National Aeronautics and Space Administration

Airborne Pulsed 2-Micron Direct Detection Lidar for CO_2 Column Measurement

Upendra Singh[1], Jirong Yu[1], Mulugeta Petros[1], Tamer Refaat[1], Ruben Remus[1], James J, Fay[1], and Karl Reithmaier[2]

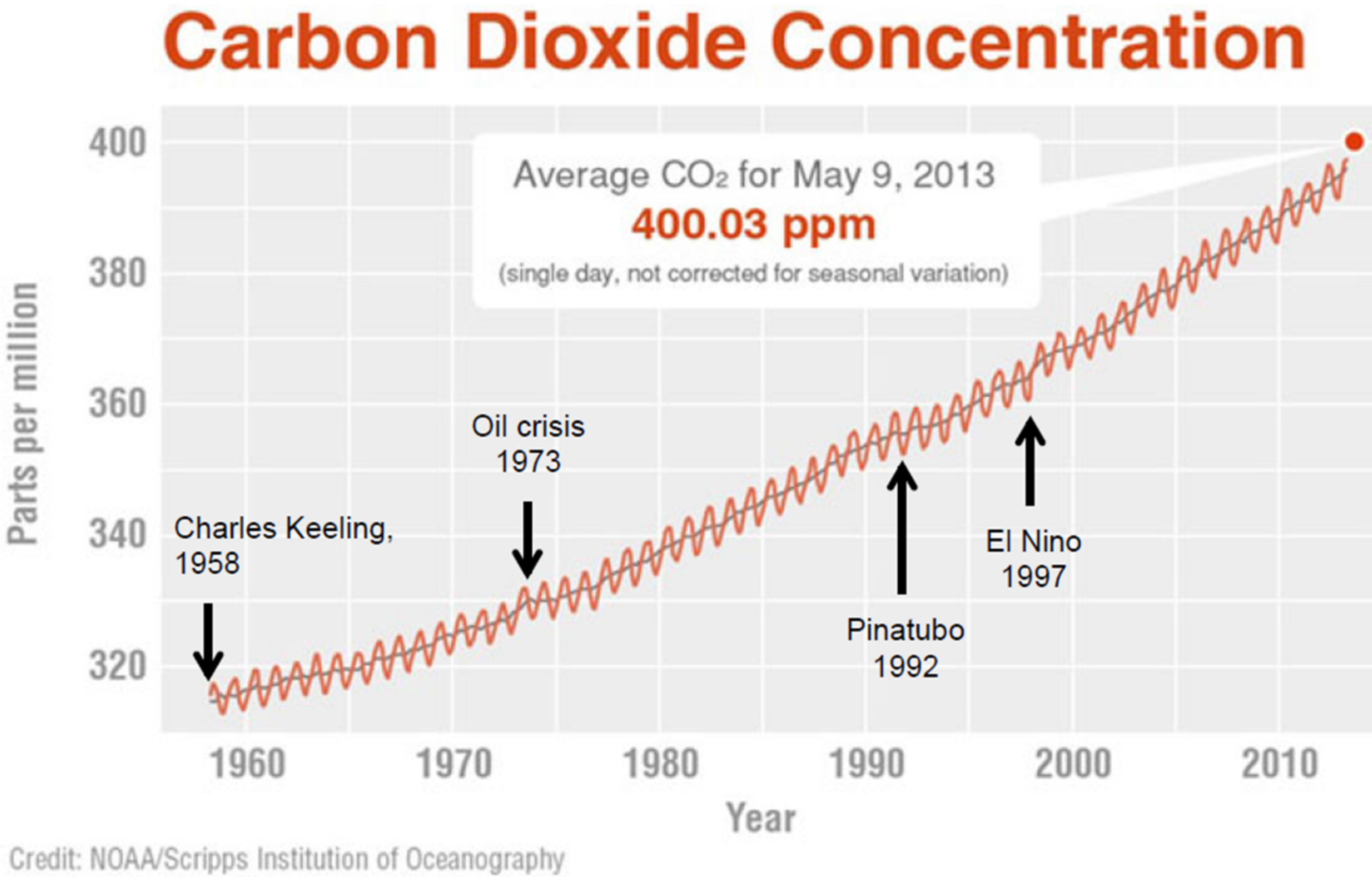
[1]*NASA Langley Research Center, MS 433, Hampton, Virginia*
[3]*Science System &Applications, Inc, One Enterprise Parkway, Hampton, Virginia*
* Upendra.N.Singh@nasa.gov

Acknowledgement: NASA Earth Science Technology Office (ESTO)

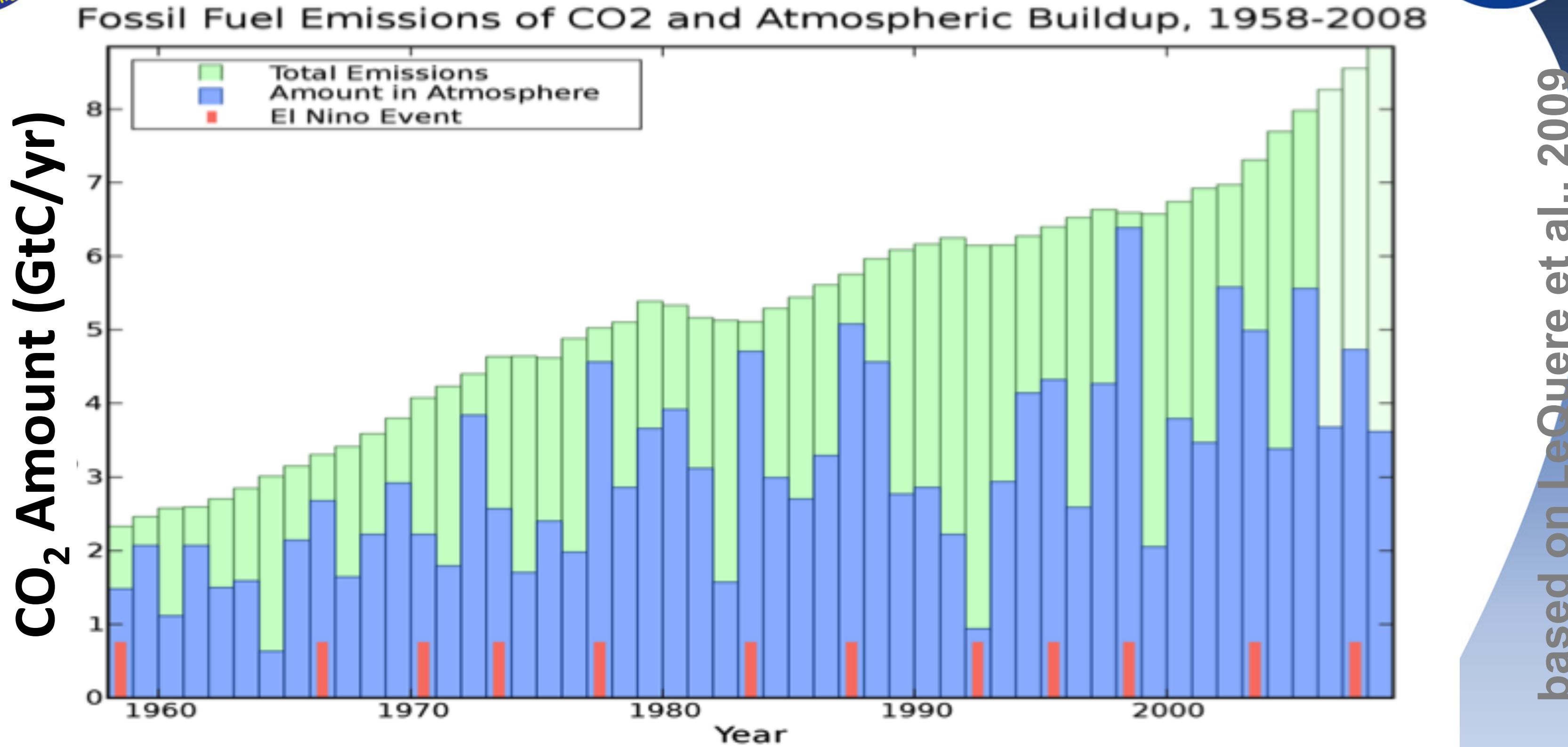
Outline

- **Objective**
  - Develop a high energy double-pulsed 2-micron direct detection IPDA lidar system to demonstrate airborne atmospheric CO_2 measurements
    - **Background**
    - **Spectroscopy and IPDA simulation**
    - **2-micron double pulsed IPDA lidar**
    - **IPDA Ground Testing**
    - **IPDA lidar Airborne Demonstration**
    - **Future Work**
    - **Summary and Conclusions**

Atmospheric CO_2 Increase



Missing CO_2 Sink?



Anthropogenic activities have added >200 Gt C to the atmosphere since 1958

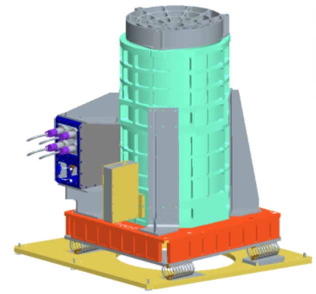
- **less than half of this CO_2 is staying in the atmosphere**
- **where are the missing CO_2 sinks?**

Development of a Double-Pulsed 2-micron Direct Detection IPDA Lidar for CO_2 Column Measurement from Airborne Platform

PI: Upendra N. Singh, NASA LaRC

Objective

- Develop, integrate and demonstrate a 2-micron pulsed Integrated Path Differential Absorption Lidar (IPDA) instrument CO_2 Column Measurement from Airborne platform
- Conduct ground validation test to demonstrate CO_2 retrieval
- Conduct engineering test flights to demonstrate CO_2 retrieval from UC-12 aircraft
- Conduct post flight data analysis for the purpose of evaluation of CO_2 measurement capability



Mobile and Airborne 2μm IPDA LIDAR system

Approach:

- Repurpose existing hardware including previously developed transmitter, receiver and data acquisition system
- Complete fabrication of transmitter, wavelength control and receiver units assembly
- Integrate existing and to be developed subsystems into a complete breadboard lidar system
- Fabricate a mechanical structure and integrate completed subsystem

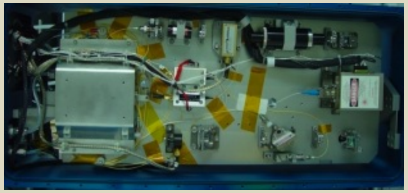
Co-Is/Partners: Jirong Yu, Mulugeta Petros, Syed Ismail, NASA LaRC

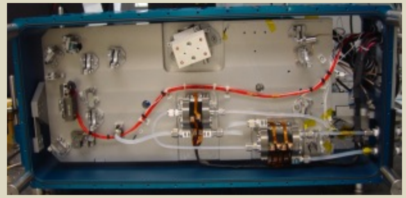
Key Milestones

- Design of laser transmitter assembly — 10/12
- Design, manufacture and assembly of receiver — 04/13
- Integrate subsystems into breadboard lidar system — 06/13
- Conduct ground test of the integrated lidar assembly — 07/13
- Integrate lidar system on UC-12 aircraft — 11/13
- Conduct post flight data analysis — 09/14

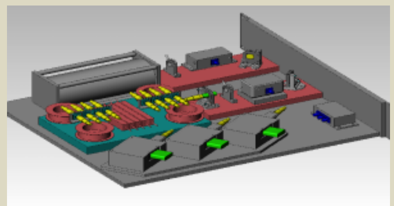
TRL_{in} = 3 TRL_{out} = 5 (AIRCRAFT)

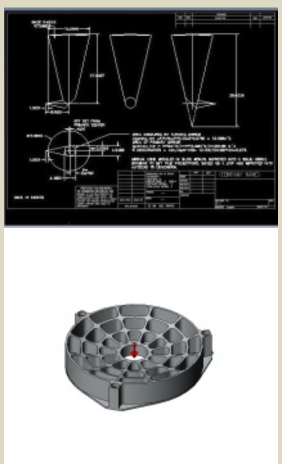
2-µm Pulsed Direct Detection CO_2 IPDA (Airborne)


Laser

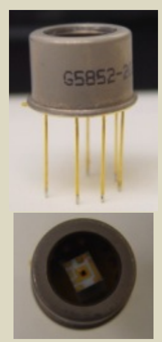

Laser


Digitizer

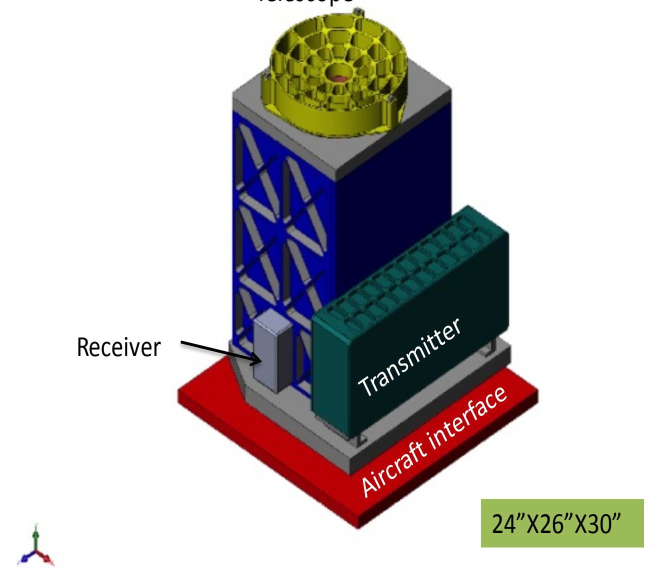

Wavelength Controller


Telescope


Thermal Control


Detector

Phase I



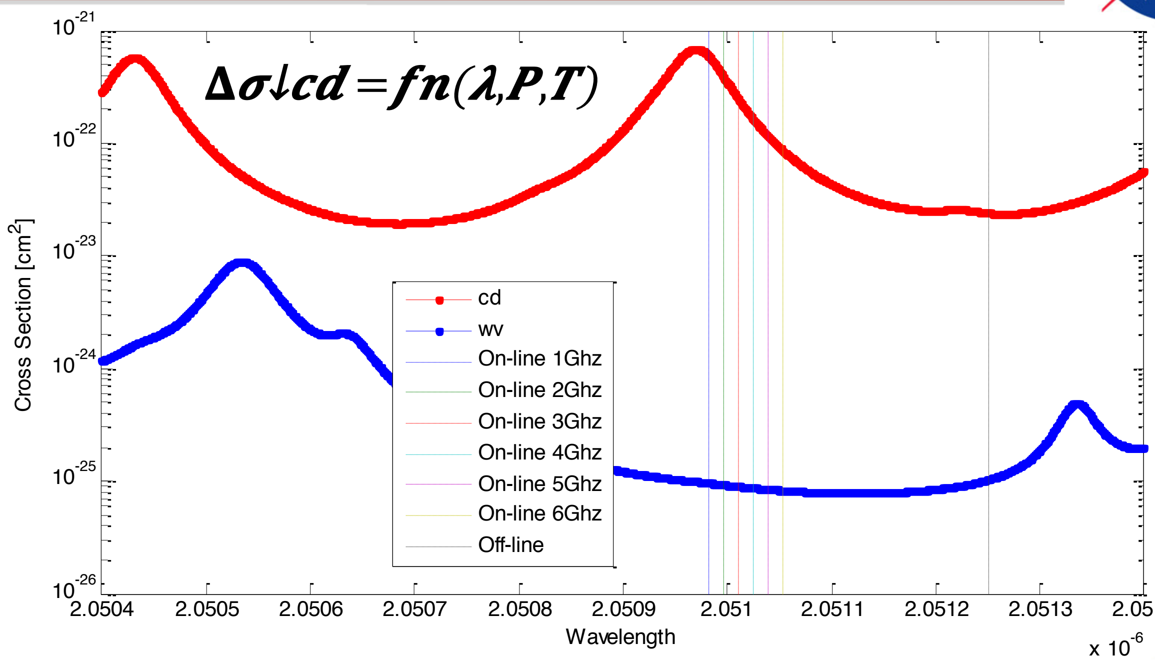
Integrated 2µm Pulsed IPDA Lidar for Airborne CO_2 Column Measurement

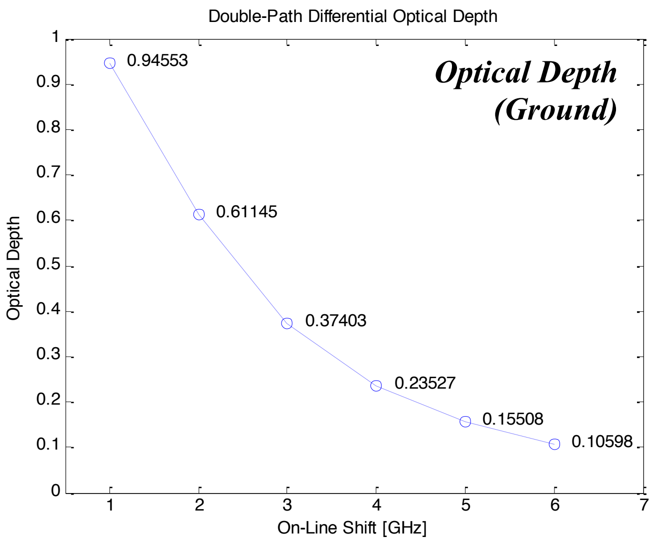
Phase II

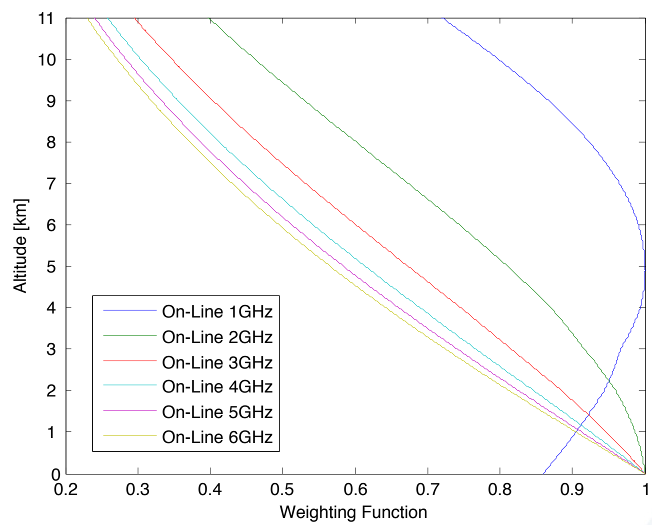
Phase III

Spectroscopy

- Standard models are used for estimating optical depth, return pulse strength, SNR and errors for any operating condition.
- Modeling and meteoro-logical data are used for XCO2 derivation.

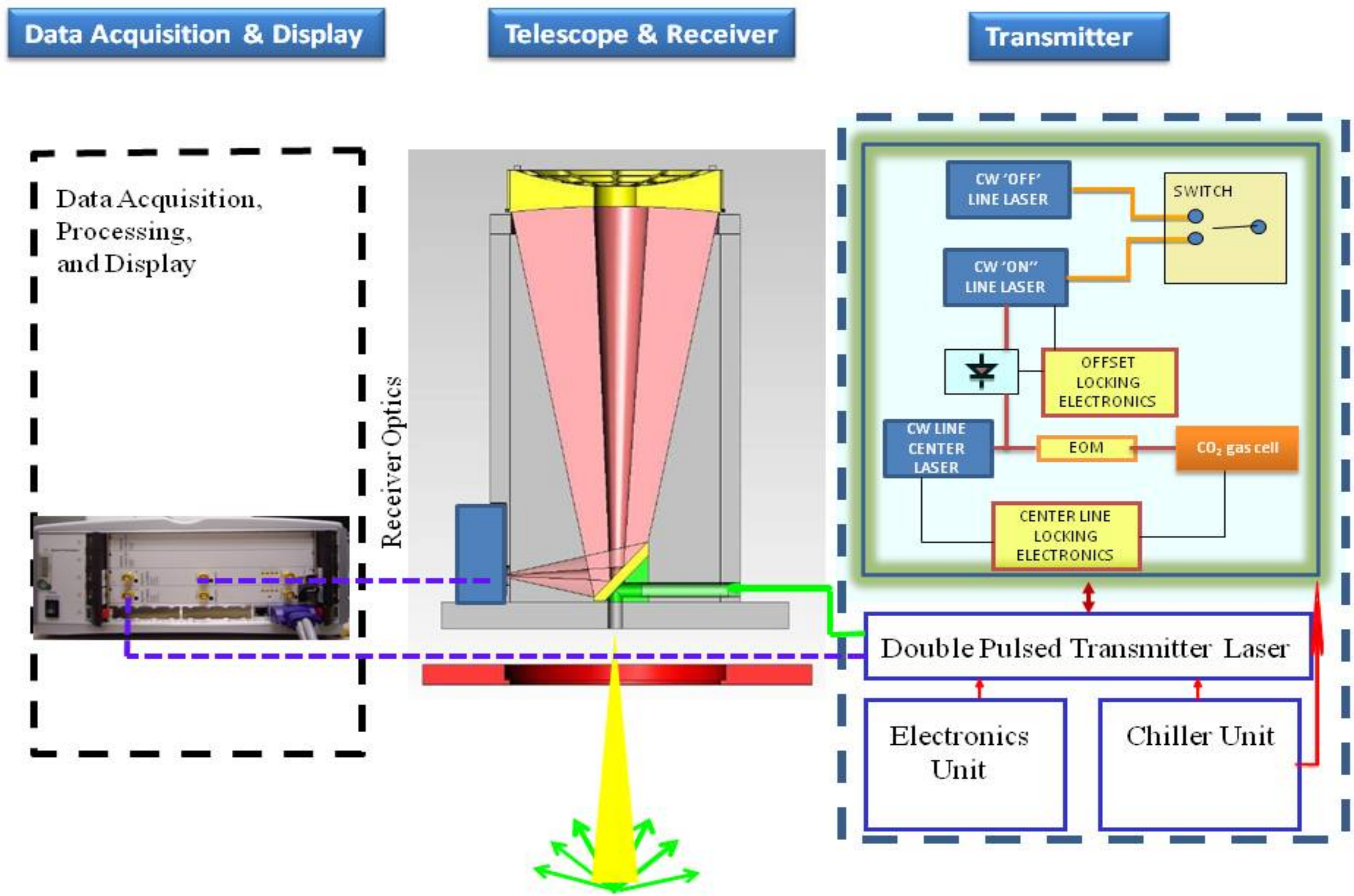






Pressure-Based Weighting-Functions (Airborne)

2-µm IPDA Lidar Schematic



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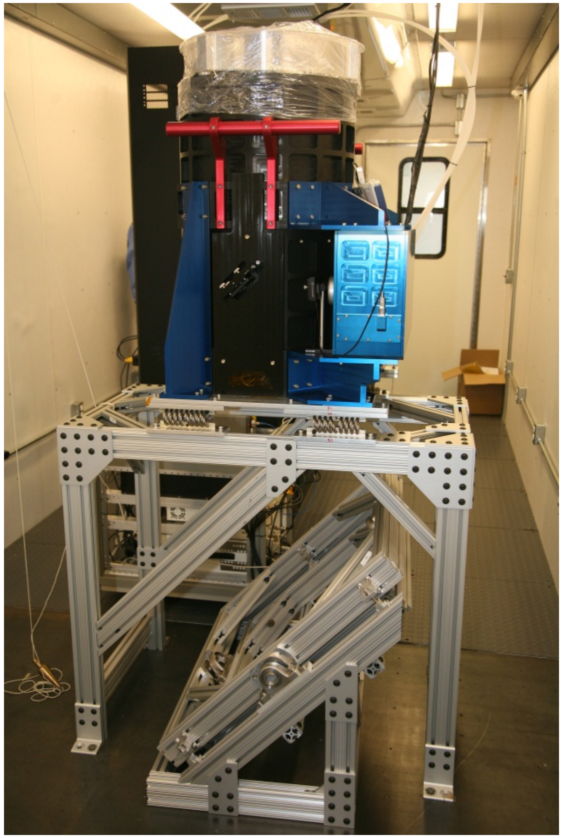
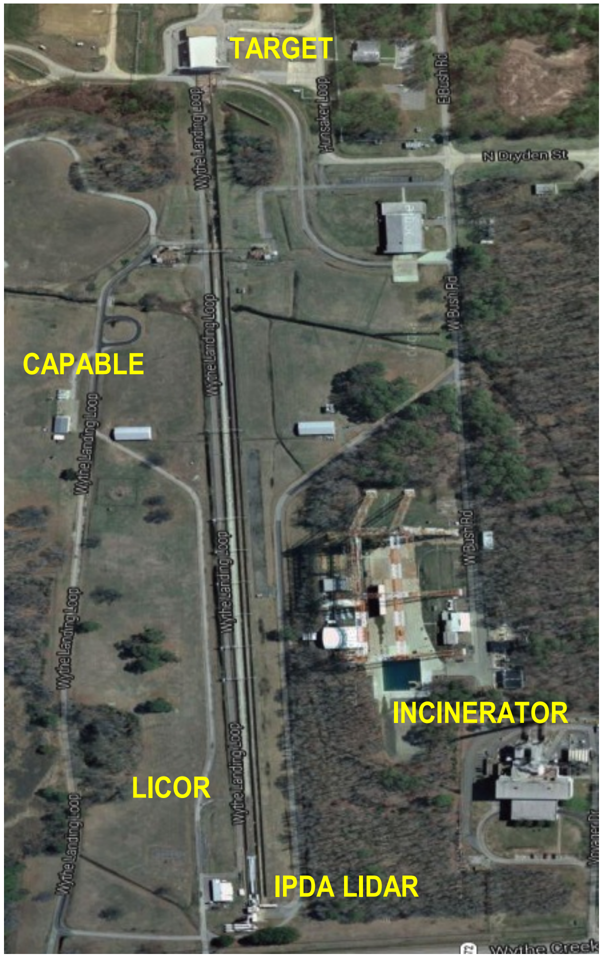
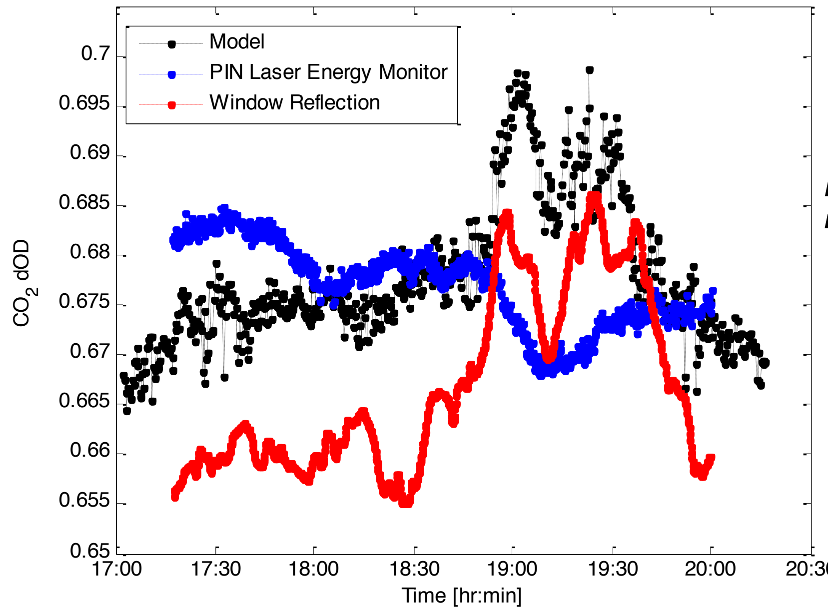
IPDA Ground Testing: IPDA Integration



IPDA Ground Testing: Setup & Measurement

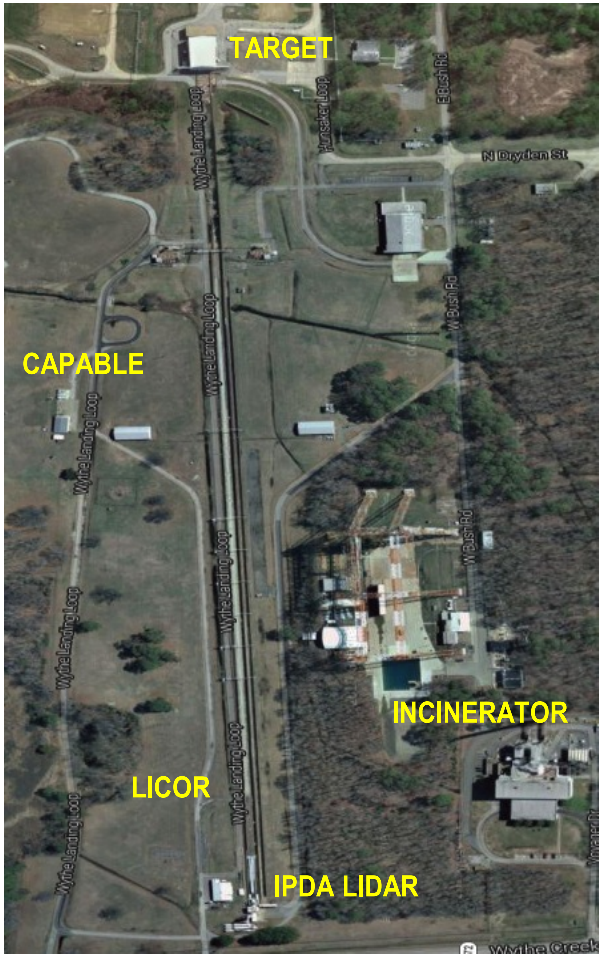


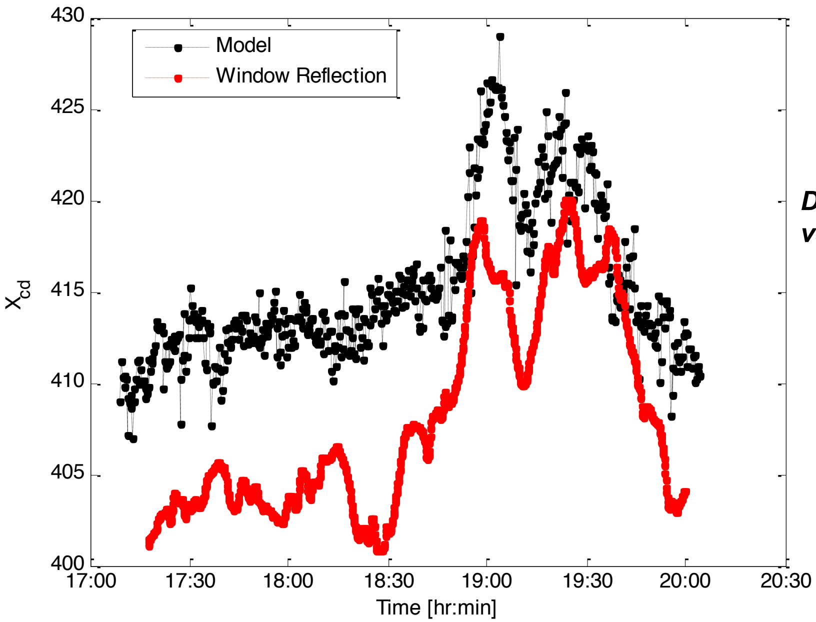


Differential optical depth–model and measurement

- IPDA ground testing conducted at LaRC on 1/24/2014.
- Modeled CO_2 optical depth was calculated from in-situ sensor (LiCor) and CAPABLE measurements.
- IPDA measured CO_2 optical depth was obtained from
  - PIN laser energy monitor with the hard target return.
  - Residual scattering (window reflection) with the hard target return.

IPDA Ground Testing: Setup & Measurement

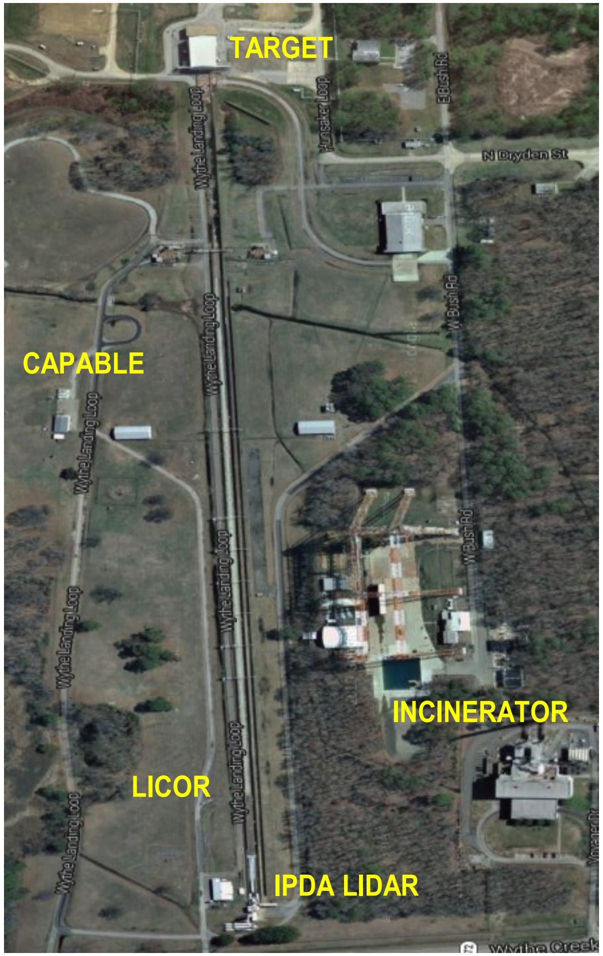


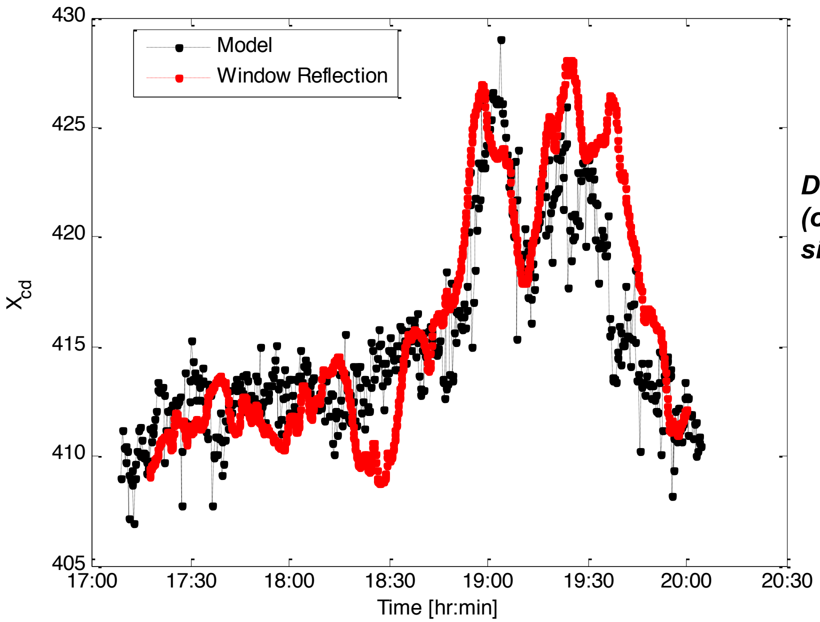


Dry mixing ratio IPDA vs (in-situ) Instrument

- Results from residual scattering better correlate to modeled differential optical depth
- Residual scattering provides self-calibration capability for the CO_2 IPDA lidar instrument

IPDA Ground Testing: Setup & Measurement

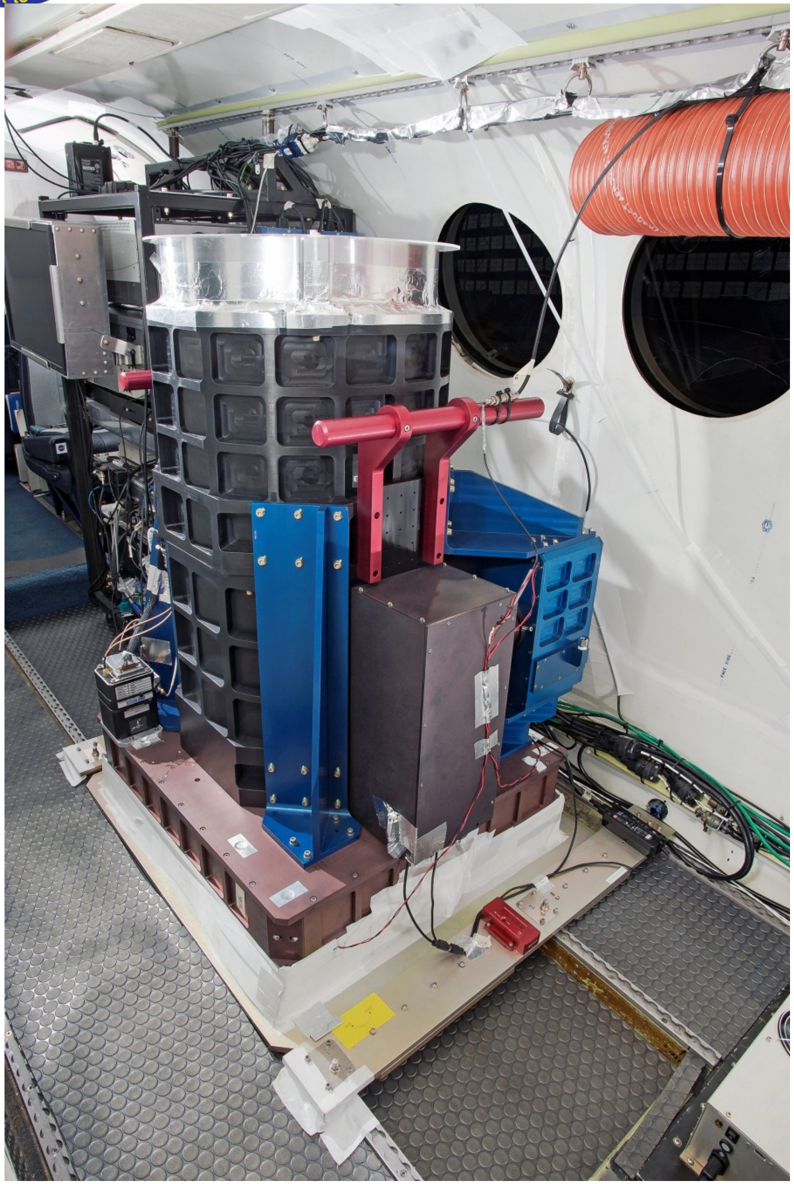




Dry mixing ratio IPDA (offset +8 ppm) vs (in-situ) Instrument

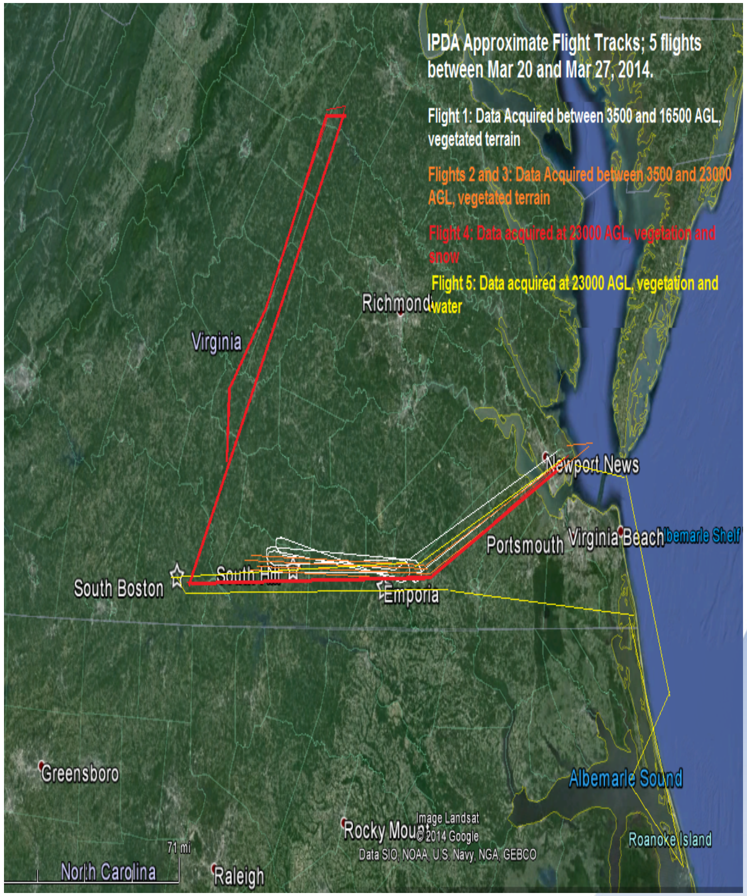
- Results indicated profile matching with 8 ppm offset between in-situ and IPDA dry mixing ratio measurements
- Offset attributed to detection system non-linearity (most probably digitizer)

Aircraft Configuration: Instrument



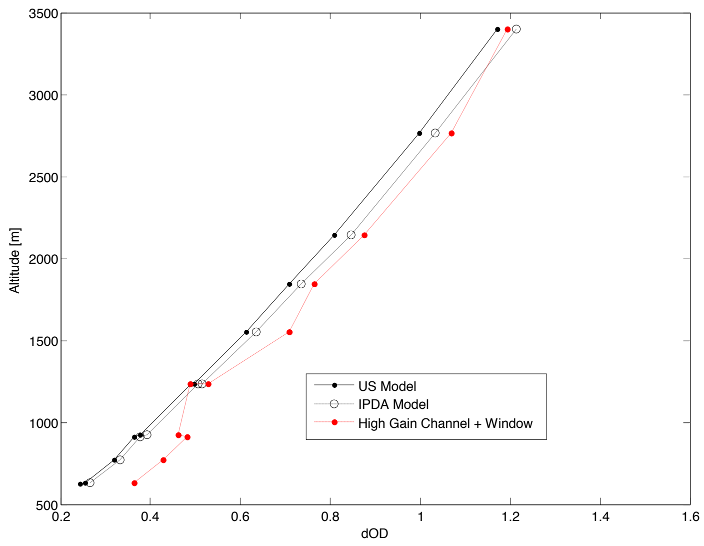
10 Flights in March & April 2014

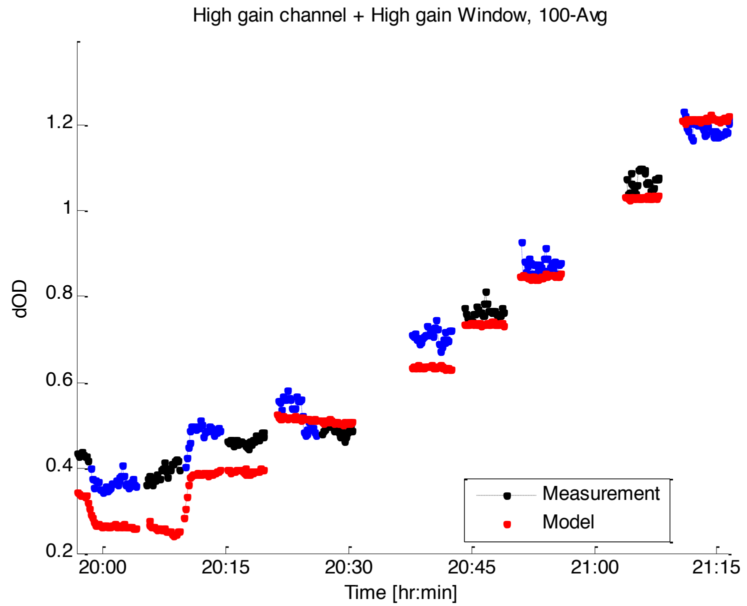
Date	Purpose	Duration	Location
March 20	Instrument Check Flight	2.1 hr	VA
March 21	Engineering	2.7 hr	VA
March 24	Engineering	3.0 hr	VA
March 27	Early morning	3.0 hr	VA
March 27	Mid-afternoon	2.5 hr	VA
March 31	Inland-Sea	2.5 hr	VA, NC
April 02	Power Station	2.4 hr	NC
April 05	With NOAA	3.7 hr	NJ
April 06	Power Station	3.0 hr	NC
April 10	Late afternoon	2.3 hr	VA



- Aircraft had temperature, pressure, humidity sensors, LiCor and GPS
- Some of the flights were supported by balloon launches

IPDA Airborne Testing: Sample Return Signals

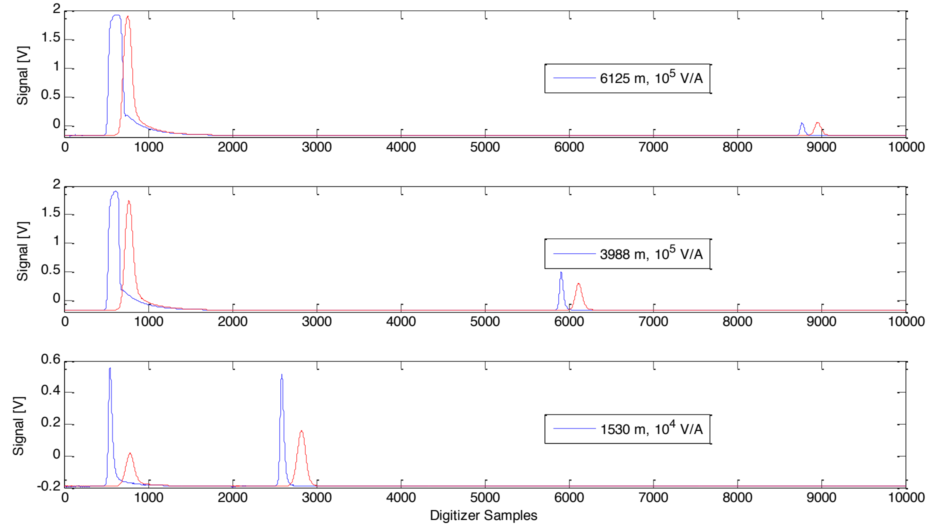


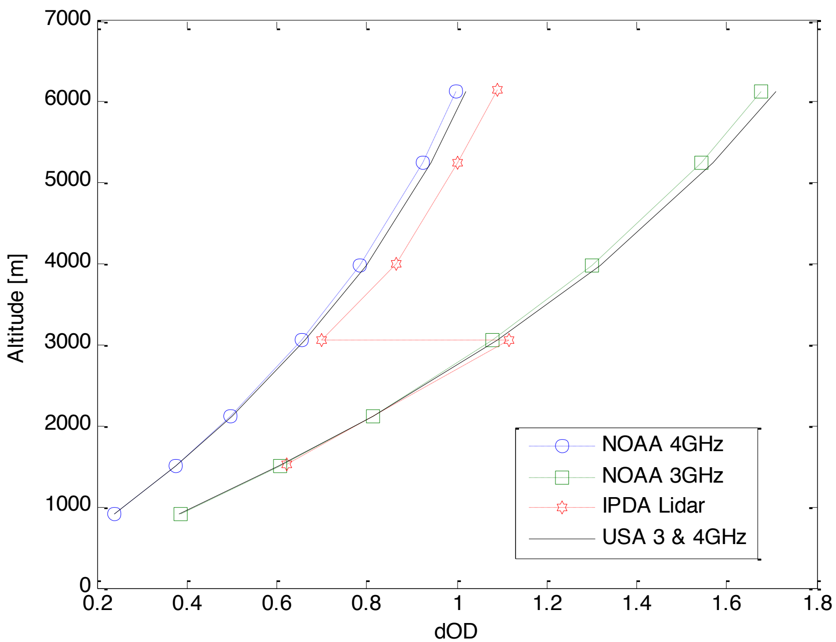


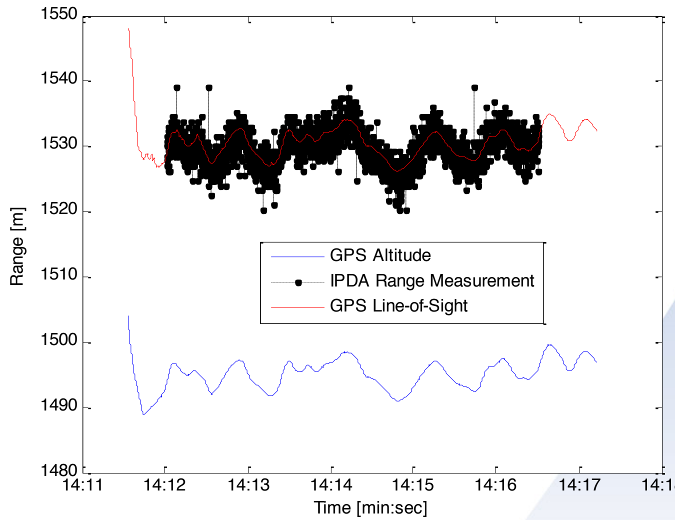
- IPDA airborne testing was conducted on April 10, 2014.
- Modeled CO_2 optical depth was calculated from CO_2 in-situ sensor (LiCor) and aircraft meteorological sensors at different altitude.
- Another modeled CO_2 optical depth was calculated using the US Standard Atmosphere at different altitude.
- Measured CO_2 optical depth was calculated from the IPDA data (black and blue dots), with 100 shot average, at different altitude.
- Energy monitoring through residual scattering and vegetation/soil ground hard target.

IPDA Airborne Testing: Sample Return Signals

- NOAA air sampling and IPDA lidar optical depth comparison.
- Return signal samples from different altitudes up to 6km.
- IPDA range measurements compared to on-board GPS.





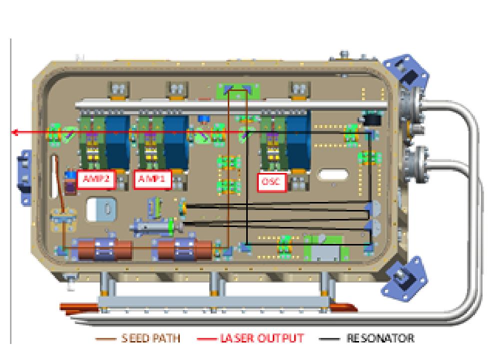


Triple-Pulsed 2-µm Direct Detection Airborne Lidar for Simultaneous and Independent CO_2 and H_2O Column Measurement – Novel Lidar Technologies and Techniques with Path to Space

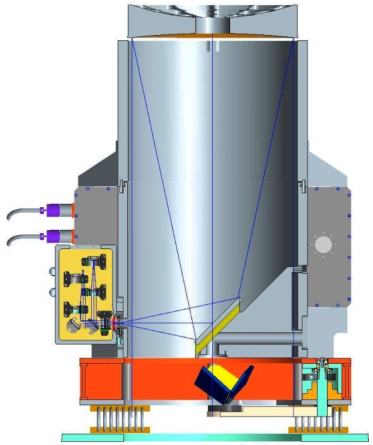
PI: Upendra Singh, NASA LaRC

Objective

- Demonstrate and validate simultaneous and independent measurement of the weighted-average column dry-air mixing ratios of carbon dioxide (XCO_2) and water vapor (XH_2O) from an airborne platform
- Design and fabricate a space-qualifiable, fully conductively-cooled, triple-pulsed, 2-*µ*m laser transmitter
- Design and develop wavelength control system for rapid and fine tuning of the three sensing lines of the CO_2/H_2O Integrated Path Differential Absorption (IPDA) lidar
- Integrate laser transmitter with receiver to develop the triple-pulsed 2-*µ*m direct detection IPDA lidar
- Conduct extensive ground and airborne column CO_2/H_2O measurement and validate with *in-situ* sensors



An example of space-qualifiable, fully conductively-cooled 2-*µ*m laser packaging from ACT 11



Integrated 2-*µ*m CO_2/H_2O Airborne packaged IPDA Lidar

Approach

- Team with industry to utilize extensive space-flight laser development expertise to build a unique triple-pulsed 2-*µ*m laser
- Develop a novel, lightweight, frequency agile, wavelength tuning and locking system for triple-pulsed IPDA Operation
- Integrate state-of-the-art laser transmitter to the existing and upgraded receiver system and strengthen for stable flight operation
- Conduct initial ground testing and validation of the IPDA lidar from a mobile lidar trailer
- Conduct extensive ground and airborne column CO_2/H_2O measurement and validate with in-situ sensors

Co-Is/Partners: Ken Davis, Penn State Univ; Jirong Yu, Mulugeta Petros, LaRC; Floyd Hovis, Fibertek, Inc.

Key Milestones

- Complete the preliminary triple pulse laser optical, mechanical, thermal and structure design and analysis — 12/14
- Complete laser wavelength control unit design — 03/15
  - Complete laser transmitter design, and [illegible] system design and breadboard testing — 09/15
- Complete fabrication and testing of laser transmitter and wavelength control unit — 07/16
- Integrate laser transmitter with wavelength control unit — 09/16
  - Complete lidar integration, and ground test — 03/17
- Conclude CO_2/H_2O airborne lidar demonstration and final report — 06/17

TRL_{in} = 3 TRL_{out} = 5

ESTO Earth Science Technology Office

2-µm CO_2 IPDA Path to Space

Table 1. Comparison of CO_2 state-of-the-art 2-µm current and proposed technology with space requirement

	Current Technology	Proposed Technology	Projected Space Reqirement [2]
	Laser Transmitter		
	Single Laser	**Single Laser**	**Two Lasers**
Technology	Liquid-Cooled, Airborne laser	Conductively-Cooled Space Qualifiable laser	Column CO_2 Space Mission
Technique	Double-Pulse	Triple-Pulse	Single-Pulse
Laser Wavelength (µm)	2.051	2.051	2.051
Pulse Energy (mJ) $1^{st}/2^{nd}/3^{rd}$ Pulse	100/30 Double Pulse	50/15/5 Triple Pulse	40/5 Single Pulse
Pulse Repetition Rate (PRF)	10	50	50
Power (W)	1.3	3.5	2.25
Pulse Width FWHM (ns)	200	30-100	50
Optical to Optical Efficiency (%)	4.0	5.0	5.0
Wall Plug Efficiency (%)	1.44	2.1	>2.0
Delay between pulses (200 µsec)	200	200	250+/-25
Transverse/Longitudinal Modes	TEM_{00}/Single Mode	TEM_{00}/Single Mode	TEM_{00}/Single Mode
Pulse Spectral Width FWHM (MHz)	2.2	4-14	> 60
Beam Quality (M^2)	2	2	< 2
Frequency Control Accuracy (MHz)	0.3	0.3	0.2
Seeding Success Rate /Spectral Purity (%)	>99/99.9	>99/99.9	>99/99.9
	Detector		
Material	InGaAs	HgCdTe	N/A
Structure	Pin photodiode	eAPD	APD
Quantum Effficiency (%)	68	80	75
Excess-Noise-Factor	---	1.1	1.5
Noise-Equivalent-Power ($fW/Hz^{1/2}$)	200	8	100

Summary and Conclusions

- A 2-micron double-pulsed, high energy IPDA lidar system has been developed
- 2-μm CO_2 IPDA lidar modeling estimates instrument performance and calculates weighting function for deriving XCO2.
- Preliminary analysis of ground based hard target measurement demonstrates the 2-μm CO_2 IPDA lidar capability of measuring CO_2 optical depth and deriving XCO2.
- The IPDA instrument was operated on NASA B-200 aircraft through different conditions
- IPDA capability was demonstrated from airborne platform
- The measurement includes ranging capability with 1 m precision
- Observed single-shot signal-to-noise ratio from hard target larger than 200
- Detailed data analysis is in progress
- Future work towards developing a triple-pulsed IPDA lidar system is progressing

2-μm IPDA Lidar Team members

C. Boyer, B. Culliton, L. Cowen, J. Fay, W. Johnson, S. Johnston, M. Jones, E. Modlin, L. Murchison, I. Pang, P. Manhart, T. Notari , M. Petros , K. Reithmaier, T. Refaat, R. Remus, D. Reichle, S. Salvatore, U. Singh, J. Yu

Publication List

1. J. Yu, M. Petros, K. Reithmaier, Y. Bai, B. Trieu, T. Refaat, M. Kavaya, U. Singh and S. Ismail, “A 2-micron pulsed integrated path differential absorption lidar development for atmospheric CO_2 concentration measurements”, 26th International Laser Radar Conference (ILRC), Porto Heli, Greece, 2012.
2. U. Singh, J. Yu, M. Petros, T. Refaat and K. Reithmaier, “Development of a pulsed 2-micron integrated path differential absorption lidar for CO_2 measurements”, Invited, Proc. of SPIE, Vol. 8872, 997209, 2013.
3. U. Singh, J. Yu, M. Petros, T. Refaat, K. Reithmaier, T. Kurosu, C. Miller and S. Dinardo, “Double-pulsed 2-micron integrated path differential absorption lidar development and column CO_2 measurement from ground and airborne platform”, 10th International Workshop on Greenhouse Gas Measurements from Space, ESA-ESTEC, Noordwijk, The Netherlands, 2014.
4. U. Singh, J. Yu, M. Petros, T. Refaat, R. Remus, J. Fay and K. Reithmaier, “Column CO_2 measurements from an airborne solid-state double-pulsed 2-micron integrated path differential absorption lidar”, International Conference on Space Optics, Tenerife, Canary Islands, Spain, 2014.
5. J. Yu, M. Petros, T. Refaat, K. Reithmaier, R. Remus, U. Singh, W. Johnson, C. Boyer, J. Fay, S. Johnson and L. Murchison, “2-micron pulsed direct detection IPDA lidar for atmospheric CO_2 measurement”, First International Conference on Space-Based Lidar Remote Sensing Techniques and Emerging Technologies, Paris, France, 2014.
6. T. Refaat, M. Petros, R. Remus, J. Yu and U. Singh, “Laser energy monitor for double-pulsed 2-μm IPDA lidar applications”, Proc. of SPIE, Vol. 9246, 924619, 2014.
7. U. Singh, J. Yu, M. Petros, T. Refaat, R. Remus, J. Fay and K. Reithmaier, “Airborne 2-micron double-pulsed integrated path differential absorption lidar for column CO_2 measurement”, Proc. of SPIE, Vol. 9246, 924601, 2014.
8. T. Refaat, M. Petros, R. Remus, J. Yu and U. Singh, “Self-calibration laser energy monitor validation for double-pulsed 2-μm CO_2 IPDA lidar applications”, in preparation, Optical Engineering.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