

Carbon Dioxide Active Remote Sensing Using Pulsed 2- μ m Lidar

Tamer F. Refaat
Remote Sensing Branch
NASA Langley Research Center
Hampton, VA, USA
tamer.f.refaat@nasa.gov

Upendra N. Singh
Engineering and Safety Center
NASA Langley Research Center
Hampton, VA, USA
upendra.n.singh@nasa.gov

Abstract— A pulsed 2- μ m Integrated Path Differential Absorption (IPDA) lidar was developed at NASA Langley Research Center for high-accuracy and high-precision measurements of atmospheric carbon dioxide (CO₂). The instrument targets the R30 CO₂ absorption line and implements high-energy tunable on-line transmitter and advanced HgCdTe avalanche photodiode receiver. During 2019 airborne validation campaign, the IPDA was tested over the ocean for retrieving the weighted-average column dry-air volume mixing ratio of CO₂ (XCO₂) from 4.5 km altitude. XCO₂ measurement resulted in 404.43 ± 1.23 ppm using 10 s average, as compared to 405.49 ppm from prediction models. This translates to 0.26% and 0.30% relative accuracy and precision, respectively. Performance models were updated to scale the IPDA technology assuming operation from a space platform. Results present XCO₂ measurements using the instrument capabilities considering different target scenarios for Earth's surface. This demonstrates the potential for the IPDA technique and technology to achieve sustained global CO₂ measurement.

Keywords—carbon dioxide, active remote sensing, IPDA lidar, airborne testing

I. INTRODUCTION

Understanding atmospheric carbon dioxide (CO₂) sources, sinks and transport flux is critical for the scientific community and policy makers. CO₂ is a dominant greenhouse gas that directly affects global warming, climate change, and the carbon cycle on Earth. Mitigating CO₂ upsurge is a social benefit that requires continuous assessments using current sensing techniques and improved future technologies [1]. CO₂ lidar active remote sensing is a potential technique that overcomes some limitations for other measurement approaches [2]. A CO₂ differential absorption lidar (DIAL) provides its own radiation source that can be tuned to target specific absorption features. Airborne range-resolved DIAL results in retrieving CO₂ vertical profiles regardless of time and geographical location. In addition, weighted-average column dry-air volume mixing ratio (XCO₂) measurement of CO₂, over certain sampling volume, can be achieved using the integrated path differential absorption (IPDA) lidar. Unlike DIAL relying on atmospheric backscatter detection, IPDA relies on hard target reflected returns. These reflections provide higher signal-to-noise ratio (SNR), which enhances XCO₂ measurement precision and accuracy [2-6]. During IPDA airborne operation, supporting meteorological and geographical sensors assist instrument modeling and retrieval algorithms for directly converting the measured optical depth into XCO₂. NASA Langley Research Center (LaRC) has been involved in maturing

high-energy pulsed 2- μ m lasers for CO₂ IPDA and wind coherent lidar transmitters [7]. Combining both measurement capabilities potentially address CO₂ flux observations, recently advocated for by the Decadal Survey, to enhance studies of the gas transport phenomena [1].

A 2- μ m, high-energy, double-pulse, IPDA lidar has been developed at LaRC for XCO₂ measurements using airborne platforms. This instrument was an upgrade for the triple-pulse IPDA for independent and simultaneous CO₂ and water vapor (H₂O) measurement [8]. The double-pulse IPDA was validated for accurate and precise XCO₂ measurement using ground testing site and airborne campaign [3-4]. The airborne validation campaign was conducted in late 2019 and included four flights, consuming 15-hours of airborne time, using the NASA B-200 aircraft. This paper presents the XCO₂ measurement results using the IPDA lidar while flying over the Ocean. Although Ocean possesses low surface reflectivity of about 5%, focusing on its return provides consistent surface reflectivity and uniform target elevation suitable for long and stable measurements for IPDA validation. Besides, nearly 71% of the Earth's surface is covered by oceans, making it prevalent natural target from space. Scaling the technology for space-based applications will be discussed.

II. AIRBORNE IPDA LIDAR TECHNOLOGY

The IPDA lidar points nadir and is compatible with the payload of small research aircrafts, such as the King Air B-200. The lidar total volume is 0.57 m³ and total weight is 430 kg distributed among two racks and transmitter/receiver structure. The total steady-state power consumption is 2 kW [4, 9]. This IPDA targets the R30 CO₂ absorption line at 2050.9669 nm, as shown in Fig. 1. The figure shows the CO₂ spectra calculated for sea-level and 5 km altitude using HITRAN data base and Voigt line model [4]. Spectral profile variation between these two levels is due to atmospheric temperature and pressure changes with altitude. The figure also presents the spectral locations for the IPDA tunable on-line and fixed off-line wavelengths set for first and second pulses, respectively. IPDA detailed specifications are listed in [3-4]. IPDA consists of a laser transmitter and a receiver, including a data acquisition system. The design of the laser allows transmitting up to four pulses, using a single-pump pulse, with different wavelengths. Depending on measurement objective, the number of transmitted pulses, their energies and wavelengths are selected independently during operation. The wavelength of each pulse is set with respect to the wavelength of the R30 line using a reference CO₂ gas cell and wavelength controller. The laser pulses are transmitted coaxially with the receiver telescope.

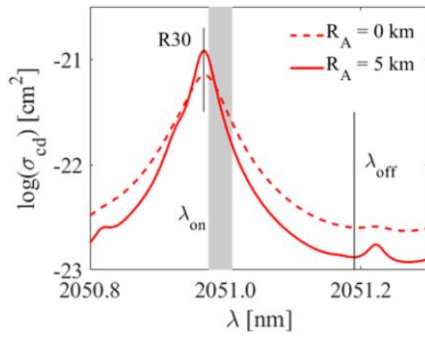


Fig. 1. Transmitted on-line and off-line wavelength settings for the 2- μ m IPDA lidar, in double pulse operational mode, with respect to CO₂ absorption spectra around R30 line. Gray area and black line mark the tunable on-line range and the fixed off-line wavelength positions [4].

A. IPDA Transmitter

During this validation campaign, the IPDA transmitter is set to produce double pulses for each pump pulse. The transmitter can provide a total maximum steady-state output energy of 80 mJ at 2- μ m. The pump repetition rate is 50 Hz, with 500 μ s pulse separation between the two pulses. Transmitter control electronics alternate the wavelength of the first and second transmitted pulses between on-line and off-line wavelengths, respectively, using ramp-and-fire injection seeding technique [3]. Off-line wavelength is set to 2051.1905 nm, 15.9 GHz away from R30 line center. The on-line wavelength is tunable between 2050.875 and 2051.010 nm, or 0.5 and 3.0 GHz, as compared to the R30 line in Fig. 1. Once the on-line position is selected, the wavelength is locked and stabilized. The transmitted energies are set to about 17.5 and 6.0 mJ for the on- and off-line pulses, respectively. During airborne operation, higher absorption loss through longer propagation range is anticipated by the on-line wavelength [4]. This is compensated for by transmitting higher on-line energy compared to off-line. While off-line transmitted energy encounters minimal absorption, it serves as normalization for the on-line accounting for losses due to atmospheric scattering and target reflectivity.

Continuous monitoring for the energy and wavelength of the transmitted laser pulses is conducted during the IPDA operation. Energy and wavelength monitors were developed and calibrated to provide real-time, per-shot, measurement for these parameters. This is important for the IPDA technique, allowing energy normalization between pulses and wavelength drift and jitter corrections, due to laser fluctuations [3-4, 10]. Correcting for laser fluctuations enhances the instrument sensitivity by reducing measurement systematic and random errors. High-speed, extended range InGaAs pin detectors are integrated within the laser enclosure for monitoring pulse energy and wavelength using direct and heterodyne detection techniques, respectively.

B. IPDA Receiver and Data Acquisition

The IPDA receiver consists of a Newtonian telescope formed by 0.4 m diameter aluminum hyperbolic primary mirror and coated flat fused silica secondary mirror. The secondary directs the return radiation to aft optics, while transmitting the expanded laser beam coaxially with the telescope. The telescope focuses the return radiation to a 300- μ m diameter spot size. The aft optics collimates, splits then re-focus the return radiation into two signal channels. A free-space InGaAs pin detector and fiber-coupled

HgCdTe electron-initiated avalanche photodiode (e-APD) form the detection systems for high- and low-signal channels, respectively (90%-10%) [11]. Receiver optical design reduces beam steering jitter effects on the collected radiation during airborne operations. The detection systems noise-equivalent-power result in 55 pW/Hz^{1/2} for the high-signal channel and 5.9 fW/Hz^{1/2} for the low-signal channel [12].

The data acquisition system for this IPDA consists of two similar, high-performance, 12-bit, two-channel digitizers. The system stores the collected signals for real-time processing and inspection. The digitizers continuously sample the high and low signal channels detectors, as well as monitor signals, at a fixed sampling rate of 1 GS/s. Laser Q-switch signal triggers data storage events that includes selected pre- and post-trigger samples. One digitizer is dedicated for transmitted energy and wavelength monitors, with a fixed record length. The other digitizer is used for the IPDA returns through the high- and low-signal channels, with a variable record length set depending on target distance or airborne altitude.

C. Supporting Instruments

Meteorological and geographical data are required during IPDA airborne operation for predicting instrument performance through IPDA model and converting the differential optical depth measurements into XCO₂. These data are obtained from other support instruments operating independently but synchronized with the IPDA onboard the aircraft [4, 11]. These support instruments include Global Positioning System (GPS), Inertial Navigation System (INS), meteorological probes and *in-situ* sensor. GPS records the lidar platform time and geolocation in terms of altitude, latitude, and longitude. INS records aircraft attitude, in the form of roll, pitch and yaw navigation angles. GPS and INS records are used for laser transmitter line-of-sight verification and determination of the ground target elevation [4]. Meteorological probes record ambient temperature and pressure at aircraft altitude. Temperature and pressure records are used to update the spectral analysis. A calibrated PICARRO commercial *in-situ* sensor was used for measuring the dry-air mixing ratios of water vapor (H₂O) and CO₂. H₂O records are used for molecular interference correction and dry-air mixing ratio derivation, while CO₂ record is used for validation comparison [4, 11].

III. ACTIVE SENSING OF XCO₂

The IPDA technique is based on the hard target lidar equation, in which the received power, P , for a transmitted radiation energy, E , set at wavelength, λ , is given by [4, 11]

$$P = \eta \cdot \varphi \cdot \frac{A}{R^2} \cdot \frac{E}{t} \cdot \rho \cdot \exp[\tau(R, \lambda)] \quad (1)$$

for a nadir airborne platform at fixed altitude, R , assuming Ocean target at sea level elevation. In (1) η is the receiver optical efficiency, φ is the overlap function, A is the receiver telescope area, t is the return signal pulse width, ρ is the target reflectivity, and τ is the total integrated double-path optical depth.

A. IPDA Model

For double-pulse operation, (1) is applied twice for on-line and off-line wavelengths, λ_{on} and λ_{off} , respectively. Solving for the differential double-path integrated optical depth, $\Delta\tau_m$, results in

$$\Delta\tau_m = \ln \left[\frac{P(\lambda_{off}) \cdot P(\lambda_{off}) / P(\lambda_{off})}{P(\lambda_{on}) \cdot P(\lambda_{on}) / P(\lambda_{on})} \right] \quad (2)$$

which is the main IPDA lidar product. For comparison and verification, the differential double-path integrated optical depth can be simulated, $\Delta\tau_s$, using the integral equation

$$\Delta\tau_s = 2 \cdot \int_R^0 \Delta\sigma_{cd}(\lambda_{on}, \lambda_{off}, r) \cdot N_{cd}(r) \cdot dr \quad (3)$$

where $\Delta\sigma_{cd}$ is the CO₂ differential cross section, obtained at λ_{on} and λ_{off} , and at atmospheric temperature and pressure at the range, r , and N_{cd} is the estimated CO₂ atmospheric number density. CO₂ number density is obtained using standard atmospheric models or supporting *in-situ* sensor, and in conjunction with HITRAN, are used to calculate the differential cross section.

B. Retrieval of XCO₂

The IPDA measured CO₂ differential double-path integrated optical depth is converted into XCO₂ using the equation

$$XCO_2 = \frac{\Delta\tau_m}{iW_{cd}} \quad (4)$$

where iW_{cd} is the range-based integrated weighting function obtained from (3), by replacing the CO₂ number density with the total dry-air number density, N_{dry} , in the form

$$iW_{cd} = 2 \cdot \int_R^0 \Delta\sigma_{cd}(\lambda_{on}, \lambda_{off}, r) \cdot N_{dry}(r) \cdot dr \quad (5)$$

Spectral analysis, meteorological records and range measurements are used for calculating the weighting function at the IPDA operating wavelengths for each transmitted shot.

C. Airborne Testing

The IPDA lidar flight campaign comprised four flights to achieve various goals. Fig. 2 shows the GPS ground tracks for these flights. Each flight included two instrument operators, aircraft pilot and navigator. The first flight was planned for testing instrument operation and verifying its performance using various settings at different altitudes, mostly targeting vegetation. The second flight was conducted over ocean targeting clear, broken cloud and cloudy conditions. The third flight was coordinated with NOAA for comparing the on-board CO₂ *in-situ* sensor with other, independently operated, CO₂ air sampling data at different altitudes over the ocean off Cape May, NJ [11]. Both *in-situ* and air sampling measurements were used to validate the IPDA measurement results, through modeling and retrieval. The fourth flight was conducted over land soil and vegetation toward Wilmington, NC, then over ocean until sunset, when return path follows the same trajectory. Therefore, this flight included both daytime and nighttime operation over land and ocean, as well as circular spiral maneuvers, as detailed in [4].

For all data records collected during flights, IPDA lidar signal processing included, background subtraction, return pulses integration, and energy normalization to obtain CO₂ double-path differential optical depths using (2). Processing also includes corrections due to laser energy fluctuations, wavelength shift, altitude and surface elevation, navigation angles and water vapor. Statistical analysis is conducted for rejecting abnormal results followed by 10-s (500) shot average. Then, the integrated weighting function is calculated using (5) for XCO₂ retrieval using (3), represented as X_{cd} . Also, (3) and (5) are used for XCO₂ prediction based on the *in-situ* measurement, represented as $X_{cd,model}$. Measurement accuracy, ΔX_{cd} , and systematic error, ϵ_s , are related and were evaluated according to

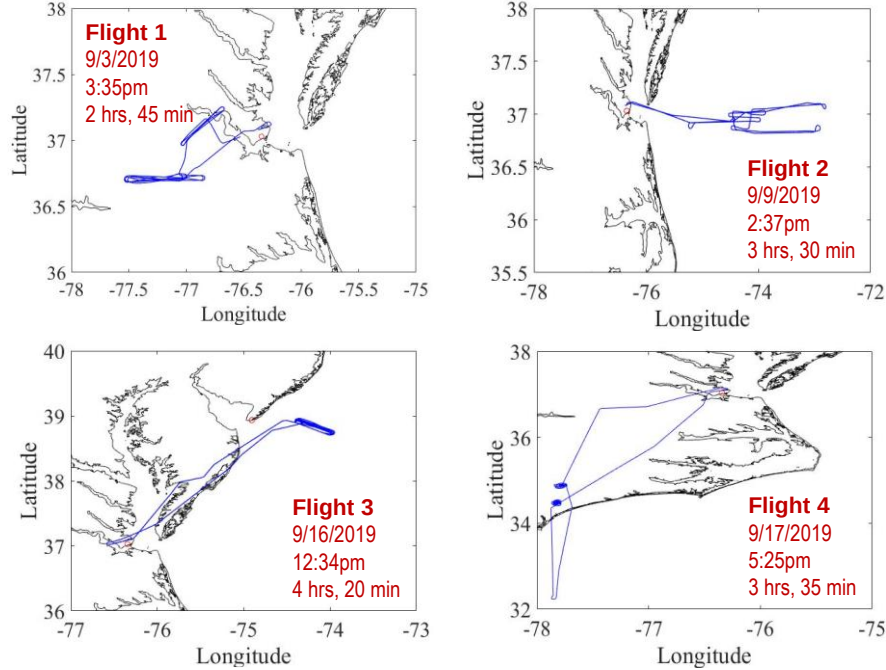


Fig. 2. Ground track for the four flights, conducted during IPDA lidar testing and validation campaign. All flights departed from Hampton, VA. Each plot includes takeoff date, local takeoff time, and flight duration.

TABLE I. IPDA PERFORMANCE FOR XCO₂ MEASUREMENT AS COMPARED TO MODEL.

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
Flight 4	1	1.6	407.38±2.48	404.34±3.55	3.04	2.54	0.75	0.63
	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	0.0644	1.6160
	2	400	400		0.25	0.23	0.0633	0.0569
	3	400	400		0.26	0.17	0.0647	0.0415
Δt_{cd} Requirement			400		0.35	0.35		
XCO ₂ Requirement			400		0.50	0.50		

$$\epsilon_S = \frac{\Delta X_{cd}}{X_{cd}} = \frac{X_{cd,model} - X_{cd}}{X_{cd}} \quad (6)$$

Standard deviations for IPDA retrieval and model prediction, $\delta X_{cd,i}$ and $\delta X_{cd,model}$, respectively, are used for estimating the precision, δX_{cd} , and random error, ϵ_R , according to

$$\epsilon_R = \frac{\delta X_{cd}}{X_{cd}} = \frac{\sqrt{\delta X_{cd,model}^2 - \delta X_{cd,i}^2}}{X_{cd}} \quad (7)$$

This accounts for eliminating natural CO₂ variability during IPDA operations. Table I lists IPDA performance results during sample records obtained over the Ocean during last three flights.

Fig. 3 shows a retrieved record for XCO₂ using the IPDA as compared to model prediction and *in-situ* measurement during the second flight. IPDA was operating from 4.7 km altitude using 3 GHz on-line. The transmitted energies were set to 8.3 mJ and 16.9 mJ for the off-line and on-line pulses, respectively. IPDA XCO₂ measurement agrees with model prediction. Difference between the *in-situ* and both modeled and measured XCO₂ is inherent to the IPDA technique due to the weighted averaging of (5). This shift is eliminated only if CO₂ is in a well-mixed condition without altitude dependence. Otherwise, the difference will exist depending on platform altitude and operating wavelengths [11].

Fig. 4 shows IPDA XCO₂ retrieved records as compared to model predictions, obtained at different conditions, in terms of altitude and on-line wavelength settings, during the third flight. At about 4 km altitude, and using 3 GHz on-line, consistent precision, of about 1.5 ppm, is observed between the second and third flights, as listed in Table I. The precision is enhanced to 0.5 ppm by operating at higher altitude, of 8 km, using the same wavelength. Higher altitude results in increased averaging column length, which reduces uncertainties. At 4.1 km altitude, precision is also enhanced by changing the on-line, from 3 GHz to 2 GHz, which is closer to R30 line center and thus improving the sensitivity. Precision deteriorates at lower altitude, of 1.6 km, and 1 GHz on-line is due to dominance of signal shot noise, where pin detection channel outperforms e-APD. Accuracy of the IPDA measurement is relative to modeling results. Therefore, accuracy deteriorates during higher CO₂ fluctuations as observed in the records of 3 GHz and 4 km altitude and 1 GHz and 1.6 km altitude. In both records, higher CO₂ fluctuations were predicted

by model and *in-situ* measurements. Natural CO₂ fluctuation is attributed to strong sources and sinks or higher accumulations that might exist which affects the differences between the mean values as indicated in (6).

Fig. 5 shows IPDA XCO₂ retrieved records as compared to model predictions, before and after sunset, during the fourth flight. The transmitted energies were set to 6.0 mJ and 17.5 mJ for the off-line and on-line pulses, respectively. Flight altitude of 4.5 km and 3 GHz on-line were maintained during these records, leading to consistent precision as compared to the second and third flights over moderate-state ocean surface, under the same operating conditions, as listed in Table I. Consistent results between daytime and nighttime measurements is expected since the instrument provides its own radiation source. The pulsed transmitter allows for background corrections resulting in IPDA independence from ambient background radiation.

The measurement and simulation results presented through these flights confirm the agreement between the IPDA XCO₂ active remote sensing and IPDA model estimates. This agreement validates the IPDA technique, using the developed technology, including measurement precision and accuracy, from an airborne platform. In addition, this agreement validates the modelling algorithms and procedures against ambiguities, which might arise due to applied spectral analysis and atmospheric models. IPDA model validation is a critical step for extending and scaling the technique for other measurement circumstances and applications that is hard to practically achieve, such as envisioning IPDA operation from a space-based platform.

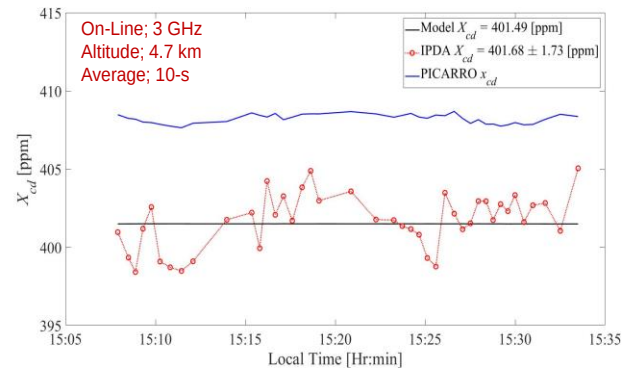


Fig. 3. XCO₂ retrieval using the IPDA as compared to model prediction and PICARRO measurement during the second flight. Off-line and on-line transmitted energies were set to 8.3 mJ and 16.9 mJ, respectively.

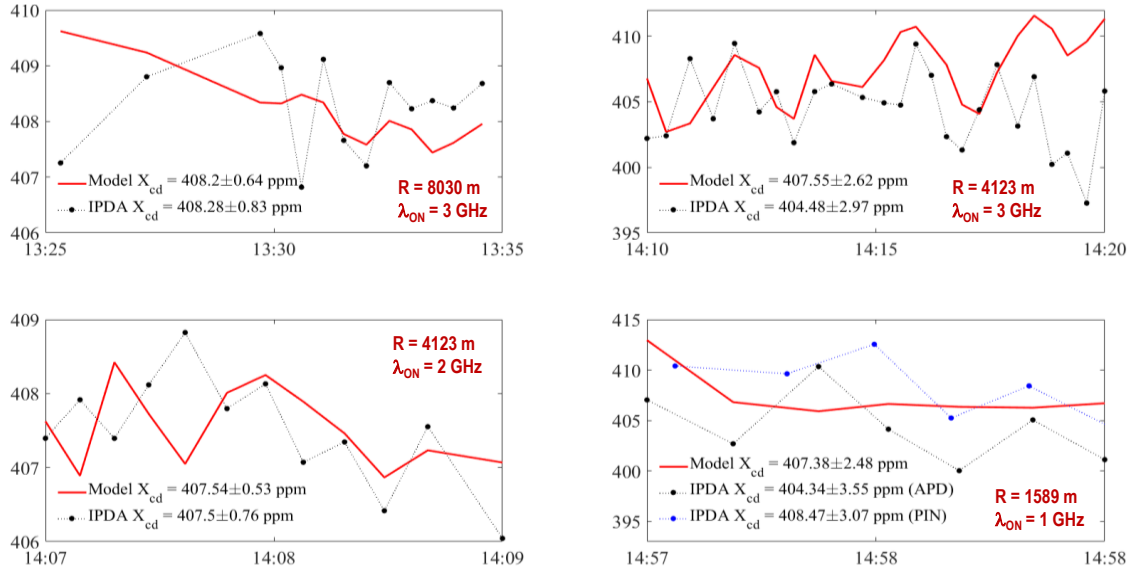


Fig. 4. XCO₂ retrieval using the IPDA, as compared to model predictions, obtained at 8.03 km and 3 GHz (top-left), 4.1 km and 3 GHz (top-right), 4.1 km and 2 GHz (bottom-left), and 1.6 km and 1 GHz (bottom-right), during the third flight. All IPDA records shown for e-APD detection system, except for lower altitude where pin outperform e-APD detection systems.

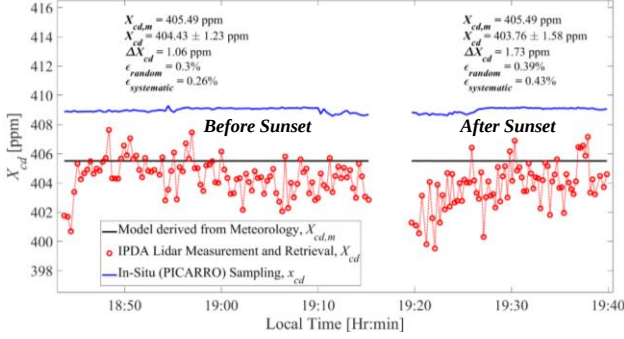


Fig. 5. IPDA XCO₂ retrieved records as compared to model predictions, and *in-situ* measurement, before and after sunset, during the fourth flight. Transmitted off-line and on-line energies, of 6.0 mJ and 17.5 mJ, respectively were used during these records [4].

IV. TECHNOLOGY SCALING FOR SPACE-BASED PLATFORM

Modeling of a space-based 2- μ m IPDA lidar was conducted for triple-pulse operation to demonstrate XCO₂ measurement capability and to evaluate random and systematic errors [13-14]. IPDA triple-pulse operation mode allows independent and simultaneous measurement of either XCO₂ using two different weighting functions or XCO₂ with single weighting function along with H₂O. Measurement of H₂O is useful for correcting molecular interference and dry-air mixing ratio derivation, without the need for an *in-situ* sensor. Therefore, transmitting three pulses increases science productivity, and enhances the transmitter efficiency by reducing the dissipated heat generated during each pump pulse [3, 8]. The performance of the high-energy laser transmitter and the sensitivity of the advanced e-APD detection system, allow for the IPDA to achieve efficient CO₂ sensing capabilities from space platforms. The IPDA model was applied for different scenarios covering common target reflectivity for different Earth surface conditions that are expected to be observed during space observations. These scenarios include land desert and vegetation, tropical land and

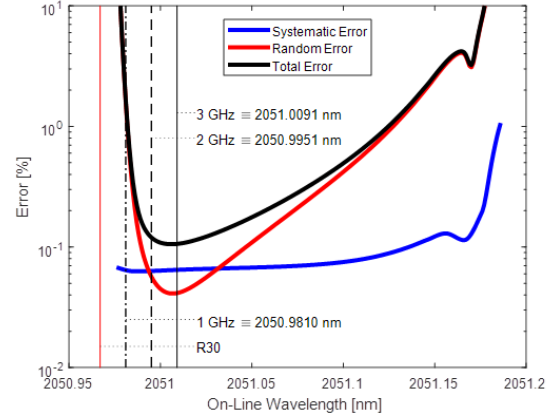


Fig. 6. Simulation results for the IPDA random and systematic errors, and total error, variation with on-line wavelength during space-based operation. Simulation assumes platform altitude of 400 km over ocean with tropical standard atmosphere, 10-s average and 5 and 15 mJ transmitted energy for the off-line and on-line pulses, respectively.

ocean, Southern Ocean and polar snow during summer and winter, thin clouds, and urban plums, as well as the Railroad Valley as a standard [2, 13]. Different aerosol and thin cloud optical depths were assumed, among mid latitude and sub-arctic summer and winter, tropics, and USA standard atmospheric models, which were included to simulate different atmospheric conditions. The model included on-line wavelength tunability, with special focus on XCO₂ measurement sensitivity for low troposphere, boundary layer and surface weighted averages [13].

Using the instrument model, total systematic error estimate is obtained by combining IPDA sensitivities to meteorological data and H₂O interference. Systematic error calculations depend on the applied atmospheric model, and associated uncertainties, and independent of aerosol and surface reflectivity. Random errors in IPDA measurement are directly related to the noise associated with the detection of the lidar signals including

variability of the surface reflectivity and slope, as well as laser speckle noise. Although random error can be reduced by shot averaging, Allan-variance analysis can be applied to define the maximum average that can be applied for a certain measurement set, without biasing the results.

The IPDA model was applied for simulating ocean return using tropical standard atmosphere, assuming 400 km space-based platform altitude, 15 mJ on-line transmitted energy, and 5 mJ off-line energy. Random error calculation was based on 10 s averaging (500 shots) and 400 ppm uniform CO₂ distribution. Table I lists the modeling conditions and results, as well as the IPDA sensitivity requirement for space-based mission as predicted by [2]. Fig. 6 shows the simulation results for the random and the systematic errors variations as a function of the on-line wavelength, as well as the total error budget for space-based operation.

Constant systematic error is observed with respect to the on-line wavelength. Random error varies with on-line wavelength, with a minimum occurring around 3 GHz. Operating closer to the line center increases the random error as expected from the results of the second flight due to shot noise domination. Away from line center both systematic and random errors increase due to reduced measurement sensitivity while on-line operating closer to the off-line. On-line setting closer to the off-line reduces the differential measurement due to lack of significant CO₂ on-line absorption. Therefore, the total error is mostly dominated by the random error while on-line is set closer to the line center or closer to the off-line. Otherwise, the total error is dominated by the systematic error, where random error is lower between 2 GHz and 4 GHz., as indicated in Table I. Table I lists the sensitivities requirement for optical depth and XCO₂ retrieval from space-based platform, using Railroad Valley reflectivity and US standard atmospheric model [2]. The 2-μm IPDA technique meets those space requirements, as predicted by the instrument model.

V. CONCLUSION

A 2-μm, high-energy, double-pulse, IPDA lidar was developed at LaRC for XCO₂ measurements using airborne platforms. This instrument was an upgrade for the triple-pulse IPDA for independent and simultaneous CO₂ and H₂O measurement. The instrument design is compatible with the NASA B-200 payload. IPDA performance was validated through an airborne campaign using four flights. Focusing on Ocean target provides stable surface reflectivity during airborne testing, which resulted in consistent CO₂ measurement precision during three different flights. Measurement and simulation results, obtained through these flights, confirm the agreement between the IPDA XCO₂ retrieval and model estimates. This agreement validates both the IPDA measurement technique and technology, as well as modelling algorithms and procedures. IPDA model validation is critical for scaling the technique to space-based platform. Modeling the IPDA was scaled for space-based application to demonstrate CO₂ measurement capability and to evaluate random and systematic errors. Space-based simulations predict 0.17 ppm random error and 0.26 ppm systematic error for XCO₂ measurements over ocean from 400 km altitude, using 3 GHz on-line and 10-s average. This IPDA lidar demonstrated reliability, readiness, and improved

performance for airborne operations and potential for future space applications. This is critical for achieving sustained global CO₂ measurements.

ACKNOWLEDGMENT

The authors acknowledge the support from NASA Earth Science Technology Office (ESTO) and NASA Langley Research Center Director's Office. The authors thank Mulugeta Petros, Ruben Remus, Charles Antill, and the 2-μm IPDA lidar team for their contribution during instrument development and validations.

REFERENCES

- [1] National Academies of Sciences, Engineering, and Medicine. Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space; The National Academies Press: Washington, DC, USA, 2018.
- [2] S. Kawa, J. Abshire, D. Baker, E. Browell, D. Crisp, S. Crowell, J. Hyon, J. Jacob, K. Jucks, B. Lin, "Active sensing of CO₂ emissions over nights, days, and seasons (ASCENDS)," *Final Report of the ASCENDS Ad Hoc Science Definition Team*, NASA/TP 219034, 2018.
- [3] T. Refaat, M. Petros, U. Singh, C. Antill, and R. Remus "High-precision and high accuracy column dry-air mixing ratio measurement of carbon dioxide using pulsed 2-μm IPDA lidar," *IEEE Transactions on Geoscience and Remote Sensing*, 58(8), 5804-5819, 2020.
- [4] T. Refaat, M. Petros, C. Antill, U. Singh, Y. Choi, J. Plant, J. Digangi, and A. Noe "Airborne testing of 2-μm pulsed IPDA lidar for active remote sensing of atmospheric carbon dioxide," *Atmosphere*, 12, 412, 2021.
- [5] U. Singh, T. Refaat, M. Petros, and S. Ismail, "Evaluation of 2-μm pulsed integrated path differential absorption lidar for carbon dioxide measurement— technology developments, measurements, and path to space," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 11(6), 2059-2067, 2018.
- [6] J. Yu, M. Petros, U. Singh, T. Refaat, K. Reithmaier, R. Remus, and W. Johnson, "An airborne 2-μm double-pulsed direct-detection lidar instrument for atmospheric CO₂ column measurements," *Journal of Atmospheric and Oceanic Technology*, 34, 385-400, 2017.
- [7] U. Singh, B. Walsh, J. Yu, M. Petros, M. Kavaya, T. Refaat, and N. Barnes, "Twenty years of Tm:Ho:YLF and LuLiF laser development for global wind and carbon dioxide active remote sensing," *Optical Materials Express*, 5(4), 827, 2015.
- [8] T. Refaat, U. Singh, J. Yu, M. Petros, S. Ismail, M. Kavaya, and K. Davis, "Evaluation of an airborne triple-pulsed 2 μm IPDA lidar for simultaneous and independent atmospheric water vapor and carbon dioxide measurements," *Applied Optics*, 54(6), 1387-1398, 2015.
- [9] T. Refaat, M. Petros, U. Singh, C. Antill, T. Wong, R. Remus, K. Reithmaier, J. Lee, S. Bowen, B. Taylor, A. Walters, A. Noe, and S. Ismail, "Airborne, direct-detection, 2-μm triple-pulse IPDA lidar for simultaneous and independent atmospheric water vapor and carbon dioxide active remote sensing," *Proc. of SPIE* 10779, 1077902, 2018.
- [10] T. Refaat, U. Singh, M. Petros, R. Remus, and J. Yu, "Self-calibration and laser energy monitor validations for a double-pulsed 2-μm CO₂ integrated path differential absorption lidar application," *Applied Optics*, 54(24), 7240-7251, 2015.
- [11] T. Refaat, U. Singh, J. Yu, M. Petros, R. Remus, and S. Ismail, "Double-pulse 2-μm integrated path differential absorption lidar airborne validation for atmospheric carbon dioxide measurement," *Applied Optics*, 55(15), 4232-4246, 2016.
- [12] T. Refaat, M. Petros, R. Remus, and U. Singh, "MCT APD detection system for atmospheric profiling applications using two-micron lidar," *EPJ Web Conf.* 237, 01013, 2020.
- [13] U. Singh, T. Refaat, S. Ismail, K. Davis, S. Kawa, R. Menzies, and M. Petros, "Feasibility study of a space-based high pulse energy 2 μm CO₂ IPDA lidar," *Applied Optics*, 56(23), 6531-6547, 2017.
- [14] U. Singh, T. Refaat, S. Ismail, M. Petros, K. Davis, S. Kawa, and R. Menzies, "Space-based active optical remote sensing of carbon dioxide column using high-energy two-micron pulsed IPDA lidar," *EPJ Web of Conferences* 176, 02001, 2018.