# Precision Column $CO_2$ Measurement from Space using Broad Band LIDAR

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*Abstract*— In order to better understand the budget of carbon dioxide in the Earth's atmosphere it is necessary to develop a global high precision understanding of the carbon dioxide column. To uncover the 'missing sink" that is responsible for the large discrepancies in the budget as we presently understand it, calculation has indicated that measurement accuracy of 1 ppm is necessary. Because typical column average $CO_2$ has now reached 380 ppm this represents a precision on the order of 0.25% for these column measurements. No species has ever been measured from space at such a precision. In recognition of the importance of understanding the $CO_2$ budget to evaluate its impact on global warming the National Research Council in its decadal survey report to NASA recommended planning for a laser based total $CO_2$ mapping mission in the near future.

The extreme measurement accuracy requirements on this mission places very strong constraints on the laser system used for the measurement. This work presents an overview of the characteristics necessary in a laser system used to make this measurement. Consideration is given to the temperature dependence, pressure broadening, and pressure shift of the $CO_2$ lines themselves and how these impact the laser system characteristics.

We are examining the possibility of making precise measurements of atmospheric carbon dioxide using a broad band source of radiation. This means that many of the difficulties in wavelength control can be treated in the detector portion of the system rather than the laser source. It also greatly reduces the number of individual lasers required to make a measurement. Simplifications such as these are extremely desirable for systems designed to operate from space.

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## 1. INTRODUCTION

$CO_2$ is the most prevalent known anthropogenic greenhouse gas. Its concentration has increased by more than 95 ppm in the last 150 years[1]. The majority of $CO_2$ variability occurs in the lower atmosphere (~1000 to 800 mbar). The natural geographic distribution and temporal variability of $CO_2$ sources and sinks however are still not well understood. Satellite instruments show promise for identifying sources and sinks globally, but typically measure the total atmospheric column. Since sources and sinks at the surface represent a small perturbation to the total column, a precision of better than 1% is required. To quantify the carbon cycle dynamics, to help predict climate change and to meet the stringent performance requirements new monitoring instruments are needed.

Over the last five years we have developed at Goddard a passive sensor to measure $CO_2$ column using scattered solar flux. This system employs Fabry-Perot etalons to create a differential response to the absorption of sunlight by carbon dioxide absorption lines near 1.57 microns. **Figure 1** shows the layout of the instrument and **Figure 2** shows the principal of operation. The most difficult aspect of meeting the precision requirements for the passive sensors is determining the path length through the atmosphere in the presence of clouds and scattering aerosols. A path length error on the order of 20 meters is sufficient to produce the 1 ppm error in the column average which is the goal of these systems. LIDARS are able to make a better determination of the path length because the source of the light used for the measurement is under control. These systems face other difficulties however predominantly because they measure at only a single frequency. This means the weighted value of the $CO_2$ cross section at this frequency must be known with great precision as it changes with temperature and pressure along the path through the atmosphere. Also the laser must be "locked" to this frequency so that drifts in the output do not ruin the measurement. We will discuss this problem next.
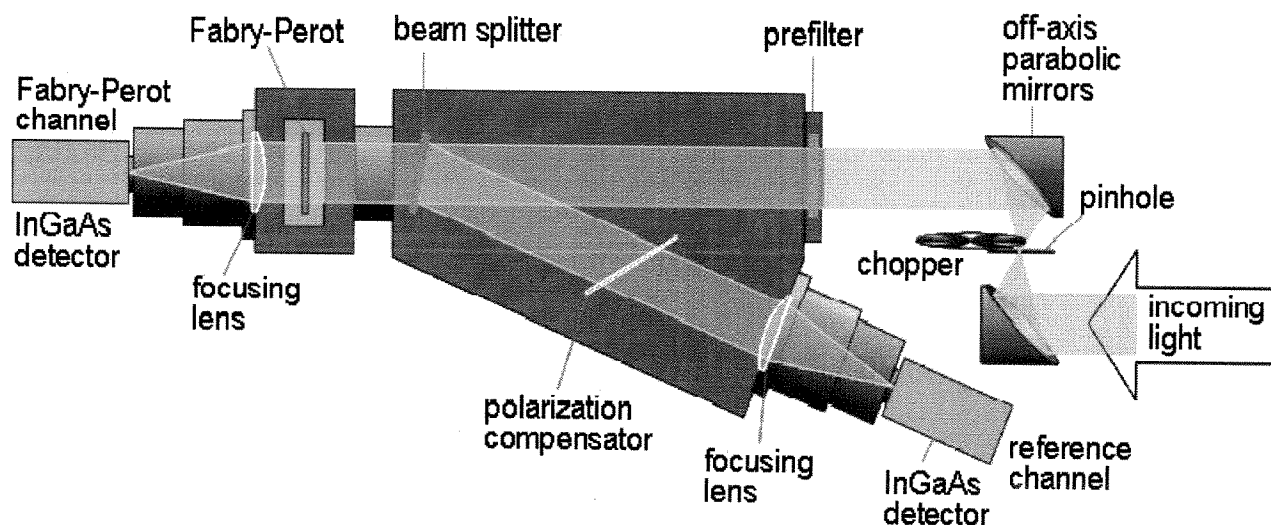
Figure 1. Incoming light passes through the bandpass filter and is split into two paths. The first path (reference channel) is detected while the second passes through the Fabry-Perot before detection (FP channel). The ratio of the signal in the 2 channels responds differentially to the atmospheric $CO_2$.
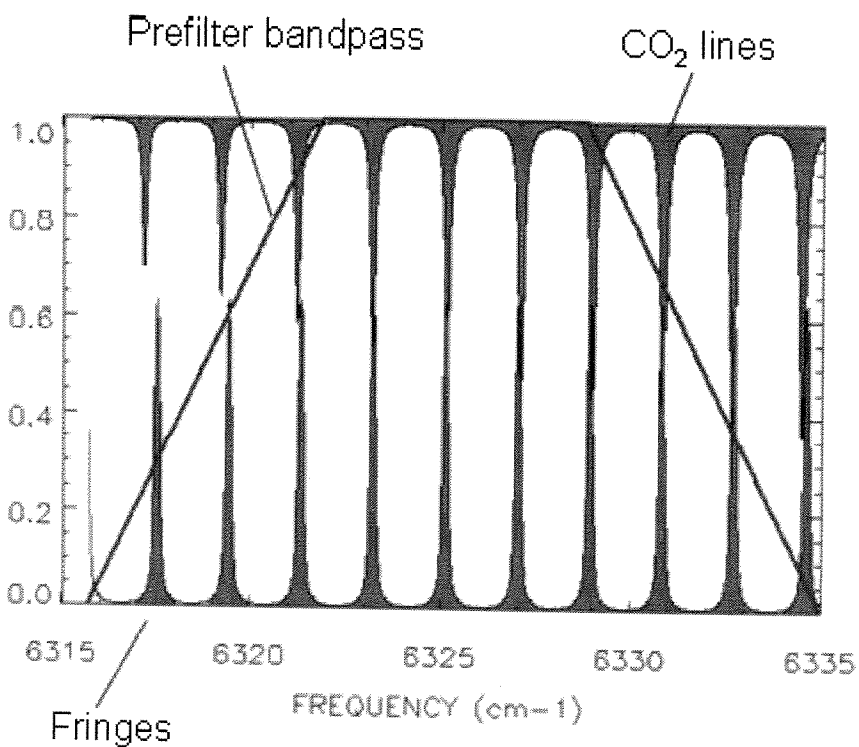


Figure 2. Top curve shows normalized solar flux at ground with $CO_2$ absorption lines. Lower curve shows Fabry-Perot transmission fringes (light blue) aligned with $CO_2$ absorption features (dark blue). Red line shows the trapezoidal shaped prefilter passband.
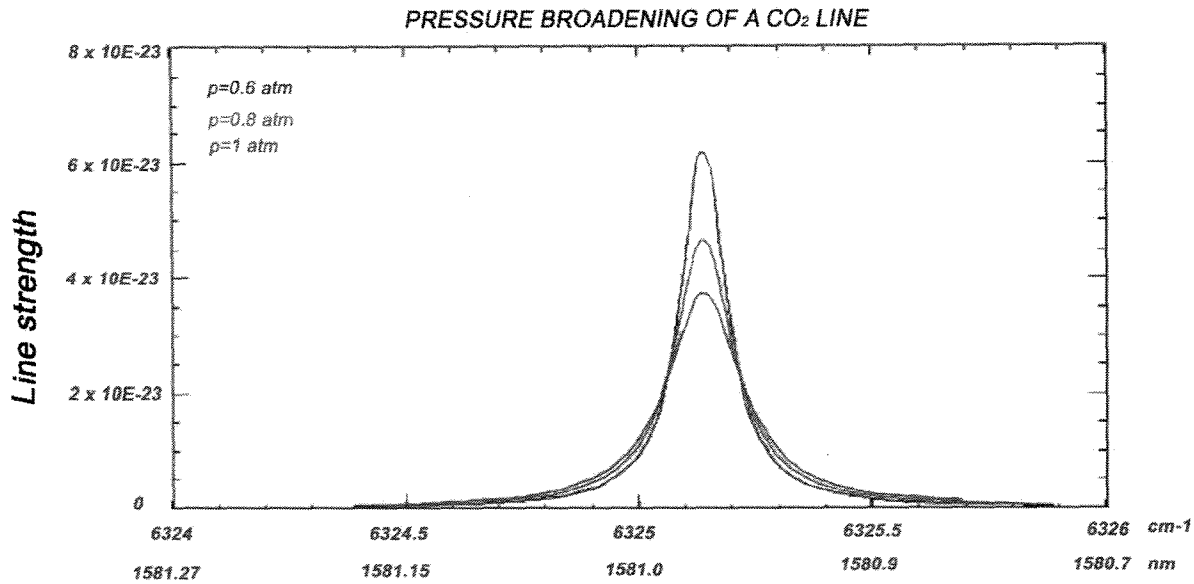
## PRESSURE BROADENING OF A CO₂ LINE

**Figure 3. This illustrates the extremely powerful effect of collisional broadening on a typical CO$_2$ line near 1.57 microns.**

## 2. SPECTROSCOPY

The absorption line shapes shown descending in **Figure 1** are rather complex. At the top of the atmosphere the width is dominated by the Doppler effect. Proceeding lower into the atmosphere collisional (pressure) broadening begins to manifest itself to a greater and greater extent. At the same time the actual line strengths are changing with the temperature of the atmosphere and finally a shift in the center frequency also occurs as the result of collisions.

The typical laser line width is substantially narrower than the pressure broadened width of these absorption features. This is to say the laser can easily sample only some portion of the overall absorption line. This can be an asset depending upon one's objective. If for example the problem is to discover regions with anomalous behavior in terms of CO$_2$ production or loss at the surface then one can target surface CO$_2$ by observing changes in the pressure broadened wings of a CO$_2$ line. Since there is only a minimal contribution to the absorption in the wing from the upper atmospheric CO$_2$ the effect of a surface source or sink will be a larger perturbation on the overall column absorption at these wavelengths. This reduces the requirement for 1 ppm precision in order to locate the source or sink. If on the other hand the objective is to quantitatively determine the size of a perturbation on the overall column then this approach will not work as well. This is because the fraction of the total column that is being observed in the wings is difficult to know from a single measurement where the strength of the absorption depends so strongly on the pressure as well as the number density of the carbon dioxide.

**Figure 3** shows the effect of pressure broadening on a typical CO$_2$ line in the 1.6 micron region. Temperature also manifests itself on the strength of absorption features through its effect on the population density of the lower level state for one of these absorptions. Lines originating from states arising from the lowest energy levels get weaker with increasing temperature and transitions arising from higher lying levels get stronger. In any manifold of absorptions there are some lines that are affected the least and these are probably the best choice for use by a laser system to measure total column. However, even a relatively well behaved line can introduce errors in the column as large as 1ppm for a 2 degree K change in temperature. Some of the satellites borne instruments that remotely determine temperature from space have temperature errors of this order. This means that using a single absorption line and relying on meteorological measurements or models to provide the temperature correction may not suffice for the CO$_2$ column measurement. Multiple laser frequencies are necessary to solve for the effects of variable pressure and temperature on the absorption line strengths and shape.

0.000009

0.000008

0.000007

0.000006

0.000005

0.000004

0.000003

0.000002

0.000001

0.000000

Power, W

1500   1520   1540   1560   1580   1600   1620   1640   1660

**Wavelength, nm**

*current 299mA*
*thermistor resistance*
*12 KOhm-15 KOhm*

*current 250mA*
*thermistor resistance*
*12 KOhm-15 KOhm*

*current 200mA,*
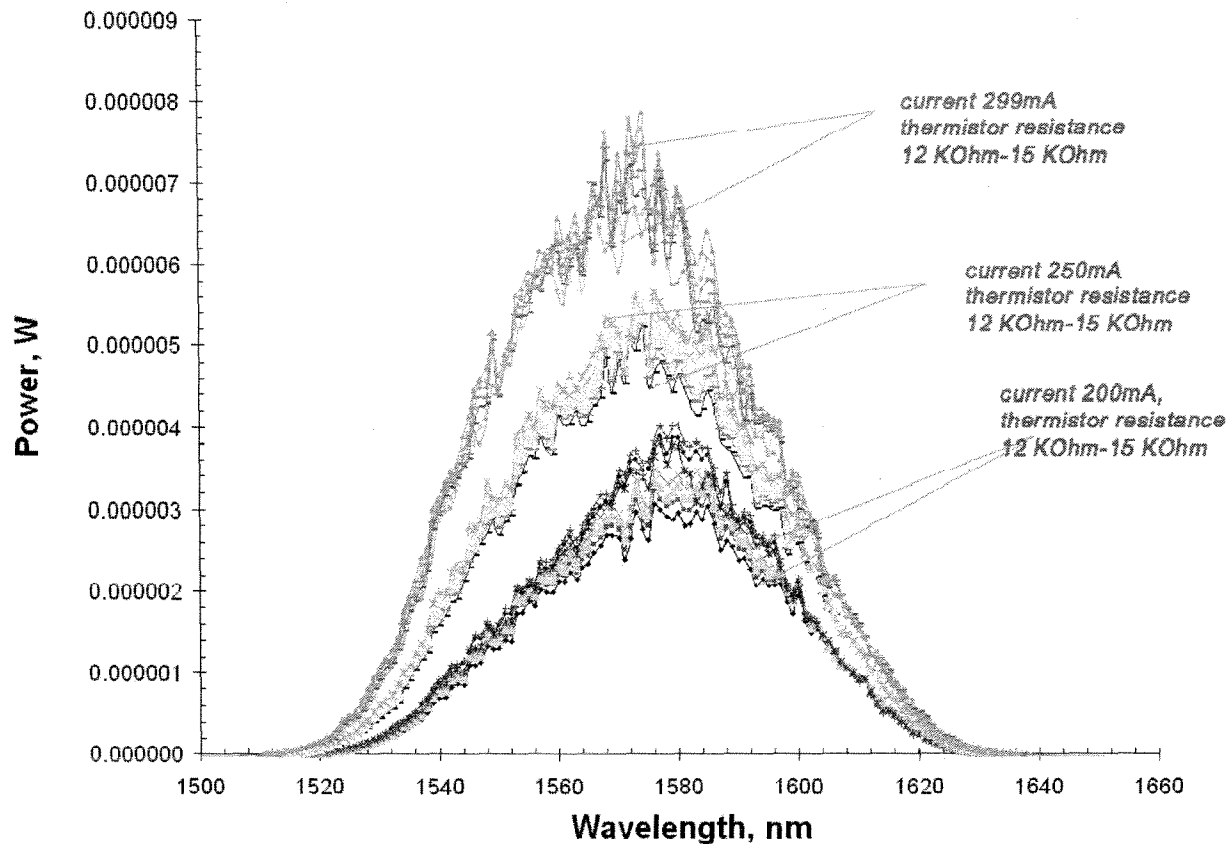*thermistor resistance*
*12 KOhm-15 KOhm*

**Figure 4. The output of an off-the-shelf superluminescent light emitting diode from Exalos, Corp. Custom diodes with narrower passbands are available. This would put more of the output in the region used by the $CO_2$ sensor improving overall efficiency of the system. The thermistor resistance values indicate slightly different operating temperatures.**

## 3. BROADBAND LIDAR

We are developing a lidar system that employs a broadband source that more or less replaces the sun as a source for our passive sensor. The source employs devices called superluminescent light emitting diode (SLED's) to generate the broad band light pulse followed by erbium doped fiber amplifiers (EDFA's) to increase the transmitted power up to a value high enough to be suitable for LIDAR. Because these sources generate all the wavelengths necessary to analyze the effects of temperature and pressure on the absorption lines it is only necessary to have a single transmitter for our lidar instead of the six or more necessary using narrow band techniques. Also it is not necessary to use complex line locking techniques to ensure stability of the transmitter. All the wavelength stability duties are absorbed by the detector for the system.

Superluminescent Light Emitting Diode (SLED) is fundamentally identical with familiar light emitting diodes (LED) and diode lasers except that its physical design is modified to suppress the formation of a laser cavity that would force it to operate at a single frequency. By modifying the composition and geometry of the SLED its output can be tailored to some extent to meet specific requirements for operating wavelength and bandwidth. **Figure 4.** shows our measurement of the output of a commercially available off the shelf SLED manufactured by EXALOS. [12] Note that ~70% of the output power lies between 1540 nm and 1600 nm and is almost centered over the 1567 nm to 1574 nm region used by the Fabry-Perot detector. The total output power for the device can be on the order of 10 mW. While this is not nearly enough output for a measurement from space it will suffice for initial laboratory work on the feasibility of the technique.

It is necessary to boost the output power up to the tens or hundreds of Watts range for longer range measurements from space or airborne platforms. Fortunately devices for just this purpose have been developed because the wavelength region used for $CO_2$ measurements just happens to correspond to the L-band for fiber optic communications. The device needed to boost the power is known as an Erbium Doped Fiber Amplifier (EDFA) and they are available commercially from a variety of vendors. We originally baselined an L-Band EDFA manufactured by a company called Amonics. [13]. More recently the possibility of using a Nd:YAG laser pumped optical parametric amplifier (OPA) has become more attractive. The advantage of the OPA approach is that the laser energy can be concentrated in a shorter pulse (~ 10 nsec) than with the EDFA. The shorter pulse reduces the extent to which background solar flux can produce a significant interference to the measurement.

Our entire system then consists of a source formed by a SLED operating in the 1560-1580nm range followed by some sort of amplifier and a small telescope used to collimate the transmitted beam. The receiver consists of a larger telescope (diameter on the order of 30-50 cm) fiber coupled to the Fabry-Perot based detector. Some consideration must be given to the electronics and signal processing techniques to be used with the system particularly in view of the fact that daytime operation with strong solar background is desired. First of all we will roughly quantify this aspect of the problem. At normal incidence the solar flux in the spectral region around 1570 nm is about 250 Watts per square meter per micron. The integrated bandpass for our filter is about .005 microns so the flux in the filter bandpass arising from the sun will be on the order of 1.25 Watts per square meter. If the field of view of our receiver telescope is about 0.1 milliradians then from a 500 km orbit we are viewing a circle on the ground about 50 meters in diameter. This has an area of about 2000 square meters so the total solar flux illuminating the area we observe is 2500 Watts. If our laser transmitter can output 200 Watts then the solar flux is roughly 12.5 times greater than our laser signal. The system electronics and data processing scheme must be capable of detecting the laser photons within this solar background. There are several methods of accomplishing this. The classic lidar approach is to emit the laser photons in pulses and detect the signal only in short regions that are temporally close to the laser photon bunch. For example one could modulate the output to consist of 0.5 microsecond pulses at a repetition rate of 10 kHz. If observations were limited to 1 microsecond windows around the expected return time for the photon bunch then integrated observation time over a second would be .01 seconds. With this scheme only 25 watts of solar photons would be observed while all the laser photons would be measured. Additional measurements of the solar photons between laser shots would provide a measurement of this solar background that could be subtracted from the laser plus solar signal to yield the laser photon level

A second approach suggested by workers at ITT is to employ modulation on the laser signal and use a lock-in amplifier to measure the signal at the modulation frequency while ignoring the essentially DC signal produced by the sun. Lock in techniques can typically detect signals in the presence of noise signals 10,000 times larger so this approach should permit observation of the laser signal even in the brightest sunlight. We will evaluate both the pulse and the lock-in techniques under this development program.

We have performed simulations of expected performance for our system. In order to detect column perturbations on the order of 1 ppm a signal-to-noise ratio of about 400:1 is required. Clearly overall performance depends on many factors within the instrument as well as the ground albedo and the atmospheric transmission. Using typical values for the relevant parameters and transmitted power comparable to that employed by other lidar technologies we find that from an aircraft flying at 5 km with a 40 cm diameter telescope and 20 Watts of transmitted laser power we could expect a signal to noise ratio (SNR) on the order of 500:1 for a single second of data collection. From a 500 km orbit with a 1 meter telescope and 200 Watts of transmitted power we could obtain an SNR in excess of 400:1 in one second. The ASCENDS (Active Sensing of $CO_2$ Emissions over Nights, Days, and Seasons) mission requirement of 100km linear resolution over land means that about 14 seconds (at typical satellite velocity of ~7 km/sec) are available to make a measurement.

# 4. CONCLUSIONS

Improved measurements of carbon dioxide on a global scale continue to be a high priority for increasing our understanding of the process of greenhouse gas induced global change. Laser based instrumentation operating from space appears to be an option for addressing this problem. The advantage of lasers is that they can determine the optical path length for the measurement process very precisely eliminating a serious source of error that may affect passive systems. Lasers can also operate without the need for sunlight and so can make measurements of the full diurnal cycle of $CO_2$ around the whole earth.

The disadvantages of lasers are that they only measure at one distinct and very specific frequency. In order to understand the effects of pressure induced shifts and pressure induced broadening it is probably necessary to measure at three different locations on a carbon dioxide absorption line. In order to understand the effects of temperature on the absorption features it is probably necessary to measure the properties of at least 2 distinct absorption features. To do this means that 6 independent laser sources locked precisely to 6 different frequencies must be flown and must continue to operate simultaneously. In order to correct column measurements for effects of terrain and weather it has been suggested that oxygen should

be measured simultaneously. This means another 6 lasers. NASA has never flown a narrow band frequency locked laser in space. NASA has never operated a system in space with 6 or 12 lasers all firing quasi simultaneously and synchronously.

We have outlined the design and advantages of a lidar system employing a single broadband source rather than a number of discrete laser wavelengths. This system has recently received funding for development from NASA's Earth Science Technology Office. Perhaps this work will lead to a whole new class of chemical remotes sensing lidars.

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