



National Aeronautics and
Space Administration



Carbon Dioxide Active Remote Sensing Using Pulsed 2- μm Lidar

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June 20, 2023

Milos, Greece

3rd international workshop on space-based lidar
remote sensing techniques and emerging technologies





Objectives



Demonstrate sensitive atmospheric CO₂ measurements using airborne 2- μ m double-pulse Integrated Path Differential Absorption (IPDA) lidar

Outline

- **Introduction**
- **IPDA Lidar**
 - Technology
 - Technique
- **IPDA Measurements**
 - Ground Testing
 - Airborne Campaign
- **IPDA Scaling for Space**
- **Conclusion**



Introduction

Several studies address CO₂ contribution to climate

Important to monitor atmospheric CO₂ for better understanding of sources, sinks and transport (flux)

➤ Range-resolve DIAL

- R22 Line, Ho:Tm:LuLiF, InGaAsSb Phototransistor
- 5 Hz, 90 mJ, 140 ns, 2.15 or 2.8 GHz on-line

➤ Double-Pulse IPDA Lidar

- R30 Line, Ho:Tm:YLF (side-pump), InGaAs pin photodiode
- 10 Hz, 90/45 mJ, 200/310 ns, 1 GHz step, 1 to 6 GHz switchable on-line
- $\delta X_{cd} = 4.2$ ppm, $\Delta X_{cd} = 1.1$ ppm, $\delta R = 0.93$ m (Airborne 6-km, Ocean)

➤ Triple-Pulse IPDA Lidar

- R30 Line, Ho:Tm:YLF (end-pump), InGaAs pin photodiode & MCT APD
- 50 Hz, 50/15/5 mJ, 30/60/100 ns, 32, 6.5 and 16 GHz fixed wavelengths
- $\delta X_{cd} = 8.0$ ppm, $\Delta X_{cd} = 32$ ppm (Airborne 7.7-km, ocean)

➤ Double-Pulse Operation of Triple-Pulse IPDA Lidar

- 50 Hz, 20/10 mJ, 32/55 ns, 0.1 to 3.0 GHz tunable on-line
- $\delta X_{cd} = 0.5$ ppm, $\Delta X_{cd} = 0.04$ ppm (Airborne 4.1-km, Ocean)

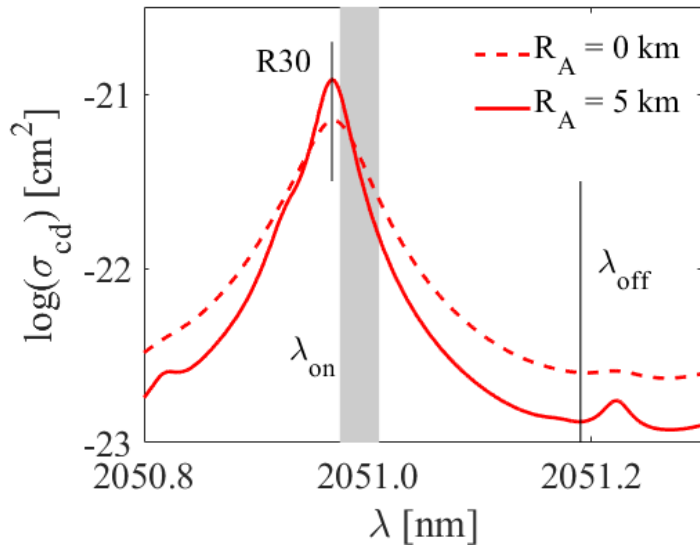
IPDA Lidar: Technology



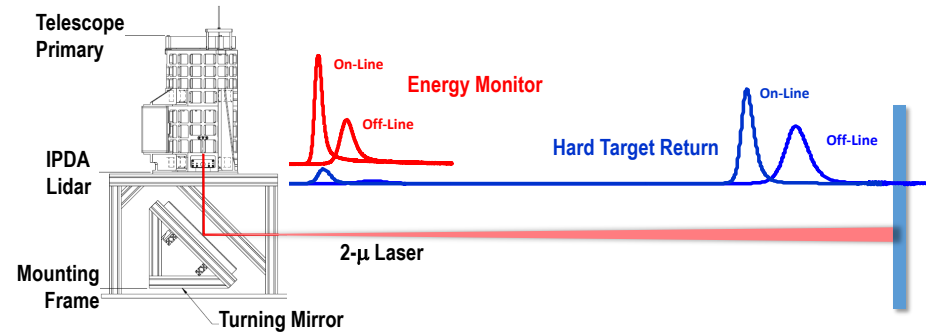
IPDA Lidar Inside NASA B-200

- IPDA integrated inside NASA B-200 aircraft
- IPDA total size is 0.5 m³, weight is 400 kg and power consumption is 2 kW
- Key Technologies
 - High-energy, pulsed 2-μm laser transmitter
 - Advanced e-APD MCT detection channel
- Support instruments/resources for meteorological and geographical data
 - GPS/INS Units
 - Ambient temperature and pressure sensor
 - Ambient CO₂ and H₂O in-situ (PICARRO)
 - DEM and standard atmospheric Models

IPDA Lidar: Technique



IPDA Model



SPIE Newsroom, 2015.

IPDA Measurement

$$\Delta\tau_{cd} = 2 \cdot \int_{R_A}^{R_G} \Delta\sigma_{cd}(\lambda_{off}, \lambda_{on}, r) \cdot N_{cd}(r) \cdot dr = \ln \left\{ \frac{P(\lambda_{off}, R_A, R_G) \cdot t(\lambda_{off})/E(\lambda_{off})}{P(\lambda_{on}, R_A, R_G) \cdot t(\lambda_{on})/E(\lambda_{on})} \right\}$$

$$X_{cd}(\lambda_{on}, R_A, R_G) = \frac{\Delta\tau_{cd}}{2 \times 10^{-6} \cdot \int_{R_A}^{R_G} \Delta\sigma_{cd}(\lambda_{off}, \lambda_{on}, r) \cdot N_{dry}(r) \cdot dr}$$

XCO₂ Retrieval

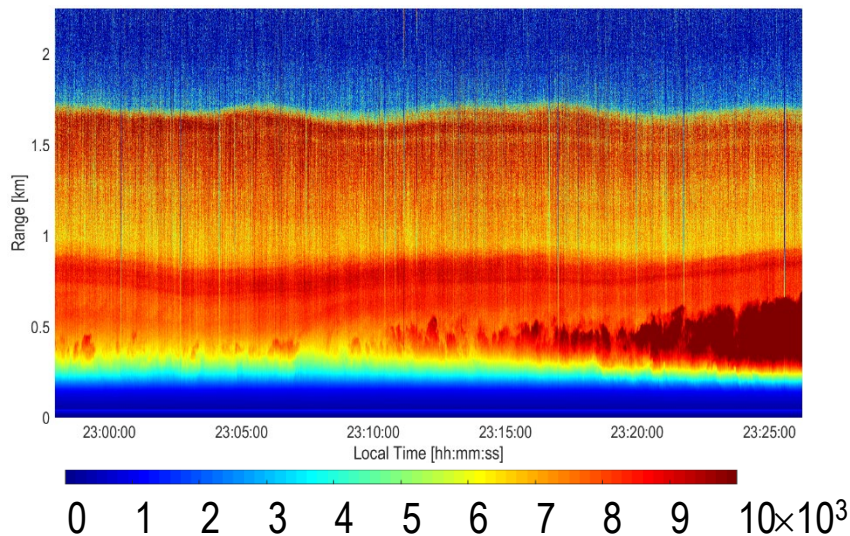
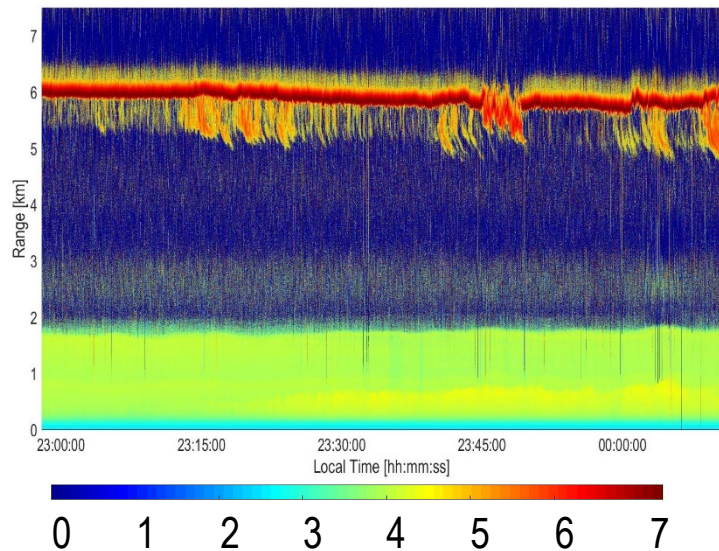
$$\varepsilon_R = \delta X_{cd}/X_{cd,r} = \sqrt{\delta X_{cd,r}^2 - \delta X_{cd,m}^2}/X_{cd,r}$$

Model Random Error
Measurement Precision

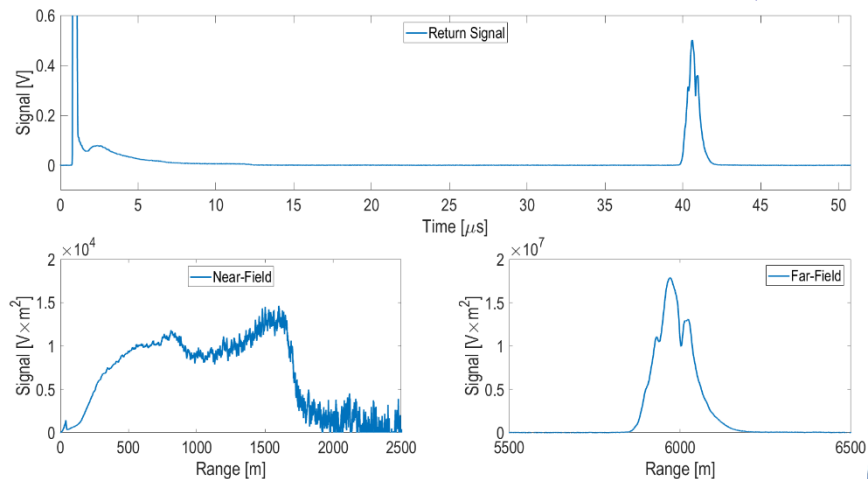
$$\varepsilon_S = \Delta X_{cd}/X_{cd,r} = (X_{cd,r} - X_{cd,m})/X_{cd,r}$$

Model Systematic Error
Measurement Accuracy

IPDA Measurements: Ground Testing

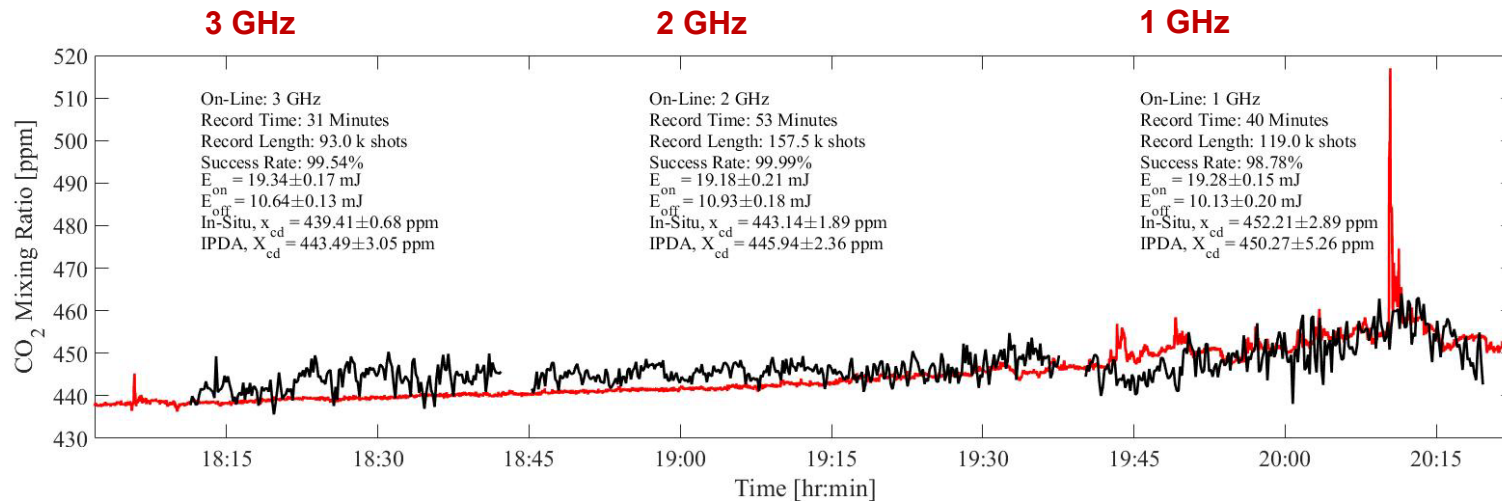


ILRC, 2019.



- Zenith ground operation targeting high-altitude (6 km) cirrus clouds
- Off-line signal processing includes background subtraction, range correction using 50 shot averaging (1 s)
- Dynamic range capable of detecting far-field clouds and near-field boundary layer structure within the same record

IPDA Measurements: Ground Testing

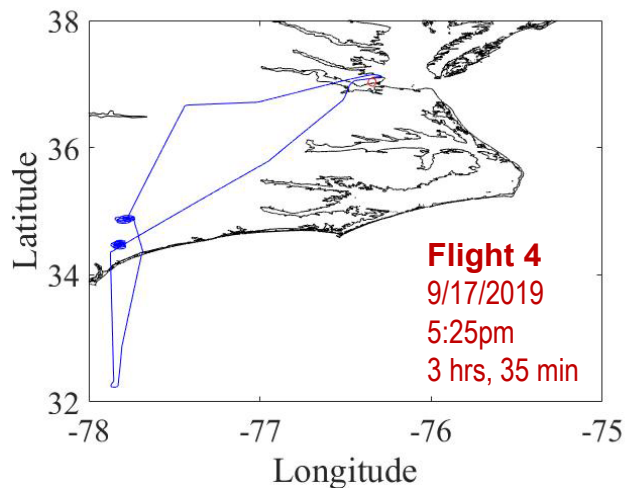
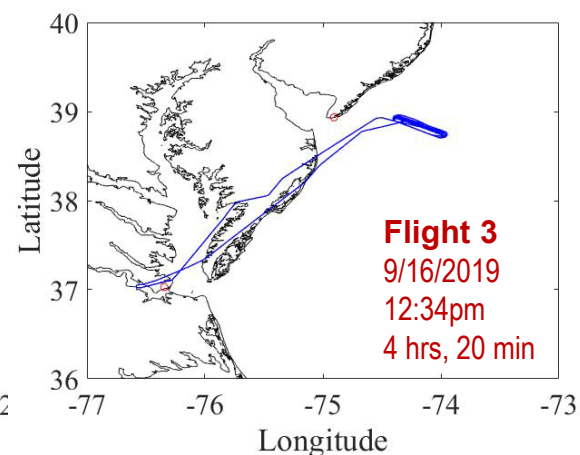
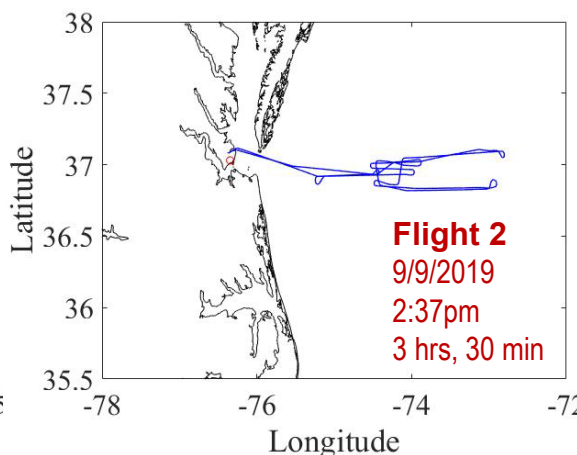
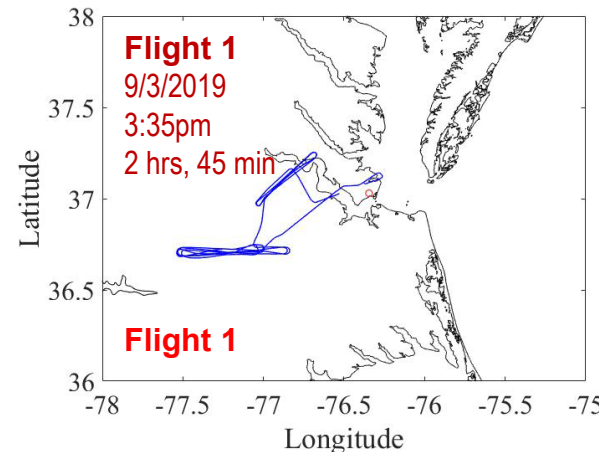


IEEE TGRS, 2020.

- Long record for CO₂ IPDA measurements (black) compared to LI-COR in-situ measurements (red)
- IPDA data for PIN detection channel using 10-s average
- Target reflectivity of 13.6% with on-line settings of 3, 2, and 1 GHz
- IPDA measurement and in-situ agreement due to short horizontal range (900 m)



IPDA Measurements: Airborne Campaign



Conducted four flights

- Flight 1: Engineering flight
- Flight 2: Over ocean cloudy/broken clouds/clear conditions (2-7 km)
- Flight 3: Land/ocean, NOAA flight (0.3-8.0 km)
- Flight 4: Over land/ocean during day/night, cloudy/clear conditions at fixed altitude (4.5 km) concurrent with tropical storm Imelda

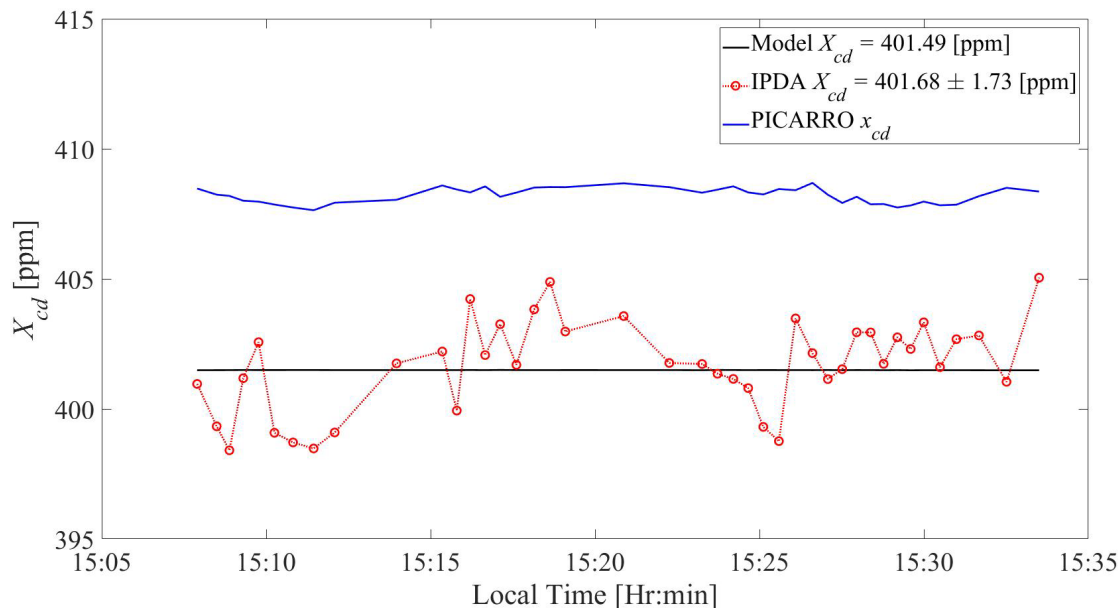
Ocean provides consistent surface reflectivity (5%) and uniform elevation (reduces systematic error)



IPDA Measurements: Airborne Campaign



Flight 2



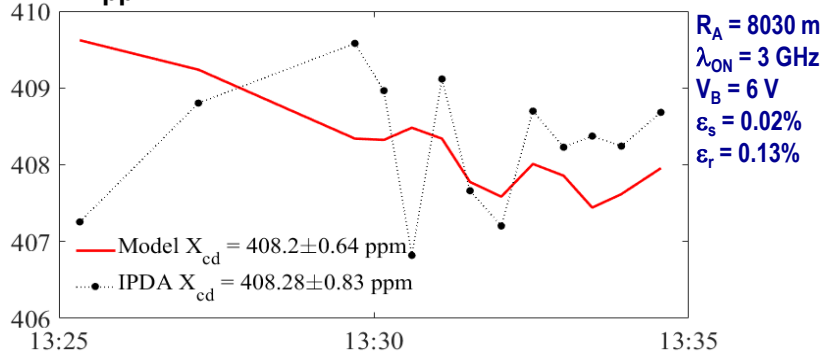
On-Line; 3 GHz
Altitude; 4.7 km
APD; 6V bias, 0 gain set, 4-pixels
Target; Ocean Return, Clear to surface
Average; 10-s
Accuracy; -0.19 ppm
Precision; 1.73 ppm
Systematic Error; -0.05%
Random Error; 0.43%

- Comparison between model (black) and measured (red) weighted-average column dry-air volume mixing ratio of CO_2 (X_{cd})
- Difference with respect to *in-situ* (blue) dry-air volume mixing ratio of CO_2 (x_{cd}) is inherent to IPDA technique
- IPDA measurements include corrections due to fluctuations of
 - Laser Energy
 - Laser Wavelength Shift
 - Altitude and Surface Elevation
 - Navigation Angles
 - Water Vapor

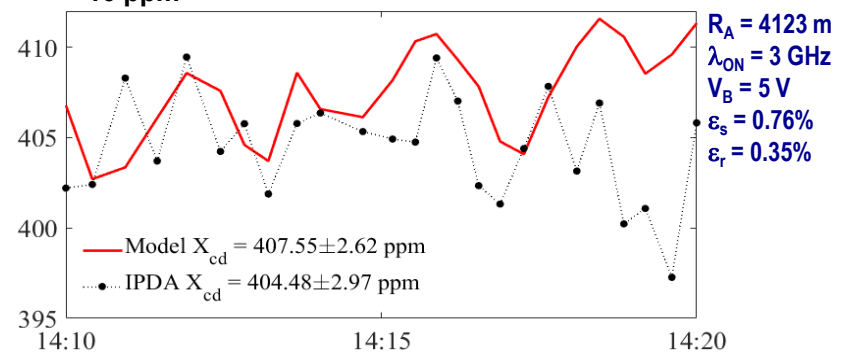
IPDA Measurements: Airborne Campaign

Flight 3

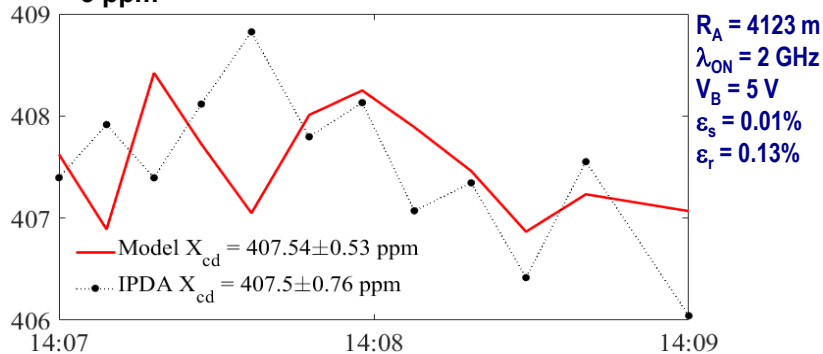
4 ppm



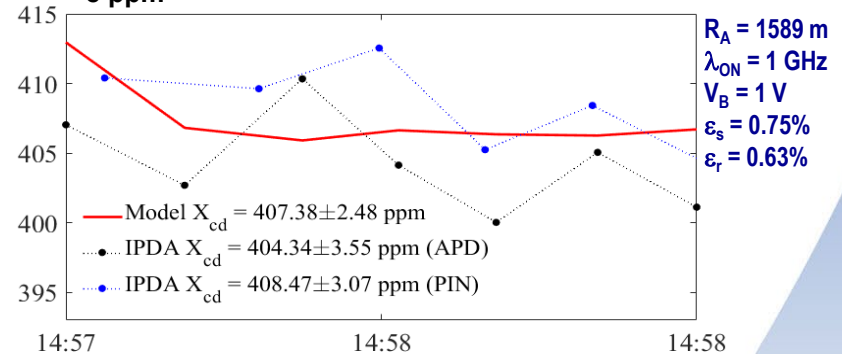
10 ppm



3 ppm



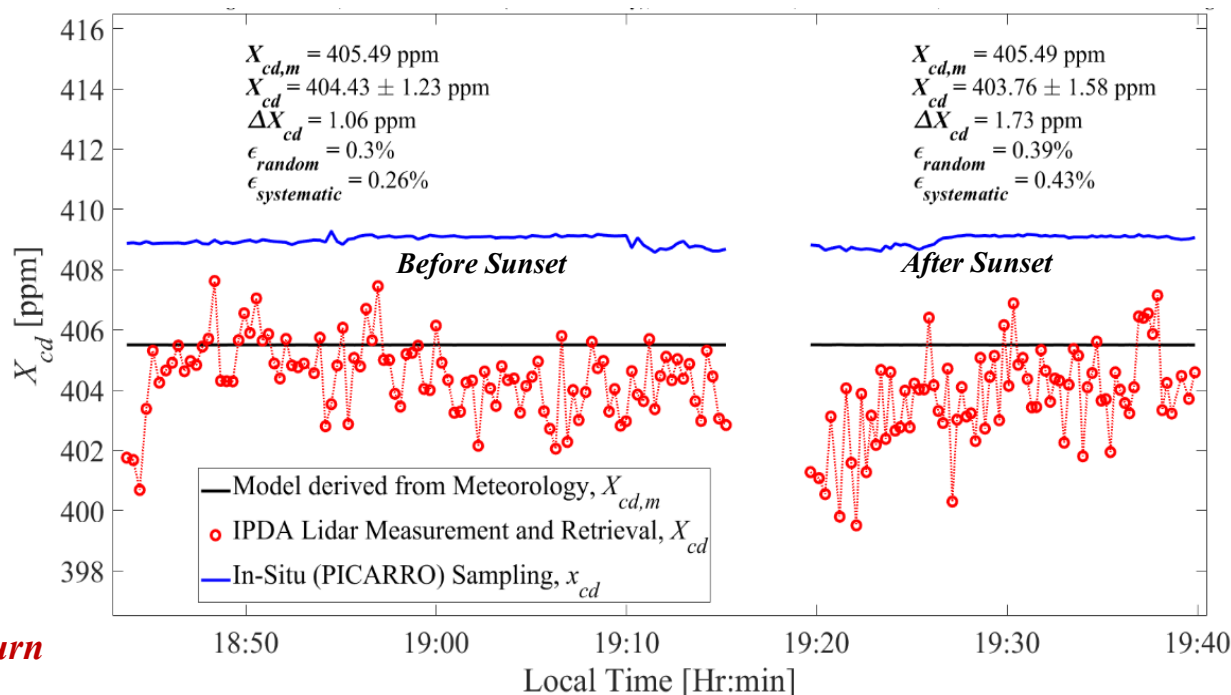
8 ppm



- Comparison between model prediction (red) and IPDA measured (black) X_{cd} at different altitudes and different on-line wavelength
- Improved model resolution
- PIN detection system (blue) performs at lower altitudes
- Enhanced systematic error observed at lower X_{cd} fluctuations

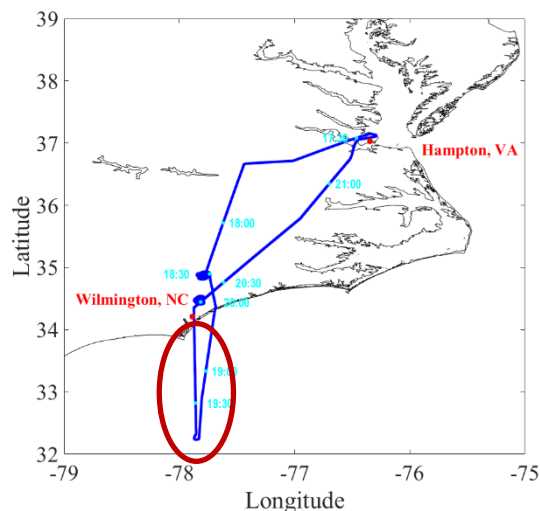
IPDA Measurements: Airborne Campaign

Flight 4



Atmosphere, 2021

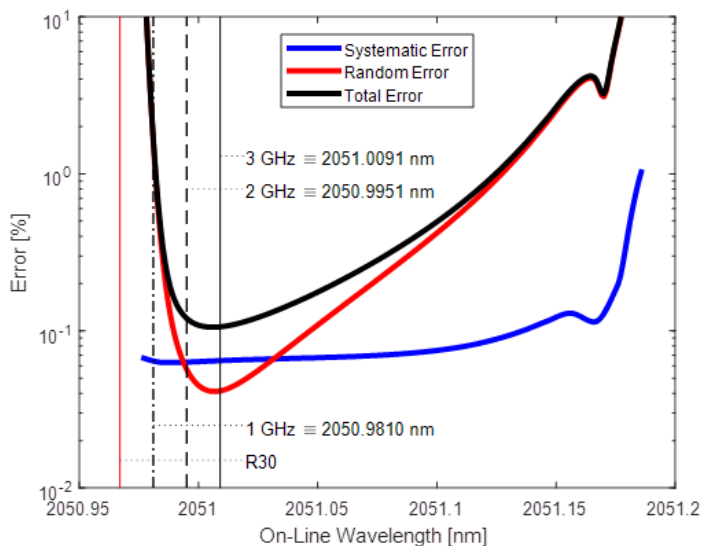
Ocean Return



- Comparison between model prediction (black) and IPDA measured (red) X_{cd} before and after sunset
- Expected consistent results between daytime and nighttime, since IPDA provides its own radiation source
- Expected higher systematic error observed initially during severe aircraft banking

IPDA Measurements: Airborne Campaign

Source	λ_{on} GHz	R km	$X_{cd,model}$ ppm	X_{cd} ppm	ΔX_{cd} ppm	δX_{cd} ppm	ϵ_S %	ϵ_R %
Flight 2	3	4.7	401.49	401.68+1.73	0.19	1.73	0.05	0.43
Flight 3	3	8.0	408.20+0.64	408.28+0.83	0.08	0.53	0.02	0.13
	3	4.1	407.55+2.62	404.48+2.97	3.07	1.39	0.76	0.35
	2	4.1	407.54+0.53	407.50+0.76	0.04	0.54	0.01	0.13
	1	1.6	407.38+2.48	404.34+3.55	3.04	2.54	0.75	0.63
Flight 4	3	4.5	405.49	404.43+1.23	1.06	1.23	0.26	0.30
	3	4.5	405.49	403.76+1.58	1.73	1.58	0.43	0.39
Space-Based Model	1	400	400		0.26	6.46	0.064	1.616
	2	400	400		0.25	0.23	0.063	0.057
	3	400	400		0.26	0.17	0.065	0.042
Δt_{cd} Requirement		400			0.35	0.35		
XCO_2 Requirement		400			0.50	0.50		



- Agreements between model estimates and IPDA measurement
- Systematic error is dominated by instrument ranging and on-line jitter
- Random error is dominated by detection noise and signal shot noise
- Consistent altitude (4.5 km) and on-line (3 GHz) result in consistent precision during different flights (1.5 ppm)
- Higher altitude results in enhanced precision (0.5 ppm) using the same wavelength (3 GHz)
- IPDA Space-Based model predictions meets Space-Based measurement requirements



Conclusions



- Double-pulse IPDA CO₂ lidar is upgraded from the triple-pulse IPDA CO₂/H₂O lidar
- Upgrades include tunable on-line laser transmitter with wavelength monitor and improved transmitted pulse energy stability
- Detection system dynamic range was extended using MCT APD and fixed-gain pin detectors
- The transmitter delivers two, high-energy, pulses at two different locked wavelengths at 50 Hz, with 500 μ s pulse separation
- Airborne testing campaign was conducted at different conditions
- Results indicated low systematic and random errors over low reflectivity ocean surface
- This IPDA lidar has improved and demonstrated reliability, operational readiness, and enhanced performance in terms of sensitivity
- Model predictions meets Space-Based measurement requirements



Acknowledgement



The 2- μ m IPDA Lidar Team Upendra Singh (PI)

Altman, Eric
Antill, Charles
Barrick, John
Bowen, Stephen
Boyer, Charles
Choi, Yonghoon
Davis, Ken
Digangi, Joshua
Farnsworth, Glenn
Ismail, Syed

Knepp, Travis
Lee, Hyung
Lee, Jane
Murchison, Luke
Menzies, Robert
Noe, Anna
Oliver, Donald
Petros, Mulugeta
Plant, James
Refaat, Tamer

Reithmaier, Karl
Remus, Ruben
Scola, Salvatore
Taylor, Bryant
Walsh, Brian
Welters, Angela
Wong, Teh-hwa
Yu, Jirong

Support

NASA Earth Science Technology Office (ESTO)
LaRC, Director's Office
LaRC, Engineering Directorate (ED)
LaRC, Science Directorate (SD)
LaRC, Research Service Directorate (RSD)
Goddard Space Flight Center (GSFC)
JET Propulsion Laboratory (JPL)
Science Systems and Applications, Inc. (SSAI)

Contribution

Michael Kavaya, Robert Menzies, Stephan Kawa, Xiaoli Sun and team
Colm Sweeney (NOAA)