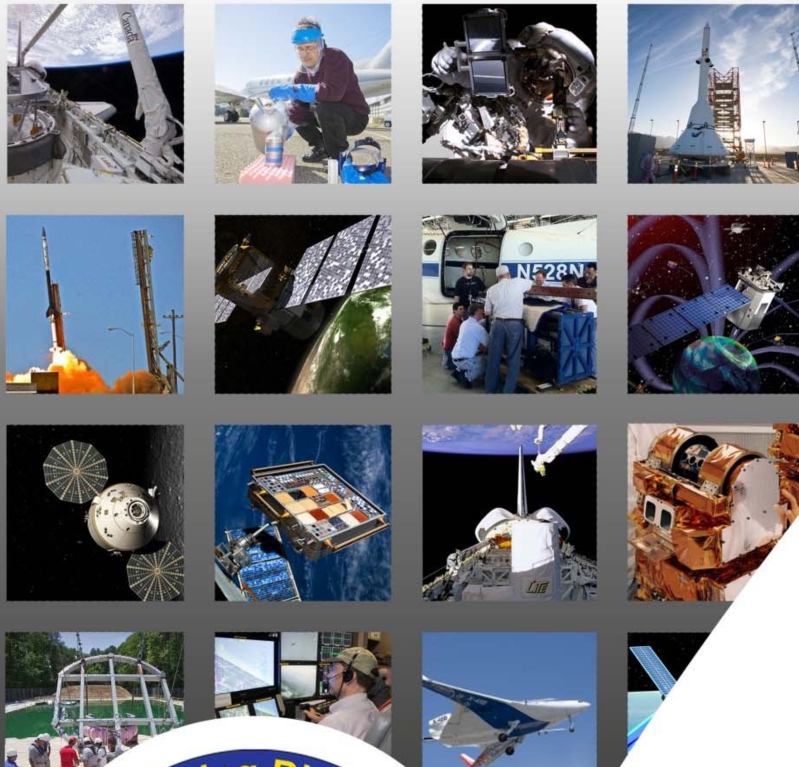

National Aeronautics and Space Administration

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


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**SPIE Remote Sensing**

**New Developments in Lidar Technology I**

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## ➢ Objectives

Demonstrate ground-based and airborne $CO_2$ measurement capability using 2-$\mu$m double-pulse IPDA lidar.

# Outline

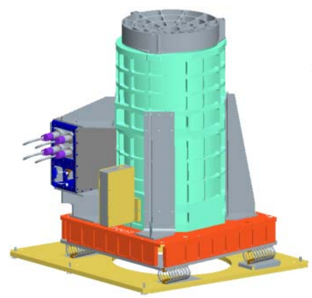
- $CO_2$ 2-μm Double-Pulse IPDA Lidar
  - **Methodology**
  - **Spectroscopy**
  - **Instrument and Integration**
  - **IPDA Ground Testing**
  - **IPDA Airborne Testing**
  - **Summary and Conclusion**

# 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

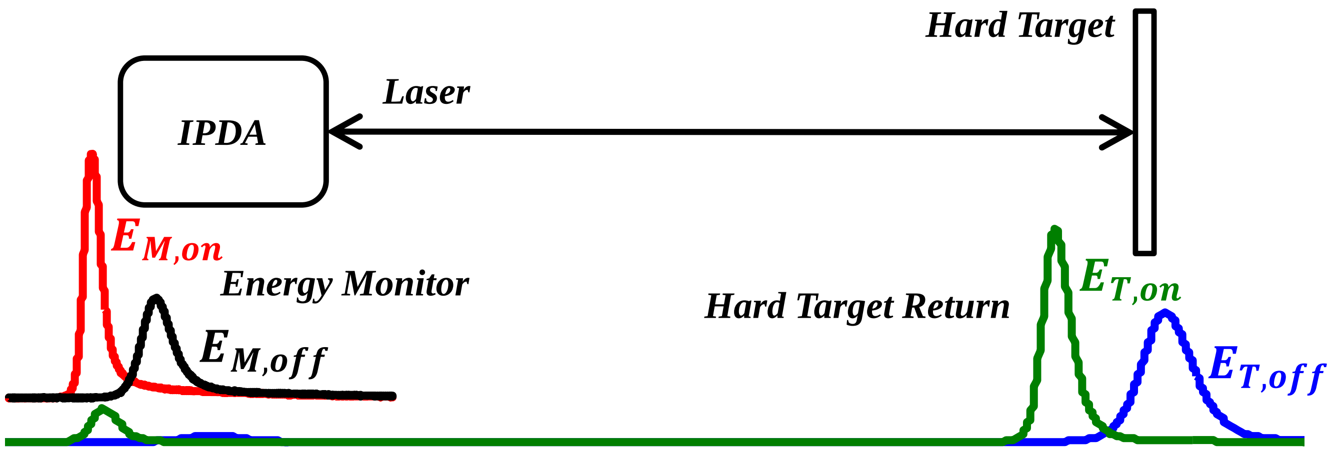
**Co-Is/Partners:** Jirong Yu, Mulugeta Petros, Syed Ismail, NASA LaRC

## 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)

# Methodology




- IPDA lidar relies on the Hard Target Lidar Equation

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

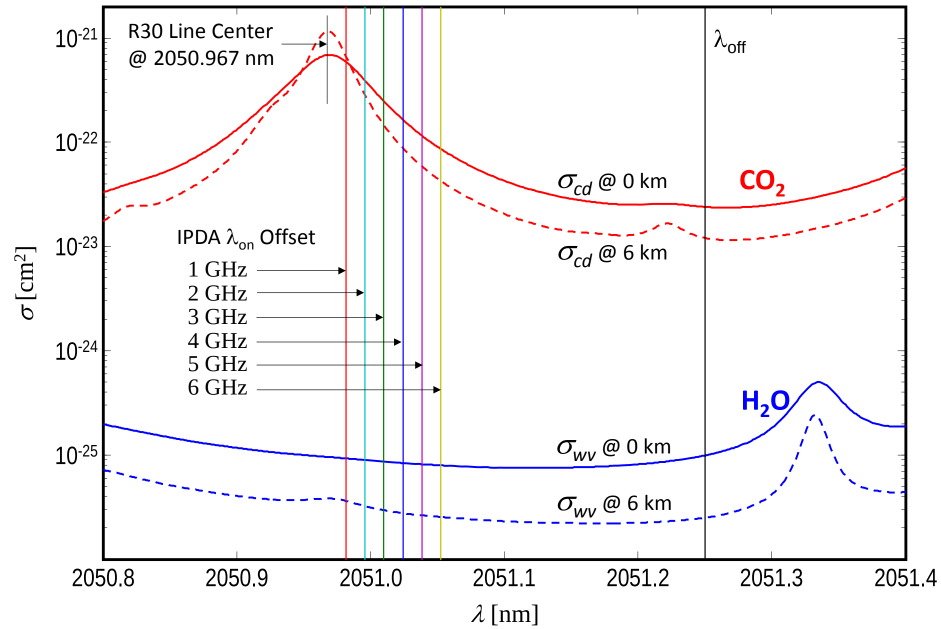
- Double-pulse tuning defines $CO_2$ differential optical depth, the main IPDA product

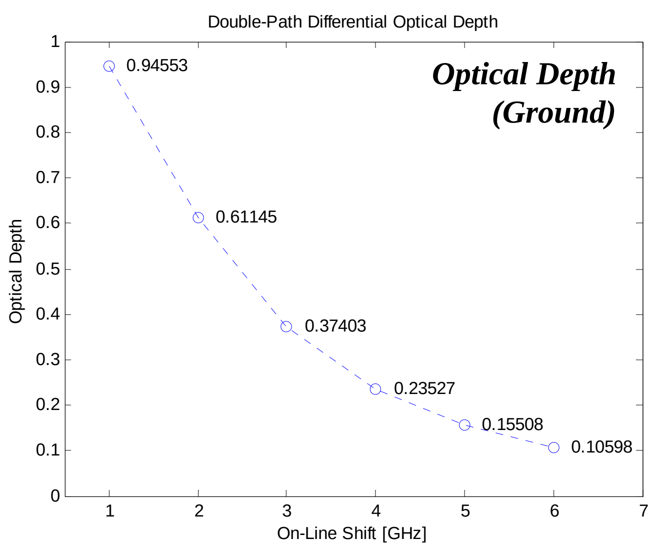
$$dOD_{cd} = \int_0^R 2 \cdot \Delta\sigma_{cd} \cdot N_{cd} \cdot dr \approx ln\left(\frac{E_{T,off} \cdot E_{M,on}}{E_{M,off} \cdot E_{T,on}}\right)$$

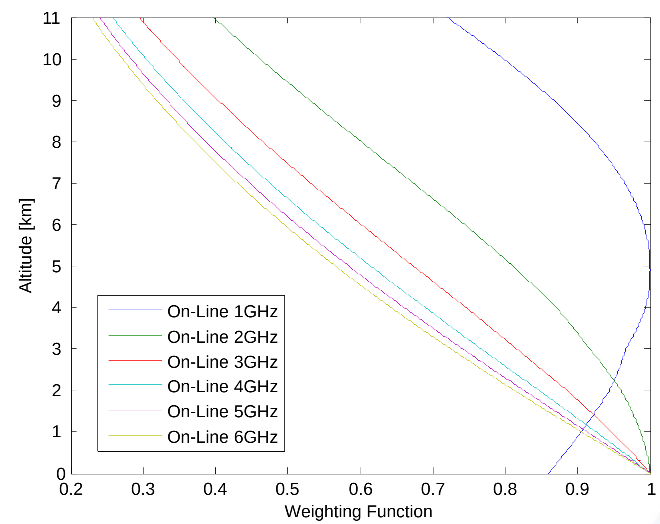
- Other IPDA products include ranging and surface reflectivity

# 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.

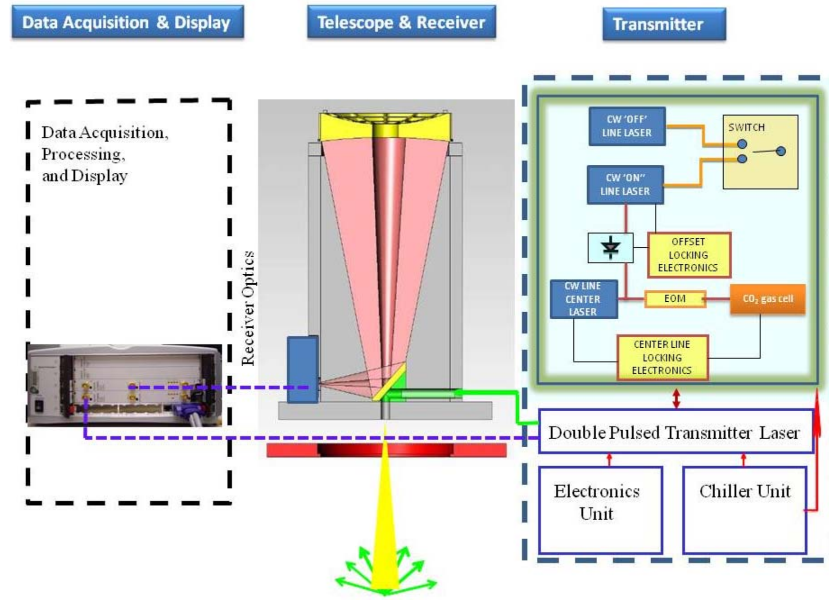


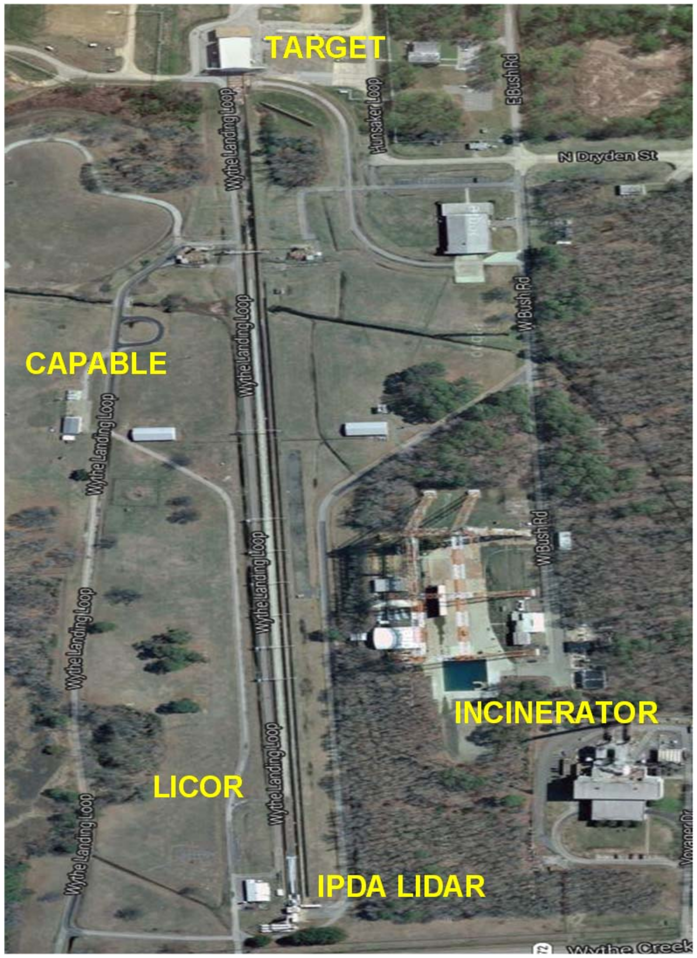

***Pressure-Based Weighting-Functions (Airborne)***

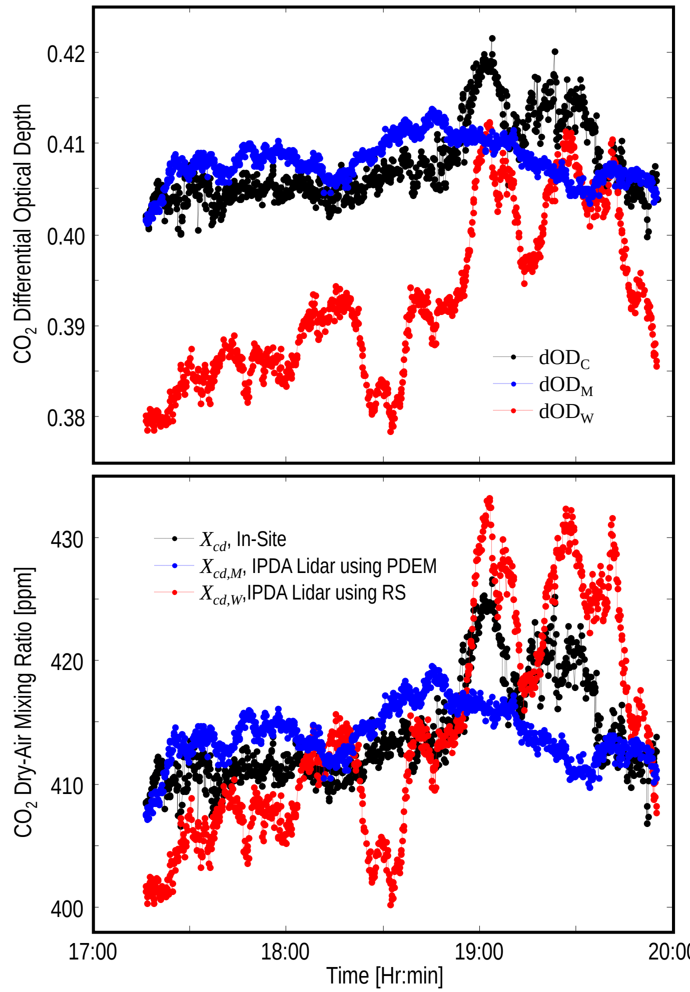
# Instrument and Integration




***2-μ double-pulse IPDA lidar***

# IPDA Ground Testing



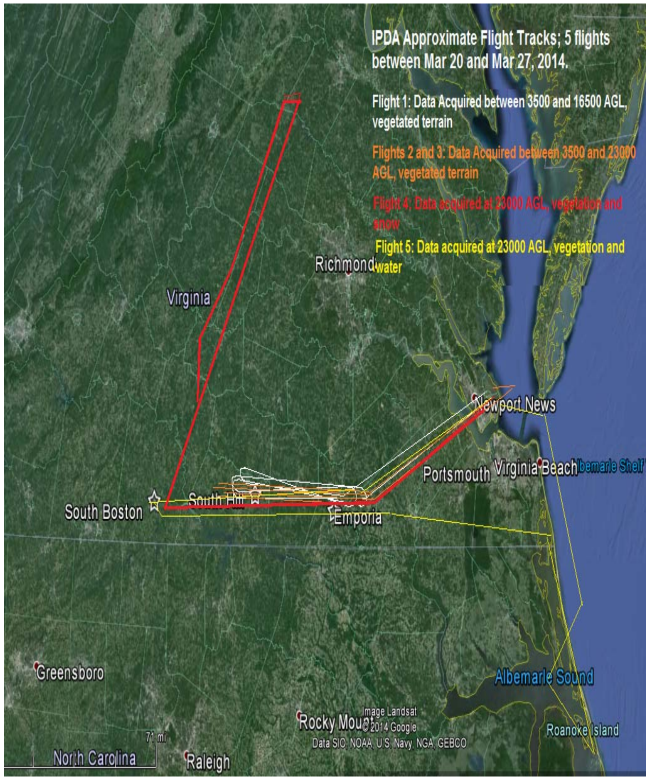




***Differential optical depth– model and measurement***

***Dry mixing ratio IPDA vs (in-situ) measurement***

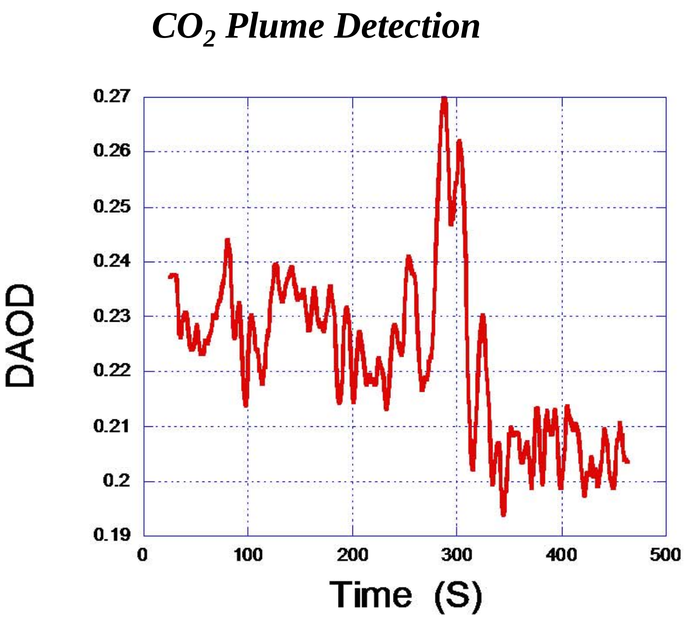
# IPDA Airborne Testing

| 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 |



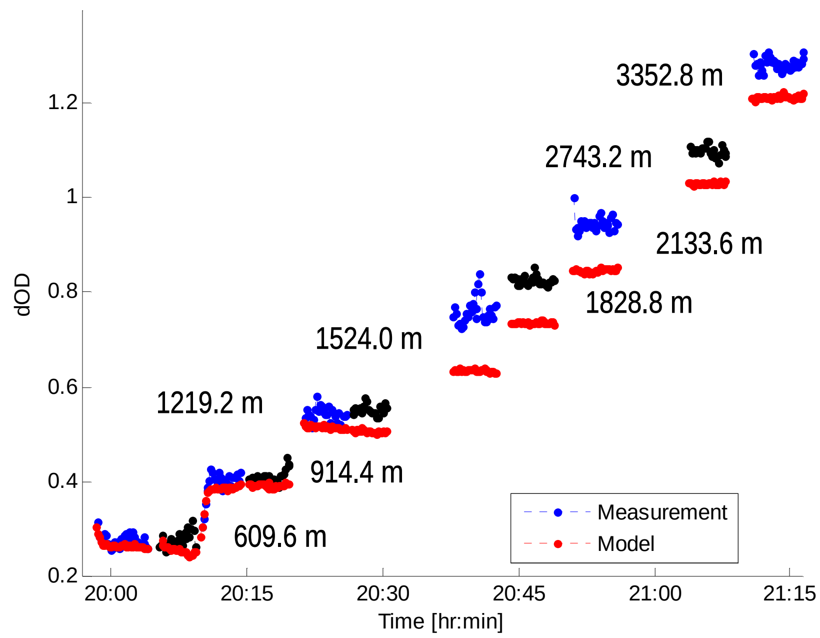

- Aircraft had temperature, pressure, humidity sensors, LiCor and GPS
- Some of the flights were supported by balloon launches

# 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-$\mu$m double-pulse IPDA lidar
- Instrument flying, against wind, above plant incinerator
- Ninth flight; 1 km altitude and 4 GHz on-line operation

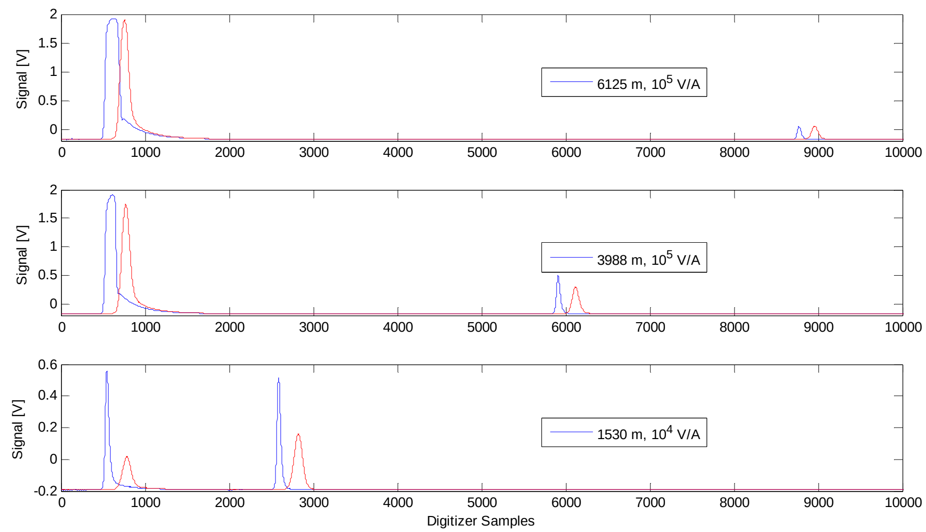
# IPDA Airborne Testing

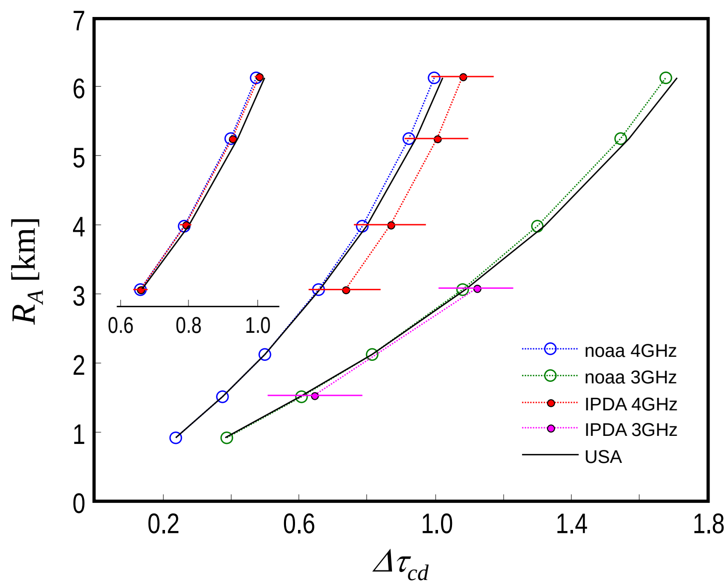


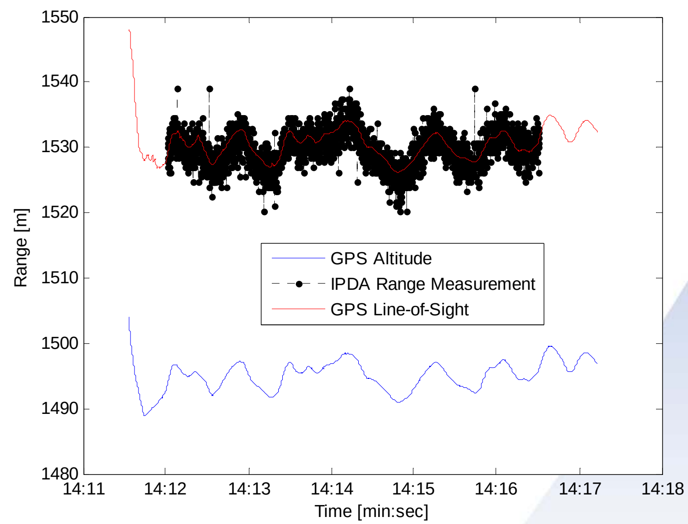

- Model derived from onboard LiCor in-situ sensor
- Data collected at different altitudes
- Tenth flight; IPDA operating at 3 GHz on-line offset

# IPDA Airborne Testing

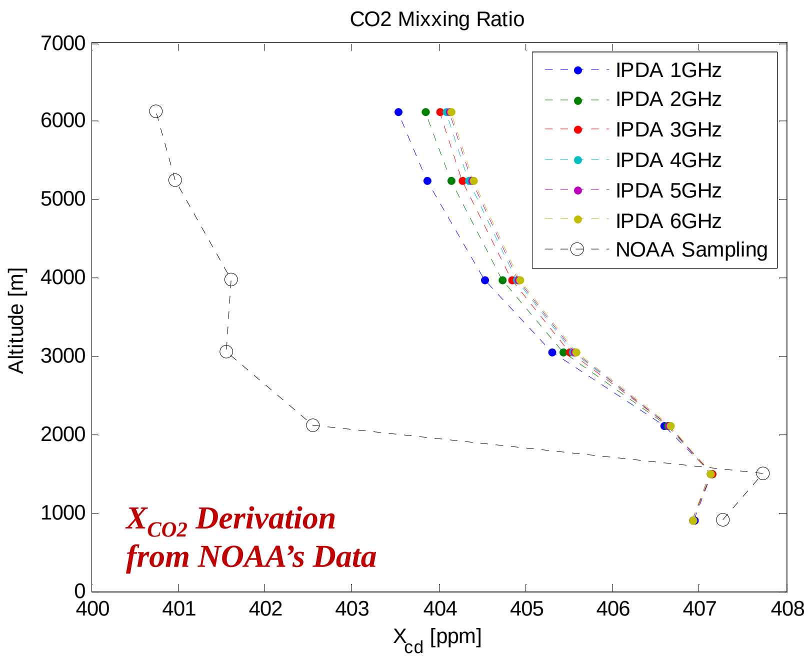
- NOAA air sampling and IPDA lidar optical depth comparison
- Return signal samples from different altitudes up to 6km
- IPDA range measurements compared to on-board GPS
- Eighth flight; IPDA operating at 3 and 4 GHz on-line offsets



# IPDA Airborne Testing

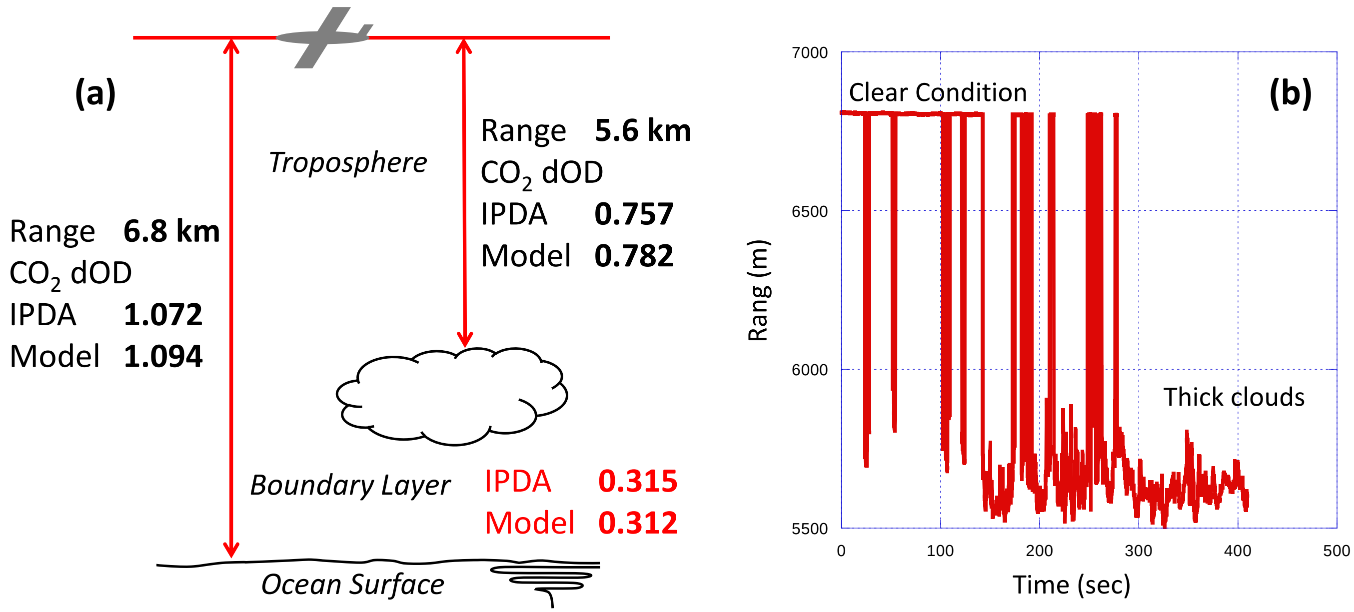



| | NOAA Air Sampling | NOAA Modeled $X_{CO2}$ | IPDA Measured $X_{CO2}$ | Sensitivity | Bias | Sensitivity % | Bias % |
|---|---|---|---|---|---|---|---|
| $R_A$ | $x_{cd}$ | $X_{cd,c}$ | $X_{cd,m}$ | $\delta X_{cd,m}$ | $\Delta X_{cd}$ | $\varepsilon_{cd,m}$ | $\beta_{cd,m}$ |
| m | ppm | ppm | ppm | 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, $\Delta X_{cd}$ ($\Delta X_{cd} = X_{cd,m} – X_{cd,c}$), 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***

## ***Path To Space***

***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?