Advanced 2-µm Ho :YLF transmitter and coherent DIAL for atmospheric CO_2 profiling in the boundary layer

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Abstract

In the framework of climate engineering, a unique approach for geochemical monitoring above a CO2 sequestration site, called SENTINELLE, is currently taking place in the south of France. Within this project, a new mobile CO_2 and Wind (COWI) lidar station has been intentionally developed at LMD/CNRS during the last three years. For an efficient monitoring, 3D scanning, good CO_2 mixing ratio accuracy (1 %) and high time (1 min) and space (100 m) resolutions are required. To fulfil these requirements, a new high power, high repetition rate, single mode 2 µm Ho :YLF laser transmitter has been designed and developed. A Pound-Drever-Hall (PDH) based innovative method has been implemented to get single mode and multi-frequency operation of the transmitter with good energy and spectral stability. Then, the laser transmitter is used in a coherent DIAL system for preliminary CO_2 mixing ratio measurements. In this paper, we detail the project and analyse the potential of coherent DIAL system in the context of CO_2 sequestration site monitoring. Then the COWI lidar is technically described and preliminary measurements are presented.

1. Introduction

In the absence of climate change policies, the fossil fuel emissions are projected to increase in the next decades. Depending on how the current carbon sinks change in the future, the atmospheric CO_2 concentration is predicted to be between 700–1000 ppmv by 2100, and global mean surface temperature between 1.1–6.4°C, with related changes in sea-level, extreme events and ecosystem drifts [1].

Keeping the atmospheric CO_2 concentration “at a level that prevents dangerous interference with the climate system” poses an unprecedented but necessary challenge to humanity. Beyond this point, global climate change would be very difficult and costly to deal with [2]. There are two main approaches: (1) to reduce emissions; (2) to capture CO_2 and store it, i.e. sequestration. Given that the switch to alternative energy sources will take many decades, it is thus very likely that at least some carbon sequestration will be needed in the near future.

Carbon sequestration involves generally three steps: (1) CO_2 capture, either from the atmosphere or at industrial sources; (2) transport; (3) storage. Capture out of the atmosphere is assumed to be much more expensive because of the low CO_2 concentration in the atmosphere relative to N_2 and O_2. For this reason, most current proposals seek to combine capturing CO_2 with power generation, with several pilot power plants planned or underway [3]. The captured CO_2 is then stored in geological formations such as old mines or gas pools and deep saline aquifers [4].

Large-scale and long time sequestrations carry risks for an eventual contamination of potable aquifer or migration and leakage of CO_2 along the transport or through geological conductive pathways (wells and faults) up to surface ecosystem and atmosphere. This requires monitoring techniques for public assurance, i.e. near surface and atmospheric detection of CO_2 concentration anomalies.

SENTINELLE is a research project supported by the French Research Agency (ANR) which has two main objectives: (1) to determine for a given site the different gas sources, with respect to geo- bio- and atmospheres, and to quantify fluxes between compartments; (2) to propose a methodology for 3D survey of a CO_2 storage site. All these results will lead to establish CO2 reference baseline and gas traceability [6].

For those research purposes, a sequestration site has been provided by TOTAL SA Company. TOTAL is conducting the first French pilot, in the southwest of France, to demonstrate the technical feasibility and reliability of an integrated CO_2 capture, transportation, injection and storage [7]. This site is used to acquire data on gas concentrations and flux in the different compartments of the near surface: geosphere (soil, superficial aquifers), biosphere and atmosphere. The time of the project 2007-2013 allowed getting data during pre, during and after injection. Strategy is based on: (1) simultaneous consideration of superficial compartments of a defined geographical area (sub-surface, soil, biosphere and near atmosphere) and (2) the development of multi sensing systems for cross combined geochemical monitoring taking into consideration the daily, seasonal and annual variability of gas exchanges.

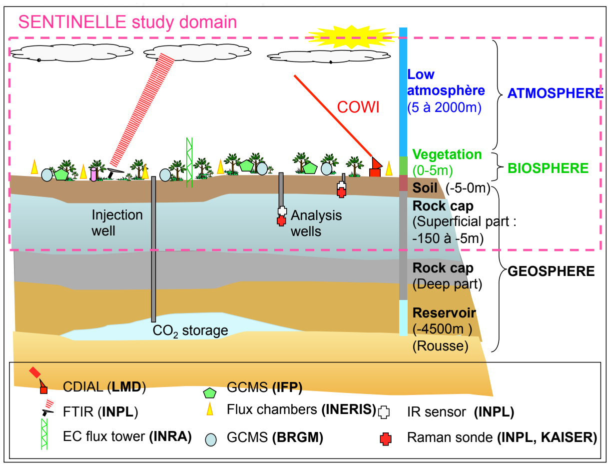

Fig. 1: Strategy of sequestration site monitoring in the SENTINELLE project. COWI: CDIAL (coherent differential absorption lidar); FTIR (Fourier transform spectrometer); EC (eddy covariance flux tower); GCMS (gas chromator mobile system).

In this framework, a new CDIAL system for 4-D CO2 and Wind measurements (COWI) was built at LMD/CNRS, Ecole Polytechnique to take care of the atmospheric compartment. These measurements will be analyzed in synergism with other sensors like FTIR, eddy-covariance flux, surface flux chambers, etc (Fig. 1).

2. COWI experimental set-up

COWI is a new CDIAL system operating at 2 µm currently in development at LMD facility. The overall experimental set-up is displayed in Fig. 2.

The CDIAL uses a new Q-switched Ho:YLF power oscillator (PO). High pulse repetition frequency (PRF) and moderate energy per pulse were chosen to optimize CO_2 differential absorption and radial velocity measurements in heterodyne detection for a given total power of the emitter. An CW powerful and linearly polarized Thulium fibered laser (commercially available from IPG Photonics) longitudinally pumps the PO. The 2051 nm operation of the PO is achieved thanks to both crystal cooling and an etalon inside the cavity.

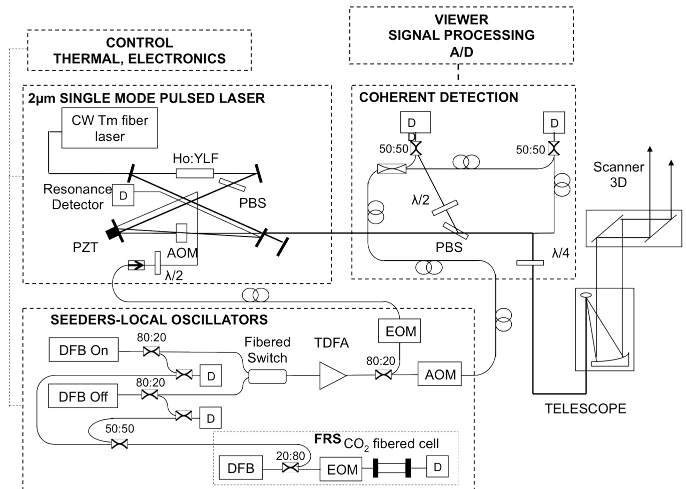

Fig. 2: COWI coherent differential absorption lidar experimental set-up. AOM: acousto-optic modulator, EOM: electro-optic modulator, PBS: polarizing beam splitter, TDFA: Thulium doped fiber amplifier, DFB: distributed feedback laser diode, FRS: frequency reference system, PZT: piezoelectric transducer.

Two DFBs seed successively, after optical amplification, the same single mode PO in a ring cavity arrangement. 2 µm optical switch and Thulium Diode Fibered Amplifier (TDFA) were specially designed and achieved for the lidar respectively by Photline Technologies [8] and ONERA (The french aerospace lab.). Given the high PRF, A Pound-Drever-Hall (PDH) based novative method has been implemented to get single mode and multi-frequency operation of the transmitter with good energy and spectral stability. The two seeders On and Off are locked to a frequency reference system (FRS). The FRS consists in a DFB locked to the center of the R30 CO_2 absorption line using the PDH technique, an all-fibered Electro-Optical-Modulator (EOM) and a CO_2 fibered absorption cell. Actually, excepted the PO which is in free space configuration, COWI is an almost all fibered lidar, including laser seeding, pumping, lidar metrology and heterodyne detection, in order to be transportable and easily deployed during field experiments.

After detection and amplification, an FPGA-based implementation of data acquisition and processing made in the lab enable us to achieve real time filtering of the good shots, spectrum analysis, frequency and power estimates and data accumulation. Further C++ and Matlab based software provide a real time view of lidar reflectivity, radial velocity and optical depth due to CO_2 differential absorption.

The overall system is implemented in a container. A scanner will enable us to make 3D measurements above the CO_2 sequestration site. A 20-m pneumatic telescopic mast and in-situ sensors (i.e. GILL HS50 sonic anemometer and LICOR 7200 CO_2 analyzer) complete the equipment of the CO2 and Wind lidar station.

3. COWI preliminary atmospheric measurements

Preliminary horizontal tests of COWI performances were made in 2012. The single mode dual frequency COWI transmitter was operated at low power (4 mJ/ 2 kHz) during the tests. Fig. 3 displays both lidar reflectivity and radial velocity at On and Off wavelengths and CO2 differential absorption optical depth and absorption coefficient. The CO2 mixing ratio was calculated using the spectroscopic data from Joly et al. [9] and in-situ meteorological data and the method described in previous papers [10].

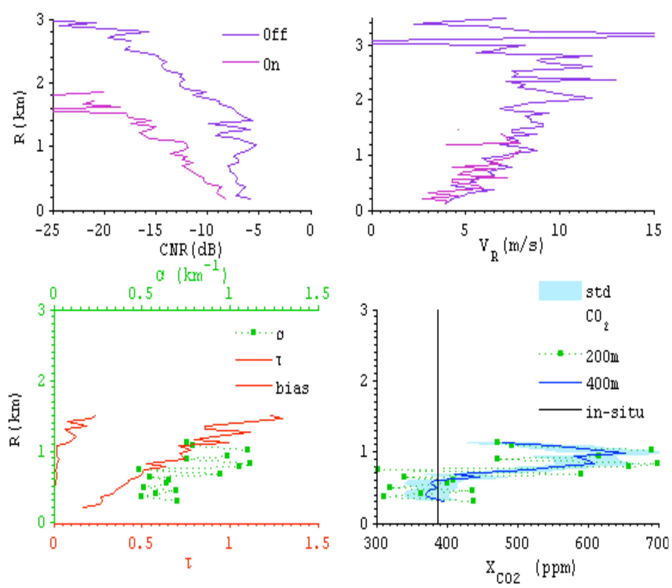

Fig. 3: Carrier to Noise Ratio (CNR), radial velocity (V_R), differential optical depth due to CO2 absorption only (τ), differential absorption coefficient (α) due to CO2 only, CO2 mixing ratio (ppm). The black solid line is for in-situ measurements and the blurred area represents the standard deviation on lidar CO2 measurements for 400 m and 4 s range and time resolution.

COWI proved to be efficient to monitor in real time an anthropogenic CO_2 plume coming from a power plant located on the Ecole Polytechnique experimental site. The anthropogenic plume was also indicated by an anomaly in the CNR standard linear decrease along the distance. The additional radial velocity measurements were used to locate the source of the emissions. Low lidar reflectivity showed that the heterodyne detection was not optimized at that time. Further optimization of the COWI transmitter and the DIAL system are on the way and will be presented at the conference.

Acknowledgments. COWI research project is supported by the French National Agency (project SENTINELLE: ANR-07-PCO2-007), the Centre National Etudes Spatiales (CNES) and the Institut National des Sciences de l'Univers (INSU-CNRS). The authors would also like to thank the french aerospace lab (ONERA), specially Guillaume Canat and Erik Lucas who built the 2-µm TDFA and also LMD mechanical engineers, Olivier Godde and Olivier Bousquet, who designed and dealt with the scanner of the COWI mobile station.

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