

Validation of a multi-frequency differential absorption LIDAR (DIAL) system from aerosol and cloud retrievals

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Abstract: A ten wavelength DIAL system based on a 100 Hz optical parametric oscillator (OPO) is used to simultaneously acquire range-resolved and integrated path dry-air CO₂ concentrations from soft cloud targets in Boulder, Colorado. © 2022 The Author(s)

1. Introduction

Validation of range-resolved differential absorption LIDAR (light detection and ranging, DIAL) concentrations present a challenging measurement problem. Direct retrievals of range-resolved greenhouse gas (GHG) concentration data are difficult to obtain by any other method, and therefore, independent measurements for validation are not easily performed. DIAL is a self-calibrating technique especially across narrow wavelength regions of a target absorption feature because the derivatives of the retrieval ratios are largely independent of the laser power and aerosol characteristics. However, systematic errors can still arise. For example, for high peak power systems, the demands for detector linearity must extend over 6 orders of magnitude or more because of the inverse distance-squared dependence of the retrieved signal intensity. Also, residual baseline effects from detector saturation recovery can adversely impact the ratios although the photon counting element of hybrid detection systems can largely alleviate their impact [1].

In our previous work [1], independent system comparisons were performed between DIAL and integrated path (IPDA) measurements [2] where good agreement was observed in the overall trends. However, the systems did not share the same optical path because the prohibitively large backscatter from hard targets (mountain rocks) would destroy the sensitive photomultiplier tubes (PMT) used in the DIAL system. Cloud targets offer a unique solution to this problem [3]. In the 1.6 μm range, many types of diffuse clouds provide a uniform and enhanced backscatter intensity for DIAL that can extend over large ranges (1-3 km range). Furthermore, the ability to positionally select for and track cloud targets that optimize the total accumulated counts while maintaining absorption linearity for single scattering events further enhances the power of IPDA methods for measurements to distant targets.

In this work, we perform simultaneous DIAL and IPDA measurements using a single high-peak-power OPO system that operates over a wavelength range from 1.6 μm to 1.65 μm . While CO₂ is the focus of the current study, similar work on CH₄ is also well within the OPO tuning range. Cloud targets were chosen at sufficiently close range (10 km) to close the gap between the range-resolved DIAL retrievals and IPDA cloud returns. The results provide for a direct comparison between these two important methods for remote sensing of GHGs.

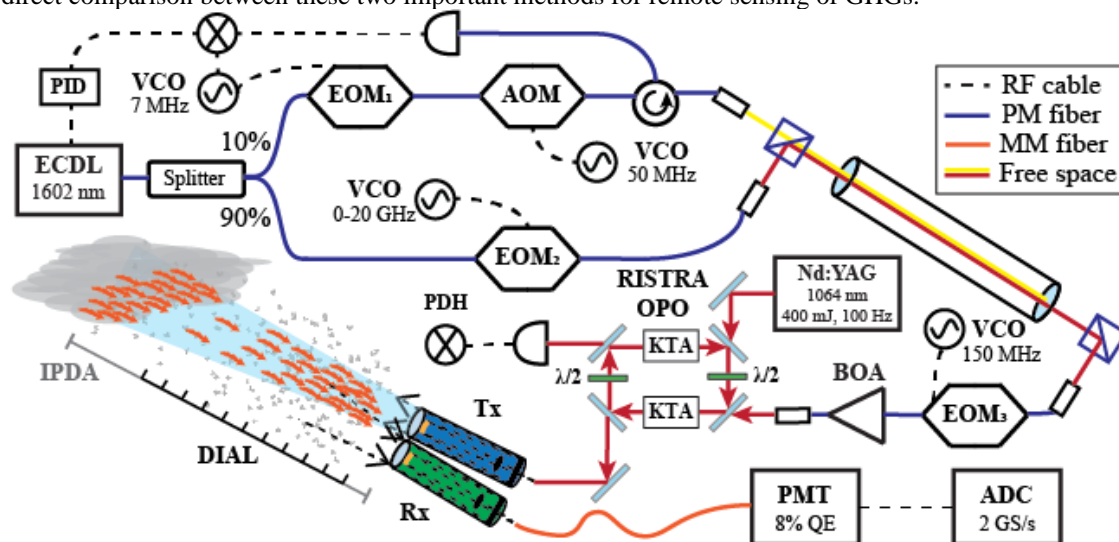


Figure 1: Schematic of the fast-switching OPO DIAL system for range resolved and integrated path CO₂ concentration measurements.

2. Experiment

The OPO laser system shown in Fig. 1 has been described elsewhere [1,2]. Briefly, a fiber-coupled, external-cavity diode laser (ECDL) is first split using a 90 % / 10 % fiber splitter. The 10 % leg is frequency shifted by 50 MHz using an AOM and coupled to invar confocal filter cavity (FSR \approx 300 MHz, finesse \approx 500) for laser frequency lock using a Pound-Drever-Hall method. The 90 % leg is sent to an electro-optic phase modulator (EOM) that is driven with a fast-switching microwave synthesizer (MWS). For an AOM frequency shift near 50 MHz, the frequencies and amplitudes of the MWS scan list are generated such that only the second order comb tooth of one sideband is transmitted through the cavity (spectral purity $>$ 30 dB) [4]. The output frequency from the filter cavity is repeatedly stepped through ten different frequencies at a 100 Hz PRF.

After amplification, the fast-switching wavelength source is coupled to the OPO cavity and then filtered using a prism separator. The signal wave beam is directed to 2 galvanometers for position control to a movable platform, expanded to a 4 in. (100 mm) diameter in a telescope and transmitted with a power near 0.5 W (Class 1 operation). The DIAL returns are collected from a 16" (400 mm) telescope, focused into a 1 mm optical fiber for detection on a PMT (quantum efficiency \approx 8%) and sampled by a 2 GS/s 8-bit analog to digital converter (ADC) for conversion to both current and photon counts.

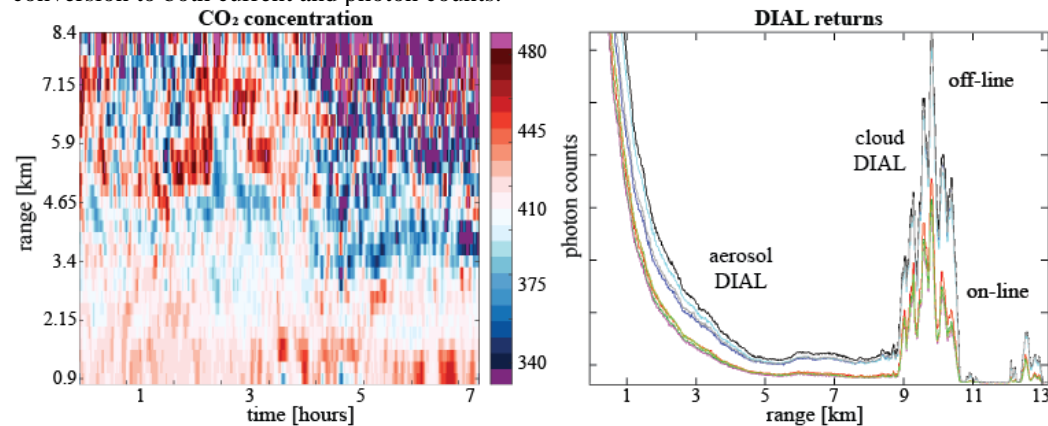


Figure 2: a) The range-resolved CO₂ concentration map from 875 m to 8375 m over Boulder, CO on 11/24/21 for a 7 hr period. The high concentrations of CO₂ near 1.25 km are partly a result of emissions from a power plant on the Univ. of Colorado campus. b) The DIAL returns for all 10 frequencies out to 13 km illustrating the enhanced returns from diffuse clouds near in the 9 km to 11 km range.

3. Results

The spectral region investigated here contains the CO₂ line at 6241.40 cm⁻¹ and the H₂O line at 6241.67 cm⁻¹. As shown in Fig. 2a, full overlap with the transmit beam begins near 625 m and the range extends to over 8 km. Range resolved concentrations are fit at 1 min intervals and for 250 m range bins. The map is slightly smoothed to give \approx 5 min temporal averages. As apparent from the bright red regions, there are several locations of high CO₂ concentration ($>$ 440 ppm) over the city of Boulder. The high levels seen near 1.25 km have significant contributions from the emissions of a power plant located on the Univ. of CO campus. Other high-level regions are seen beyond 5 km in the first 3 hours but are of unknown origin.

For the first part of the night, the returns beyond 8.5 km are dominated by backscatter from diffuse low-level clouds that hovered near the top of the Rocky Mountains (\approx 500 m above the city). The DIAL returns from all ten frequencies are shown in Fig. 2b for a 10 min interval. The signals from the 5 off-resonance frequencies are significantly stronger than the 5 on-line CO₂ colors as expected for a \approx 20 km pathlength. For the IPDA analysis, the total area at each color is integrated and the pathlength used to determine the average column concentration is calculated from the center of mass of the cloud returns. While further analysis is needed to determine the powers transmitted, the statistical uncertainties associated with the IPDA integrated areas are $<$ 0.2 %.

In this work, we have demonstrated a 100 Hz DIAL system for simultaneous measurements of the dry-air CO₂ concentrations over the Boulder, CO. Range-resolved measurements were performed up to 8.5 km at 250 m resolution and have revealed several "hot" spots over the city. Integrated path measurements to low level clouds are shown to have low statistical uncertainties and will be used for the validation of the range-resolved returns.

4. References

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