Test Results for the Broad Band Carbon Dioxide Lidar

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Abstract-We describe the basis for a new type of LIDAR employing a spectrally wide laser beam that we are developing as a candidate for NASA's ASCENDS mission to measure the total column of CO2 from space with very great precision. The instrument recently concluded its first ever tests from an airborne platform. Results from these tests will be presented and discussed.

I. Introduction

There is a great need for measurements of atmospheric carbon dioxide concentration with high spatial and temporal resolution for global and regional studies of the carbon cycle. Such measurements will better resolve the linkage between global warming and anthropogenic CO2 emissions. In the Decadal Survey of Earth Science the National Research Council recommended that NASA develop, build, and fly a laser based system for precision measurement of total carbon dioxide column (the ASCENDS mission). The mission demands measurements of CO2 to a precision of 1 ppm out of the total ~400 ppm column in order to locate sources and sinks. Achieving this 400:1 precision is made more difficult due to the strong dependence on changes in atmospheric pressure and temperature of atmospheric carbon dioxide absorption line position, shape, and strength. Most lidar systems currently under development as candidates for the ASCENDS mission require multiple lasers operating at different, very narrow bandwidth wavelengths in order to resolve these effects. NASA has never flown a narrow band wavelength controlled laser in space. Our team at Goddard Space Flight Center (GSFC) is developing a lidar system for column CO2 measurement based on an innovative new lidar technique employing a spectrally broad laser source and using a Fabry-Perot based detector. Our lidar is capable of mitigating inaccuracy associated with atmospherically induced variations in CO2 absorption line shape and strength while reducing the number of individual different wavelength lasers required from three or more to only one. It also reduces the requirement for source wavelength stability, instead putting this responsibility on the Fabry-Perot based receiver.

II. The Instrument

As with all lidar systems the instrument can broadly be divided into a source and a receiver. The most common technique for measuring the abundance of chemical species in the atmosphere is differential absorption lidar (DIAL). In this technique two different wavelengths are transmitted into the atmosphere—one that is absorbed by the species of interest and one that is less strongly absorbed. By measuring the difference in the attenuation of the two wavelengths after passage through the atmosphere the abundance of the absorbing species can be calculated. If the atmospheric backscatter is sufficiently strong this measurement can be made at different ranges (determined by the time of flight of the laser beam) so that a profile of concentration versus range can be obtained. The lidars for the ASCENDS mission will not attempt to do this. Backscatter at the CO2 absorption wavelengths is weak and the precision requirements for ASCENDS mandate a large signal to noise ratio (SNR). Instead all of these systems will use reflection of the transmitted laser light off the Earth’s surface.

Because the CO2 absorption strength is not constant but varies with temperature and pressure, all the ASCENDS candidate lidars employ more than 2 wavelengths in an effort to untangle the effects of varying atmospheric temperature and pressure on the CO2 absorption line strength. In fact our specific broadband lidar transmits a range of wavelengths almost 1 nm wide that spans three CO2 absorption lines. There are a number of ways to generate this spectrally broad output. Perhaps the best employs a fiber laser (erbium for the 1.57 micron CO2 lines or thulium for the 2.05 micron lines) that has been demonstrated recently by Northrop Grumman. Erbium doped fiber amplifiers (EDFA) can generate either a spectrally broad or narrow output and indeed a number of the competing narrow band lidars currently employ EDFAs. Our present implementation of the broad band lidar uses an optical parametric amplifier pumped by a Nd:YAG laser. This is probably not the appropriate technology for space but offers the highest power at the lowest cost for the purposes of our demonstration.

Because our source emits wavelengths that are strongly absorbed by CO2 as well as wavelengths that are only weakly absorbed all in a single laser pulse, we use the receiver portion of our lidar to separate the wavelengths and provide our “differential” absorption. To do this we use a Fabry-Perot interferometer. (FP) A FP is perhaps the simplest form of interferometer. One can be constructed using a single piece of glass by polishing it flat and parallel

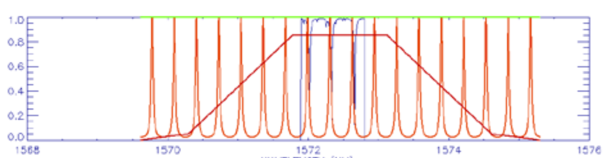

Figure 1. This depicts the operation of our lidar receiver. The heavy red line shows the transmission of our bandpass filter. The thin red show the transmission of the FP. The thin blue square top is an idealized broad laser output. It envelops three CO2 absorption lines. The FP is temperature tuned onto the CO2 lines.

on opposite sides and putting a partially reflecting coating on the surface. Light passing through the FP bounces back and forth between the two surface crating interference with the result that only it only transmits light for which and integral number of half wavelengths exactly fits between the two surfaces. By changing the thickness of the glass plate different colors can be allowed to pass. By changing the reflectivity the width of the passband can be controlled. We select a reflectivity such that the width of a passband is very nearly the same as the width of a CO2 absorption and we place the FP inside an oven so that the temperature can be controlled. Changing the temperature changes the optical thickness of our FP and thereby changes the wavelengths that are transmitted. Figure 1 depicts an idealized set up of our receiver. The laser emits light in the region between the two blue lines (~1571.9 nm-1572.8 nm) CO2 has three absorption lines in this spectral region and their relative transmission from a few km altitude is shown in dark blue. Our lidar receiver has two channels. The FP channel has both the bandpass filter and the FP in front of the detector. Thus it responds mostly to light that can be absorbed by the CO2. The reference (REF) channel only has the bandpass filter in front of the detector. Most of the light that reaches this detector is unaffected by CO2.

Figure 2 is the lidar system with one

Figure 2. This shows the Broad Band Lidar just prior to installation in the DC-8. The side covers are removed.

side of its box removed to show the telescope and receiver section. Figure 3 shows the lidar installed in the cargo bay of the DC-8. In operation the laser fires at a rate of 10 Hz. We record the signals from the FP and REF channels as a function of time and average 8 shots together. Figure 4 shows a plot of the raw data for the two channels. The peak at 2000 nsec is the initial fire of the laser. There are actually two peaks within a few nanoseconds here the first is from scattered light within the instrument container when the laser fires. This serves to indicate t=0 for ranging to the ground. The second peak is a sample of the transmitted light delayed by passage through a fiber optic cable. This signal serves to monitor the performance of the system and enables corrections for drifts in the detector or the FP temperature etc. The second large peak at about 6600 nsec is the reflected light signal from the ground. Comparing the changes in the ratios of the FP and REF channel for this signal enables calculation of the CO2 column between the aircraft and the ground.

Figure 3. This is the instrument installed in the cargo bay of the DC-8. The circular object in the right foreground is the mirror used to reflect the laser beam and receiver filed of view down through a port ion the AC centerline.

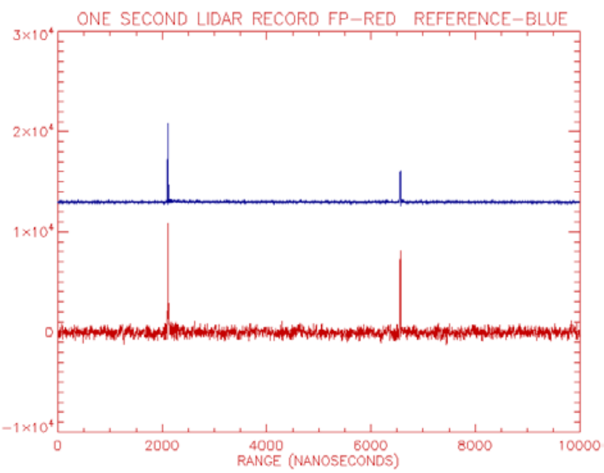

Figure 4. This shows a typical lidar return signal. FP channel is red and REF is blue. Peak at 2000 is the laser fire-that at 6600 is the ground return.

III. Data Analysis

The analysis for data obtained on our test flights proceeds from Beer's Law of Absorption which may be stated as follows:

$$I = I_0 \exp(-n\,\sigma\, z). \qquad (1)$$

Where I is the intensity of the absorbed light, I_0 is the intensity before absorption, n is the number density of absorbers, σ is the absorption cross section, z is the range through the absorbing medium and exp is the exponential function. We may also write

$$\log(I/ I_0) = -n \quad \sigma\, z \qquad (2)$$

which shows that the log of the ratio of the absorbed intensity to the initial intensity is a linear function of the range and the absorber number density. With a DIAL system we essentially measure I, I_0, and z. We presume to have measured the absorption cross section in the laboratory so we can solve for n which is the number of CO2 per square cm along the absorption path.

In fact the lidar system measurement of I_0 involves a number of instrumental factors (eg. percentage of transmitted light sampled, filter and FP transmission, detector response etc.). The measurement of I also involves many of these same factors plus the transmission of the atmosphere, the reflectivity of the ground etc. In principle the instrumental factors could all be measured or calculated but this is cumbersome and difficult to do in fact. Instead we make a second measurement (call them $\underline{I}_0$ and $\underline{I}$) at a second wavelength using the same equipment. Beers law should hold for this second measurement except that σ will have a different value. Subtracting the two equations yields

$$\log(I/I_0)-\log(\underline{I}/\underline{I}_0) = -n(\sigma-\underline{\sigma})z. \qquad (3)$$

The great news is that for this measurement all the instrumental factors in the measurement divide out and if we choose the two wavelengths so that ground reflectivity and atmospheric transmission are the same (except for absorption by CO2) then our raw measurement of the difference of the two ratios is the same as the actual difference of the two ratios. If we know the difference between the two absorption coefficients we can solve for carbon dioxide abundance. This is the principle of differential absorption lidar and it is one of the reasons why great precision might be obtainable for the ASCENDS mission.

As noted before the difference between the absorption coefficients has to be measured in the lab and also noted that in the real atmosphere they are not constants but depend on pressure and temperature. From our knowledge of the behavior of spectroscopic line shapes with temperature and pressure we can deduce the correct values of these absorption coefficients if we make a few additional measurements at other wavelengths. This is the approach generally being used in the candidate lidars for ASCENDS.

The situation for the broadband lidar is slightly different. Because the measurements for the broad band lidar are made over a range of wavelengths the absorption cross sections we use in our analysis are weighted averages over a span of wavelengths. Essentially our σ is an integral of the CO2 absorption over all 3 lines multiplied by the transmission of the FP and the bandpass filter and our $\underline{\sigma}$ is an integral of the CO2 absorption multiplied by the transmission of the bandpass filter alone. By judicious choice of the bandpass filter and FP transmission characteristics it is possible to reduce very significantly the effects of pressure and temperature on these *average* cross sections.

These average cross sections could in principle be calculated by measurements of the filter and FP transmission and using cross sections for CO2 obtained in the lab. They could also be determined by calibrating the whole instrument in the lab introducing known amounts of CO2 into the absorption path of the instrument and noting the instrument response. Eventually we will probably use both methods. For the present we have adopted a different approach. The purpose of our test flights was not to measure carbon dioxide but rather to demonstrate the measurement capability of the broad band approach and to investigate the characteristics of the instrument. We already know the approximate column abundance of CO2 is about 390 ppm. Using the pressure and aircraft attitude measurements from the DC-8 along with the range information from the lidar we can calculate what fraction of the total airmass the lidar has probed. Multiplying this fraction by 390 give the approximate amount of CO2 that the instrument has sensed. Comparing this number to the signal response of the lidar permits the calculation of the difference in absorption coefficients for the FP and REF channels. In fact if we plot the log of the FP/REF ratio versus the amount of CO2 sensed (essentially the product of n and z) then the result should be a line with a slope equal to this difference of average absorption coefficients (σ - $\underline{\sigma}$). The next section shows the progression of the data analysis to achieve this plot.

IV. Flight Data

Figure 5 shows the raw FP channel signals collected during the test flight of May 2, 2011. Each point on the plot represents an average of 8 laser shots obtained over a period of roughly one second. The considerable variation in signal levels arises from a variety of causes including but not limited to fluctuations in laser power, changes in ground reflectivity, changes in aircraft attitude and altitude, and to a small

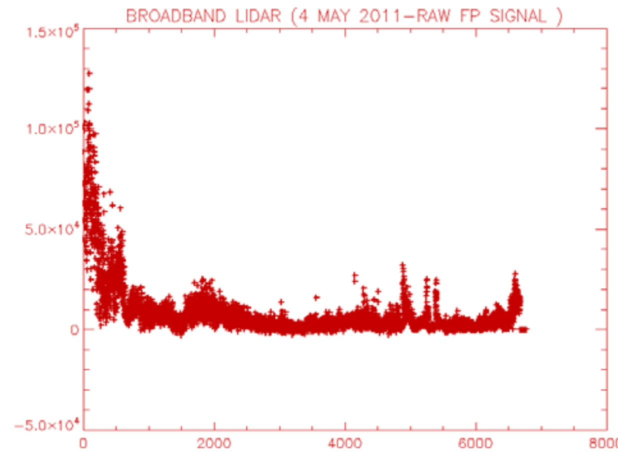

Figure 5. This is raw data from the FP channel over the entire flight. It shows the rapid drop in laser power in the first 20 minutes of flight.

extent changes in the CO2 abundance. The rapid drop in signal over the first 300 data points is symptomatic of deteriorating laser power that we experienced throughout the measurement campaign. This has been traced to failure of a temperature control for the OPO crystals. Taking the ratio of these data with the signals obtained by the REF channel normalizes out effect due to laser power changes and surface reflectivity changes. The result of this normalization is shown in figure 6.

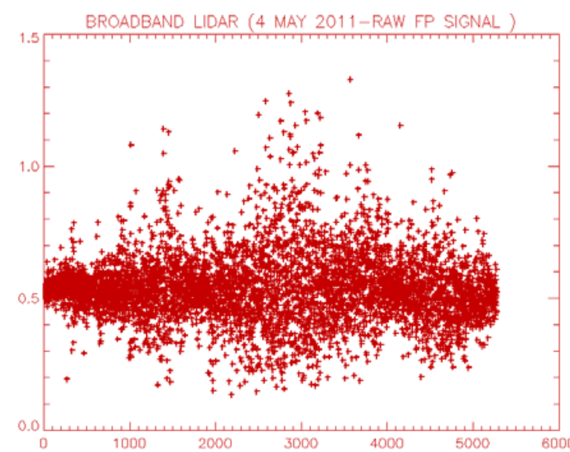

Figure 6. This is the FP/REF ratio over the whole flight.

The results now are dominated by statistical noise and the effects of range changes caused by aircraft attitude and altitude. We take 30 second averages to reduce statistical noise in figure 7.

While the data shown in this figure still appear to have a serious noise component comparison of the ratio with the lidar range (shown in figure 7) shows that some of the variation actually arises from changes in the amount of carbon dioxide sensed as the range from the aircraft to the ground changes

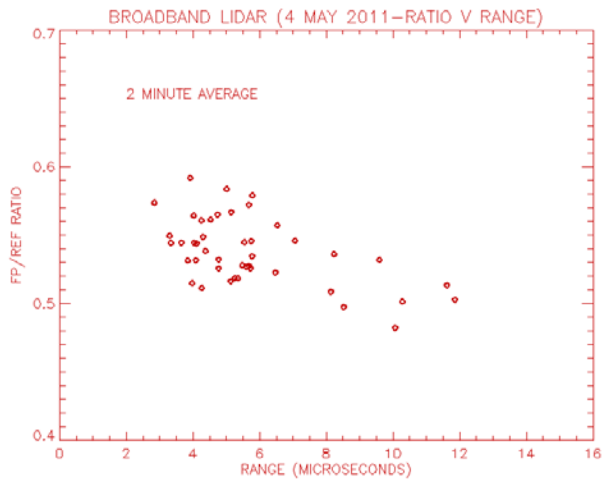

Figure 7. Two minute averages ratio versus lidar range shows evidence of CO2 absorption.

There should not be a direct relationship because range changes caused by banking the aircraft do not produce the same change in airmass as range changes caused by the terrain. Some of the noise may be the result of a single very noisy data point caused by a misfire of the laser—the data has not yet been scrubbed for obvious bad points that should be omitted.

In any event the range and aircraft attitude data can be used to deduce the vertical range to the ground. This can

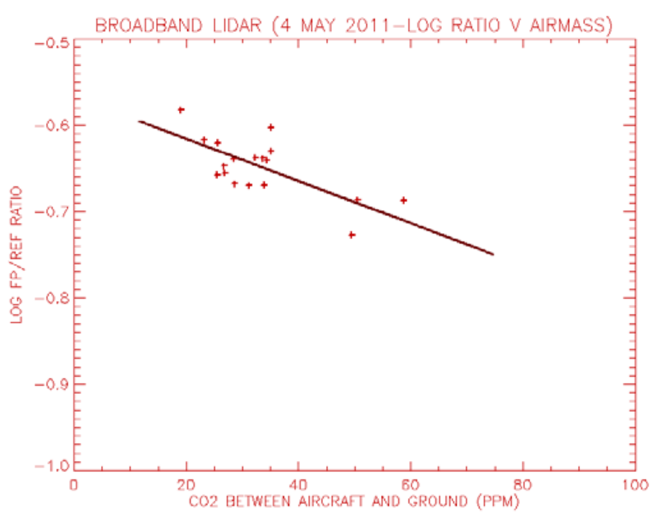

Figure 8. Log FP/REF ratio versus calculated CO2 abundance.

be used in conjunction with the DC-8 pressure and pressure altitude measurements to calculate the airmass and effectively the total CO2 along the absorption path for each shot. We plot the log of the FP/REF ratio against these derived CO2 in figure 10 where we have averaged the data over 5 minutes. This plot shows that the Broad Band Lidar is measuring CO2. The signal to noise ratio here not good enough. The excuses will be given in the final section.

V. Conclusion

The broad band lidar has succeeded in making an airborne measurement of CO2 in its first ever field trial. The instrument performance however was poor. Part of the reason is the very low laser power available with the failing laser we employed. We expected to be transmitting tens of milliJoules with every laser shot but actual measured performance was only a few milliJoules. Average transmitted power for the above measurements was less than 100 milliWatts. Our system could potentially exceed this output by a factor of 30.

We also had difficulties with our detectors. At some point during the campaign they were damaged by being hit with too much power. Replacing them should improve the SNR by more than two orders of magnitude. Because the signal levels were so weak we were unable to work at greater ranges. Plots of the rate of signal drop with range do not show the requisite inverse range squared dependence. This means we were operating in the near field for the lidar where complete overlap between the transmitted laser power and the receiver has not been achieved. In this region the system is critically sensitive to very small misalignments that can be caused by aircraft vibration and temperature changes. In our next series of tests we will use a more conservative (ie larger) field of view to permit overlap at a shorter range. Solar background will increase in doing this but background did not appear to be an issue on the first test flights.

Meeting the precision requirements called for by ASCENDS depends on two factors. The first is the precision of the measurement of I and I_0. All lidar technologies are faced with similar problems in reducing the error of these measurements. The Abshire group at Goddard is using photomultiplier tubes (PMT) as detectors and both the Abshire and Browell group are using erbium doped fiber amplifiers (EDFA) as their laser source, The broadband lidar could be implemented just as well using PMTs and EDFAs. Many factors including primarily cost induced us to make the choices for implementation that we made for the Broad Band LIDAR
In fact the fiber lasers developed by Northrop Grumman appear to be ideal sources for the Broad Band approach but we were unable to secure one operating in the 1572 nm band for this campaign. The second factor that is crucial for the ASCENDS mission is the stability of the effective cross section for the retrieval. As noted above σ depends on temperature and pressure but the value used in the data retrieval also depends on the degree to which water vapor contributes to the measured absorption. It depends on the

wavelength stability and baseline stability of the laser source and the filters in the receiver and the efficiency of the detectors used as well. One of the strengths of the broadband lidar, as we implement it, is that the same detector, filter, and FP are used to measure I_0 as we use to measure I. In this way we are somewhat immune to 'drifts' in the components of the system. During the May 4 flight the system exhibited about a 4% change in the t=0 absorption ratio down and back up while the laser power was falling. It was stable to better than 1% during most of the flight and drifted down and back about 4% is the last hour of the flight. The cargo bay where the laser is mounted is subject to large changes in temperature and our system has no protection from these swings. The gain of our APD detectors is known to change with temperature. We can correct for these changes to some extent but we cannot determine with certainty if changes in laser wavelength are responsible for a slight change in the ratio. We have proposed to ESTO to construct a wavelength differentiating receiver which would permit corrections for changes in the spectral shape of the laser output again using the same sensor for performance monitoring as for sensing the lidar signal. This would probably provide the best possible solution for long term stability for the ASCENDS.

The system is scheduled to participate in an ASCENDS lidar intercomparison experiment again on the DC-8 this July August. We expect to have the laser power up by an order of magnitude and the detector noise down by two orders of magnitude. We will have a larger receiver field of view which will reduce potential bias arising from alignment effects. We hope to be able to implement the wavelength differentiating receiver as we continue to tangle with this daunting technological challenge.