Airborne IPDA Lidar Measurements: Factors in Optimizing Measurement Sensitivity and Precision

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Abstract: The JPL CO2LAS airborne instrument is an IPDA lidar with a coherent detection receiver that is used for atmospheric CO2 measurements. Since the objective is high accuracy retrievals of column CO2, dealing with environmental variables, along with speckle-induced fluctuations, is a major consideration. Surface reflectance is an inherent data product. In fact it is an essential dataset used in the algorithm for high accuracy retrieval of the CO2 column abundances. We discuss the use of surface reflectance and elevation datasets for tuning the differential absorption retrieval algorithm to optimize sensitivity to CO2 sources and sinks of various spatial scales. Extensions to measurement of other atmospheric constituents are included.

Keywords: Laser, Lidar, Coherent, Differential Absorption, Airborne

1. Introduction

Atmospheric CO_2 is a long-lived greenhouse gas, with sources and sinks primarily at the surface. Seeking improved capability to determine the fluxes of CO2 on various spatial scales, national space agencies have invested in Earth-orbiting passive spectrometers viewing reflected solar radiation. These instruments are providing valuable insight into the capabilities of this technique. Improved determination of CO_2 fluxes from the air and from Earth-orbit requires extraordinary high precision and low bias. 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_2 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. Much can be learned from lidar measurements of CO_2 that applies to measurements of other greenhouse gases (e.g., CO, CH_4, H_2O) and other constituents that play important roles in atmospheric chemistry.

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 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 references [1-4].)

Multiple flights of our airborne CO_2 LAS instrument have demonstrated the capability to observe various sources as well as large-scale CO_2 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.

Minimizing measurement uncertainty and bias is extremely important. There can be many contributors to bias. Here we provide a brief instrument overview and discuss sources of uncertainty and potential bias that we have had to contend with in CO_2 retrievals. Some are inherent to the measurement from airborne or space-based platforms and apply to lidar retrievals in general.

2. Airborne CO_2 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 lasers. 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 at 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. The instrument is described in more detail in reference [5].

The return signals from each channel are digitized followed by conversion to the frequency domain. 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 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 collections of these sums.

3. Speckle Noise and Environmental Effects on Measurement Precision

Attainment of CO2 measurement precision of the level of ~0.3% or 1 ppm is a very challenging endeavor. Speckle noise is a multiplicative noise that is inherent in coherent detection. The statistics are well known, and we have incorporated a one-dimensional version of a technique from the digital image enhancement and noise filtering community [6], to filter speckle noise. We continue to incorporate into our retrieval algorithms methods for minimizing environmental 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. [2-5, 7]. Here we discuss uncertainties due to the combination of topography and reflectance variability of surface and above-ground scatterers. Various means of minimizing these influences on the retrievals are discussed in Ref. [8].

The heterogeneity of surface materials and above-ground scatterers, natural and man-made, can cause sudden changes in lidar reflectance, and consideration must be given to an understanding of how this affects the column CO2 retrieval when that retrieval is an average over a portion of the ground track that includes large changes in reflectance. Sharp changes in reflectivity (e.g., water-land boundaries, or road crossings) can be problematic for IPDA systems with displacements between the on-line and off-line footprints [9], necessitating careful investigation of potential sources of misalignment. Reflectance-weighting is inherent in the lidar measurement, i.e. the high-reflectance areas are weighted preferentially in the average. When combined with elevation changes within the along-track average, this has the potential of biasing the resulting retrieval. Elevation weighting must be implemented in the retrieval algorithm to account for this inherent reflectance weighting within the ground track averaging segment, in order to mitigate biases associated with this effect. An example is shown in Figure 1, a ground track over a high elevation region of the British Columbia Coastal mountains during the August 7, 2011 flight, with snow-cover being prevalent. The low backscatter segments correspond to the snow-covered regions.

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 30 m. Elevation slopes are computed, and data points over slopes above a threshold value are masked out. Co-aligned profiling laser altimetry at the same wavelength, with 3-5 m vertical resolution and high along-track resolution, would improve accuracy.

Results will be discussed.

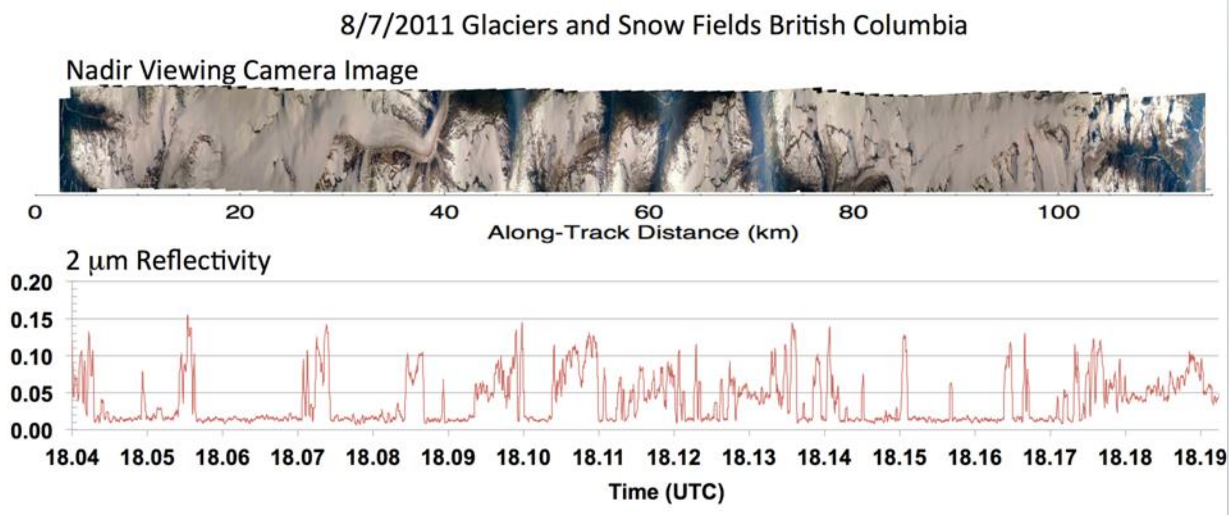

Figure 1. Surface backscatter at the airborne lidar 2.05 µm wavelength (in units of sr-1) during a portion of the northbound flight segment over the British Columbia Coastal Mountains, August 7, 2011. The imagery shows a mixture of snow covered areas (low backscatter), glacier segments (the blue streaks), and patches of bare rock, dirt, alpine flora. The lidar footprint track is centered in the imagery. Time duration from left to right: 9 min.

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5. References

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