

FLIGHT DEMONSTRATION OF A 2-MICRON, DOUBLE PULSED CO₂ IPDA LIDAR INSTRUMENT

Jirong Yu¹, Mulugeta Petros¹, Upendra Singh¹, Tamer Refaat¹, Karl Reithmaier², Ruben Remus¹,
William Johnson³

¹ NASA Langley Research Center, MS 468, Hampton, VA 23681 USA, j.yu@nasa.gov

² Science System & Applications, Inc, One Enterprise Parkway, Hampton, Virginia 23666 USA

³ Michigan Aerospace Corporation, 1777 Highland Dr. # B, Ann Arbor, MI 48108 USA

ABSTRACT

NASA Langley Research Center (LaRC) developed a double pulsed, high energy 2-micron Integrated Path Differential Absorption (IPDA) lidar instrument to measure atmospheric CO₂ column density. The 2- μ m double pulsed IPDA lidar was flown ten times in March and April of 2014. It was determined that the IPDA lidar measurement is in good agreement with an in-situ CO₂ measurement by a collocated NOAA flight. The average column CO₂ density difference between the IPDA lidar measurements and the NOAA air samples is 1.48ppm in the flight altitudes of 3 to 6.1 km.

1. INTRODUCTION

NASA Langley Research Center (LaRC) has developed a double-pulsed, high energy, 2-micron direct detection IPDA lidar instrument (Yu et.al). Lidars operating in the 2 μ m band offer high near-surface CO₂ measurement sensitivity due to the intrinsically stronger absorption lines (Menzies and Tratt 2003, Caron and Durand 2009). The objective of the airborne demonstration of the newly developed 2-micron pulsed IPDA lidar is to demonstrate the functionality and capability of the lidar instrument. The airborne IPDA lidar made measurements at different flight altitudes up to 8.3 km limited by aircraft capability and different ground target conditions such as vegetation, soil, ocean surface, snow and sand, and different cloud conditions. Strong lidar return signals were obtained for both on and off-line wavelengths at all flight altitudes. The CO₂ column dry mixing ratio is derived from the IPDA lidar measurement and available meteorological data profiles. This paper describes the measurement results of the 2-micron pulsed IPDA lidar instrument during this airborne campaign demonstration.

2. AIRBORNE DEMONSTRATION

2.1 Data Signal to Noise Ratio

Strong lidar return signals were obtained for both on and off-line wavelengths at different altitudes. Figure 1 shows lidar signal examples at two different lidar operating conditions. There are two pair of peaks in the return signal. The first pair of signal peaks are the on and off-line pulse signals reflected from the airplane window. The second pair of peaks are on and off-line pulse signals from the hard target echo. The off-line signals are intentionally offset from the on-line return signals in order to see the on and off-line return signals clearly. In fact, they are overlapped with each other in terms of range. Fig. 1a corresponds to a lidar signal with a flight at 1372 meters with pre-amplifier setting at 10³. Since the airplane is at a low altitude, there is little absorption for the on-line pulse, thus, the amplitudes of the on-line and off-line returning signals are close to the amplitudes of the on and off-line laser pulses recorded by an energy monitor. Fig. 1b shows the lidar signal with an airplane flying at 6096 meters with pre-amplifier gain setting 10⁵. Due to the longer absorption path length relative to the conditions in Fig 1a, the return signal amplitude from the on-line pulse is reduced. Therefore, the lidar signals from on and off-line pulses are comparable as shown in Fig. 1b. The inserts in Fig. 1 are the enlarged ground return signals. It clearly shows that the ground return signal is strong with high signal to noise ratio. The SNR is defined as the ratio of the area integrated under the return lidar signal waveform divided by baseline RMS noise, times the same time interval used to integrate the lidar signal.

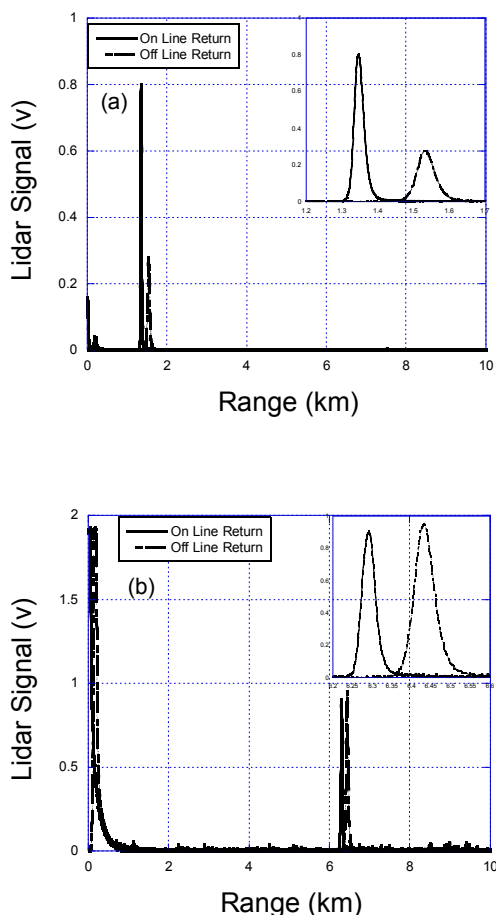


Fig. 1. IPDA lidar signal examples. The preamplifier gain settings are 10^3 and 10^5 for (a) and (b), respectively

Table 1. On and Off-line return signal SNR at various ground conditions

	Lidar S/N		Flight altitude (m)	Preamp gain
	On line	Off line		
Soil/Veg.	287	478	6818	10^5
Sea Surface	90	138	6811	10^5
Cloud Tops	234	281	5631	10^5

2.2 DAOD Measurement Statistics

The lidar measures the backscattered signals from hard targets normalized to their emitted energy samples recorded by an energy monitor. The key measurement parameter is the differential absorption optical depth (DAOD), which is defined as the optical depth difference between the on and off-line frequency. DAOD can be calculated according to equation 1.

$$DAOD = \ln[(P_{off} t_{off} / E_{off}) / (P_{on} t_{on} / E_{on})] \quad (1)$$

where the P_i is the lidar return signal power, E_i is the transmitted laser energy, and t_i is the effective pulse width of the return signal at the on or off-line frequency.

The accuracy of the DAOD measurements depends on the lidar signal and noise characteristics, and lidar system bias errors. Since the objective of the flights is to demonstrate functionality of the newly developed instrument, many lidar instrument settings were adjusted during the flights. Adjustments include the pre-amplifier gain, the on-line frequency shift from the R30 absorption peak, the receiver bandwidth, and the laser output energy. The instrument measured DAOD is compared with a model simulated DAOD value. The model used here is the US standard atmospheric model with an assumed atmospheric CO_2 concentration of 395 ppm.

Fig. 2 depicts an example of the DAOD measurement results. The data shown was taken in the morning on Mar. 27, 2014 over land at a flight altitude 6706 meters. The land condition varies between rural and residential areas.

Fig. 2a is a DAOD calculation based on a single shot return signal. The on line frequency is locked at 4 GHz from the R30 absorption peak. The preamplifier gain is at 10^5 . The DAOD mean value for the single shot measurement is 1.0587 with a standard deviation of 0.0457. The model predicts the mean value of 1.0553. Random error can be reduced by shot averaging. Fig. 2b shows the result with 100 points moving average, which corresponds to 10 seconds average. The standard deviation is improved to 0.0123 for the lidar data as shown in Fig. 2b.

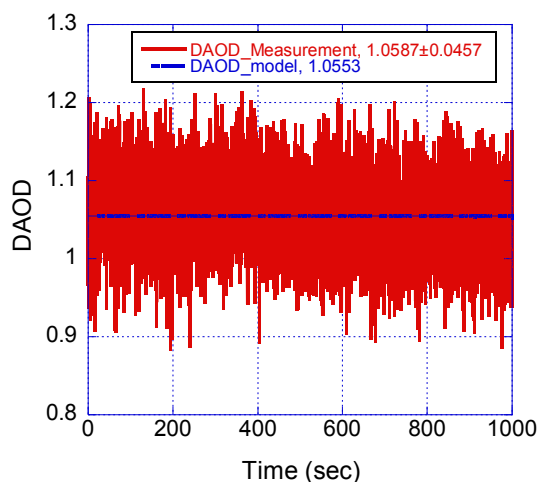


Fig. 2a. DAOD measurement by the IPDA lidar. The measurement is derived from a single shot return signal. It is compared to model predicted DAOD value.

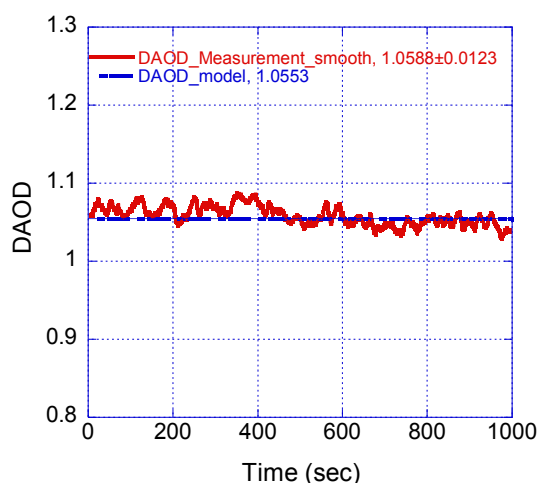


Fig. 2b. DAOD measurement by the IPDA lidar. The measurement is the result of 10s (100 shots) average.

2.3 CO₂ Mixing Ratio Measurement Validation

On 5 April 2014, NOAA conducted an air-sampling flight over the Atlantic Ocean off the coast of Cape May, New Jersey (CM; 38.83°N-74.32°W). The programmable multi-flask air sampling system provided very high precision for the CO₂ mixing ratio measurement per sample. It also measures temperature, pressure, relative humidity and other trace gases. This data can be used to make direct comparison and validation for

the 2-micron IPDA lidar CO₂ mixing ratio measurements.

Flying the IPDA lidar over the ocean provides a target with near consistent surface reflectivity, which tends to reduce measurement uncertainty compared to elevated continental grounds that varies in both reflectivity and scattering surface elevation. The NOAA flight collected data at seven different altitudes, starting from 6126 meters and gradually descending to 912 meters. (6126, 5243, 3977, 3052, 2127, 1505, 912 m). It provided coarse vertical CO₂ and meteorological data profiles. Due to airspace restriction, our flight flew over the same location half an hour after the NOAA flight. The IPDA lidar flew at the same altitudes as the NOAA flight. The on-line frequency was set at 4 GHz from the R30 line absorption peak for the flight altitude above 3052 meters. The on-line frequency was changed to 3 GHz from the R30 line absorption peak below a flight altitude of 3052 meters because of less absorption due to shorter range. At an altitude of 3052 meters, the data with on-line frequency shift at both 3 and 4 GHz was taken.

The profiles of CO₂ mixing ratio x_{cd} , temperature, pressure, and water vapor from the ground to 8 km can be obtained by linear extrapolation of the NOAA data. To make the direct comparison to the IPDA lidar column density measurement, the CO₂ weighted-average column dry-air volume-mixing ratio, $X_{cd, c}$, can be calculated. At a certain altitude, it is a weighted integration of x_{cd} from that altitude to the surface.

IPDA lidar measures the DAOD according to equation 2. Using the NOAA measured meteorological data profile, the CO₂ weighted-average column dry-air volume-mixing ratio, $X_{cd, m}$, can be obtained with the lidar measured DAOD value. Then, the lidar measured $X_{cd, m}$ can be directly compared to the NOAA measurement $X_{cd, c}$. The subscripts m and c represent the IPDA lidar measurement and the calculated result from them respectively. As shown in Fig. 2b there appears to be a small drift in the measured DAOD value, or a gradient in the CO₂ column value, due to land condition changes over the flight track.

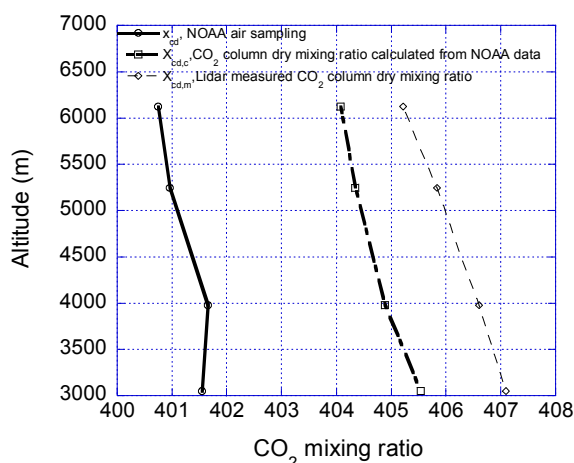


Fig. 3. CO₂ mixing ratio versus altitude calculated from NOAA flask sample data and from the IPDA lidar measurement.

Figure 3 shows the Xcd comparison between the IPDA lidar instrument measurement Xcd, m, and the model from the NOAA in-situ instrument, Xcd, c. The Xcd, m is the result of the 100 pulse average to reduce the error introduced from random noise. The direct comparison between Xcd, c, and Xcd, m, revealed that the column integrated CO₂ mixing ratio measured by the IPDA lidar instrument is higher than that derived from NOAA flask air sampling. The average difference is 1.4775 ppm, which corresponds to a 0.36% difference between the two instruments. This direct comparison between the two independent measurements validates the high precision measurement capability of the 2- μ m double-pulsed IPDA lidar instrument.

3. CONCLUSIONS

NASA LaRC developed a double-pulse, 2- μ m integrated path differential absorption (IPDA) lidar instrument for atmospheric CO₂ measurement. Advantages of the 2-micron high energy pulsed IPDA remote sensing technique include a high signal-to-noise ratio measurement with accurate ranging; favorable weighting function towards the ground surface to measure the source and sinks of the CO₂; and the capability to directly eliminate contaminations from aerosols and clouds to yield high accuracy CO₂ column measurements. IPDA CO₂ differential optical depth measurement results agree well with model prediction. With 10 s average, the standard deviation of the DAOD

measurement is 0.0145. Compared to the CO₂ mixing ratio measured by NOAA flask sampling data, the 2-micron IPDA lidar provided an accurate measurement with 0.36% difference.

ACKNOWLEDGEMENT

The authors would like to thank the NASA Earth Science Technology Office for funding this project. The authors acknowledge support from the Engineering and Research Services Directorates at NASA Langley Research Center. Thanks also go to the dedicated efforts of the Research Systems Integration Branch personnel who made the airborne flight testing possible. Acknowledgements also go to the LaRC CAPABLE team and to NOAA for providing public information that is significant for the science validation process. The authors also would like to thank Dr. Robert Menzies at JPL, Dr. Syed Ismail and Anthony Notari at LaRC for very useful discussion, advice and help.

REFERENCES

- Caron J., and Y. Durand, 2009: Operating wavelengths optimization for a spaceborne lidar measuring atmospheric CO₂. *Appl. Opt.*, 48, 5413-5422
- Menzies, R. T. and D. M. Tratt, 2003: Differential laser absorption spectrometry for global profiling of tropospheric carbon dioxide: selection of optimum sounding frequencies for high-precision measurements. *Appl. Opt.*, 42, 6569-6577
- T. Refaat, U. Singh, J. Yu, M. Petros, S. Ismail, M. Kavaya, K. Davis, 2015: Evaluation of an airborne triple-pulsed 2 μ m IPDA lidar for simultaneous and independent atmospheric water vapor and carbon dioxide measurements, *Appl. Opt.* 54, 1387-1398.
- Yu J., M. Petros, U. N. Singh, T. Refaat, K. Reithmaier, R. Remus, W. Johnson: An Airborne 2-micron Double-Pulsed Direct Detection Lidar Instrument for Atmospheric CO₂ Column Measurements, *JTECH*, in press