HETERODYNE DIAL MEASUREMENTS OF ATMOSPHERIC CO2: NUMERICAL SIMULATION AND EXPERIMENTAL RESULTS

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ABSTRACT

A Heterodyne Differential Absorption Lidar (HDIAL) for monitoring atmospheric CO2 concentration is presented. The design of the lidar system is discussed including the 2.06-µm pulsed laser transmitter, heterodyne detection and signal processing. Moreover a numerical simulation in the time domain for HDIAL enables to evaluate the lidar performance for such measurements. Finally preliminary experimental results are presented and compared to the results of realistic simulations.

1. INTRODUCTION

The rise of atmospheric CO2, the primary anthropogenic contribution to the greenhouse effect, is documented at many observing sites around the world [1-2]. Over the past 200 years, the CO2 concentration has increased by 30% in response to industrial emissions and land-use change. Climate models predict a global warming between 1.5 °C and 4°C for a doubling of the current CO2 concentration. To predict the future rate of increase of atmospheric CO2 concentration there is a strong need to quantify carbon sources and sinks at a regional scale, to know and understand the temporal distribution and cause of its variations. High-precision global measurements of atmospheric CO2 profiles, ultimately from space are required. To improve our understanding of carbon cycle fluxes, then measurement accuracy of 0.5-1 % (i.e. 1-3 ppm) in the free troposphere and in the boundary layer are needed. A heterodyne lidar based on 2-µm wavelength lasers has already been developed and used at “Service d’Aéronomie-IPSL” for wind profiling [3]. With certain modification as presented hereafter, a capability exists for making differential absorption lidar (DIAL) measurements of water vapour and carbon dioxide. HDIAL measurements offer a high spatial resolution, a relatively temperature insensitive measurement technique, an interference free technique from other absorbing gases and it can be applied during daytime or nighttimes conditions. In this paper the HDIAL system is described and the first measurements discussed. Moreover, in response to a new ESA proposal i.e. “Study on Observation Techniques and Sensors Concepts for the Observation of CO2 from space”, a new study so-called “Future Atmospheric Carbon dioxide Testing from Space” [4] has began at IPSL. From then on, an-end to-end simulator in the time domain will be useful to analyse HDIAL system performance for measurements from ground-based, airborne and space-based platforms. In this paper, a first version of this simulator is tested for ground-based measurements. Both simulation and experimental results allow fruitful investigation of systematic and statistical errors and HDIAL potential to measure CO2 concentration with the required accuracy.

2. SPECTROSCOPIC CONSIDERATIONS

An important issue in atmospheric CO2 concentration measurements is the selection of the most suitable absorption line characterized by: temperature insensitivity of the cross section, line strength suited in terms of optical depth, non-interference from other lines such as water vapour, coincidence with suitable probing laser wavelengths.

Fig.1. Transmission spectrum for CO2 (375 ppm) and H2O (10 g.kg⁻¹) in the 2.05-2.07 µm range for a 5 km vertical path starting from the ground level.
Consideration on temperature insensitivity at line centre indicates the lower state level energy \( (E^\prime) \) needs to be around \( \sim 300 \text{ cm}^{-1} \). Moreover, assuming a heterodyne detection, an optimum atmospheric optical thickness equal to \( \sim 1 \) exists in order to minimize the relative error on CO\(_2\) concentration. Using the GEISA database [3] with Voigt line shapes, it show that CO\(_2\) lines in the 2.05-2.07 \( \mu \text{m} \) range are well suited (Fig. 1) for atmospheric measurements. These data are used both in the end to end simulator and to analyse the experimental results.

2. DIAL SYSTEM

The HDIAL is based on a Ho:Tm:YLF laser transmitter. The specifications are listed in Table 1. A Ho:Tm/YLF laser is well suited to DIAL measurement due to its tunability over several CO\(_2\) lines in the 2.05-2.07 \( \mu \text{m} \) range. In addition it is eye-safe. As shown in Fig. 2, a Ho:Tm/YLF pulsed laser is pumped by a 5W-10Hz-pulsed Alexandrite laser in a ring configuration with an acousto-optic unit (AOM 2) for Q switching and a Lyot filter for tuning. Line narrowing and fine frequency control are done by injection seeding using a cw laser.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy</td>
<td>10 mJ</td>
</tr>
<tr>
<td>- Pulse repetition rate for one wavelength only</td>
<td>10 Hz</td>
</tr>
<tr>
<td>- Pulse repetition rate for a wavelength pair ON-OFF</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Pulse width</td>
<td>140 ns</td>
</tr>
<tr>
<td>Off-line wavelength</td>
<td>2064.41 nm</td>
</tr>
<tr>
<td>On-line wavelength</td>
<td>2063.2 nm</td>
</tr>
<tr>
<td>Telescope aperture</td>
<td>100 mm</td>
</tr>
<tr>
<td>Detection</td>
<td>InGaAs photodiodes (( \eta = 70% ))</td>
</tr>
</tbody>
</table>

Tab.1. Experimental set up

An acousto-optic modulator (AOM 1) is used to generate a 25 MHz intermediate frequency between the cw local oscillator and the pulsed laser. There are actually two injection-seed lasers involved, one Ho:Tm:YLF for the absorbing wavelength (on-line seed) and a Ho:Tm:LuLiF\(_4\) for the non-absorbing wavelength (off-line seed). The 2nd wavelength is also used for wind profiling using the Doppler technique. Each seeder laser includes a 780-nm-cw-diode laser, an etalon and a PZT-adjustable output coupler for fine tuning.

Fig. 2. Experimental set up of the 2.06 \( \mu \text{m} \) HDIAL
Off-line and on-line lasers are locked thanks to a spectro-acoustic absorption cell containing CO₂ (or H₂O) at low pressure to result in a narrow width absorption line for fine tuning on the absorption line of interest and to avoid H₂O absorption lines. A switching of the ON and OFF probing wavelengths is made possible by 2 choppers (see Fig. 2). Heterodyne detection provides a better accuracy than direct detection for low signal strength and is also suitable to make wind profiling.

3. NUMERICAL SIMULATION

An end-to-end numerical model in the time domain [6] is used to assess the performance of the HDIAL system under realistic atmospheric conditions. It combines laser beam propagation, heterodyne efficiency, the interaction with atmosphere, spectroscopic data. The time model is based on a slicing of the scattering medium along the beam propagation axis. A convolution over the wave fields originating from the various slices within the probing laser pulse followed by an optical mixing with the local oscillator onto the receiver are performed to determined the heterodyne current. The random phase from the various slices are uncorrelated resulting in temporal speckles. Moreover the return power due to a single time sample is randomly distributed according to a negative exponential probability density function. Thus, the interaction with distributed Mie scatterers and diffuse topographic targets can be accounted for in the HDIAL signal. Then the final heterodyne current intensity is the sum of both the lidar signal and noise currents.

A reference model for the atmosphere (so called ESA-RMA) including aerosols, molecules and typical cloud backscatter and extinction, ground and sea reflectance, atmospheric refractive turbulence, pressure and temperature profiles, CO₂ mixing ratio and background radiance is used. Figure 3 displays example of HDIAL measurements using this model including an Alto-Stratus cloud at 4km altitude. The various parameters of the actual HDIAL set up used during the experiments are introduced into the model to obtain realistic Carrier-to-Noise Ratio (CNR). The theoretical values (from the RMA) and simulated values of the apparent backscatter coefficient ($\beta T^2$) are displayed for both the On and Off wavelengths (Fig. 4).

A squarer estimator is used to calculate the return power. Figure 4 put the light on HDIAL detection limit (CNR > -20 dB) and the impact of time speckle on the measurement accuracy. The optical depth follows the theoretical calculations provided the CNR is sufficient for the On-line signal namely in the boundary layer (for range resolved measurement) and at cloud altitude (for column content measurement). An average over one hundred On-Off pairs is necessary to achieve a relative error below 10% for a 1 km column content and a 50% relative error over a 75 m bin in the boundary layer.

![Fig. 4. Comparison of (1) Simulated On-line (gray line) and Off-line (black line) CNR, (4) theoretical and simulated On-line (black line) and Off-line (black line) apparent backscatter coefficient $\beta T^2$, (2) and (3) theoretical (black line) and simulated (gray line) optical depth $\tau$ and local optical depth $\delta \tau$ (for a 75-m bin) and (5) and (6) their respective errors for a 100 shot-pair averaging.](image)

Fig. 3. Simulated On-line (bottom) and Off-line (top) heterodyne currents. Off line return displays a large signal from an Altostratus cloud located at 4 km altitude.
3. FIRST EXPERIMENTAL RESULTS

A second local oscillator is presently in operation early February 2004. However, for it was not built yet at the time of the submission, we present here some preliminary results using one single laser transmitter. On-line and Off-line measurements were recorded sequentially by tuning the injection laser. Figure 5 displays CNR, apparent backscatter coefficient $\beta(z)T^2$ and optical depth profiles. Presently, the model is used with experimental $\beta T^2$ profiles, and the parameters are slightly adjusted to obtain the same On- and Off-line CNR as obtained from experiments. The spectroscopic information make use of the nearby radio sounding to compute theoretical optical depth values to compare with the retrieved values. The comparison shows he retrieved optical depth profile is well fitted by theoretical values assuming a 370 ppm-CO$_2$ concentration in the 0.2-1.2 km range. Indeed, the relative error on a 1 km-optical depth is less than 10% for a 100 shot-pair averaging.

The comparison between simulation and experiment shows the time speckle effect explains most of fluctuation of the retrieved optical depth for the CNR values under consideration here.

4. CONCLUSION

The numerical simulations and preliminary measurements are encouraging to address the feasibility of heterodyne DIAL system to measure CO$_2$ concentration. However, to obtain the required accuracy a large shot-pair averaging is necessary. At present, new experiments are conducted with the two local oscillators and choppers as explained in the text. The results will be presented at the conference. Also, our numerical model has proved to be efficient to simulate realistically performance of HDIAL system.

5. REFERENCES


4. see P.H. Flamant paper at the same conference.
