National Aeronautics and
Space Administration

# A Novel Triple-Pulsed 2-µm Lidar for Simultaneous and Independent $CO_2$ and $H_2O$ Column Measurement

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# Outline

- Introduction
- 2-micron double pulsed IPDA lidar methodology
- Spectroscopy and IPDA  simulation
- 2-micron double pulsed IPDA lidar
- IPDA lidar Airborne Demonstration
- 2-micron triple pulsed IPDA lidar methodology
- Triple pulsed lidar performance model
- Summary and Conclusions

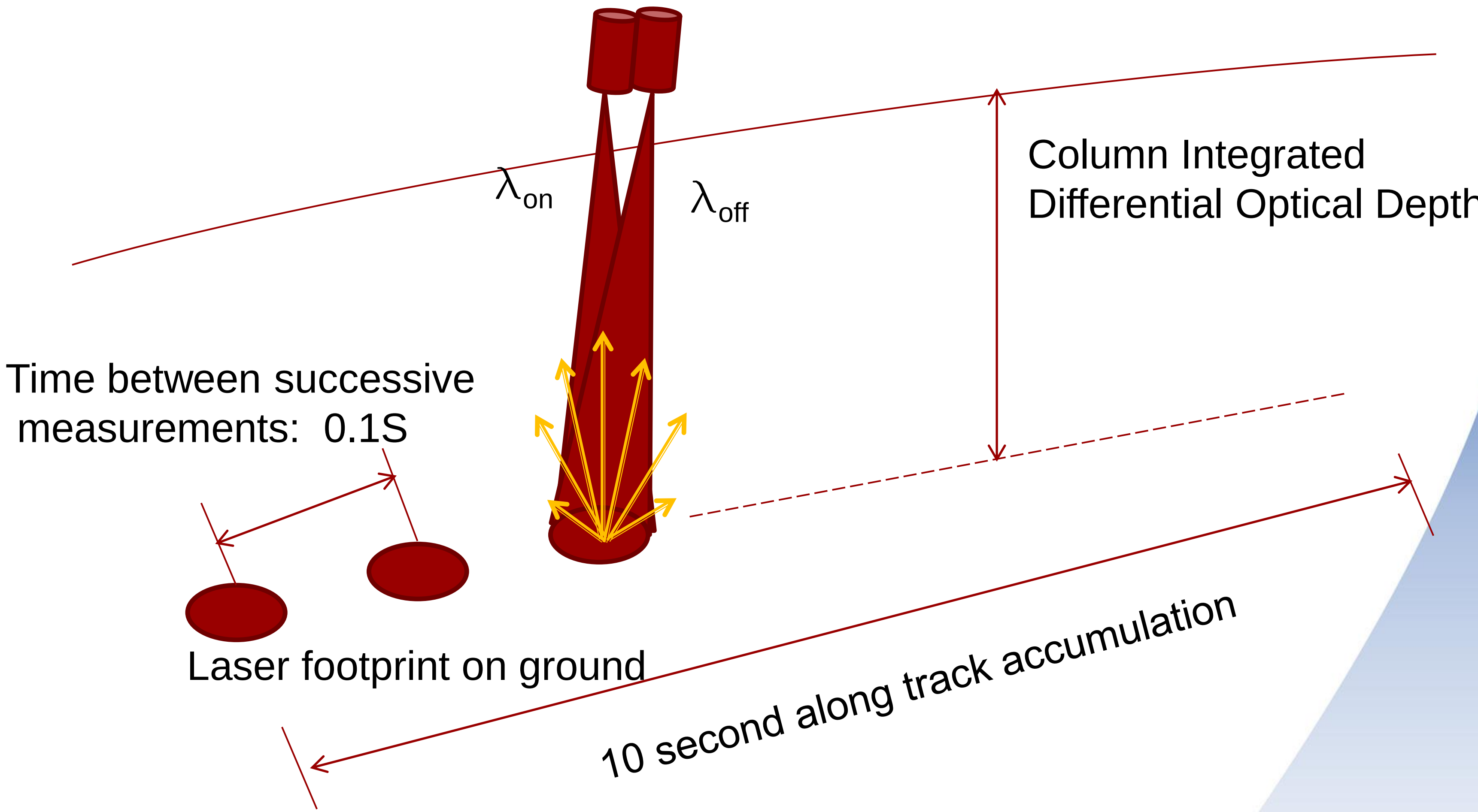
# Introduction

- The study of global warming needs precisely and accurately measuring greenhouse gases concentrations in the atmosphere. $CO_2$ and $H_2O$ are important greenhouse gases that significantly contribute to the carbon cycle and global radiation budget on Earth
- NRC Decadal Survey recommends a mission for Active Sensing of Carbon Dioxide ($CO_2$) over Nights, Days and Seasons (ASCENDS)
- 2 micron laser is a viable IPDA transmitter to measure $CO_2$ and $H_2O$ column density from space
- The objective is to demonstrate a first airborne direct detection 2 micron IPDA lidar for $CO_2$ and $H_2O$ measurements.

# 2µm Pulsed Lidar Approach

- Unambiguously defines the optical path of the detected signal; eliminate contamination from aerosols and clouds to yield high accuracy measurements
- Auxiliary altimetry lidar may not needed
- The weighting function in the 2-µm region is most favorable for making $CO_2$ measurements near the surface and PBL, where the sources and sinks of $CO_2$ are located
- Straightforward data analysis
- The pulse approach can potentially determine $CO_2$ concentrations as a function of distance, a valuable data product that is not easily available

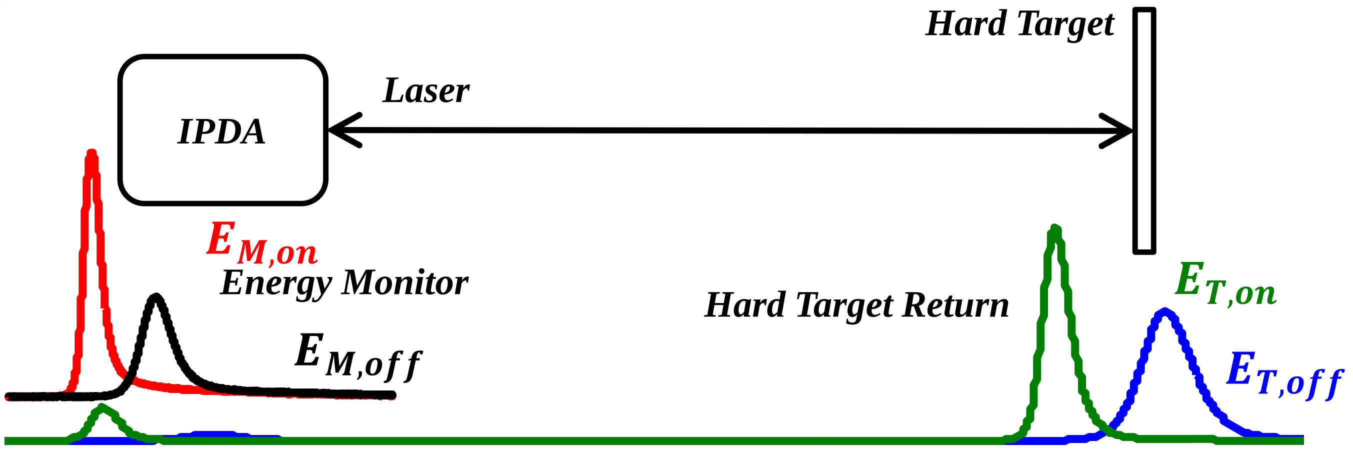
# Principle of IPDA Measurement Using Surface Targets




Transmit and receive near nadir-pointing laser beams with on and off-line wavelength channels

- Ground surface reflection (land and sea)
- Measure difference in integrated path absorption at these two wavelengths

# Methodology




- IPDA lidar relies on the Hard Target Lidar Equation

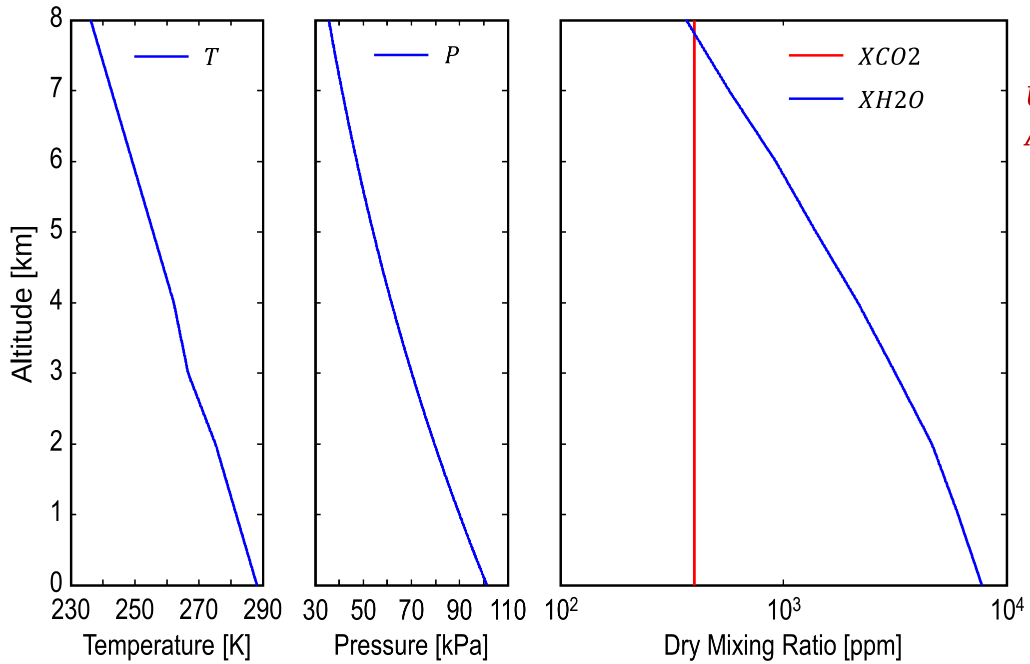
$$E_T = \eta_r \cdot \varphi_r \cdot \frac{A_t}{\Delta R^2} \cdot E_M \cdot \frac{\rho}{\pi} \cdot exp[-OD(\lambda, R_G)]$$

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

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

- Other IPDA products include ranging and surface reflectivity.

# Modeling: XCO2 Extraction




***US Standard Atmospheric Model.***

- Provided availability of meteorological data, differential optical depth can be converted into dry mixing ration (XCO2)

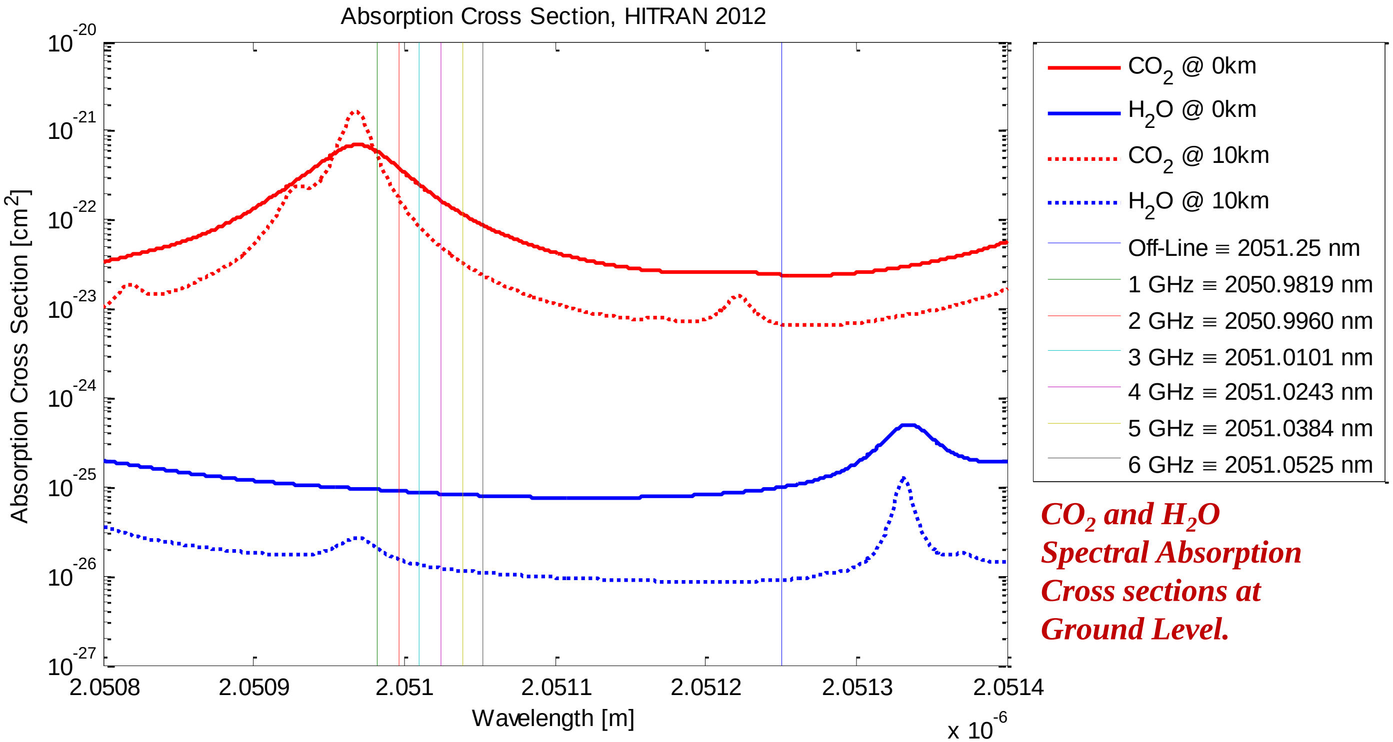
$$N_{dry} = N_{air} - N_{wv}$$

$$N_{wv} = fn(RH)$$

$$N_{air} = \frac{P}{k \cdot T}$$

$$XCO2 = \frac{DAOD_{cd}}{\int_0^R 2 \cdot \Delta\sigma_{cd} \cdot N_{dry} \cdot dr} = \frac{N_{cd}}{N_{dry}}$$

# Modeling: Spectroscopy

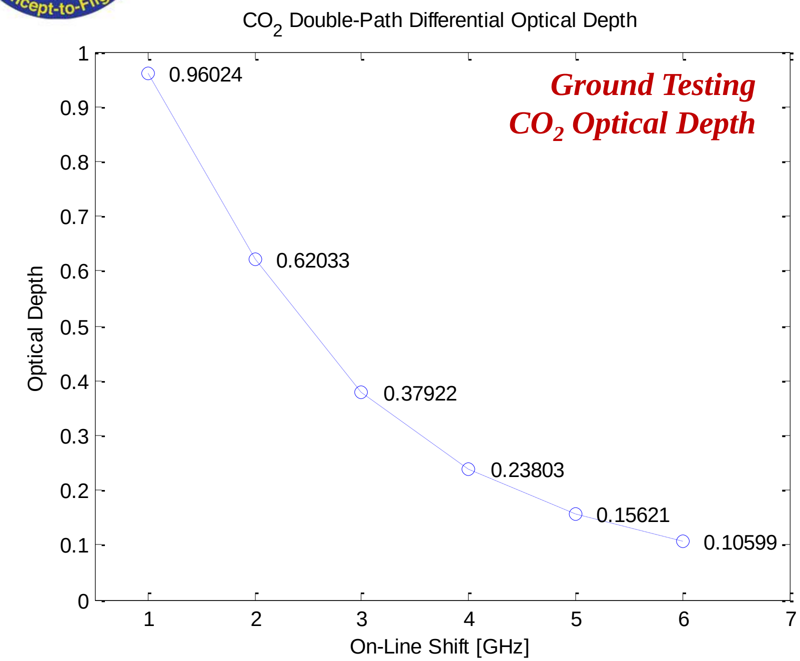


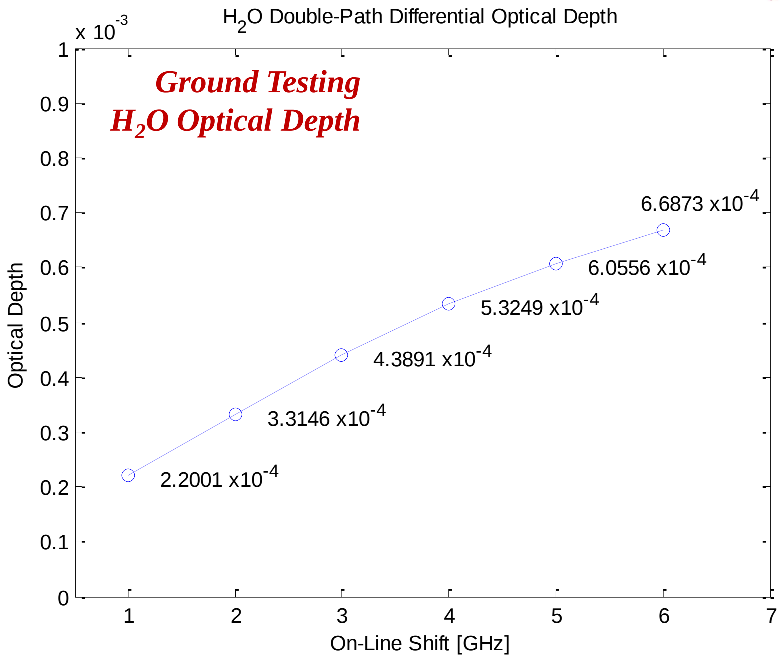

***$CO_2$ and $H_2O$ Spectral Absorption Cross sections at Ground Level.***

$$\Delta\sigma_{cd} = fn(\lambda, P, T)$$

- Calculated using HITRAN 2012 database targeting $CO_2$ R30 line
- Voigt line profile was assumed
- Calculation includes 5550 $CO_2$ neighboring lines from 2044.22 nm to 2059.57 nm
- Calculation includes 1816 $H_2O$ neighboring lines from 2022.21 nm to 2080.36 nm
- US Standard Atmospheric model was assumed

# Modeling: Products



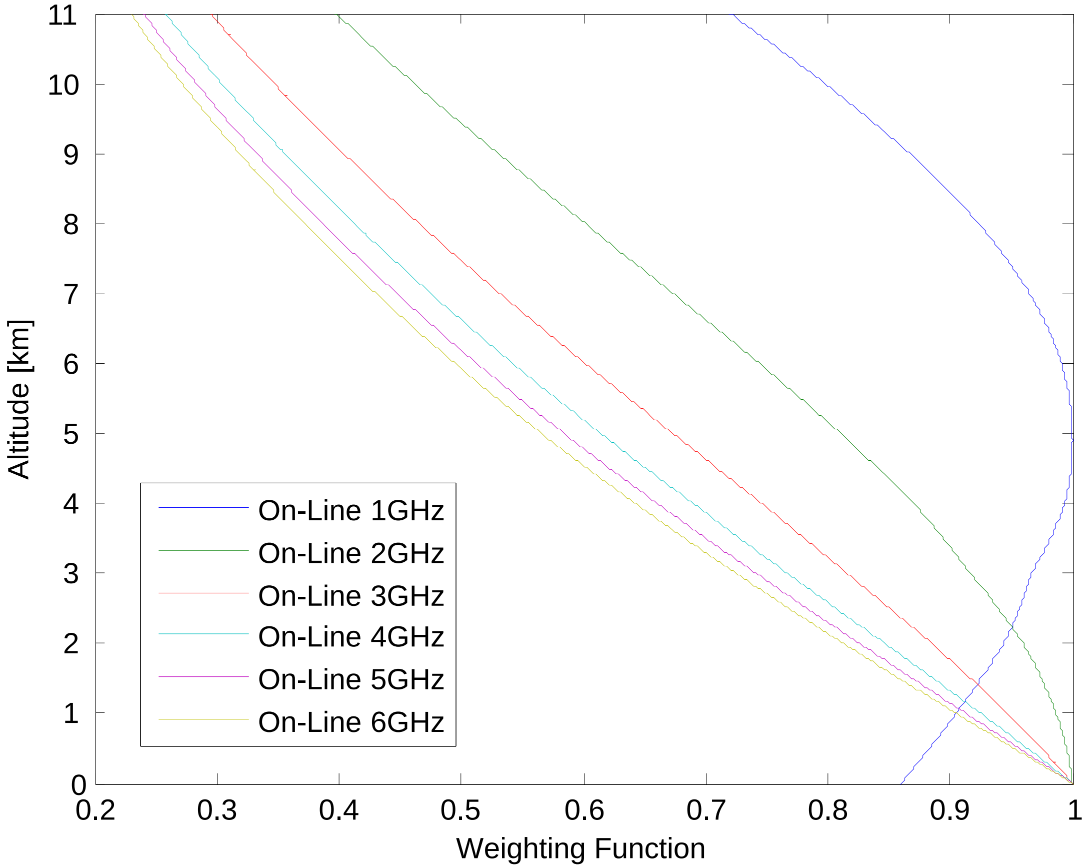

- **Using Standard Models**

IPDA lidar modeling products includes estimates for optical depth, return pulse strength, signal-to-noise ratio and random and systematic errors for any operating condition

- **Using meteorological data**

IPDA lidar modeling derives weighting functions required for XCO2 derivation

# Airborne Pressure-Based Weighting- Functions

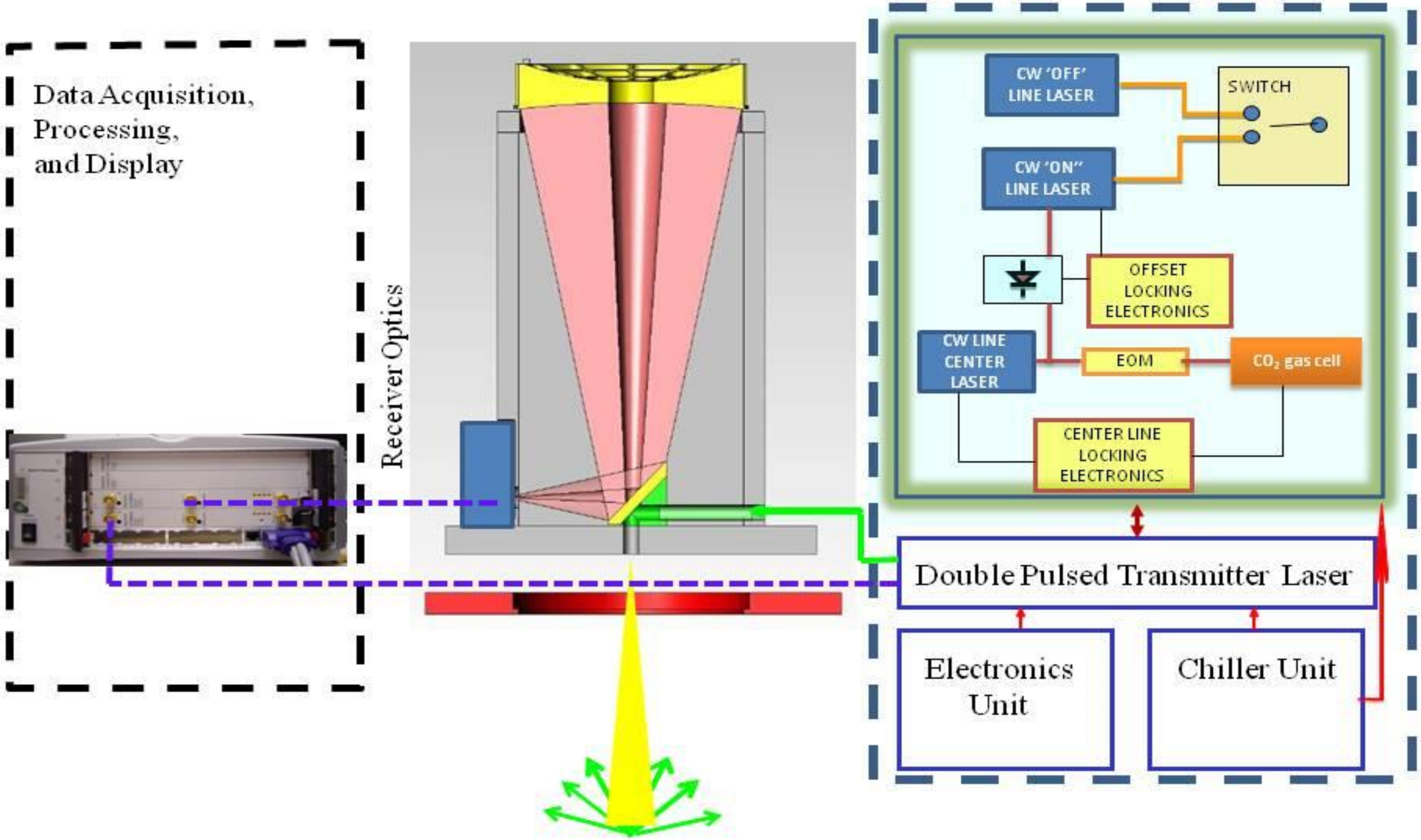


# System Schematic

Data Acquisition & Display

Telescope & Receiver

Transmitter

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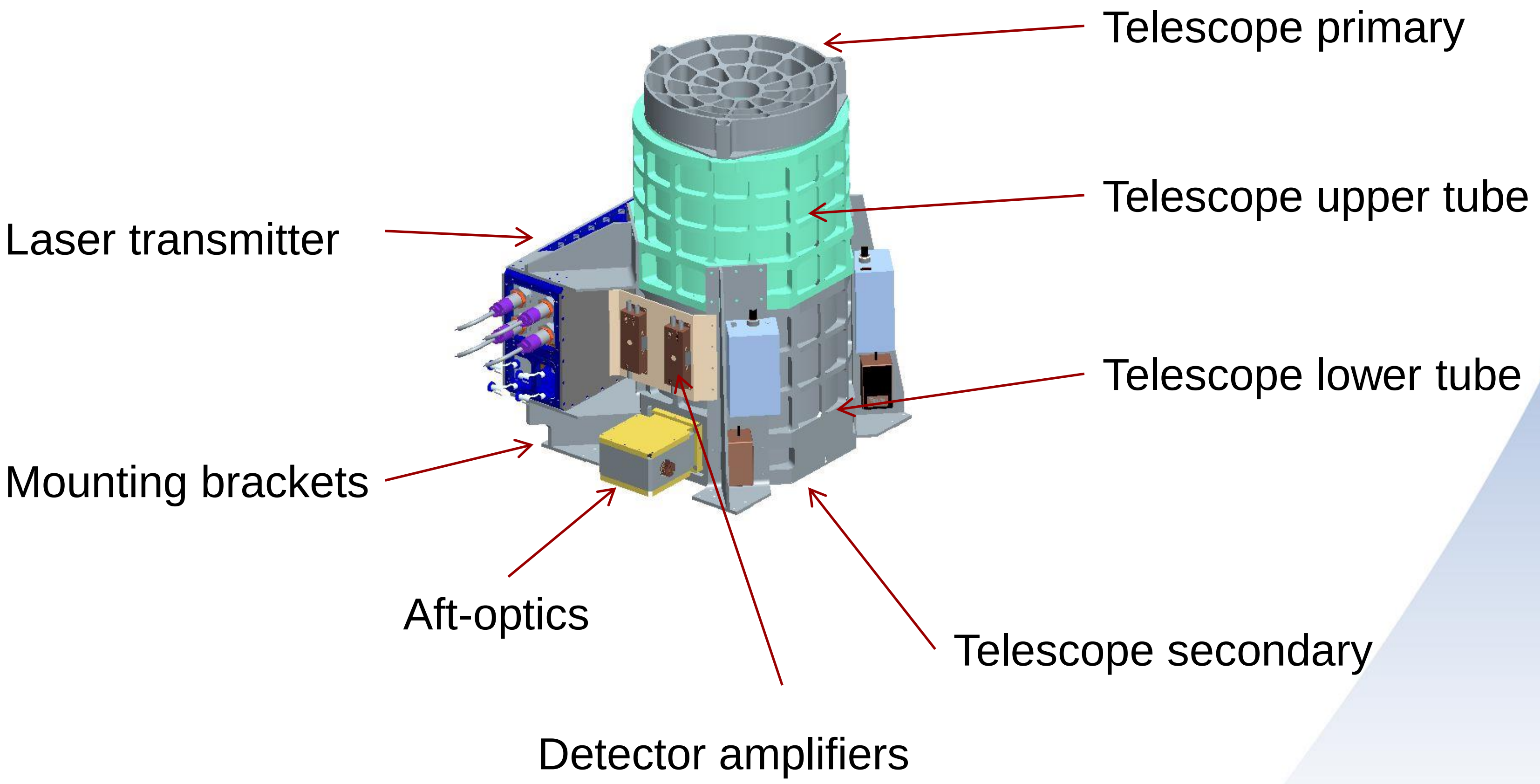
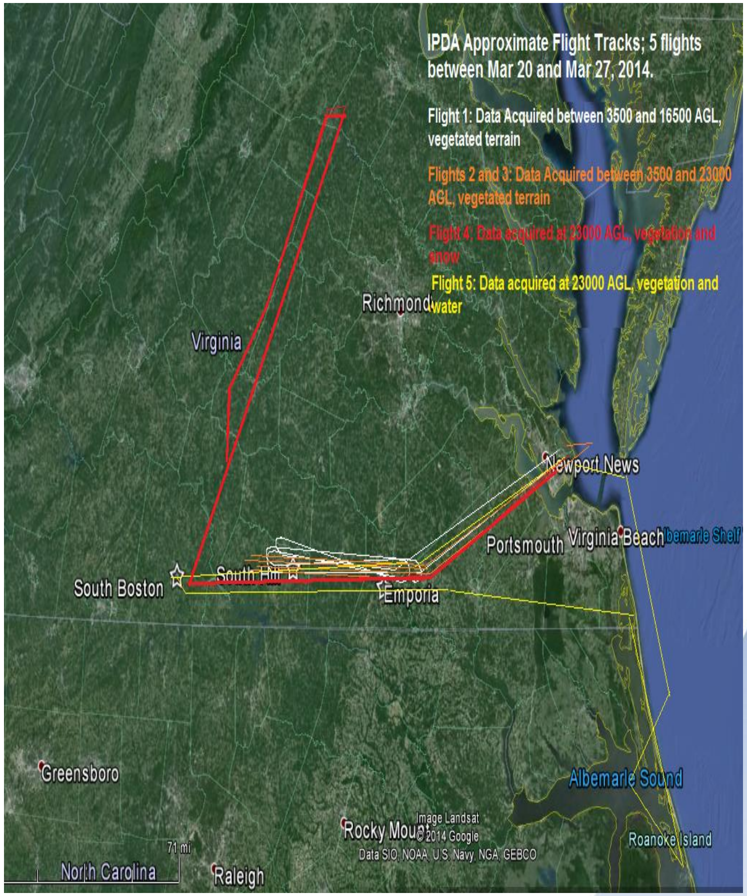
# Integrated IPDA Lidar



# 2-micron double pulsed IPDA lidar in airplane

# 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 |

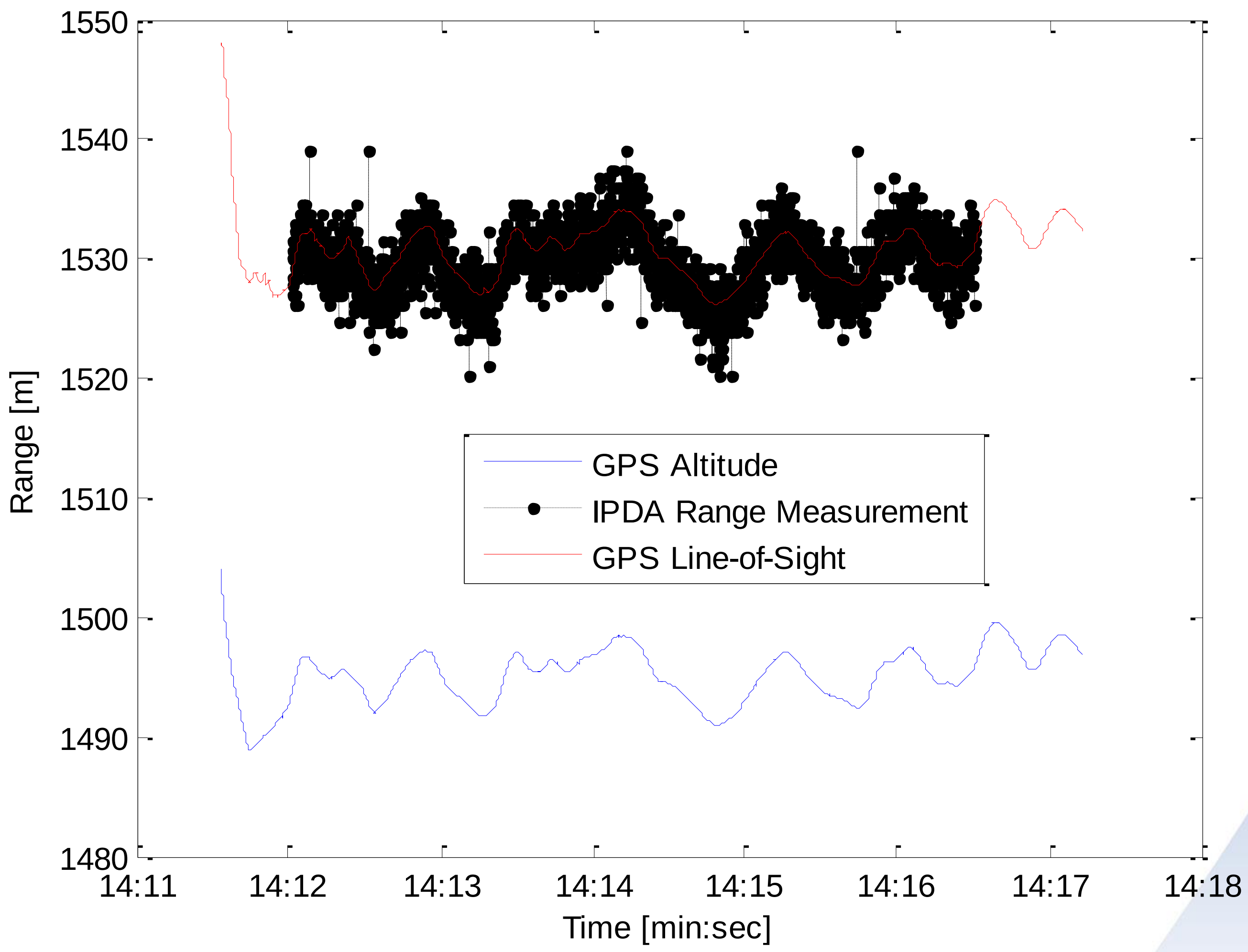



- Aircraft had temperature, pressure, humidity sensors, LiCor and GPS
- Some of the flights were supported by balloon launches

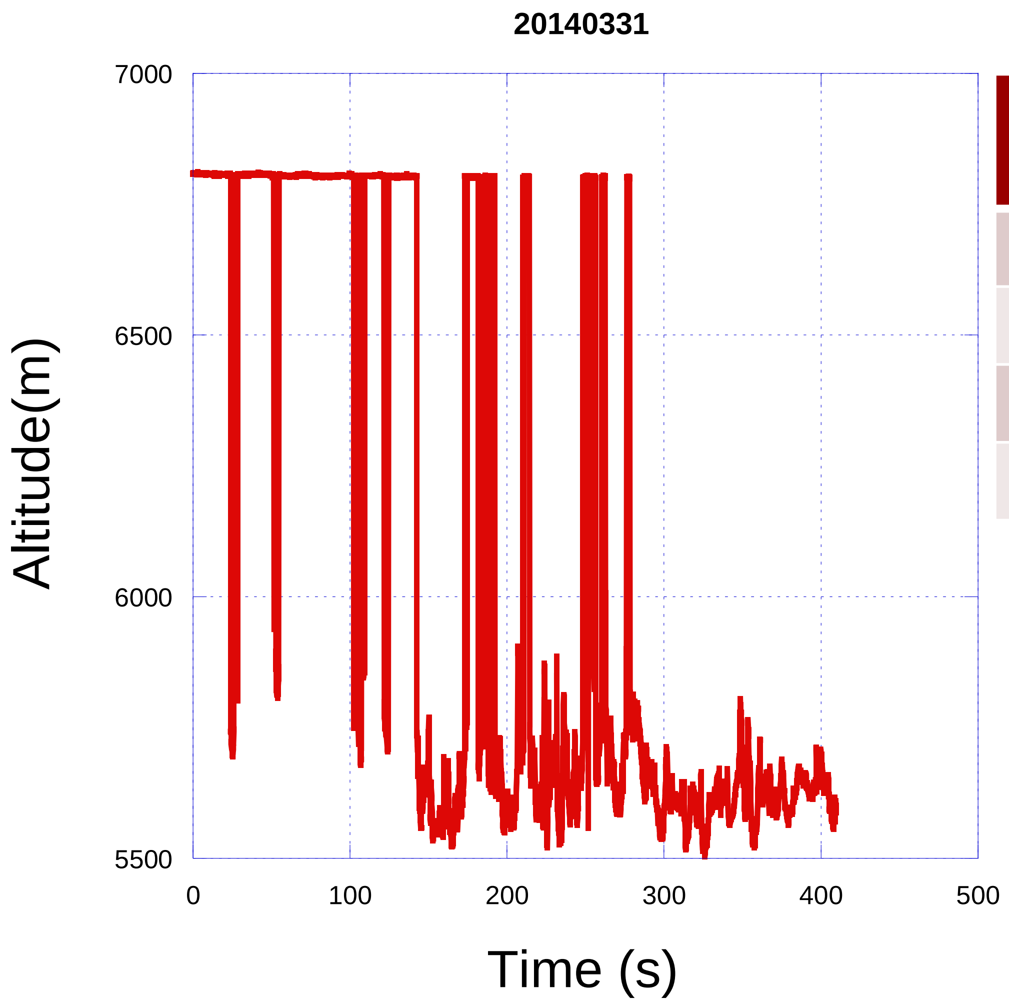
# IPDA Lidar Capability

- Ranging
- Cloud Slicing
- Signals at various ground condition
- DAOD
- Power Station
- Flight data comparison with NOAA flights which collects a flask at multiple altitudes to obtain vertical profile
- Lidar Sensitivity

# Ranging Capability

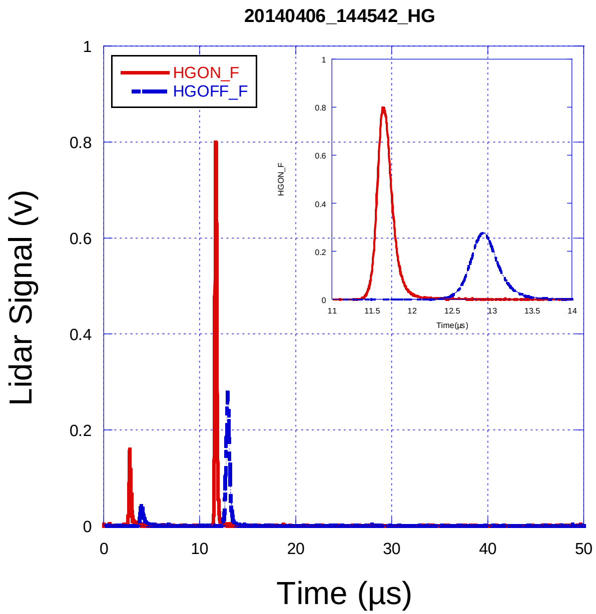


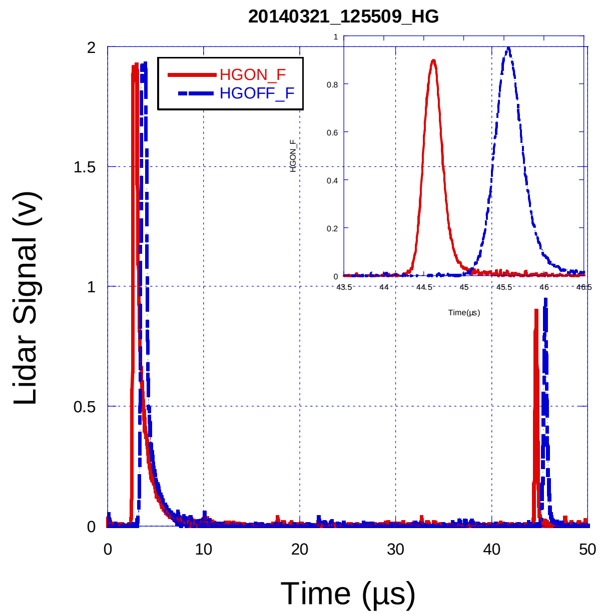
# Cloud Slicing




| | Alt. m | DAOD Lidar | DAOD Model | dDAOD |
|---|---|---|---|---|
| Ocean | 6805 | 1.072 | 1.094 | |
| Cloud | 5631 | 0.757 | 0.782 | |
| Lidar | | | | 0.315 |
| Model | | | | 0.312 |

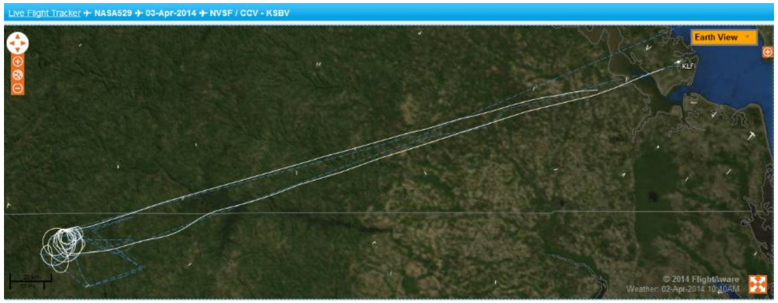
# IPDA Airborne Lidar: Sample Return Signals



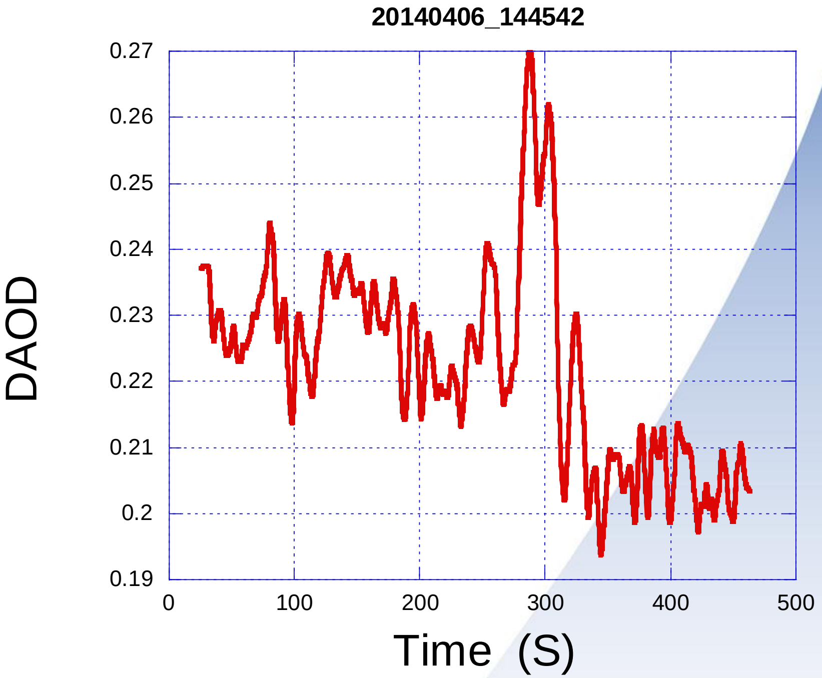




| | Lidar Signal | SNR (peak) | SNR (power) | DAOD Model | DAOD w/mon. |
|---|---|---|---|---|---|
| Veg/Soil | 1.89 | 398 | 485 | 1.0551 | 1.0550 |
| Sea | 0.552 | 111 | 139 | 1.0551 | 1.0883 |
| Cloud | 1.78 | 328 | 452 | 0.7805 | 0.757 |

# Power Station Roxboro

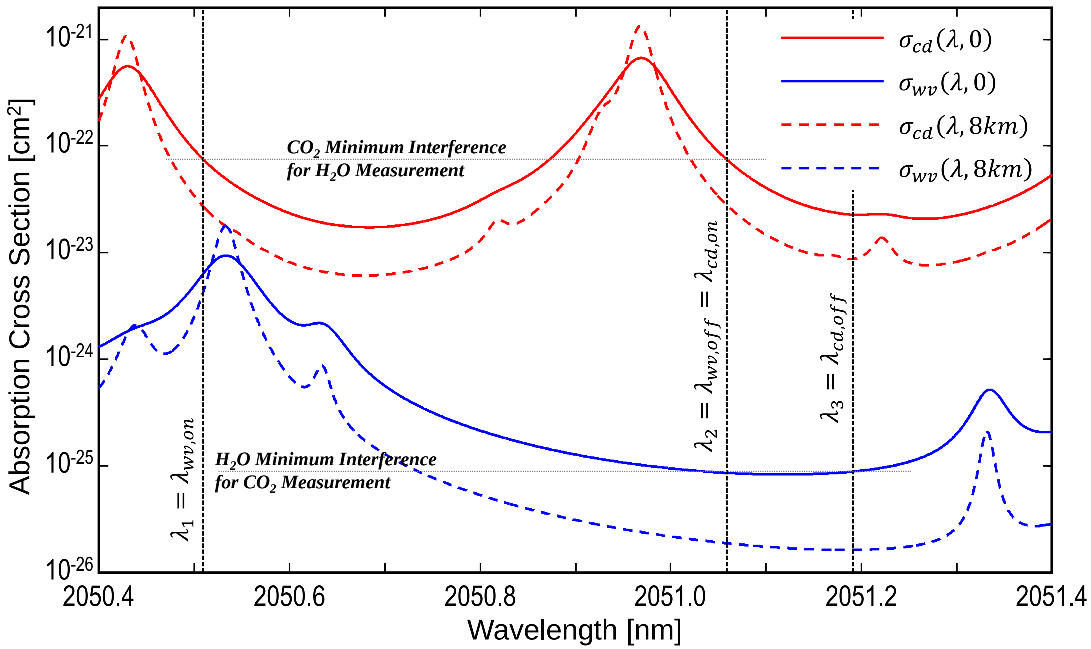







36° 28'52.79"N79° 04'08.97"W

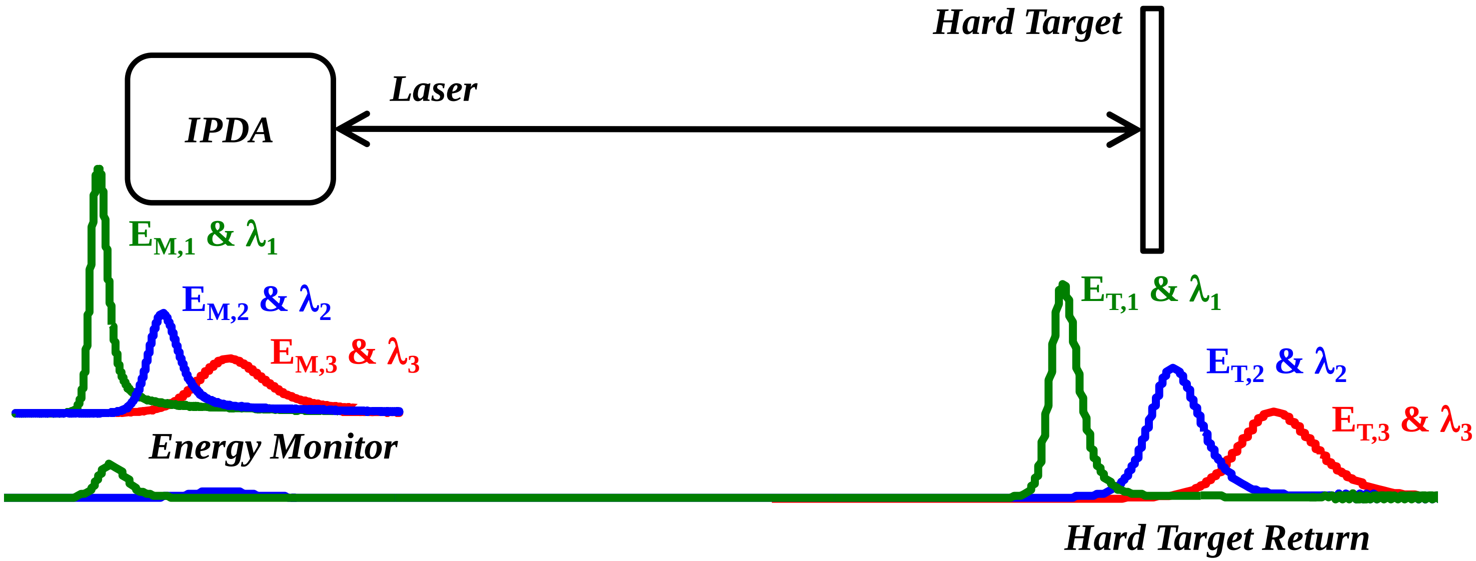
# Methodology




- With proper wavelength selection, independent $H_2O$ & $CO_2$ measurement is achieved

$$\begin{bmatrix} dOD_{1,2} \\ dOD_{2,3} \end{bmatrix} = \begin{bmatrix} ln\left(\dfrac{E_{T,2} \cdot E_{M,1}}{E_{M,2} \cdot E_{T,1}}\right) \\ ln\left(\dfrac{E_{T,3} \cdot E_{M,2}}{E_{M,3} \cdot E_{T,2}}\right) \end{bmatrix} = \begin{bmatrix} iWF_{wv}^{1,2} & 0 \\ 0 & iWF_{cd}^{2,3} \end{bmatrix} \cdot \begin{bmatrix} X_{wv} \\ X_{cd} \end{bmatrix}$$

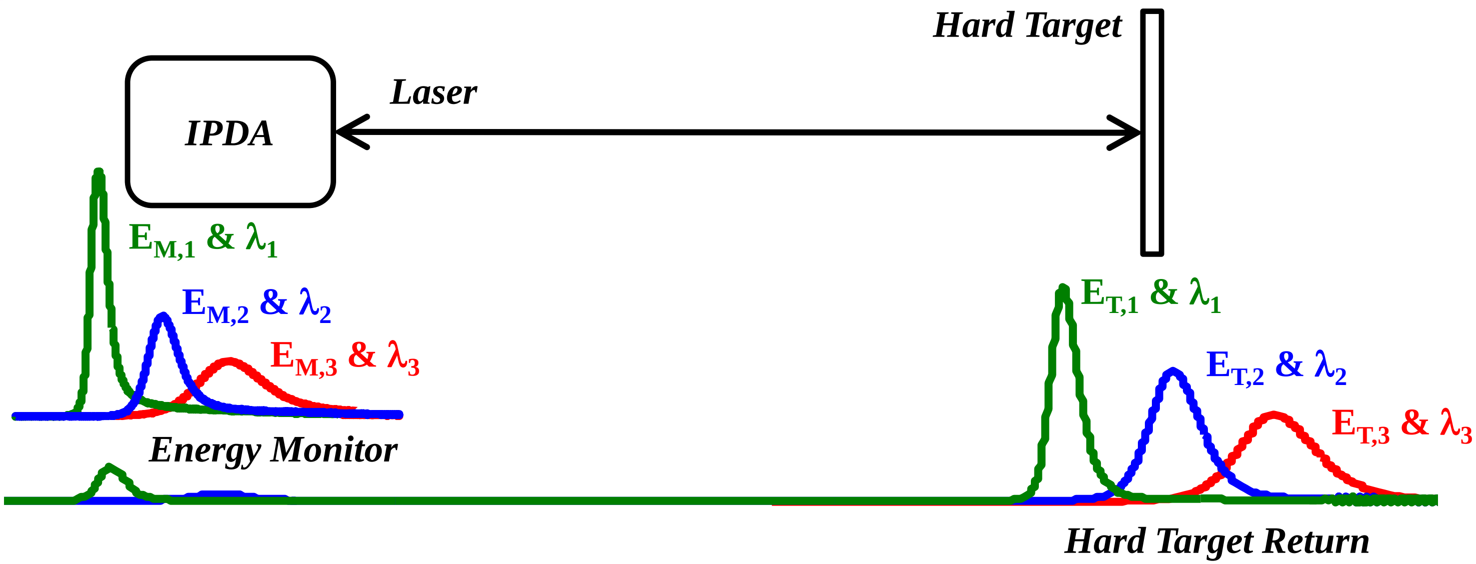
# Methodology




- IPDA lidar relies on the Hard Target Lidar Equation

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

# Methodology

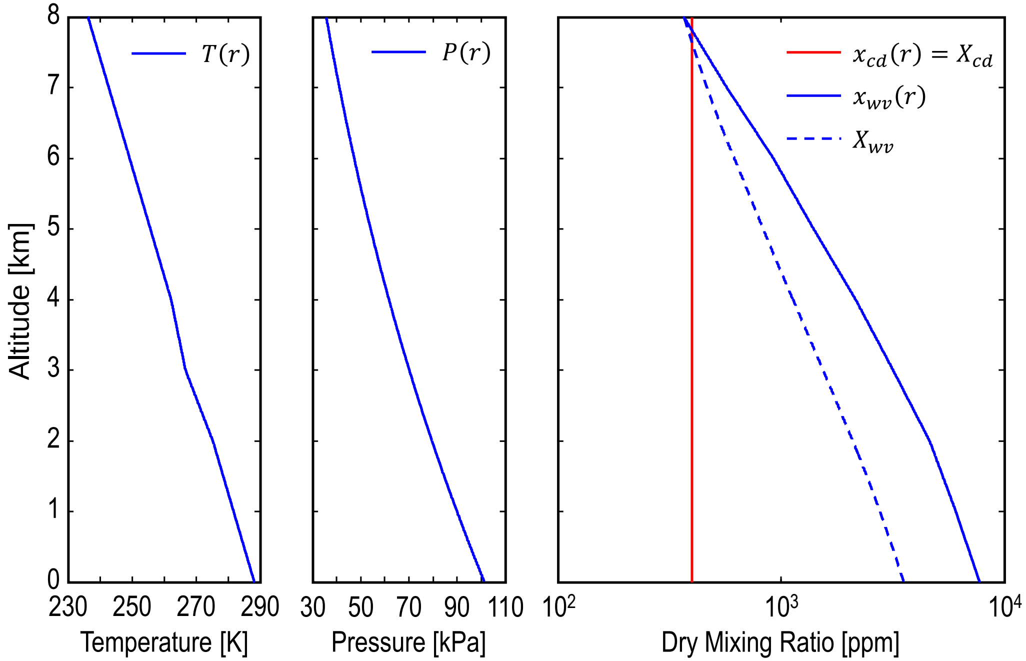



- Triple-pulse tuning defines $H_2O$ & $CO_2$ differential optical depth, the main IPDA product, simultaneously

$$dOD_{1,2} = \int_0^R 2 \cdot \left(\Delta\sigma_{wv}^{1,2} \cdot N_{wv} + \Delta\sigma_{cd}^{1,2} \cdot N_{cd}\right) \cdot dr = ln\left(\frac{E_{T,2} \cdot E_{M,1}}{E_{M,2} \cdot E_{T,1}}\right)$$

$$dOD_{2,3} = \int_0^R 2 \cdot \left(\Delta\sigma_{wv}^{2,3} \cdot N_{wv} + \Delta\sigma_{cd}^{2,3} \cdot N_{cd}\right) \cdot dr = ln\left(\frac{E_{T,3} \cdot E_{M,2}}{E_{M,3} \cdot E_{T,2}}\right)$$

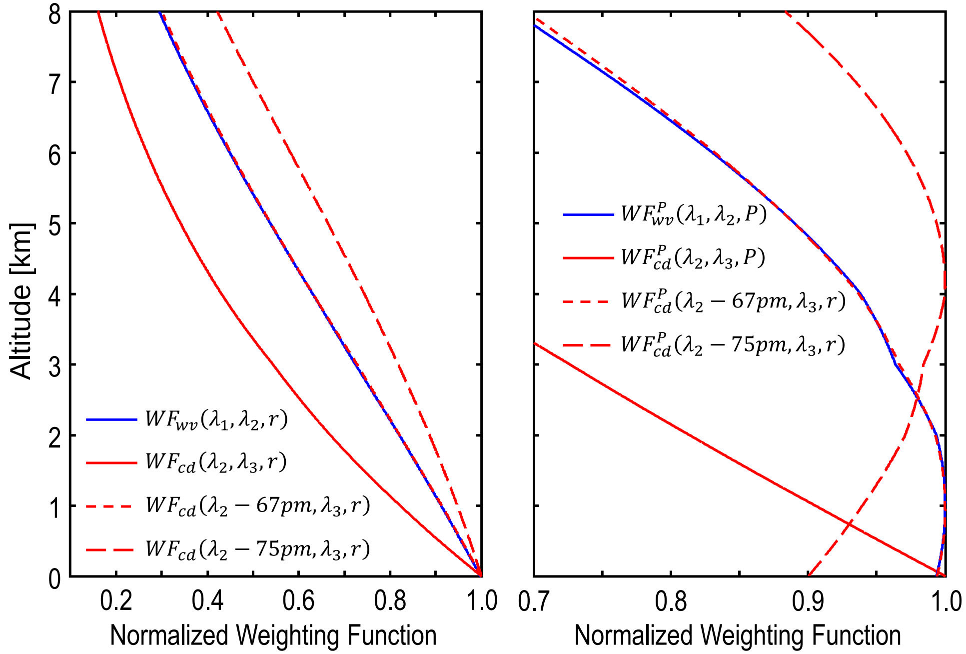
# Methodology




- $H_2O$ & $CO_2$ weighted-average column dry-air volume-mixing ratios can be determined, assuming proper definition of the weighting functions

$$\begin{bmatrix} dOD_{1,2} \\ dOD_{2,3} \end{bmatrix} = \begin{bmatrix} ln\left(\frac{E_{T,2} \cdot E_{M,1}}{E_{M,2} \cdot E_{T,1}}\right) \\ ln\left(\frac{E_{T,3} \cdot E_{M,2}}{E_{M,3} \cdot E_{T,2}}\right) \end{bmatrix} = \begin{bmatrix} iWF_{wv}^{1,2} & iWF_{cd}^{1,2} \\ iWF_{wv}^{2,3} & iWF_{cd}^{2,3} \end{bmatrix} \cdot \begin{bmatrix} X_{wv} \\ X_{cd} \end{bmatrix}$$

# Methodology




- With other wavelength selection, independent and simultaneous $CO_2$ measurement is achieved using two different weighting functions

$$\begin{bmatrix} dOD_{1,2} \\ dOD_{2,3} \end{bmatrix} = \begin{bmatrix} ln\left(\frac{E_{T,2}\cdot E_{M,1}}{E_{M,2}\cdot E_{T,1}}\right) \\ ln\left(\frac{E_{T,3}\cdot E_{M,2}}{E_{M,3}\cdot E_{T,2}}\right) \end{bmatrix} = \begin{bmatrix} 0 & iWF_{cd}^{1,2} \\ 0 & iWF_{cd}^{2,3} \end{bmatrix} \cdot \begin{bmatrix} X_{wv} \\ X_{cd} \end{bmatrix}$$

# Technology Requirement

| | | | |
|---|---|---|---|
| Transmitter | Wavelength | Energy | Pulse Width |
| | $\lambda_1$=2050.5094 nm | 50 mJ | 30 nsec |
| | $\lambda_2$=2051.0590 nm | 15 mJ | 60 nsec |
| | $\lambda_3$=2051.1915 nm | 5 mJ | 100 nsec |
| | Repetition Rate | | 50 Hz |
| | Beam Quality | | 2.0 ($M^2$) |
| | Bean Divergence | | 150 µrad |
| | Laser Line-Width | | *Transform Limited* |
| | Frequency Control Accuracy | | < 1 MHz |
| | Spectral Purity | | 99.9% |
| | Wall-Plug Efficiency | | 2% |
| | Beam Expansion | | x10 |
| Receiver | Optical Efficiency | | 65% |
| | Telescope Diameter | | 40 cm |
| | Optical Filter Spectral Width | | 1.6 nm |
| | Field-of-View | | 300 µrad |
| Detector [a)] | Operating Temperature | | -20°C |
| | Bias Voltage | | 300 mV |
| | Quantum Efficiency | | 67.75% |
| | Dark Current | | 3.7 nA |
| | Capacitance | | 29.3 pF |
| TIA [b)] | Gain | | $10^6$ V/A |
| | Bandwidth | | 3.5 MHz |
| | Noise Current Spectral Density | | 450 fA/$Hz^{1/2}$ |
| | Noise Voltage Spectral Density | | 2.8 nV/$Hz^{1/2}$ |
| Env. | Background Solar Irradiance | | 0.5 mW/$m^2$.nm.sr |
| | Surface Reflectivity (vegi/ocean) | | 0.09/0.08 |
| | Aircraft Speed | | 100 m/s |

a) InGaAs pin, Hamamatsu Inc., G5853-203. b) FEMTO, DHPCA-100

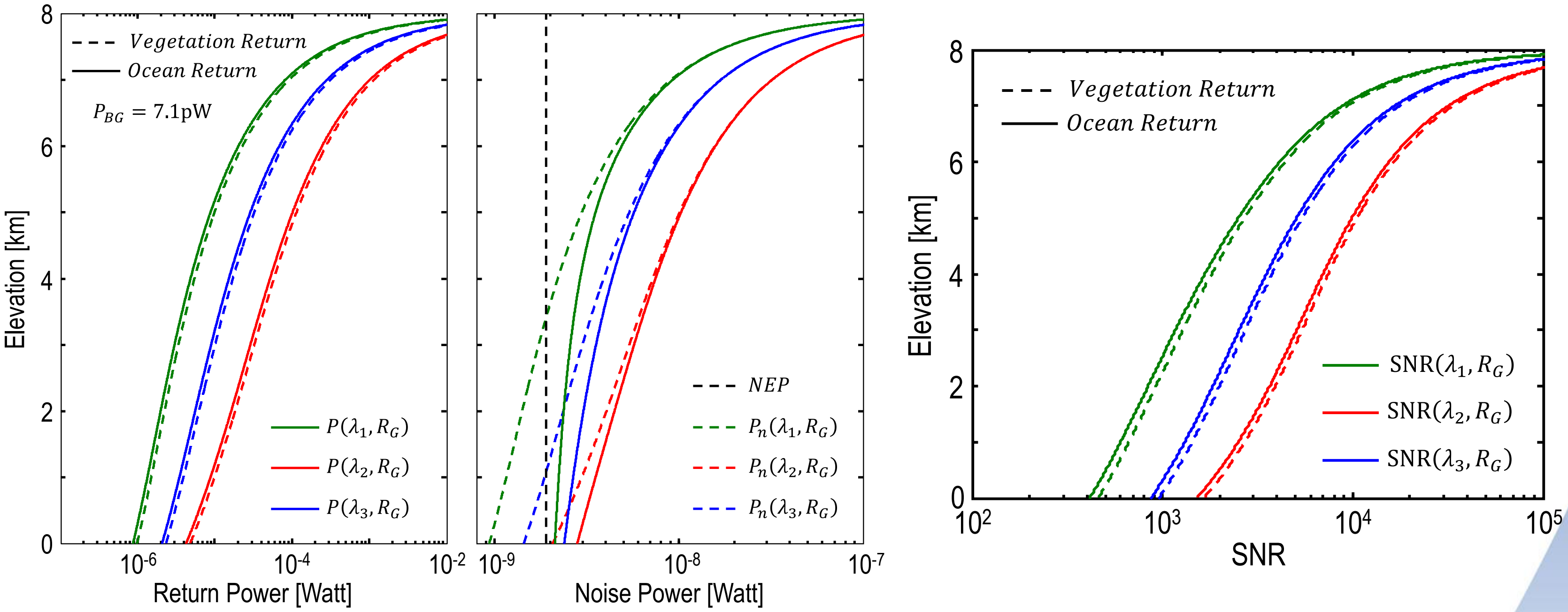
New Technology

- 2-µm triple-pulse laser
- Individual pulse switching, tuning and locking
- Sufficient pulse energy
- High repetition rate for averaging
- Better detection and proper characterization

Repurposed Technology

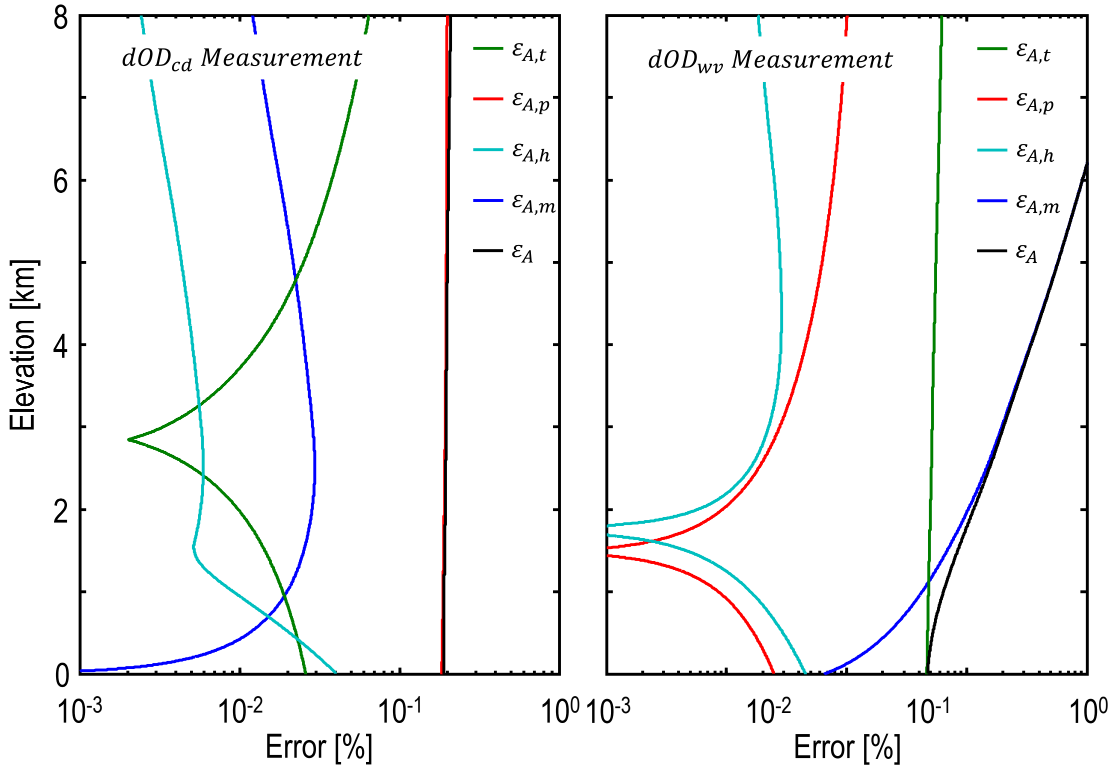
- Receiver telescope and optics
- Updated operational software
- Updated analysis algorithms
- Testing facilities

# IPDA Lidar Performance




- Triple-pulse $H_2O$ & $CO_2$ IPDA lidar modeling assuming airborne operation from 8km altitude
- Focus on return signal simulation and estimates on dominant error sources

# Error Budget

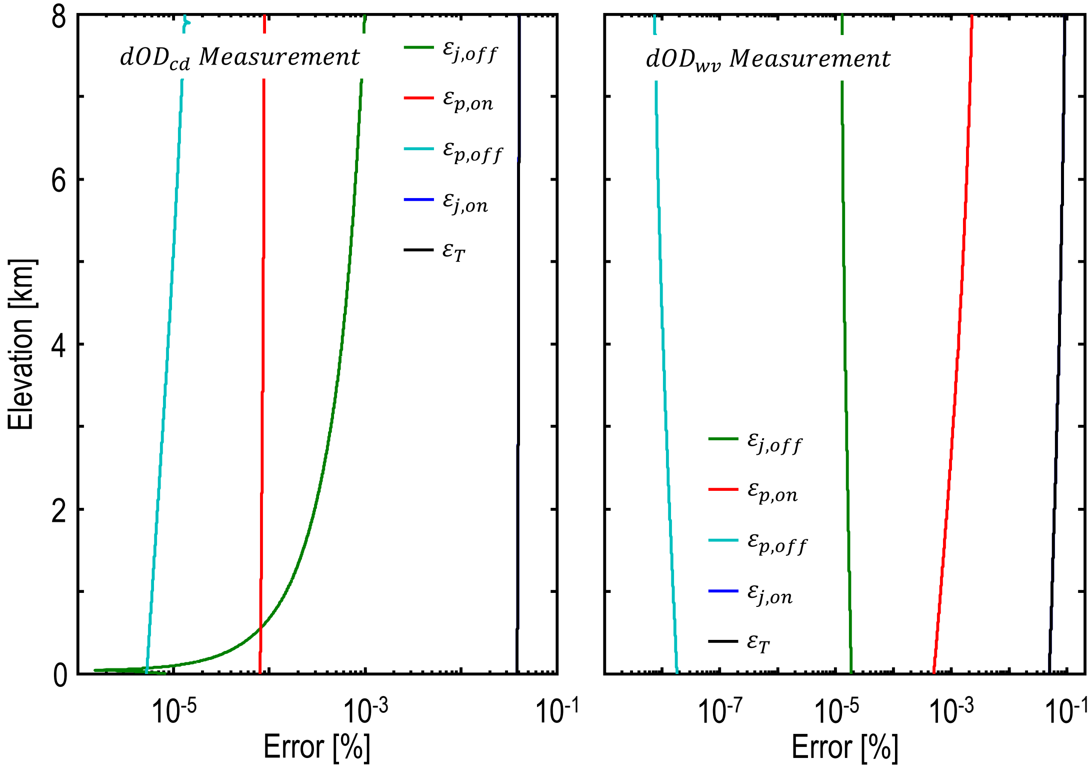



- Atmospheric systematic error, $\boldsymbol{\varepsilon_A}$, include

  Molecular interference, $\boldsymbol{\varepsilon_{A,m}}$
  
  Temperature uncertainty, $\boldsymbol{\varepsilon_{A,t}}$
  
  Pressure uncertainty, $\boldsymbol{\varepsilon_{A,p}}$
  
  Relative humidity uncertainty, $\boldsymbol{\varepsilon_{A,h}}$

$$\boldsymbol{\varepsilon_A = \sqrt{\varepsilon_{A,t}^2 + \varepsilon_{A,p}^2 + \varepsilon_{A,h}^2 + \varepsilon_{A,m}^2}}$$

# Error Budget



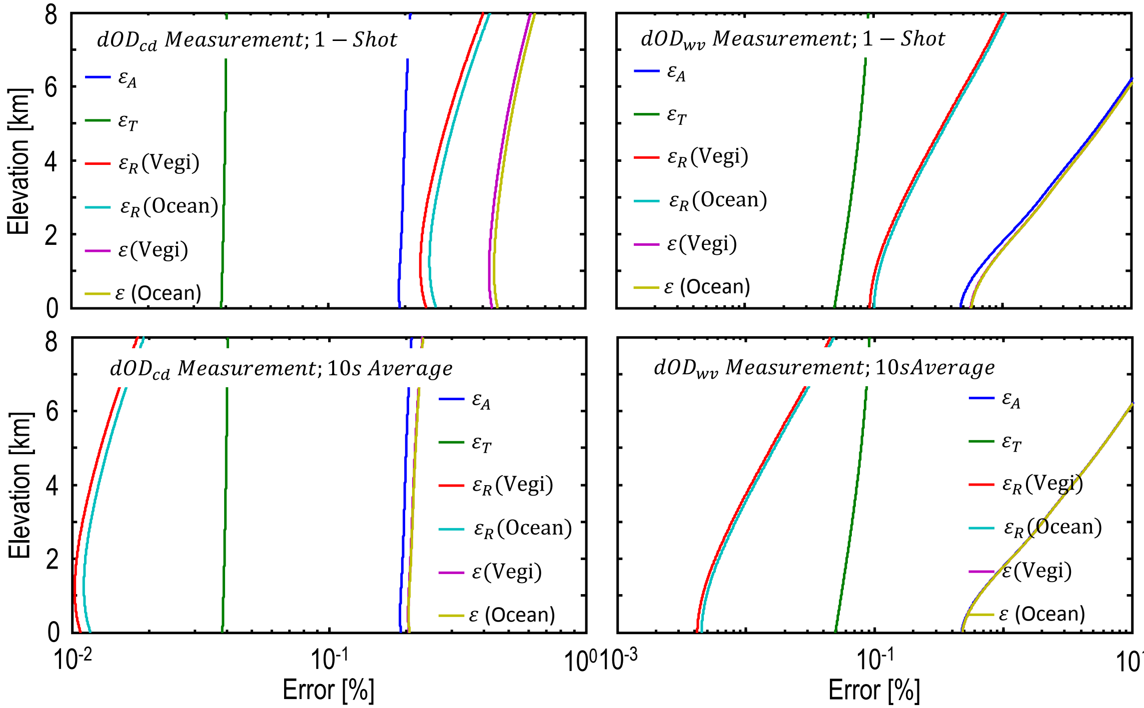

- Transmitter systematic error, $\boldsymbol{\varepsilon_T}$, include

$$\varepsilon_T = \sqrt{\varepsilon_{j,on}^2 + \varepsilon_{j,off}^2 + \varepsilon_{p,on}^2 + \varepsilon_{p,off}^2}$$

On- and off-line jitters, $\boldsymbol{\varepsilon_{j,on}}$ and $\boldsymbol{\varepsilon_{j,off}}$

On- and off-line laser line width, $\boldsymbol{\varepsilon_{p,on}}$ and $\boldsymbol{\varepsilon_{p,off}}$

# Error Budget




$$\varepsilon = \frac{\delta[dOD]}{dOD} = \varepsilon_R/\sqrt{s} + \sqrt{\varepsilon_A^2 + \varepsilon_T^2}$$

- Random error, $\varepsilon_R$, include all fixed and signal-dependent noise sources
- Triple-pulse IPDA lidar simulation resulted in 0.5% and 0.2% differential optical depth errors with 10 s average assuming 8 km flight altitude for water vapor and carbon dioxide, respectively.

# Summary (Double Pulsed Lidar)

- Developed a 2-μm double-pulsed laser transmitter and IPDA lidar system for $CO_2$ measurement
- Completed simulation and modeling of the 2-μm IPDA lidar instrument projected performance and science data retrieval algorithms
- Successful airborne IPDA lidar operation demonstrating robust integration and reliability
- Demonstrated airborne IPDA return signals obtained through different weighting functions and ground conditions, including soil, vegetation, ocean, sand and snow, beside cloud slicing capability all with high single-shot signal-to-noise ratio exceeding 100
- Airborne off-off-line testing applied to quantify both systematic (bias) and random (sensitivity) errors
- Bias and sensitivity verified through DAOD measurement
- Analysis of water vapor interference on $CO_2$ measurement indicated minimal error contribution due to precise selection, tuning and locking of the selected operational wavelengths.

# Summary (Triple Pulsed Lidar)

- Feasibility of 2-μm triple-pulse IPDA lidar for simultaneous and independent $X_{cd}$ and $X_{wv}$ measurements from an airborne platform was analyzed.
- Unique capabilities include weighting the measurements toward the surface, the ABL or the free troposphere.
- Study is based on the planned development of the 2.0-μm triple-pulse laser technology, with independent tuning and locking at three different wavelengths.
- Integrated receiver and detection system developed at NASA LaRC is assumed in the analysis.
- Availability of mobile lidar laboratory at NASA LaRC provides instrument testing, characterization and evaluation, beside future field deployments.
- $X_{wv}$ & $X_{cd}$ IPDA instrument simulation resulted in 0.5% and 0.2% differential optical depth errors with 10 s average assuming 8 km flight altitude for water vapor and carbon dioxide, respectively.
- Development of a new remote sensing capability for investigating the distributions and variability of atmospheric $H_2O$ and $CO_2$ will enable a better understanding of the carbon and water cycles of the ecosystems.