

# Airborne Laser Absorption Spectrometer Measurements of CO<sub>2</sub> Column Mixing Ratios: Source and Sink Detection in the Atmospheric Environment

Robert T. Menzies\*, Gary D. Spiers, Joseph C. Jacob

*Jet Propulsion Laboratory, California Institute of Technology  
4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.*

*\*Email: rmenzies@jpl.nasa.gov*

## ABSTRACT

The JPL airborne Laser Absorption Spectrometer instrument has been flown several times in the 2007-2011 time frame for the purpose of measuring CO<sub>2</sub> mixing ratios in the lower atmosphere. The four most recent flight campaigns were on the NASA DC-8 research aircraft, in support of the NASA ASCENDS (Active Sensing of CO<sub>2</sub> Emissions over Nights, Days, and Seasons) mission formulation studies. This instrument operates in the 2.05- $\mu$ m spectral region. The Integrated Path Differential Absorption (IPDA) method is used to retrieve weighted CO<sub>2</sub> column mixing ratios. We present key features of the CO<sub>2</sub>LAS signal processing, data analysis, and the calibration/validation methodology. Results from flights in various U.S. locations during the past three years include observed mid-day CO<sub>2</sub> drawdown in the Midwest, also cases of point-source and regional plume detection that enable the calculation of emission rates.

## 1. INTRODUCTION

Atmospheric CO<sub>2</sub> is a long-lived greenhouse gas, with sources and sinks primarily at the surface. Seeking improved capability to determine the fluxes of CO<sub>2</sub> on various spatial scales, national space agencies have invested in Earth-orbiting passive spectrometers viewing reflected solar radiation. GOSAT (Greenhouse Gases Observing Satellite) was launched in January, 2009, and OCO-2 (Orbiting Carbon Observatory) was launched in August, 2014. These instruments are providing valuable insight into the capabilities of this technique. They have provided an unprecedented number of CO<sub>2</sub> soundings on a global scale. Cloud and aerosol scattering, terrain

complexities within the IFOV, and limited SNR (Signal to Noise Ratio) outside of daytime mid-latitudes are inherent issues that can be mitigated or eliminated using laser-based integrated path differential absorption (IPDA). An airborne laser-based approach to high-precision measurements of atmospheric CO<sub>2</sub> offers the potential to provide the high-accuracy mixing ratio measurements on regional scales with spatial resolution that is useful to the carbon cycle research community. The airborne environment is a good test of the component technologies and system designs. Experience with airborne IPDA lidars is also critical in assessing the instrument parameters and retrieval algorithms that are relevant to Earth-orbiting observations.

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. 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 by detuning the on-line frequency to a location one to three halfwidths from line center results in selective probing of the CO<sub>2</sub> in the lower troposphere, where the CO<sub>2</sub> mixing ratio variability of interest is the highest. (Typical weighting functions for CO<sub>2</sub> sounding are found in references [1-4].) The JPL Laser Absorption Spectrometer (LAS) instrument probes a well characterized pressure-broadened absorption line profile at an offset of approximately two surface-pressure halfwidths in order to provide weighting functions suitable for peak response to CO<sub>2</sub> near the surface.

Multiple flights of our airborne CO<sub>2</sub> LAS instrument have demonstrated the capability to observe various sources as well as large-scale CO<sub>2</sub> drawdown in the U.S. Midwest due to photosynthesis in the July/August time frame. Flights have also provided experience dealing with partially cloudy atmospheres, land surfaces with varied terrain and topography, and bodies of water with various degrees of surface roughness. These 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. Here we provide a brief instrument overview and discuss selected results from flights on the NASA DC-8 research aircraft during campaigns in July/August, 2011, February/March, 2013, and August, 2014.

## 2. AIRBORNE CO<sub>2</sub> LAS INSTRUMENT OVERVIEW

The instrument was jointly developed by JPL and Lockheed Martin Coherent Technologies (LMCT) with funding from the NASA Earth Science Technology Office Instrument Incubator Program. The 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. Each channel has a dedicated heterodyne detector, and a cw single frequency compact Tm,Ho:YLF 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<sub>2</sub> absorption line at 4875.749 cm<sup>-1</sup> 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<sub>2</sub> absorption cell. The online and offline lasers are frequency offset-locked to this reference laser. Tunability of the on-line laser allows CO<sub>2</sub> measurement flexibility through on-line frequency adjustment. (The

atmospheric CO<sub>2</sub> line has a pressure-broadened FWHM of about 4 GHz near sea-level pressure.) The instrument is described in more detail in reference [5].

A frequency offset is required between the return signals and their corresponding local oscillators for heterodyne detection. By pointing the transmit beams at an offset from nadir, the return signals will experience a Doppler shift that depends on the aircraft velocity and pitch angle, thereby eliminating the need for an additional frequency shifting device in the receiver. The instrument is mounted on a frame that provides a suitable off-nadir angle. 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. 16K FFT’s are the default in the processing scheme. The sampling duration is approximately equal to the speckle decorrelation time of the signal,  $\tau_{decorr}$ , which is  $\sim 0.3$  ms for the NASA DC-8 at nominal cruise speed. A pre-selected number of periodograms is summed, and the remainder of the signal processing steps operate on a collection of these sums.

## 3. ENVIRONMENTAL EFFECTS ON MEASUREMENT PRECISION

Attainment of CO<sub>2</sub> measurement precision of the level of  $\sim 0.3\%$  or 1 ppm is a very challenging endeavor. We continue to incorporate into our retrieval algorithms methods for minimizing atmospheric and surface effects, particularly as potential sources of bias. Discussion of the effects of meteorological parameter uncertainties on the CO<sub>2</sub> measurement uncertainty can be found in Refs. [4-6]. Three additional important categories are (1) cloud detection and filtering; (2) topography; and (3) spectral reflectances of surface and above-ground scatterers. Various means of minimizing these influences on the retrievals are discussed in Ref. [7].

Methods must be developed for filtering out the scattering effects of clouds. Clouds in the field-of-

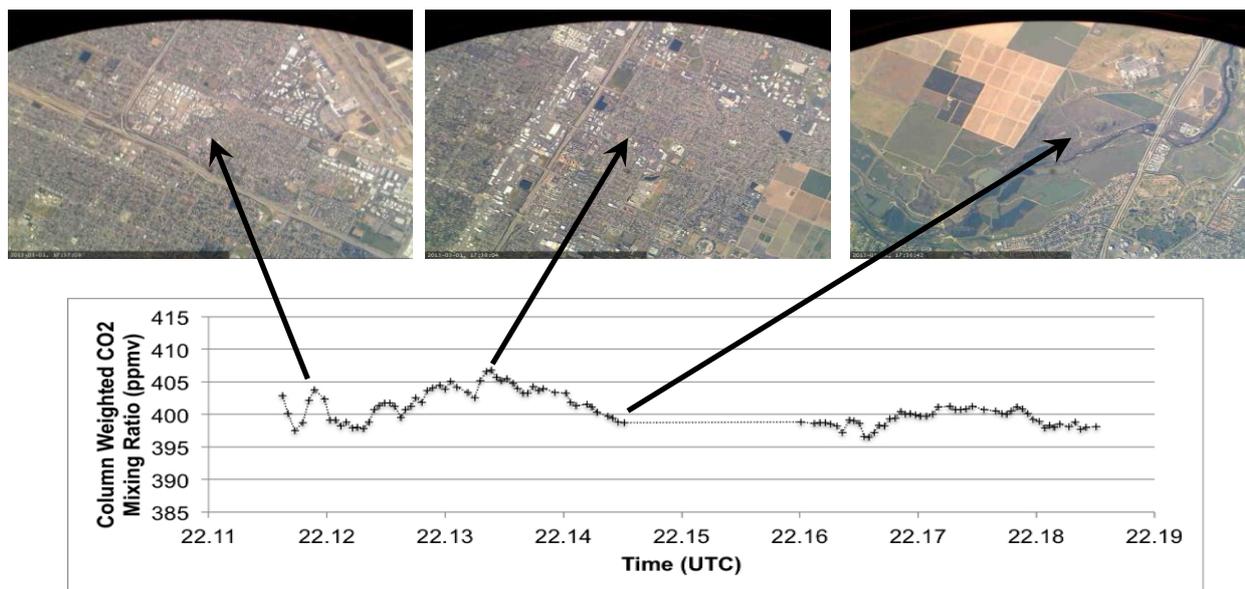
view (FOV) reduce the path length, and if not recognized, bias the CO<sub>2</sub> retrieval. If the lidar provides time-of-flight to the backscatter source (e.g. a range-gated pulsed system, or an FM/CW system), any sources of backscatter other than that which occurs at the expected range to the surface can be set aside or filtered out. In the current implementation of our airborne system, we do not have this capability. We employ alternative methods to detect and filter out the backscatter signals that are due to clouds in the field of view. The heterodyne signals backscattered from the surface are sufficiently narrow to permit identification of cloud backscatter if there is cloud movement relative to the surface. In practice the backscatter signals from cumulus and stratocumulus are spectrally broadened also. This provides a convenient filtering method. Another filtering method depends on the ability to discern an abrupt reduction in measured DAOD (differential absorption optical depth) due to a cloud in the FOV.

We use the SRTM database along with the aircraft INS/GPS data to determine surface elevation at the laser transmitter footprint location along the ground track, with an along-track resolution of approximately 50 m. Even with sophisticated use of the SRTM database, time-dependent systematic

errors of ~ 10-20 m in scattering surface elevation can occur over e.g. mountain forests. Co-aligned profiling laser altimetry with 3-5 m vertical resolution and suitably high along-track resolution would mitigate this potential error source.

**4. POINT SOURCE AND URBAN PLUME DETECTION: EMISSION RATE QUANTIFICATION**

Observations of mid-day summer drawdown of CO<sub>2</sub> over agricultural areas in the U.S. Midwest are reported in Ref. [7]. During one flight in 2011, the track was downwind of the Four Corners power plant in New Mexico. An emission rate based on the observed column CO<sub>2</sub> increase and MERRA wind data agreed closely with the reported annual total emission [9]. CO<sub>2</sub> retrievals from 2013 and 2014 flights also show evidence of urban plumes. Here we show in Fig. 1 an example of elevated CO<sub>2</sub> when flying over Fresno, California in March, 2013. We are comparing airborne LAS observations with total carbon emission databases including EDGAR, FFDAS, and ODIAC. Our observations indicate the potential of the airborne IPDA lidar to assess emission rates from urban areas. Results will be discussed.



**Figure 1.** Elevated column CO<sub>2</sub> over Fresno, California, March 2, 2013.

## ACKNOWLEDGEMENT

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