Development of double and triple-pulsed 2-micron IPDA lidars for column CO_2 measurements

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ABSTRACT

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 complicated due to different interactions with various climate components that include the atmosphere, the biosphere and the hydrosphere. 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. These uncertainties are mainly due to insufficient spatial and temporal mapping of the gas. Therefore it is required to have more rapid and accurate CO_2 monitoring with higher uniform coverage and higher resolution. CO_2 DIAL operating in the 2-μm band offer better near-surface CO_2 measurement sensitivity due to the intrinsically stronger absorption lines. 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 and triple-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.

Keywords: Active remote sensing, carbon dioxide, DIAL, IPDA lidar, double-pulsed laser, triple-pulsed laser

1. INTRODUCTION

Understanding the interactions and transport of atmospheric carbon dioxide (CO_2) around Earth is critical for carbon cycle studies and climate predictions [1-5]. Extensive worldwide efforts for monitoring atmospheric CO_2 are currently taking place through various remote sensing techniques. Nevertheless, high uncertainties exist in quantifying CO_2 sources and sinks due to insufficient spacial and temporal mapping of the gas. Thus, higher accuracy and more rapid CO_2 monitoring is required with better uniform coverage and higher resolution. This requirement was addressed by many international satellite missions, which rely on passive remote sensing techniques. Present satellite instruments monitoring CO_2 from space include SCIAMACHY, TES, AIRS, IASI, GOSAT and OCO-2 [6-11]. Among these, OCO-2 is fully dedicated for CO_2 monitoring and focusing mainly on the gas sources and sinks [11]. Some of these satellite systems have shown the potential to meet the spatial coverage to improve CO_2 flux estimates on continental scales. However, satellite passive sensors are unable to meet the accuracy required to aid in better quantifying the terrestrial sources and sinks due to some limitations. For example, 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 yet. 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

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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.

DIAL instruments operating in the 2-μm band offer better near-surface CO_2 measurement sensitivity due to the intrinsically stronger absorption lines than the 1.6μm. Using 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 20 years, NASA Langley Research Center (LaRC) contributed in developing several 2-μm CO_2 DIAL systems and technologies based on 2-μm pulsed transmitters [22]. This paper presents the current status of the 2-μm CO_2 integrated path differential absorption (IPDA) lidar systems development at NASA LaRC. This includes a validated airborne double-pulse IPDA lidar as well as the current integration of a second airborne triple-pulse IPDA lidar. CO_2 measurement results from the double-pulse IPDA will be presented. Triple-pulse measurement concept will be discussed as well as the potential of scaling such technologies to a space mission will be addressed.

2. PULSED 2-MICRON IPDA REMOTE SENSING TECHNIQUE FOR CO_2 MEASUREMENT

Remote sensing using the IPDA lidar is suitable for monitoring different atmospheric trace gases [23]. Similar to DIAL, the technique relies on the differentiation between strong and weak absorbing features of the gas to be monitored with respect to wavelength, namely the on-line and off-line wavelengths, respectively. Unlike DIAL, IPDA depends on hard target return signals that are proportional to the gas content throughout the whole range, or column, after normalization to the transmitted laser energy [24]. Therefore, IPDA is a special case of DIAL, were the range cell is defined for the whole range, with a result of weighted-average measurement of the gas content within that column. The loss of the range-resolved profiling sensitivity that is provided through conventional DIAL is a limitation of IPDA technique. On the other hand, relying on hard target and laser energy monitor strong signals provides high signal-to-noise ratio (SNR) which contributes significantly to the measurement sensitivity and accuracy of the IPDA technique [22-24].

IPDA lidar systems operating at the 2-μm wavelength are best suited for monitoring atmospheric CO_2. This is due to the existence of several strong absorption features of the gas in this wavelength. The R30 CO_2 line, located at 2050.9670 nm, provides an attractive absorption cross section with unique characteristics that include low temperature sensitivity and low interference from higher abundant water vapor (H_2O) molecules, as indicated in figure 1. The figure compares the composite absorption spectra for CO_2 and H_2O. The spectra were derived using the HITRAN database for line parameters, assuming US standard atmospheric model and Voigt line profile at two different altitudes [22-23]. Altitude specifications are based on the IPDA operating platforms: 0 km for ground-based testing and evaluation and 8 km for airborne operation, assuming a small aircraft such as the NASA B-200. Figure 2 compares the double-pulse and triple-pulse IPDA principle of operation. In the double-pulse IPDA system, two laser pulses are generated and transmitted within 200 μsec with a single pump pulse [25-26]. A unique wavelength control capability enables tuning the first and second pulses to the on-line and off-line wavelengths, as indicated in figure 1. In addition, on-line wavelength selection can be altered to achieve 1 to 6 GHz offset from the CO_2 R30 line center toward longer wavelength, with 1 GHz step size. In the triple-pulse operation, similar pump pulse produces three successive 2-μm laser pulses, 150 μsec apart. Using an enhanced wavelength control scheme, each of these pulses can be tuned and locked at different wavelength, as shown in figure 1. In the triple-pulse operation scenario shown in figure 1, wavelength selection is optimized for simultaneous and independent measurements of both CO_2 and H_2O [23]. Based on wavelength selection, different measurement scenarios could be achieved, including simultaneous and independent CO_2 measurement with two different weighting functions [22]. The 2-μm CO_2 double-pulse IPDA lidar system was successfully designed, integrated and demonstrated at NASA LaRC [24-26]. Currently, an updated triple-pulse IPDA lidar instrument is under development at the same institute [23, 27].

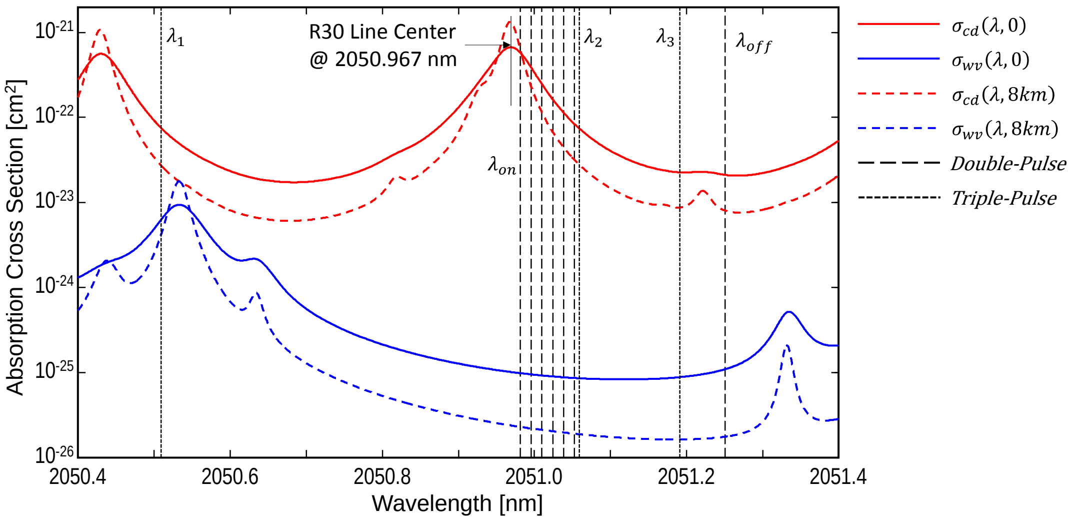


Figure 1. Comparison of H_2O and CO_2 absorption cross-section spectra, σ_{wv} and σ_{cd}, respectively, at ground (0 km) and onboard a mid-altitude aircraft (8 km). Temperature and pressure profiles used in the calculation were obtained from the US Standard atmospheric model. Vertical lines mark the instrument operating wavelengths for the double-pulse and triple-pulse IPDA lidar instruments.

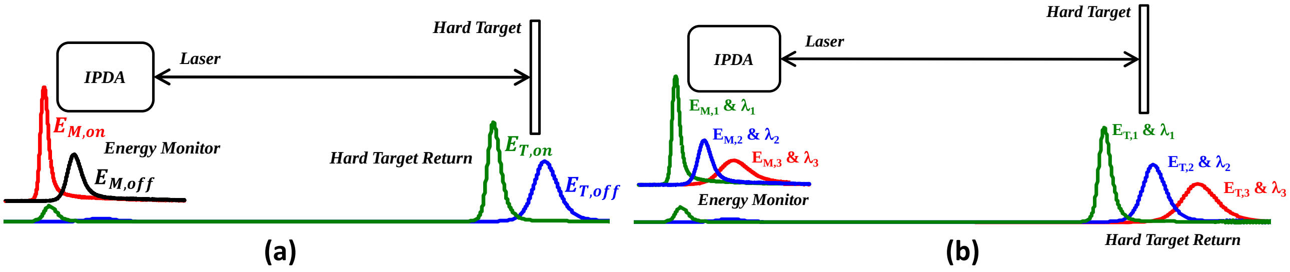


Figure 2. Principle of operation of the 2-μm (a) double-pulse and (b) triple-pulse IPDA lidar for atmospheric CO_2 measurement. EM and ET are the measured energies from the transmitted laser monitor and hard target return, respectively.

3. DOUBLE-PULSE IPDA

In the double-pulse 2-μm IPDA the transmitter produces two successive laser pulses with 10 Hz repetition rate. The compact, rugged, highly reliable 2-μm laser transmitter is based on the Ho:Tm:YLF high-energy pulsed laser technology which is capable of generating above than 140 mJ total energy. This laser is side pumped by AlGaAs diode arrays at 792 nm. The exact wavelengths of the pulsed laser transmitter are controlled by a wavelength control unit. The first pulse and the second pulse are injection seeded alternatively by the on-line and the off-line wavelengths, respectively. Transmitted pulse energies are monitored, per shot, to normalize the hard target return in the final analysis. 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 airborne operation. 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 40-cm diameter aluminum primary mirror. The shape of the primary mirror is hyperbolic to minimize 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 optical 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 2-μm IPDA lidar application. After amplification, the lidar signals are digitized and stored through a data acquisition unit. The data acquisition unit is based on two digitizers. The first is a 10-Bit, 500 MS/s digitizer for laser energy monitoring and the second is a 12-bit, 200 MS/s digitizer for measuring the hard target returns. Detectors are coupled to the digitizers through variable gain, high speed trans-impedance amplifiers. Digitizers and data storage are hosted through a personal computer. The system is capable of transferring data at sustained rates up to 400 MB/s to the host computer. Figure 3b shows a schematic of the IPDA receiver including ray tracing of the transmitted and collected radiation [24-26].

The integrated IPDA lidar was installed inside a mobile trailer for initial testing and alignment verification. A 24 inch flat mirror, installed underneath the telescope, was use for turning the transmitted beam and telescope field-of-view from nadir to horizontal direction through a side window. This allows pointing the IPDA to a set of calibrated hard targets, with known reflectivity, located at about 857 m away from the trailer. Collocated in the site is the Chemistry and Physics Atmospheric Boundary Layer Experiment (CAPABLE), which is a ground-based observation site for studying atmospheric conditions in the Tidewater region of Virginia. CAPABLE provides continuous ground meteorological monitoring for pressure, temperature and relative humidity, which are valuable for the 2-µm double-pulse CO_2 IPDA lidar modelling for instrument validation on ground. In addition, an in-situ LiCor CO_2 and H_2O gas analyzer was installed at fixed location that allows better estimates of the CO_2 mixing ratio in the test location. Finally, it is worth mentioning the collocation of the Hampton-NASA Steam Plant, which is a solid waste incinerator used for steam generation. Depending on the incinerator operating cycles, higher than normal CO_2 mixing ratio was observed at the IPDA test location [26]. The 2-µm double-pulse 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. Analysis of the ground test data indicated IPDA lidar sensitivity to atmospheric CO_2 concentration. Figure 3 compares the IPDA CO_2 column-averaged dry-air volume mixing ratio to the in-situ sensor measurement. The CO_2 column-average dry-air volume mixing ratio was obtained from the IPDA measured differential optical depth and the metrological data obtained from CAPABLE. For the IPDA both energy monitor and residual scattering data were evaluated. Temporal profile agreement is observed between IPDA and in-situ measurement, with -0.43 and 14.59 ppm offsets obtained from energy monitor and residual scattering, respectively [28].

The 2-µm double-pulse 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. Two operators are required to accompany the instrument during operation. The 2-µm double-pulse CO_2 IPDA lidar airborne testing was conducted during ten daytime flights, spanning more than 27 hours, during March 20, 2014 through April 10, 2014. IPDA lidar airborne testing included different operating and environmental conditions. Environmental conditions

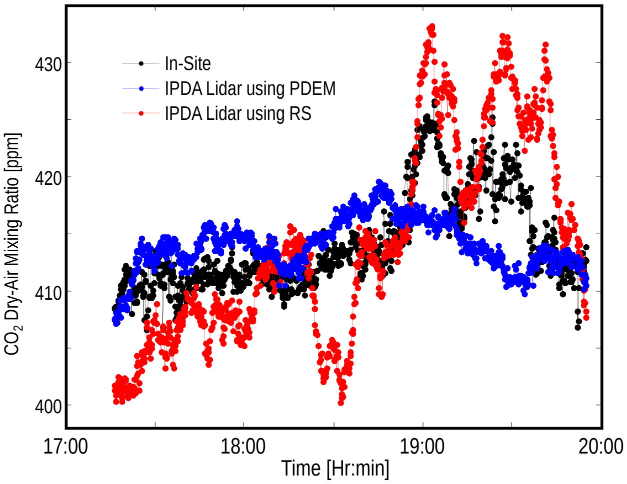


Figure 3. Comparison between CO_2 column-average dry-air mixing ratio measurements obtained from the 2-µm double-pulse IPDA lidar and CO_2 dry-air in-situ sampling. IPDA data is presented for calibrated pin-detector energy monitor (PDEM) and residual scattering (RS). IPDA results were obtained at 3 GHz on-line and corrected for -0.4 and 14.6 ppm offsets for the PDEM and RS, respectively. Time resolution is 10 sec [28].

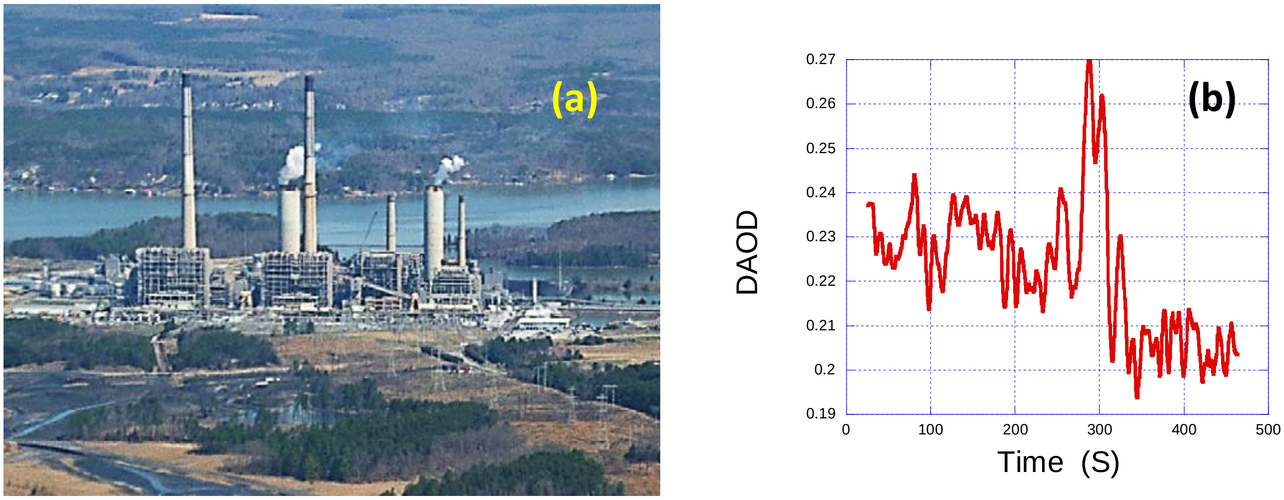


Figure 4. (a) Aerial picture of Roxboro steam plant, Semora, North Carolina. With more than 2 GW capacity, it is one of the largest power plants in the United States. The plant rely on coal-firing, which results in producing significant plumes of CO_2. (b) CO_2 optical depth measurement from the 2-µm double-pulse IPDA lidar while flying above Roxboro steam plant incinerator. Against wind flight track results in the shown CO_2 optical depth profile. Data collected during ninth flight while the 2-µm double-pulse IPDA was operating from 1 km altitude at 4 GHz on-line setting [25-26].

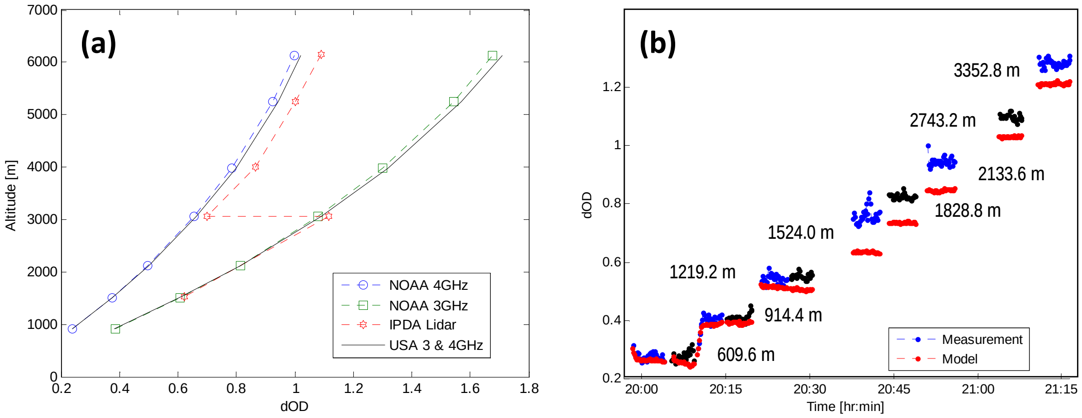


Figure 5. Comparison of the 2-µm double-pulse IPDA CO_2 differential optical depth measurement to different modeling results. (a) Model results were derived from an independent airborne CO_2 in-situ flask sampling conducted by NOAA during the IPDA eight flight [25-26]. (b) Model results were derived from onboard LiCor in-situ sensor operated after normalizing the aircraft cabin pressure to the ambient during the tenth flight. In this flight, the IPDA was operating at 3 GHz on-line offset at different altitudes as listed in the figure.

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 lidar sensitivity to CO_2 plums [26]. Figure 4 shows an example of the 2-µm double-pulse IPDA lidar airborne CO_2 plume detection during crossing Roxboro Power Plant, North Carolina, on the ninth flight. Figure 5 compares the CO_2 differential optical depth measurements obtained from the 2-µm double-pulse IPDA lidar to models driven differential optical depths obtained from different CO_2 in-situ sensors. These sensors include independent NOAA flight air sampling, which took place 30 min before the eighth flight, and LiCor in-situ sampler instrument onboard the B-200. Although, flight results indicated successful CO_2 active remote sensing using the 2-µm double-pulse IPDA lidar instrument, work is undergoing to investigate observed offsets in optical depth measurements.

4. TRIPLE-PULSE IPDA

H_2O is the most dominant greenhouse gas and most interfering molecule for CO_2 measurement. A common problem in CO_2 measurement in the IR spectral region, including the 2 µm, is significant interference from H_2O absorption, which limits the measurement sensitivity. In addition, knowledge of H_2O distribution is essential for obtaining the dry-air number density for converting measured CO_2 optical depth, the primary IPDA product, into dry-air mixing ratio. This requirement drives the need for obtaining accurate meteorological data including H_2O. 2-µm triple-pulse IPDA provides a solution for this problem by simultaneously and independently measuring both CO_2 and H_2O with the same instrument. This will significantly enhance the CO_2 measurement while raises the total efficiency of the IPDA instrument [23]. To examine the measurement principle of both molecule, figure 1 shows a special case of the independent and precise wavelength tuning of the three transmitted pulses. In such case, the CO_2 sensing wavelengths are set to λ_2 and λ_3 equal to the CO_2 on-line and off-line, respectively. Notice that at these wavelengths H_2O cross section would cancel out. Similarly, by setting λ_1 equal to the H_2O on-line and repurposing λ_2 as the H_2O off line, H_2O measurement can be obtained while CO_2 cross sections cancels out. The triple pulse operation leads to CO_2 and H_2O simultaneous sensing, while the specific wavelength tuning leads to an independent measurements. Sharing a single wavelength (λ_2 is the CO_2 on-line and the H_2O off-line) would ease the instrument requirement from quadruple-pulsing to triple-pulsing. Currently, development and integration of this 2-µm triple-pulse IPDA lidar instrument in ongoing at NASA LaRC [23, 26]

The triple-pulse capability of the 2-µm IPDA would allow simultaneous and independent measurement of CO_2 using two different weighting functions. This is demonstrated in figure 6. For example, weighting function selection allows measuring CO_2 concentration near the surface for studying source and sink interactions. With the same off-line and the third pulse tuned to different weighting function CO_2 concentration in free troposphere can be targeted simultaneously and independently for studying the gas transport. This unique feature would be attractive for achieving adaptive measurement targets for space applications. Table 1 compares the main parameters for the demonstrated 2-µm double-pulse IPDA and triple-pulse IPDA lidar instrument to the space requirement for CO_2 active remote sensing mission. Space requirements were driven from a study conducted by European Space Agency (ESA) [2]. ESA objective is to develop future space borne active sensing mission for measuring the dry-air mixing ratio of CO_2 throughout the atmosphere with a high accuracy on the ppm level [2]. 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 increasing the efficiency by a factor of three. The triple pulsing eliminates the challenge and complexity in co-aligning and bore-sighting three independent beams. Measurements with

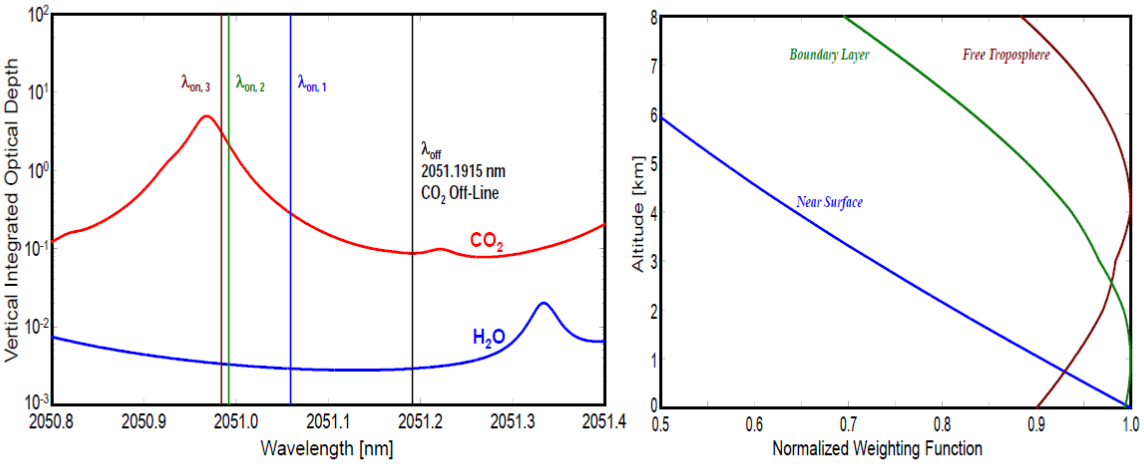
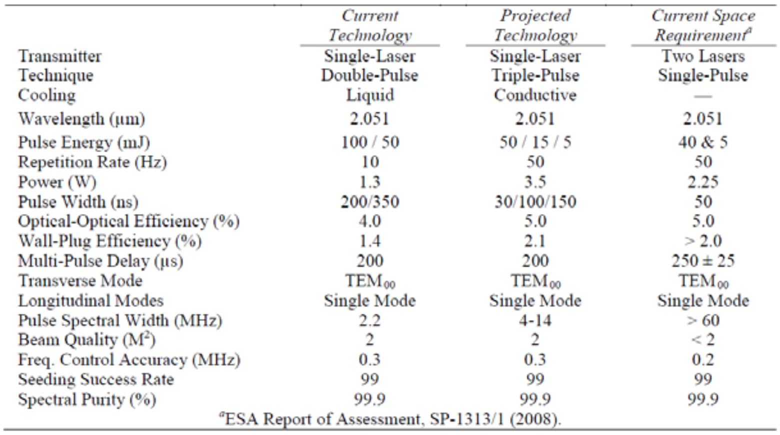


Figure 6. (a) Comparison of the CO_2 and H_2O integrated optical depths derived using the HITRAN database for line parameters and US Standard model for metrological profiles. Vertical color coded lines mark selected wavelengths for the three laser pulses, for simultaneous CO_2 measurements with two different weighting functions. (b) Corresponding color coded peak-normalized pressure-based weighting functions for the selected CO_2 on-line wavelength [22].

Table 4. Comparison of CO_2 active remote sensing state-of-the-art 2-µm laser transmitters, developed at NASA LaRC, with space requirements



	Current Technology	*Projected Technology*	*Current Space Requirement*[a]
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

[a] ESA Report of Assessment, SP-1313/1 (2008).

adaptive targeting would be valuable tool for a space mission. Depending on the geographical location of the space-borne IPDA instrument footprint, measurements with different CO_2 weighting would aid in investigating the gas sources and sinks and the transport phenomena. Including the H_2O sensing in some regions, such as the tropics, would enhance the CO_2 measurement accuracy. Relying on active remote sensing mission would ease the sensing track restrictions and include day and night measurements.

5. SUMMARY AND CONCLUSIONS

Understanding climate change through identification of global CO_2 sources and sinks and transport flux is a current societal interest that is addressed by NASA. Space-borne CO_2 passive remote sensors have limited capabilities which can be overcome through active remote sensing. This led to the desired NASA active remote sensing of the CO_2. A solutions for such goal is the 2-µm pulsed IPDA lidar technique. NASA LaRC identified the desired pulsed laser attributes and wavelength regions for CO_2 active remote sensors through different component level developments. Recently, NASA LaRC demonstrated the capability of CO_2 airborne measurement using 2-µm double-pulse IPDA lidar technique. The instrument was validated on ground and onboard B-200 aircraft at altitudes up to 6 km using different operating conditions. Extending the technological capabilities, LaRC is currently developing a unique triple-pulsed 2-µm IPDA lidar. With wavelength optimization, this instrument is capable of achieving two simultaneous and independent measurements. The triple-pulse IPDA can either target H_2O and CO_2 measurements or target CO_2 measurements with two different weighting functions. The measurement type and/or weighting could be switched instantaneously during operation for adaptive targeting to accommodate different environmental conditions. Such capabilities can be further extended for future space-based applications.

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