CO_2 Mixing Ratio Retrievals from JPL Airborne Laser Absorption Spectrometer Flight Campaigns in 2009-2010

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1. Introduction

An airborne or Earth-orbiting laser-based approach to high-precision measurements of atmospheric CO_2 offers the potential to provide the high-accuracy mixing ratio measurements on regional and global scales with spatial resolution that is desired by the carbon cycle research community. The Laser Absorption Spectrometer (LAS) technique that we describe here involves probing a well characterized pressure-broadened absorption line profile with one or more laser frequencies in order to provide weighting functions suitable for retrieving mixing ratio with vertical profile information.[1] If the Earth surface provides the multi-wavelength backscatter signals that are differentially attenuated by the intervening atmosphere, we refer to this as Integrated Path Differential Absorption (IPDA).

An advantage of the active laser-based measurement approach is that day-night global coverage is obtained. The passive spectrometer approach that detects the spectrum of the scattered sunlight is constrained to regions where the solar zenith angle is suitable, resulting in no coverage on the night side and sparse coverage at high latitudes, particularly in winter. Another advantage of the LAS measurement approach is that it can be designed to be strongly responsive to the lower troposphere. The passive spectrometer approach that detects upwelling thermal radiation is constrained by poor temperature contrast between the Earth surface and the lower troposphere and its weighting functions are most sensitive to the middle and upper troposphere.

The principles of the IPDA technique for two frequency-tuned transmitted (and detected) signals are as follows. (The “on-line” signal at λ_1 is tuned to a frequency that overlaps the CO2 absorption line of interest, while the “off-line” signal at λ_2 is tuned to a frequency in the vicinity for which there is minimum overlap with absorption lines.) Start with the expression for Differential Atmospheric Optical Thickness between on- and off-line transmitted signals

$$DAOT = \int_0^R (\sigma_1(z) - \sigma_2(z)) n(z) dz$$

where R is the total path length or range, $\sigma_1(z) - \sigma_2(z)$ is the local differential cross section at z that is a function of pressure and temperature, and $n(z)$ is the local CO_2 number density. The quantity $n(z)$ can be expressed as $q(z)n_{air}(z)$ where $q(z)$ is the CO_2 mixing ratio. Knowledge of the water vapor mixing ratio is necessary in order to derive the dry air column-weighted mixing ratio, XCO_2.

For CO2 measurement from space assuming a nadir or near-nadir view, a weighted column dry air mixing ratio is obtained from the IPDA sounding because the absorption lines are pressure-broadened in the lower atmosphere and because there is some temperature dependence of both the line strength and the linewidth. Thus the cross section at the probing on-line frequency is dependent on altitude. The weighting favors the lower troposphere when the on-line frequency is detuned one or more (surface pressure) halfwidths from line center. We can use this to advantage in the LAS technique, as mentioned above. Detuning the on-line frequency several halfwidths from line center results in selective probing of the CO2 in the lower troposphere, where the CO2 mixing ratio variability of interest is the highest. (Typical weighting functions for CO_2 sounding are found in reference [2].

Multiple flights of an airborne CO_2 LAS instrument over land sites with varied terrain and topography and over bodies of water provide the opportunity to demonstrate the suitability of the LAS IPDA technique, to evaluate the instrument technology, and to develop and refine the high precision retrieval algorithms that are essential. With an aircraft platform, multiple overpasses at different altitudes can provide vertical profile information in addition to what can be obtained when taking advantage of the inherent vertical weighting functions. The instrument that we briefly describe here utilizes a CO_2 absorption line in the 2-μm band. The linestrength of the selected absorption line is sufficiently large that suitable differential absorption exists for high sensitivity measurement over relatively short (~ 2 km) pathlengths. Thus CO_2 mixing ratios can be retrieved in layers with thicknesses of this dimension when overflying a selected ground track at multiple altitudes.

The relatively large linestrengths in the 2.05 μm band have also enabled ground-based measurements of CO_2 using DIAL and IPDA approaches.[3,4]

2. Airborne CO_2 LAS Instrument Overview

The CO_2 LAS instrument was jointly developed by JPL and Lockheed Martin Coherent Technologies (LMCT) with funding from the NASA Earth Science Technology Office Instrument Incubator Program. This instrument employs CW transmitters and coherent detection receivers. The CO_2 LAS transceiver approach is to utilize heterodyne detection, implementing a narrow bandwidth receiver, with frequency-stabilized narrow-linewidth laser transmitters and local oscillators. The transceiver consists of two separate transmit/receive channels for the on-line and off-line components of the IPDA measurement. The transmitter frequencies are carefully stabilized with respect to a selected CO2 absorption line. Each channel has a dedicated heterodyne detector, and a cw single frequency laser which acts both as the transmit laser and the local oscillator for heterodyne detection of the return signal. The transceiver includes a third laser locked to a frequency near line center of the R(30) CO_2 absorption line at 4875.749 cm^{-1} that provides an optical frequency reference for frequency offset-lock tuning of the other lasers. This is accomplished using a temperature controlled, hermetically sealed CO_2 absorption cell with an internal pressure of a few Torr. The on-line laser is frequency offset-locked to this reference laser. The on-line laser is tunable over a range of several GHz with respect to the fixed frequency of the reference laser, using a piezo-electrically-positioned resonator end-mirror. Tunability of the on-line laser allows CO_2 measurement flexibility through on-line frequency adjustment. (The atmospheric CO2 line has a pressure-broadened FWHM of about 4 GHz near sea-level pressure.) A small fraction of the output from the on-line laser is combined with the output from the reference laser for frequency offset locking. The offset frequency accuracy is better than 5 kHz when locked. When properly locked, the effective linewidth of the offset-locked laser is then dominated by the short-term frequency jitter of the reference laser. The off-line laser is offset locked with respect to the on-line laser frequency.

The CO_2 LAS key instrument parameters are provided in Table 1.

Parameter	Value
CO_2 line center frequency	4875.749 cm^{-1}
On-line frequency Off-line frequency	4875.882 cm^{-1} 4875.225 cm^{-1}
Laser output power	100 mW
Transmit/Receive Telescope apertures	10 cm diameter
Receiver FOV (diffraction limited)	60 μrad
Photomixer type	InGaAs
Receiver heterodyne frequency window	9-21 MHz
Signal Digitization	14 bits / 50 MHz

Table 1. JPL airborne LAS instrument paramters

A frequency offset is required between the return signals and their corresponding local oscillators for low noise heterodyne detection. By pointing the transmit beams at a known offset from nadir, the return signals will experience a nominally fixed Doppler shift for a given aircraft velocity, thereby eliminating the need for an additional frequency shifting device in the receiver. The nominal heterodyne offset frequency is 15 MHz. The LAS instrument has flown on two aircraft, a chartered Twin Otter and the NASA DC-8 research aircraft. The typical Twin Otter ground speed is nominally 55-60 m/s. The DC-8 ground speed was altitude dependent, over a range of about 150-220 m/s.

The IF photomixer signals from the on-line and off-line channels are amplified and bandwidth limited to a nominal 9-21 MHz window. The signals from each channel are digitized with a 50 Msamples/sec, 14-bit digitizer. The samples are transformed into the spectral domain using an FFT operation followed by conversion to periodograms. The commonly used "squarer" estimator is used to determine the return power in each channel. Both 4K and 16K FFT's have been employed in the study of the signals. In each case, the sampling duration (80 μs for the 4K FFT, 320 μs for the 16 FFT) is less than or approximately equal to the speckle decorrelation time of the signal, τ_{decorr} , which is ~ 1 ms for the nominal Twin Otter cruise speed and ~ 0.3 ms for the DC-8.

A pre-selected number of periodograms is summed, and the remainder of the signal processing steps operate on a collection of these sums over g individual periodograms. The signal power becomes a gamma-distributed random variable. The sum of k independent exponentially distributed random variables, each of which has a mean value θ, can be described by the gamma function, $f(x; k,\theta)$, with integer values of k, whose shape approaches a Gaussian with increasing k, in accordance with the central limit theorem..

3. Atmospheric Effects on Measurement Precision

Attainment of CO_2 measurement precision of the level of ~0.3% or 1 ppm is a very challenging endeavor, starting with the need to obtain a very high instrumental signal-to-noise ratio (SNR) within the measurement time, and involving knowledge of all atmospheric quantities that might impact the determination of the optical depth due to CO_2 absorption at a level of a few parts in 10^4. These include surface pressure, temperature and water vapor profiles, as well as optical properties and vertical distributions of thin clouds that may be present in the atmospheric column. Reliance on the meteorological products (e.g., temperature profiles, surface pressures) from ground-based and airborne sensors, as well as sonde launches, are critical. Discussion of the effects of meteorological parameter uncertainties on the CO_2 measurement uncertainty can be found in Refs. [2,5,6].

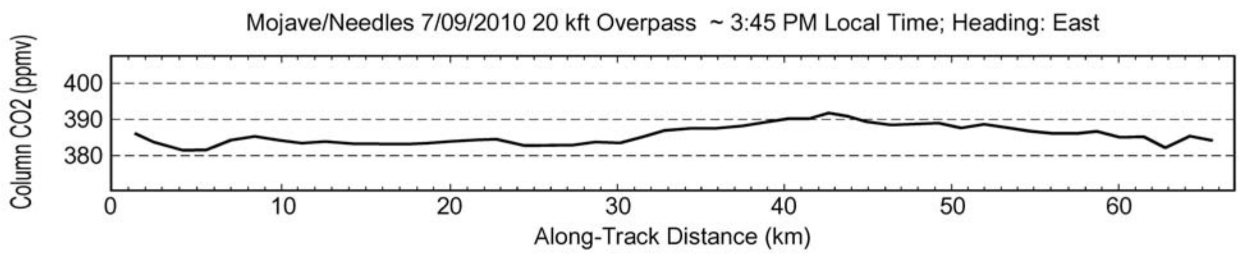
4. 2009 and 2010 Campaigns

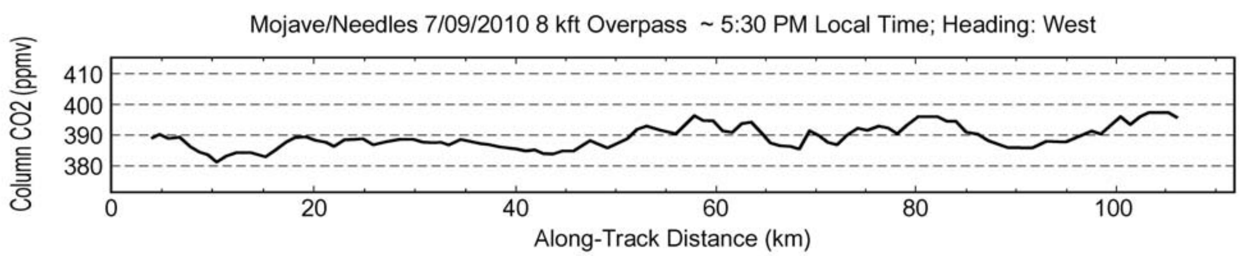
There were two flight campaigns in 2009: (1) El Mirage dry lake in the Mojave desert in mid-April, and (2) vicinity of the Oklahoma DOE Southern Great Plains (SGP) site in July/August. The main purpose of the El Mirage campaign was to evaluate the stability and repeatability of retrieved CO_2 *DAOT* that could be obtained when flying over a flat surface with nearly uniform, high albedo. Repeated overpasses were conducted at multiple altitudes in order to assess variability of the retrievals. *DAOT* values were measured in layers defined by the upper and lower bounds of the overpasses and the different altitudes. The path length through the layer was determined by the on-board GPS. The Oklahoma campaign was coordinated with other airborne CO_2 measurement teams, including two other airborne IPDA systems and an airborne *in situ* CO_2 measurement capability. The aircraft containing the IPDA systems flew over a common fixed latitude ground track at several predetermined altitudes. The airborne *in situ* sensor was used to produce vertical profiles near the midpoint of the ground tracks. Results obtained with the JPL LAS are reported in Ref. [6].

A notable result from the Oklahoma campaign is that the the *in situ* profile data helped to confirm the day-to-day repeatability of the LAS measurements. The predetermined altitudes of the LAS overflights ranged between 7 kft and 10 kft. Comparisons between the JPL LAS measured column-weighted mixing ratios and the *in situ* derived vertical profiles confirmed that there was very little variability in the CO_2 mixing ratio within the 7-10 kft layer from day to day, while significant variability occurred at the lower altitudes.

During the month of July, 2010 the CO_2 LAS instrument flew on the NASA DC-8 research aircraft over 5 sites with distinctive characteristics: (1) Central Valley, California; (2) Mojave Desert near Needles, California; (3) Railroad Valley, Nevada; (4) DOE SGP site in Oklahoma; (5) Pacific Ocean off the coast near the border between California and Baja California. For each site, the aircraft was flown in multiple overpasses at a number of altitudes. A spiral was also flown over each site, allowing the on-board *in situ* sensors to collect vertical profile meteorological data.

An example of the retrieved weighted-column CO_2 mixing ratios using the LAS data and the retrieval algorithms is shown here, for columns of 8 kft (~2.4 km) and 20 kft (~ 6 km) thicknesses between the aircraft overpass altitude and the surface. Speckle statistics produce an rms fluctuation of ~ 2 ppm equivalent in this case. The overpass averages show column average mixing ratios that are very nearly the same, which is consistent with the uniformity of the mixing ratio profile obtained with the sonde sensor that was launched near the ground track.





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