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Column carbon dioxide and water vapor measurements by an airborne triple-pulse integrated path differential absorption lidar – novel lidar technologies and techniques with path to space

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COLUMN CARBONN DIOXIDE AND WATER VAPOR MEASUREMENTS BY AN AIRBORNE TRIPLE-PULSE INTEGRATED PATH DIFFERENTIAL ABSORPTION LIDAR – NOVEL LIDAR TECHNOLOGIES AND TECHNIQUES WITH PATH TO SPACE

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I. INTRODUCTION

The 2-micron wavelength region is suitable for atmospheric carbon dioxide (CO_2) measurements due to the existence of distinct absorption features for the gas at this wavelength region [1]. For more than 20 years, researchers at NASA Langley Research Center (LaRC) have developed several high-energy and high repetition rate 2-micron pulsed lasers [2]. Currently, LaRC team is engaged in designing, developing and demonstrating a triple-pulsed 2-micron direct detection Integrated Path Differential Absorption (IPDA) lidar to measure the weighted-average column dry-air mixing ratios of carbon dioxide (XCO_2) and water vapor (XH_2O) from an airborne platform [1, 3-5]. This novel technique allows measurement of the two most dominant greenhouse gases, simultaneously and independently, using a single instrument. This paper will provide status and details of the development of this airborne 2-micron triple-pulse IPDA lidar. The presented work will focus on the advancement of critical IPDA lidar components. Updates on the state-of-the-art triple-pulse laser transmitter will be presented including the status of seed laser locking, wavelength control, receiver and detector upgrades, laser packaging and lidar integration. Future plans for IPDA lidar ground integration, testing and flight validation will also be discussed. This work enables new Earth observation measurements, while reducing risk, cost, size, volume, mass and development time of required instruments.

The lack of spatially extensive, high-accuracy atmospheric CO_2 data limits the ability to construct accurate inverse estimates of the sources and sinks of the gas. Airborne full range-resolved differential absorption lidar (DIAL) measurements of CO_2 appear to be beyond near-term technological capability. In absence of range-resolved DIAL capabilities, airborne XCO_2 measurements weighted toward the boundary layer (BL) are ideal for studying CO_2 sources and sinks [6-8]. This is achieved using IPDA lidar technique, which relies on stronger hard target return signals rather than weak atmospheric scattering. In addition, an airborne instrument provides an excellent complement to the temporally-rich but spatially sparse in-situ measurement network. The BL weighted XCO_2 data can be used to evaluate the ability of GOSAT and OCO-2 to detect spatial variability in lower tropospheric CO_2. Simultaneous measurement of XCO_2 and XH_2O enables the study of coupled carbon and water cycles [9-10].

The design of the airborne triple-pulse IPDA lidar instrument enables development of technologies for space-based system for global CO_2 measurement [2, 6]. NASA and JAXA have developed and successfully launched space-based passive remote sensors to monitor global distribution of CO_2 [10-11]. There are planned mission by China, France and ESA to launch satellites with passive remote sensing instrument to monitor carbon dioxide emissions around the globe [6]. These activities have resulted in intense collaboration to advance carbon and climate science. There is a need for similar international collaboration to enable an active CO_2 space-based mission to understand critically important processes related to CO_2 sources and sinks and to provide validation of various CO_2 sensing systems.

II. TRIPLE-PULSE IPDA LIDAR

Based on the successful demonstration of the double-pulse IPDA lidar, the triple-pulse IPDA lidar transmitter generates three successive laser pulses for every pump pulse at pump repetition rate of 50 Hz [12]. Table 1 compares the double-pulse and triple-pulse 2-μm IPDA lidar transmitters [1-2, 6, 12]. The three pulses are 150 μsec apart and locked to three different wavelengths, as shown schematically in Fig.1. Using an enhanced wavelength control scheme the wavelength of each of these pulses can be tuned and locked at different wavelength, as marked in Fig.2. One scenario of wavelength selection is demonstrated in the same figure. The CO_2 on and off-line wavelengths are selected around the R30 line, so that both would have similar H_2O absorption to minimizes water vapour interference on CO_2 measurements. Similarly, H_2O on- and off-line are selected around the nearest H_2O absorption peak such that carbon dioxide interference is minimized in the H_2O measurement.

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Table 1. Comparison of CO_2 active remote sensing state-of-the-art 2-µm laser transmitters, developed at NASA LaRC, with ESA space requirements [2, 6].

	Current Technology	*Projected Technology*	*Space Requirement*
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

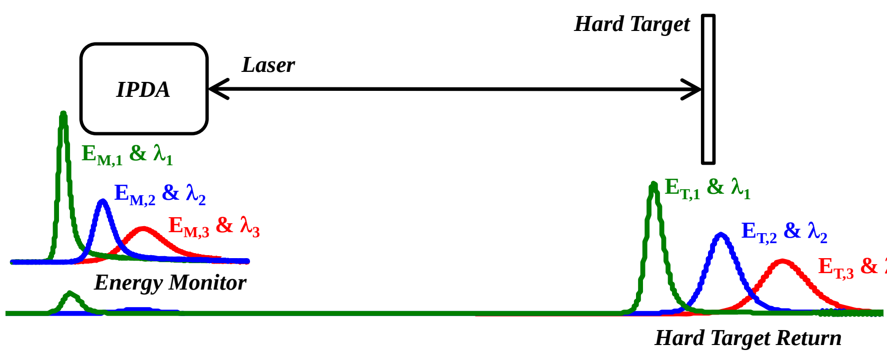

Fig. 1. 2-µm triple-pulse IPDA lidar principle of operation for simultaneous atmospheric CO_2 and H_2O measurement. The energy of each transmitted pulse is monitored inside laser enclosure. The wavelength of each pulse can be tuned and locked independently to any position around the CO_2 R30 line. One wavelength criteria for minimizing molecular interference errors is presented in Fig.2.

However, both CO_2 on-line and H_2O off-line measurements share the same wavelength, which enables simultaneous measurement of both molecules with three pulses rather than four pulses almost independently while avoiding interference from each other [1].

Other scenarios could be achieved with the same IPDA instrument just by tuning and locking the operating wavelengths of the three pulses to different positions. For example, wavelength tuning allows measuring CO_2 with two different weighting functions simultaneously as shown in Fig.3. Fig.3 indicates that the selected CO_2 on-line wavelength is optimized for near-surface measurements. Shifting this wavelength by 67 or 75 pm would tune the weighting function to optimize measurements in the BL or lower troposphere. This IPDA tuning feature results in a unique adaptive targeting capability. For an airborne IPDA lidar, adaptive targeting would tune and lock the instrument sensing wavelength to meet certain measurement objective depending on the target or Earth's surface condition and environment.

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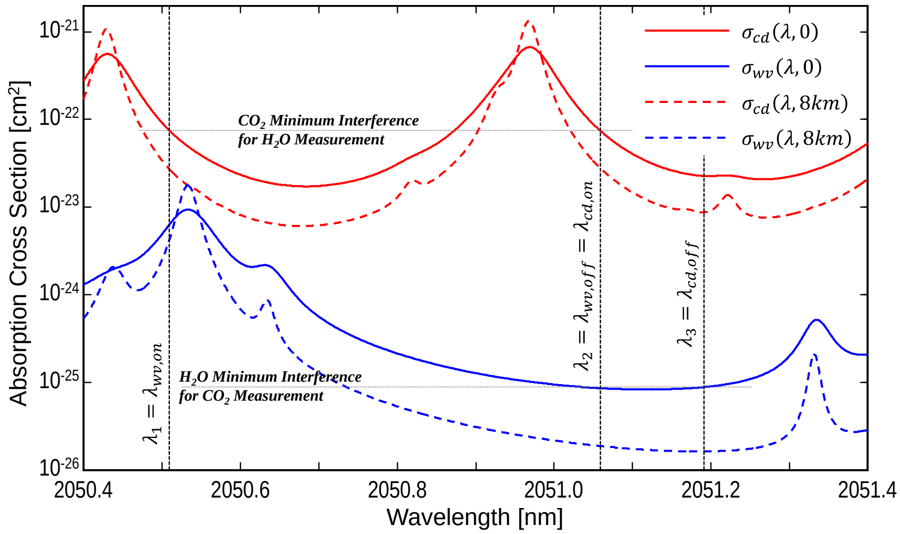

Fig. 2. Comparison of the H_2O and CO_2 absorption cross-section spectra, σ_{wv} and σ_{cd}, respectively, at ground (0 km) and mid-altitude aircraft (8 km). Temperature and pressure profiles used in the calculation were obtained from the US Standard atmospheric model. Vertical lines mark the instrument operating wavelengths for CO_2 and H_2O independent measurements. Note that λ_1 is the H_2O on-line, λ_2 serves as the H_2O off-line, and the CO_2 on-line and λ_3 is the CO_2 off-line. The horizontal lines point to cancellation of molecular interference errors [1].

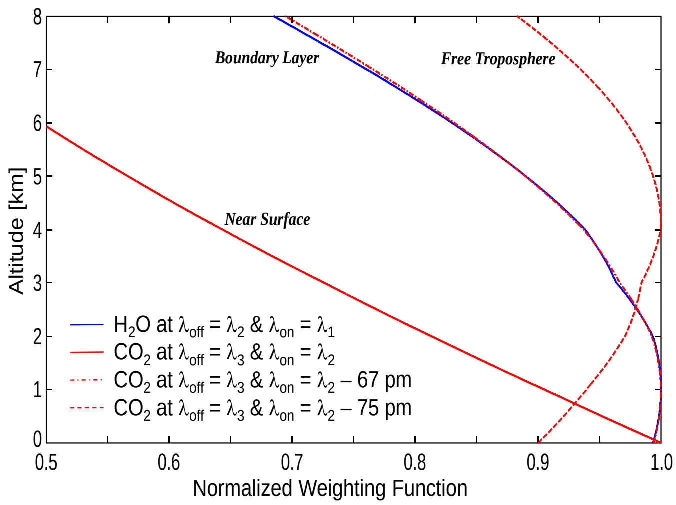

Fig. 3. H_2O and CO_2 pressure-based normalized weighting functions versus altitude at selected spectral positions for an airborne nadir pointing IPDA measurement. H_2O and CO_2 measurements are weighted to BL and near the surface, respectively, for operating wavelength shown in Fig.2. Tuning CO_2 on-line wavelength 67 and 75 pm away from the selected location optimize the IPDA measurement to within BL or free troposphere.

A. Triple-Pulse Transmitter

The triple-pulse IPDA laser transmitter is based on the Ho:Tm:YLF high-energy 2-μm pulsed laser technology, with end pumping using 792 nm AlGaAs diode arrays [4]. Relative to the pump pulse, Q-switch triple-trigger produces three successive laser pulses with relatively controlled energies and pulse-widths. Pulses in this arrangement are separated by approximately 150-200 μsec. Thermal analysis was conducted to design proper heat dissipation out of the laser crystal to avoid permanent damage. A prototype oscillator with triple pulsing capability has already been demonstrated. Fig.4 shows a single-shot pulse record generated from the oscillator. Final laser configuration including thermal analysis and alignment optimization is currently on going to achieve higher energies.

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A study indicated that ±1 MHz on-line wavelength jitter is the dominant transmitter systematic error source for this triple-pulse IPDA instrument [1]. This drives the need for a precise wavelength locking mechanism to reduce such error. The exact wavelengths of the pulsed laser transmitter are controlled by a wavelength control unit. The unique wavelength control of the triple pulses uses a single semiconductor laser diode, obtained from NASA Jet Propulsion Laboratory (JPL) and provides three different seeds of any frequency setting within 35 GHz offset from the locked CO_2 R30 line center reference [13-15]. This unit includes several electronic, optical and electro-optic components which were acquired and characterized at NASA LaRC. Laser diode driver electronics results in a wavelength jitter of ±6.1 MHz This jitter is significantly reduced to ±650.1 kHz using center line locking electronics, as demonstrated in Fig.5 [14]. This meets the jitter limit objective [1]. Work is in progress to finalize this unit and apply it as the seed source for the oscillator.

B. IPDA Receiver, detection and Data Acquisition Systems

Similar to the double-pulse IPDA, the 2-μm triple-pulse IPDA lidar receiver consists of a 0.4 m Newtonian telescope that focuses the radiation onto 300 μm diameter spot. The telescope secondary mirror is a two surface dichroic flat. One surface turns the return radiation 90º to the side integrated aft-optics. The opposite surface is used to transmit the expanded laser beam coaxially with the telescope. A single automated mount is used for bore-sight alignment. The radiation collected by the telescope is focused, collimated, filtered then applied to a 90%-10% beam splitter. The 90% signal channel is an exact replica of the double-pulsed lidar using an InGaAs pin photodiode. The 10% channel is planned to be used with an HgCdTe electron-initiated avalanche photodiode (e-APD) detector [16]. These e-APD devices are space-qualifiable and were validated for airborne lidar operation at 1.6-μm at NASA Goddard Space Flight Center (GSFC) [17]. In co-ordination with NASA Earth Science Technology Office (ESTO), LaRC is collaborating with GSFC to integrate this detector into the 2-μm IPDA. This e-APD exhibit less than 0.5 $fW/Hz^{1/2}$ noise-equivalent-power (NEP) and is expected to enhance the 2-μm IPDA detection performance by reducing random errors.

The IPDA lidar hard target return signals are digitized and stored using a data acquisition unit. The data acquisition unit is based on two similar high-performance digitizers (Agilent; U5303A). Each digitizer consists of 2-channels that are digitized at 1 GS/s. Both units are enabled through the pump pules and triggered from the laser Q-switch driver. One digitizer is dedicated to the IPDA lidar hard target return signals, with a variable record length of about 70k samples. The other digitizer is dedicated to laser energy monitors, which are integrated within the transmitter enclosure, with a fixed record length of 10k. Real-time data processing allows visual inspection of measured return signal strengths, optical depths and signal-to-noise ratios. Both raw data and/or processed data storage options are available, which significantly alter storage capacity [4].

C. Instrument Integration and Validation Plans

During double-pulse IPDA lidar development, a trailer was prepared as a mobile lidar laboratory for instrument ground testing at NASA LaRC and ground-based field validation campaigns. This trailer, shown in Fig.6, will be reused for the triple-pulse IPDA initial integration and ground testing. In addition, availability of the double-pulse instrument provides an excellent test bed for different triple-pulse component evaluation such as, updated laser control electronics, seeding, e-APD detection and data acquisition. Anticipated laser transmitter and integrated

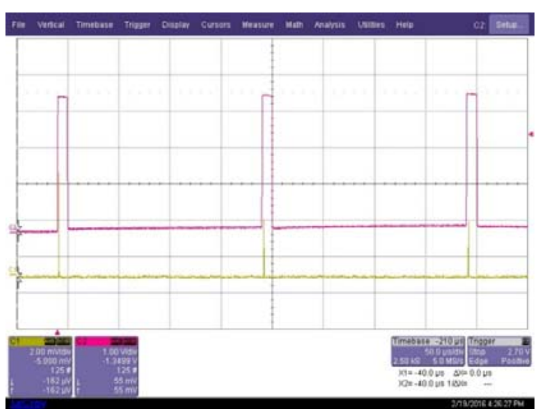

Fig. 4. Oscilloscope record for a successful triple-pulse operation. The record shows the three pulse profiles (yellow) relative to the Q-switch triggers (red).

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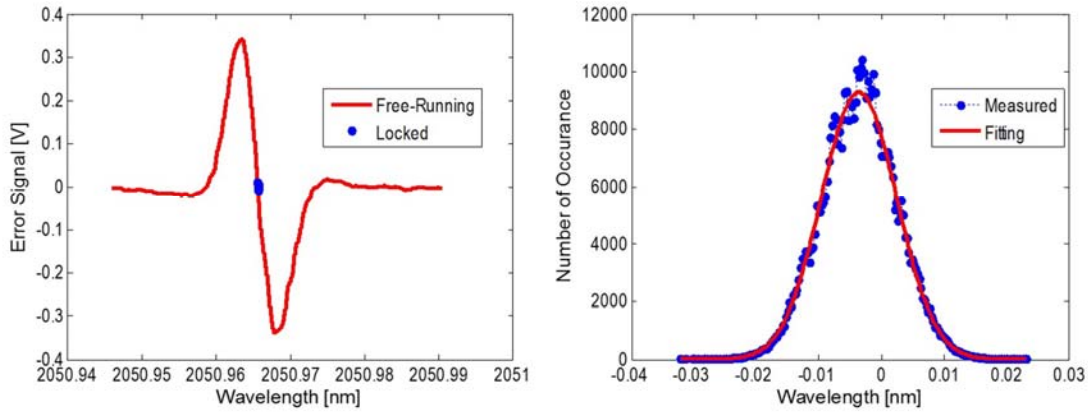
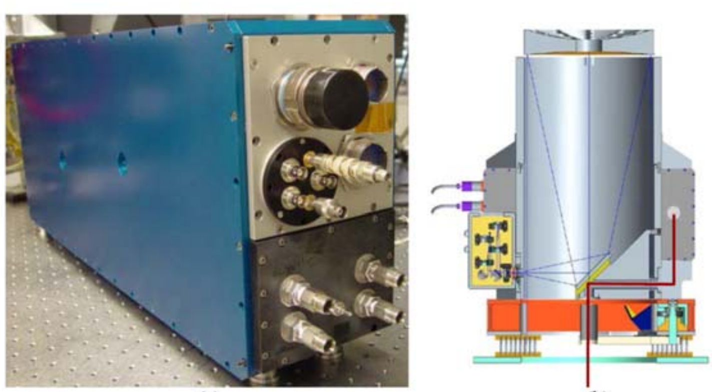


Fig. 5. Comparison of the error signals for the center line locking electronics free-running and locked modes (left). Statistical analysis and Gaussian fitting (right) of the locked wavelength results in wavelength mean and standard deviation of 2050.966967 nm and 0.00913 pm, respectively. This standard deviation translates to ±650.1 kHz wavelength jitter.

Fig. 6. Picture of the mobile lidar laboratory. Located at NASA LaRC, the laboratory is used for IPDA instrument integration and horizontal and vertical pointed ground testing, as well as future field deployment.



(a) (b)

Fig. 7. (a) Projected packaging of the 2-µm IPDA laser transmitter. The transmitter is 11.5×26.5×6.4 inch (29×67.3×16.5 cm) in size and weight less than 70lbs (31.75 kg). (b) Schematic of the 2-µm IPDA system. Red lines mark the expended transmitted beam and blue lines mark the return radiation focused onto two detection channels with InGaAs pin and HgCdTe e-APD detectors.

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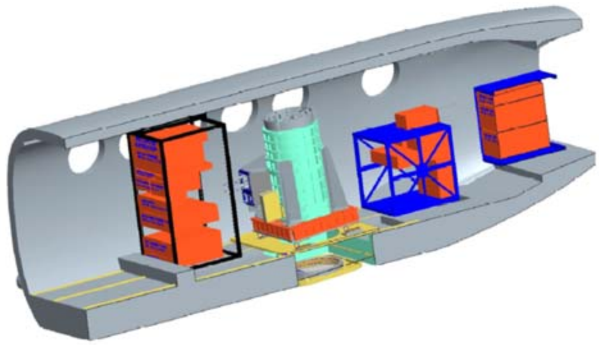

Fig. 8. Projection of the 2-μm triple-pulse IPDA instrument integration inside the NASA B-200 aircraft.

triple-pulse IPDA lidar are shown in Fig.7. Once complete, airborne integration would start by installing the instrument to the NASA B-200 aircraft. The IPDA accommodation inside the aircraft is shown in Fig.8. The instrument size, weight and power consumption were designed to meet the payload requirements for such small aircraft. This design allows instrument integration to any larger airborne research platform for future missions. Other housekeeping instruments will be integrated into the B-200 aircraft as well, which will include a LiCor in-situ sensor for CO_2 and H_2O mixing ratio measurement, Inertial Navigation and Global Positioning Systems (INS/GPS) for global timing, aircraft position, altitude and angles measurements and a video recorder for target identification. Besides, aircraft built-in sensors provide altitude, pressure, temperature and relative humidity sampling at flight position.

The 2-μm triple-pulse IPDA lidar validation is important to assess both CO_2 and H_2O atmospheric measurements. Instrument validation will start during instrument integration in the mobile lidar laboratory. The mobile laboratory enables IPDA lidar horizontal measurement using a set of calibrated hard targets and vertical atmospheric measurements using clouds as hard target. Ground validation objectives are to check the IPDA lidar operational readiness before aircraft deployment. This will be achieved by obtaining IPDA signals and noise to evaluate instrument systematic and random errors, comparing IPDA lidar errors to instrument performance models and to compare with CO_2 and H_2O measurements against correlative in-situ instruments. Other objectives include transporting the mobile lidar laboratory, with the integrated instrument, to different tall tower sites, such as WLEF tall tower in Park Falls, Wisconsin, and the Southern Great Plains ARM site in Lamont, Oklahoma.

For airborne validation, initial engineering flights would focus on instrument operation and comparing airborne and ground performances. Later flights would focus on comparing CO_2 and H_2O measurements against correlative in-situ sensors and models. Further validation will rely on onboard sensors as well as coordinated measurements with other independent sensors, such as NOAA air-sampling and Pennsylvania State University passive sensors, in collaboration with the science community. Airborne validation will be planned to target different conditions such as different surface reflectivity, day and night background, clear, cloudy and broken cloud conditions, variable surface elevation and urban pollution and plume detection. The validation may also cover different locations such as the Upper Midwest summer, where strong vertical and horizontal spatial gradients in atmospheric CO_2 occur due to agricultural activities and urban deployments in winter/summer, with flight around isolated urban Centers to identify a clear and polluted BL CO_2 plumes. The 2-μm triple-pulse validation activities provide opportunities to coordinate with ACT-America flights.

III. TRIPLE-PULSE IPDA FOR CO_2 SPACE-BASED ACTIVE REMOTE SENSING

The 2-μm triple-pulse IPDA lidar instrument development allows technologies advancement for CO_2 measurements from space. This development is planned to enable significant technical and technological advances in the transmitter, detection and data retrieval capabilities that are critical for a space-based mission. Table 1 compares the transmitter technology parameters of the demonstrated double-pulsed airborne IPDA lidar system, the triple-pulsed IPDA lidar system under development, and recently released pulsed 2-μm IPDA technology space requirements from ESA [6]. ESA objective is to develop future space borne active sensing mission for measuring the dry-air mixing ratio of CO_2 in the troposphere with a high accuracy on the 1.0 ppm level [6]. The new triple-pulse laser will meet or exceeds most of the transmitter requirements for space-borne CO_2 measurement. The unique triple pulse capability has additional advantages. Having one laser delivering, near simultaneously, three pulses at different frequencies eliminates the complexity and need of three different lasers. This is a significant step towards reducing mass, size and power consumption of the instrument to one third and

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increasing the efficiency by a factor of three. The triple pulsing from single laser oscillator eliminates the challenge and complexity in co-aligning and bore-sighting three independent beams. This early development of space qualifiable lasers and air-borne operations will reduce the risk towards future space operation.

Feasibility studies of a space-based CO_2 active remote sensing using the 2-μm triple-pulse IPDA lidar is in progress. Preliminary analysis using a 1.5 m telescope, assuming Railroad Valley reference conditions, have been conducted and the performance predictions are encouraging [8]. A 400 km 88 degree inclination, dawn-to-dusk Sun synchronous orbit with a 16 day repeat cycle are assumed. This will provide good latitudinal coverage and sampling over $1^{o}\times1^{o}$ grid. Initial estimates of spacecraft mass and power, for the CO_2 IPDA lidar payload, are 400kg and 750W, respectively, for a 3 years mission lifetime. This lidar payload can be accommodated using several launch vehicle. Further analysis of different global Earth's targets including land vegetation, desert, tropics and polar snow as well as ocean for summer and winter, along with thin clouds and urban plumes, as special cases are being studied. The main objective of the study focuses on conducting a parametric study for an optimized IPDA system to enhance signal-to-noise ratio and meet error budget requirements, including both random and systematic errors, and to select wavelengths for adaptive targeting.

IV. SUMMAARY AND CONCLUSIONS

The societal benefits of understanding climate change through identification of global carbon dioxide sources and sinks led to the desired NASA's active sensing of CO_2 emissions over nights, days, and seasons (ASCENDS) space-based missions of global carbon dioxide measurements [18]. The ASCENDS study advocates an active CO_2 remote sensing mission to provide critical global CO_2 measurements. In absence of mature technological capability of CO_2 range-resolved DIAL, the favored solutions are direct detection pulsed IPDA lidar. A 2-μm triple-pulse IPDA lidar instrument is being developed at NASA LaRC. This active remote sensing IPDA instrument has the capability to measure both atmospheric CO_2 and H_2O. Wavelength selection and laser transmitter operation allows measuring both species independently and simultaneously. Instrument design is based on knowledge gathered through the previous successfully demonstrated 2-μm double-pulse IPDA lidar. Critical transmitter and receiver systems enhancements were implemented in the new triple-pulse design that significantly advance the IPDA technology. In the transmitter, modifications included triple-pulse operation, 50 Hz pulse repetition rate of the laser, and wavelength control design, based on a single seed laser diode from NASA JPL. The receiver updates include additional high performance e-APD detector and advanced data acquisition system. The e-APD detector supplied by NASA GSFC, is a state-of-art, space qualifiable device that was validated for lidar applications. Progress of the 2-μm triple-pulse IPDA development program is on schedule. Instrument validation plans are being discussed and plans to collaborate with different institutes are underway.

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