FIELD TESTING OF A TWO-MICRON DIAL SYSTEM FOR PROFILING ATMOSPHERIC CARBON DIOXIDE

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ABSTRACT

A 2-µm DIAL system has been developed at NASA Langley Research Center through the NASA Instrument Incubator Program. The system utilizes a tunable 2-µm pulsed laser and an IR phototransistor for the transmitter and the receiver, respectively. The system targets the CO_2 absorption line R22 in the 2.05-µm band. Field experiments were conducted at West Branch, Iowa, for evaluating the system for CO_2 measurement by comparison with *in-situ* sensors. The CO_2 *in-situ* sensors were located on the NOAA's WBI tower at 31, 99 and 379 m altitudes, besides the NOAA's aircraft was sampling at higher altitudes. Preliminary results demonstrated the capabilities of the DIAL system in profiling atmospheric CO_2 using the 2-µm wavelength. Results of these experiments will be presented and discussed.

1. INTRODUCTION

A ground-based 2-µm DIAL system for profiling atmospheric CO_2 was developed at NASA Langley Research Center as part of the NASA Instrument Incubator Program [1-3]. The system was designed for atmospheric boundary layer studies and for possible validation of future space-based CO_2 sensors. The system utilizes different components developed through the NASA Laser Risk Reduction Program, such as a tunable, pulsed, 2-µm laser and IR hetero-junction phototransistor (HPT) detector. The 2-µm DIAL operated over the R22 CO_2 absorption line, which was characterized by narrowband laser spectroscopy.

The design of the DIAL system was based on a 2-µm backscatter lidar, which incorporated a HPT detector [4]. As a first demonstration of IR phototransistors in lidars, the system went through different validation experiments [4-6]. These experiments included comparison of the HPT detector with standard InGaAs avalanche photodiode (APD) in a 1.5-µm lidar [5, 6], and comparison of the system performance with standard aerosol lidars operating at 0.5 and 1.0-µm, using photomultiplier tube (PMT) and Si APD, respectively [4]. The system was integrated inside a trailer which aided in deploying the instrument in different validation locations.

The 2-µm DIAL system was initially tested for CO_2 measurements at NASA Langley Research Center [4]. This test reveals the influence of the metrological data on the system performance among other issues. This includes interference from water vapor absorption at the selected operating wavelength, and sensitivity to atmospheric temperature and pressure through the combination of the influence of both H_2O and CO_2 absorption cross sections and the dry mixing ratio. This led to further investigation of the system capabilities through a field trip to West Branch, Iowa in the summer of 2008. At this location, three CO_2 *in-situ* sensors were installed and operated by NOAA on the KWKB-TV tower (WBI tower) at 31, 99 and 379 m altitudes. The WBI site has several advantages for the CO_2 DIAL measurements in the zenith including easy access of *in-situ* sensors data for instrument validation. The WBI sensors sample the agricultural ecosystems in the corn-belt. This region is considered to contain the lowest levels of CO_2 in North America in the summertime due to the strong uptake by the corn and other corps [7]. This enables detection of the large variability in CO_2 over day and night through the photosynthesis and the respiratory processes. In addition, complementary NOAA aircraft sampling aided in obtaining CO_2 mixing ratios at higher altitudes. Metrological sonde launches were conducted near the measurement location (twice daily) to obtain temperature, pressure and relative humidity profiles which aids in reducing the uncertainty in the DIAL calculation. Some of the significant results of the WBI validation trip will be presented and discussed in this paper.

2. SYSYEM LAYOUT

The CO_2 DIAL system was constructed at NASA Langley Research Center inside an environmentally controlled trailer. A window installed on the trailer roof allows operation of the lidar in the zenith mode. The lidar transmitter consists of a 2-µm, 90-mJ, 140-ns, 5-Hz pulsed Ho:Tm:LuLiF laser that was designed for CO_2 DIAL applications [8]. The laser is injection seeded by CW lasers to produce a tunable single-frequency spectrum of 3.4 MHz linewidth. The laser utilizes a CO_2 gas cell to lock onto the R22 line peak as a reference. Tuning the DIAL on-line to the R22 line peak causes strong absorption limiting the penetration range of the transmitted beam. Thus, a side-line wavelength was selected and locked at either 2.15 or 2.80 GHz away from the line center [4]. The unlocked off-line was selected further away (2053.45 nm) from the line center. The output beam is then expanded (20X) and steered upward using folding mirrors and transmitted coaxially with the receiver telescope. Beam expansion limits the divergence to 85 μ-radians.

The DIAL receiver design is based on HPT [9-10]. HPT has several advantages over InGaAs pin and HgCdTe p-n 2-μm detectors, including high gain and quantum efficiency with low Noise-Equivalent-Power (NEP). The disadvantages of the HPT include high dark current and long settling time [12]. The dark current problem was compensated by proper electronic design, while the bandwidth effect was recovered by de-convolution algorithm [6].

An all-aluminum, Cassegrain, 40 cm diameter, F/2.2 telescope was installed to collect the backscattered radiation. The telescope was designed to achieve a small focus area (180 μm diameter) that allows the coupling of collected radiation into a fiber optic cable. To reduce the day background, the telescope filed-of-view was set to 350 μ-radians by the inlet of the optical cable. The fiber output is collimated and focused using triplet lens design which focuses the radiation onto the 200 μm diameter HPT sensitive area. The main features of the HPT detection system electronics include computer controlled detector bias; temperature control electronics; trans-impedance amplifier with dark current compensation; voltage amplifier with offset and gain adjustments. Digital electronics control the setting of the detection system. The detection system was powered by rechargeable batteries (10 hr operation) for noise minimization. The telescope, optics and HPT detection system are enclosed inside an aluminum box to limit stray radiation. The detection system output was applied to a 12-bit, 5-MS/s waveform digitizer. Single shot profiles were stored in the system computer for further analysis.

3. DATA ANALYSIS

Figure 1 shows the flowchart of the DIAL data analysis scheme to retrieve the CO_2 mixing ratio. The parameters of the R22 CO_2 line and the strongest 59 neighboring lines were obtained following the work of Toth, et. al. [13, 14] and Regalia-Jarlot, et. al. [15], beside the parameters of H_2O 88 neighboring lines obtained from HITRAN (HITRAN 2004). Voigt profile was used for spectral line modeling for both CO_2 and H_2O as a function of atmospheric temperature and pressure. Temperature, pressure and relative humidity profiles were obtained from the sonde data. Using temperature profiles, Goff-Gratch formula is applied to obtain the water vapor saturated pressure, which used with the humidity profile to achieve the water vapor partial pressure. Then, applying the Ideal Gas Law water vapor and dry air number densities were calculated. This process was adopted to obtain time and range dependence.

The backscattered signal calculation procedure included eliminating shots with saturation or glitches and background subtraction. Next, shot averaging and range smoothing were applied before iterative de-convolution to recover the resolution and reduce the noise. Then, the DIAL equation is applied along with correction for the water vapor absorption. Finally, using the dry air distribution, the CO_2 mixing ratio is calculated.

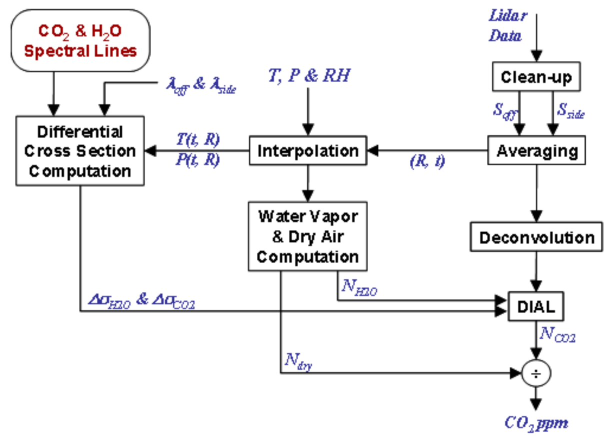

Figure 1. Carbon dioxide DIAL calculation and data analysis flowchart. The analysis insures fixed spatial and temporal resolutions to match the retrieved backscattered profiles.

4. CO_2 TEMPORAL PROFILING

The DIAL system was operated almost continuously from the morning of July 5th till the afternoon of July 6th, 2008. Figure 2 shows the lidar false color diagram for the off-line and side-line range corrected profiles. In the first and last sections (labeled I & IIIB on figure) the side-line was tuned 2.8 GHz off the R22 line center and during the night it was operated at 2.15 GHz. Metrological data were collected twice during the daytime and standard atmospheric models were applied for night time. Initial CO_2 mixing ratio profiles at a range resolution of 30 m were obtained by averaging 300 laser shot pairs and deconvolution of signals with 100 iterations. These data were further averaged to obtain CO_2 profiles at 300 to 450 m range resolutions with 5-points temporal smoothing average. Figure 2 also shows a comparison of the DIAL with the WBI tower-379 m sensor.

Night measurements indicated lower noise compared to day due to the influence of the day background. Since it is closer to the line peak, operating at 2.15 GHz side-line resulted in better near-field sensitivity but with higher attenuation due to stronger absorption. Tuning further away from the line peak, at 2.80 GHz, allows range extension leading to better far-field sensitivity.

5. CO_2 COLUMN MEASUREMENT

One advantage of the DIAL system is the ability to perform integrated CO_2 column measurements. This is demonstrated using data collected on June 26, 2008. On that day, weather conditions included a continuous, variable altitude cirrus cloud, as indicated in the false color diagrams of Figure 3. Vertical column integration was performed between the near-field high scattering from the boundary layer and the far-field scattering from the cloud. Thus, the column length was variable ranging in the 4 to 9 km range. Following the lidar equation, the effective average CO_2 mixing ratio, M_{cd}, was calculated for the column integrated through ranges r_1 and r_2 of the DIAL equation given by

$$M_{cd} = \frac{\frac{1}{2}\ln\left(\frac{P_r(r_1)}{P_r(r_2)}\right) - \int_{r_1}^{r_2} \Delta\sigma_{wv} \cdot N_{wv} \cdot dr}{\int_{r_1}^{r_2} \Delta\sigma_{cd} \cdot N_{dry} \cdot dr}, \qquad (1)$$

where $P_r(r)$ is the side-line to off-line backscatter power ratio, $\Delta\sigma_{cd}$ and $\Delta\sigma_{wv}$ are the CO_2 and H_2O differential cross sections, N_{wv} and N_{dry} are the water vapor and dry air number densities. The integrals of equation (1) were performed numerically using Simpson's definite integral rule.

Figure 3 shows the range corrected lidar signals for the off-line (top) and side-line (bottom) in log scale. Also, shown in the figure are the calculated CO_2 effective average mixing ratio from the column DIAL integration, compared with the mixing ratio of the WBI tower 379 m *in-situ* sensor data. The side-line was tuned to 2.8 GHz. DIAL data analysis included 200 shot averages without de-convolution.

6. CONCLUSION

A 2-µm CO_2 DIAL system has been developed and integrated at NASA Langley Research Center. The system utilizes advanced technologies in the form of a tunable 2-µm pulsed laser and an IR phototransistor for the DIAL transmitter and receiver, respectively. The transmitter was designed to operate at the R22 CO_2 line with tunability to operate at different side-line locations. The system was able to quantify atmospheric carbon dioxide concentrations in the boundary layer, as shown by comparison with *in-situ* sensors. Near-site meteorological data sounding aided in demonstrating the capability of the DIAL system. This was achieved by defining and correcting the water vapor influence on the CO_2 measurements. An optimum side-line and off-line wavelength selection would minimize the influence of water vapor. Further system improvements needed include locking the off-line position, implementing a daytime filter and double-pulse operation.

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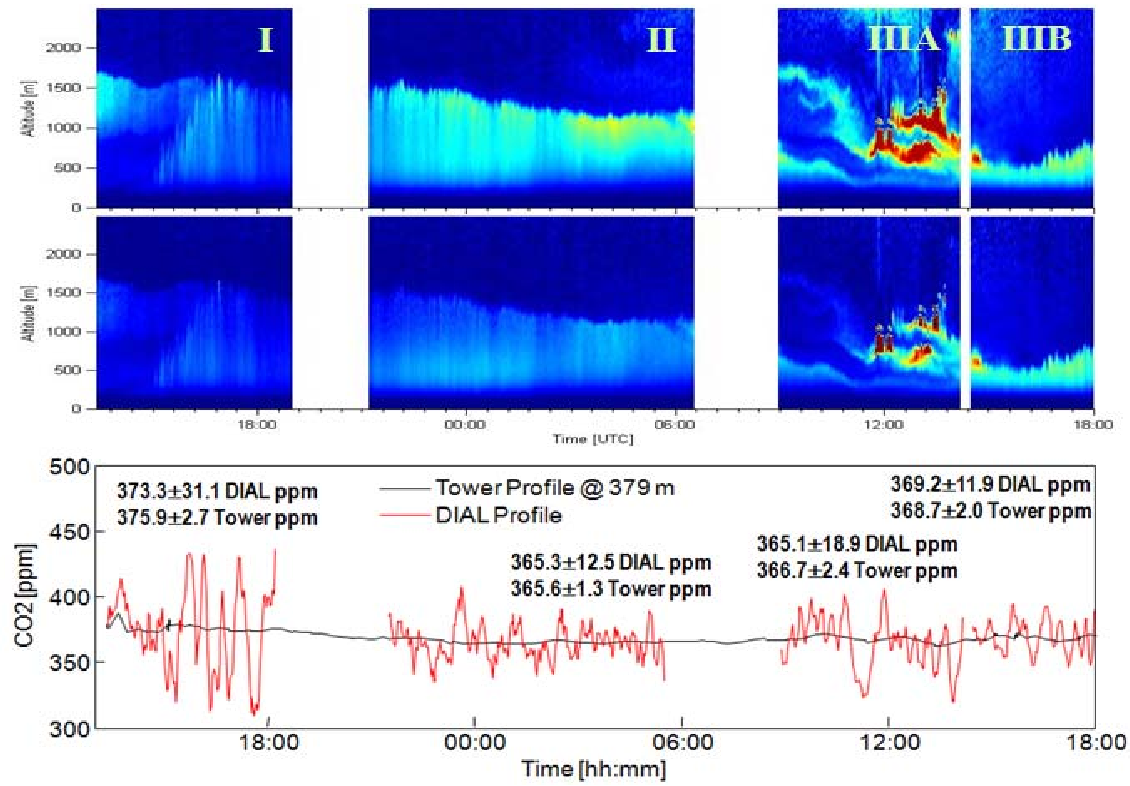

Figure 2. False color diagrams for the off-line (top) and side-line (middle) of the range corrected signal profiles. The data was collecting from the morning of July 5th till the afternoon of July 6th, 2008 with 2.80 GHz (sections I and IIIB) and 2.15 (sections II and IIIA) tuning. The calculated CO_2 mixing ratio of the DIAL and 379 m tower sensor are compared in the bottom.

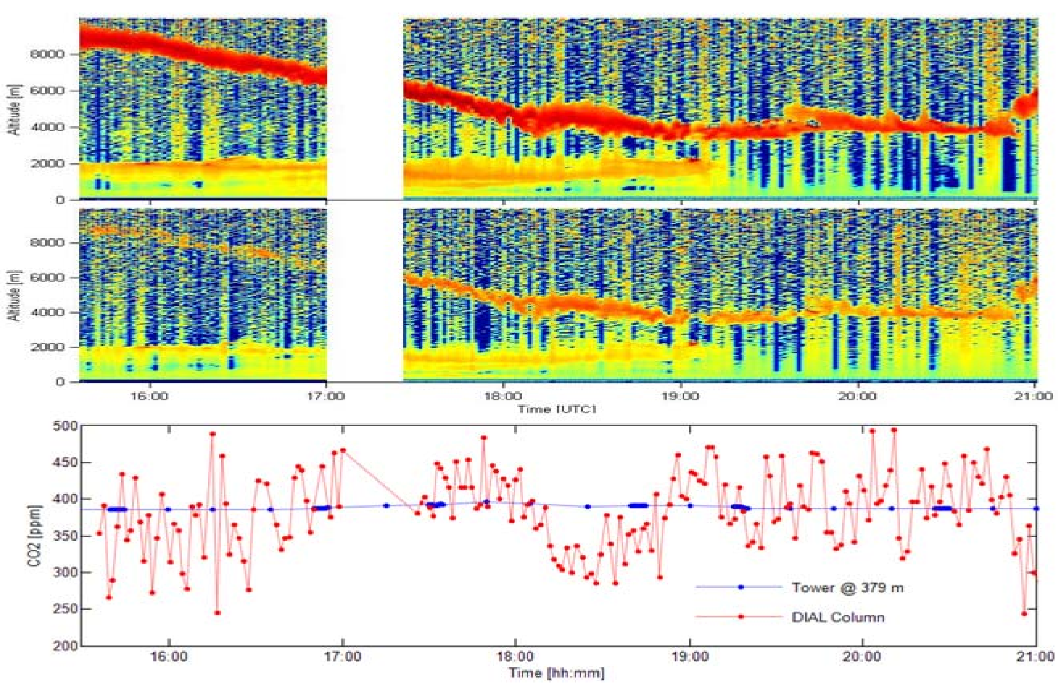

Figure 3. False color diagrams for the log of the range corrected off-line and side-line profiles (top and middle) from measurements on June 26, 2008. The calculated effective average CO_2 mixing ratio of the DIAL and tower sensor are compared in the bottom.