Laser Sounder for global measurements of CO2 from space

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ABSTRACT

We have developed a laser technique for the remote measurement of the tropospheric CO2 concentrations from space. Our goal is to develop a space instrument and mission approach for active CO2 measurements. Our technique uses several on and off-line wavelengths tuned to the CO2 absorption line. Simultaneous measurements of O2 column are planned using a selected region in the Oxygen A-band. Laser altimetry and atmospheric backscatter profiles can also be measured simultaneously, which permits determining the surface height and measurements made to thick cloud tops and through aerosol layers.

1. INTRODUCTION

Measurements from ice cores show that atmospheric CO2 concentrations are higher now than they have been in the past 400,000 years. It is becoming increasingly important to understand the nature and processes of the CO2 sinks and sources, on a global scale, in order to make predictions of future climate change.

Accurate measurements of tropospheric CO2 abundance with global-coverage, 300 km spatial and monthly temporal resolution are needed to quantify processes that regulate CO2 storage by the land and oceans.

The NASA Orbiting Carbon Observatory (OCO), which failed to reach orbit after launch earlier this year, was the first NASA space mission focused on measuring total column CO2 and O2 by detecting the spectral absorption in reflected sunlight. The OCO mission was a key first step in our understanding of the carbon cycle however, there were unavoidable limitations imposed by the passive measurement approach. These include best accuracy only during daytime at moderate to high sun angles, interference by cloud and aerosol scattering, and limited signal from CO2 variability in the lower tropospheric CO2 column. The recent NRC Decadal Survey for Earth Science [1] has recommended addressing these un-met needs in a laser-based CO2 measuring mission called ASCENDS.

2. APPROACH

Previous and some ongoing efforts to develop laser instruments for measuring atmospheric CO2 have used the 4.88 um [2] and 2 um [3-6] bands. Our approach uses the 1570nm band and a dual channel laser absorption spectrometer, which continuously measures at nadir from a near polar circular orbit. It uses tunable fiber laser transmitters allowing simultaneous measurement of the absorption from a CO2 absorption line in the 1570 nm band [12] and O2 extinction in the oxygen A-band, and aerosol backscatter in the same measurement path. It directs the narrow co-aligned laser beams from the instrument's lasers toward nadir, and measures the energy of the laser echoes reflected from land and water surfaces.

The lasers are a MOPA architecture using tunable diode seed lasers and fiber amplifiers, and have spectral widths much narrower than the gas absorption lines. The space instrument receiver will use a 1-m diameter telescope and photon counting detectors, and will measure the energy of the laser echoes from the surface along with scattering from any clouds and aerosols in the path. The gas extinction and column densities for the CO2 and O2 gases are estimated from the ratio of the on- and off-line signals via the differential optical absorption technique. Pulsed laser signals and time gating are used to isolate the laser echo signals from the surface, and to exclude photons scattered from clouds and atmospheric aerosols.

The 1570 nm CO2 band [13] is well suited for this measurement. It is largely free from interference, and is within the spectral range of high power lasers and sensitive photon counting detectors. Our technique uses several on- and off-line wavelengths tuned to the gas absorption line. The choice of wavelengths allows us to weigh the measurement sensitivity to the atmospheric column below 5 km and maximizes sensitivity to CO2 changes in the boundary layer where variations caused by surface sources and sinks are largest. Simultaneous measurements of O2 column are planned using a selected region in the Oxygen A-band. Laser altimetry and atmospheric backscatter profiles are also measured simultaneously, which permits determining the surface height and measurements made to thick cloud tops and through aerosol layers.

The laser sounder approach has some fundamental advantages over measurements with passive sensors using reflected sunlight. It measures gas absorption in a common nadir/zenith path and the narrow laser divergence produces small laser footprints. The laser sources allow measurements in sunlight and darkness allowing global coverage. It can measure continuously over the ocean, to cloud tops and through broken clouds. The lasers are pulsed and potential measurement errors from scattering from clouds and aerosols are greatly reduced by using time gating in the receiver. Nonetheless, the optical absorption change due to a few ppm change in CO2 is quite small, <1%, which makes achieving measurement sensitivity and

© Proceedings of the 8th International Symposium on Tropospheric Profiling, ISBN 978-90-6960-233-2
Delft, The Netherlands, October 2009. Editors, A. Apituley, H.W.J. Russchenberg, W.A.A. Monna

stabilities challenging. Signal-to-noise ratios and measurement stabilities of > 700:1 are needed to allow CO2 mixing ratio estimates at the few ppm level.

3. AIRBORNE INSTRUMENT DESCRIPTION

We have demonstrated key aspects of the laser transmitter, detector and receiver approaches in the laboratory. We have also measured O2 over a long open horizontal path using a breadboard version of the sensor.

In preparation for a space mission we have packaged our laboratory breadboard instrument into a NASA aircraft.

The aircraft we chose was a Lear-25 jet operated by NASA Glenn Research Center (Figure 1).

Figure 1. *NASA Glenn Aircraft chosen for the CO2 Sounder airborne campaign.*

The Lear-25 was chosen primarily for its high altitude capability (> 45000 ft) that allows us to fly above most clouds and demonstrate the sensitivity of the sensor.

The airborne instrument (Figure 2) uses a narrow linewidth wavelength tunable pulsed laser transmitter allowing simultaneous measurement of the absorption from a CO2 absorption line in the 1572 nm band and surface height and aerosol backscatter all in the same path. It directs the narrow co-aligned laser beam toward the custom nadir port of the aircraft (Figure 3), and measures the energy of the laser echoes reflected from land and water surfaces.

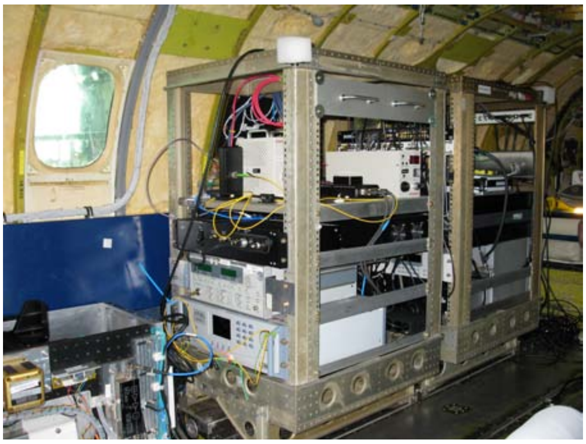

Figure 2.*CO2 Sounder Instrument in the LearJet-25.*

The wavelength of single laser is swept across the CO2 line in 20 steps per scan, at a scan rate of 450 Hz. The time-and wavelength resolved laser backscatter is collected by the telescope, detected by a photomultiplier and recorded by a photon counting timing system with 1 second integration time. The receiver uses a 20 cm diameter commercial telescope. The gas extinction and column densities for the CO2 are obtained from a retrieval algorithm that fits the observed scan while accounting for atmospheric temperature, pressure, and water vapor.

Figure 3.*LearJet-25 nadir Windows used for the CO2 Sounder airborne campaign.*

4. AIRBORNE CAMPAIGN PRELIMINARY RESULTS

During the fall 2008 and summer of 2009 we made measurements of atmospheric CO2 absorption from the aircraft to the surface during several flights. We did several flights over northern and southern Ohio, over Nebraska, and Illinois. Several flights were also made over the US Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) site in northern Oklahoma.

These flights covered a variety of land surface types, water surfaces and through thin clouds, broken clouds and to cloud tops.

Most, but not all, of our flights used a "stair-stepped" pattern, i.e. increasing or decreasing flight altitude over a box or rectangle of several tens of kilometres. Figure 4 shows an example of one of our 2008 Oklahoma flights superimposed on a Google Earth Map.

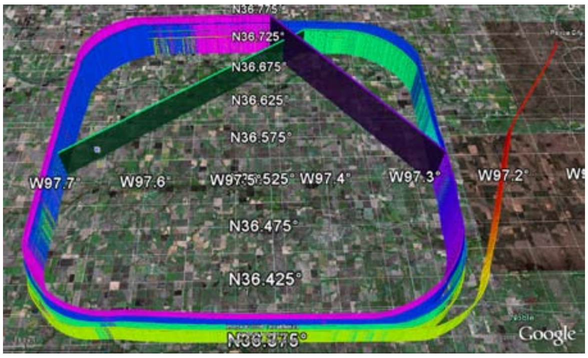

Figure 4.*Sample path of a LearJet-25 flight pattern during our CO2 Sounder airborne campaign.*

These flights were also coordinated with DOE investigators who flew an in-situ CO2 sensor on a Cessna aircraft inside the CO2 Sounder flight pattern – but at much lower altitudes.

Preliminary results from approximately 4 hours of airborne measurements from 3-8 km during our 2008 flights show very good agreement with the DOE in-situ sensor.

Figure 5 shows the measured CO2 column number density (with the error bars in black) vs. calculated (in red) as a function of flight altitude.

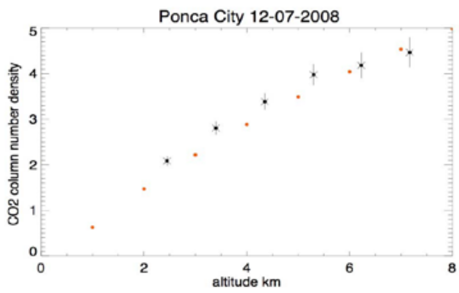

Figure 5.*Comparison of measured CO2 column number density vs. calculated as a function of flight altitude.*

Similarly data from a later flight in the summer of 2009 over Illinois show a fairly linear increase in absorption with increasing altitude (Figure 6).

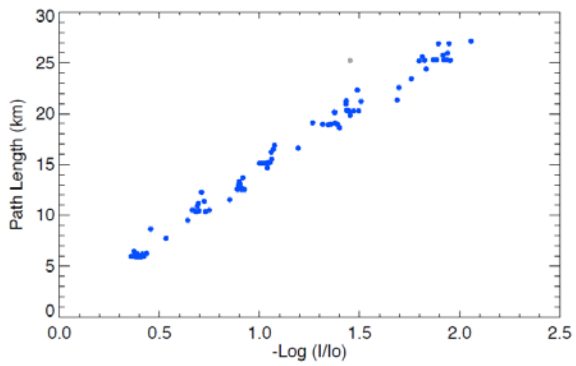

Figure 6.*Pathlength vs. absorption.*

5. SUMMARY

The laser sounder approach has some fundamental advantages over measurements with passive sensors using reflected sunlight. It measures gas absorption in a common nadir/zenith path and the narrow laser divergence produces small laser footprints. The laser sources allow measurements in sunlight and darkness allowing global coverage. It can measure continuously over the ocean, to cloud tops and through broken clouds. The lasers are pulsed and potential measurement errors from scattering from clouds and aerosols are greatly reduced by using time gating in the receiver.

Preliminary results from our recent airborne campaign show that this approach can meet the science requirements for the ASCENDS mission.

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