COLUMN CO_2 MEASUREMENT FROM AN AIRBORNE SOLID-STATE DOUBLE-PULSED 2-MICRON INTEGRATED PATH DIFFERENTIAL ABSORPTION LIDAR

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I. INTRODUCTION

Carbon dioxide (CO_2) is an important greenhouse gas that significantly contributes to the carbon cycle and global radiation budget on Earth. CO_2 role on Earth's climate is rather complicated due to different interactions with various climate components that include the atmosphere, the biosphere and the hydrosphere [1-2]. These interactions define CO_2 sources and sinks that influence the gas transport fluxes worldwide. Understanding the interactions and transport of atmospheric CO_2 around Earth is critical for carbon cycle studies and climate predictions through environment models [3-5]. Although extensive worldwide efforts for monitoring atmospheric CO_2 through various techniques, including *in-situ* and passive sensors, are taking place high uncertainties exist in quantifying CO_2 sources and sinks mainly due to insufficient spacial and temporal monitoring of the gas. Therefore it is required to have more rapid and accurate CO_2 monitoring with higher uniform coverage and higher resolution. This was addressed by many international satellite missions. Satellites offered many advantages including the ability of continuously measuring CO_2 in tropical regions and over southern oceans [1-2]. Present satellite instruments monitoring CO_2 from space include SCIAMACHY, TES, AIRS, IASI and GOSAT [6-10]. To focus only on CO_2 and address the issue of the gas sources and sinks, OCO-2 is fully dedicated for CO_2 monitoring [11]. Some of these systems have shown the potential to meet the spatial coverage to improve CO_2 flux estimates on continental scales. However, satellite passive remote sensors are unable to meet the accuracy required to aid in better quantifying the terrestrial sources and sinks due to some limitations. For instance, shortwave infrared instruments rely on solar illumination which restricts their orbits and latitudinal coverage. Alternatively, thermal infrared systems relying on Earth's radiation are not sensitive to the lower atmosphere where the largest CO_2 interactions occur. Furthermore, passive remote sensing systems involve retrieval complexities which suffer from aerosol and cloud contamination and radiation path length uncertainties [12]. Active remote sensing of CO_2 is an alternative technique that has the potential to overcome the limitation of the passive sensors.

CO_2 active remote sensing has been demonstrated using the differential absorption lidar (DIAL) technique [13-21]. Both 1.6 and 2.0 μm are suitable for atmospheric CO_2 measurements due to the existence of distinct absorption feathers for the gas at these particular wavelengths. Although CO_2 DIAL systems demonstrations were provided for systems validity from ground or airborne platforms, a complete CO_2 DIAL mission that contributes to the science community has not been established. A number of worldwide teams have been engaged in developing CO_2 DIAL instruments using different transmitters and detection methods. In France, a CO_2 DIAL was developed based on 2-μm pulsed crystal-open path cavity transmitter and heterodyne detection [13]. In Germany a 1.6-μm pulsed optical parametric oscillator transmitter with direct detection has been developed [14]. In Japan similar systems were developed for ground based measurement [15-16]. In the USA, the National Research Council Decadal Survey recommended an active laser-based CO_2 mission, "Active Sensing of CO_2 Emissions over Night, Days, and Seasons (ASCENDS)", to increase our understanding of CO_2 sources, sinks, and fluxes worldwide [1]. Research groups at NASA are currently involved in developing different CO_2 DIAL instruments. Two of these instruments operate at 1.6 μm have been developed and deployed as airborne systems for atmospheric CO_2 column measurements [17, 19]. One instrument is based on an intensity modulated continue wave (CW) approach [19], the other on a high pulse repletion frequency, low pulse-energy approach [17]. These airborne CO_2 DIAL systems operating at 1.57-μm utilize mature laser and detector technologies by taking advantage of the technology development outcomes in the telecom industry.

CO_2 DIAL operating in the 2-μm band offer better near-surface CO_2 measurement sensitivity due to the intrinsically stronger absorption lines. Using a 2.05-μm CW laser absorption spectrometer employing coherent detection method, airborne measurements of CO_2 column abundance has been demonstrated [18]. For more than 15 years, NASA Langley Research Center (LaRC) contributed in developing several 2-μm CO_2 DIAL systems and technologies. This paper focuses on the current development of the airborne double-pulsed 2-μm CO_2 integrated path differential absorption (IPDA) lidar system at NASA LaRC. This includes the IPDA system development and integration. Results from ground and airborne CO_2 IPDA testing will be presented. The potential of scaling such technology to a space mission will be addressed.

II. TWO-MICRON CARBON DIOXIDE IPDA LIADR SYSTEM

Double-pulse 2-μm lasers have been developed with energy as high as 600 mJ and up to 10 Hz repetition rate [22]. A single pump pulse produces the two laser pulses at the 2-μm wavelength which are separated by 150 μs. Both pulses can be tuned and locked separately around 2.05μm wavelength. Implementing this laser for a CO_2 IPDA system, the first and second pulses are tuned and locked to strong and weak absorption features of the molecule known as the on-line and off-line wavelengths, respectively. Applying the double-pulse laser in IPDA system enhances the CO_2 measurement capability by increasing the overlap of the sampled volume between the on-line and off-line [23-24]. IPDA offers measurements with higher signal-to-noise ratio compared to conventional range-resolved DIAL. This is due to the fact that IPDA rely on the much stronger energy monitors and hard target returns that are best suited for airborne platforms, rather than weak atmospheric scattering returns provided in range-resolved DIAL. In absence of range profiling, the IPDA technique measures the total integrated column content from the instrument to the hard target but with weighting that can be tuned by controlling the transmitted wavelengths. Therefore, the transmitter could be tuned to weight the column measurement to the surface for optimum CO_2 interaction studies or up to the free troposphere for optimum transport studies. Currently, NASA LaRC is developing and enhancing IPDA data processing algorithms for CO_2 column measurement from an airborne platform [23-24]. Fig. 1 shows an isometric view of the key components of the 2-μm CO_2 IPDA system.

A. IPDA Lidar Transmitter

The compact, rugged, highly reliable CO_2 IPDA laser transmitter is capable of generating 100 mJ at 10 Hz [22-23]. The transmitter is based on the Ho:Tm:YLF high-energy 2-μm pulsed laser technology. This laser transmitter is side pumped by AlGaAs diode arrays at 792 nm and designed to operate in a unique double pulse format to mitigate the effect of the surface reflection difference between the on-and-off line pulses on the precision of the IPDA measurement. When the Ho upper laser level population reaches its maximum value at the end of the pump cycle, a first Q-switched pulse is generated which extracts the energy stored in the Ho $^5I_7$ upper laser level, resulting in a sharp decrease in the upper laser level population. Then, a new population equilibrium between the Tm $^3F_4$ and Ho $^5I_7$ manifolds is established by energy transfer from the excited Tm ions towards Ho ions even though the pump no longer exists. The population at Ho upper laser level $^5I_7$ comes to its second maximum about 150 μs after the first pulse. The second Q-switch pulse is triggered at this moment resulting in the desired double pulse operation. A unique feature of this laser operation is that it provides two Q-switched pulses with a single pump pulse [22].

The exact wavelengths of the pulsed laser transmitter are controlled by the wavelength control unit. The first pulse and the second pulse are injection seeded alternately by the on-line and the off-line wavelengths. All the optical mounts are custom designed with space heritage. They are designed to be adjustable and lockable and hardened to withstand vibrations that can occur during operation in an airborne environment. Fig. 2a shows a picture of the engineering packaged laser transmitter. This laser transmitter is 11.5×26.5×6.4 inch (29×67.3×16.5 cm) in size, and weighted less than 70lbs (31.75 kg). Transmitter packaging includes a beam expander at the laser outlet which results in a final 2.54 cm output beam diameter.

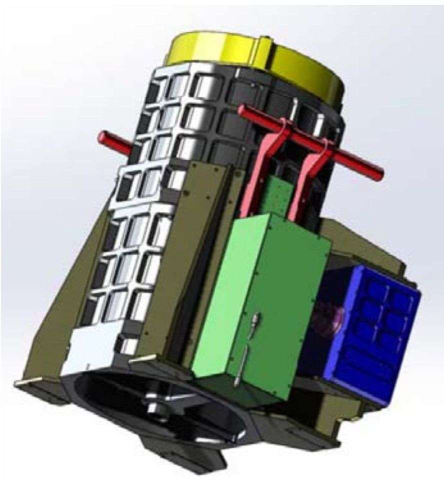


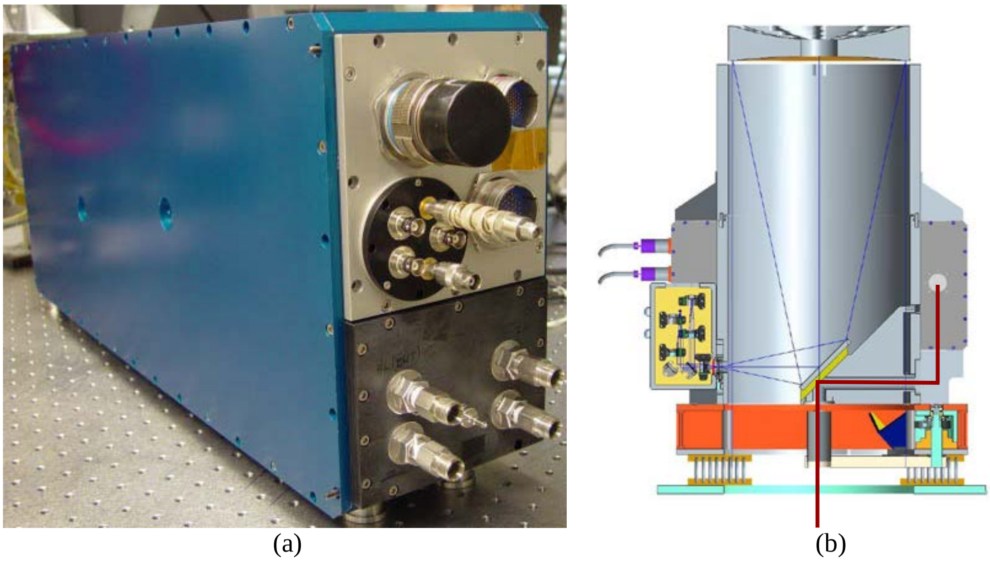
Fig. 1. Key components of the 2-μm CO_2 IPDA lidar system. These includes the telescope structure (gray), primary mirror (yellow), laser transmitter box (blue) and beam steering optics (green).

B. IPDA Lidar Receiver

The IPDA receiver consists of a telescope that focuses the radiation onto two detectors through aft-optics. The receiver telescope is a custom designed Newtonian type with 40cm diameter aluminium primary mirror. The shape of the primary mirror is hyperbolic to minimize the aberration, so that the returning signal can be focused to less than 300 μm diameter spot size compatible with the radiation detectors. The telescope is designed to maintain the focus point position in the temperature range between 5 and 35 °C. 300 μm diameter InGaAs pin photodiodes (Hamamatsu; G5853) were selected for this mission. Two detectors accommodate high and low gain channels after beam splitting. Detector characterization resulted in a noise-equivalent-power of 6.8×10^{-14} $W/Hz^{0.5}$ at 30°C that is suited for the IPDA lidar application. After amplification the lidar signals are digitized and stored by a data acquisition unit. The data acquisition unit is based on two digitizers. The first is a 10-Bit, 2 GS/s digitizer (Agilent; U1065A) for laser energy monitoring and the second is a 12-bit, 420 MS/s digitizer (Agilent; U1066A) for measuring the hard target return. Detectors are coupled to the digitizers through variable gain, high speed trans-impedance amplifiers (FEMTO; DHPCA-100). Digitizers and data storage are hosted through a personal computer that runs Microsoft XP with a 64-bit/66 MHz PCI bus. The system is capable of transferring data at sustained rates up to 400 MB/s to the host computer. Fig. 2b shows a schematic of the IPDA receiver including ray tracing of the transmitted and collected radiation [23-24].

III. IPDA GROUND TESTING

The integrated IPDA lidar was installed inside a mobile trailer, shown in fig. 3a, for initial testing and alignment verification. A 24 inch flat mirror was installed underneath the telescope at 45^o for turning the transmitted beam and telescope field-of-view from nadir to horizontal direction through a side window, as shown in fig. 3b. This allows pointing the IPDA to a set of calibrated hard targets, with known reflectivity, located at about 857 m away from the trailer. Fig. 4a shows an aerial picture of the test site at NASA LaRC. Collocated in the site is the Chemistry and Physics Atmospheric Boundary Layer Experiment (CAPABLE). CAPABLE is a ground-based observation site for studying atmospheric conditions in the Tidewater region of Virginia, which operates through collaborative effort between the Science Directorate at NASA LaRC, the U.S. Environmental Protection Agency and the Virginia Department of Environmental Quality [25]. CAPABLE instruments continuously measure pollutants, such as ozone, nitrogen dioxide, carbon monoxide and aerosols. Besides, CAPABLE provides continuous ground meteorological monitoring, such as pressure, temperature and relative humidity. This data is valuable for the 2-μm CO_2 IPDA lidar modelling for instrument validation on ground. In addition, an *in-situ* CO_2 and H_2O gas analyser (LiCor; LI-840A) was installed at fixed location as shown in fig. 4a. This allows better estimates of the CO_2 mixing ratio in the test location for better evaluation of the 2-μm CO_2 IPDA lidar instrument. Finally, it is worth mentioning the collocation of the Hampton-NASA Steam Plant [26], which is a solid waste incinerator (fig. 4a) used for steam generation. Depending on the incinerator operating cycles, higher than normal CO_2 mixing ratio was observed at the IPDA test location.



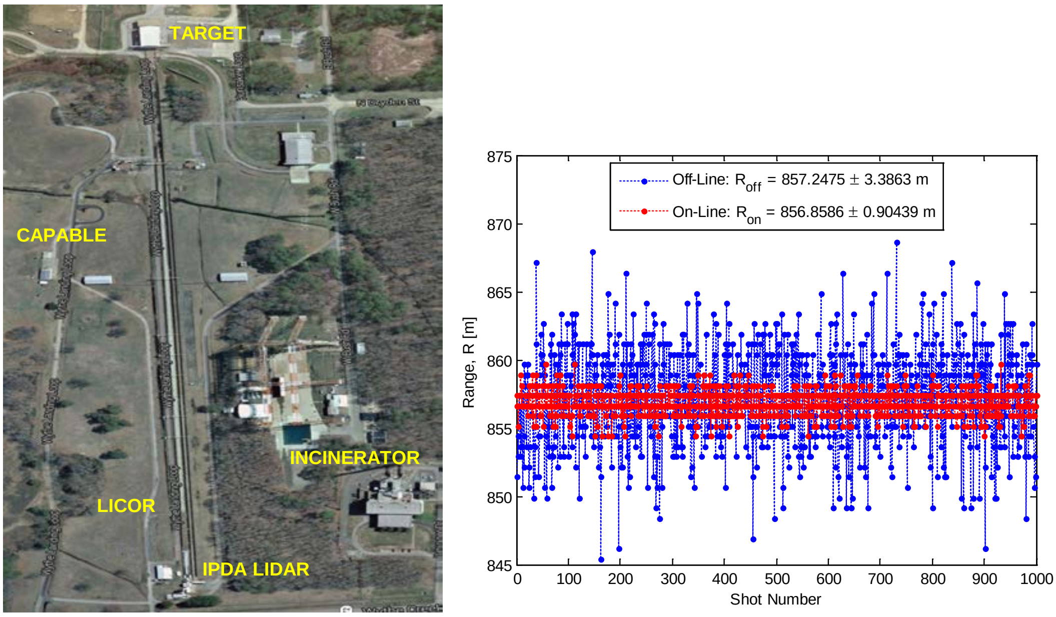
(a) (b)

Fig. 2. (a) Package 2-μm IPDA laser transmitter. The transmitter is 11.5×26.5×6.4 inch (29×67.3×16.5 cm) in size, and weighted less than 70lbs (31.75 kg). (b) Schematic of the 2-μm IPDA receiver system. Red lines mark the expended transmitted beam and blue lines mark the return radiation focused onto the detectors.

(a) (b)

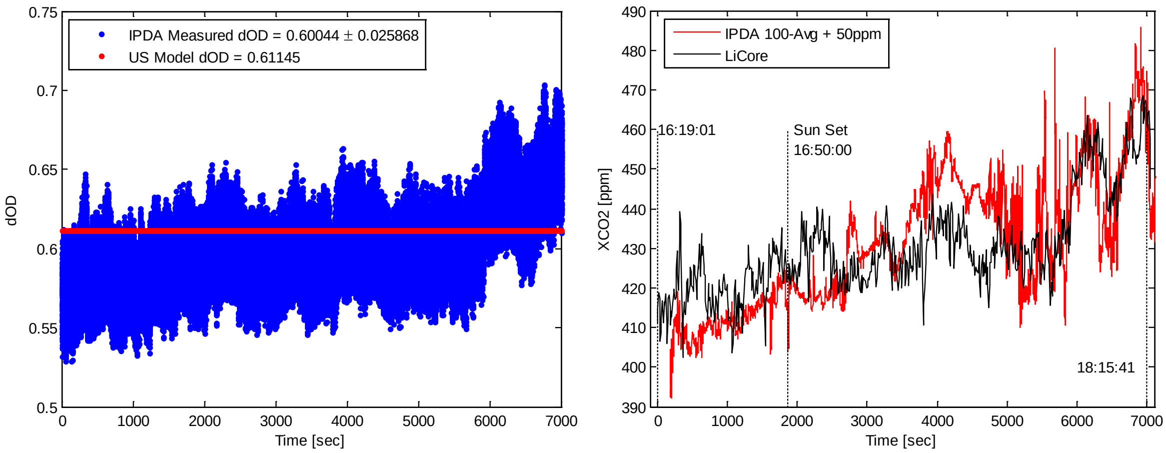
Fig. 3. (a) 35 ft trailer used as a mobile laboratory for hosting the 2-μm CO_2 IPDA lidar for ground testing. A 17 inch widow on the trailer side provides IPDA access to calibrated hard targets. (b) IPDA inside the trailer installed on an aluminium frame. A 45^o 24 inch mirror directs the IPDA to the calibrated hard targets.

IPDA lidar ground testing included different operating conditions, in terms of signal conditioning settings, target reflectivity and on-line offsets from the CO_2 R30 line center. Ranging capability is another advantage of the pulsed IPDA lidar. Range measurement between the IPDA and the hard target was achieved by monitoring the time delay between the transmitted and return pulses. Converting the time delay into distance using the speed of light the IPDA column length is determined, as demonstrated in fig. 4b, for both on-line and off-line wavelengths. Results are consistent with the nominal setting of the trailer relative to the hard target. Preliminary analysis of the ground test data indicated IPDA lidar sensitivity to atmospheric CO_2 concentration. Fig. 5a compares the CO_2 differential optical depth measured by the IPDA lidar to the theoretical value. The theoretical differential optical depth was derived using the US standard atmospheric model [27]. Besides, the IPDA measured differential optical depth was converted to CO_2 dry mixing ratio, using metrological data obtained from CAPABLE. Fig. 5b compares the CO_2 dry mixing ratio calculated using the IPDA results to the measured using the *in-situ* sensor. General temporal profile agreement is observed between both curves, after correcting for 50 ppm offset which is caused due to nonlinearities.



(a) (b)

Fig. 4. (a) Aerial picture of the 2-μm CO_2 IPDA ground testing site at NASA LaRC. (b) IPDA range determination using both the 2 GHz on-line and off-line wavelengths.



(a) (b)

Fig. 5. (a) Single-shot CO_2 double-path differential optical depth measurement obtained from the IPDA lidar compared to theoretical value calculated using US standard model. (b) 2 μm IPDA integrated-column CO_2 dry mixing ratio comparison with *in-situ* measurement. IPDA CO_2 dry mixing ratio was obtained using CAPABLE data for differential optical depth conversion after 10 sec averaging. Data collected using 2 GHz on-line offset.

IV. IPDA AIRBORNE TESTING

The 2-μm CO_2 IPDA lidar is designed for integration into a small research aircraft. The IPDA instrument size, weight and power consumption were restricted to the NASA B-200 payload requirements. This allows the system to be easily adopted in any larger airborne research platform, such as the NASA DC-8 aircraft, for future missions. In addition to the IPDA lidar, other housekeeping instruments were integrated into the B-200 aircraft. These included the *in-situ* sensor (LiCor) for CO_2 dry mixing ratio measurement, GPS for aircraft position, altitude and angles measurements and video recorder for target identification. Besides, aircraft built-in sensors provided altitude, pressure, temperature and relative humidity sampling at the flight position. Time stamps were adjusted to the GPS global timing. Fig. 6 shows the NASA B-200 aircraft and the integrated IPDA instrument inside. Two operators are required to accompany the instrument during operation.

The 2-μm CO_2 IPDA lidar airborne testing was conducted during ten daytime flights, spanning more than 20 hours, during March 20, 2014 through April 10, 2014. Flights were conducted from NASA LaRC through Langley Air force Base, Hampton, Virginia. Meteorological balloon radiosonde was independently lunched from CAPABLE site, mostly during the beginning and the end of each flight. This allows for atmospheric pressure, temperature and relative humidity vertical profiling estimates for IPDA modelling verifications. IPDA lidar airborne testing included different operating and environmental conditions. Environmental conditions included different flight altitude up to 6 km, different ground target conditions such as vegetation, soil, ocean, snow and sand and different cloud conditions. Besides, some flights targeted power plant incinerators for investigating the IPDA sensitivity to CO_2 plums. Preliminary analysis of the airborne test data indicated the IPDA lidar sensitivity to atmospheric CO_2 up to 6 km altitude over ocean target. In spite of the mechanical stresses due to shaking and vibration in the small aircraft environment, the IPDA lidar did not losses alignment resulting in about 190 GB worth of raw data.

On April 5, 2014, the NASA B-200 flight coincided with another NOAA air sampling flight [28]. Due to flight control restrictions, there was a 30 minute time lag between NOAA and NASA flights. Nevertheless, the IPDA lidar on board NASA flight sampled the same geographical location as the NOAA flask samples over the Atlantic Ocean out of the east shore of New Jersey. CO_2 flask-sampling results and meteorological data provided by NOAA were valuable for the NASA LaRC IPDA lidar instrument testing. Fig. 7 shows the averaged IPDA return on-line and off-line signals at different altitudes. In each record, the first pulse is attributed to systematic effects from aircraft window and/or telescope secondary mirror radiation leaks. Similar to ground testing, the altitude information can be deducted by comparing the time delay between the first pulse and the ground return pulse. Fig. 8a compares the flight altitude, obtained from the GPS to the range calculated from the IPDA data. The GPS flight altitude was converted to line-of-sight measurement after correcting for the aircraft pitch and roll angles, obtained from the GPS. Fig. 8b compares the CO_2 differential optical depth obtained from the IPDA data and modelled from NOAA flask sampling data. IPDA indicated a consistent CO_2 differential optical depth offset of about 0.07, similar to what was observed on ground testing.

(a) (b) (c)

Fig. 6. (a) Some team members participated in the 2-µm CO_2 IPDA lidar airborne testing in front of the NASA B-200 aircraft. 2-µm IPDA lidar instrument (a) and electronic rack (b) integrated inside the aircraft.

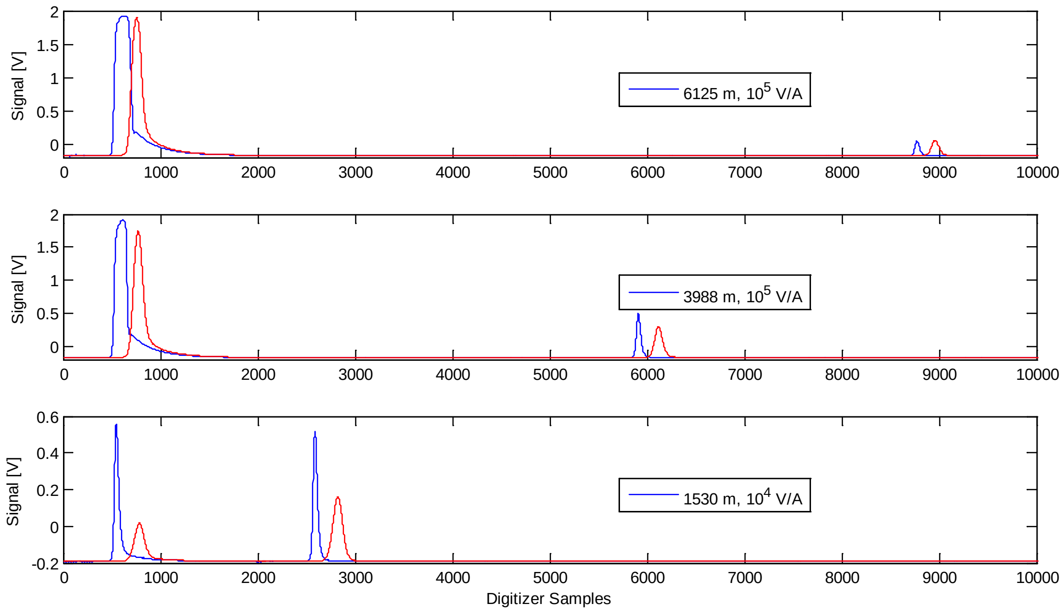


Fig. 7. 2-µm CO_2 IPDA averaged on-line and off-line return signals from different altitudes. Data collected using 4 GHz on-line offset and 200 MS/s digitizer sampling rate.

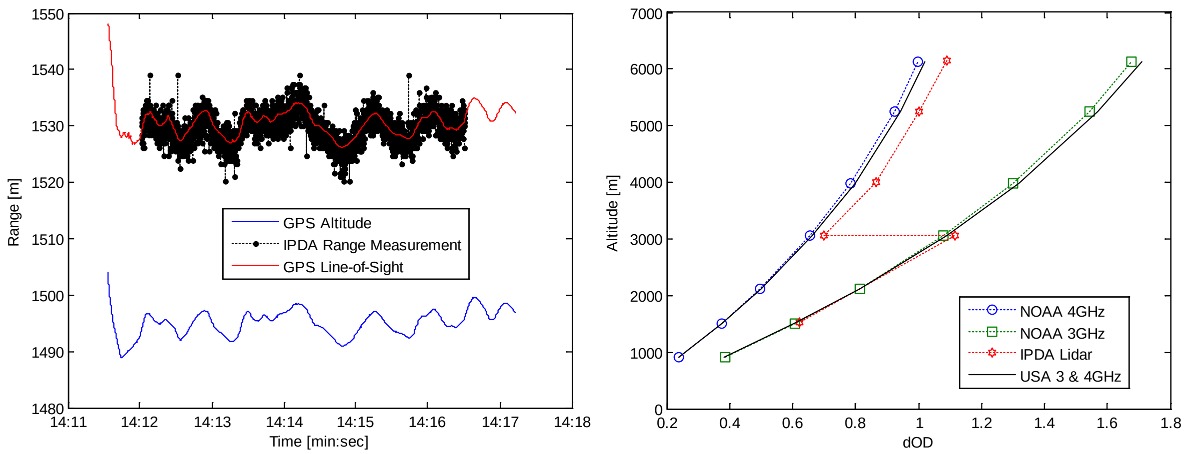


Fig. 8. (a) GPS flight altitude corrected to the pitch and roll angles to obtain the IPDA line-of sight compared to the IPDA range measurement. (b) CO_2 differential optical depth versus altitude calculated from NOAA flask sample data and from the IPDA lidar. Results are compared to US standard model calculations.

V. SUMMARY AND CONCLUSIONS

Understanding atmospheric CO_2 interactions and transport dynamics is important for studying carbon cycle and global radiation budget on Earth. *In-suit* and satellite based passive remote sensors have several limitations that could be recovered with active remote sensors. CO_2 active remote sensing has been demonstrated at NASA LaRC using the DIAL technique. NASA LaRC developed a double-pulse, 2-μm integrated path differential absorption (IPDA) lidar instrument for atmospheric CO_2 measurement. Advantages of the IPDA remote sensing technique include high signal-to-noise ratio measurement with accurate ranging. The 2-μm CO_2 IPDA transmitter is capable of producing 100mJ energy per pulse at 10 Hz repetition rate. High accuracy, stable and repeatable wavelength control and switching unit have been integrated within the transmitter. The IPDA also include a high quality 16 inch telescope and a commercial detector, electronics and data acquisition that has been integrated. The whole IPDA lidar structure is compactly and ruggedly packaged to fit in the NASA B-200 research aircraft. Ground and airborne testing of the 2-μm IPDA lidar was conducted at NASA LaRC through several validation procedures. This included instrument performance modeling through standard atmosphere and meteorological sampling. IPDA CO_2 differential optical depth measurement results agree with ground *in-situ* measurements and with CO_2 airborne sampling conducted by NOAA. Consistent differential optical depth offset, of about 0.1, was observed in the measurement. Further detailed data processing is under work. This airborne 2-μm IPDA lidar provides a unique CO_2 measurement tool that could be scaled to future space missions.

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