National Aeronautics and Space Administration

Double-pulsed 2-μm lidar validation for atmospheric CO_2 measurements

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SPIE Remote Sensing

New Developments in Lidar Technology I

9645-1

Monday, September 21, 2015

Toulouse, France

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Objectives

Demonstrate ground-based and airborne CO_2 measurement capability using 2-μm double-pulse IPDA lidar.

Outline

- CO_2 2-μm Double-Pulse IPDA Lidar
  - **Methodology**
  - **Spectroscopy**
  - **Instrument and Integration**
  - **IPDA Ground Testing**
  - **IPDA Airborne Testing**
  - **Summary and Conclusion**

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

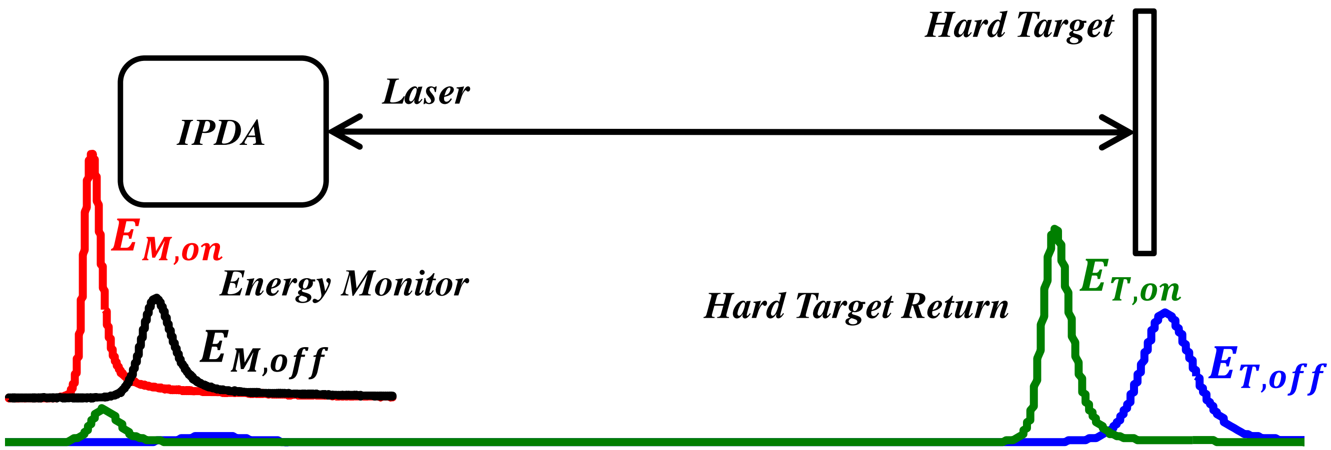
Key Milestones

• 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)

ESTO Earth Science Technology Office

Methodology



- IPDA lidar relies on the Hard Target Lidar Equation

$$E_T = \eta_r \cdot \varphi_r \cdot \frac{A_t}{\Delta R^2} \cdot E_M \cdot \frac{\rho}{\pi} \cdot exp[-OD(\lambda, R_G)]$$

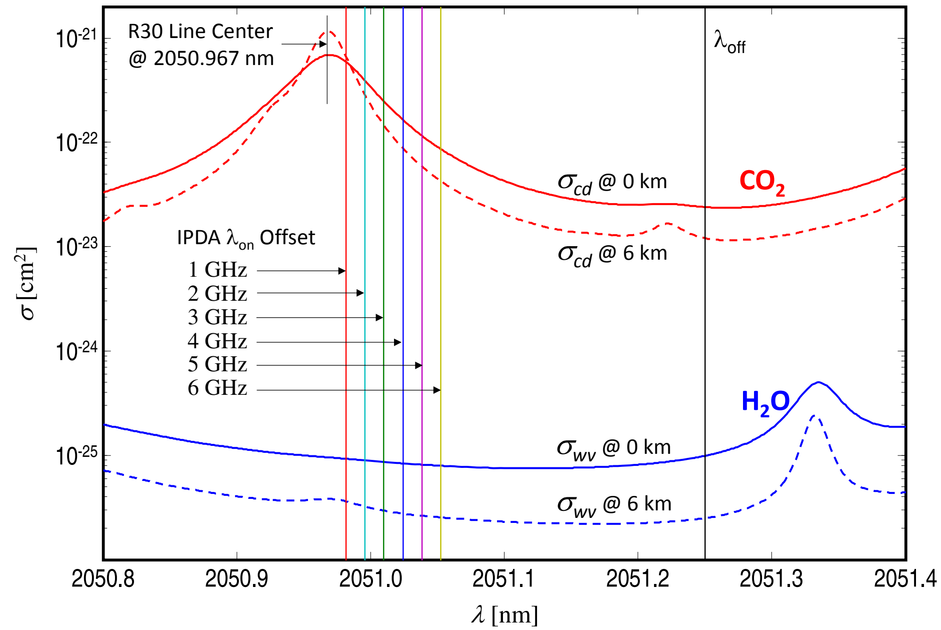
- Double-pulse tuning defines CO_2 differential optical depth, the main IPDA product

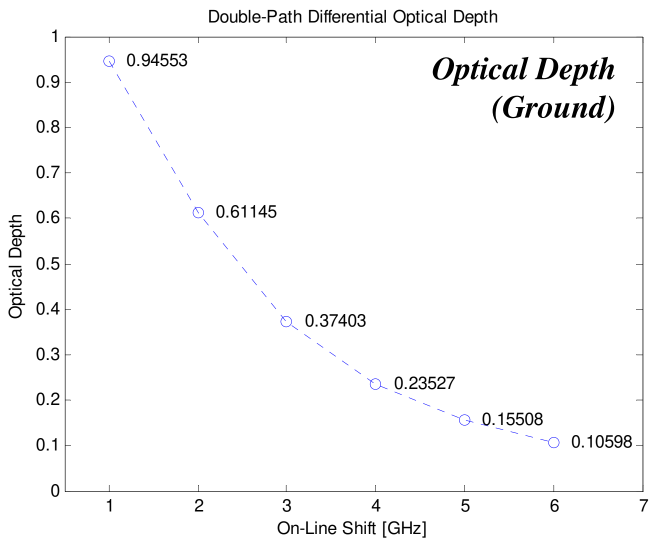
$$dOD_{cd} = \int_0^R 2 \cdot \Delta\sigma_{cd} \cdot N_{cd} \cdot dr \approx ln\left(\frac{E_{T,off} \cdot E_{M,on}}{E_{M,off} \cdot E_{T,on}}\right)$$

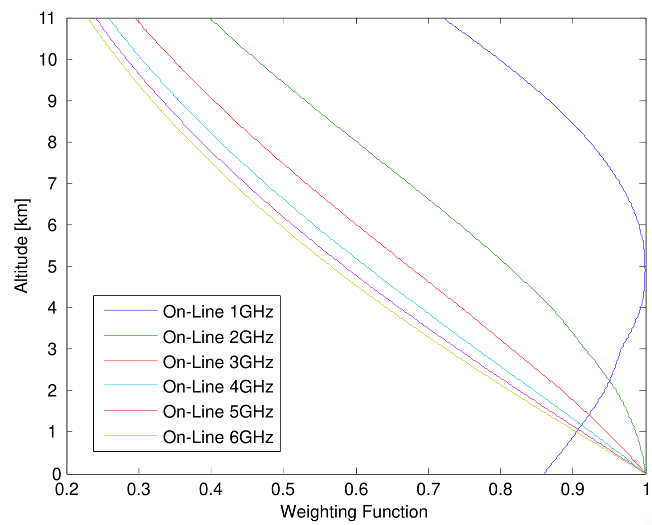
- Other IPDA products include ranging and surface reflectivity

Spectroscopy

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

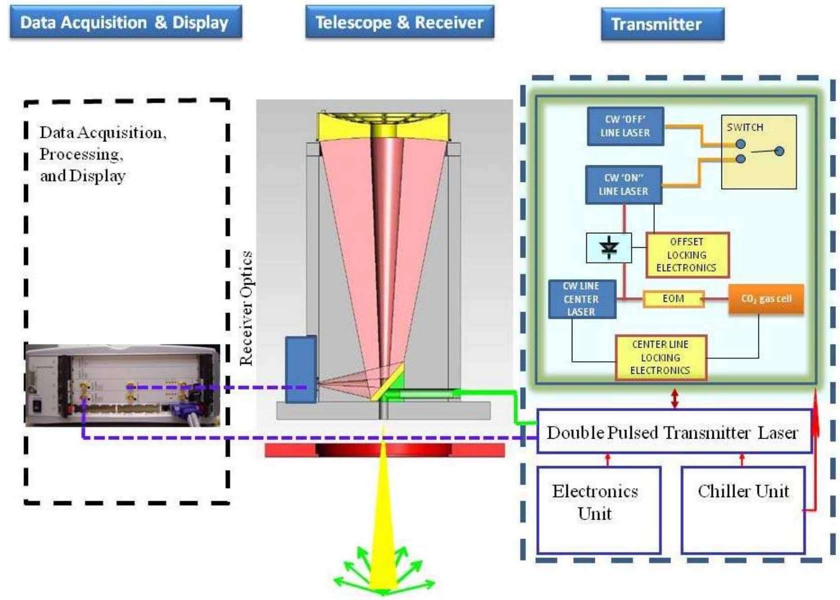






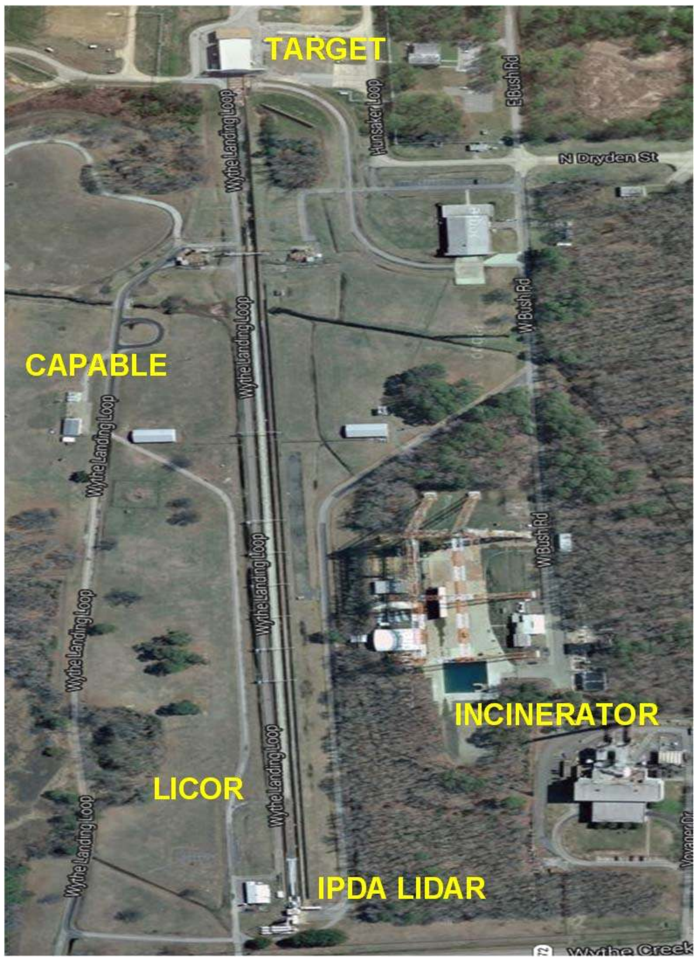
Pressure-Based Weighting-Functions (Airborne)

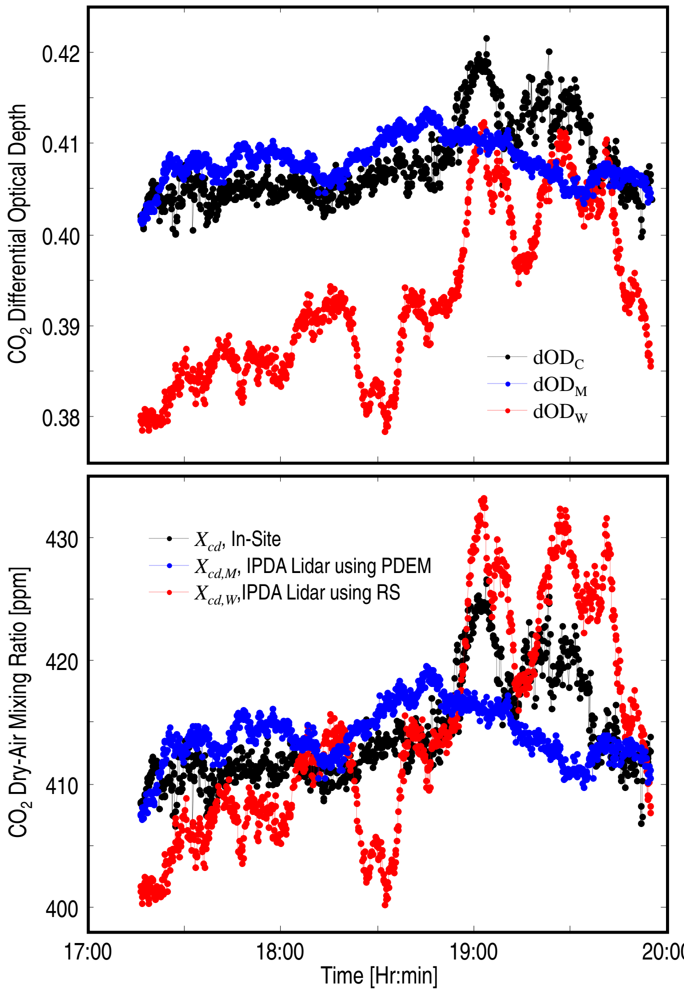
Instrument and Integration



2-μ double-pulse IPDA lidar

IPDA Ground Testing



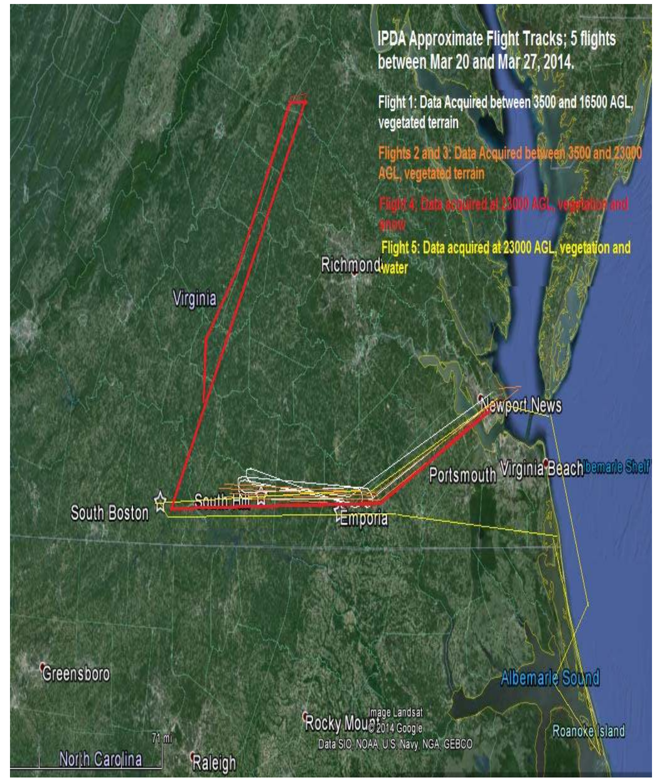


Differential optical depth– model and measurement

Dry mixing ratio IPDA vs (in-situ) measurement

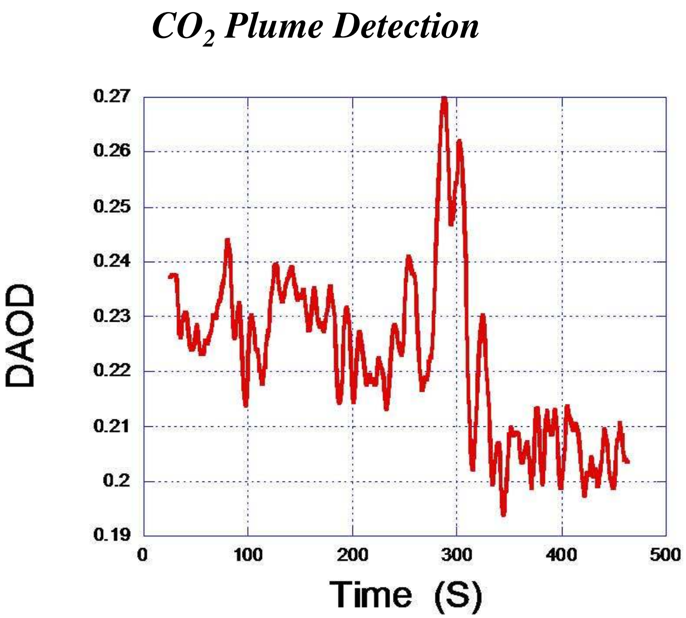
IPDA Airborne Testing

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



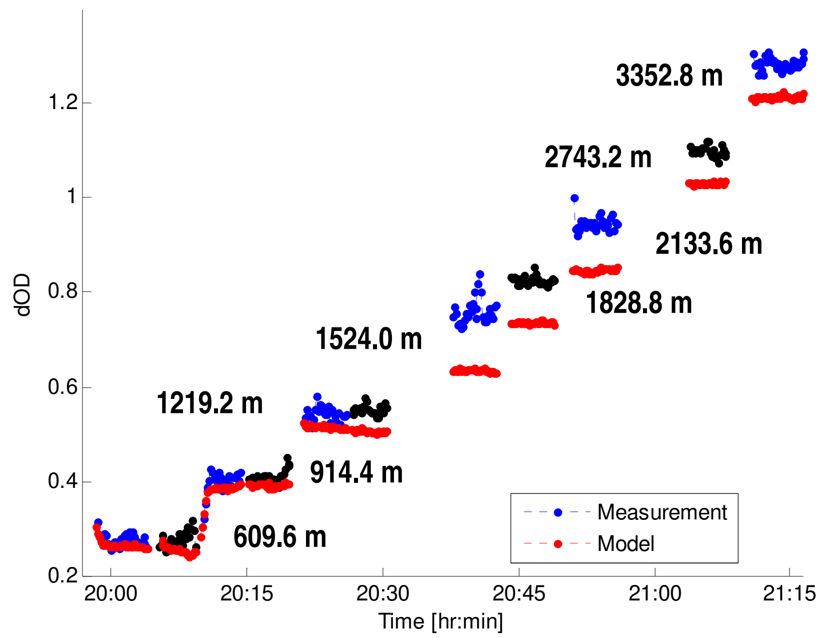
- Aircraft had temperature, pressure, humidity sensors, LiCor and GPS
- Some of the flights were supported by balloon launches

IPDA Airborne Testing



- Aerial picture of Roxboro steam plant, Semora, North Carolina
- 2 GW capacity (one of the largest power plants in the USA)
- Plant rely on coal-firing resulting in significant CO_2 plumes
- CO_2 optical depth measurement from the 2-µm double-pulse IPDA lidar
- Instrument flying, against wind, above plant incinerator
- Ninth flight; 1 km altitude and 4 GHz on-line operation

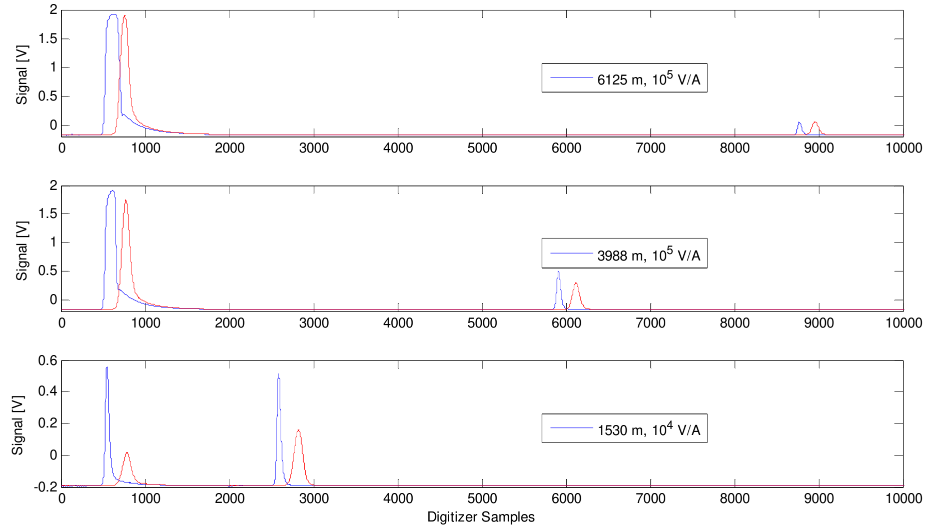
IPDA Airborne Testing

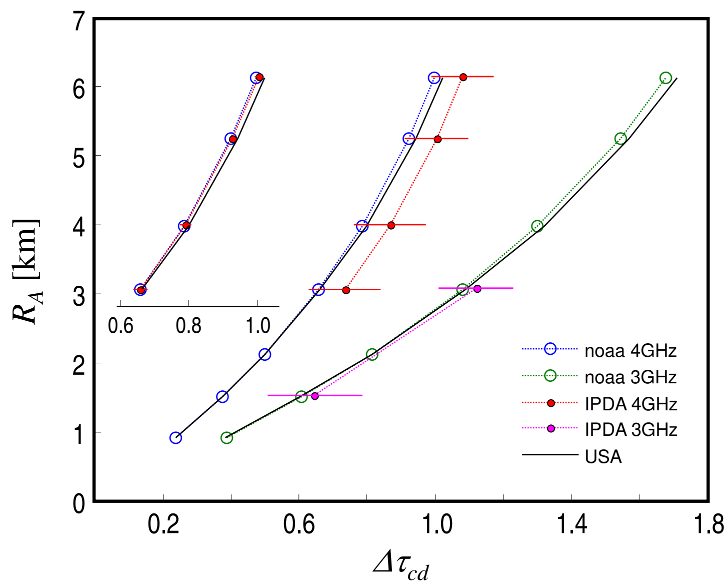


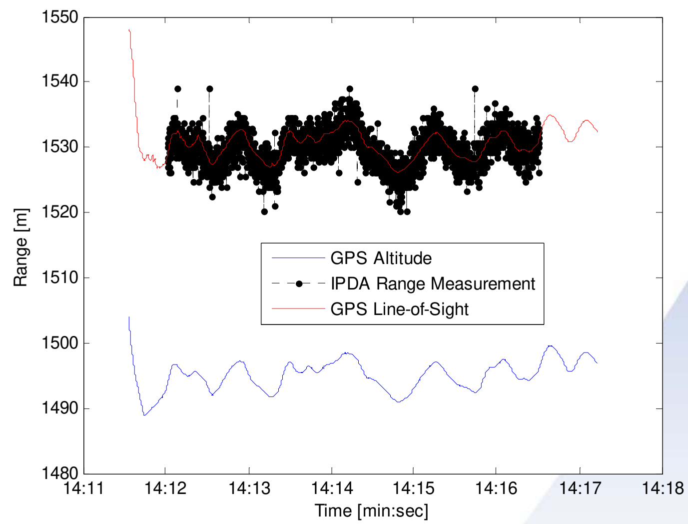
- Model derived from onboard LiCor in-situ sensor
- Data collected at different altitudes
- Tenth flight; IPDA operating at 3 GHz on-line offset

IPDA Airborne Testing

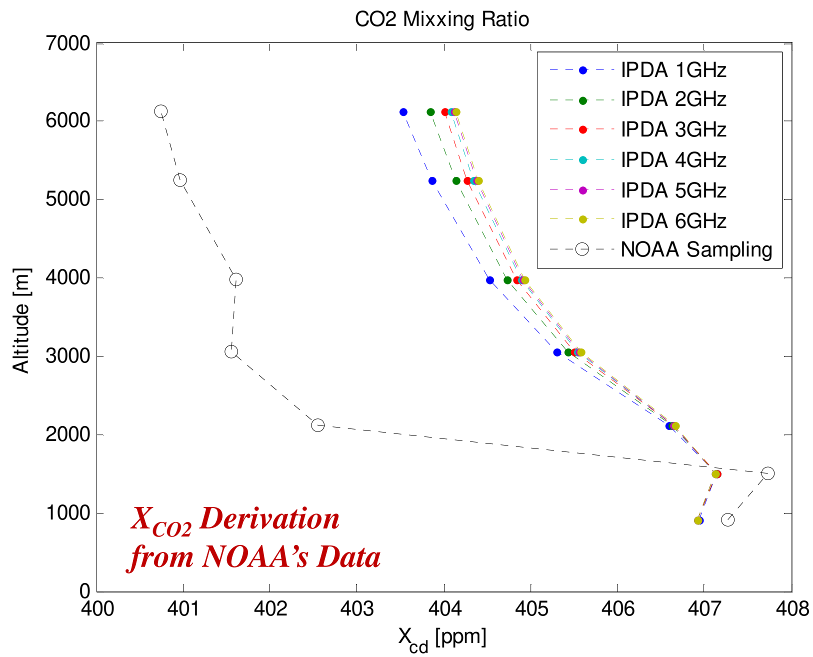
- NOAA air sampling and IPDA lidar optical depth comparison
- Return signal samples from different altitudes up to 6km
- IPDA range measurements compared to on-board GPS
- Eighth flight; IPDA operating at 3 and 4 GHz on-line offsets







IPDA Airborne Testing

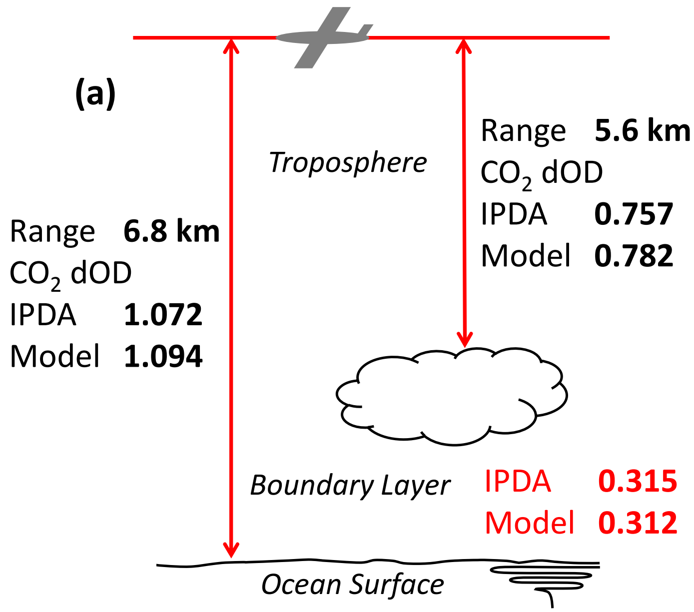


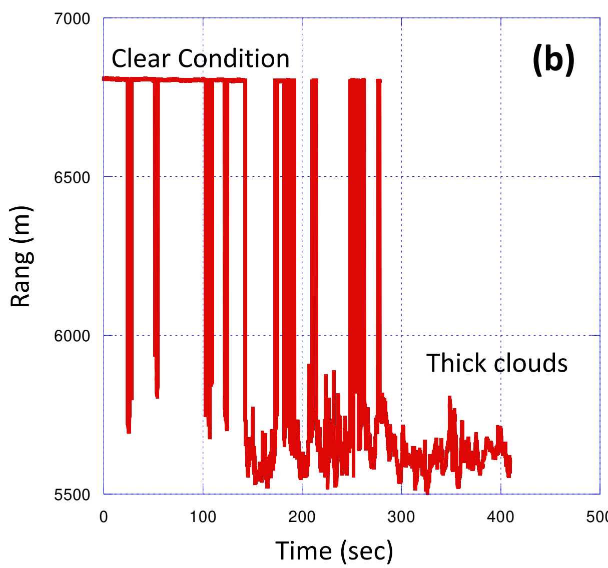
	NOAA Air Sampling	*NOAA Modeled X_{CO2}*	*IPDA Measured X_{CO2}*	*Sensitivity*	*Bias*	*Sensitivity %*	*Bias %*
R_A	x_{cd}	$X_{cd,c}$	$X_{cd,m}$	$\delta X_{cd,m}$	ΔX_{cd}	$\varepsilon_{cd,m}$	$\beta_{cd,m}$
m	ppm	ppm	ppm	ppm	ppm	%	%
6125.6	400.75	404.08	405.22	4.15	1.14	1.02	0.28
5242.6	400.96	404.34	405.84	4.74	1.50	1.17	0.37
3976.7	401.61	404.89	406.60	8.69	1.71	2.14	0.42
3051.9	401.55	405.54	407.10	12.83	1.56	3.15	0.38

Comparison of the airborne air-sampling measurements, x_{cd}, and weighted average column dry-air volume-mixing ratio of CO_2, X_{cd}, for 4 GHz on-line wavelength setting at different altitude. X_{cd} are obtained from modeling through NOAA data, $X_{cd,c}$, and the IPDA lidar differential optical depth measurements, $X_{cd,m}$. IPDA X_{cd} measurement standard deviation, $\delta X_{cd,m}$, offset, ΔX_{cd} ($\Delta X_{cd} = X_{cd,m} - X_{cd,c}$), and measurement error, $\varepsilon_{cd,m}$ ($\varepsilon_{cd,m} = \delta X_{cd,m}/X_{cd,m}$), are also listed. As well as the measurement bias ($\beta_{cd,m} = \Delta X_{cd}/X_{cd,m}$)

IPDA Airborne Testing

Cloud Slicing





- Schematic of cloud slicing concept for CO_2 measurement within the atmospheric boundary layer.
- Difference in CO_2 measured differential optical depth from clear and thick cumulus clouds conditions, representing total column range and free troposphere, respectively, estimates the boundary layer CO_2 content.
- IPDA ranging capability aids in distinguishing and selecting the data for clear and thick cloud conditions.

Specifications

Triple-Pulse

	Current Technology	Projected Technology	Current Space Requirement[a]
Transmitter	Single-Laser	Single-Laser	Two Lasers
Technique	Double-Pulse	Triple-Pulse	Single-Pulse
Cooling	Liquid	Conductive	—
Wavelength (μm)	2.051	2.051	2.051
Pulse Energy (mJ)	100 / 50	50 / 15 / 5	40 & 5
Repetition Rate (Hz)	10	50	50
Power (W)	1.3	3.5	2.25
Pulse Width (ns)	200/350	30/100/150	50
Optical-Optical Efficiency (%)	4.0	5.0	5.0
Wall-Plug Efficiency (%)	1.4	2.1	> 2.0
Multi-Pulse Delay (μs)	200	200	250 ± 25
Transverse Mode	TEM_{00}	TEM_{00}	TEM_{00}
Longitudinal Modes	Single Mode	Single Mode	Single Mode
Pulse Spectral Width (MHz)	2.2	4-14	> 60
Beam Quality (M^2)	2	2	< 2
Freq. Control Accuracy (MHz)	0.3	0.3	0.2
Seeding Success Rate	99	99	99
Spectral Purity (%)	99.9	99.9	99.9

[a]ESA Report of Assessment, SP-1313/1 (2008).

Future Work

<u>Path To Space</u>

Comparing 2-μm Double-Pulse IPDA and Triple-Pulse IPDA to ESA Requirements for CO_2 Space Mission

Conclusions

- CO_2 2-μm double-pulse IPDA lidar development and validation at NASA LaRC
- Double-pulse IPDA ground testing demonstrated successful CO_2 measurement as compared to in-situ sensors
- Double-pulse IPDA CO_2 airborne measurements agrees with different validation models through different sources;
  - CO_2 plume detection
  - Onboard CO_2 sensor
  - NOAA air sampling
- Cloud slicing technique separates boundary layer and free troposphere CO_2 measurements, for better source and sink and transport studies.
- IPDA lidar extended capabilities through triple-pulse operation, for simultaneous and independent CO_2 and H_2O measurement.
- 2-μm IPDA lidar meets or exceeds current space requirement set by ESA, projected in A-SCOPE

Questions?