

Broadband Lidar technique for precision CO₂ measurement

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ABSTRACT

Presented are preliminary experimental results, sensitivity measurements and discuss our new CO₂ lidar system under development. The system is employing an erbium-doped fiber amplifier (EDFA), superluminescent light emitting diode (SLED) as a source and our previously developed Fabry-Perot interferometer subsystem as a detector part.

Global measurement of carbon dioxide column with the aim of discovering and quantifying unknown sources and sinks has been a high priority for the last decade. The goal of Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS) mission is to significantly enhance the understanding of the role of CO₂ in the global carbon cycle. The National Academy of Sciences recommended in its decadal survey that NASA put in orbit a CO₂ lidar to satisfy this long standing need. Existing passive sensors suffer from two shortcomings. Their measurement precision can be compromised by the path length uncertainties arising from scattering within the atmosphere. Also passive sensors using sunlight cannot observe the column at night. Both of these difficulties can be ameliorated by lidar techniques.

Lidar systems present their own set of problems however. Temperature changes in the atmosphere alter the cross section for individual CO₂ absorption features while the different atmospheric pressures encountered passing through the atmosphere broaden the absorption lines. Currently proposed lidars require multiple lasers operating at multiple wavelengths simultaneously in order to untangle these effects.

The current goal is to develop an ultra precise, inexpensive new lidar system for precise column measurements of CO₂ changes in the lower atmosphere that uses a Fabry-Perot interferometer based system as the detector portion of the instrument and replaces the narrow band laser commonly used in lidars with the newly available high power SLED as the source. This approach reduces the number of individual lasers used in the system from three or more to one—considerably reducing the risk of failure. It also tremendously reduces the requirement for wavelength stability in the source putting this responsibility instead on the Fabry-Perot subsystem.

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1. INTRODUCTION

One of NASA's strategic goals is to study the Earth from different platforms using novel techniques "to advance scientific understanding and meet societal needs"¹. This goal requires the continuing development of new technologies and capabilities. Climate change and climate prediction studies require monitoring of the global carbon cycle. To determine carbon cycling dynamics and to understand the processes controlling sources and sinks, integrated measurements, observations, and improved modeling is needed. CO₂ has a critical role in climate change because of the uncertainty in understanding its cycle between the land, ocean, atmosphere and biosphere (**Figure1**). Carbon dioxide concentration has increased by more than 95 ppm in the last 150 years^{2, 3}. The majority of CO₂ variability occurs in the lower atmosphere (~1000 to 800 mbar). The natural geographic distribution and temporal variability of CO₂

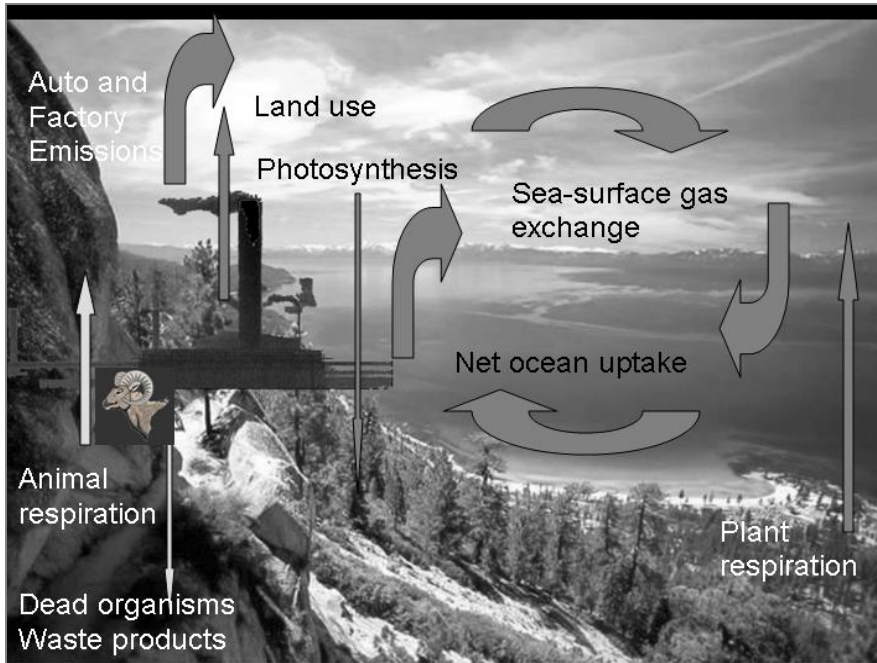


Figure 1. The Earth's carbon cycle. Carbon cycles through pools or reservoirs of carbon on land, in the ocean, and in sedimentary rock formations over daily, seasonal, annual, millennial, and geological time scales.

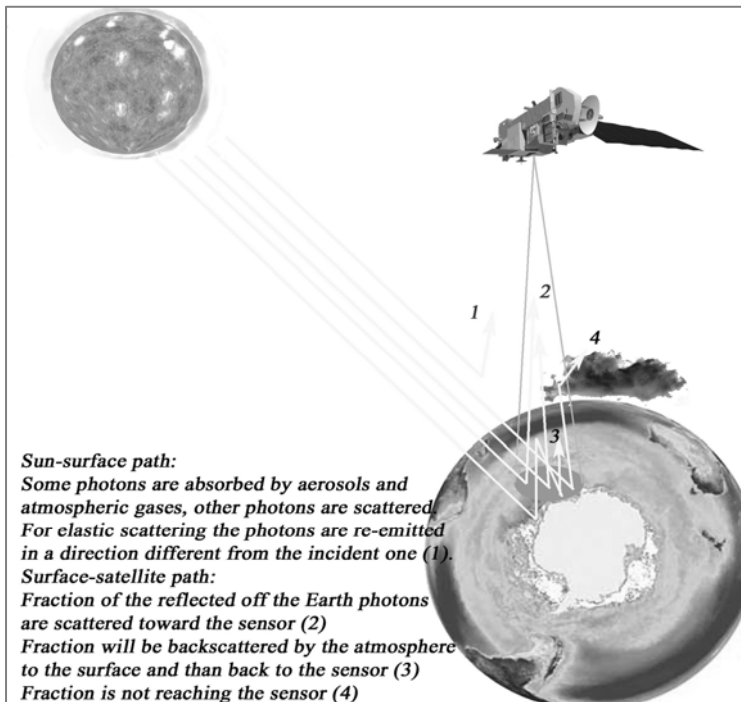


Figure 2 The most difficult aspect of meeting the precision requirements for the passive sensors is determining the path length through the atmosphere in the presence of clouds and scattering aerosols. A path length error on the order of 20 meters is sufficient to produce the 1 ppm error in the column average which is the goal of these systems.

sources and sinks however are still not well understood^{3, 4, 5, 6}. 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 (**Figure 2**). To quantify the carbon cycle dynamics, to help predict climate change^{7, 8, 9, 10} and to meet the stringent performance requirements new monitoring instruments are needed.

Solutions to the questions and uncertainties regarding CO₂ sources and sinks are generally thought to be data limited. Our knowledge of atmospheric carbon processes comes from ground network and satellite measurements which includes the long term, in situ CO₂ measurement program led by the NOAA. These data are used in inverse studies such as TransCom 3 transport/flux estimation experiment^{11, 12}. The in situ measurements are very precise (uncertainties on the order of 0.1 ppm) and accurate, but are necessarily limited in time and space and do not measure the whole atmospheric column.

To characterize the spatial distribution the devices need to be flown over large areas and at different altitude. Space-based CO₂ column measurements with 1 ppm precision were predicted

to reduce inferred CO₂ flux uncertainties of annual mean fluxes from greater than 1.2 GtC region⁻¹ year⁻¹ to less than 0.5 GtC region⁻¹ year⁻¹ when averaged over the annual cycle.⁸

Theoretical calculations, employing instrument models, indicate that high-sensitivity measurements of column CO₂ from space using reflected sunlight are feasible with current technology^{13,14,15}. However the measurement precision requirements are so strict, that relatively minor measurement effects may produce serious errors¹³. Principal among these effects is variation of the atmospheric depth or path over which the CO₂ absorption takes place (**Figure 2**). Because variations in terrain height and/or surface pressure create gradients in CO₂ column density greater than those due to source/sink effects, column measurements must be normalized for the total atmospheric density. Generally, this is expected to come from collocated measurements of atmospheric O₂ column, in particular the O₂ A-band near 760 nm¹⁴. In addition, aerosol and cirrus scattering will significantly alter the sunlight path through the atmosphere and hence the spectral attenuation.

Ground-based absorption measurements of the CO₂ column are carried out by Fourier Transform Infrared spectrometry coupled with a sun tracking system. While these FT-IR techniques offer good sensitivities, cost and size limit the viability for this instrumentation to fill in the sparse spatial network of surface measurements and ultimately resolve major source and sink regions.

Several instrumental approaches are currently being pursued within NASA to enable high-precision measurements of atmospheric CO₂. One of the promising techniques is the detection of absorption by CO₂ in reflected sunlight from the Earth's surface at near-infrared wavelengths (~1.6 μm). That is the goal of OCO (Orbiting Carbon Observatory) scheduled for launch in 2008^{19, 20, 21, 22}. OCO is going to use three bore-sighted, high resolution, grating spectrometers provided by Hamilton Sundstrand Sensor Systems. A similar approach at Goddard is being taken with the Fabry-Perot Interferometer for Column CO₂ (FPICC) instrument^{14, 15, 16, 17, 18}. The instrument is using a remote sensing passive interferometric technique for continuous detection of CO₂, H₂O and O₂ with the required accuracy.

We have demonstrated that the interferometer has significant capabilities to detect CO₂, O₂ and H₂O in the laboratory and have shown that it responds to reflected and direct sunlight in the expected manner. Results from ground testing and flight testing have already been reported to the science community and published in refereed journals. An estimate of the system performance from the ground indicates that with its current design it can detect changes in the CO₂ column as small as 2.3 ppm with a one second average and better than 1 ppm in less than 10 seconds averaging. It detects changes in the O₂ column as small as 0.1%, with a time resolution of 1 second using direct sun light.

The airborne instrument using light reflected off the ground has a sensitivity of about 2%. The reduced sensitivity arises because the atmospheric scattering processes make the path length more variable and uncertain (See the Text Box next page entitled The Path Length Problem). Measurement using the glint promises to obviate consideration of these atmospheric scattering effects. However the technique used with the Fabry-Perot interferometer is passive and is limited to daytime and fair weather conditions. Because sun is the source of illumination it changes with solar angle and atmospheric conditions which means that for those measurements detailed atmospheric information is also needed.

Laser based (active) systems are not subject to these limitations. Obviously they can work at night as well as day. In addition it is simpler to understand the light path for a laser instrument because timing a laser pulse yields the path length directly.

This work presents an overview of the characteristics necessary in a laser system used to make a precise CO₂ measurement. Consideration is given to the temperature dependence, pressure broadening, and pressure shift of the CO₂ 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.

The Path Length Problem

If the entire atmospheric column could be compressed into a box with a constant pressure of one atmosphere the box would be roughly seven kilometers thick.

A change in the column by 1 part in 400 then would represent a change in the box thickness of $7000/400=17.5$ meters.

This means that a change in the optical path of light that is being used to measure the CO₂ column as small as 17.5 meters would produce a change in the column measurement of about 1ppm—the desired measurement precision.

Clearly changes in terrain can produce path length deviations much larger than this -so a successful CO₂ measurement must include some method of determining this path length.

Simultaneous measurement of the O₂ column has been suggested since this also corrects for changes arising from meteorology. Atmospheric scattering can produce path length changes much larger than 17.5m and depending on the distribution of scattering particles and the elevation of the sun the changes can be either positive or negative.

The OCO science team intends to use radiative transfer calculations to reduce the uncertainty in path length.

Laser approaches are much more direct. By measuring the time elapsed between the emission of a laser pulse and the detection of the reflected return then multiplying by the speed of light the path length can be determined very precisely.

2. DESCRIPTION OF THE TECHNOLOGY

The instrument that we are currently developing operates on the principle of differential absorption. This means that the instrument examines the transmission of light through the atmosphere at two or more different wavelengths that are absorbed differently by the species one wishes to measure. There are then two principal elements involved in the measurement—the source and the detector. Passive systems use natural processes such as sunlight or atmospheric emission to generate a number of different wavelengths which are separated for analysis by the detector. Most laser based systems (eg. DIAL lidars) use two or more different laser sources to provide different wavelengths. These systems then might use the same detector for the multiple wavelengths using time separation or modulation to differentiate the signals coming from the different lasers.

Our system uses as a detector that can differentiate wavelengths just as conventional passive sensors. The detector was originally developed as the Fabry-Perot passive sensor measuring CO₂ using reflected sunlight. Our new approach is made possible by the emergence of a new type of source—the superluminescent light emitting diode (SLED). The SLED has the same high brightness and collimation characteristics as a conventional laser but it emits light over a broader range of wavelengths than conventional lasers. This permits a differential absorption measurement employing a single source with wavelength differentiation in the detector. The new approach has a number of practical advantages for a field instrument that will be discussed later but first we will describe the properties of the existing Fabry-Perot interferometer that will serve as our detector.

3. FABRY-PEROT INTERFEROMETER

The Fabry-Perot Interferometer instrument uses a solid Fabry-Perot etalon to restrict the measurement to light in atmospheric absorption bands. Light passing through the etalon undergoes multiple reflections on each inside surface, creating an interference pattern of evenly spaced fringes as a function of wavelength. At wavelengths where these fringes peak (constructive interference), light passes through the

etalon. At the troughs of these fringes, (destructive interference) light is blocked. We adjust the thickness of the etalon so that the separation (in frequency) of the transmitted fringes is equal to the almost constant separation of the atmospheric absorption lines. By adjusting the temperature of the etalon (which changes the index of refraction of the glass) the transmission fringes can be brought into nearly exact correspondence with the absorptions. When this is done changes in the amount of absorption in the atmosphere strongly affect the amount of light transmitted by the etalon.

A narrow-band filter is used to confine the overall spectral band pass of the instrument to the region of interest. Light through the band pass filter is split and detected simultaneously in two channels: direct (reference) and after passing through the etalon. Changing atmospheric absorption changes the reference channel illumination only slightly, but changes the light passing through the Fabry-Perot substantially. Changes in overall intensity affect the two channels equally. Thus, a change in the ratio of the signal through the Fabry-Perot to that of the reference is sensitive to absorption by the atmospheric constituent under consideration¹⁵.

A schematic of the carbon dioxide component of the FPI instrument used in ground testing is shown in **Figure 3**. In this design, incoming light is focused onto a 2 mm diameter aperture to restrict the field of view of the instrument. The light is modulated at 400 Hz with a chopper (Stanford Research Systems, SR540) and then re-collimated as it emerges from the aperture. The re-collimated light passes through the 1567-1574 nm bandpass prefilter (Barr Associates), ~10% of which is reflected by the beam splitter (CVI) through the reference channel and focused onto one of two thermo-electric cooled InGaAs photodiode detectors (Oriel Instruments). Light passing through the beam splitter enters the temperature.

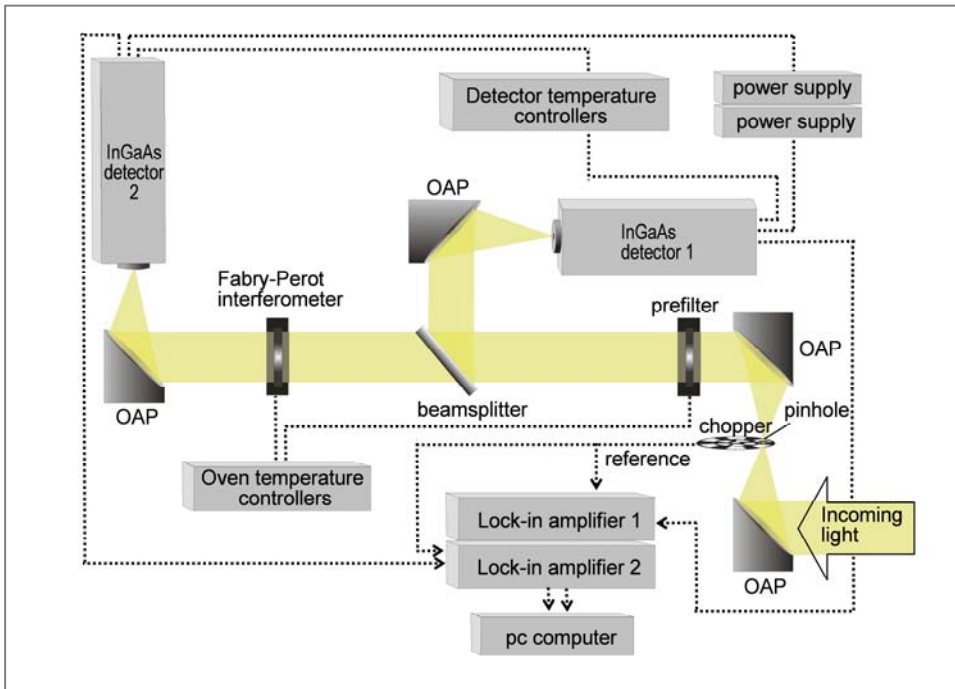


Figure 3. Schematic for CO₂ channel of FPI instrument that will serve as the receiver section for our lidar. Long term wavelength stability for this system has been demonstrated on aircraft missions and by multiple month ground based experiments.

controlled Fabry-Perot etalon and is focused onto the second InGaAs detector. Signals from the detectors are amplified and processed by two lock-in amplifiers (Stanford Research Systems, SR830 DSP). Custom Lab VIEW software (National Instruments, version 6.1) has been developed for controlling the measurement system as well as analyzing the detected signals from both channels.

At the core of this instrument is a Fabry-Perot interferometer composed of solid fused silica with a free spectral range (FSR) of 0.306 nm, a refractive index of 1.443 at $\lambda=1571$ nm, and a clear aperture of 50 mm. The interference fringe pattern produced by a Fabry-Perot Interferometer is described by the Airy function. The free spectral range is the distance between these interference fringes, determined by the wavelength of the interfering light, the thickness of the etalon and the refractive index of the etalon material. Thus, the spacing between fringes can be approximately matched to the spacing of CO₂ lines through etalon thickness. Similarly, the width of fringes can be approximately matched to CO₂ line width by appropriate choice of reflectance of the etalon surfaces. The separation and width of the FP transmission fringes can be adjusted to incorporate different portions of the absorption line shapes with different weights. We have adjusted them to include a large fraction of the wings of the profile which thereby gives greater weight to the lower tropospheric portion of the column.

Alignment between fringes and CO₂ absorption transitions can be further adjusted by temperature tuning the Fabry-Perot. This is demonstrated in **Figure 4**, where two laser scans of carbon dioxide (1 atm) in an absorption cell are obtained with the instrument etalon at temperatures of 40° and 48°C. Fringes from the Fabry-Perot channel shown in blue are compared with CO₂ absorption lines from the reference channel in pink with the bandpass prefilter defining the wavelength range of the instrument. The 48°C scan clearly shows better overlap between fringes and lines than the 40°C scan.

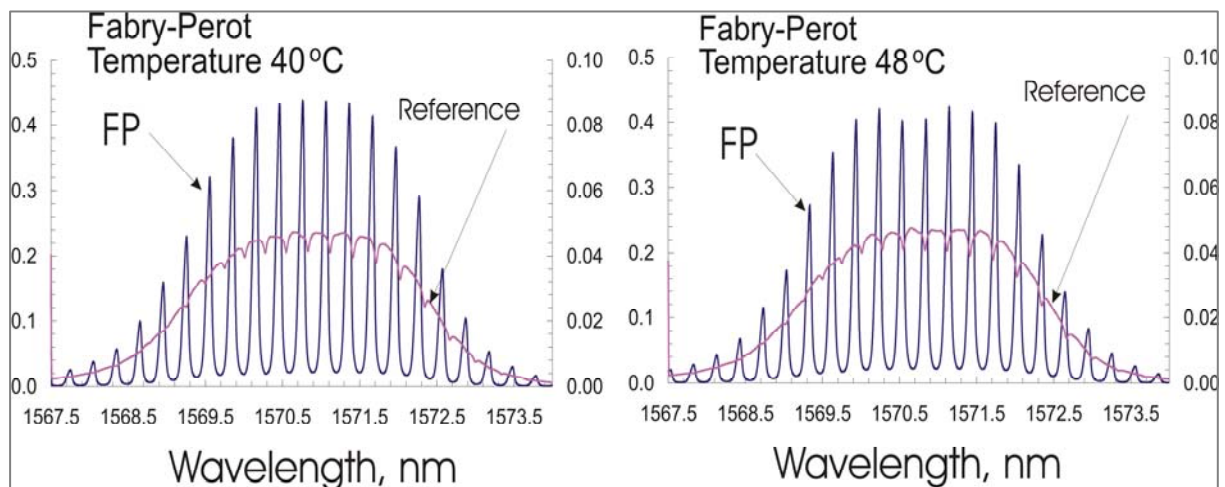


Figure 4. Overlap between fringes and CO₂ lines at two Fabry-Perot temperatures. The combination of etalon thickness, etalon coating reflectivity, and temperature is used to control the overlap of the fringes with the absorption lines.

4. AIRBORNE TEST RESULTS

For the airborne or satellite measurements the light passing through the atmosphere reflects on the Earth's surface before entering the instrument platform. The flight hardened version of the instrument was tested at two flight campaigns at NASA Dryden Research Center and at New Hampshire for the Polar Aura Validation campaign on NASA's DC-8 research airplane. Flights were conducted over a variety of surfaces (vegetation, water, snow) and under different atmospheric conditions. An in situ instrument provided CO₂ profiles up to the flight altitude. Temperature and density profiles were available from the aircraft data system. Comparison of FP radiometer data at different altitudes with the integrated in situ profiles formed the basic measure of the remote sensing sensitivity and provided a reference calibration. Data for the airborne tests were collected viewing in nadir direction. Simultaneous measurements of carbon dioxide and oxygen are shown in **Figure 5(a,b)**. In both plots, the ratio of Fabry-Perot to Reference signals are compared to the altitude of the plane, corresponding to changes in the total path length of sunlight through the absorber. For CO₂ channel the ratio of Fabry-Perot to Reference signals (blue) are inversely

proportional to the column of CO₂ measured and consequently the altitude from which measurements are made (red). As expected, changes in ratio clearly track changes in altitude. We have used the change in ratio with altitude to estimate the instrument response. We obtained a value of -0.44 for the change in ratio divided by the change in total column - indicating a ratio change of approximately 40% for a change of one air mass. Improvements to the instrument since this time have increased this value. Results from the flight experiments were reported^{14, 15, 16, 17.}

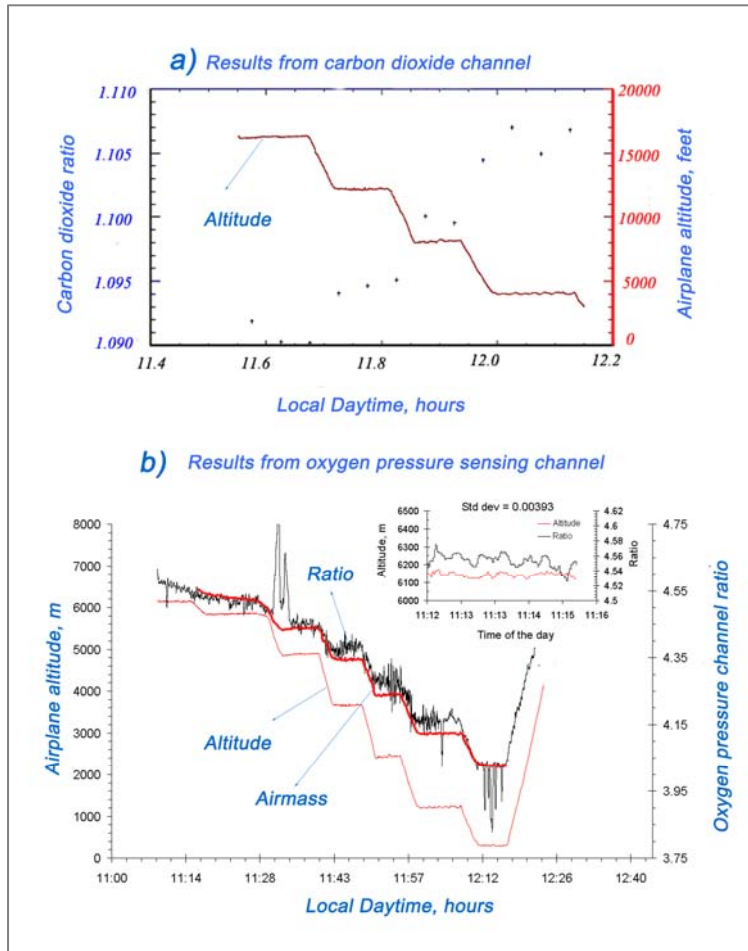


Figure 5 The instruments response to the altitude in meters at airborne mission. a) The CO₂ ratio of Fabry-Perot to Reference signals is shown compared to changes in altitude on a May 14, 2004 flight. As the aircraft descends the photon pathlength gets shorter so the absorption in the Fabry-Perot subchannel decreases. b) The Ratio for the pressure-sensing channel (O₂) and air mass as a function of time are shown. The embedded graph shows the blown images of the measured Ratio and altitude for four minutes. The standard deviation is calculated to be 0.00393.

airborne platforms. Fortunately devices for just this purpose have been developed because the wavelength region used for CO₂ 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. **Figure 7** demonstrates the broad range of wavelengths that can be amplified simultaneously using a L-Band EDFA manufactured by a company called Amonics. [AMONICS, 2007]

5. THE SUPERLUMINESCENT LIGHT EMITTING DIODE SOURCE

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 bandwidth²³. **Figure 6** shows the output of a commercially available off the shelf SLED manufactured by EXALOS. [EXALOS]

The power scale is logarithmic so ~70% of the output power lies between 1540nm and 1600 nm and is almost centered over the 1567nm 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

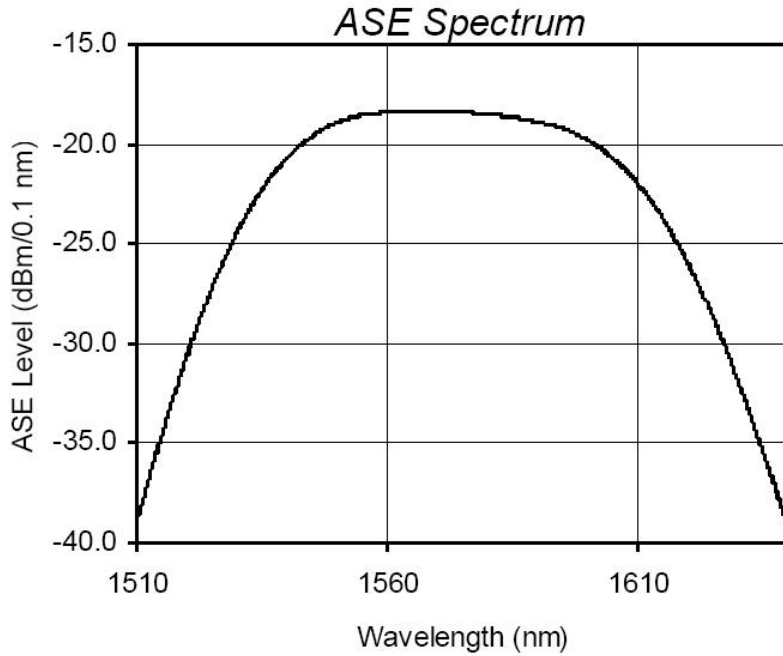


Figure 6. This figure shows the power versus wavelength for an off-the-shelf SLED. This device would suffice for our initial studies. Diodes with more power centered at 1570 nm can be fabricated.

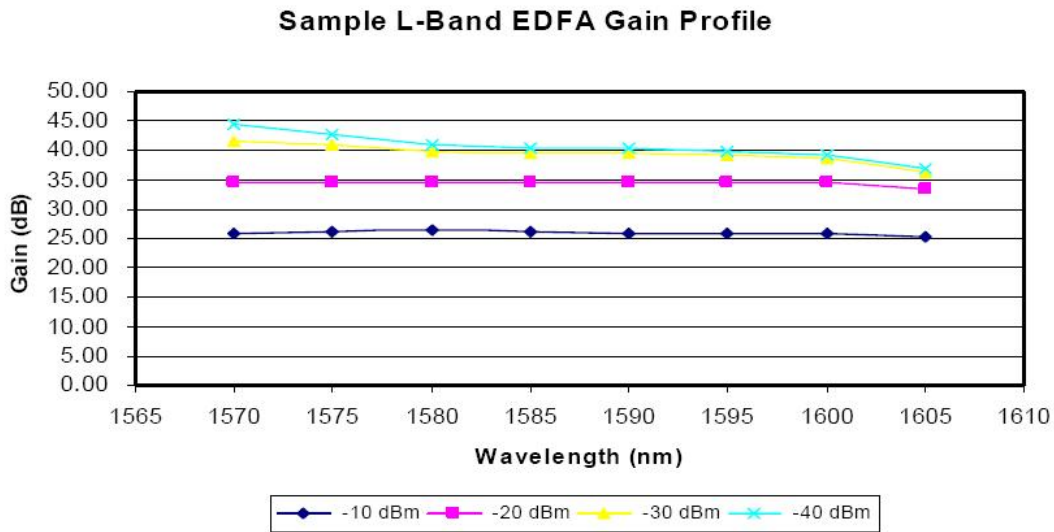


Figure 7. This demonstrates the gain versus wavelength for a commercially available EDFA for various values of injected power. The EDFA will be used to boost the output of the SLED.

Our entire system then consists of a source formed by a SLED operating in the 1560-1580nm range followed by an L-Band EDFA 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. Next steps and the prospects for a space borne system will be discussed.

6. 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 CO₂ around the whole earth.

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