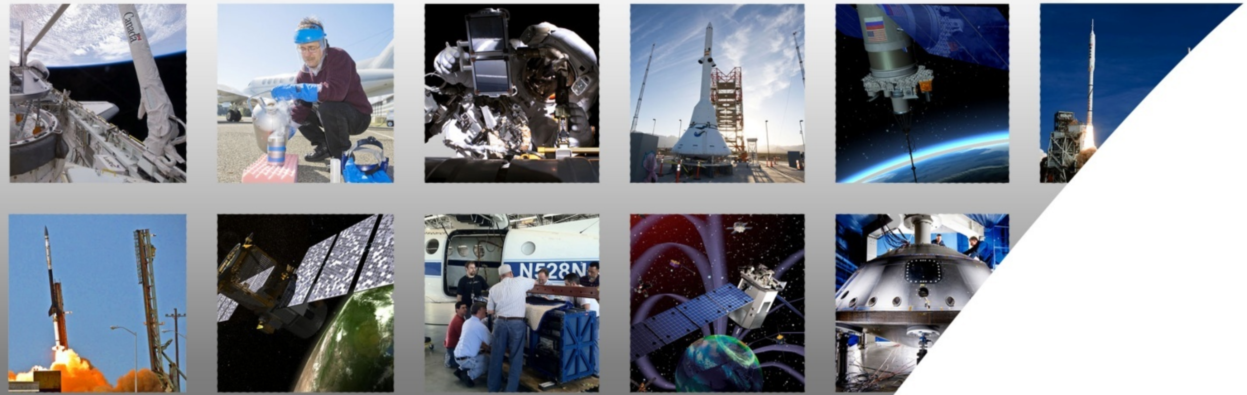
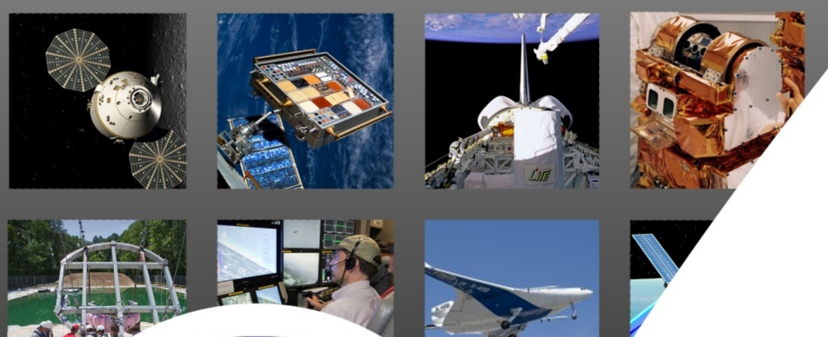




National Aeronautics and
Space Administration

Development of Double and Tripled-Pulsed 2-micron IPDA Lidars for Column CO_2 Measurement

Upendra N. Singh*, Tamer F. Refaat, Mulugeta Petros, and Jirong Yu
NASA Langley Research Center

Earth Science Technology Forum
June 24, 2015

California Institute of Technology, Pasadena, California

Acknowledgement: Research and development supported by NASA Earth Science Technology Office (ESTO)

➢ Objectives

Demonstrate CO_2 measurement capability using 2-μm double-pulse IPDA lidar.

Extend measurement capability to include H_2O using 2-μm triple-pulse IPDA lidar.

Outline

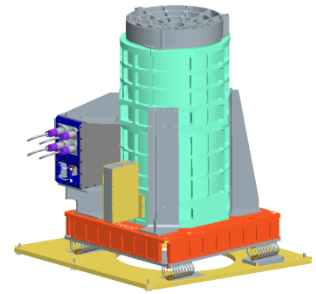
- CO_2 Double-Pulse 2-μm IPDA Lidar
  - Methodology
  - Spectroscopy
  - Instrument and Integration
  - IPDA Ground Testing
  - IPDA Airborne Testing
- CO_2 and H_2O Triple-Pulse 2-μm IPDA Lidar
  - Methodology
  - System Design
  - Specifications

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

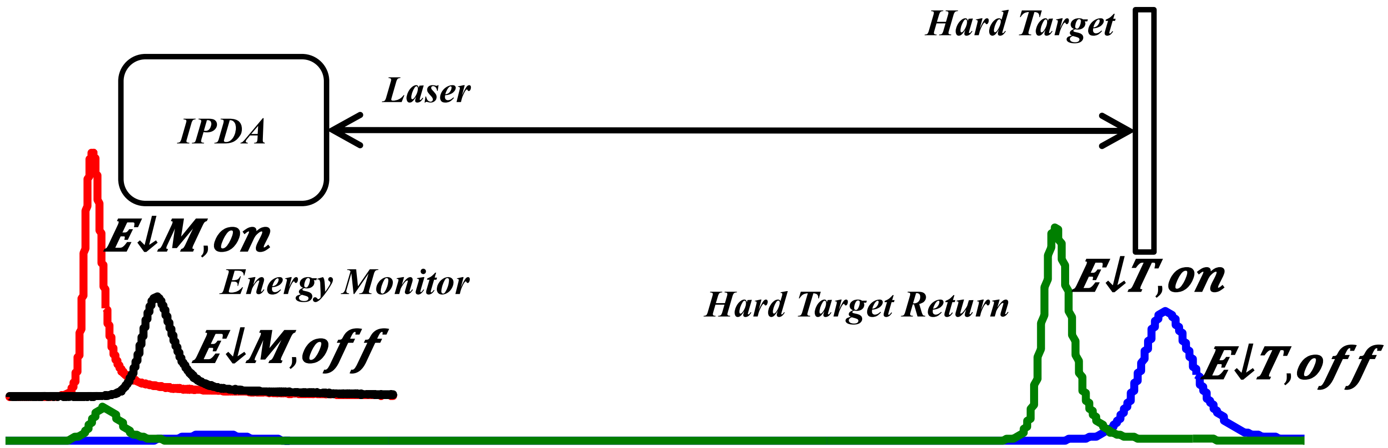
Co-Is/Partners: Jirong Yu, Mulugeta Petros, Syed Ismail, NASA LaRC

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)

Modeling: Methodology



- IPDA lidar relies on the Hard Target Lidar Equation

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

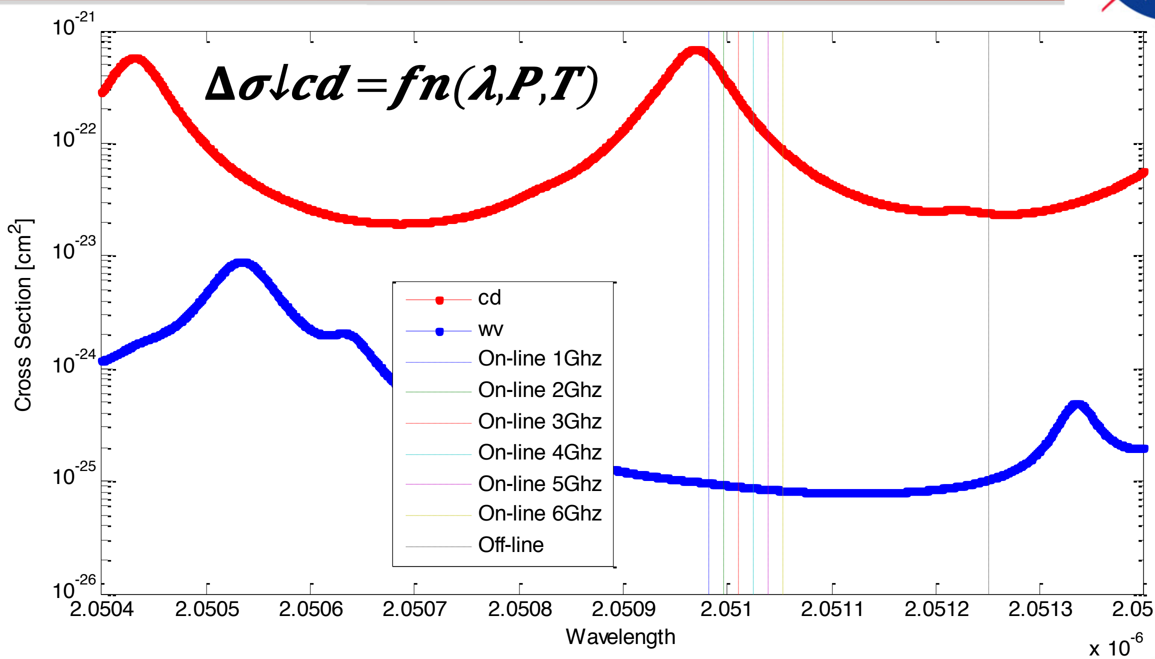
- Double-pulse tuning defines CO_2 differential optical depth, the main IPDA product

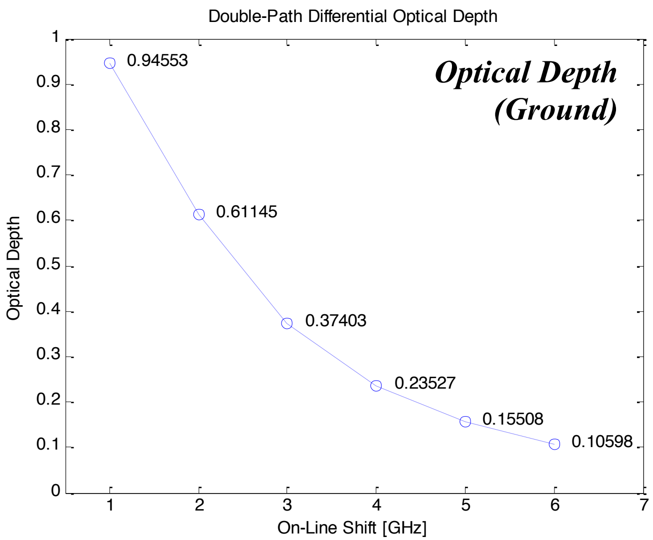
$$dOD_{cd} = \int_0^{R} 2 \cdot \Delta\sigma_{cd} \cdot N_{cd} \cdot dr \approx \ln(E_{T,off} \cdot E_{M,on} / E_{M,off} \cdot$$

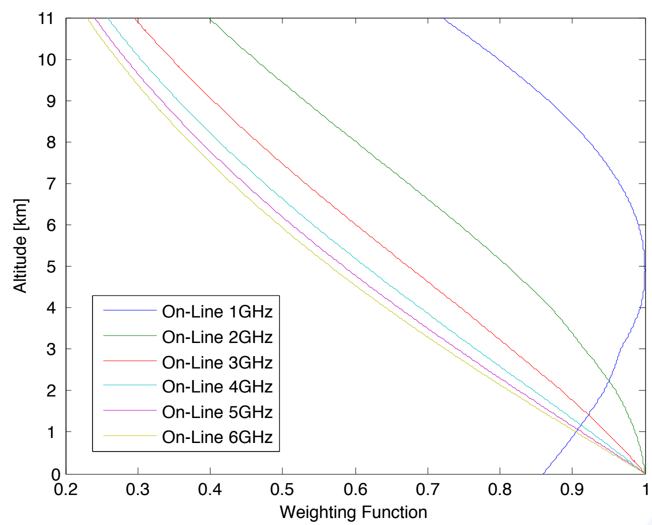
- Other IPDA products include ranging and surface reflectivity

Spectroscopy

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

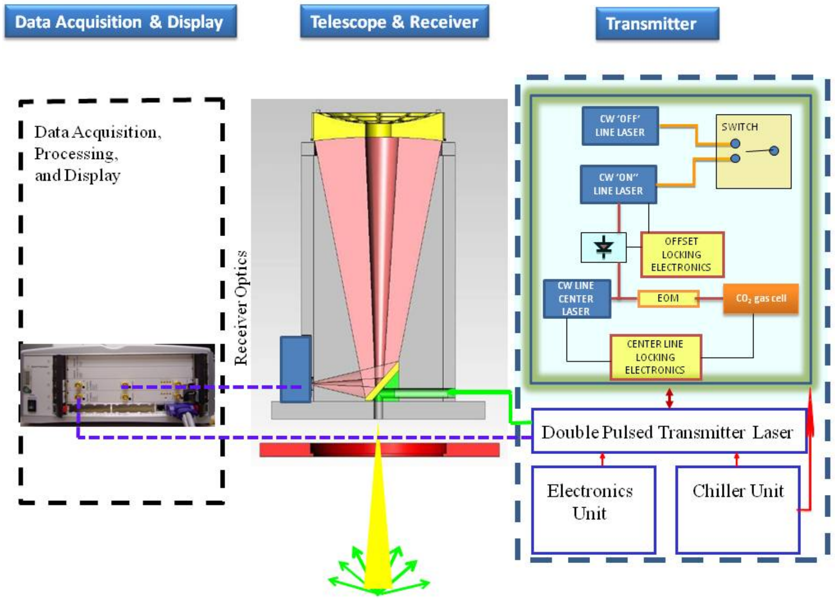




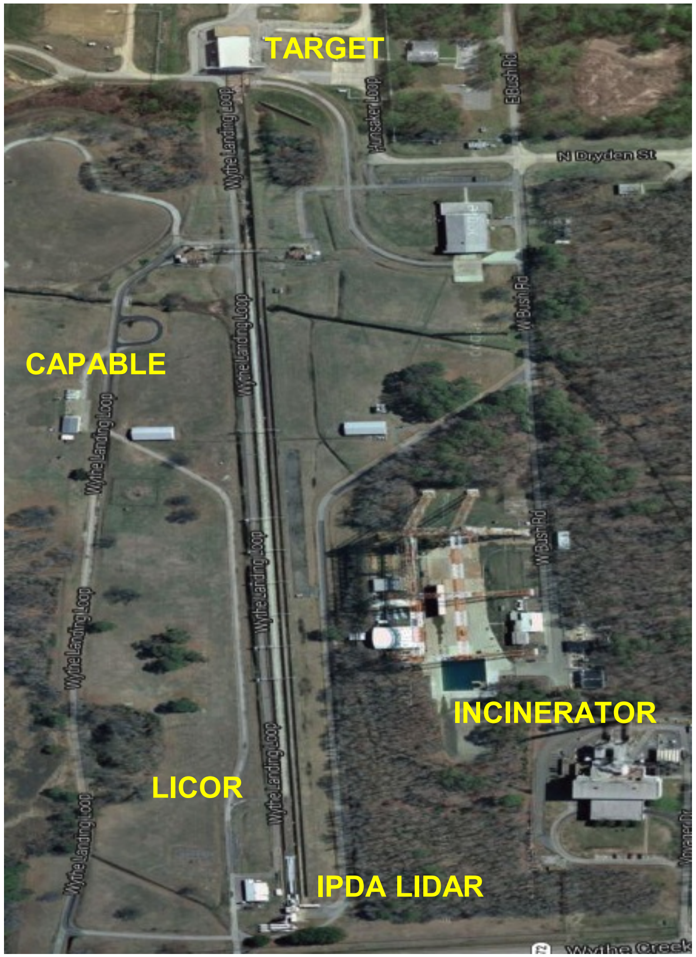


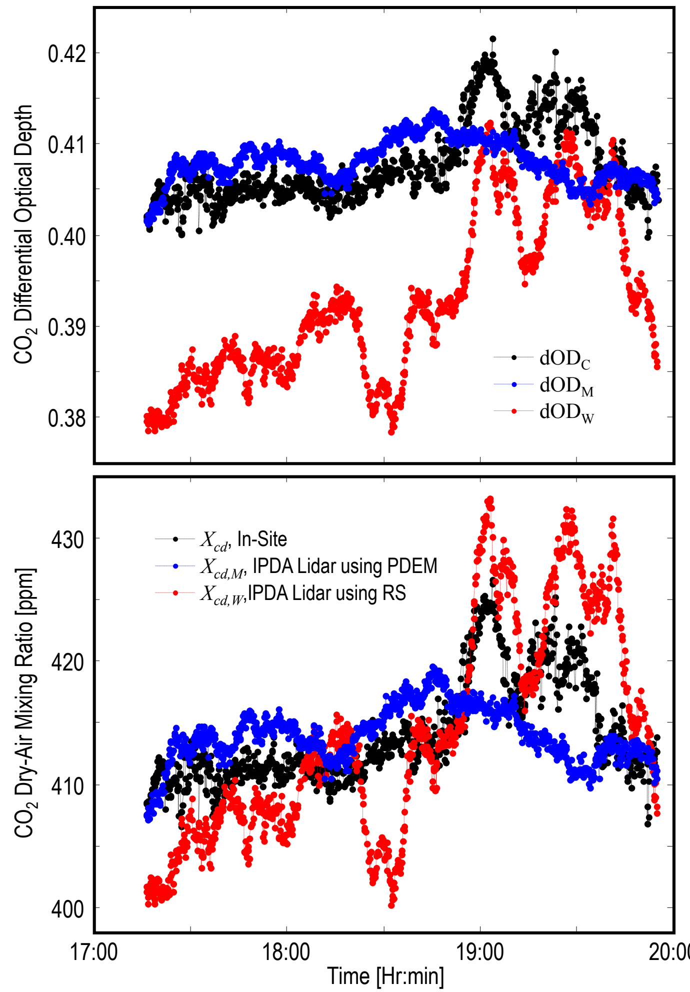
Pressure-Based Weighting-Functions (Airborne)

2-micron double pulsed IPDA lidar



IPDA Ground Testing: Setup & Measurement



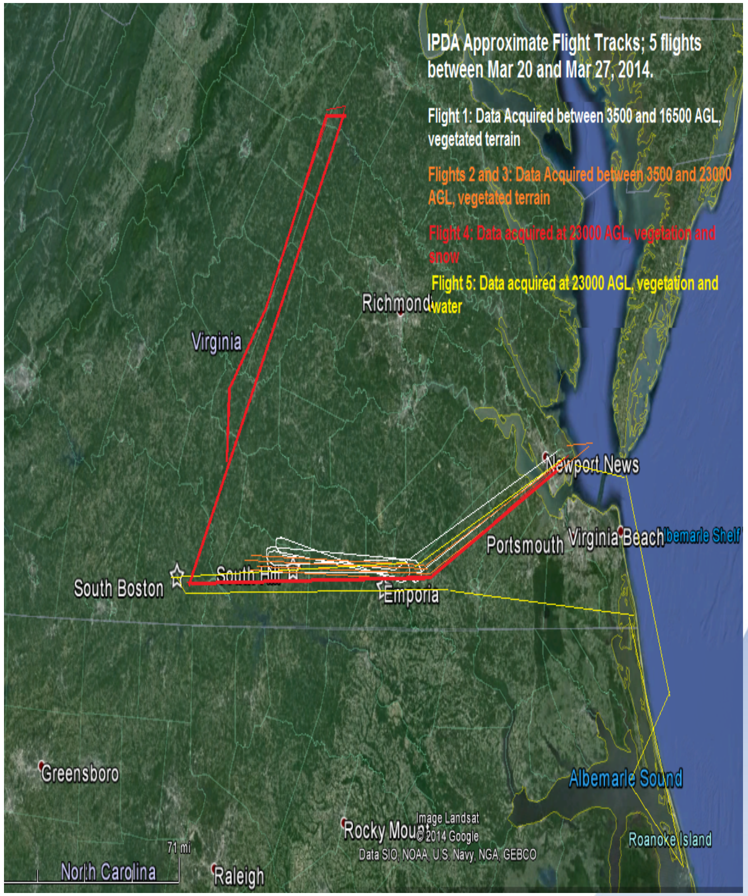


Differential optical depth–model and measurement

Dry mixing ratio IPDA vs (in-situ) measurement

10 Flights in March & April 2014

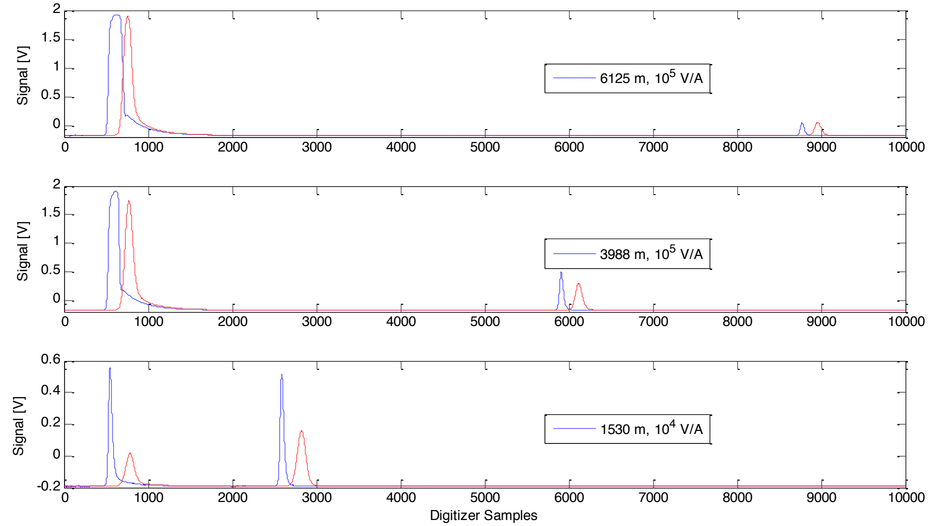
Date	Purpose	Duration	Location
March 20	Instrument Check Flight	2.1 hr	VA
March 21	Engineering	2.7 hr	VA
March 24	Engineering	3.0 hr	VA
March 27	Early morning	3.0 hr	VA
March 27	Mid-afternoon	2.5 hr	VA
March 31	Inland-Sea	2.5 hr	VA, NC
April 02	Power Station	2.4 hr	NC
April 05	With NOAA	3.7 hr	NJ
April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

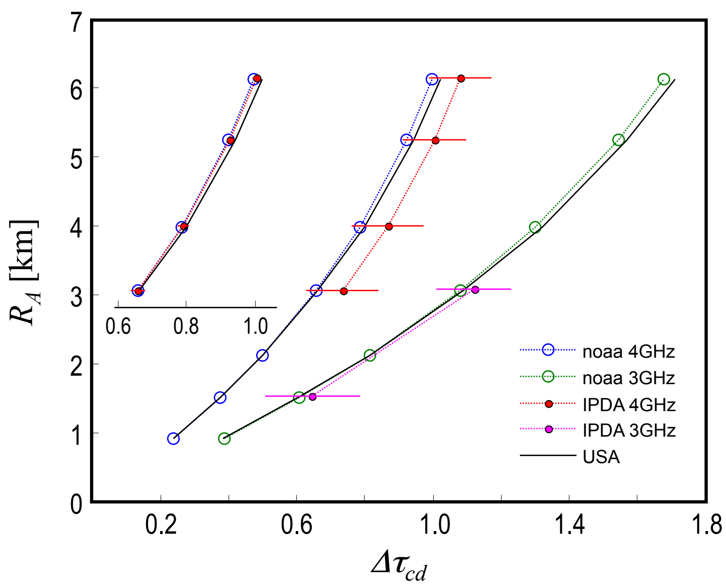


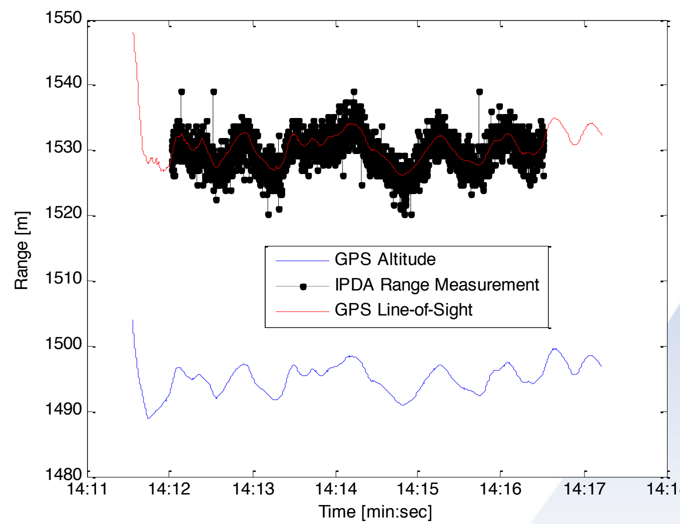
- Aircraft had temperature, pressure, humidity sensors, LiCor and GPS
- Some of the flights were supported by balloon launches

IPDA Airborne Testing: Sample Return Signals

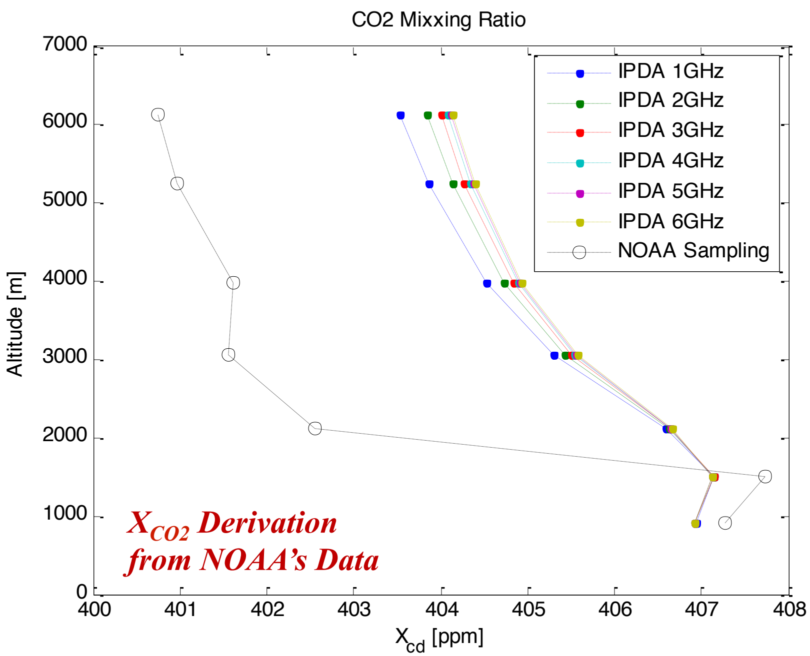
- NOAA air sampling and IPDA lidar optical depth comparison.
- Return signal samples from different altitudes up to 6km.
- IPDA range measurements compared to on-board GPS.







IPDA Airborne Testing: Sample Return Signals



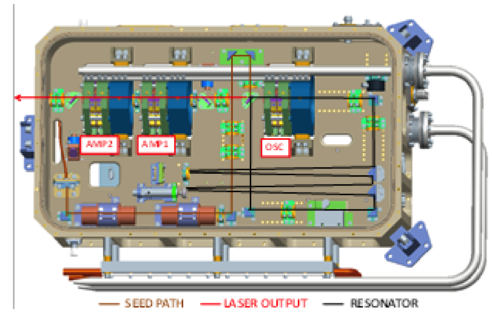
	NOAA Air Sampling	*NOAA Modeled X_{CO2}*	*IPDA Measured X_{CO2}*	*Sensitivity*	*Bias*	*Sensitivity %*	*Bias %*
R_A	x_{cd}	$X_{cd,c}$	$X_{cd,m}$	$\delta X_{cd,m}$	ΔX_{cd}	$\varepsilon_{cd,m}$	$\beta_{cd,m}$
m	ppm	ppm	ppm	ppm	ppm	%	%
6125.6	400.75	404.08	405.22	4.15	1.14	1.02	0.28
5242.6	400.96	404.34	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 ($\beta_{cd,m} = \Delta X_{cd}/X_{cd,m}$)

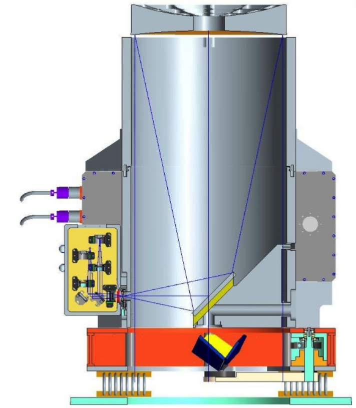
Triple-Pulsed 2-μm Direct Detection Airborne Lidar for Simultaneous and Independent CO_2 and H_2O Column Measurement

PI: Upendra Singh, NASA LaRC

- 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-μm 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-μm 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-μm laser packaging from ACT 11



Integrated 2-μm CO_2/H_2O Airborne packaged IPDA Lidar

- Team with industry to utilize extensive space-flight laser development expertise to build a unique triple-pulsed 2-μm 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.

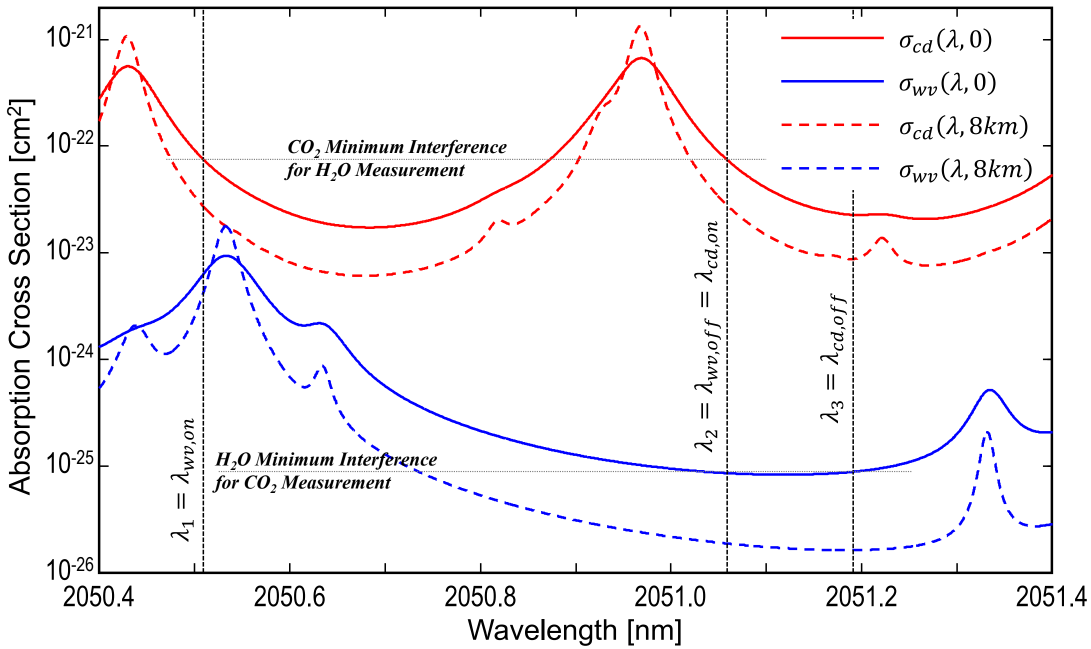
- Complete the preliminary triple pulse laser optical, mechanical, thermal and structure design and analysis — 12/14
- Complete laser wavelength control unit design — 2/15
  - Complete laser transmitter design, and mechanical lidar system design — 05/15
- Complete fabrication and testing of laser transmitter and wavelength control unit — 12/15
- Integrate laser transmitter with wavelength control unit — 04/16
- Complete lidar instrument integration, and ground test — 08/16

06/17

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

IIP-13-0048

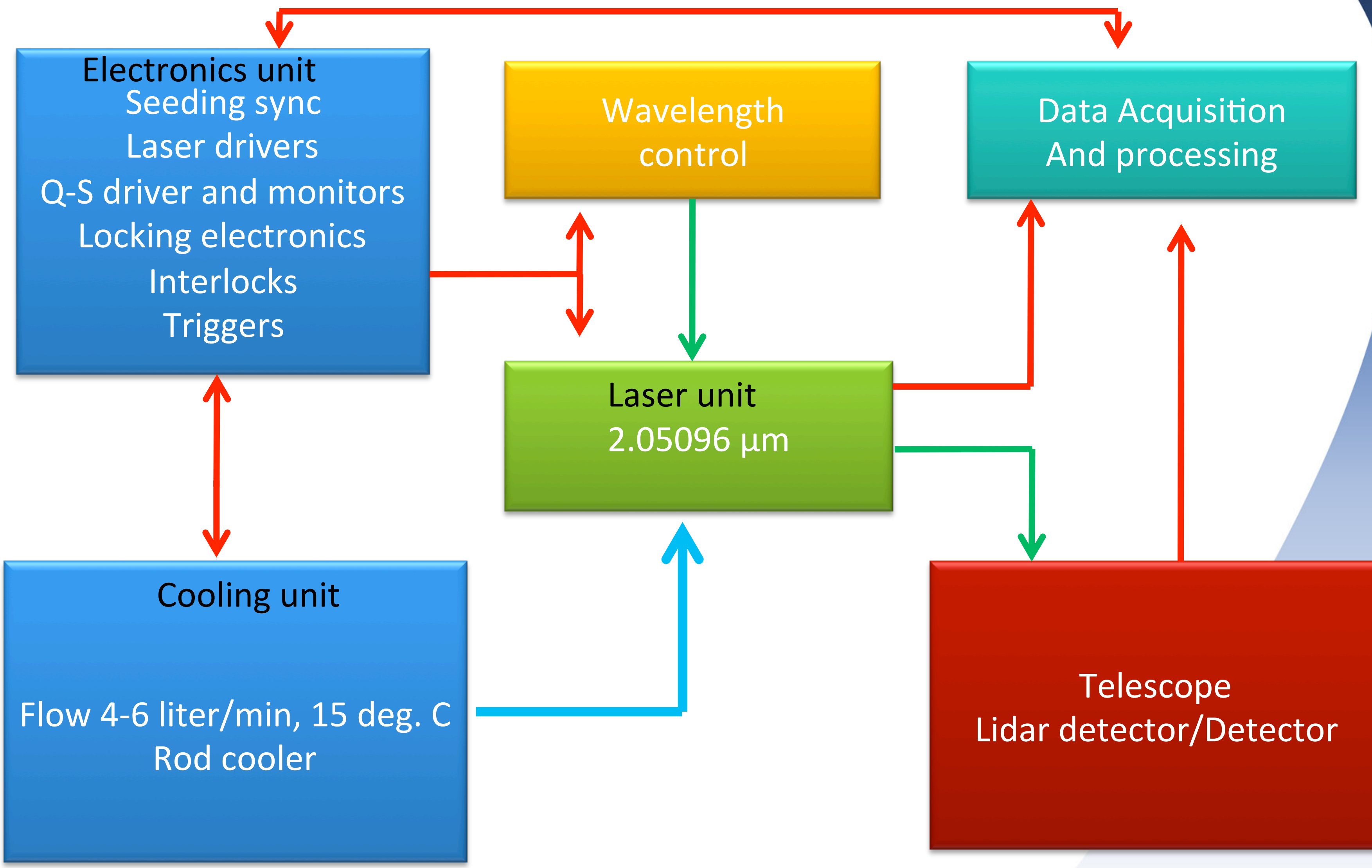
Methodology



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

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

System Block Diagram



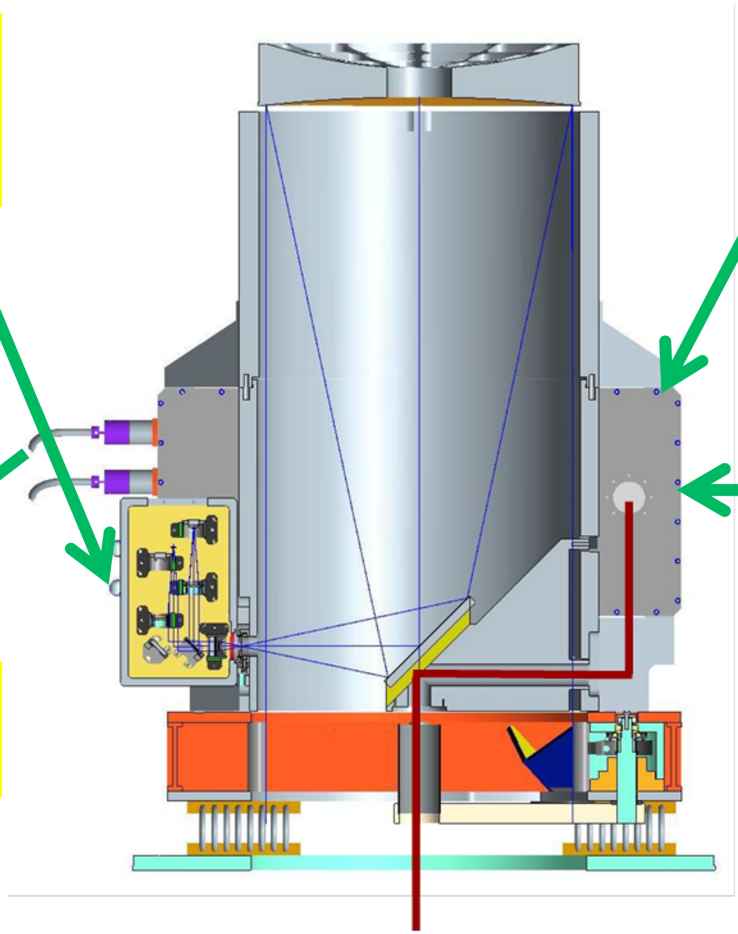
Key component development and integration to the existing IPDA lidar system

Interchangeable AFT optics and detector assembly

Upgraded digitizer and data acquisition system

Replace double-pulsed laser by triple-pulsed laser

Triple pulse locked wavelength seeding through new wavelength control and switching assembly



Laser Transmitter

OBJECTIVE: 50mJ,15mJ,5mJ triple pulsed output laser

- Laser transmitter design status:
  Crystal selection , concentration optimization, size optimization
- Crystal growth and fabrication –DONE

- Laser Resonator Design
- 0.5 meter long ring resonator with in an end-pump configuration

- The 792nm pump Beam has to match the 2μm beam size with a fixed divergence

- Optical layout and component placement configured.

Major constraints and Rationales:

Thermal Dissipation of high repetition rate of an end pump system

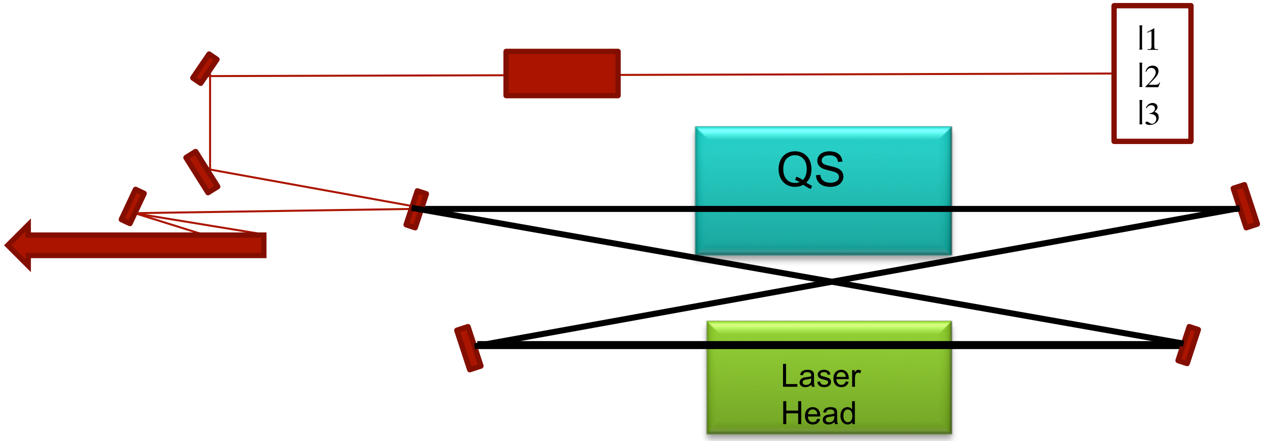
Large Q-Switch
Laser alignment immunity to vibration environment

The divergence has to match the 400 micron telescope field of view

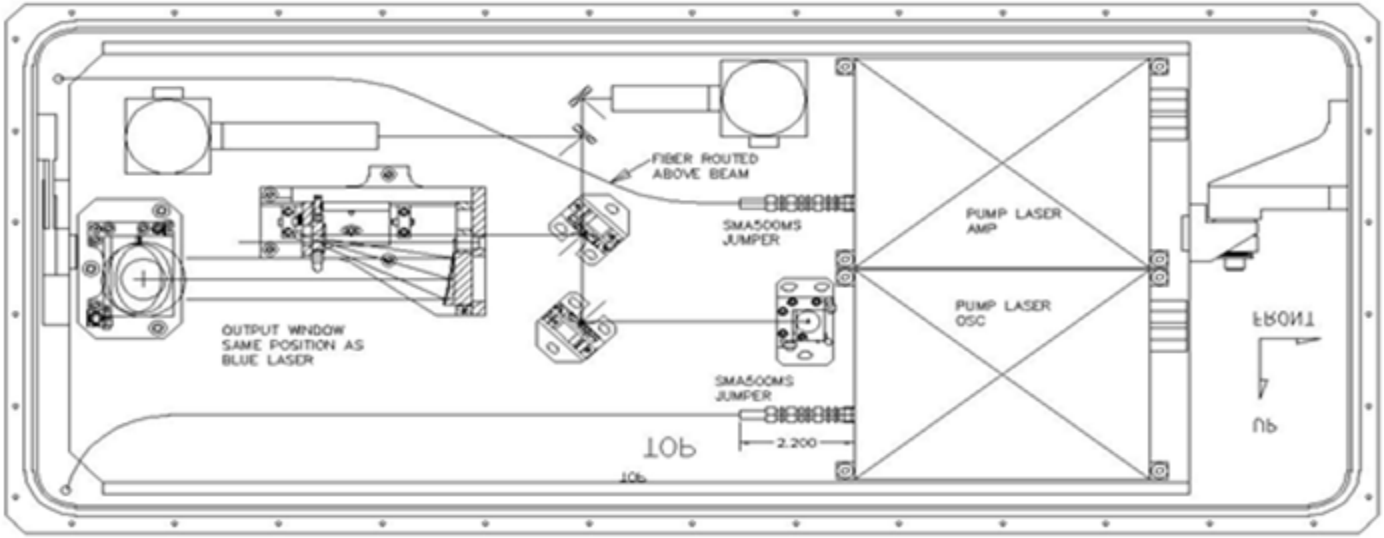
Optical bench and enclosure size to remain the same to match the overall lidar footprint and configuration

Transmitter Design

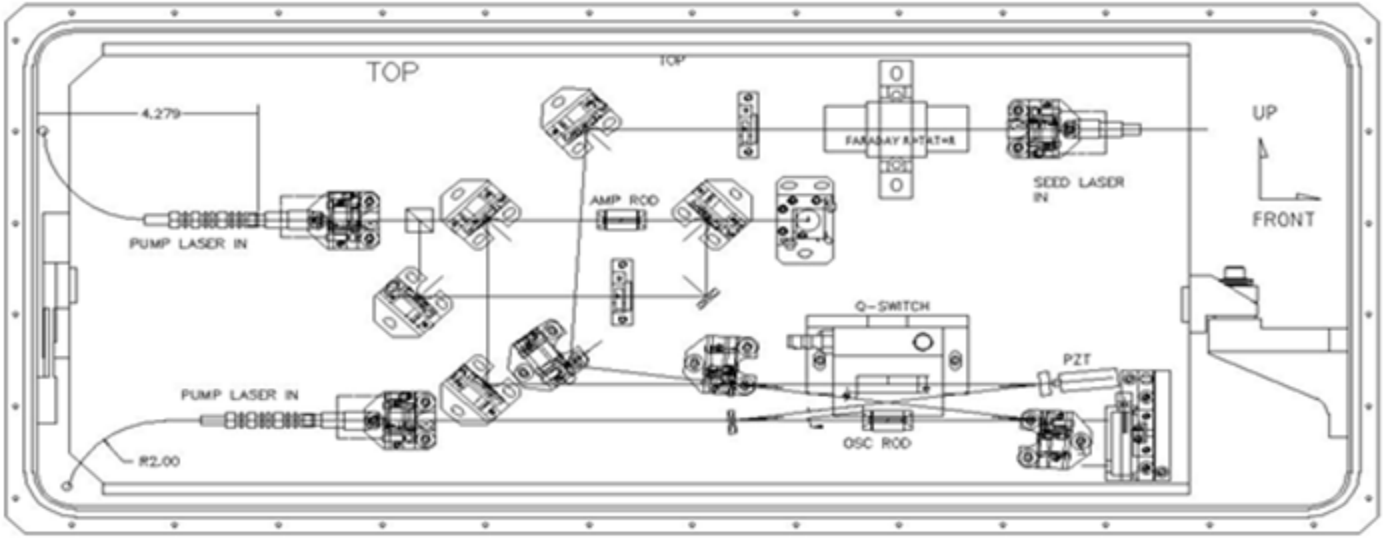
Item	Parameter	Rationale
Laser Enclosure	Blue laser 6”x26”x11”	compatibility
Laser Configuration	Oscillator + Amplifier	
Output Reflectivity	70%	
size	2x2x15	Heat extraction
Pump configuration	End pump	Higher efficiency



Laser transmitter layout



Back



Front

Wavelength control

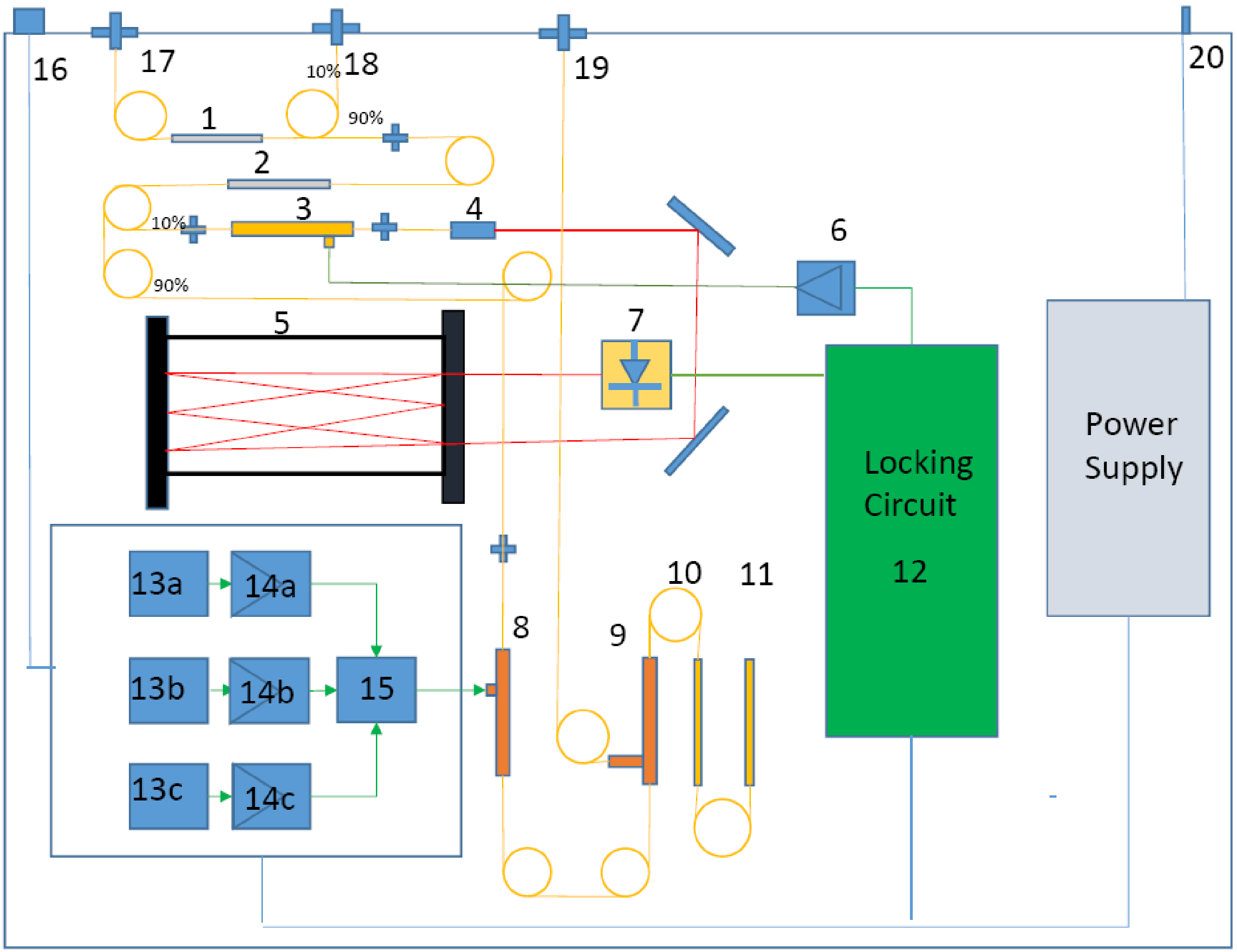
OBJECTIVE: Generate three distinct wavelengths, with respect to a CO_2 absorption center-line locked wavelength.

1. Characterize three different seed laser technologies, Solid-State laser, Fiber laser and Semi-conductor laser and compare the suitability for the system with respect to :

a) output power,
b) single frequency operation,
c) short/long term wavelength stability,
d) tuning range,
e) tuning speed,
f) CO_2 absorption center-line locking suitability
g) power consumption and
h) volume and weight.

2. The best laser will be locked to the CO_2 line
3. The three wavelengths will be generated as side band using Electro-optic modulators and fiber filters

Wavelength Control, Line Center Locking and Side Line Generation Layout



1,2 90/10 Fiber Splitter
3 200 MHz EO modulator
4 Fiber collimator
5 CO2 Cell
6 200 MHz RF Amplifier
7 Detector assembly
8 6-32GHz EO modulator
9 Fiber circulator
10,11 Fiber Filters
12 Online Locking circuit
13 RF Oscillators (6.5/16/32GHz)
14 RF Amps
15 RF switch
16 Switch Control (from LTC)
17 Seed laser input (fiber)
18 Seed laser monitor (fiber)
19 Seed laser output (fiber)
20 24V Power Input (from LTC)

System specifications

Transmitter	Wavelength	Energy	Pulse Width
	λ_1=2050.5094 nm	50 mJ	30 nsec
	λ_2=2051.0590 nm	15 mJ	60 nsec
	λ_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

Path to Space

	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).

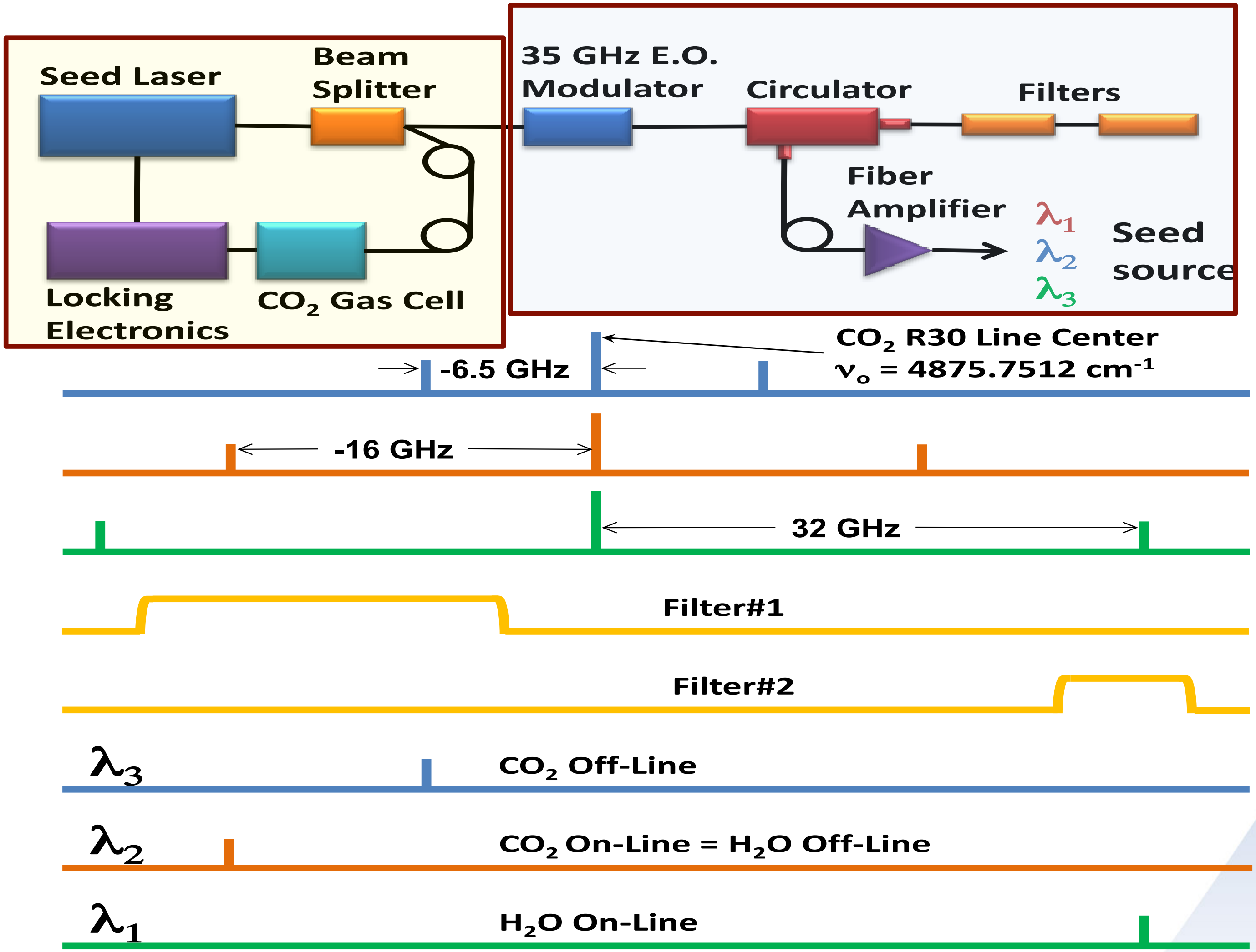
Conclusions

- CO_2 2-μm double-pulse IPDA lidar integration and validation at NASA LaRC
- Ground testing demonstrated successful CO_2 measurement as compared to in-situ sensors
- CO_2 airborne measurements agrees with validation models through NOAA air sampling
- IPDA lidar extended capabilities through triple-pulse operation, for simultaneous and independent CO_2 and H_2O measurement.
- Individual pulse wavelength tuning is achieved through advanced wavelength control unit
- LaRC is collaborating with NASA GSFC in developing AFT optics assembly and an advanced HgCdTe e-APD detector system for 2-micron IPDA lidar
- LaRC is also collaborating with JPL in incorporating and integrating a semiconductor seed laser in the wavelength control unit for triple-pulse seeding and switching
- Once realized, triple-pulse IPDA lidar will meet or exceeds current space requirement set by ESA, projected in A-SCOPE.

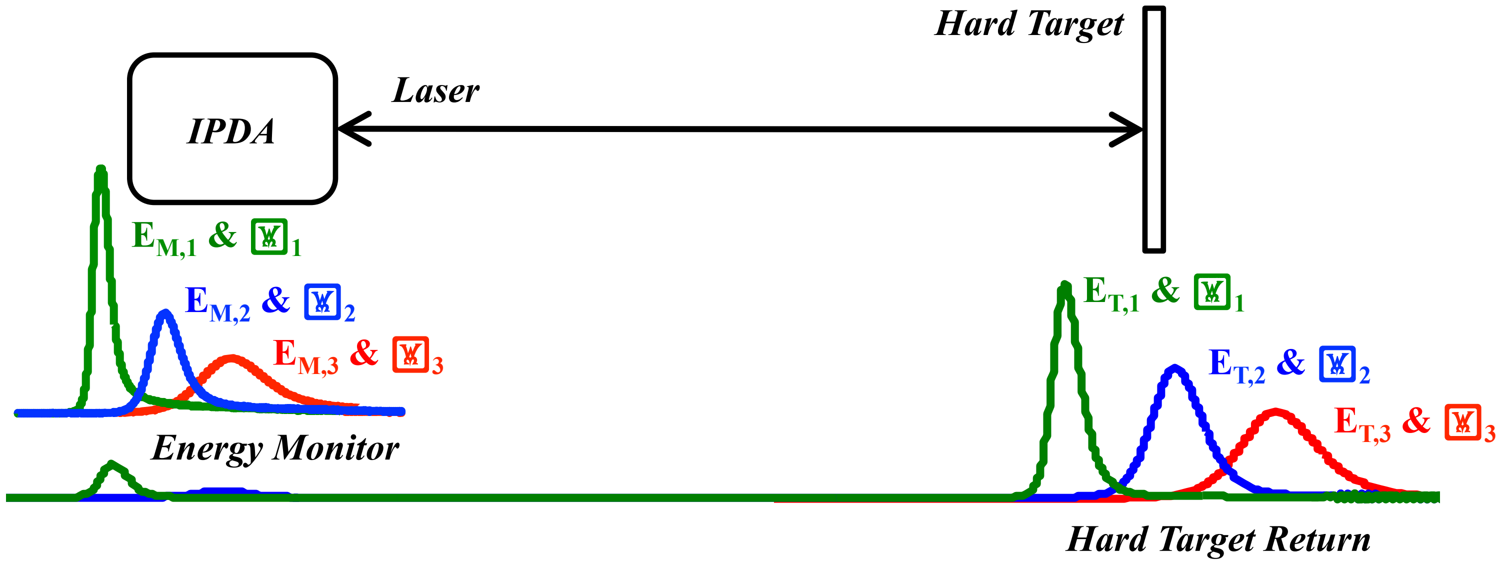
Questions?

BACKUP

Triple Frequency Generating Scheme



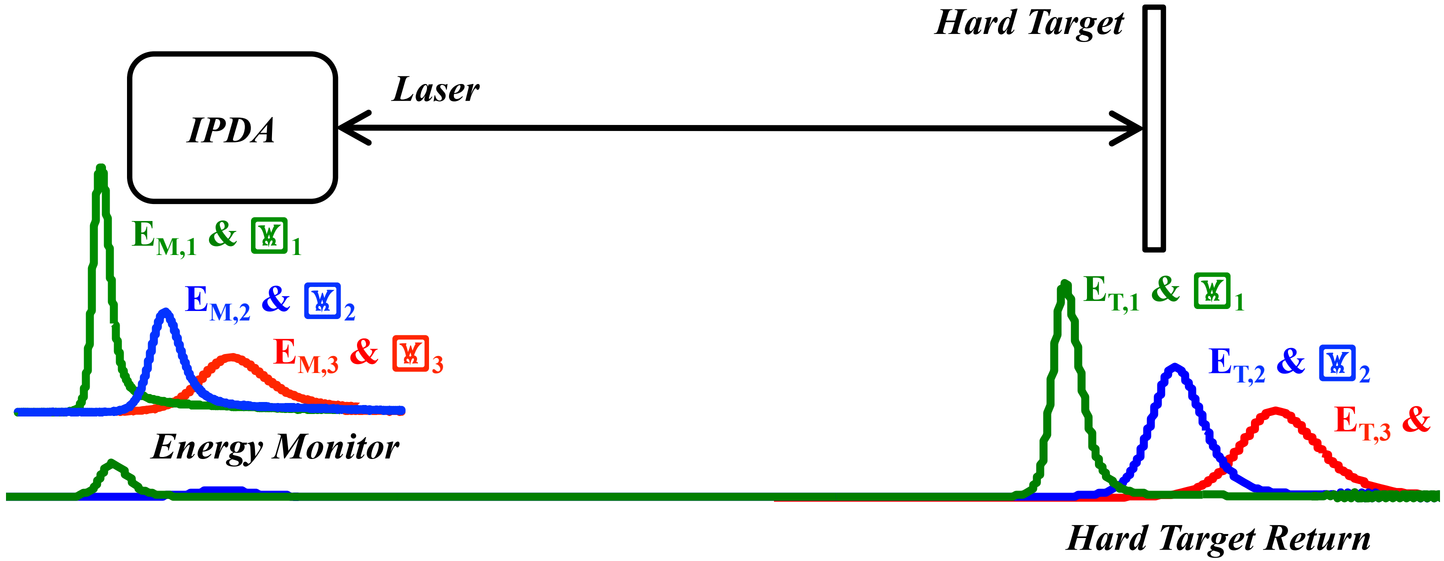
Methodology



- 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

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

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