VALIDATION OF DOUBLE-PULSE 1572 NM INTEGRATED PATH DIFFERENTIAL ABSORPTION LIDAR MEASUREMENT OF CARBON DIOXIDE

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ABSTRACT

A ground-based double-pulse 1572 nm integrated path differential absorption (IPDA) lidar was developed for carbon dioxide (CO_2) column concentrations measurement. The lidar measured the CO_2 concentrations continuously by receiving the scattered echo signal from a building about 1300 m away. The other two instruments of TDLAS and in-situ CO_2 analyzer measured the CO_2 concentrations on the same time. A CO_2 concentration measurement of 430 ppm with 1.637 ppm standard error was achieved.

1. INTRODUCTION

CO_2 is one of the main atmospheric greenhouse gases and plays an important role in global climate change. Global CO_2 concentrations with high precision measurements are significant for understanding the carbon cycle and improving the climate forecast model. A more accurate and effective technique to measure global atmospheric CO_2 concentrations has become strongly required. Differential absorption lidar (DIAL) technique is an effective method for trace gas concentrations measurement with high accuracy and sensitivity. In order to measure column CO_2 (XCO_2) concentrations from space, the integrated path differential absorption (IPDA) lidar is proposed [1-3.] . Usually 1.57 μm and 2 μm wavelength laser sources are acted as the preferred transmitter for IPDA lidar to measure XCO_2[4-6.]. Although the laser frequency stability is stricter for 1.57 μm than 2 μm laser source, the 1.57 μm lidar shows lower interference from water vapor and lower sensitivity from atmospheric temperature [7.]. In this paper, an IPDA lidar prototype system for CO_2 concentration measurement based on 1.57μm and some experiment results are presented. The optimized on-line and off-line wavelengths are 6361.2250 cm^{-1} and 6360.979 cm^{-1} respectively, which are shown in Figure 1. The lidar are compared with TDLAS and in-situ CO_2 analyzer (Los Gatos) in measuring the CO_2, and good agreements are shown.

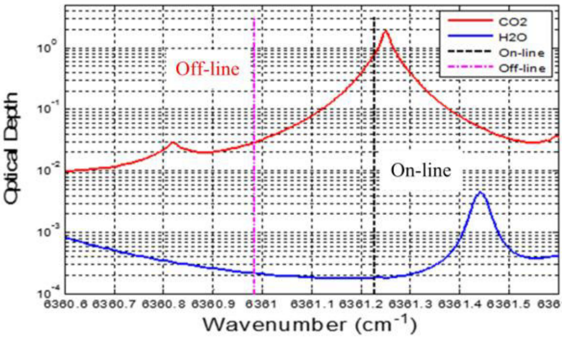

Figure 1 Operation wavelength of the IPDA lidar

2. SYSTEM CONFIGURATION

The block diagram of the IPDA lidar system is shown in Figure 2. This system consisted of the laser transmitter, the receiver, and the data acquisition and controller. The laser transmitter output 1572 nm and 1064 nm double-pulse lasers simultaneously. The double pulse's separation was 200 μs. The 1064nm laser was used to measure range to hard target. The 1572nm laser with on-line wavelength 6361.2250 cm^{-1} and off-line wavelength 6360.979 cm^{-1} was used to measure CO_2 concentrations. The 1572 nm laser was generated by the seeder injected optical parametric oscillator (OPO) method with single frequency 1064 nm laser acted as the pump laser pulse. The 1572 nm laser single pulse energy was about 1mJ with 50 Hz repetition rate and 20 ns pulse duration. In the laser transmitter, part of

1572 nm pulsed laser was received by an integrating sphere and detected by an InGaAs PIN photodiode. It was sampled and acted as the transmitting laser energy calibration reference. The receiver was composed of a 200 mm Schmidt-Cassegrain telescope, an 1572 nm detector channel and an 1064 nm detector channel. The 1572 nm detector channel signal was amplified by a 2 MHz bandwidth amplifier. Then the signal was sampled by an 100M/s AD card in the data acquisition and controller unit. The specifications of the system are summarized in the table 1.

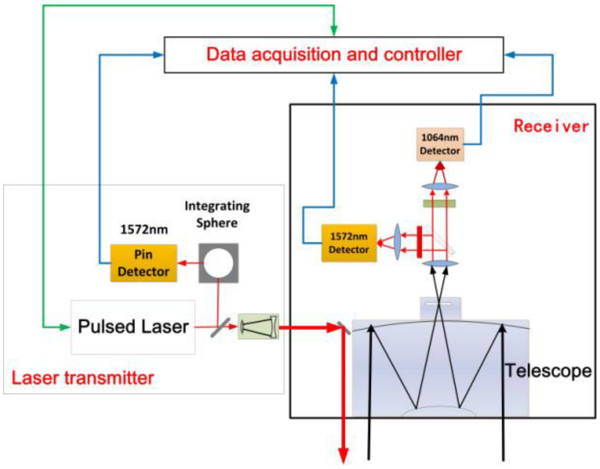

Figure 2 Block diagrams of the IPDA lidar system

Table1 Specifications of the lidar system

Parameters	value
Wavelength	1572 nm/1064 nm
Pulse energy	1 mJ@1572nm 5 mJ@1064nm
Pulse width	20 ns
Frequency stability	0.3MHz
Pulse repetition rate	50 Hz (double pulse)
Beam divergence	0.2 mrad
Telescope	Φ200 mm
FOV	0.5 mrad
Detector	Thorlabs PDA20CS-EC PIN Licel InGaAs APD module Licel Si APD module
AD	100M/s ,14bit, NI PCI5122

3. RESULTS

3.1 Retrieval method

The CO_2 differential absorption optical depth (DAOD) was calculated from the following expression:

$$DAOD = \int_0^R N_{CO_2}(r)\Delta\sigma(r)dr = \frac{1}{2}\ln\frac{P_{off}}{P_{on}}\frac{P_{on0}}{P_{off0}} , \quad (1)$$

Where $\Delta\sigma(r) = \sigma_{on} - \sigma_{off}$ was the differential absorption section, P_{on} and P_{off} were the echo signals from IPDA double pulses, P_{on0} and P_{off0} were the transmitting energy reference signals. Usually, multiple pulses were averaged to calculate DAOD with high accuracy.

The column CO_2 concentration (XCO_2) could be calculated from the DAOD and the integrated weighting function WF, and was expressed as:

$$\begin{aligned} XCO_2 &== \frac{DAOD}{\int_{P_{TOA}}^{P_{surf}} WF(p,T)dp} , \\ WF(P,T) &= \frac{\Delta\sigma_{CO_2}(P,T) * N_{air}}{1+\rho_{H_2O}} , \\ N_{air} &= \frac{P \cdot NA}{RT} . \end{aligned} \quad (2)$$

Where the weighting function $WF(p,T)$ was related to operational on-line and off-line wavelengths, and atmospheric parameters such as pressure and temperature and water vapor concentrations.

The XCO_2 relative random error (RRE) was expressed in the following as:

$$RRE = \frac{\Delta XCO_2}{XCO_2} = \frac{\Delta DAOD}{DAOD} = \frac{1}{2 \cdot DAOD} \frac{1}{\cdot SNR} , \quad (3)$$

Where the SNR was the signal to noise ratio of total echo and energy monitor reference signals. So when the DAOD kept constant, RRE was only decided by the SNR. For lower RRE, higher SNR was required.

3.2 Experiments

Ground validation experiments were carried out for the IPDA lidar system compared with TDLAS and in-situ CO_2 analyzer instruments. Atmosphere pressure, temperature and water vapor concentration were recorded by the Davis weather station.

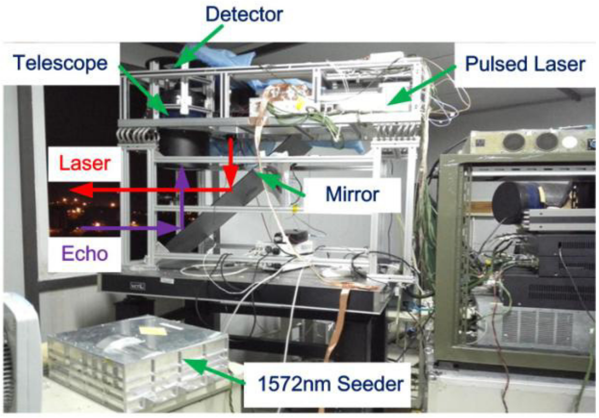

Figure 3 The IPDA lidar prototype

Figure 3 shows the IPDA lidar prototype. The transmitting laser beam was rotated 90 degrees by a mirror, and then passed the window in the lab to the atmosphere. The lab was on the top of five-story building. The lidar would receive the echo signal scattered by a building about 1300 m away. Then the XCO_2 in horizontal plane could be measured by the lidar. On the same time, the in-situ CO_2 analyzer could measure the CO_2 concentrations outside the lab with accuracy less than 0.3 ppm. The TDLAS instrument also was used to make comparisons. But it was different from the lidar and the path length was only about 120 m. Because the energy of its light was not enough to measure long-distance CO_2.

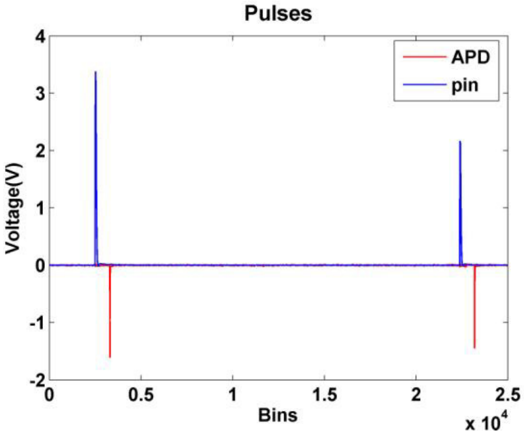

Figure 4 The lidar acquired double pulse echo and energy monitor signals

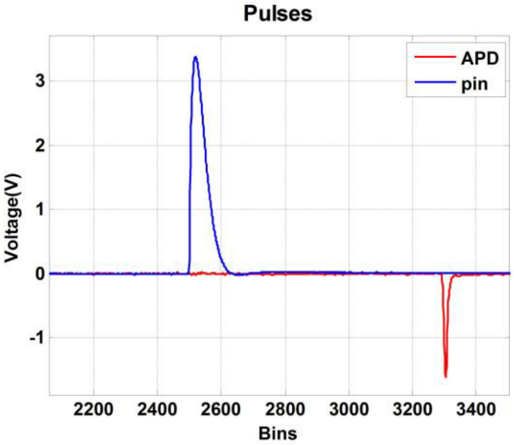

Figure 5 Single pulse echo and energy monitor signals waveform

The lidar acquired double pulse echo and energy monitor signals, shown in Figure 4. Energy monitor signals were received by a PIN detector with positive voltage. And the scattered echo signals were received by an APD detector with negative voltage output. The single pulse echo and energy monitor signals waveform are shown in Figure 5.

From the measured atmospheric parameters and calculated weighting function and background XCO_2 of about 400 ppm, we can calculate the theoretical value of DAOD which was 0.087. On-line and off-line normalized single echo signals are presented in Figure 6. When 4000 pulses averaged, the ratio of on-line and off-line normalized echo signal which is also the ratio in the log term of equation (1), shown in Figure 7. Then we got the DAOD, as shown in Figure 8. The mean DAOD was 0.0877, which agree with the theoretical DAOD.

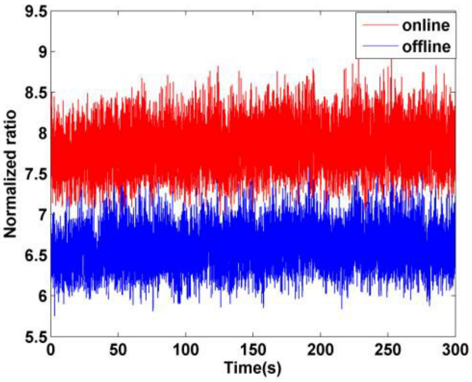

Figure 6 On-line and off-line normalized echo signal

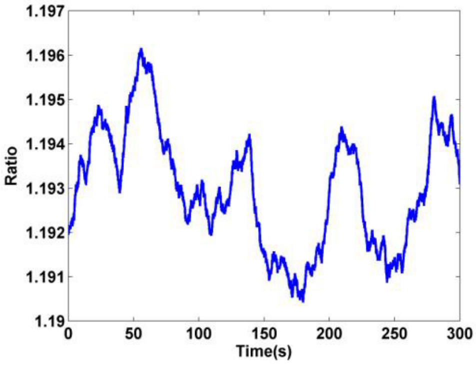

Figure 7 Ratio of on-line and off-line normalized echo signal

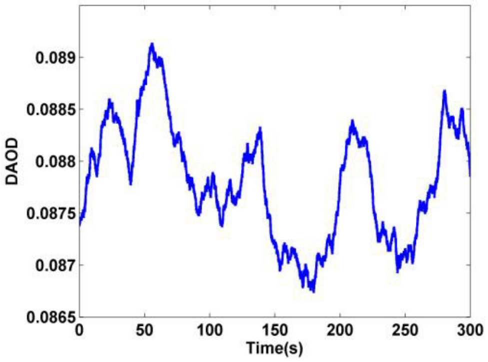

Figure 8 Calculated DAOD

The IPDA lidar retrieved XCO_2 compared with Los Gatos in-situ analyzer measured CO_2 concentration is shown in Figure 9. The mean XCO_2 from lidar is about 430 ppm with 1.637 ppm standard error. Both lidar and in-situ analyzer measured data agree well. On another day, the IPDA lidar retrieved XCO_2 is also compared with TDLAS, presented in Figure 10. The TDLAS path length was about 120 m and the cube corner retro-reflector target azimuth was different from the lidar scattered building wall. But both showed good correlation.

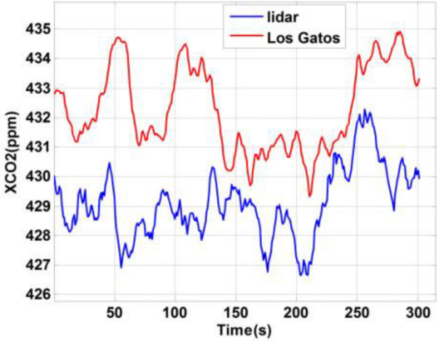

Figure 9 Comparison of XCO2 measured by lidar and Los Gatos in-situ analyzer

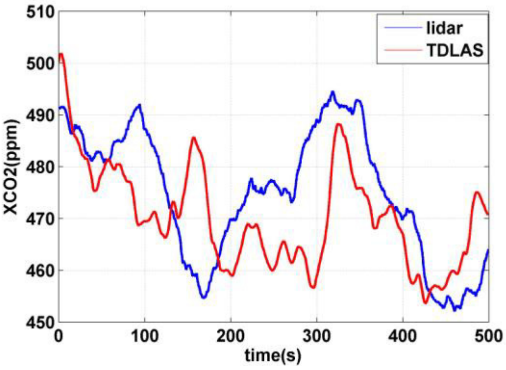

Figure 10 Comparison of XCO_2 measured by lidar and TDLAS

4. CONCLUSIONS

A ground-based double-pulse 1572 nm integrated path differential absorption (IPDA) lidar was developed for carbon dioxide (CO_2) column concentrations measurement. The lidar was compared with TDLAS and in-situ CO_2 analyzer to measure the column CO_2 concentrations. Good agreement was shown. When 4000 pulses averaged, the mean XCO_2 of 1300 m path length from lidar was about 430 ppm with 1.637 ppm standard error. This lidar will be upgraded soon for XCO_2 measurement in future airborne platform.

ACKNOWLEDGEMENT

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