DESIGN, DEVELOPMENT, AND VALIDATION OF A HIGH SENSITIVITY DIAL SYSTEM FOR PROFILING ATMOSPHERIC CO_2

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ABSTRACT

NASA's Earth Science Technology Office's (ESTO) Instrument Incubator Program has funded a 3-year program for the design, development, evaluation and fielding of a ground-based 2-micron Differential Absorption Lidar (DIAL) CO_2 profiling system for atmospheric boundary layer (ABL) studies and validation of space-based CO_2 sensors. This 2-micron DIAL system using pulsed Ho:Tm:YLF lasers is a collaborative effort between NASA Langley, Pennsylvania State University and JPL. The capability and lidar development activities of this system are presented in this paper.

1. INTRODUCTION

The atmospheric burden of CO_2 is increasing in response to widespread anthropogenic combustion of fossil fuels. Roughly half of the emitted CO_2 is absorbed by the Earth's oceans and terrestrial ecosystems [1]. This uptake [2] varies annually from 1 to 6 PgC yr^{-1}. Understanding source/sink processes and the geographic patterns of carbon fluxes are primary goals of carbon cycle science. Uncertainty in predictions of the carbon cycle is one of the leading sources of uncertainty in projections of future climate [3]. A double pulsed DIAL system operating in the 2.05 micron band of CO_2 is being developed for profiling CO_2 in the low-to-mid troposphere. There are several advantages of this system over passive remote sensing systems including day/night operation, reduction or elimination of interference from clouds and aerosols, and direct and straight forward inversion that leads to better quality data and faster retrievals with few assumptions. The scientific rationale for profiling CO_2, the capability of the DIAL system and its development are presented in this paper.

2. NEED FOR AND ADVANTAGES OF PROFILING CO_2

Annually averaged, inter-hemispheric, and continental to marine ABL CO_2 mixing ratio differences are on the order of 1 to 3 ppm [4]. Thus 0.2 ppm has long been a benchmark for required instrumental precision. Achieving this level of precision is difficult with remote sensors. Much larger mixing ratio differences emerge, however, at smaller spatial and temporal scales. Larger scale diurnal variations as a result of ecosystem-atmosphere exchange are observed in the ABL. As an example, hourly averaged CO_2 measurements that were made during the week of May 30, 2004 at Greenbelt, MD (39.01°N, 76.89°W) using an in situ Licor-6262 CO2/H2O analyzer are shown in Figure 1. During 5 out of 7 days the diurnal variations were in the range of 70-90 ppm and even the smallest daily range exceeded 20 ppm. Measurement of the differences in CO_2 concentrations between ABL and free troposphere are needed to retrieve the exchange of CO_2 fluxes between these two regions. A ground-based lidar profiling system with ability to delineate ABL CO_2 from the free tropospheric CO_2 is needed that can operate during day or night. CO_2 distributions in the troposphere are linked to transport and dynamical processes in the atmosphere and are associated with near-surface sources and sinks. In many instances exchange of ABL CO_2 with the free troposphere takes place through convective activity and passage of weather fronts. Hurwitz et al. [5], describe several synoptic passages and document 10 to 20 ppm mixing ratio changes that result from frontal passages. Thouret et al. [6], have shown that there is a high probability of observing more than one layered structure above the boundary layer at any time. An example of the observations of several CO_2 layers using an in situ gas analyzer (LI-COR 6252, [7]) is given in Figure 2. These (preliminary) data were taken from a NASA DC-8 aircraft flight on February 24, 2006 as part of the INTEX-B field experiment. This flight followed a near latitudinal track from Grand Forks, ND to Houston, TX

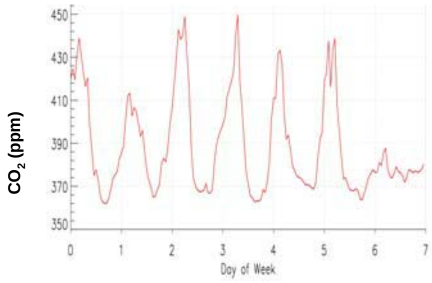

Figure 1, Diurnal variations of CO_2 using in situ LI-6262 sensor during the week of May 30, 2004.

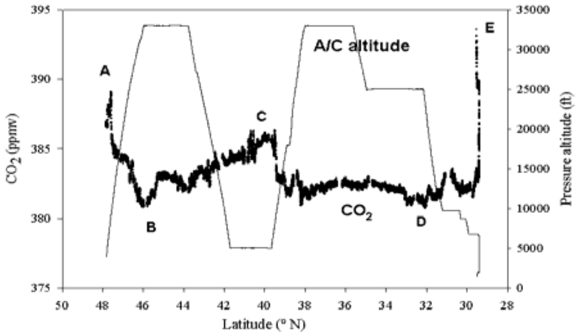

Figure 2, Variations in CO_2 measured by the LI-6252 along the DC-8 flight track during INTEX-B. Preliminary in situ data reveal A) BL to free trop transition, B) stratospheric air, C) biogenic and anthropogenic sources, D) tropical air, and E) free trop to BL transition.

across the US. The airborne in situ CO_2 measurements were made at several level altitude legs and during ascent and descent segments. A number of layers in the boundary layer, free and upper troposphere were observed. Air masses associated with these layers have influences from near-surface ecosystems, biogenic and anthropogenic sources, tropical air intrusions near the subtropical jet at low latitudes and intrusion of polar stratospheric air in the vicinity of polar jet. These CO_2 variations associated with different air masses indicate the advantages of using even point sensor CO_2 measurements as a tracer of dynamical, transport, pollution, biogenic activity in the atmosphere and show the tremendous advantages a remote profiling system would have. Airborne sampling shows that the majority of the vertical structures in CO_2 mixing ratios are found within the lowest 5 km of the troposphere [4]. Thus, the requirements of this DIAL system development are: 0.5% (1.5 ppm) precision for vertical differences in the 30 minute mean mixing ratio resolved every 1 km from 0.5 to 5 km above ground. Estimates of other sources of error will be discussed in this paper.

3. CAPABILITIES OF THE CO_2 PROFILING SYSTEM

This DIAL system is an evolution from an existing coherent detection DIAL system [8,9] that has been used to demonstrate a high CO_2 measurement sensitivity with a $\sigma = 1.5\%$. The object of the current development is achieving a higher sensitivity to the level of $\sigma = 0.5\%$ using the direct detection technique that is insensitive to speckle and coherence length effects from atmospheric turbulence that influence heterodyne detection systems. It incorporates many transmitter and receiver developments from various NASA programs. A discussion of and more recent advances in these areas are presented in the next subsection.

Table 1. Lidar parameters

Pulse energy = 90 mJ
Pulse width = 180 ns
Pulse repetition rate = 5 Hz doublets
Spectrum = single frequency
On-line wavelength = 2050.967 nm
Off-line wavelength = 2051.017 nm
Beam quality < 1.3 time diffraction limit
Long term (one hour) stability < 2 MHz
Telescope diameter = 16”
Detector—AlGaAsSb/InGaAsSb phototransistor

The DIAL system incorporates a high pulse energy, tunable, wavelength-stabilized, and double-pulsed laser that operates over a pre-selected temperature insensitive strong CO_2 absorption line in the 2.05 μm band. A 16” telescope increases the photon signals collected at the detector by a factor of 16 over our previous system. The lidar parameters are given in Table 1, and a block diagram of the laser and optical system is shown in Figure 3.

DIAL performance calculations were done using the lidar parameters in Table 1. A mid-latitude summer atmosphere, a background aerosol model, a

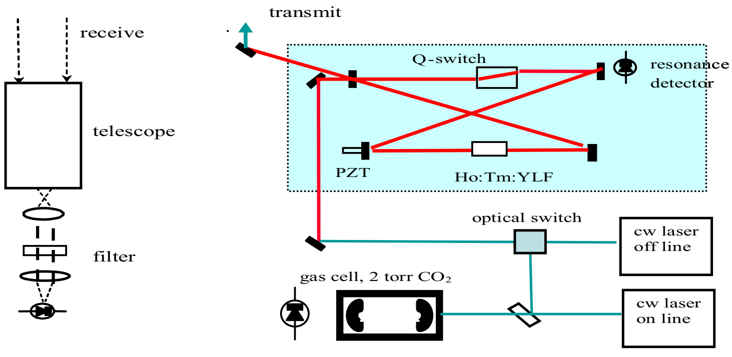

Figure 3, Block diagram of the laser and optical system.

night background, and a CO_2 absorption line at 2050.967 nm operating with the on-line in the side-line position at 20 pm from the line center was used in these computations. The projected precision [10] of a DIAL system using near and far field receivers are shown in Figure 4. The gains for the near and far field detectors were 36.8 and 2737 respectively with the corresponding NEP values of 7.02E-13 and 4.6 E-14 ($W/Hz^{1/2}$) at bias voltages of 2V (at 20^0 C) and 4V (at -20^0C).

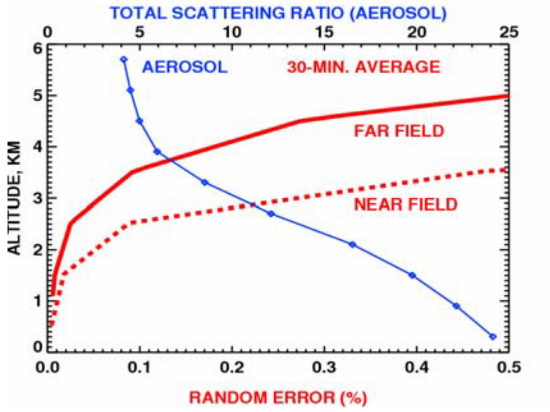

Figure 4, Projected errors in DIAL measurements using near (8') and far field (16") receivers.

3.1 Line selection and Transmitter development

A temperature insensitive [11] CO_2 R 30 line at 2050.967 nm will be used for operating the tunable Ho:Tm:YLF laser. The CO_2 line will be fully characterized using a tunable high-resolution (New Focus Model #6335) laser diode at the Jet Propulsion Laboratory. Accurate spectroscopic parameters will be derived that are critical to realizing ground-based CO_2 lidar detection strategy. The low pressure line position is known to an uncertainty less than 6×10^{-5} cm^{-1} [12]. The ambient temperature line strength will be determined to 2%, the line width to 3%, and the atmospheric pressure shift to 5×10^{-4} cm^{-1} using a multispectral fitting technique.

Recent improvements in performance of the laser transmitter include double-pulse operation as demonstrated in the past with other DIAL systems. The double-pulse is injection seeded with the different on-off wavelength for each pulse of the doublet. The wavelength switching is accomplished by having two injection seed lasers that can be rapidly (in under 1 µs) switched by an electro-optic device controlled by a simple logic signal. One of the seed lasers is tuned to the CO_2 line and the second is tuned off line. The on-line laser is referenced to a CO_2 absorption cell at low pressure, and recent work has improved the performance of the wavelength locking to a level within 390 kHz standard deviation over hour-long time periods. This level of stabilization to line center reflects a factor of 10 improvement over our previous implementation, realized by converting to an external frequency modulation technique rather than wavelength dithering of the laser cavity length. An option now exists for tuning the on-line laser to the side of the line rather than the center of the line. By using the side of the absorption line the optical depth of the DIAL measurement can be tailored for optimal performance. The side line reference is made by locking one seed laser onto line center and referencing a second laser to the center-line laser by monitoring the heterodyne beat signal between the two. A feedback loop, with results shown in Figure 5, has been implemented to lock the side-line laser to the center-line laser.

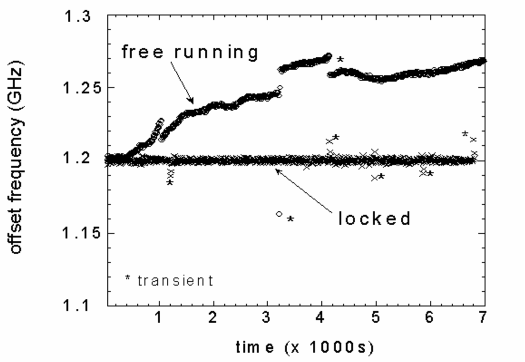

Figure 5: Comparison of side-line tuned CW laser locked and free-running. Free-running drift exceeds 75 MHz. locked performance shows a residual jitter of 1.4 MHz peak-to-peak deviation.

3.2 Receiver system

Two receiver channels are planned to capture the full dynamic range of signals in the near (with in the boundary layer 0.5 to 2.0 km range) and far field (above the boundary layer >1 km). The far field receiver uses a 16 inch diameter F/2.2 all aluminum telescope. The light is reflected by the primary and secondary mirrors and is focused into a 550 micron diameter fiber optic cable. The receiver optics includes a collimating lens, narrowband interference filter, focusing lens, protective window, and detector. The optical design includes focusing the optical signal onto a spot diameter on the 200 micron diameter detector. The near field channel uses a smaller 8" telescope.

A new phototransistor (InGaAsSb/AlGaAsSb; AstroPower) with a 200 µm sensitive area diameter and 400 µm total area diameter will be used as the detector. The advantages of the phototransistor are its high gain (up to 3000), lower noise equivalent power (NEP), and higher quantum efficiency (~70%) compared to the traditional extended wavelength PIN photodiodes. Characterization of these detectors is well underway at Langley and it is found that at high operating gains (~3000) the bandwidth is lower and the recovery times longer. To capture rapid variations of signals in the lower troposphere, a low gain setting for the phototransistor will be used for the near field and a high gain setting for the far field. Atmospheric tests will be conducted to optimize the gain settings. The response time of the near field phototransistor with a gain of 36.8 (part # A1-b10; AstroPower) compared to an InGaAs PIN detector (1 mm diameter, part # G5853; Hamamatsu) is shown in Figure 6. The bandwidth of the PIN detector is 15MHz, as specified in the manufacturer data sheet. It is seen that the response time of the phototransistor is comparable to that of the PIN diode.

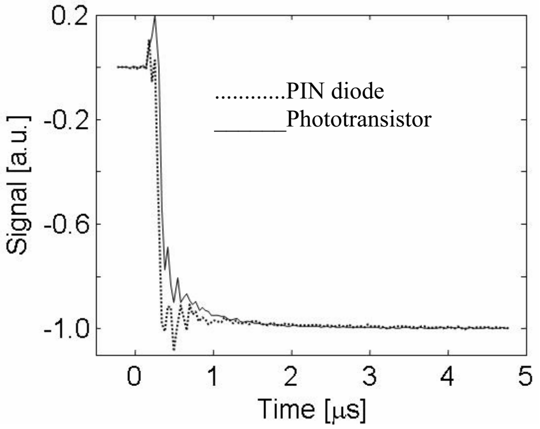

Figure 6, Response time of the near field phototransistor with a gain of 36.8 compared to an InGaAs PIN detector.

Multi-channel data acquisition consist mainly of the National Instruments (NI) hardware/software using a NI PXI-5922 2-Channel 24-Bit Flexible Resolution Digitizer. This digitizer will allow 18-Bits (16-Bits ENOB) of simultaneous sampling at 5 MS/s with a dynamic range of roughly 54 dB. Linearity is so high according to the manufacture that no instruments exist to measure it. The data acquisition software hosting the overall system is the NI LabVIEW. A laptop will be used to command and control the receiver electronics, adjust detector bias voltages, to adjust dark current offset, and for data storage.

4. TESTING AND VALIDATION

After the DIAL system is integrated its performance will be tested by conducting comparisons with a well calibrated ground-based in situ gas analyzer (LI-COR 6252, [7]) at NASA Langley. A fully tested deployable system will be validated by conducting intensive comparisons using ground, tower and airborne LI-COR 7000 sensors at the ARM site in central Oklahoma, or a future NOAA-CMDL tall tower site. Field evaluation of the DIAL will be conducted in year 3 of the project in coordination with field observations of the North American Carbon Plan (NACP) and OCO validation activities.

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5. REFERENCES

1. Battle, M. et al., “Global carbon sinks and their variability inferred from atmospheric O_2 and $\delta^{13}C$”, *Science*, **287**, 2467-2470, 2000.
2. Conway, T.J., et al., “Evidence for interannual variability of the carbon cycle from the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory Global Air Sampling Network” *J. Geophys. Res.,* **99**, 22831-22855, 1994.
3. Friedlingstein, P. et al., “Positive feedback between future climate change and the carbon cycle”, *Geophys. Res. Lett.*, **28**, 1543-1546, 2001.
4. Yi, C. et al., The observed covariance between ecosystem carbon exchange and atmospheric boundary layer dynamics in North Wisconsin, *J. Geophys.Res*, 109(D08302): doi10.1029/2003JD004164, 2004.
5. Hurwitz, M.D. et al., “Advection of carbon dioxide in the presence of storm systems over a northern Wisconsin forest” *J. Atmos. Sci.*, **61**, 607-618. 2004.
6. Thouret, V. et al., General characteristics of tropospheric trace constituent layers observed in the MOZAIC program, *J. Geophys. Res.*, 105, 17,379-17,392, 2000.
7. Vay, S.A. et al., “Airborne observations of the tropospheric CO_2 distributions and its controlling factors over the South Pacific basin”, *J. Geophys. Res.*, **104**, 5663-5676, 1999.
8. Koch, G. J. et al., , Coherent differential absorption lidar measurements of CO2, Appl. Opt. 43, 5092-5099, 2004.
9. Singh et al., Combined 2-μm DIAL and Doppler lidar: application to the atmosphere of Earth or Mars, This conference.
10. Ismail, S. and E.V. Browell, “Airborne and Spaceborne lidar measurements of water vapor, a sensitivity analysis”, *Appl. Opt.*, **28**, 3603-3615, 1989.
11. Menzies, R.T. and D.M. Tratt, “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, 2003.
12. Miller C. E. and Brown, Near infrared spectroscopy of CO_2 $^{16}O^{12}C^{16}O$ line positions, *J. Mol Spectrosc.*, 228, 329-354, 2004.