

## Measurements of Atmospheric CO<sub>2</sub> Column in Cloudy Weather Conditions using An IM-CW Lidar at 1.57 Micron

Bing Lin<sup>1</sup>, Michael D. Obland<sup>1</sup>, F. Wallace Harrison<sup>1</sup>, Amin R. Nehrir<sup>1</sup>,  
Edward V. Browell<sup>2</sup>, Syed Ismail<sup>1</sup>, Joel Campbell<sup>1</sup>, Jeremy Dobler<sup>3</sup>,  
Byron Meadows<sup>1</sup>, Tai-Fang Fan<sup>4</sup>, and Susan A. Kooi<sup>4</sup>

<sup>1</sup>NASA Langley Research Center, Hampton, VA 23681

<sup>2</sup>STARSS II Affiliate, NASA Langley Research Center, Hampton, VA 23681

<sup>3</sup>Exelis Inc., Ft. Wayne, IN 46818

<sup>4</sup>Science System and Application, Inc, Hampton, VA 23666  
Langley Research Center, Hampton, VA 23681

### 1. Introduction

Changes in atmospheric carbon dioxide (CO<sub>2</sub>) concentrations are considered as one of the key factors in the net radiative heating to the Earth's climate system and in determining future global climate change [1, 2]. The U.S. National Research Council has identified the need for an Active Sensing of CO<sub>2</sub> Emission over Nights, Days and Seasons (ASCENDS) space mission [3] to reduce uncertainties in and to gain a better understanding of CO<sub>2</sub> sources and sinks.

In preparing for the ASCENDS mission, NASA Langley Research Center and Exelis Inc. have jointly developed and demonstrated the capability of CO<sub>2</sub> column measurements with an intensity-modulated continuous-wave (IM-CW) lidar. Results of CO<sub>2</sub> column measurements from aircraft flight campaigns using the prototype IM-CW lidar, Multifunctional Fiber Laser Lidar (MFL), have been very encouraging [4, 5]. MFL operates in the 1.57- $\mu$ m CO<sub>2</sub> absorption band with one laser wavelength positioned on the CO<sub>2</sub> absorption line center (online) at 1571.112 nm, and two other laser wavelengths (offlines) positioned  $\pm 50$  pm on either side of the absorption line. CO<sub>2</sub> column differential absorption optical depth (DAOD) values are derived from combined online and offline measurements using the Integrated Path Differential Absorption (IPDA) approach. The signal-to-noise ratio (SNR) for clear sky IPDA measurements of CO<sub>2</sub> DAOD for a 10-s average

was found to be as high as 1300, resulting in an error 0.077% or equivalent XCO<sub>2</sub> column precision of  $\sim 0.3$  ppm [4, 6].

Measuring CO<sub>2</sub> column density in the presence of thin cirrus clouds, broken clouds, or cloud decks is a challenging task for both active and passive remote sensors. Passive CO<sub>2</sub> retrievals avoid cloudy pixels and use only clear sky measurements [7]. The purpose of this study is to extend the atmospheric CO<sub>2</sub> column measurements of the IM-CW lidar from clear skies to cloudy conditions. Under thin cirrus conditions, IM-CW lidar returns from the surface can be clearly separated from those from thin cirrus clouds because the received lidar returns contain vertically-resolved range information as a result of the range-encoded intensity modulation of transmitted lidar signals [4, 5, 8]. In the presence of low-level optically-thick scattered clouds or cloud decks, the lidar returns from the clouds are strong enough to measure CO<sub>2</sub> column DAODs from the instrument to the clouds.

### 2. Instrumentation and methodology

The basic architecture of MFL for CO<sub>2</sub> column measurements has been discussed in detail in References 4 and 5. Basically, the seed Distributed Feedback Lasers (DFBs) are locked to the CO<sub>2</sub> online and offline wavelengths and fed into their corresponding intensity modulators to impart their unique ranging-codes (i.e., swept frequency) to each laser beam. A swept-frequency technique with 500-KHz bandwidth and center frequency around 350 KHz is used,

which enables the ranging measurements and the ability to separate the cloud and surface returns. The intensity modulated lasers are then simultaneously amplified using an Erbium Doped Fiber Amplifier (EDFA) to increase the transmitted power. A tiny fraction of the amplified laser power is picked off via an optical tap inside of the EDFA and sent to a detector as reference signals for transmitted laser-power normalization and calibration at the online and offline wavelengths. The lidar backscattered returns are recorded by the MFL receiver and used as science signals for the CO<sub>2</sub> DAOD measurements. Digitized science and reference signals are processed by correlating these data with their corresponding range-encoded waveforms. The magnitude and position of the synthetic pulses of these correlation outputs represent the power and time-delay, respectively, of the received signals. Thus, range estimation and the discrimination of surface returns from cloud returns are achieved based on the outputs of the correlation. CO<sub>2</sub> DAOD values can also be retrieved from a combination of online and offline signal powers using the IPDA technique.

### 3. Airborne flight campaign data

The data used in this study were collected with the MFL during the ASCENDS 2011 summer and 2013 winter airborne flight campaigns. Two flight cases are discussed: one for DAOD retrievals to the surface through optically thin cirrus clouds and the other to the tops of optically thick low clouds. In-situ measurements of the atmospheric profiles of CO<sub>2</sub> concentration, temperature, pressure, and humidity were obtained during aircraft spirals for comparison with the MFL remote measurements in each case.

The thin cirrus cloud case studied here was obtained over an arid/semi-arid region around 0000 UT on 23 February 2013 near Blythe, California. The analyzed leg of this flight was maintained at an altitude of about 12.2 km, and the extended thin cirrus clouds were observed just below the aircraft. Fig. 1 shows the measured atmospheric profile as correlation power of lidar

returns. Both online and offline channels clearly showed the thin cirrus clouds just below the aircraft (range close to zero). There were some changes in the range to the surface (lower panels), which resulted from small changes in the surface topography. Our estimation indicated that the average cloud optical depth of these cirrus clouds was about 0.158 with large variability ranging from near zero to as large as 0.8 with the median 0.135.

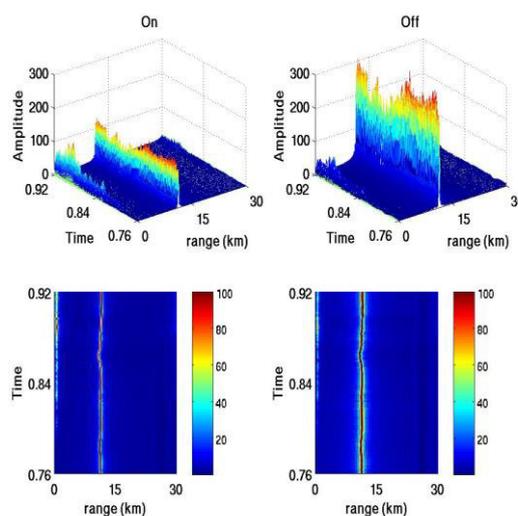


Fig.1 Lidar measured atmospheric profiles for online (left) and offline (right) observations.

The DAOD of CO<sub>2</sub> column to the surface and its equivalent XCO<sub>2</sub> values retrieved from 0.1-s integration are shown in Fig. 2. CO<sub>2</sub> column DAOD estimates for both clear (blue points) and cloudy (presence of intervening thin cirrus clouds; red points) conditions for this flight leg are plotted separately. Their mean and standard deviations are listed in the figure to compare with those derived from in-situ measurements (also listed). Compared to in-situ derived CO<sub>2</sub> DAOD column values, the lidar DAOD measurements were slightly smaller (about 0.004). Spatiotemporal differences in remotely sensed and in-situ observations are expected to account for the absolute differences between the two measurements.

The data for thick low cloud case were obtained over an agriculturally vegetated area on 10

August 2011 in the vicinity of West Branch, Iowa. Because the SNR of DAOD is proportional to the product of DAOD value and SNR of the online and offline power ratio [5], only high altitude observations of the multiple legs (1 to 7) of the flight were considered, which corresponding legs 4, 5 and 7. The flight altitudes for these legs were approximately 7.8, 9.4, and 12.5 km, respectively. The rms error of the range estimates was generally within 3 meters, which is very good and should also be adequate to meet space mission science requirements. DAOD retrievals (Fig. 3) showed consistent high precision results among the three legs although variations in DAOD retrievals to cumulus clouds were much larger than those to the surface owing to smaller DAOD values and weaker lidar power returns from the clouds. Relative precision of CO<sub>2</sub> DAOD column to surface was about 1.3 to 2.2% for these legs. Increasing integration time to 10-s would increase the precision to less than 0.18%. Compared to the errors of CO<sub>2</sub> column to surface, errors in CO<sub>2</sub> column to cloud tops increased due to weak cloud lidar returns.

#### 4. Summary

This study evaluated the capability of IM-CW laser absorption lidar for CO<sub>2</sub> column measurements in cases of thin cirrus and thick fair weather boundary layer cumulus clouds. For thin cirrus clouds, consistent CO<sub>2</sub> DAOD and equivalent XCO<sub>2</sub> column values to surface for clear and cloudy skies were obtained in a 12-km altitude flight over an arid/semiarid region. The clear sky precision for the flight campaign case studied was about 0.72% for a 0.1-s integration. Under a very complicated multi-layer cloud environment of the mid-west vegetated area case with flight altitudes 8 to 12 km, the precision of the estimated CO<sub>2</sub> DAOD column to surface was as low as 1.3 – 2.2 % for 0.1-s integration. The precision of CO<sub>2</sub> column measurements to thick clouds was about a factor of 2 to 3 lower than that to the surface owing to much weaker lidar power returns from clouds and a smaller CO<sub>2</sub> column DAOD compared to those for the surface. These results indicate the potential of IM-CW lidar for

CO<sub>2</sub> measurements over cloudy scenes in space applications.

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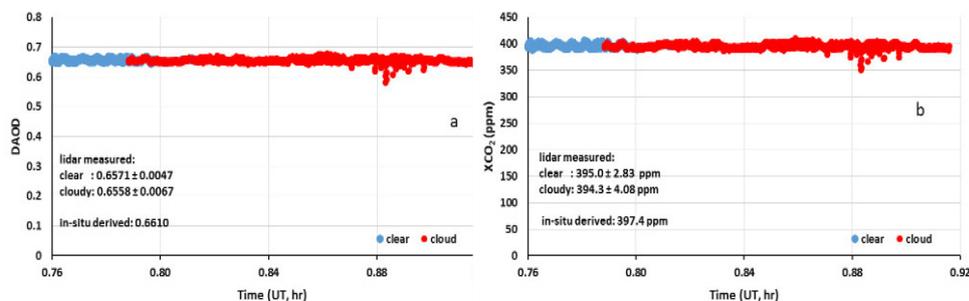


Fig. 2 Plotted are DAOD (a) of CO<sub>2</sub> column to the ground and its equivalent XCO<sub>2</sub> (b) values retrieved from 0.1-s integration of lidar measurements for both clear (blue points) and cloudy (red points) conditions. Their means and standard deviations as well as their corresponding in-situ derived values are listed.

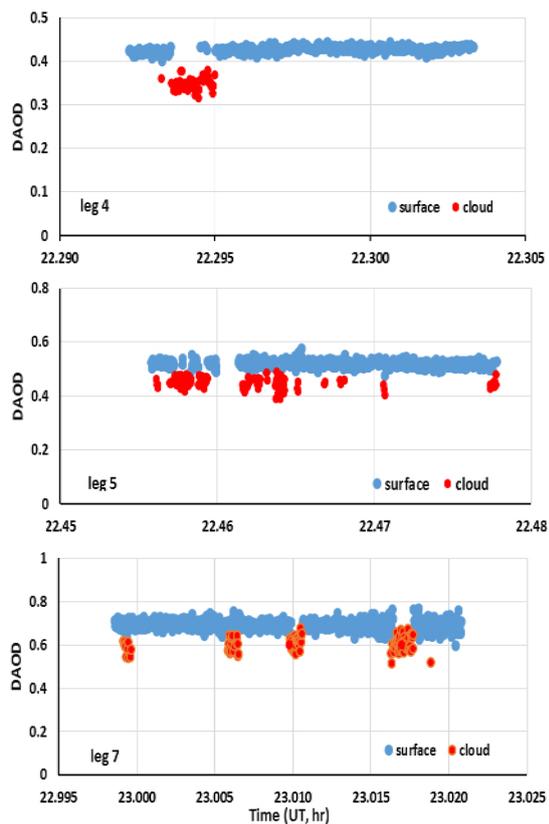


Fig. 3. CO<sub>2</sub> DAOD measurements to the surface (blue) and clouds (red) for legs 4, 5 and 7