Methods for retrievals of CO_2 mixing ratios from JPL Laser Absorption Spectrometer flights during a summer 2011 campaign

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The JPL airborne Laser Absorption Spectrometer instrument has been flown several times in the 2007-2011 time frame for the purpose of measuring CO2 mixing ratios in the lower atmosphere. This instrument employs CW laser transmitters and coherent detection receivers in the 2.05-μm spectral region. The Integrated Path Differential Absorption (IPDA) method is used to retrieve weighted CO2 column mixing ratios. We present key features of the evolving LAS signal processing and data analysis algorithms and the calibration/validation methodology. Results from 2011 flights in various U.S. locations include observed mid-day CO_2 drawdown in the Midwest and high spatial resolution plume detection during a leg downwind of the Four Corners power plant in New Mexico.

1. Introduction

Atmospheric CO_2 is a long-lived gas, with sources and sinks primarily at the surface. The GOSAT (Greenhouse Gases Observing Satellite), launched in January, 2009, has provided valuable insight into the capabilities of a passive spectrometer viewing reflected solar radiation[1,2]. 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 absorption spectrometer techniques as differentiated from passive spectrometer techniques. 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 approach that we employ is Integrated Path Differential Absorption (IPDA), using the Earth surface to provide the multi-wavelength backscatter signals that are differentially attenuated by the intervening atmosphere. The JPL Laser Absorption Spectrometer (LAS) instrument that we describe here involves probing a well characterized pressure-broadened absorption line profile with in order to provide weighting functions suitable for peak response to CO_2 near the surface.[3,4]

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. Detuning the on-line frequency to a location one to three 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 [4].)

Multiple flights of an airborne CO_2 LAS instrument in partially cloudy atmospheres 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. A great deal of experience has resulted from multiple flights on the NASA DC-8 research aircraft during campaigns in July/August, 2011 and February/March, 2013.

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 transmit/receive apertures are 10 cm diameter. 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 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_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 JPL CO_2 LAS instrument is described in more detail in reference [7].

A frequency offset is required between the return signals and their corresponding local oscillators for 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. Recent flights have been on the NASA DC-8 aircraft. During measurement periods, the DC-8 ground speed varies over a range of about 150-220 m/s, depending on atmospheric conditions and flight altitude. The instrument is mounted on a frame that provides a suitable off-nadir angle.

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. 16K FFT's are the default in the processing scheme. The sampling duration is approximately equal to the speckle decorrelation time of the signal, τ_{decorr} , which is ~ 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. Environmental Effects on Measurement Precision

Attainment of CO_2 measurement precision of the level of ~0.3% or 1 ppm is a very challenging endeavor. We are continuing 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_2 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.

High accuracy range to the scattering surface is critical. The "scattering surface" is obviously not always the ground elevation over land.

Methods must be developed for filtering out the scattering effects of thin clouds that may be present in the atmospheric column. Clouds in the FOV reduce the path length, and if not recognized, bias the CO_2 retrieval. In cases of scattered cloud and broken cloud cover, breaks or holes exist that permit soundings down to the surface some fraction of the time. The small transmitter footprint of the lidar provides an inherent capability to acquire

retrievals in such circumstances. 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. However we do 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 the cloud movement relative to the surface, along the line-of-sight, exceeds 0.5 m/s. Since the typical point-ahead angle in the DC-8 is ~ 0.1 rad, this corresponds to a threshold horizontal motion of 5 m/s. However in practice the backscatter signals from cumulus and stratocumulus are spectrally broadened. This provides another filtering method. This spectral broadening is typical of backscatter from cumulus and also stratocumulus. Broadened backscatter signals from stratocumulus were observed during an August 2, 2011 flight over the Pacific off the coast of southern California. During the August 10 flight from California to the upper Midwest, extensive fair weather cumulus were encountered. Periodograms corresponding to 40 ms of integration time (about 8 meters of along-track averaging for the nominal 200 m/s aircraft speed) are filtered out of the CO_2 retrieval data if the signal spectral widths exceed the normal value associated with surface returns. This technique works quite well for filtering out the times when cumulus is in the FOV.

Another filtering method depends on the ability to discern an abrupt reduction in measured DAOD (differential absorption optical depth) that would likely be due to the presence of a cloud in the field-of-view (FOV). Clouds shorten the effective path length over which the differential absorption measurement is made, thus causing a decrease in the measured DAOD when present. For a cloud OD above a threshold value, this decrease is evident. An example is shown in **Figure 1,** during a mid-day traverse/overpass of the West Branch Iowa (WBI) tall tower at ~2850 m altitude above ground level. The ground track distance covered by this traverse, from left to right, is approximately 60 km. The sharp boundaries between the relatively stable retrieved CO_2 column mixing ratio in the 370-375 ppm range and the depressed values are evidence of the cloud impacts. The smaller depressions in retrieved CO_2 column in the 21.78-21.79 UTC time period (corresponding to about 7 km of track length) are due to occasions when the FOV passed over segments of thin cloud, barely visible in the nadir camera images. The OD threshold for cloud detectability depends on the instrumental DAOD measurement uncertainty over an appropriate averaging interval, and also on the cloud altitude.

The retrieved weighted column CO_2 mixing ratios in the clear air regions of this tower overpass shown in **Figure 1** average 371-375 ppmv, much lower than background CO_2 mixing ratio values in the 390-400 ppmv range. This is evidence of mid-day drawdown due to photosynthetic assimilation by crops over this large-scale agricultural region. *In situ* vertical profile data obtained near the WBI tower from on on-board Picarro instrument indicated boundary layer CO_2 mixing ratio values ~ 365 ppmv, and free troposphere values in the 380-384 ppmv range below 3 km altitude. The magnitude of this mid-day decrease in the boundary layer mixing ratio is consistent with other reported measurements. Mid-day CO_2 levels in this region during July/August are among the lowest in North America due to strong uptake by corn and other crops.

Knowledge of the surface elevation and the associated surface pressure at the location of the lidar footprint is important for the CO_2 retrievals. When the ground track is over hilly or mountainous terrain, the rapid changes in surface elevation require either co-aligned laser altimetry or other tools and data sources in order to control the contribution of elevation errors to the overall error budget. We use the SRTM database along with the aircraft INS/GPS data to determine surface elevation at the laser transmitter footprint along the ground track, with an along-track resolution of approximately 50 m. A 2-dimensional smoothing algorithm is used to avoid discontinuities in the elevation vs. time as the ground track crosses the SRTM 25-m pixel boundaries. Our on-line and off-line signal power data are archived at a 25 Hz rate (8-m averaging along track at the nominal aircraft 200 m/s ground speed), with further averaging prior to calculation of the $\ln(P_{off}/P_{on})$. 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 error source.

Point Source Plume Detection and Emission Rate Measurement

On August 9, 2011, the DC-8 flew a northward flight segment at 15 kft pressure altitude whose ground track was downwind of the 4-Corners Power Plant, located in San Juan County, New Mexico (36.690 N, 108.483 W). The ground track was within a few hundred meters of the plant site. The plant has five coal-fired units, with spacing such that the emissions appear to originate from three sources, separated by approximately 400 m and 200 m respectively. Column CO_2 measurements were made with along-track resolution of 15 m over a 1-km segment immediately downwind of the plant, which was clearly sufficient to resolve the three plumes from the various stacks. These LAS measurements, along with model-provided wind data, enabled estimation of the power plant CO_2 emission rate. Results will be discussed.
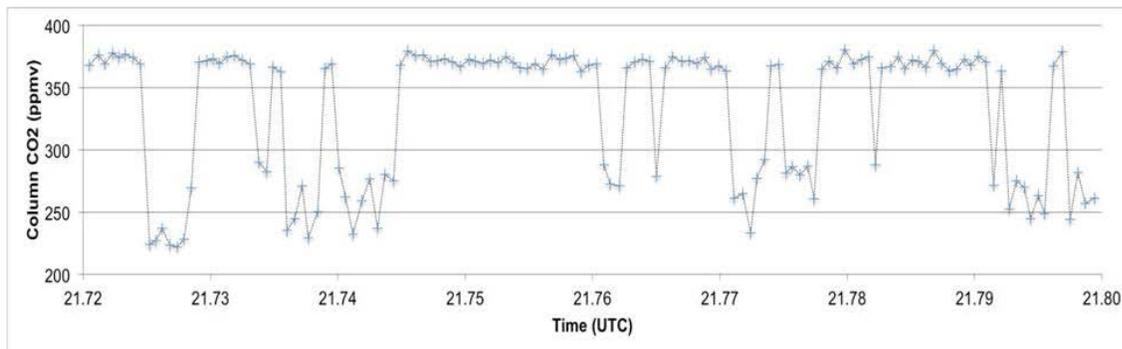

Figure 1. . Impact of scattered cloud cover on column CO_2 retrieval during a WBI Tower traverse leg.

Acknowledgements

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