National Aeronautics and
Space Administration

Overview of Technology Developments, Ground/Airborne Measurements and Feasibility Studies of High Pulse Energy 2-micron IPDA for Carbon Dioxide Measurements from Space

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Objectives

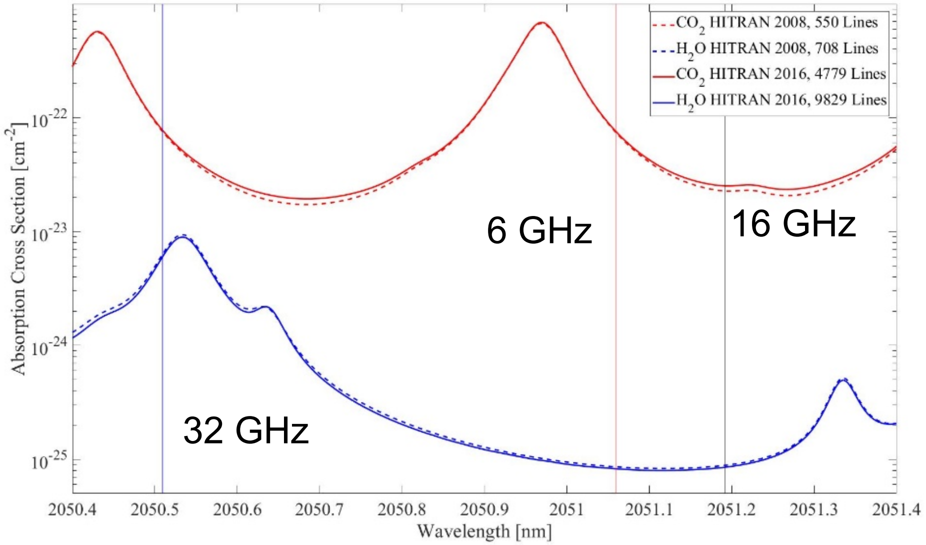
- ☐ Demonstration of an airborne triple-pulse, 2-?m, IPDA lidar for simultaneous and independent measurement of the weighted-average column dry-air mixing ratios of carbon dioxide (XCO2) and water vapor (XH2O)
- ☐ Scaling IPDA lidar technology for the assessment of space-based global XCO2 measurement

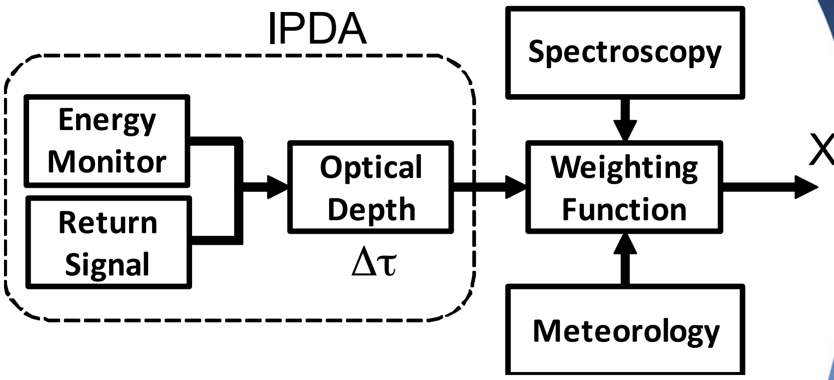
Outline

- Methodology
- Technology Development
- Technology Demonstration
- IPDA Space-Based Scaling
- IPDA Roadmap
- Conclusions

Methodology

US Standard Atmosphere at surface





IPDA

Energy Monitor

Return Signal

Optical Depth

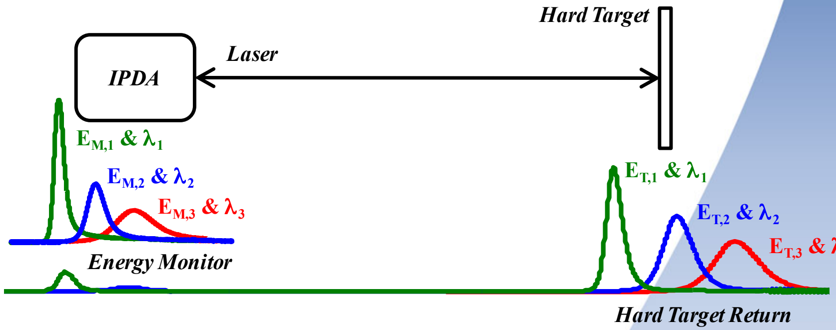
$\Delta\tau$

Spectroscopy

Weighting Function

Meteorology

X



IPDA

Laser

Hard Target

$E_{M,1}$ & λ_1

$E_{M,2}$ & λ_2

$E_{M,3}$ & λ_3

Energy Monitor

$E_{T,1}$ & λ_1

$E_{T,2}$ & λ_2

$E_{T,3}$ & λ_3

Hard Target Return

- Optical depth is the main IPDA product
- Other IPDA products include ranging and target surface height
- Spectroscopy and meteorological data are required to obtain mixing ratios
- Meteorological data obtained from other sensors or models (US Standard Atmosphere)
- Triple-pulse independent wavelength tuning defines H_2O & CO_2 differential optical depth simultaneously and independently

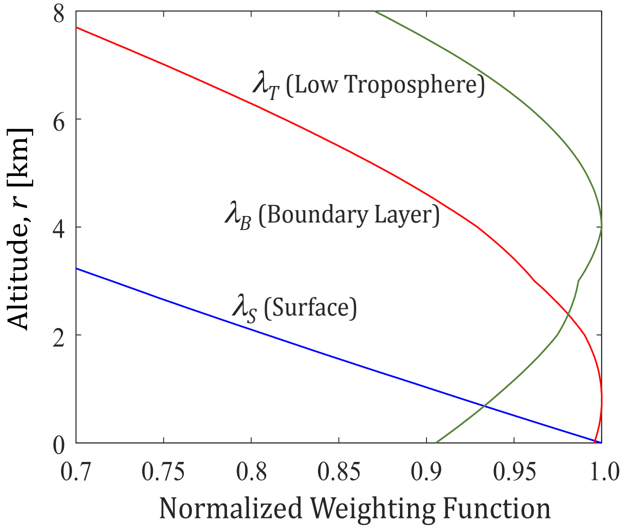
Technology Development

- Development of space-qualifiable, fully conductively-cooled, triple-pulsed, 2-μm laser transmitter
- Development of wavelength control system for rapid and fine tuning of three locked sensing for CO_2 and H_2O IPDA lidar transmitter
- Integrate transmitter with receiver and data acquisition to develop the triple-pulsed 2-μm direct detection IPDA lidar

Technology Development

IPDA Lidar Transmitter	On-Line Wavelength, λ_{on}	Tunable [a]
	Off-Line Wavelength, λ_{off}	2051.1915 nm
	Pulse Energy, E	50 / 15 / 5 mJ
	Pulse Width, t_p	30 / 60 / 100 ns
	Pulse Separation, T_s	150 – 300 μs
	Triple-Pulse Repetition Rate, f_p	50 Hz
	Beam Quality	2.0 (M^2)
	Beam Divergence, ϕ_b	100 μrad
	Laser Line Width	Transform Limited
	Frequency Control Accuracy	±650 kHz
	Spectral Purity	99.9%
	Electrical to Optical Efficiency	4%
	Beam Expansion	×10
IPDA Lidar Receiver	Optical Efficiency, η_r	60%
	Telescope Diameter, D_T	1.5 m
	Telescope Obscuration, O_T	10%
	Optical Filter Spectral Width, FW	1 nm
	Field-of-View, FOV	150 μrad
	Detector Responsivity, $\mathfrak{R}$ [b]	295.3 A/W
	Detector Gain, M	308
	Detector Excess Noise Factor, F	1.03
	Detection Bandwidth, BW	10 MHz
	Noise-Equivalent-Power, NEP	1 fW/Hz$^{1/2}$
	Laser-to-Telescope Overlap, φ_r	1.00

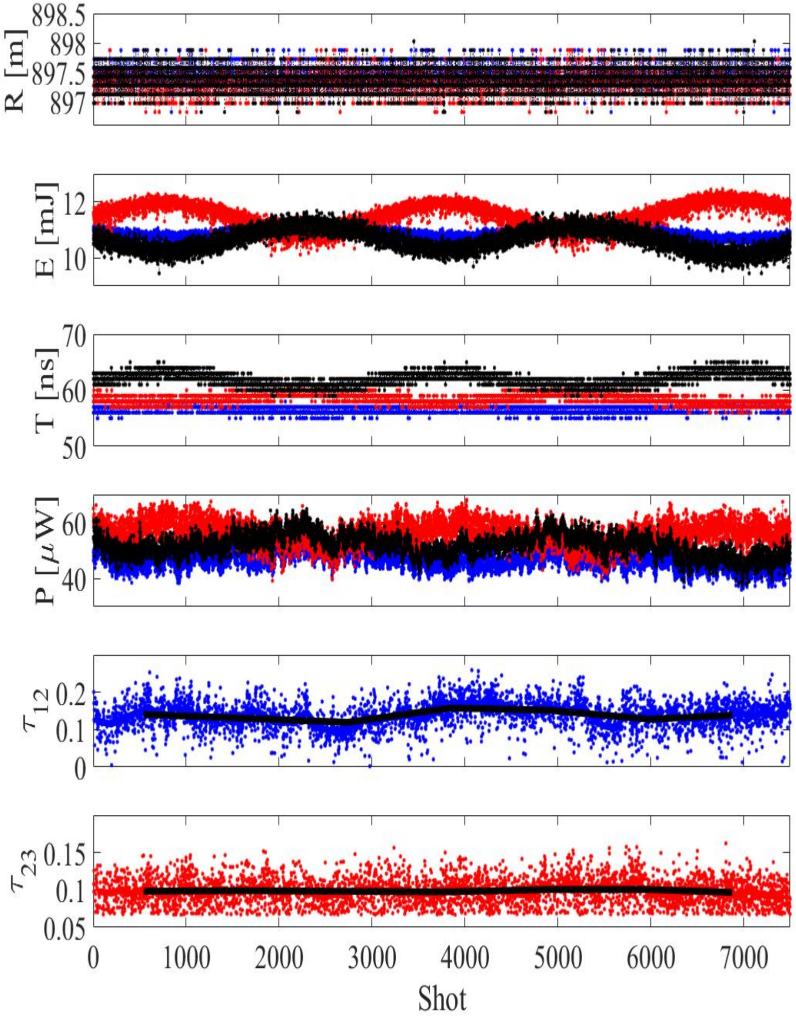
CO$_2$ Weighting Functions



- IPDA lidar design parameters meet, or exceed, space-based requirements, set by ESA (A-Scope) and NASA (ASCENDS)
- Focusing on CO$_2$, tunable 2-⍰m triple-pulse transmitter enables XCO2 measurements using two different weighting functions simultaneously

Technology Demonstration

Preliminary Ground Testing



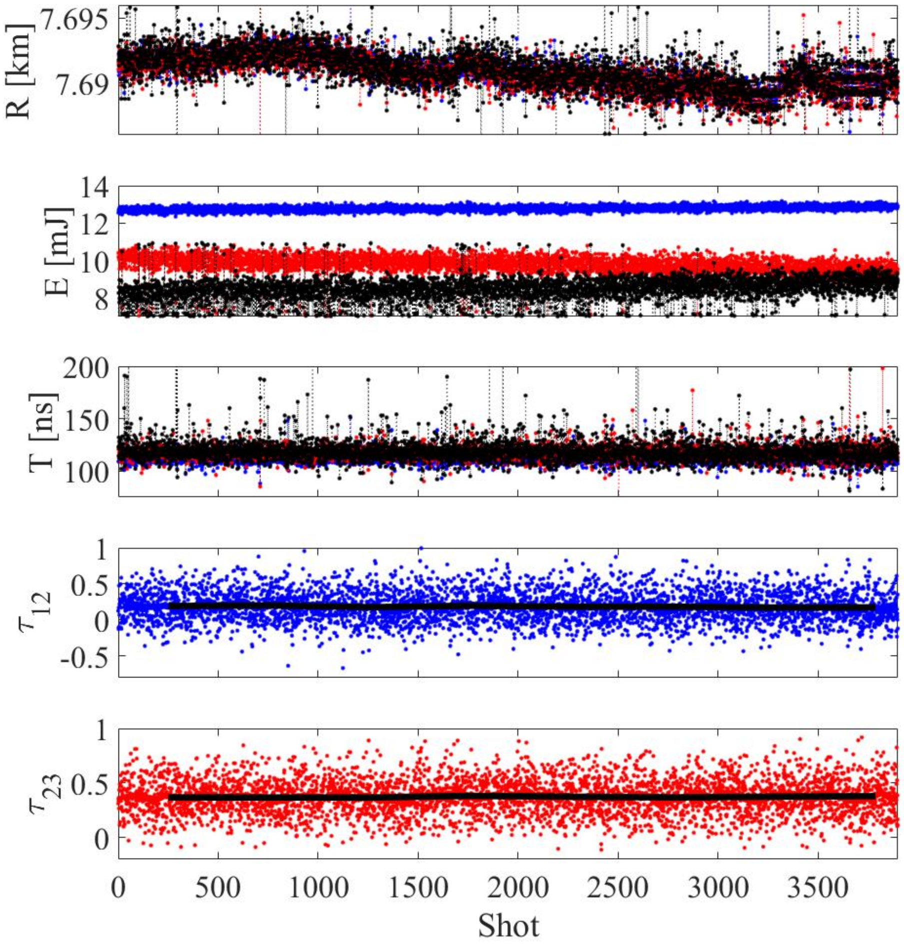
	(CO_2) τ_{23}	(H_2O) τ_{12}
Single-Shot	0.0955 ± 0.0215	0.1408 ± 0.0361
50 Shots (1s)	0.0986 ± 0.0049	0.1384 ± 0.0182
500 Shots (10s)	0.0987 ± 0.0015	0.1382 ± 0.0134
Met. Model	0.1045 ± 0.0001	0.1759 ± 0.0005
US Standard Model	0.1029*	0.1866

	XCO2	XH2O
Single-Shot	392.3 ± 71.9	5057.8 ± 1398.8
50 Shots (1s)	436.9 ± 19.8	5037.1 ± 673.2
500 Shots (10s)	425.9 ± 6.0	5353.2 ± 496.6
Met. Model	422.0 ± 0.4	6481.9 ± 17.5
US Standard Model	422.0*	7750.0

- Conducted January 10, 2018
- Tuned to 32, 6 and 16 GHz seeding
- 2.5 min. records (7500 shots)
- IPDA range (897m) consistent with Rangefinder measurement (894m)
- IPDA range uncertainty of 0.2 m is consistent with the sampling rate (0.15 m)
- Results compared to US Standard Atmosphere and Meteorology models

Technology Demonstration

Preliminary Airborne Testing



	$(CO_2)\ \tau_{23}$	$(H_2O)\ \tau_{12}$
Single-Shot	0.3692 ± 0.1609	0.1709 ± 0.2124
50 Shots (1s)	0.3724 ± 0.0224	0.1840 ± 0.0284
500 Shots (10s)	0.3704 ± 0.0079	0.1864 ± 0.0124
US Standard Model	0.3895	0.5623

- Conducted on February 27, 2018
- Flight over ocean at Cape May, NJ
- NOAA co-flight
- Tuned to 32, 6 and 16 GHz seeding
- 5 min. records (15.5k shots)
- IPDA range (7.7 km) is consistent with GPS.
- High return pulse width due surface wave elevation.

IPDA Space-Based Scaling

Global scenarios for IPDA performance simulations

	Scenario	Model	ρ	τ_a
1	Rail Road Valley (RRV)[b]	USA	0.510	0.0165
2	Land, Desert	USA	0.410	0.2380
3	Land, Vegetation	USA	0.090	0.0289
4	Tropics, Land	TRO	0.090	0.0530
5	Tropics, Ocean	TRO	0.079	0.0420
6	South Ocean, Summer	MLS	0.079	0.0273
7	South Ocean, Winter	MLW	0.079	0.0475
8	Polar Snow, Summer	SAS	0.020	0.0210
9	Polar Snow, Winter	SAW	0.020	0.0210
10	Thin Clouds	USA	0.510	0.0500
11	Urban Plumes, Wet Land	USA	0.079	0.1340
12	Urban Plumes, Dry Land	USA	0.090	0.1340

[a] Atmospheric models: U.S. Standard (USA), Mid-Latitude Summer (MLS), Mid-Latitude Winter (MLW), Tropics (TRO), Sub-Arctic Summer (SAS) and Sub-Arctic Winter (SAW);

[b] RRV is a reference surface with high reflectivity (ρ) that includes a 1.23 enhancement factor.

[C] τ_a is the aerosol optical depth.

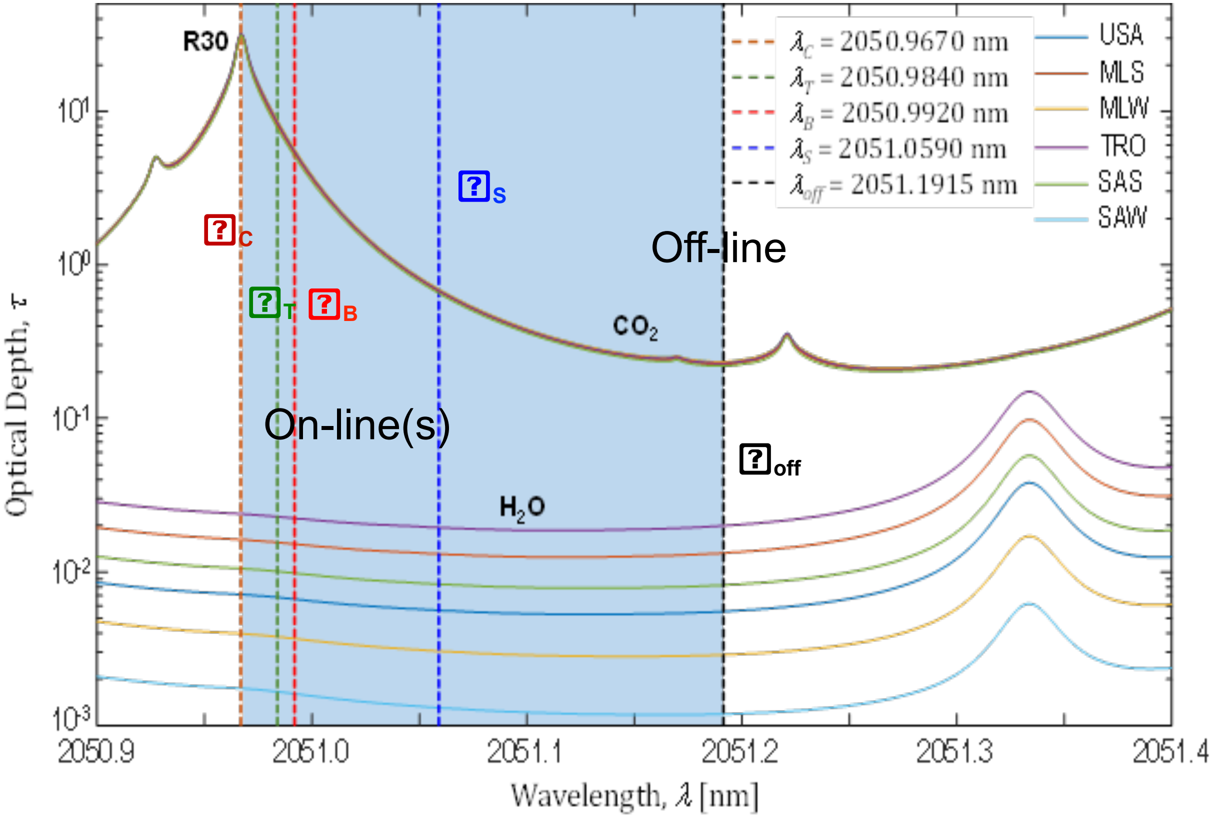
Requirements for space-based CO_2 IPDA lidar

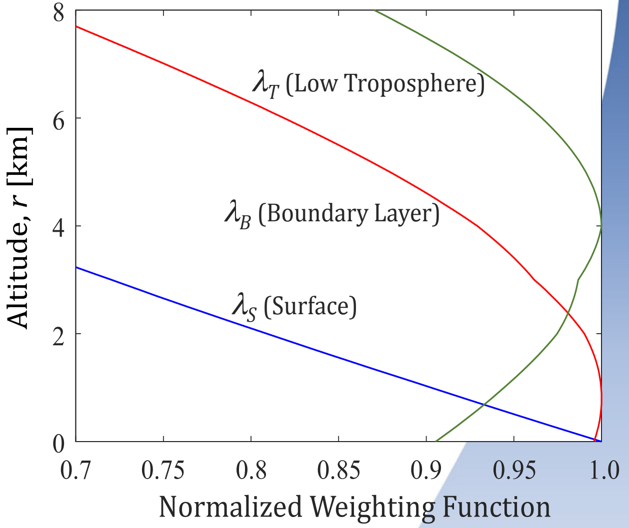
Parameter	Requirement
Random error in CO_2 dry-air column mixing ratio	0.50 ppm
Systematic error in CO_2 dry-air column mixing ratio	0.50 ppm
Random error in CO_2 differential optical depth, ε_R [a]	0.35 ppm
Systematic error in CO_2 differential optical depth, ε_S	0.35 ppm
Ranging error to the surface, ε_c	< 3.0 m
Laser footprint diameter	≤ 100 m
Laser pulse frequency	≥ 50 Hz

[a] Over RRV reference surface reflectivity, under clear conditions and 10 s observational interval

- Conduct feasibility study of space-based IPDA technique for XCO2 measurements
- assess XCO2 measurement sensitivity based on the performance of achieved technology, assuming variety of atmospheric and surface conditions (global scenarios)
- Compare IPDA projected errors with space-based requirements

IPDA Space-Based Scaling

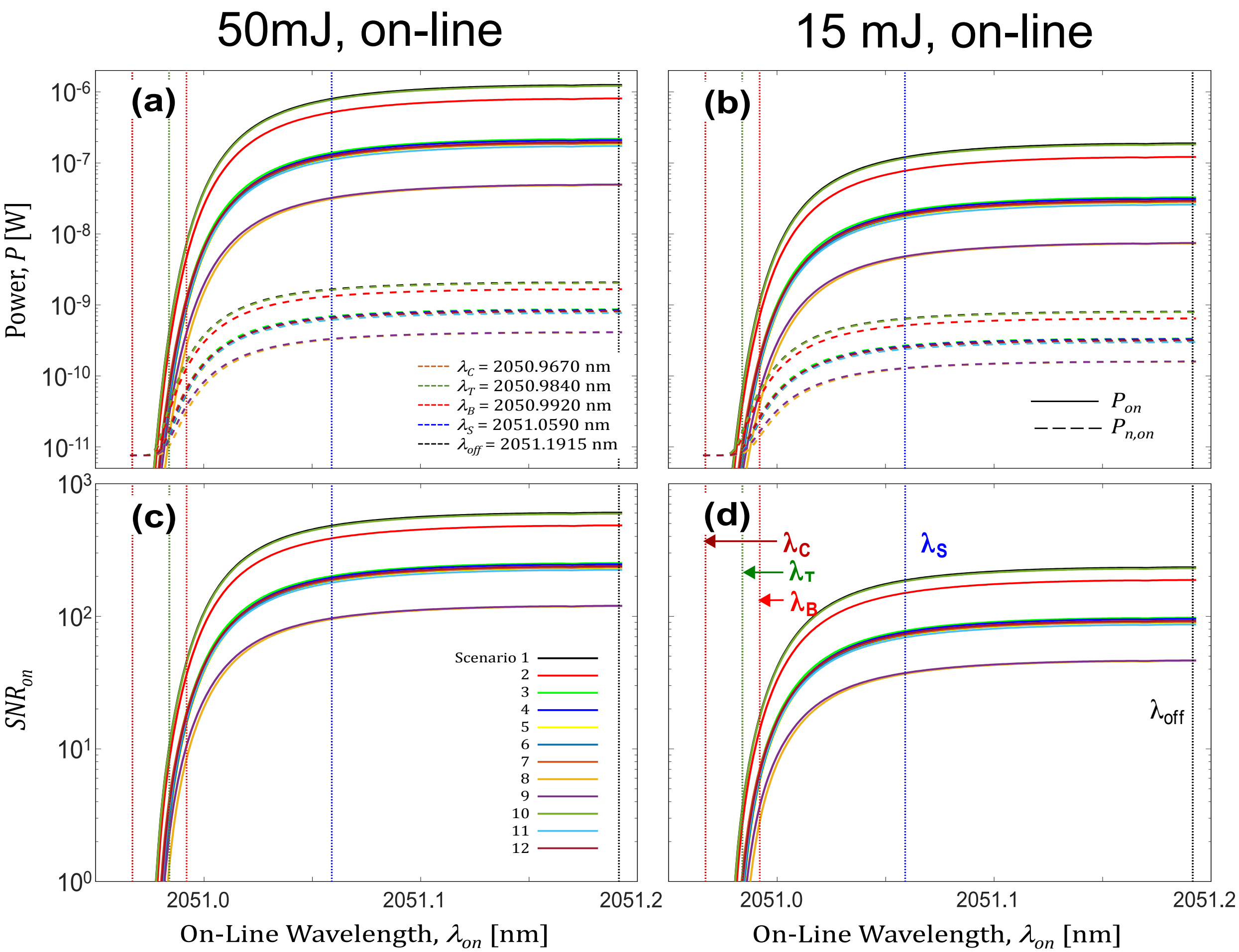

CO$_2$ Absorption and H$_2$O interference


CO$_2$ Weighting Functions

- XCO2 error analysis conducted as a function of the on-line wavelength to demonstrate adaptive targeting
- Focus on three wavelength for optimum weighting function for surface, boundary layer and lower troposphere measurements

IPDA Space-Based Scaling

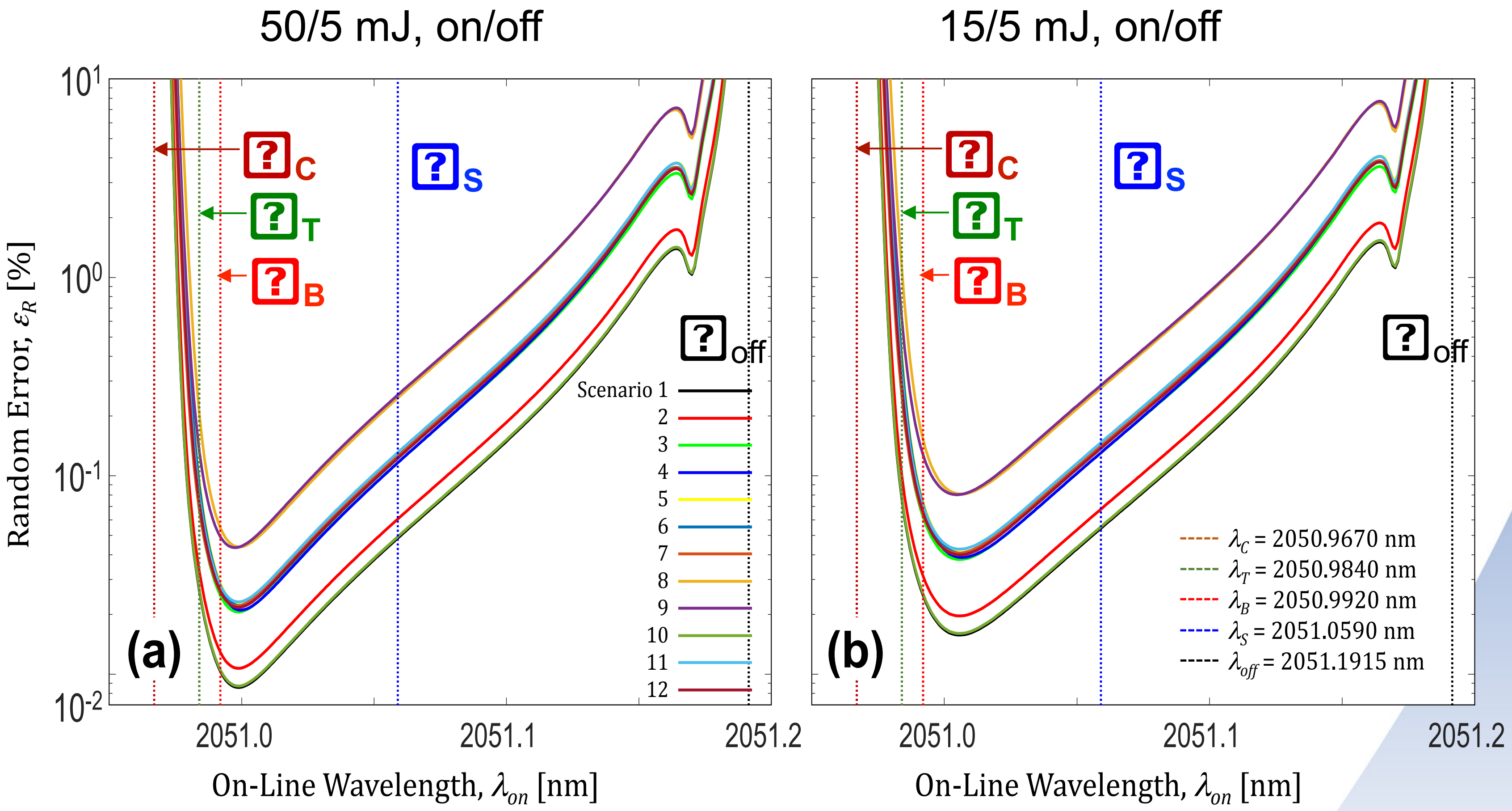
Return Signal Power and SNR



- Simulated IPDA on-line return power and signal-to-noise ratio, assuming 15 and 50 mJ transmitted energies

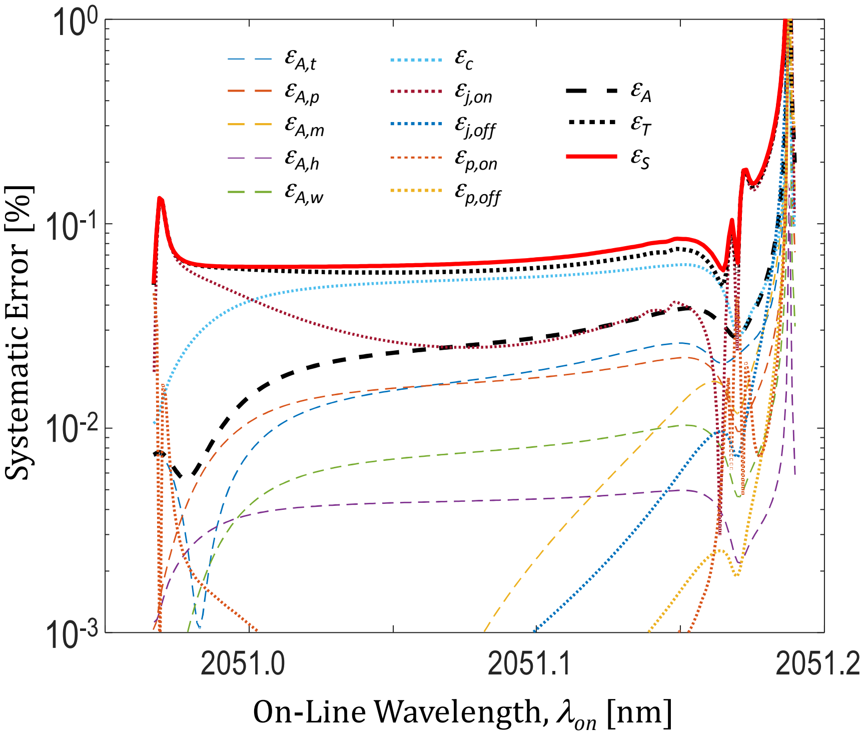
IPDA Space-Based Scaling

Optical Depth Random Error Variation with On-Line Wavelength



- Simulated IPDA random error assuming 15 and 50 mJ transmitted energies
- Random error is based on 10 sec. average and RRV reference surface, using 1 fW/Hz$^{1/2}$ MCT e-APD

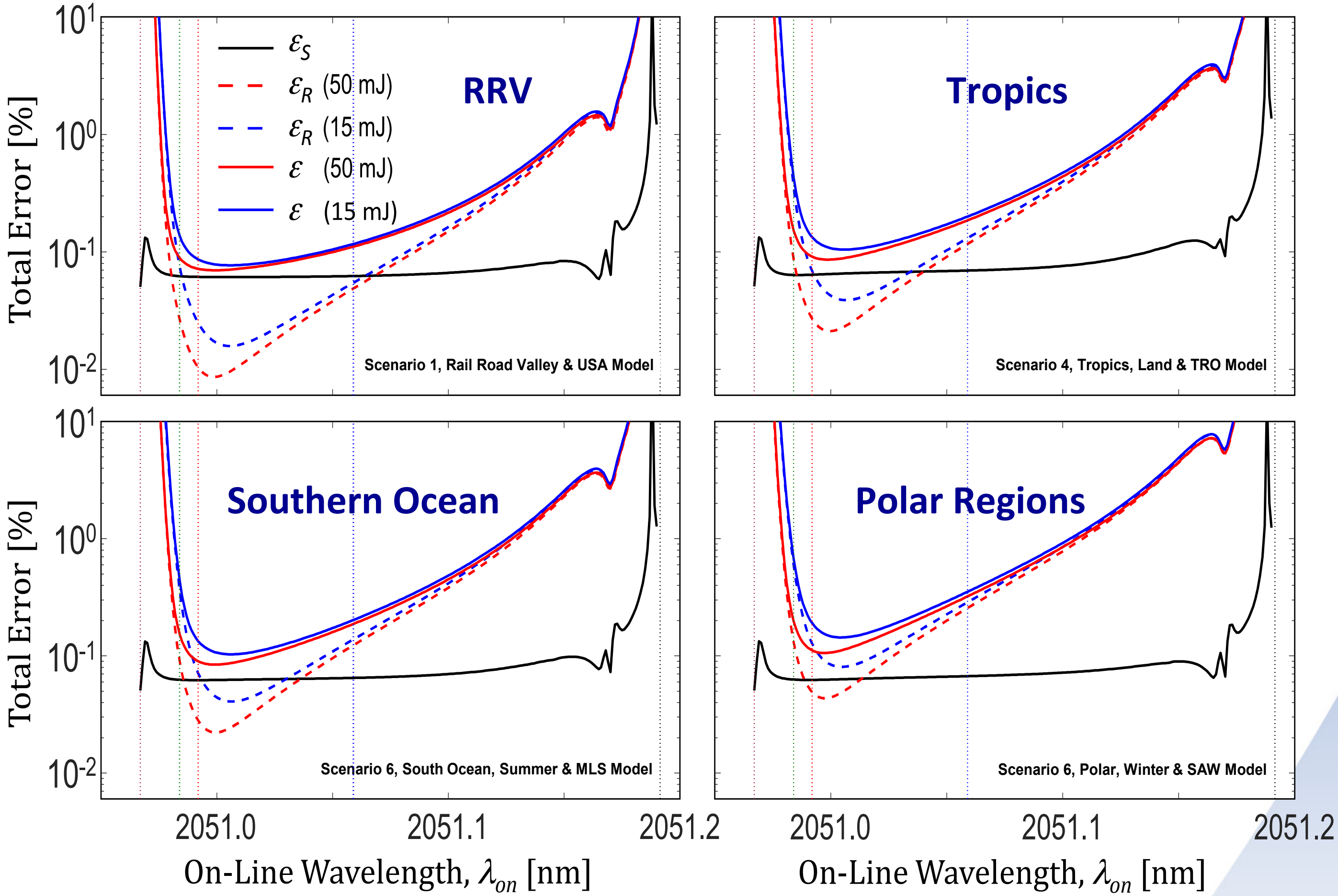
IPDA Space-Based Scaling



Systematic Errors from Atmospheric and IPDA Transmitter Uncertainties

- Simulated IPDA systematic error, $\boxed{?}_S$, is the sum of the atmospheric error, $\boxed{?}_A$, and IPDA transmitter error, $\boxed{?}_T$
- Atmospheric error includes temperature, $\boxed{?}_{A,t}$, pressure, $\boxed{?}_{A,p}$, molecular interference, $\boxed{?}_{A,m}$, relative humidity, $\boxed{?}_{A,h}$, and water vapor broadening, $\boxed{?}_{SA,w}$
- Transmitter error includes laser jitters , $\boxed{?}_j$, and line profiles , $\boxed{?}_p$,

IPDA Space-Based Scaling

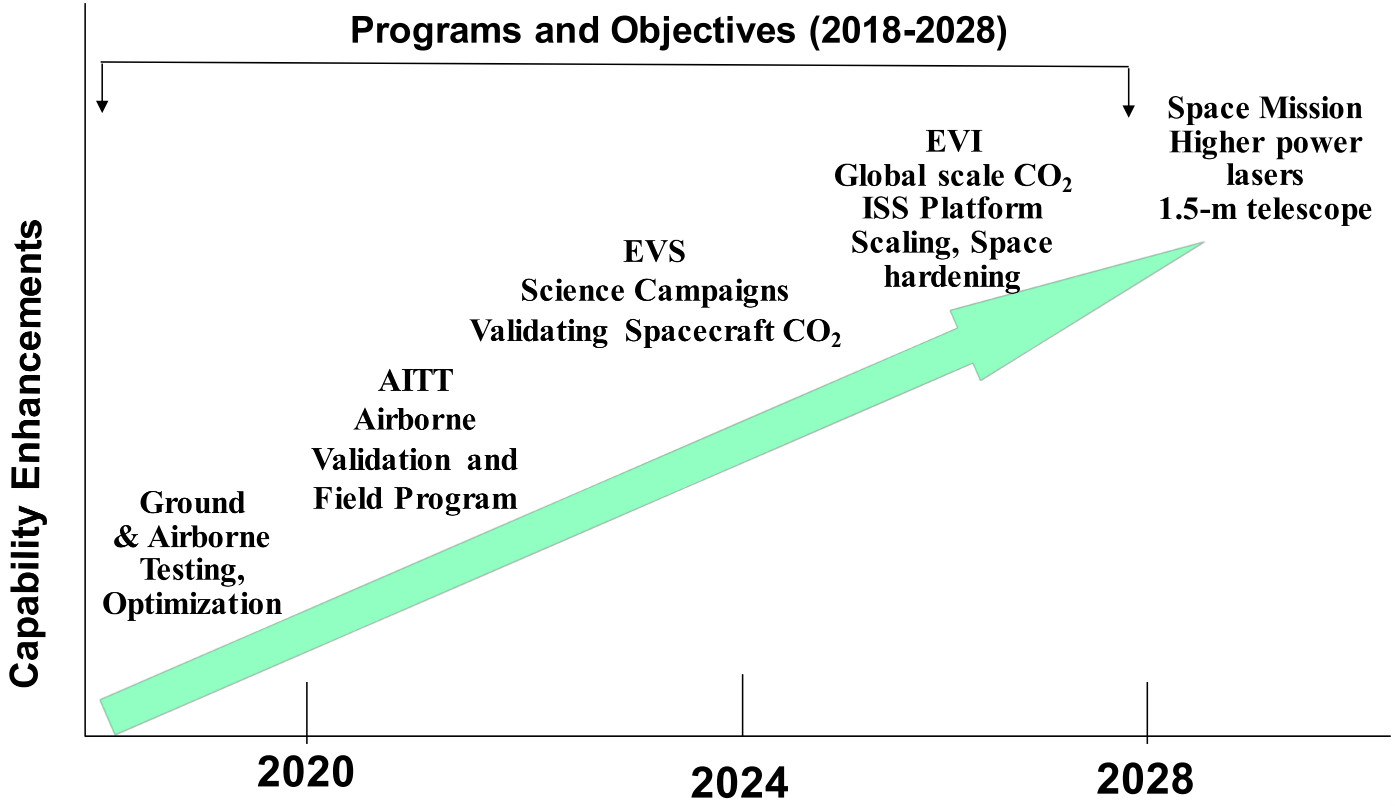


Total Error Budget

- Projected total error budget for critical regions
- Wavelength tuning achieves minimum error for different measurement location
- Example; estimated <0.35 ppm precision 0.3 ppm bias in low trop column CO_2 optical depth

IPDA Roadmap

CO2 IPDA Lidar Technology Development Roadmap



Programs and Objectives (2018-2028)

Ground
& Airborne
Testing,
Optimization

AITT
Airborne
Validation and
Field Program

EVS
Science Campaigns
Validating Spacecraft CO_2

EVI
Global scale CO_2
ISS Platform
Scaling, Space
hardening

Space Mission
Higher power
lasers
1.5-m telescope

- Projected triple-pulse, 2-μm IPDA lidar technology development roadmap for active optical remote sensing of global carbon dioxide from space

Conclusions

- An airborne tripled-pulsed IPDA lidar was developed at NASA LaRC for simultaneous and independent measurement of column water vapor and carbon dioxide
- This IPDA is based on a state-of-the-art triple-pulse 2-mm laser transmitter, seeded with tunable and locked wavelength for each pulse
- Ground and airborne testing indicated successful IPDA operation
- Modeling of space-based 2-mm IPDA to evaluate random and systematic errors and demonstrate performance capability, while focusing on carbon dioxide measurement
- IPDA capabilities includes carbon dioxide measurements with different weighting functions simultaneously; and tunablity to adopt to specified environmental conditions
- Estimated <0.35 ppm precision 0.3 ppm bias in low trop column CO_2 optical depth equivalent measurements with 10 s signal averaging Railroad Valley Reference surface condition
- Using reanalysis of global meteorological surface pressure data, CO_2 column mixing ratio measurements with high precision (0.5 ppm), and high accuracy (0.5 ppm) can be achieved to meet science objectives