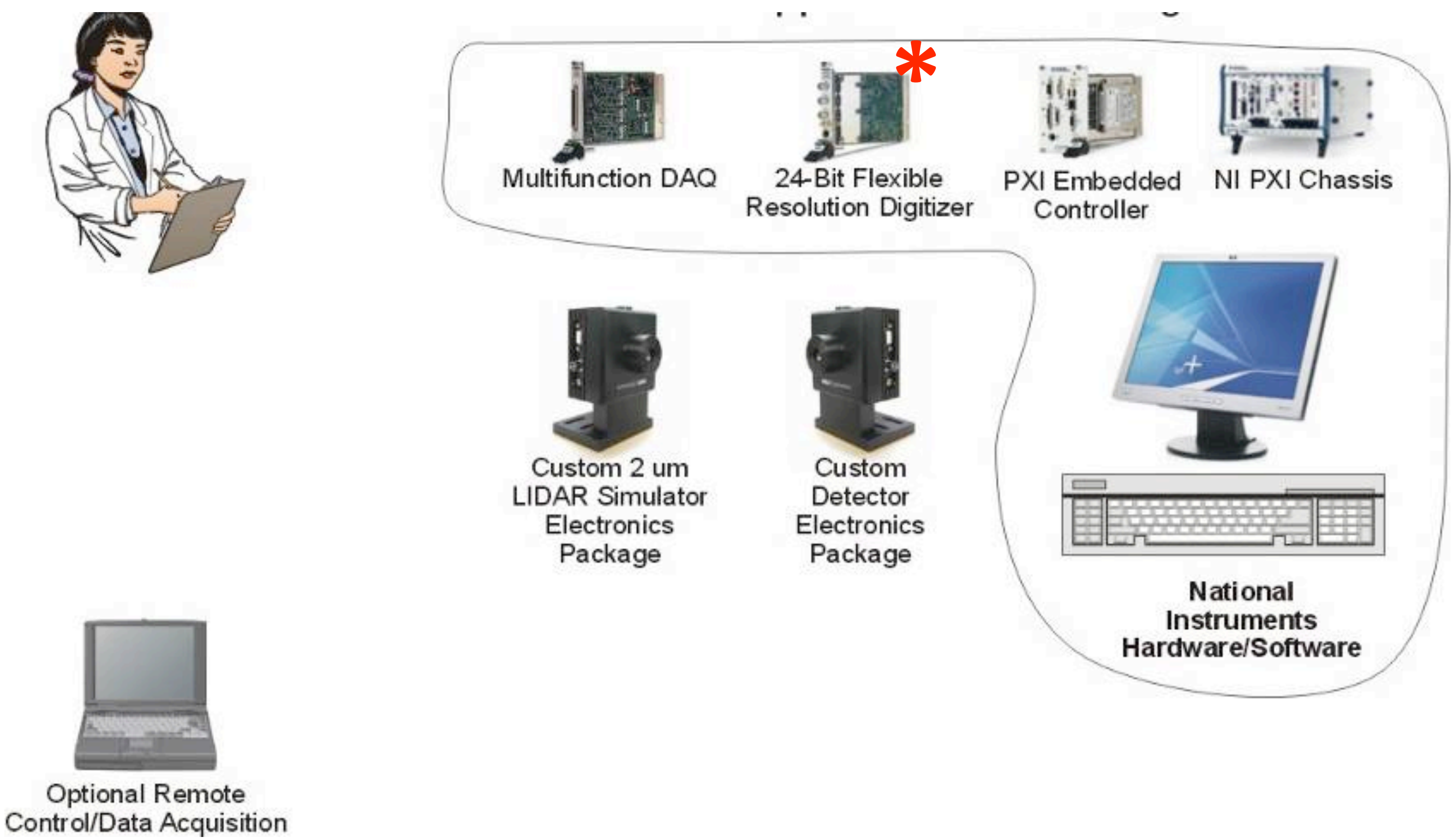
Detector Amplifier Packaging and Mounting



Vertical mounting of the detector chamber.

Detector mounting and packaging

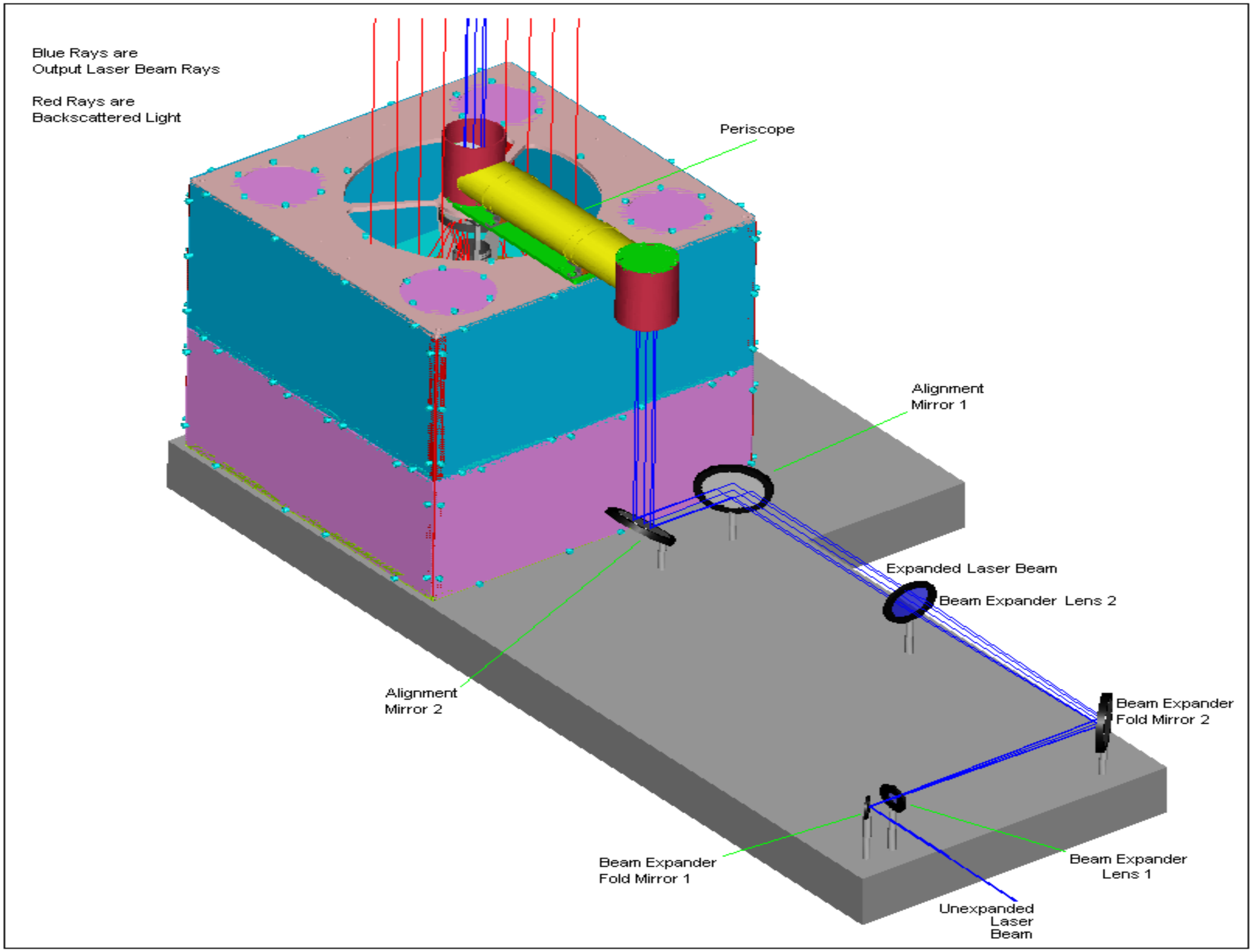
Receiver data acquisition system design



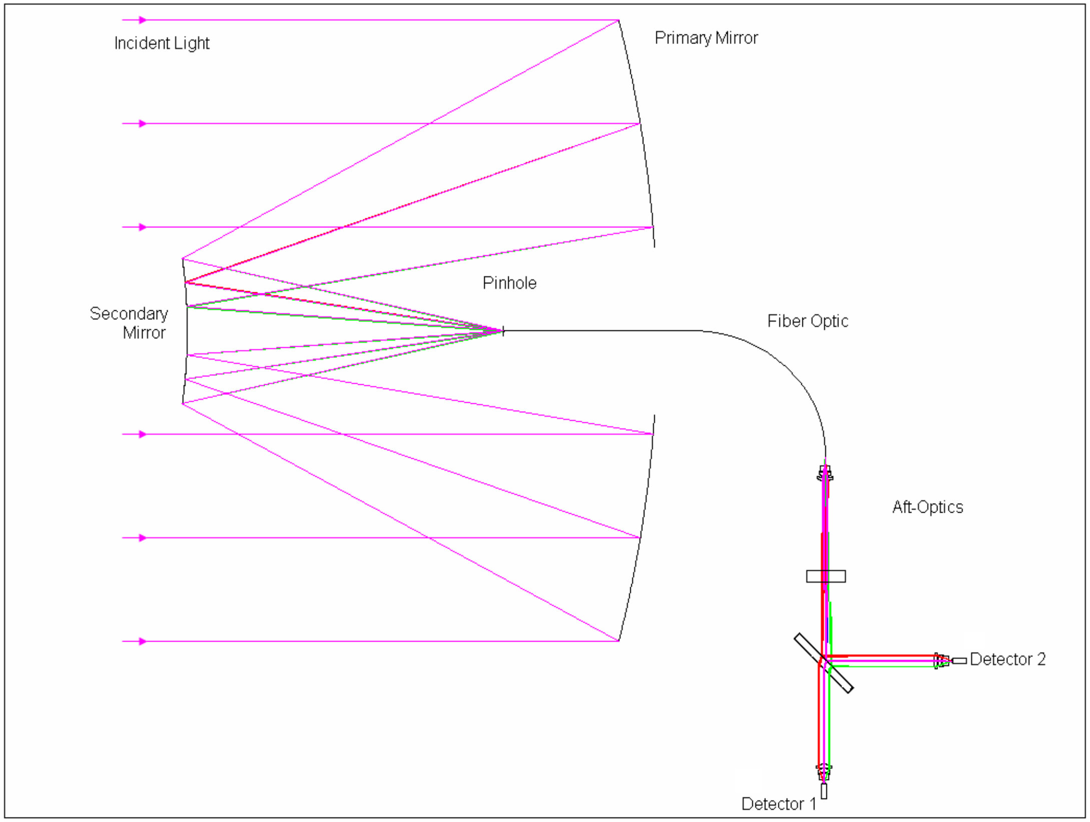
*** 24-Bit digitizer was replaced by a 12-Bit digitizer due to poor high frequency performance of 24-bit digitizer**

System Integration and Testing at Langley

Schematic of Lidar configuration including beam expander and periscope



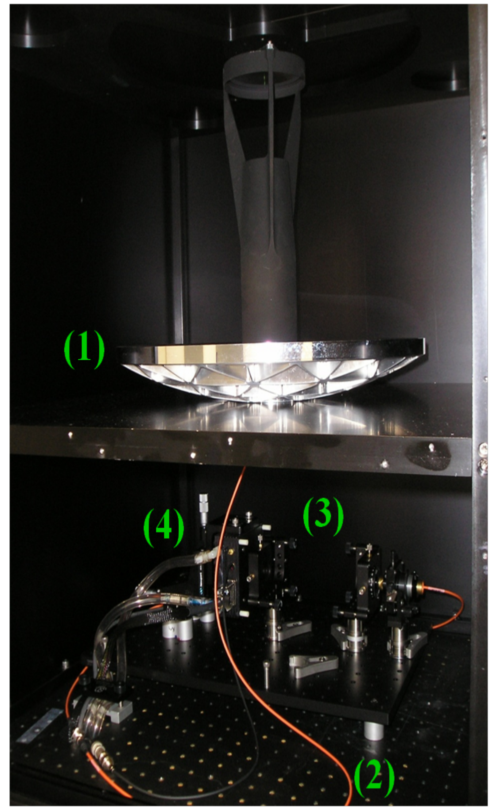
Receiver Optical Layout



Receiver and System Integration

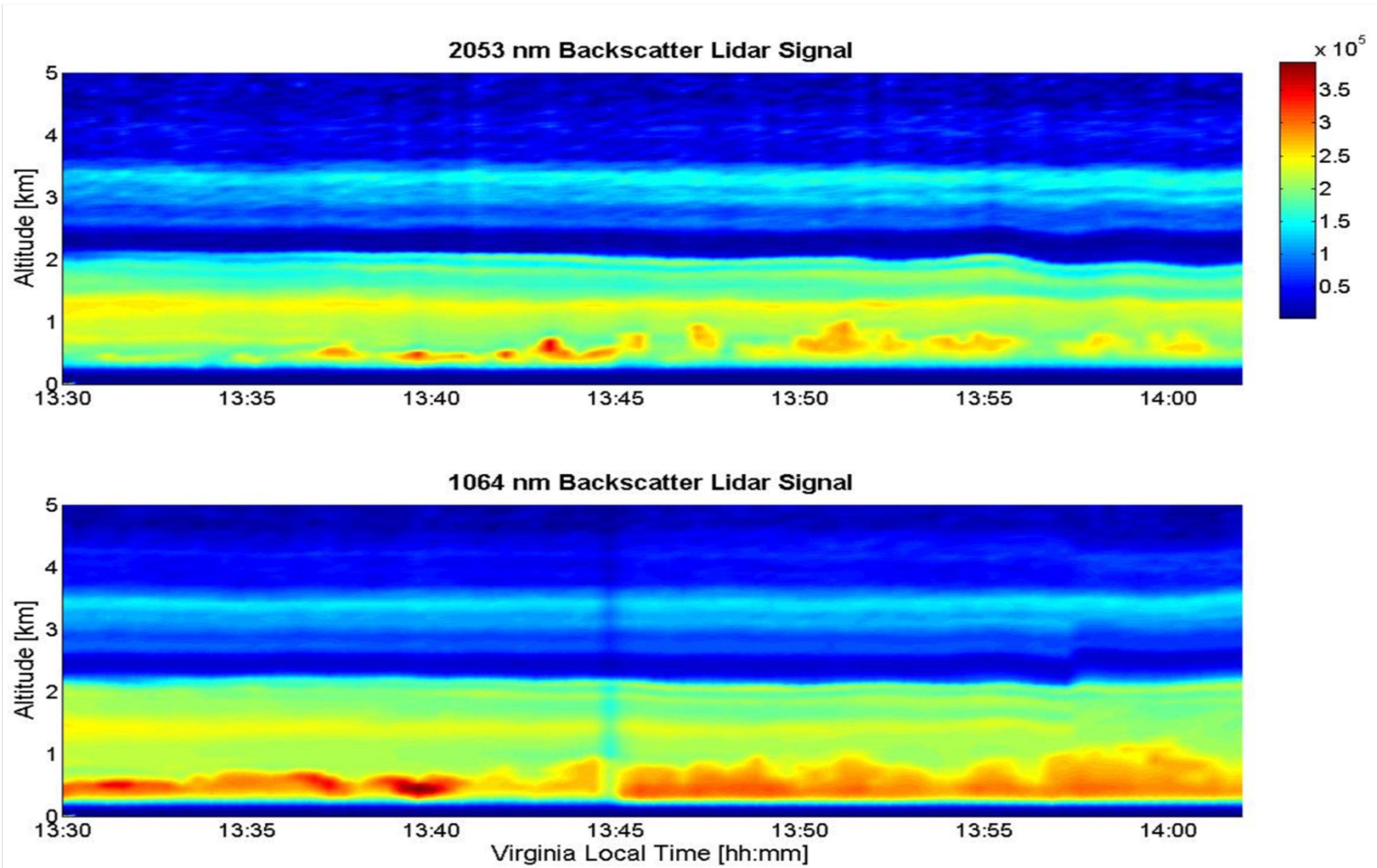
Receiver system hardware including 16” all aluminum telescope (1), fiber coupled (2) to aft-optics (3) that focuses the radiation onto the detector (4).

Beam expander lens (1) and beam steering optics (2) guide the transmitted beam to the atmosphere co-axially with the telescope though top window (3). Receiver enclosure box (4) allows for optics shielding and components environmental control.

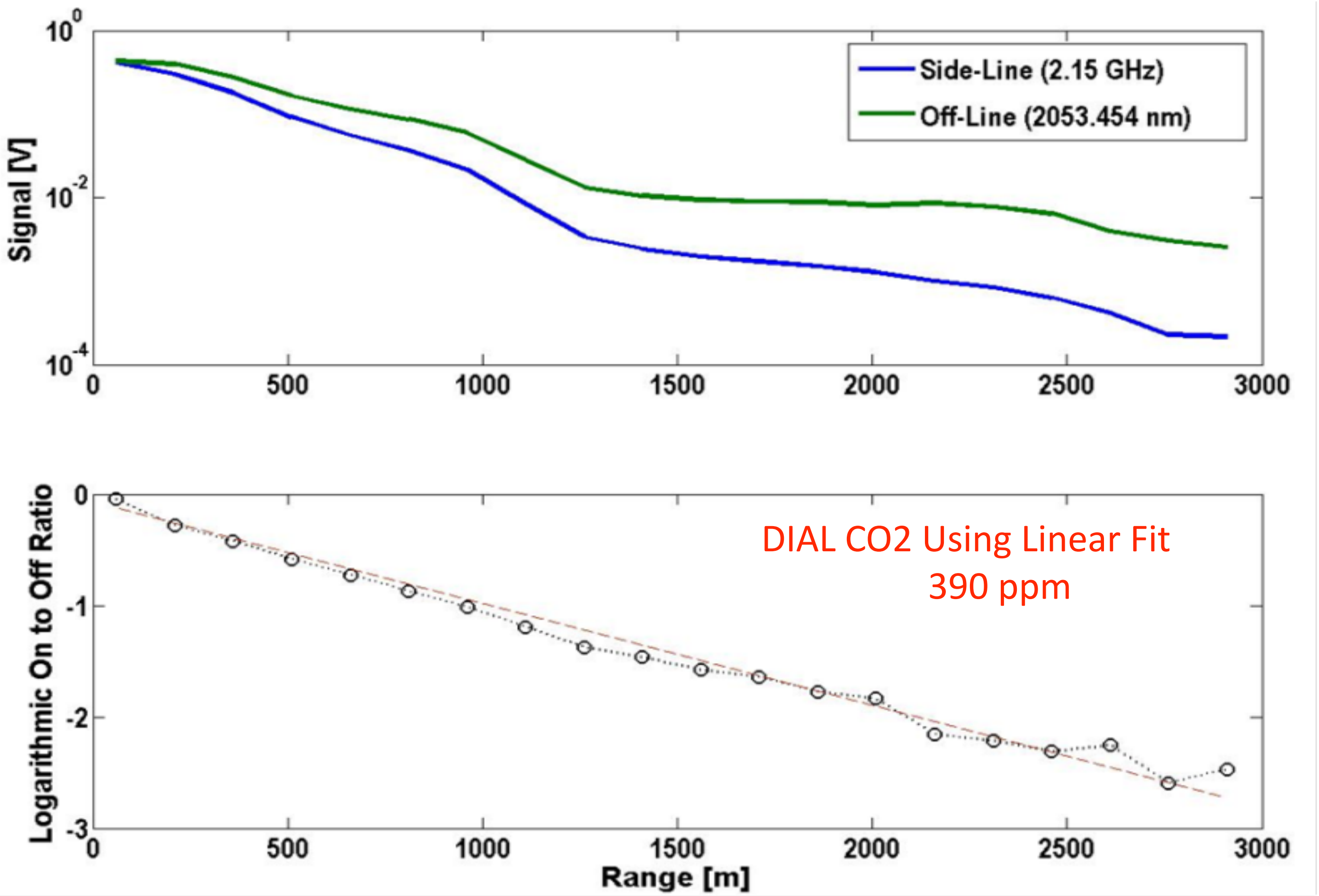


2 Micron DIAL Testing in Backscatter Mode at Langley

(Comparisons between 2 Micron and 1 Micron backscatter; April 25, 2008)



Lidar testing in DIAL in side-line mode at Langley (May 15, 2008)



Improved Spectroscopic Parameters for Accurate Atmospheric CO_2 Profiling (at JPL)

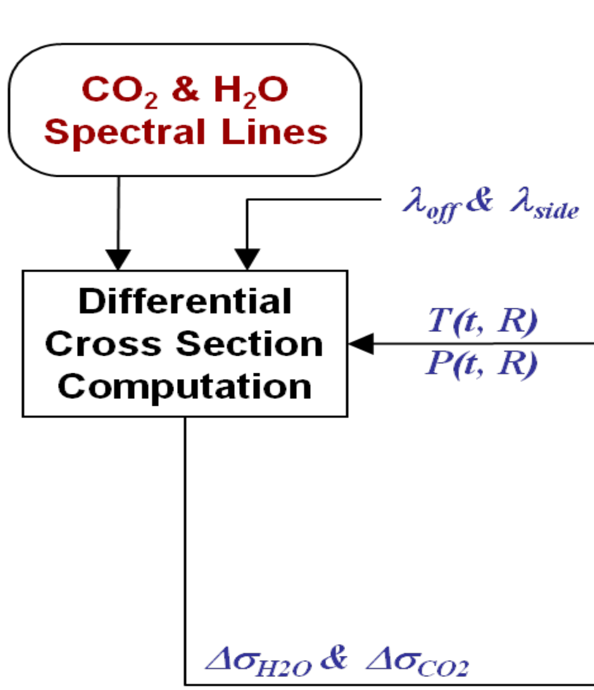
Spectroscopy Task

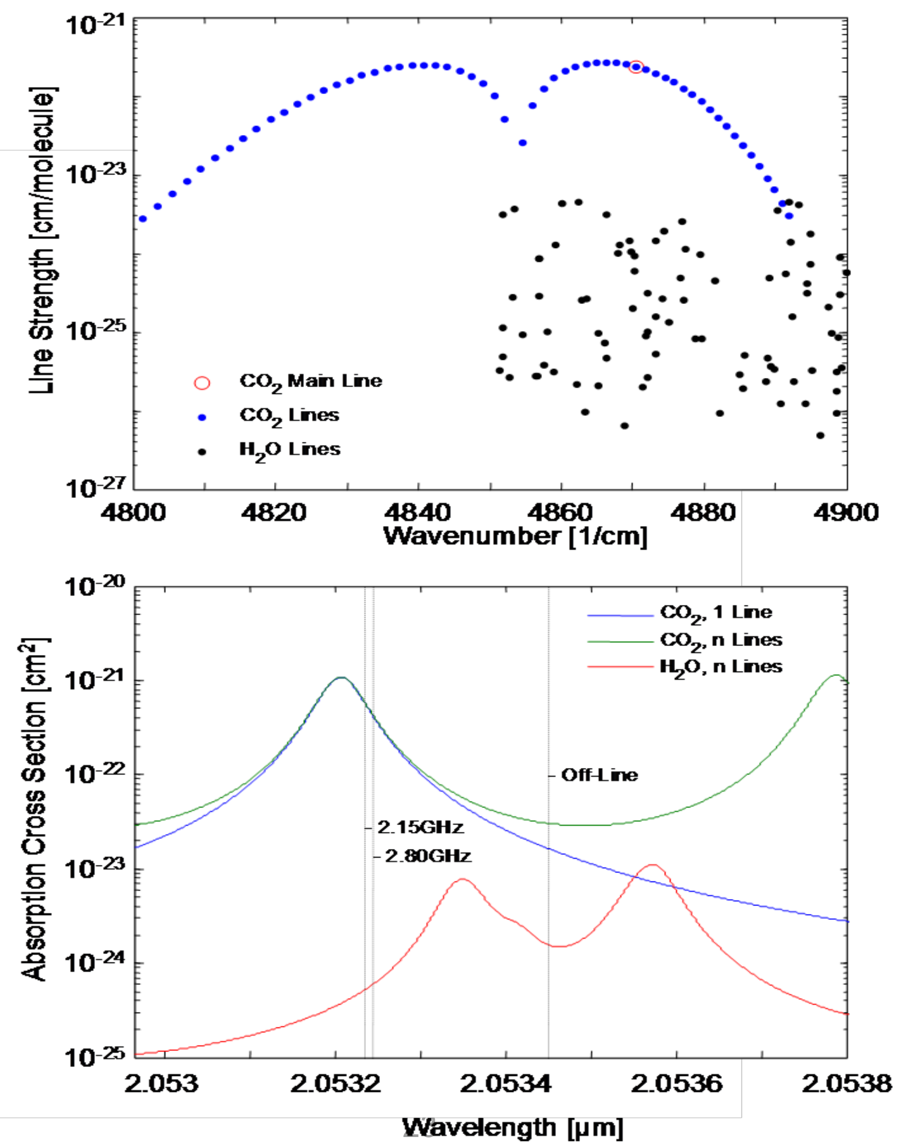
Determine spectroscopic parameters for the 20013 ← 00001 R(22) transition at 2053.204 nm (4870.436 cm^{-1})

Key line shape parameters

- Zero pressure line position
  - 4870.43636 ± 0.00002 cm^{-1}
- Line strength
  - S = 2.416E-22 cm^{-1}/(molecule cm^{-2}) @ 296K
  - Obs-Calc = -0.05%
  - Difference from HITRAN2004 = 15.36%
  - Agrees to within 0.21% of Regalia-Jarnot et al. [*JQSRT* **101**, 325-338 (2006)]
- Air-broadened width (HWHM)
  - b^0 = 0.0715 cm^{-1} atm^{-1} @ 296K
  - Uncertainty (Db^0) = 1.1% of b^0
- Pressure induced frequency shift (air)
  - d^0 = -4.88×10^{-3} cm^{-1} atm^{-1} @ 296K
  - Uncertainty (Dd^0) = 7.0% of d^0
- Off-diagonal Relaxation Matrix element coefficients, cm^{-1} atm^{-1} @ 296 K)
  - W_{ij}^{Self} (R20-22) = 0.0331(5) W_{ij}^{Self} (R22-24) = 0.0322(5)
  - W_{ij}^{Air} (R20-22) = 0.0232(9) W_{ij}^{Air} (R22-24) = 0.0233(9)
  - Values in parentheses represent 1s uncertainty in units of the least significant digit

DIAL CROSS SECTION CALCULATIONS USING LINE SPECTERSAL INFORMATION





$$\sigma = \frac{S_C}{\alpha_D^2} \cdot \frac{\alpha_L \cdot \ln(2)}{\pi^{3/2}} \cdot \int_{-\infty}^{\infty} \frac{\exp\left(-t^2\right)}{\left(\frac{\alpha_L}{\alpha_D} \cdot \sqrt{\ln(2)}\right)^2 + \left(\frac{\nu - \nu_C}{\alpha_D} \cdot \sqrt{\ln(2)} - t\right)^2} \cdot dt$$

$$\alpha_L = \left(\frac{T_o}{T}\right)^n \cdot \left[\alpha_{air} \cdot (P - P_s) + \alpha_{self} \cdot P_s\right] \qquad \alpha_D = \frac{\nu_C}{c} \cdot \sqrt{\frac{2 \cdot k \cdot T \cdot \ln(2)}{m}}$$

RETRIEVAL OF DRY CO2 MIXING RATIO

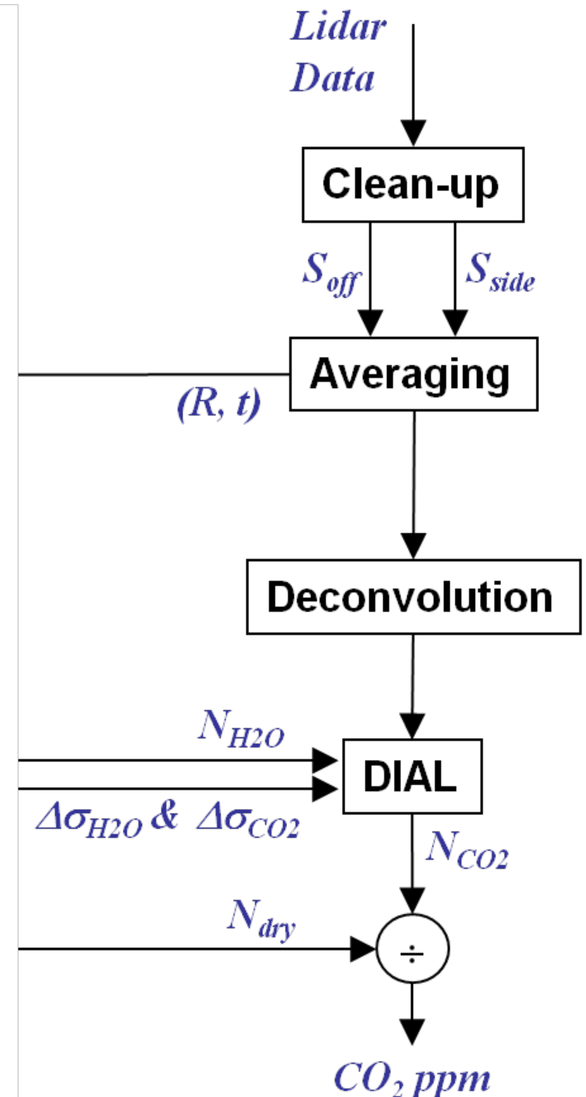
- Data clean-up includes background subtraction, removing saturated or indistinguishable shots.
- Shot and smoothing averaging are applied.
- Defining system transfer function and apply iterative deconvolution.
- Apply the DIAL equation while correcting for the water vapor absorption, to obtain carbon dioxide number density.
- Using the dry air distribution, the carbon dioxide ppm is calculated.

$$N(R) = \frac{1}{2\cdot\Delta R}\left[\ln\left(\left.\frac{P_{on}}{P_{of}}\right|_{R}\right) - \ln\left(\left.\frac{P_{on}}{P_{of}}\right|_{R+\Delta R}\right)\right]$$

$$N(R) = \Delta\sigma_{CO_2}\cdot N_{CO_2} + \Delta\sigma_{H_2O}\cdot N_{H_2O}$$

Or, for column measurement;

$$\frac{N_{CD}}{N_{dry}} = \frac{\frac{1}{\Delta r}\log_e\left(\frac{P_{on}(r_1)/P_{off}(r_1)}{P_{on}(r_2)/P_{off}(r_2)}\right) - \left[\Delta\sigma_{WV}(r_1)\cdot N_{WV}(r_1) + \Delta\sigma_{WV}(r_2)\cdot N_{WV}(r_2)\right] - 2\cdot\sum_{i=2}^{n-1}\Delta\sigma_{WV}(r_i)\cdot N_{WV}(r_i)}{\left[\Delta\sigma_{CD}(r_1)\cdot N_{dry}(r_1) + \Delta\sigma_{CD}(r_2)\cdot N_{dry}(r_2)\right] - 2\cdot\sum_{i=2}^{n-1}\Delta\sigma_{CD}(r_i)\cdot N_{dry}(r_i)}$$



Field Experiment to Test DIAL in collaboration with Penn State
Project goals

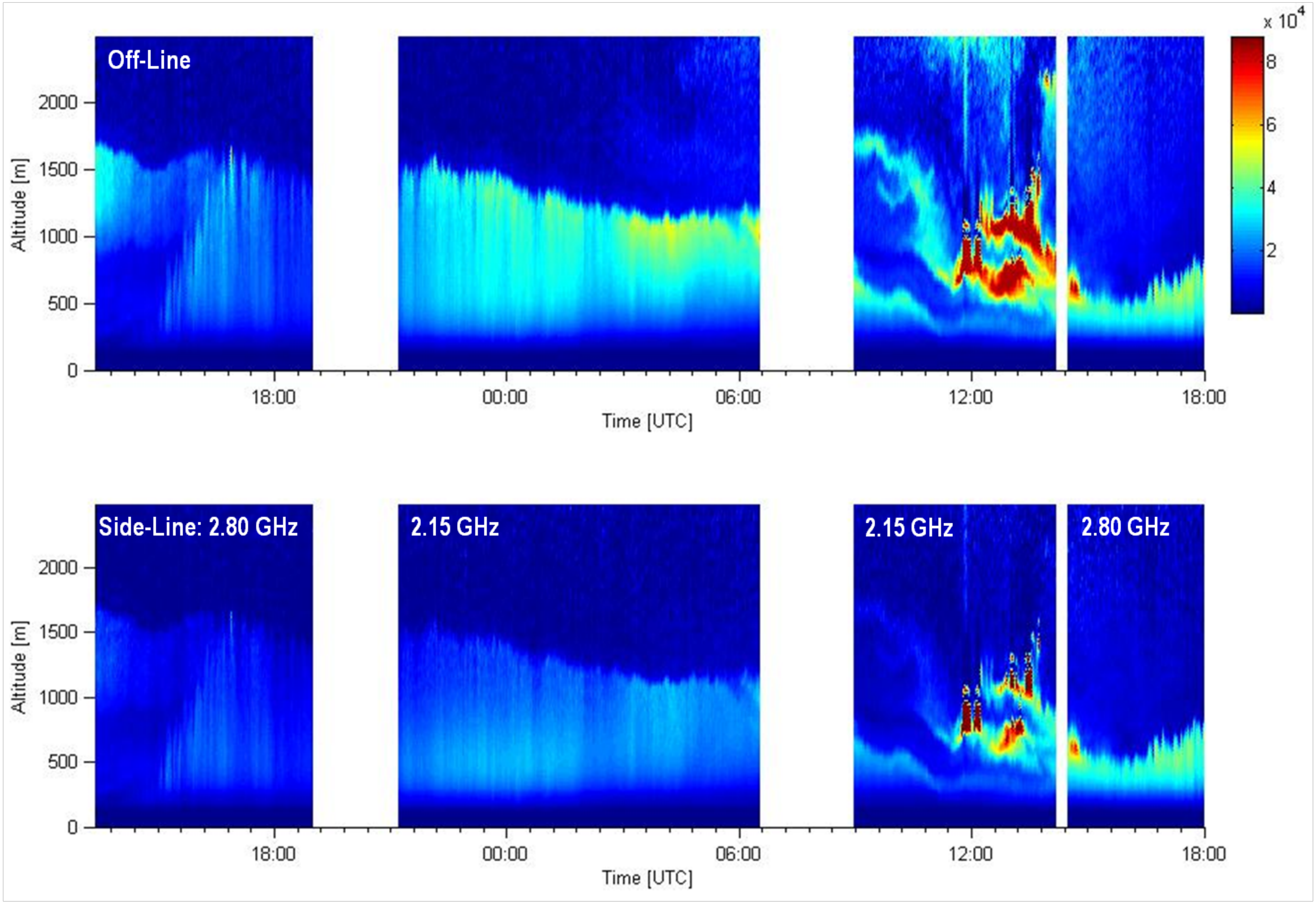
- Evaluate the accuracy and precision of the CO_2 DIAL system, in particular its ability to measure:
  - Typical atmospheric boundary layer - free troposphere CO_2 difference.
  - Typical synoptic variability in CO_2 in both the free troposphere and the atmospheric boundary layer.
- Collect observations that have the potential to be merged into the broader context of the North American Carbon Program (NACP) Midcontinental Intensive (MCI) regional study.

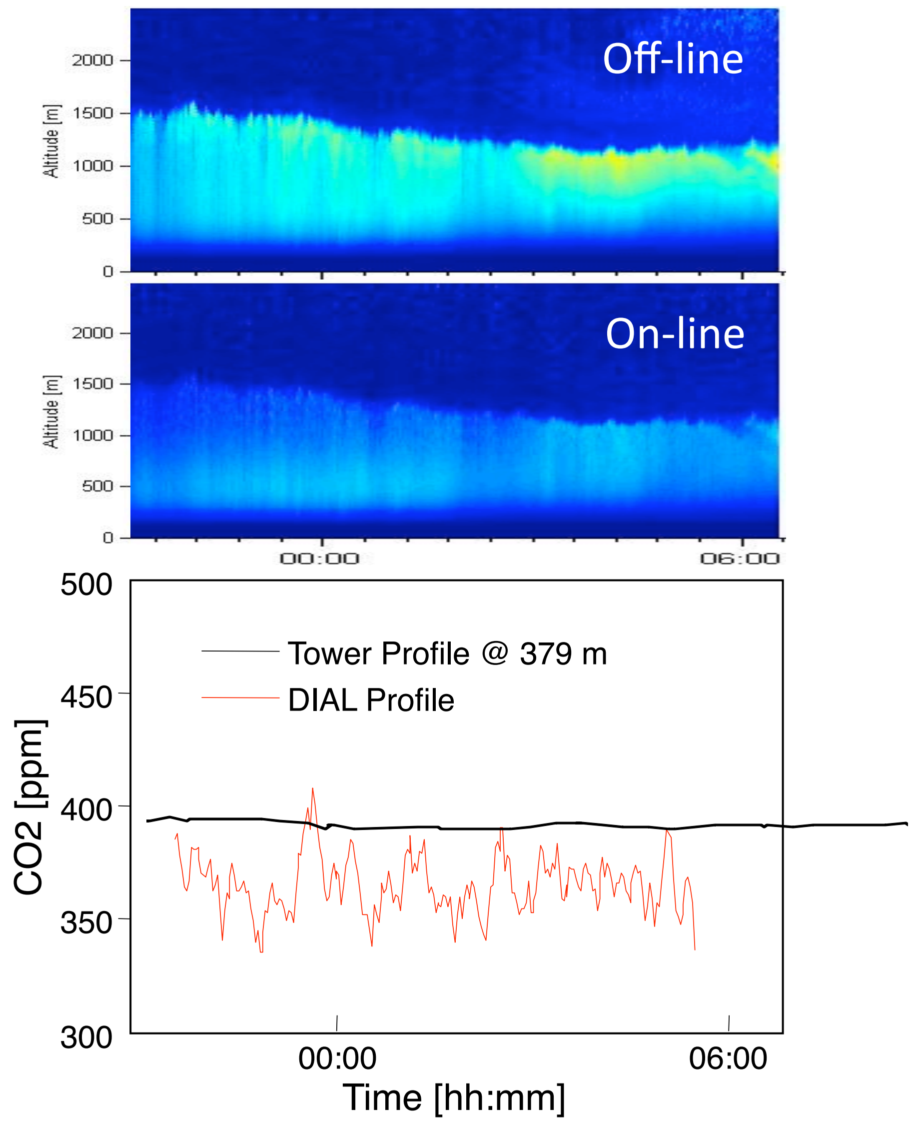
Photo below is actually NOAA tall tower site in Texas - shown to illustrate the type of observing platform. Photo at left is from the Iowa tall tower. Photos courtesy of NOAA's Global Monitoring Division.

West Branch, Iowa tall tower

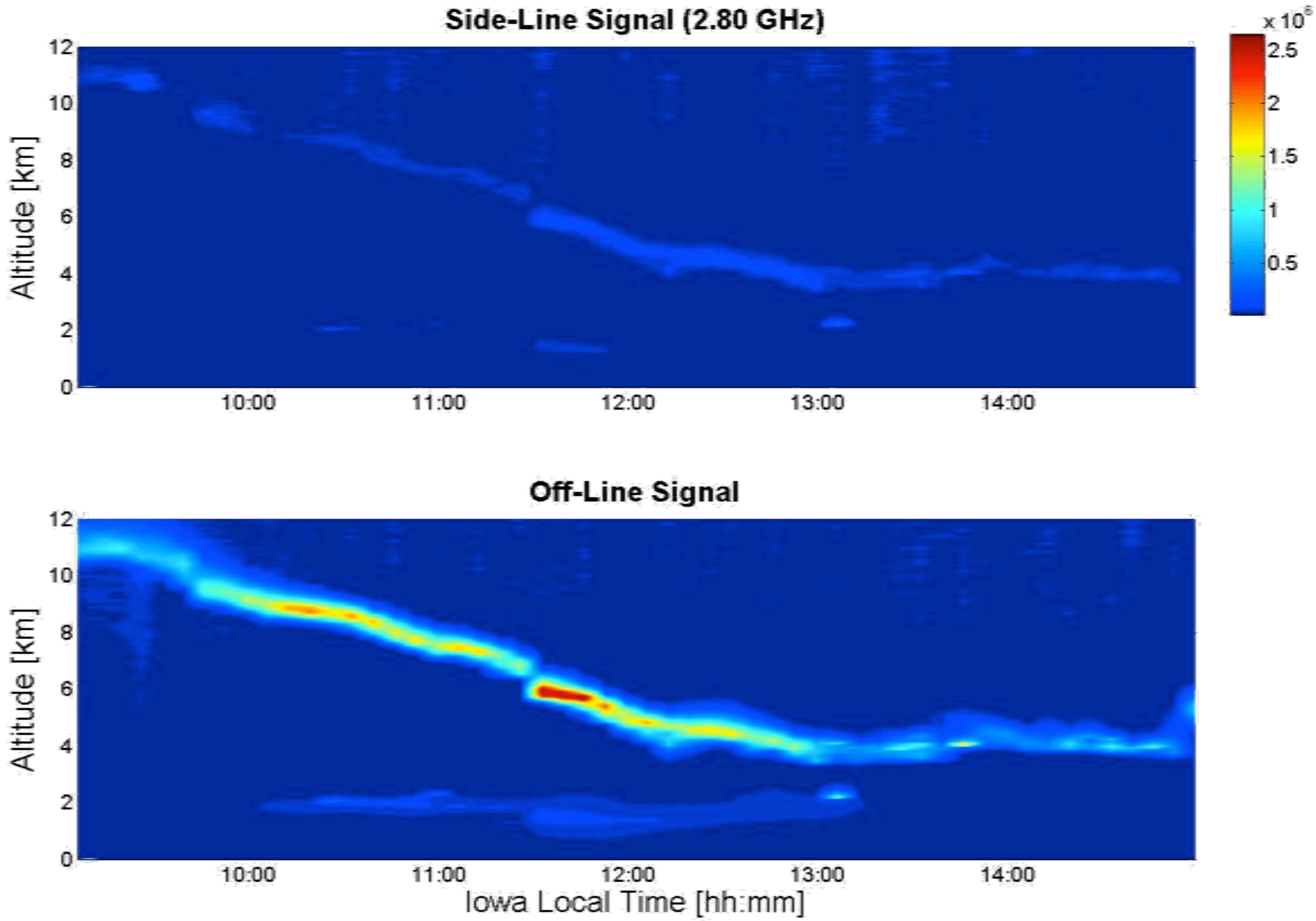
Continuous CO2 measurements at 31, 99 and 379 m above ground level.

Range Corrected Color-History-Diagram of Morning-to-Night & Night-to-Morning Transitions for Off-Line and Side-Line Lidar Signals obtained on July 5-6, 2008 at West Branch, Iowa.

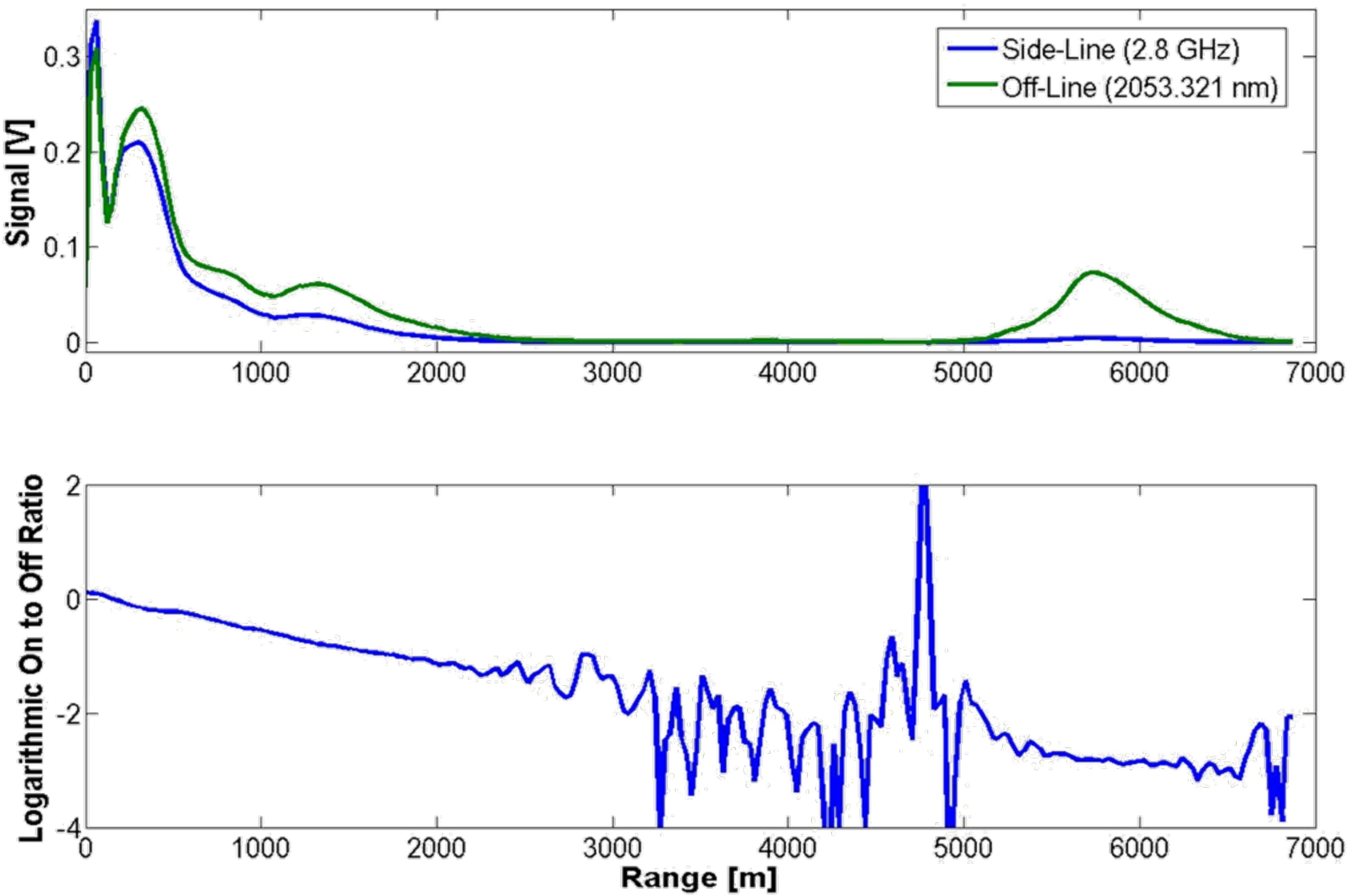



Off-line
On-line
Altitude [m]
2000
1500
1000
500
0
00:00
06:00
CO2 [ppm]
500
450
400
350
300
Tower Profile @ 379 m
DIAL Profile
Time [hh:mm]

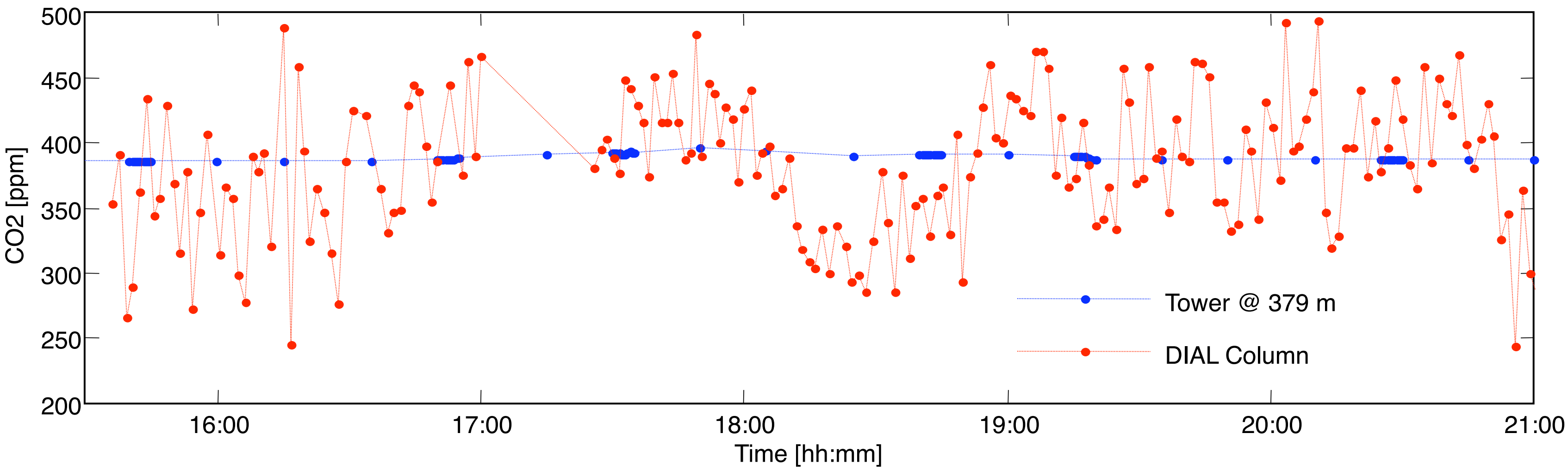
2-micron DIAL Testing at Iowa on/off Signal of a Aerosol Feature (June 26, 2008)



On/Off Signal Profiles from June 26, 2008



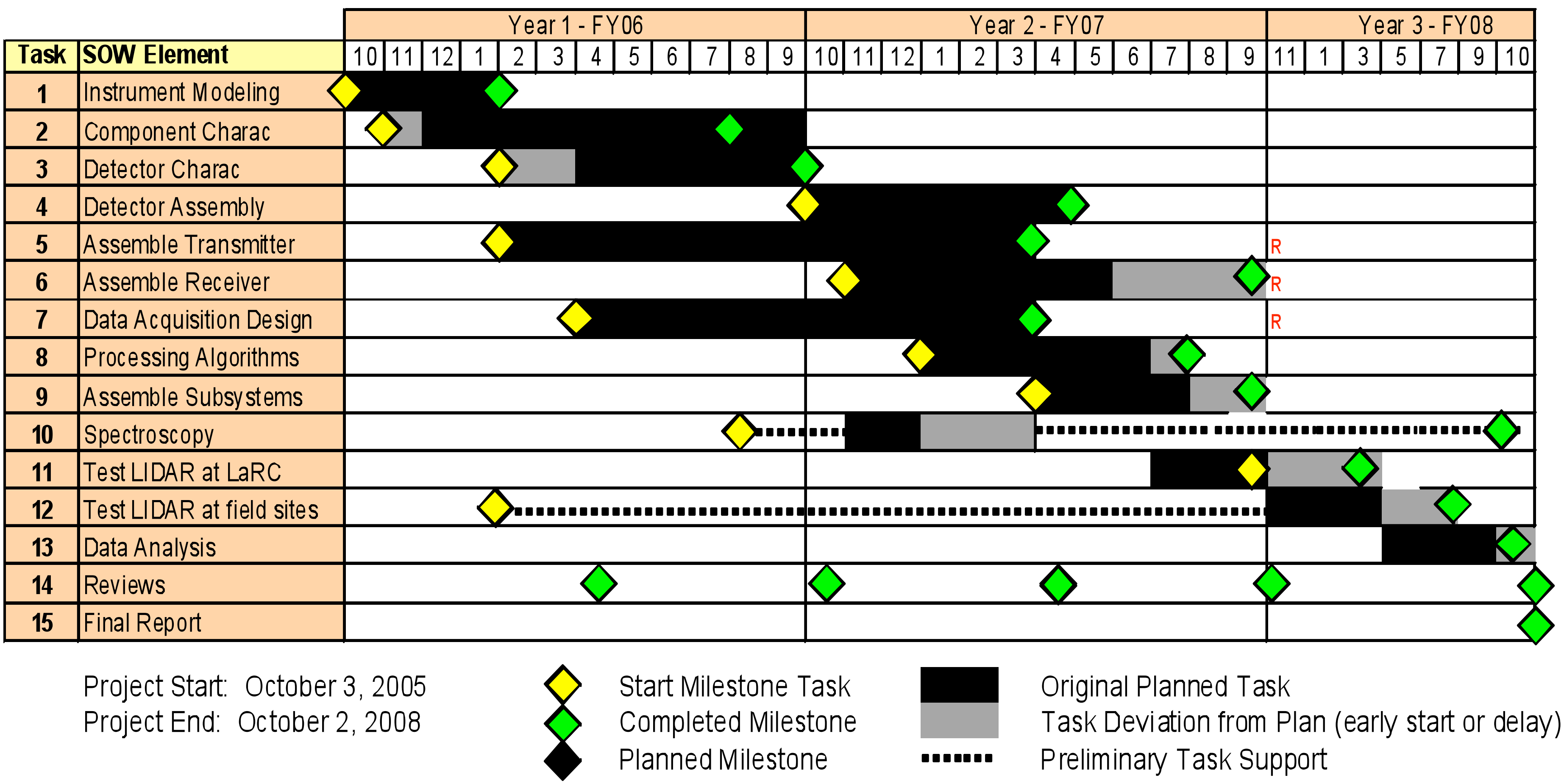
July 26, 2008 Column CO_2 measurements
(Near field to peak of aerosol layer)



DIAL Mean ppm	383.0 ppm
DIAL Standard Deviation	52.5 ppm
Tower Mean ppm	388.3 ppm
Tower Standard Deviation	2.3 ppm

Development and Evaluation of a 2-Micron Differential Absorption Lidar for Profiling CO2

IIP-04-0090 Principal Investigator: Syed Ismail, NASA LaRC



Summary

•2-micron IIP DIAL program concluded successfully by completing all milestones on time and within cost.

•Demonstrated high vertical resolution CO_2 profiling capability within the boundary layer and column measurements to long ranges.

•This is the first direct detection demonstration of CO_2 DIAL profiling capability from instrument concept to field demonstration.

•Laser TRL was advanced from TRL 4 to TRL 5, detector TRL from TRL 3 to TRL 5, and system TRL was advanced to TRL 5.

•Research results from this work have been published in 4 Journal publications, and presented in a number of conference presentations including invited talks.

•Slight modifications and system optimization will lead to many applications for satellite validation, scientific field experiments, and in pollution monitoring for climate studies.

Recommendations

•It is recommended that the DIAL system be reconfigured to operate on the CO_2 line at 2.051 micron using the Ho:Tm:YLF laser for enhanced performance (~double energy, double pulsing, minimum interference from H_2O).

•System optimization with custom optics, lower detector temperature operation, improved optical coupling, e-m interference….

•Scanning system (being acquired from other programs) be added and be housed in a permanent trailer and used as a test-bed and for field deployment.

•New detectors are being developed including HgCdTe, and InGaAs APD's, and some European companies have been funded by ESA and JPL are making advances that can enhance the performance of 2-micron direct detection DIAL systems in the future.

•System be operated using hard target for column CO2 measurements and the major step will be operations from aircraft in the nadir mode.

Journal Publications

Grady J. Koch, Jeffrey Y. Beyon, Fabien Gibert, Bruce W. Barnes, Syed Ismail et al., Side-line tunable laser transmitter for differential absorption lidar measurements of CO_2: design and application to atmospheric measurements, ***Applied Optics***, Vol. 47, Issue 7, pp. 944-956, 2008.

T. Refaat, S. Ismail, T. Mack, N. Abedin, S. Mayor & S. Spuler, "Infrared phototransistor validation for atmospheric remote sensing application using the Raman-shifted eye-safe aerosol lidar (REAL)", ***Optical Engineering***, Vol. 46, No. 8, 086001, August 2007.

T. Refaat, S. Ismail, N. Abedin, S. Spuler, S. Mayor & U. Singh, "Lidar Backscatter Signal Recovery from Phototransistor Systematic Effect by Deconvolution", ***Applied Optics***, Vol. 47, No. 29, pp. 5281, 2008.

T. Refaat, S. Ismail, G. Koch, M. Rubio, T. Mack, A. Notari, J. Collins, J. Lewis, R. De Young, Y. Choi, N. Abedin & U. Singh, "Backscatter 2-µm lidar validation for atmospheric CO_2 DIAL applications", ***IEEE Transaction of Geoscience and Remote Sensing***, In press.

Conferences and Presentations

- S. Ismail, *et al.*, "Development of a ground-based CO_2 profiling DIAL system for atmospheric boundary layer studies", Eos. Trans. AGU, 86(52), Fall Meet. Suppl., B41B-0183, San Francisco, California, 2005.
- S. Ismail, *et al.*, "Progress towards the development of a ground based, airborne, and space-bases CO_2 profiling DIAL systems", Geophysical Research Abstracts, Vol. 8, 08030, European Geoscience Union, Vienna, Austria, 2006.
- S. Ismail, *et al.*, "Development of a ground-based 2-micron differential absorption lidar system to profile tropospheric CO_2", Sixth Annual Earth Science Technology Conference (ESTC), NASA's Earth Science Technology Office (ESTO), College Park, Maryland, 2006.
- S. Ismail, *et al.*, "Design, development, and validation of a high sensitivity DIAL system for profiling CO_2", 23rd International Laser Radar Conference (ILRC 23), Nara, Japan, 2006.
- S. Ismail, *et al.*, "A ground-based 2-micron DIAL system to profile tropospheric CO_2 and aerosol distributions for atmospheric studies", Invited Paper, Lidar Remote Sensing for the Environmental Monitoring VII, SPIE Asia-Pacific Remote Sensing, 6409-09, Goa, India, 2006.
- S. Ismail, *et al.*, "Development of a ground-based 2-micron DIAL system to profile tropospheric CO_2 and aerosol distribution for atmospheric studies", Eos. Trans. AGU, 87(52), Fall Meet. Suppl., A13D-0960, San Francisco, California, 2006.
- S. Ismail, *et al.*, "Technology developments in laser, detector, and receiver system for an atmospheric CO_2 lidar profiling system", Seventh Annual Earth Science Technology Conference, (ESTC), NASA's Earth Science Technology Office (ESTO), College Park, Maryland, 2007.
- S. Ismail, *et al.*, "Development and applications of a ground-based 2-micron DIAL system to profile tropospheric CO_2", IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Barcelona, Spain, 2007.
- S. Ismail, *et al.*, "Development of laser, detector, and receiver systems for an atmospheric CO_2 lidar profiling system", IEEE Aerospace Conference, Big Sky, Montana, March 2008.
- S. Ismail, *et al.*, "Development of a continuously operating CO_2 lidar profiling system for field studies and satellite validation", 18th Conference on Atmospheric Biogeosciences, American Meteorological Society, Orlando, Florida, 2008.

Conferences and Presentations

- T. Refaat, *et al.*, "Backscatter lidar detection system using IR phototransistors", 24th International Laser Radar Conference (ILRC 24), Boulder, Colorado, 2008.
- S. Ismail, *et al.*, "Development and initial testing of a high sensitivity DIAL system for profiling atmospheric CO_2", *ASCEND Meeting*, Michigan, Illinois, 2008.
- T . Refaat, *et al.*, "High resolution 2-μm aerosol backscatter profiling lidar for CO_2 DIAL Application", Asia-Pacific Remote Sensing, Noumea, New Caledonia, 2008.
- S. Ismail, *et al.*, "Development and evaluation of a high sensitivity DIAL system for profiling atmospheric CO_2", Toulouse, France, 2008.
- S. Ismail, *et al.,* "Development and Field Testing of a Continuously Operating CO2 Lidar Profiling System", Eos Trans. AGU, 90(22), Jt. Assem. Suppl., A33D-05, 2009.
- T . Refaat, *et al.*, "Testing of a Two-Micron Lidar System for Carbon Dioxide Profiling in the Atmosphere", Title, Eos Trans. AGU, 90(52), Fall Meet. Suppl., A41C-0112, 2009.
- T . Refaat, *et al.*, "Field testing of a two-micron DIAL system for profiling atmospheric carbon dioxide", 25th International Laser Radar Conference (ILRC 25), St Petersburg, Russia, 2010.