

DEVELOPMENT OF A DIFFERENTIAL ABSORPTION LIDAR FOR
IDENTIFICATION OF CARBON SEQUESTRATION
SITE LEAKAGE

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Physics

MONTANA STATE UNIVERSITY
Bozeman, Montana

November 2013

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ACKNOWLEDGEMENTS

First and foremost I want to thank my wife Kristin, for providing such strong and loving support during all these years in graduate school, I could not have done it without you! Thank you to Kevin Repasky for providing so much prompt support and guidance. You put your students first, and for this I am very grateful. Thank you to John Carlsten for your encouragement and an ever open door to answer any question. Thank you to the 2 micron IPDA team at NASA Langley Research Center for providing me with such a unique and amazing opportunity to fulfill a childhood dream of working at NASA. Thank you to all of the staff in the Physics and Electrical Engineering Department for providing so much experience and support. Thank you to all of my family, friends, and fellow church members for helping me to stay happy and balanced through all of the many long days when it seemed like graduate school would get the best of me.

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ABSTRACT

This thesis describes the development and deployment of a near-infrared scanning micropulse differential absorption lidar (DIAL) system for monitoring carbon dioxide sequestration site integrity. The DIAL utilizes a custom-built lidar (light detection and ranging) transmitter system based on two commercial tunable diode lasers operating at 1.571 μm , an acousto-optic modulator, fiber optic switches, and an Erbium-doped fiber amplifier to generate 65 μJ 200 ns pulses at a 15 kHz repetition rate. Backscattered laser transmitter light is collected with an 11 inch Schmidt-Cassegrain telescope where it is optically filtered to reduce background noise. A fiber-coupled photomultiplier tube operating in the photon counting mode is then used to monitor the collected return signal. Averaging over periods typically of one hour permit range-resolved measurements of carbon dioxide from 1 to 2.5 km with a typical error of 40 ppm. For monitoring a field site, the system scans over a field area by pointing the transmitter and receiver with a computer controlled motorized commercial telescope base. The system has made autonomous field measurements in an agricultural field adjacent to Montana State University and at the Kevin Dome carbon sequestration site in rural northern Montana. Comparisons have been made with an in situ sensor showing agreement between the two measurements to within the 40 error of the DIAL.

In addition to the work on the 1.57 micron DIAL, this thesis also presents work done at NASA Langley Research Center on the development and deployment of a 2 micron integrated path differential absorption (IPDA) lidar. The 2 micron system utilizes a low repetition rate 140 mJ double pulsed Ho:Tm:YLF laser developed at NASA Langley.

INTRODUCTION

The Earth's dry atmosphere consists of nitrogen, oxygen, argon, and carbon dioxide, listed by concentration, along with many other minor constituents¹. While each gas plays a role in the dynamics of the Earth's climate, carbon dioxide especially has been isolated as a trace gas of great concern in the Earth's atmosphere, due to its recently rapidly rising concentration and the potential climatic consequences of this increase²⁻⁵. The historical trends of carbon dioxide are monitored in several ways. The farthest reaching historically are concentration measurements based on ice core data taken from around the world such as in Russia and in the Antarctic. Data taken from these ice cores provides historical CO₂ trends that span many tens of thousands of years. These trends indicate that, while there have been historical fluctuations, the largest pre-industrial concentration of CO₂ was no more than 300 ppm⁵⁻⁷ (Figure 1).

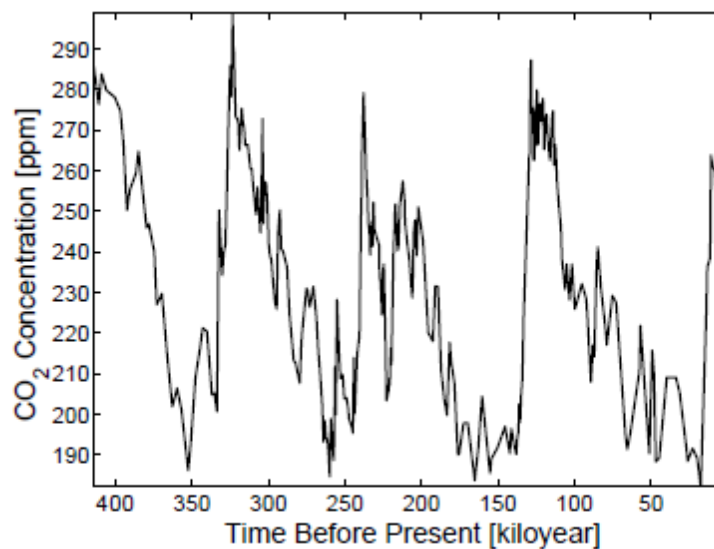


Figure 1: Ice core data of carbon dioxide concentration from 400 kiloyears ago to the present showing the historic behavior of atmospheric carbon dioxide concentration.

More recently over the last century, carbon dioxide has been monitored directly at remote sites around the globe. These monitoring stations have measured a rising trend in carbon dioxide concentration^{2,3} (Figure 2).

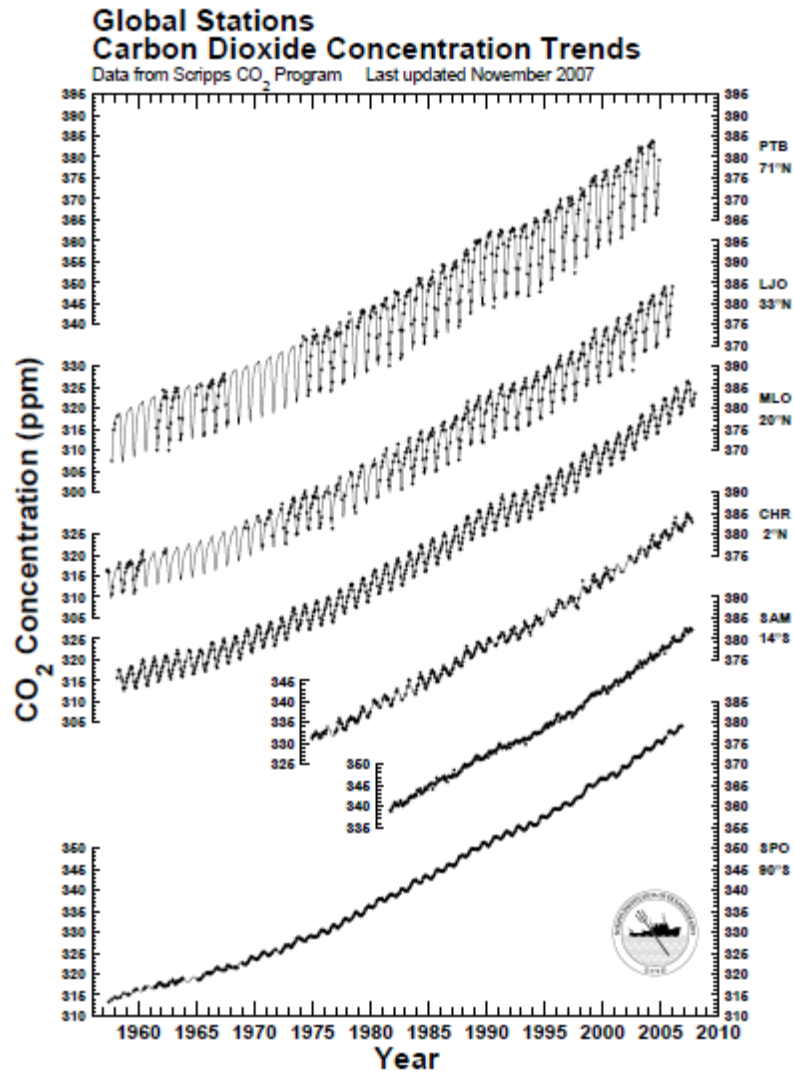


Figure 2: Comparisons of CO₂ data from multiple global monitoring stations shows the same increasing trend in atmospheric CO₂ concentrations.

While there are a variety of factors that influence the global climate, the concentration of carbon dioxide is relevant due to its ability to absorb the emitted thermal

radiation from the Earth's surface, thus trapping more of the incoming solar radiation which affects the Earth's energy balance⁸. This increased energy absorption can have significant effects on global climate including not only rising temperatures but extreme weather events, from rising sea levels, and polar ice melting³. Measurements of the Earth's temperature at more than 30,000 sites around the globe have shown both an upward shift in the average temperature around the globe along with a widening of the Earth's temperature distribution³ (Figure 3). This means that the Earth is both getting warmer, and experiencing more temperature extremes.

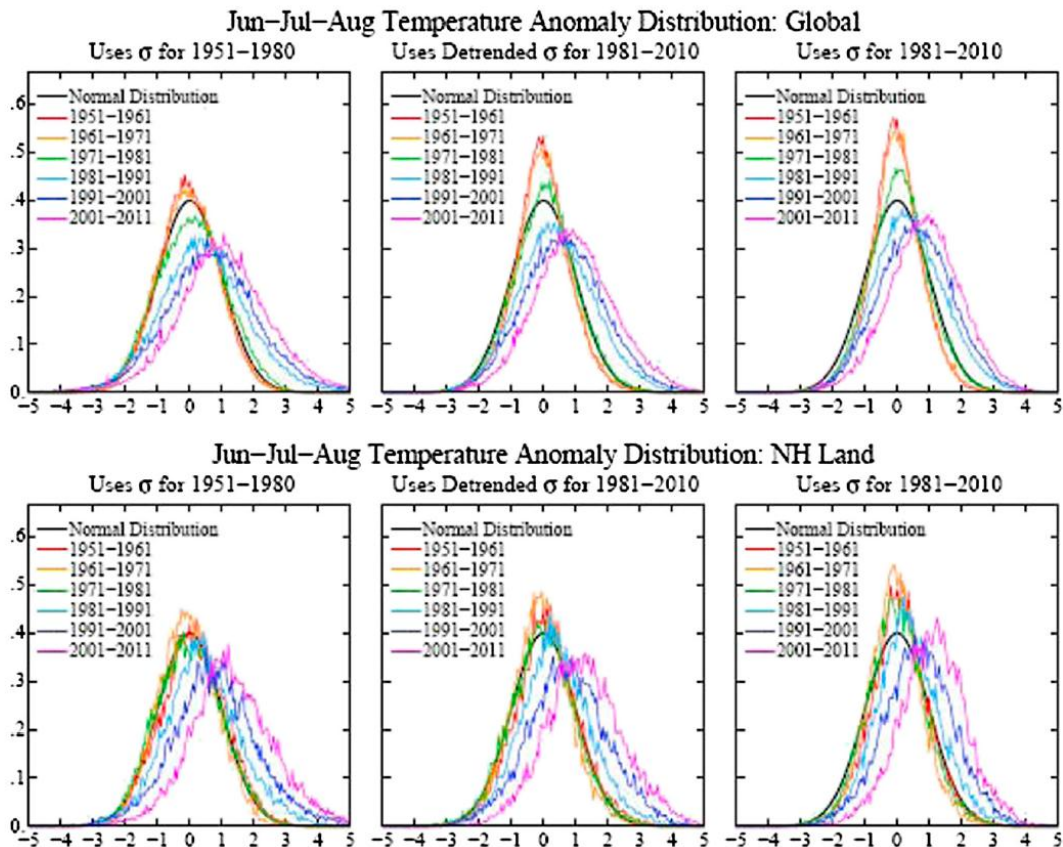


Figure 3: Distributions of global temperature distributions from 1951-2010. The width of the temperature distributions for each decade shows broadening that can be related to increased anomalous temperature events³.

The way that carbon dioxide changes the net energy absorbed by the sun is through a mechanism known as the greenhouse effect. When visible solar radiation strikes the Earth's atmosphere, the majority of the energy passes through the atmosphere without being absorbed. Upon striking the Earth's surface, the energy contained in this visible light gets reradiated at longer optical wavelengths. Some gases in the Earth's atmosphere are capable of absorbing these longer wavelengths, and these are known as "greenhouse gases". While there are many different greenhouse gases present in the Earth's atmosphere such as water vapor, carbon dioxide, and methane, carbon dioxide has gotten the attention of the climate community due to its long persistence in the Earth's atmosphere, large absorptive capabilities, and growing concentration due in part to human activity⁹⁻¹⁷.

There are many sources and sinks of carbon dioxide on Earth, and the full picture of the carbon cycle is incomplete¹⁸. A distinguishing characteristic of carbon dioxide from water vapor or methane as a greenhouse gas is the sheer volume being added to the atmosphere by anthropogenic sources. These sources tend to have the common fact that they operate off of combustion of petroleum or coal derivatives. Industrialization of the modern world has built a vast infrastructure that as of 2012 consumes 88 million barrels of oil per day and 3724 million tonnes oil equivalent annually¹⁹. This translates to 9.5 Petagrams (Pg) of carbon dioxide emitted in to the Earth's atmosphere each year as of 2011²⁰, and that number is expected to rise with a growing world demand for energy. The predicted rise in global temperatures depends in part on the maximum concentration of

CO₂ in the atmosphere. If the concentration can be capped at lower values by emission reduction measures, lower rises in global temperatures are expected^{20, 21}.

In an effort to reduce carbon emissions while still maintaining a petroleum based energy infrastructure, carbon sequestration has been proposed and is being implemented as a preventative action against rising carbon dioxide levels. Carbon sequestration is the process of storing carbon dioxide by a variety of methods to prevent the carbon dioxide from otherwise being released in to the Earth's atmosphere. Large localized emitters of carbon dioxide, which make up 39.6 percent of the total United States carbon emissions as of 2010²², capture CO₂ gas at their emission point. Once captured, typical current sequestration practices then force this CO₂ in to a supercritical fluid state for pumping underground in to subterranean formations that lend themselves well to long term carbon storage. These formations are often abandoned oil wells or deep saline aquifers²³. To date there are 83 active carbon sequestration projects worldwide as of February 2013 and 32 announced sites are under active development²². The current estimated viable carbon sequestration capacity of identified sequestration type formations in the United States and parts of Canada alone is 12.9 metric Petatons²⁴. Thus carbon sequestration has the potential to make a significant impact on the carbon emission picture over the next several decades.

With the potential positive environmental impacts of carbon sequestration, and the 83 sites already active, it is necessary to consider what risks carbon sequestration sites pose to the health of the environment. While in principle sequestration sites lend themselves well to long term high integrity storage of carbon dioxide, this long term

integrity is not guaranteed. Any sequestration site has the capability of leaking its stored carbon dioxide at the injection well site or through fault lines that either exist upon injection or are formed as a result of the injection processes or seismic activity²⁵⁻²⁷. A need exists then to monitor the integrity of every site for leakage of carbon dioxide. Monitoring of these sites is no easy task however. Current sizes of sequestration subsurface storage structures range from 10's acres such as those at the Zama storage project in Alberta, Canada to hundreds of square miles such as those at the Kevin Dome site²². These geologic storage sites also all share the common fact that they are often in semi-remote locations, which complicates the task of site monitoring due to the logistical matter of providing a steady support infrastructure to the monitoring operation.

If a leak were to occur at a sequestration site, the source of the leak would most likely originate either at the injection well or from deep underground at a fault or fracture²⁵⁻²⁷. If the leaking carbon dioxide originated from a subsurface fault, it would have a long underground path to diffuse through and would spread out before reaching the surface, as the storage structures are typically 100's to 1000's of meters underground. This means that if a leak were to occur, it would not be a highly localized leak, but, instead would be a plume of carbon dioxide diffused over an area 100's of square meters in size and persistent in time over the course of hours or days by current modeling estimates^{28,29}. If a leak does occur due to subsurface fault seepage, its location will not always be known. This adds to the challenge of monitoring site integrity in that the monitoring technology needs to be well suited to identifying spatially large plumes but

also needs to be able to monitor the entire area of the sequestration site to identify newly emerging leaks.

There are three main integrity measurement environments for monitoring carbon sequestration sites, from which the combination of measurements made aids in quantifying site integrity and evaluating existing and potential environmental and health risks: subsurface, near-surface, and atmospheric environments. Subsurface monitoring technology is diverse, based on a variety of technologies such as vertical seismic profiling, sample well logging, pulsed neutron capture³⁰, and gamma ray logging to name a few³¹(Figure 4).

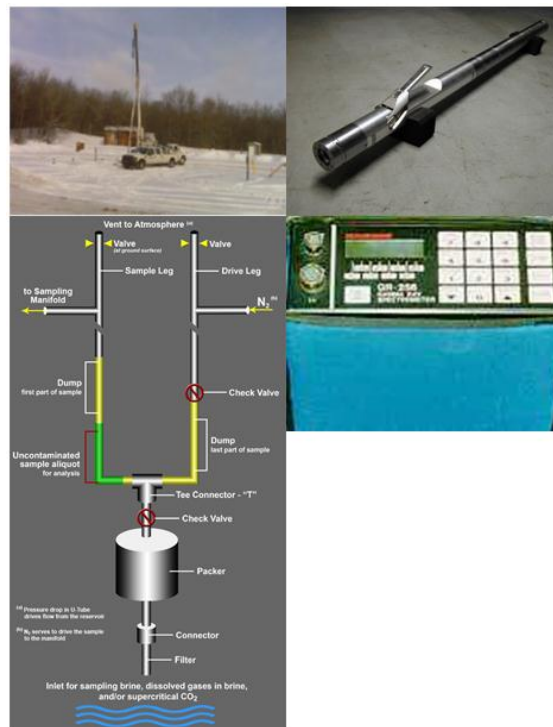


Figure 4: Upper Left: Pulsed Neutron Capture tool being run off of a mast truck. Upper Right: Vertical seismic profiling instrument³². Lower Left: U-tube sampler used for sampling fluids within a storage formation³³. Lower Right: Gamma Ray spectrometer used for gamma ray logging³⁴.

In conjunction with the subsurface monitoring, near surface monitoring technologies are just as diverse as the subsurface technologies, but, share the common goal of identification of potential site leakage and evaluating site hazards. These technologies range from environmental stress monitoring techniques such as identification of plant stresses through hyperspectral³⁵ imaging (Figure 5), groundwater monitoring for identification of groundwater contamination from site seepage, and subsurface gas concentration measurements. Environmental stress monitoring is especially useful in scanning large areas the size of the whole site or larger from an airplane. Analysis of images of the plants living at the site surface can identify zones of plants under stress potentially from overexposure to elevated carbon dioxide concentrations. These zones can then be more carefully analyzed by atmospheric and other near surface technologies for potential site leakage.

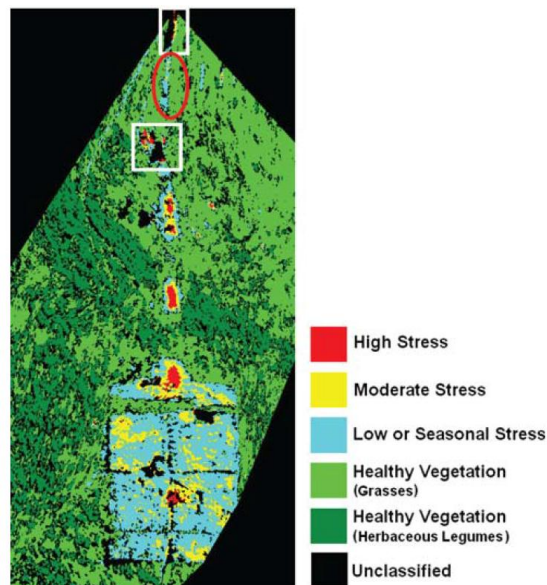


Figure 5: Using hyperspectral imaging to identify plant stressed caused by CO₂ seepage³⁵

The third type of monitoring technology for sequestration sites is atmospheric monitoring technology. As with the near and subsurface environments, measurement techniques and technologies are diverse, and include systems such as eddy covariance towers and open path infrared gas analyzers (Figure 6).



Figure 6: Left: Open path infrared CO₂ analyzer³⁶ Right: Eddy covariance analyzer³⁷
 Eddy covariance instruments measure not only the concentration of gas, but, estimate the flux of the gas of interest by correlation between measured wind currents and concentrations. These instruments are useful for sequestration sites since they do not make physical contact with the surface whose gas flux is being measured, are autonomous, and are more sensitive to scales of m² to km².³⁸

Current CO₂ direct detection technology falls under two basic categories: electrochemical, and optical. Detectors based on electrochemical interactions between carbon dioxide and electrode type materials exist and are quite affordable and prevalent. Unfortunately, they have the disadvantage that at ambient atmospheric concentrations, their accuracy, typically 10-50 % error, is outside of the tolerances allowed for sequestration site monitoring (current models estimate that above ground concentrations would be elevated by 10's-100's of ppm above ambient (~400 ppm) for many sequestration site leaks^{28,29}). Optical detector systems have the advantage of high

sensitivity even at low ambient concentrations and are generally insensitive to interfering gases. However, even the most affordable of these devices that are a few thousand dollars individually, can add up to tremendous costs when scaled to a network of tens or hundreds of detectors, making them economically unsuitable for being a building block for a large area detector network³⁹.

In the interest of keeping long term monitoring costs at a minimum for sequestration sites, any monitoring technology must be able to monitor a large area with a minimum of user interaction for long periods of time in a remote and rugged environment. Generating a support infrastructure and maintaining its operation increases the monitoring costs as well as complicating the logistics of maintaining the monitoring technology over such a large area. Ideally, such sequestration sites could be monitored with a small number of detectors capable of monitoring large areas. Remote sensing technology is capable of such a demand^{40,41}. Remote sensing instruments are capable of monitoring large areas from a single location. Centralization of equipment reduces infrastructure needs as well as simplifies logistical needs or maintaining equipment. In addition, while a single remote sensing instrument alone is often more expensive than their point sensor counterparts, the remote sensing systems have the capability to replace multiple point detectors, making the economics of large area monitoring more cost effective. Specifically, a single scanning lidar based gas remote sensing system can replace tens if not hundreds of point detectors. Scanning lidar systems are less sensitive to localize point sources of trace gases of interest, and are instead well suited to

identifying large plumes of trace gases such as carbon dioxide, making them ideal monitoring systems for carbon sequestration site integrity verification.

An eye-safe scanning differential absorption lidar (DIAL) system capable of monitoring above ground concentrations of CO₂ at carbon sequestration sites has been developed at Montana State University. The system operates at a laser wavelength of 1.57 microns, allowing for the instrument to be constructed from commercial-off-the-shelf components that minimize the total instrument cost. This thesis focuses primarily on the design, development, and field testing and measurements made with the DIAL at Montana State University. Data collected at the Zero Emissions Research Technology (ZERT) site, a field site in Bozeman Montana constructed for testing sequestration site monitoring technologies, as well as at the future Kevin Dome sequestration site is presented and discussed. In addition, this thesis presents work done at NASA Langley Research center assisting in the development and testing of a 2 micron integrated path differential absorption lidar (IPDA) for measuring atmospheric carbon dioxide concentrations.

THEORY

Light Detection and Ranging

Light detection and ranging (lidar) is a remote sensing technique that uses scattered laser light to measure and quantify atmospheric parameters of interest. In its simplest form, a basic lidar system consists of a laser transmitter and an optical receiver (Figure 7).

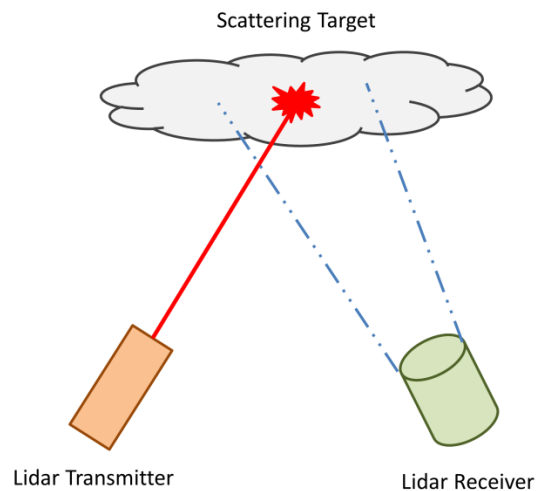


Figure 7: Basic elements of a lidar system include a transmitter, typically a pulsed laser source, and a lidar receiver which is typically a telescope with its field of view aimed at the atmospheric volume of interest being probed by the laser light.

Laser light is emitted from the laser transmitter. Upon interaction with a target such as the ground or aerosol particles, some of the laser light is scattered by the target. A portion of this scattered light is captured and analyzed by an optical receiver. Analyzing the backscattered light's properties allows the user to quantify characteristics of either the target or the target's environment. Lidar has the advantage over passive remote sensing techniques, in that by measuring the time between the emission of radiation and the

detection of the backscattered radiation, the distance to the scattering target can be calculated knowing the speed of light. This allows information to be gathered not only about the properties of the target, but also the location of the target. This is advantageous particularly for remote gas concentration measurements like those made by the DIAL and IPDA systems discussed in this thesis, because information about the range to the scattering target is necessary for accurate quantification of gas concentrations. In general, the theoretical number of backscattered photons captured by an optical receiver can be calculated by using the lidar equation⁴².

$$N(\lambda, r) = N_0(\lambda) \frac{A}{r^2} \Delta r \beta(\lambda, r) T_A^2(\lambda, r) \varepsilon_0(r) \varepsilon_R(\lambda) \varepsilon_D(\lambda) \quad (1)$$

where $N_0(\lambda)$ is the number of photons in the outgoing laser pulse, A is the area of the receiver, $\Delta r = \frac{\tau c}{2}$ is the range bin size, τ is the pulse duration, c is the speed of light, $\beta(\lambda, r)$ is the backscatter coefficient, $T_A^2(\lambda, r)$ is the round trip atmospheric transmission, $\varepsilon_0(r)$ is the geometric overlap function, $\varepsilon_R(\lambda)$ is the receiver optics transmission, and $\varepsilon_D(\lambda)$ is the detector efficiency.

Differential Absorption Lidar

The round trip atmospheric transmission can be written⁴²

$$T_A^2(\lambda, r) = e^{-2 \int_0^{r_f} \kappa(\lambda, r') dr'} e^{-2 \int_0^{r_f} \sigma(\lambda, r') N_d(r') dr'} \quad (2)$$

where $\kappa(\lambda, r)$ is the atmospheric extinction coefficient, $\sigma(\lambda, r)$ is the molecular absorption cross-section, r_f is the distance to the pulse in the atmosphere, and $N_d(r)$ is the number density of molecules. Inspection of the lidar equation reveals that the magnitude of the backscattered radiation is affected by parameters that can be separated in to two

types: instrumental and environmental. Instrumental parameters such as the area of the optical receiver or the laser transmitter pulse energy are independent from environmental conditions. Environmental parameters such as round trip atmospheric transmission efficiency and backscatter probability are dependent on the conditions or the environment at a given range. This dependence allows for one to measure environmental parameters of interest based on careful inspection of the backscattered signal intensity if the instrument parameters are well understood and characterized. Thorough characterization of all instrument parameters used to calibrate the lidar instrument is not trivial, and measurements of environmental parameters of interest can be highly sensitive to errors in the instrument calibration⁴³. If one is interested in certain environmental parameters such as a trace gas concentration, a technique known as Differential Absorption Lidar (DIAL) is well suited to this task as it is fairly insensitive to instrument parameters. This thesis focuses mainly on DIAL, but, a portion of this thesis will also discuss work done at NASA Langley Research Center on an Integrated Path Differential Absorption Lidar (IPDA), which is a variation on the DIAL measurement technique.

DIAL is essentially two lidar measurements of the same volume of air but at different laser wavelengths. When two different wavelengths are used, the round trip transmission is different for each wavelength, since the physical processes underlying the round trip transmission including (Rayleigh scattering, Mie Scattering, Molecular Absorption)⁴⁴ are all wavelength dependent. If the difference in wavelength is sufficiently small, on the order of nanometers, for the two lidar measurements the change in attenuation of the lidar pulse due to Rayleigh and Mie scattering embodied in the

atmospheric extinction coefficient, is negligibly small. In contrast, the change in attenuation due to molecular absorption can still be significant depending on the choice in the two wavelengths used. Typically, one lidar measurement is made with a wavelength, commonly referred to as the online wavelength, near or at the center of a molecular absorption feature. The second lidar measurement is made with a wavelength, commonly referred to the offline wavelength, far in the wing of a molecular absorption feature. Direct comparison of the measured backscattered intensity between the offline and online wavelength measurements shows a difference in attenuation that can be uniquely attributed to molecular absorption of a trace gas of interest. Referring to equation 2, we see that this attenuation depends on the number of absorbing molecules per volume in the atmospheric volume and on the absorption cross section of those molecules. The more molecules interact with the lidar pulse and the larger their absorption cross section, the greater the observed attenuation of the online backscattered intensity in comparison to the offline wavelength.

Number Density Calculations for the IPDA and DIAL

For the integrated path differential absorption measurement described in chapter 5, one can calculate the average number of absorbing molecules per cubic centimeter between the transmitter and the scattering target at range r that cause this difference in attenuation by first taking the natural log of the backscattered number of photons collected at the online and offline wavelengths⁴²

$$\ln N(\lambda_{online}, r) = \ln \left\{ C N_0(\lambda_{online}) e^{-2 \int_0^T \kappa(\lambda_{online}, r') dr'} e^{-2 \int_0^T \sigma(\lambda_{online}, r') N_d(r') dr'} \right\} \quad (3)$$

$$\ln N(\lambda_{online}, r) = -2 \int_0^r \kappa(\lambda_{online}, r') dr' - 2 \int_0^r \sigma(\lambda_{online}, r') N_d(r') dr' + \ln CN_0(\lambda_{online}) \quad (4)$$

If we assume that the atmospheric extinction coefficient, molecular number density, and absorption cross section are all constant from 0 to r , then equations 3 and 4 can be written as

$$\ln N(\lambda_{online}, r) = -2\kappa(\lambda_{online})r - 2\sigma(\lambda_{online})N_d r + \ln CN_0(\lambda_{online}) \quad (5)$$

$$\ln N(\lambda_{offline}, r) = -2\kappa(\lambda_{offline})r - 2\sigma(\lambda_{offline})N_d r + \ln CN_0(\lambda_{offline}) \quad (6)$$

For the many DIAL and IPDA systems such as those described in this thesis the atmospheric extinction coefficient for the offline and online wavelengths is nearly identical due to the small difference in online and offline wavelengths. With this in mind, taking the difference of the online and offline round trip transmission gives

$$\ln N(\lambda_{online}, r) - \ln N(\lambda_{offline}, r) = 2 \left(\sigma(\lambda_{offline}) - \sigma(\lambda_{online}) \right) N_d r + \ln CN_0(\lambda_{offline}) - \ln CN_0(\lambda_{online}) \quad (7)$$

which can be solved for N_d , the number density of absorbing molecules

$$N_d = \frac{\ln \left(\frac{N(\lambda_{offline}, r)}{N_0(\lambda_{offline})} \bigg/ \frac{N(\lambda_{online}, r)}{N_0(\lambda_{online})} \right)}{2\Delta\sigma r} \quad (8)$$

For IPDA measurements, the N_0 is measured before the lidar pulse leaves the transmitter, and typically the target at range r is either the ground for airborne measurements, clouds for vertical measurements, or a variety of possible hard targets available for horizontal measurements (trees, buildings, etc.) This line of sight average concentration contains

useful information, but, it is limited in two ways. First, it requires accurate measurement of the transmitted pulse energy N_0 . Second, it provides no information about the spatial variability of the CO_2 along the line of sight of the lidar. The DIAL technique bypasses the first limitation by using the backscattered intensity at a range r_0 , which is closer to the lidar transceiver than r_f , as a reference for the attenuation observed at r_f (Figure 8).

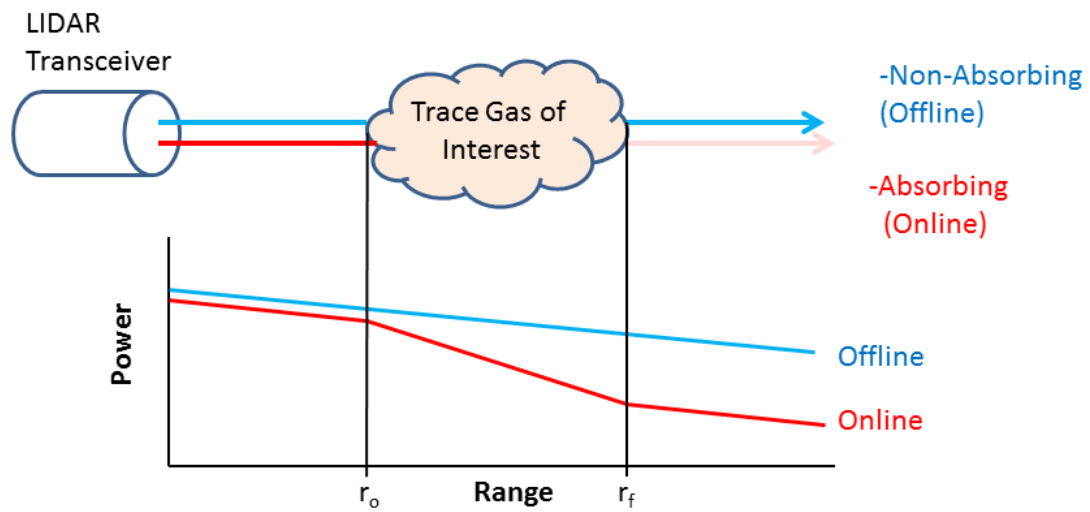


Figure 8: The DIAL measurement is effectively a column integrated average concentration measurement like IPDA, except that instead of using the transmitted pulse energy as the reference for the round trip attenuation for the light scattered from r_f , the signal scattered from the range r_0 is used instead. This enables an average concentration measurement between ranges r_0 and r_f without measurement of the transmitted pulse energy.

Effectively, a column averaged measurement between r_0 and r is being performed with the backscattered signal measured at r_0 filling the role of N_0 . With these changes, the

average concentration of the molecule of interest between ranges r_o and r_f is

$$\langle N_d \left(\frac{r_f - r_o}{2} \right) \rangle = \frac{\ln \left(\frac{\frac{N(\lambda_{offline}, r_f)}{N(\lambda_{offline}, r_o)}}{\frac{N(\lambda_{online}, r_f)}{N(\lambda_{online}, r_o)}} \right)}{2\Delta\sigma(r_f - r_o)} \quad (9)$$

Absorption Band Selection

In order to quantify the number of absorbing molecules interacting with the lidar pulse that causes the increased attenuation, the value of the absorption cross section at the online and offline wavelengths must be known. It is at this point that a decision must be made about which online and offline wavelengths to use. Several criteria must be met by the wavelengths for the DIAL instrument to be able to make a gas concentration measurement with reasonable accuracy and precision⁴⁵. The online and offline wavelengths' absorption cross sections must not vary more than a few percent with reasonable changes in atmospheric conditions and the online absorption must be sufficiently strong to identify a difference in signal attenuation while not being so strong that all of the lidar pulse light is absorbed before reaching the desired measurement range. It is also desirable that there be a minimum of interference from absorption due to other molecules such as water vapor⁴⁶⁻⁴⁸. In addition, all of the photonics components need to be commercially available at the online and offline wavelengths to make the measurement. For the DIAL discussed in this thesis which has been developed for monitoring carbon dioxide, the absorption band near 1.57 μm was chosen for its combination of reasonable absorption strength, and maturity and commercial availability

of photonics components developed by the telecommunications industry. On the other hand, the IPDA measurements at NASA Langley were made in the 2 micron absorption band which have larger cross sections, but require custom lasers. Using the Hitran 2008 database⁴⁹, a plot of the atmospheric transmission as a function of wavelength is shown in Figure 9.

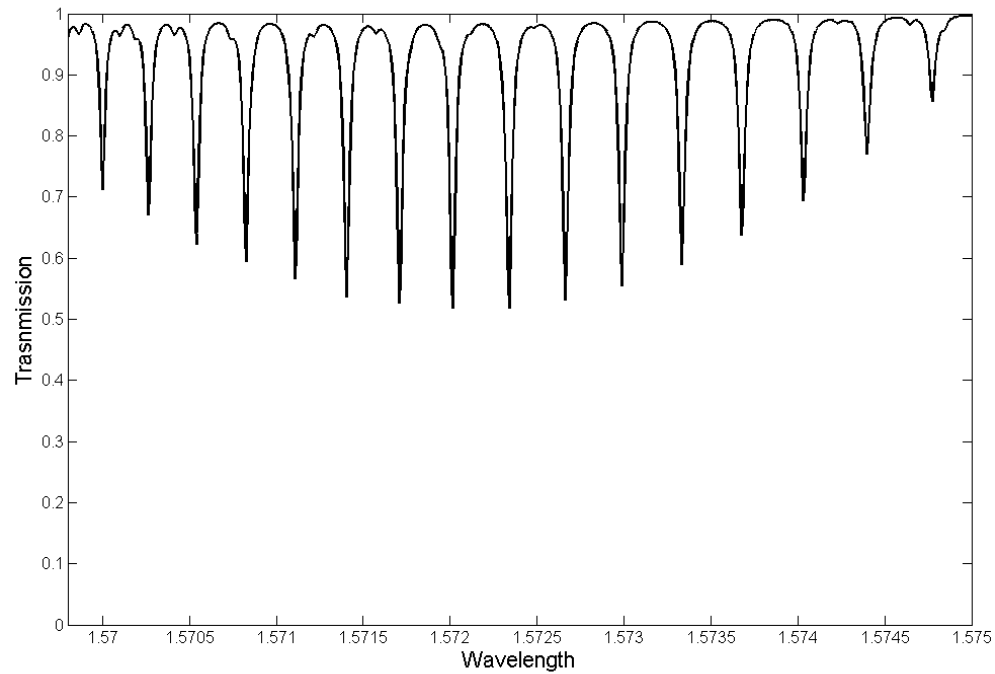


Figure 9: Plot of the total atmospheric transmission as a function of wavelength for a path length of 10 km at 296 K, atmospheric pressure of 1 atm, and a CO₂ concentration of 390 ppm. The spectrum is dominated by CO₂ absorption but also includes H₂O absorption lines.

Absorption Line Selection Criteria

After the decision was made to focus on the 1.57 micron absorption band for the DIAL measurements, selection of the final absorption line to be used was based on the interest of minimizing the absorption sensitivity of the online and offline wavelengths to

varying ambient conditions, while maximizing the round trip absorption. To determine which absorption feature within the 1.5 micron band to choose, it is necessary to examine how the round trip absorption is affected by changes in ambient conditions. Changes in pressure, temperature, and relative humidity are the strongest sources of round trip absorption variation for a given ambient CO₂ number density. Variations in pressure and temperature directly affect the magnitude of the absorption cross section used to calculate the CO₂ number density, and for that reason accurate knowledge of the magnitude of the absorption cross section at a given pressure and temperature is necessary for accurate DIAL measurements to be made.

Absorption Cross Section Temperature Dependence

The absorption cross section can be calculated with knowledge of the linestrength at the operating temperature T . For the DIAL measurements, a Voight Function, which is a convolution of the Gaussian and Lorentzian lineshapes that result from temperature and pressure broadening respectively, was used. With this absorption lineshape functional form, the absorption cross section is⁴⁶

$$\sigma = S(T) \frac{\ln(2)}{\pi^{3/2}} \frac{\gamma_L}{\gamma_D^2} \int_{-\infty}^{\infty} \frac{e^{-t^2}}{\left(\frac{\gamma_L}{\gamma_D}\right)^2 \ln 2 + \left[\frac{\nu - \nu_0}{\gamma_D} (\ln 2)^{1/2} - t\right]^2} dt \quad (10)$$

where ν is the wavenumber at which the cross section is being calculated. The pressure broadened linewidth at temperature T and pressure P is $\gamma_L = \gamma_0 \left(\frac{P}{P_0}\right) \left(\frac{T_0}{T}\right)^\alpha$ where γ_0 is the Lorentz linewidth at temperature T_0 and pressure P_0 , and α the linewidth temperature dependence parameter. The Doppler broadened linewidth (HWHM) is $\gamma_D =$

$\left(\frac{\nu_0}{c}\right)\left(\frac{2kT\ln 2}{m'}\right)^{1/2}$ where m' is the mass of the molecule. The integral represents the convolution of the Gaussian and Lorentzian lineshapes. For this DIAL system, the Lorentz linewidth was retrieved from the HITRAN 2008 Database⁴⁹. Since the DIAL system makes all of its measurements horizontally, there is no variation in absorption cross section due to changes in pressure along the lidar's line of propagation. The linestrength $S(T)$ is calculated with⁴⁶

$$S(T) = S_0 \left(\frac{T_0}{T}\right) \left[\frac{1 - \exp(-hcv_0/kT)}{1 - \exp(-hcv_0/kT_0)} \right] \exp \left[\frac{hc}{k} \left(\frac{1}{T_0} - \frac{1}{T} \right) E'' \right] \quad (11)$$

where S_0 is the linestrength at temperature T_0 , T is the temperature at which the line strength is being calculated, h is Planck's constant, ν_0 is the wavenumber associated with the absorption line center, k is Boltzmann's constant, and E'' is the energy above the ground state of the lower energy level associated with the absorption.

Temperature Sensitivity Considerations

Care was taken in selection of the specific online and offline wavelengths to be used to minimize the sensitivity of the number density measurement to the atmospheric temperature that results from temperature dependence of the absorption cross section. Minimization of temperature sensitivity is advantageous for monitoring instruments such as the DIAL that in principle will make measurements in a variety of climates and seasons and thus a large range in ambient temperatures. To minimize sensitivity, temperature sensitivity of the absorption cross section was calculated as⁴⁶

$$\frac{1}{\sigma} \frac{d\sigma}{dT} \approx \frac{1}{T - T'} \frac{\sigma(T) - \sigma(T')}{\left(\frac{\sigma(T) + \sigma(T')}{2} \right)} \quad (12)$$

A plot of the sensitivity as a function of temperature is shown in Figure 10 based on the parameters listed in Table 1.

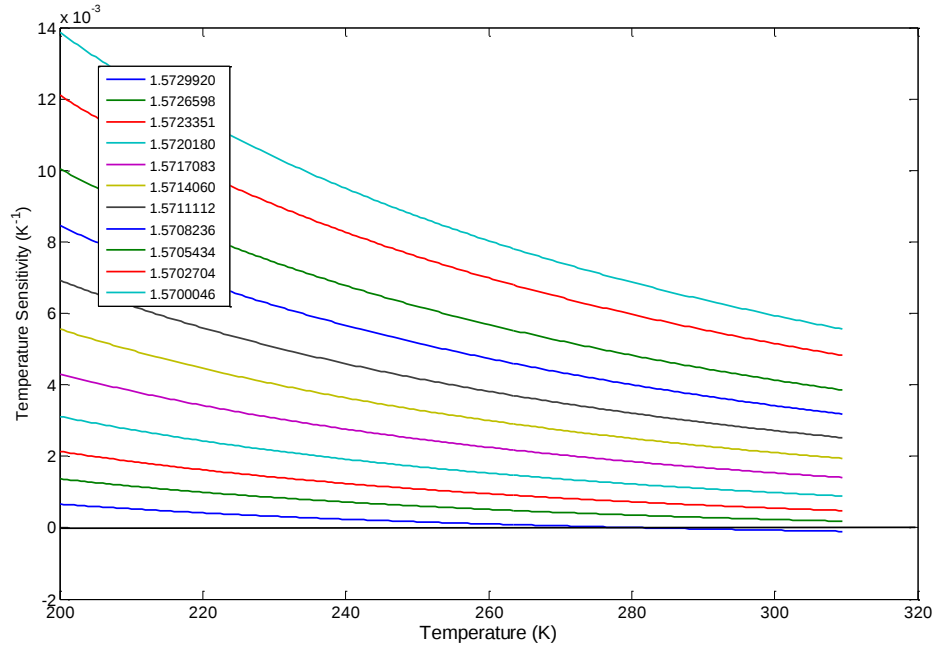


Figure 10: Plot of the temperature sensitivity of absorption lines in the absorption band of interest.

As can be seen on Figure 10, the absorption feature centered at 1.5708236 microns (lowest blue curve) is the least temperature sensitive around room temperature. The 11 absorption line parameters for the lines plotted in Figure 4 as well as the water vapor lines within this range are tabulated in Table 1. The line chosen was 1.5714060 μm as shown in blue in Table 1. This line was chosen because it is one of the strongest absorption lines in the band and it does not have any overlapping water vapor absorption features, as will be discussed in coming sections.

Molecule	Line Center μm	Line Center cm^{-1}	Line strength $\times 10^{-23} \text{ cm}^{-1}$ mol^{-1}	Lorentzian Linewidth (HWHM) cm^{-1}	Ground State Energy cm^{-1}	a
CO ₂	1.5729920	6357.312	1.6600	0.0780	60.870	0.70
H ₂ O	1.5728510	6357.881	0.0034	0.0750	610.340	0.58
CO ₂	1.5726598	6358.654	1.7300	0.0760	81.940	0.69
CO ₂	1.5723351	6359.967	1.7400	0.0749	106.120	0.67
CO ₂	1.5720180	6361.250	1.7100	0.0730	133.439	0.67
H ₂ O	1.5718192	6362.055	0.0026	0.0177	1327.110	0.06
CO ₂	1.5717083	6362.504	1.6200	0.0729	163.868	0.69
H ₂ O	1.5715257	6363.243	0.0065	0.0625	1813.223	0.41
CO ₂	1.5714060	6363.728	1.5100	0.0720	197.416	0.70
CO ₂	1.5711112	6364.922	1.3700	0.0710	234.083	0.71
CO ₂	1.5708236	6366.087	1.2200	0.0701	273.868	0.73
H ₂ O	1.5706108	6366.950	0.0037	0.0770	1122.709	0.53
CO ₂	1.5705434	6367.223	1.0600	0.0700	316.770	0.74
H ₂ O	1.5702740	6368.315	0.0042	0.0840	982.900	0.56
CO ₂	1.5702704	6368.330	0.9030	0.0900	362.788	0.82
CO ₂	1.5700046	6369.408	0.7550	0.0880	411.923	0.82

Table 1: Parameters for selected CO₂ and H₂O absorption features near 1.57 μm from the HITRAN 2008 database⁴⁹. These parameters were tabulated for a temperature of 296 K and an atmospheric pressure of 1 atm. The chosen absorption feature used for the CO₂ DIAL is highlighted in blue.

Dry Air Mixing Ratio Calculation

For a given DIAL measurement, the number density calculated from equation 9 is not as commonly used when discussing atmospheric carbon dioxide concentrations. Instead, typically concentrations are quoted in parts per million by volume. In order to convert the number density to parts per million, a calculation is made to estimate the total number of molecules present at the ambient pressure and temperature in a cubic centimeter of air using

$$PPM = 10^6 \left(\frac{N_d}{N_L} \right) \left(\frac{T}{273} \right) \left(\frac{101.33}{P} \right) \quad (13)$$

where N_d is the measured number density of CO_2 , $N_L = 2.687 \times 10^{19} \text{ mol/cm}^3$ is Loschmidt's number which represents the number of air molecules in a cm^3 at $T=296\text{K}$ and $P=101.33 \text{ kPa}$, T is the ambient temperature in K, and P is the ambient pressure in kPa. It should be noted that this is for air, not dry air, which is a quantity typically of greater interest to those involved in atmospheric science. In order to calculate the parts per million of CO_2 by volume of all molecules in that volume excluding water vapor to yield the dry air mixing ratio, equation 13 must be modified to subtract out the number of water vapor molecules present in the volume giving

$$PPM = 10^6 \left(\frac{N_d}{N_L} \right) \left(\frac{T}{273} \right) \left(\frac{101.33}{P} \right) \left(\frac{1}{1 - RHP(T)/P} \right) \quad (14)$$

Where RH is the relative humidity, $P(T)$ is the saturation pressure as a function of temperature for water vapor, and P is the ambient pressure. This correction was only applied to the IPDA measurements, whereas the DIAL measurements described in chapter 4 used equation 13 for the air mixing ratio. For the DIAL measurements, this correction was not applied first because the in situ sensor used for making comparisons with the DIAL measurements made its CO_2 measurements for air, not dry air. Secondly, the precision requirements for sequestration site monitoring are not as strict as those for the atmospheric monitoring purpose of the IPDA, so the small correction factor was not a requirement for the DIAL measurement application.

Water Vapor Interference Correction

For the DIAL system, the least temperature sensitive absorption line is flanked by water vapor absorption lines. This is not desirable because any absorption due to water vapor (or any interfering gas in general) biases the measured number densities away from the true value depending on the location of the interfering absorption line. This manifests itself as different rates of attenuation of the online and offline lidar signals due to additional attenuation occurring from water vapor optical absorption. While the bias for this absorption band is small (on the order of a few ppm) due to the weak water vapor absorption lines, in the interest of minimizing any interference from water vapor absorption, a line centered at $1.5714060\ \mu\text{m}$ was chosen to minimize water vapor interference.

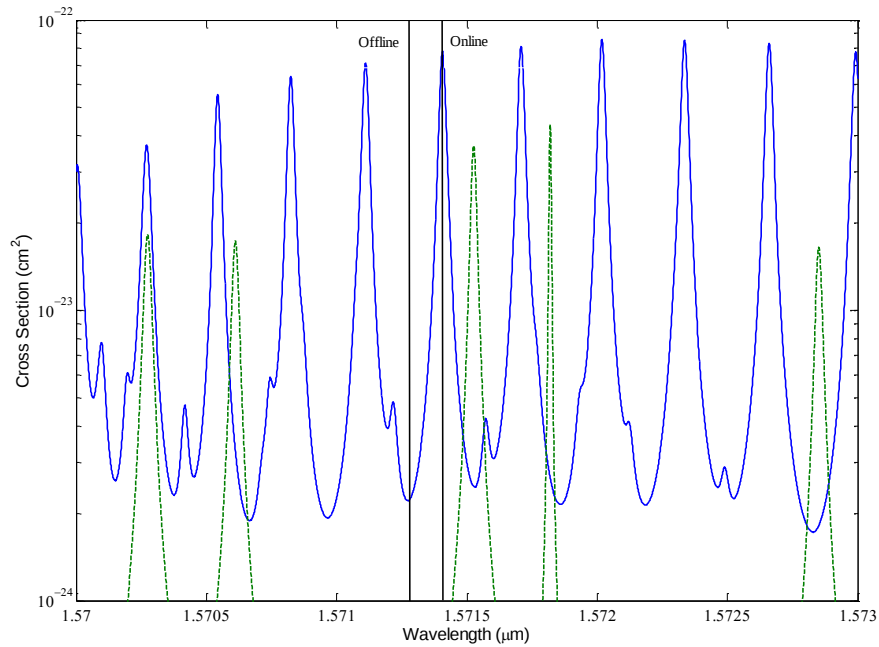


Figure 11: Plot of the cross section of CO_2 (blue) and water vapor (green) as a function of wavelength at 296 K and 0.85 atm

For the DIAL measurement, interference from the water vapor amounted to less than 1 ppm error on the measured CO₂ concentration. However, for the higher precision IPDA measurements discussed in chapter 5, interference from water vapor is accounted for by a correction factor applied to equation 8 which changes N_d to be calculated as

$$N_d = \frac{\ln \left(\frac{N(\lambda_{offline}, r)}{N_0(\lambda_{offline})} \bigg/ \frac{N(\lambda_{online}, r)}{N_0(\lambda_{online})} \right)}{2\Delta\sigma r} - N_{d,H_2O} \frac{\Delta\sigma_{H_2O}}{\Delta\sigma_{CO_2}} \quad (15)$$

where $\Delta\sigma_{H_2O} = \sigma_{on,H_2O} - \sigma_{off,H_2O}$ is the difference in absorption cross sections for water vapor at the online and offline wavelengths and N_{d,H_2O} is the average water vapor number density between r_i and r_0 .

Weighting Function for Vertical IPDA Measurements

In addition to the correction factor applied to the IPDA CO₂ number density calculations for water vapor interference, an additional correction factor must be applied to equation 15 for accurate CO₂ number density measurements. This correction factor must be applied to the IPDA measurement when the beam is oriented vertically. The correction factor is based on the fact that the CO₂ absorption linewidth is a function of pressure. For the IPDA measurement, the online wavelength is positioned not on line center, but, instead is positioned on the side of the absorption line. The primary reason for positioning the online wavelength at the side of the absorption line is that the attenuation is so strong at line center for the absorption line chosen that for typical round trip path lengths on the order of km's, the beam would be attenuated below measurable

levels. As a result of this side line tuning of the online wavelength, as the pulse propagates through different layers of the atmosphere that are all at different pressures, the CO₂ absorption varies with the different altitudes. This causes more of the round trip absorption to occur at lower altitudes near the surface where the pressure is high, and less absorption to occur along the section of the beam path located at lower pressure high altitudes. To correct for this varying absorption due to changes in pressure, a weighting function is employed that accounts for the varying attenuation encountered at different altitudes to give a vertically weighted column average mixing ratio⁵⁰

$$\overline{N_d} = \frac{\int_{p_{TA}}^{p_{surf}} N_{d,Dry\ Air\ CO_2}(p) w(p,T) dp}{\int_{p_{TA}}^{p_{surf}} w(p,T) dp} \quad (16)$$

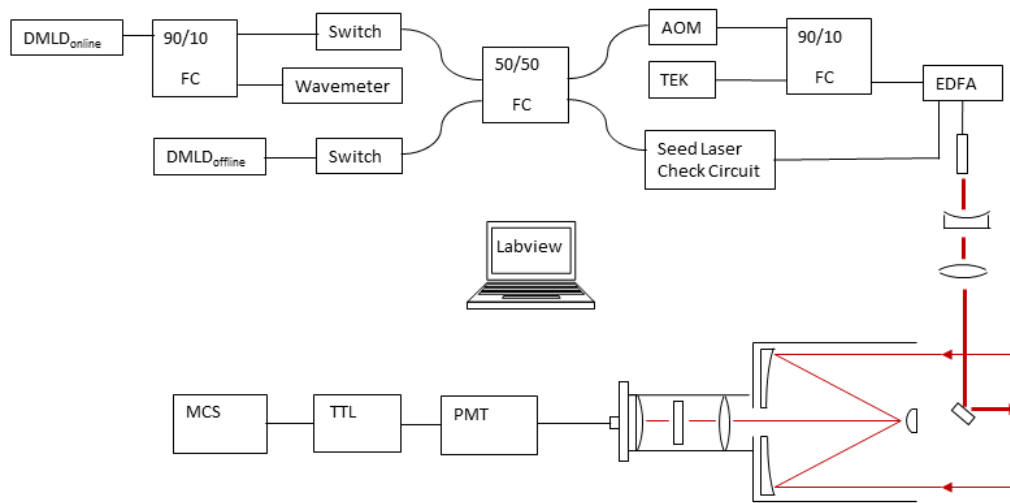
where the weighting function $w(p,T)$ is

$$w(p,T) = \frac{\sigma_{on}(p,T) - \sigma_{off}(p,T)}{gM_{air}} \quad (17)$$

which uses the now pressure dependent absorption cross sections for the online and offline wavelength, the M_{air} is the average mass of a dry air molecule.

SYSTEM DESIGN AND CONSTRUCTION

The DIAL system like all laser radar systems consists of a transmitter and a receiver. The laser transmitter is based on an injection seeding erbium doped fiber amplifier (EDFA) with an optical pulse train.



ACRONYM KEY

DMLD = Discrete Mode Laser Diode
 FC = Fiber Coupler
 AOM = Acousto-Optic Modulator
 EDFA = Erbium Doped Fiber Amplifier

TEK = Tektronics Source
 PMT = PhotoMultiplier Tube
 MCS = MultiChannel Scaler

Figure 12: Schematic of the DIAL system components.

The seeding begins with two tunable fiber pigtailed diode laser modules (Figure 13). The modules contain the laser diodes as well as a thermoelectric cooler (TEC) for temperature control of the laser diode and a built in optical isolator for protection against optical feedback.



Figure 13: Seed laser diode module from Eblana Photonics (Part NO: EP1571-DM-BAA) consisting of a fiber pigtailed laser diode mounted internally on a thermo-electric cooler.

The laser modules are fiber pigtailed with polarization maintaining fiber and each laser module is mounted into a laser diode mount from ILX lightwave (ILX LDM-4980). The laser mounts themselves have a built in TEC for setting the temperature of the baseplate on which the lasers are mounted. The laser diode mount TEC's are useful for setting the baseplate temperature near the laser diode temperature so that the smaller internal laser diode module TEC's do not require as much drive current to maintain the lasers at a given temperature. Each baseplate TEC is controlled with a Wavelength Electronics temperature controller (WTC3253, Figure 14).

During normal operation, the online laser is set to an operating temperature of 48.14 degrees Celsius, and the offline laser is set to 54.57 degrees Celsius. The laser diode TEC's for both lasers are controlled by an ILX Lightwave 3742B laser diode driver. These laser diode drivers set and hold the laser diode temperature with a proportional, integral, derivative (PID) loop control. For normal laser operation, the diode mount temperature was set to minimize the drive current through the laser diode TECs. This was done to improve the temperature stability of the laser diodes, and was set by adjusting the laser diode mount temperature set point while monitoring the laser

diode TEC drive current until the drive current reached a minimum value. Once the operating temperatures were set for stable single mode laser operation, the temperatures were not adjusted.

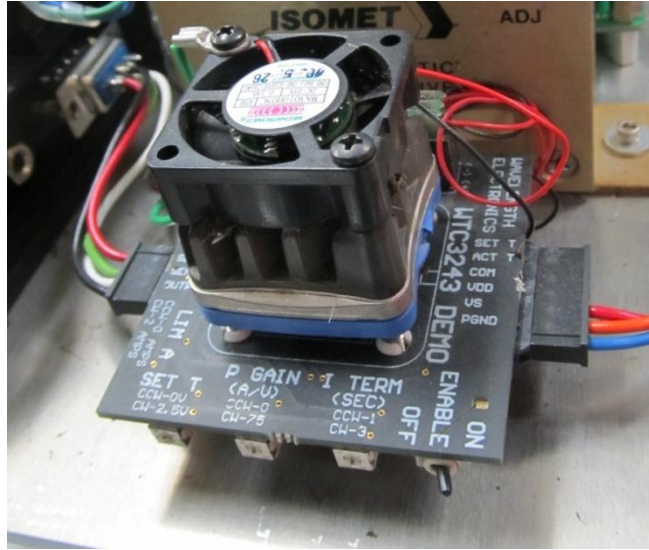


Figure 14: Wavelength Electronics TEC controllers that control the baseplate TEC's built in to the laser diode mounts that house the seed lasers.

Of the two seed lasers, one laser diode is set at the offline wavelength and one laser is set at the online wavelength by adjusting their drive currents and operating temperatures. The lasers have a factory specified linewidth of approximately 2 MHz. For validation, measurements were made of the seed laser effective linewidth using a self-heterodyne linewidth measurement as described in chapter 4. With this measurement the online laser had a measured linewidth (full width half maximum) of 10 MHz, and the offline laser had a measured linewidth of 150 MHz. The discrepancy between the measured linewidth and the factory specified linewidth was attributed to the fast frequency jitter in the carrier frequency (See Chapter 4).

Switching between the offline and online wavelengths every two seconds was accomplished with a combination of two computer controllable fiber optic signal switches (Agiltron LB 1x1, LBSW-115171323, Figure 15) and a 50/50 fiber coupler.

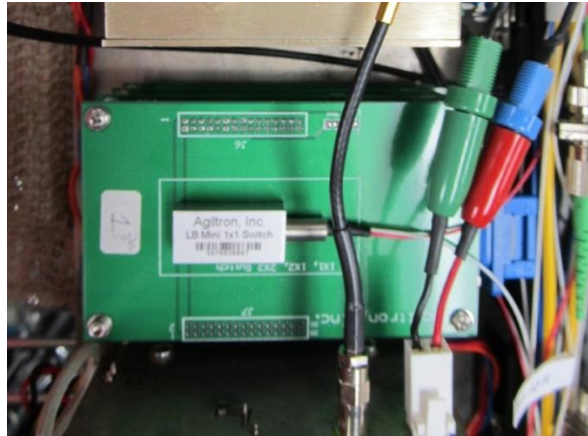


Figure 15: Photo of Agiltron Lightbend 1x1 switches used for controlling which seed laser seeded the transmitter optical train.

Switching was done with two 1x1 signal switches as opposed to using a 2x1 switch because 2x1 switches have a dead time at their output as they switch from one input to the other (Figures 16 and 17). This is not desirable for the fiber amplifier, as the dead time for low loss mechanical switches, on the order of several milliseconds, is too long for the amplifier to operate without a seeding signal, as will be discussed in greater detail in the amplifier section. With two independent switches acting as simple on off switches, the second laser switch can be enabled and given enough time to produce an output before the first switch is disabled (Figures 16 and 17).

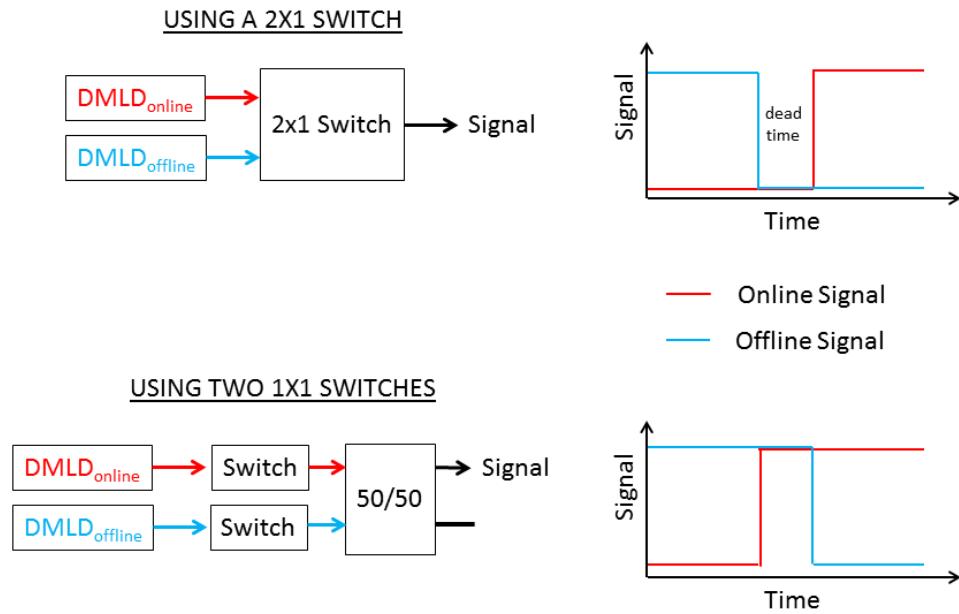


Figure 16: Comparison of using two 1x1 switches vs. a 2x1 switch. A 2x1 switch has an unacceptable dead time when switching between one input and the other that would be detrimental to the EDFA performance.

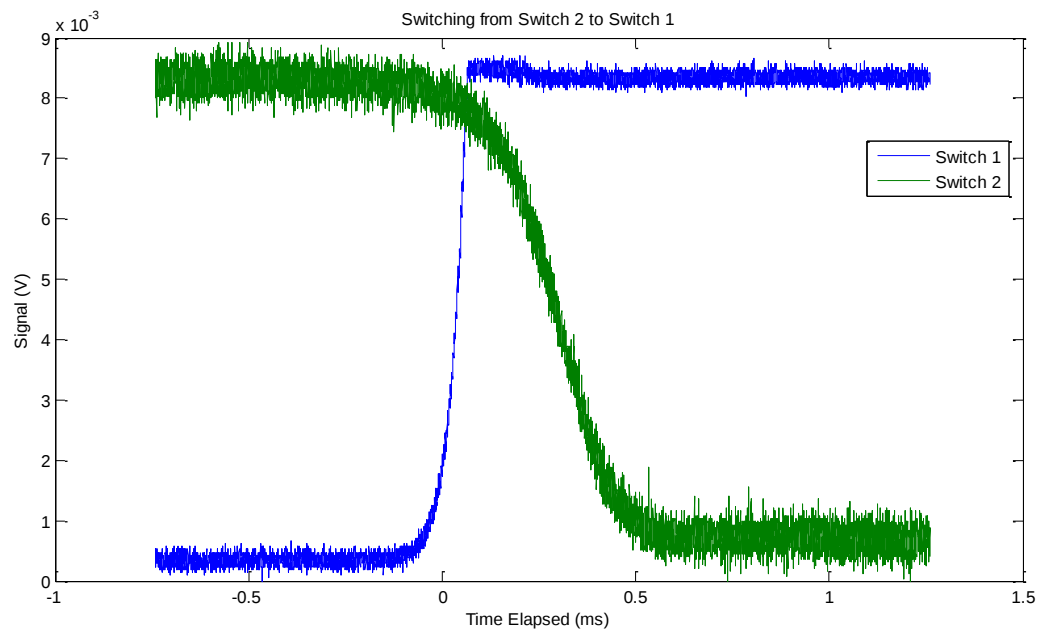


Figure 17: Screen shot of the switching scheme used by the DIAL with two 1x1 switches. By turning the second switch on before turning the first switch off the EDFA is continuously seeded.

In this way, the amplifier always has a seed signal to maintain stable operation of the amplifier. As is depicted in Figure 6, for 0.5 ms the amplifier is being seeded with two wavelengths. The lidar data produced during this brief window of time is useless for DIAL measurements since both wavelengths are present in the backscattered signal. A signal switch is employed that will be discussed further in a later section is used to discard any data collected during this time period of dual wavelength operation. After the fiber optic switches, a 50/50 fiber coupler (Thorlabs 10202A-50-APC) is employed to provide an optical path for either diode laser to seed the amplifier. The other end of the 50/50 coupler that is not directed towards the AOM and EDFA is connected to a seed laser check circuit (Figures 18 and 19)

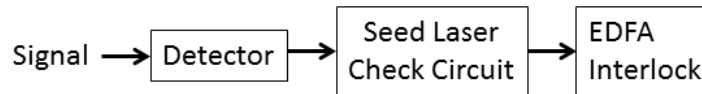


Figure 18: Block diagram of the seed laser check circuit.

One output of the 50/50 fiber coupler is connected to a Thorlabs D400FC optical detector. The analog output of this detector is monitored by a custom made seed laser check circuit. This circuit is connected to the interlock of the EDFA, and if no optical signal is present which represents the seed signal not going into the EDFA, the seed laser check circuit disables emission of the EDFA by opening the interlock with a relay. This protects the EDFA from operating without a seed laser, which can potentially damage the EDFA.

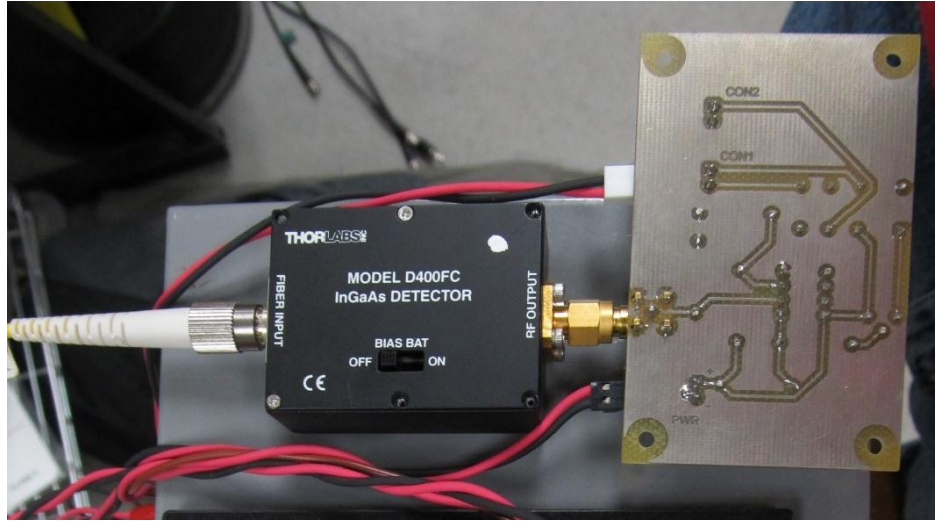


Figure 19: Photo of the seed laser check circuit attached to the optical detector.

This circuit monitors for a loss of seed signal and trips the interlock on the EDFA in the event a seed laser signal is lost. This protective feature guards against the EDFA operating without a seed signal which is highly undesirable. The seed lasers are run CW for frequency stability, but, the lidar itself requires a pulsed light source. To generate a train of optical pulses, a fiber pigtailed acousto-optic modulator (AOM) made by Brimrose (AMM-100-20-25-1573-2FP, Figure 20) is used to convert the CW signal in to a pulse train.

When power is not applied to the AOM, no optical signal leaves the output fiber. To transmit the input optical signal to the output fiber, an RF electrical driving signal is applied to the electrical connection of the AOM module. This signal modulates an acoustic transducer on the side of a section of glass that the light is propagating through. The acoustic wave forms a grating that the incident light beam scatters from, and the first order scattered beam is coupled in to the fiber optic output.



Figure 20: Brimrose AOM used to generate the seeding pulse train for the EDFA.

The AOM operates effectively as a fast on/off switch, which chops the CW input signal from the seed lasers in to an optical pulse train. The AOM also introduces a small 100 MHz frequency offset in the laser signal, which is accounted for in the wavelength locking. For the DIAL the AOM is modulated on and off with an AOM driver made by Isomet connected to a pulse train generator (Stanford Research Systems DG645, Figure 21). The pulse train generator is easily configured through its user interface for arbitrary pulse durations and repetition rates, allowing the user a high level of control over the lidar pulse characteristics.



Figure 21: Pulse train generator used for setting the pulse repetition rate and pulse duration control signal for the AOM.

The trigger output from the pulse train generator also synchronizes the AMCS USB data acquisition unit to the lidar pulses. For normal operation, the pulse duration is set to 200 ns which is the minimum pulse duration the AOM can generate, and the pulse repetition rate is set to 15 kHz. 15 kHz was found to be the best compromise between higher repetition rates where the rate was so high that the signals from previous pulses were still present when the next laser shot was fired and lower rates where SBS became a concern (See Chapter 4). During normal operation, the seed lasers will slowly drift in operating wavelength 10's of pm over the course of several hours. To correct for small drifts, as well as to repeatedly set the online laser's operating wavelength at the center of the absorption line being used for the DIAL, a 90/10 fiber coupler is used just after the online laser's output to sample a small fraction of the online laser light with a wavemeter (Burleigh WA-1500, later replaced by a Bristol 621, Figure 22).

During data collection periods, the wavelength measured with the wavemeter is read by the controlling PC via a GPIB connection. If the wavelength is measured to be outside a user specified tolerance, typically 0.5 pm (the wavemeter's precision), the diode current for the online laser is adjusted until the laser is back within the tolerance window. The WA-1500 wavemeter can measure an absolute laser wavelength with a precision of 36.4 MHz. During typical data collection periods, the offline laser wavelength is set with the wavemeter before the data collection period, and then is not monitored again during data collection since its exact wavelength is not as critical to the DIAL measurement as the online laser's wavelength is.



Figure 22: Burleigh WA-1500 (Left) and Bristol 621 (Right) wavemeters used for online laser locking. The Bristol 621 replaced the WA-1500 for the Kevin Dome measurements described in chapter 4.

EDFA

The laser pulse train at the output of the AOM first passes through a 90/10 fiber coupler, which has its other input connected to a Tektronics tunable diode laser source (LPB 1100, Figure 23).



Figure 23: Tektronics source used to maintain EDFA operation with pulsed seed laser signal.

The Tektronics source is set to emit 1 mW of fiber coupled laser light at 1560 nm. The reason for having this source in the fiber optic train is that the EDFA has a built in input power monitoring circuit designed to disable amplifier emission in the absence of a seed laser signal of sufficient intensity. The EDFA used is a CW amplifier, and it expects to see a CW seed laser signal. For the DIAL however, the pulses injected in to the amplifier are not long enough in duration to register a signal on the EDFA's built in power monitor. To seed with our signal and bypass the built in power monitoring, the Tektronics source is used deceive the EDFA's input power monitoring circuitry, but, since the 1560 nm light is 10 nm outside the amplifier's optical gain bandwidth, the 1560 nm light does not get amplified to contaminate the EDFA output spectrum.

As stated previously, the EDFA is a commercial CW fiber amplifier designed for telecommunications applications (IPG Photonics EAR-K-L, Figure 24). The amplifier is

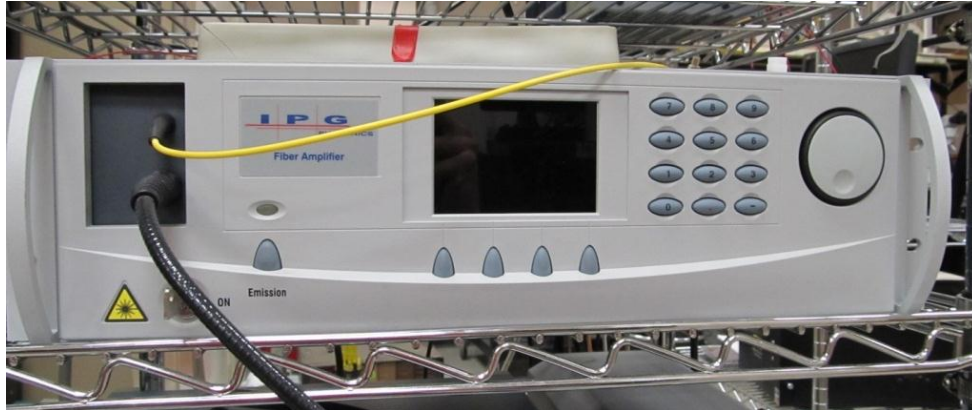


Figure 24: IPG Photonics EAR-5K-L Erbium doped fiber amplifier used for the DIAL.

capable of operating in either a constant power or constant gain mode. In constant power mode, the gain of the amplifier is adjusted automatically to maintain a fixed power output. In constant gain mode, the pump diode current in the amplifier remains fixed, and the output power is neither monitored nor adjusted. For the DIAL, the amplifier is being operated in constant gain mode. When the input is a pulse train instead of a CW input, the amplifier was found to operate erratically in constant power mode, as the output power monitor within the amplifier does not accurately measure the pulsed output power and as a result tended to dramatically overshoot the desired output power risking damage to the amplifier. In constant gain mode, the pump diode current was adjusted to typically 1.50 Amps to reach the desired average output power.

Beam Expander/Eye Safety

Under normal operation, the laser transmitter output parameters are listed in Table 2.

Pulse Duration	200	ns
Pulse Energy	65	μJ
Repetition Rate	15	kHz
Wavelength (online/offline)	1.5714069/ 1.5712585	μm

Table 2: Transmitter pulse parameters used during normal operation.

A major design goal for the DIAL was to build an instrument that was eye safe under normal operation. Since the DIAL will be scanning horizontally over large areas that will often contain sequestration site personnel, reducing the DIAL's irradiance to eye safe levels for both aided and unaided viewing to maintain the health and safety of personnel is critical. At 1.5 microns, the eye safe requirements from the American National Standards for Safe Use of Lasers (ANSI-Z136.1-1993) laser safety guidelines require a maximum permissible exposure (MPE) of $6.67 \mu\text{J}/\text{cm}^2$. Limiting the output pulse energy of the laser transmitter to a maximum of $66 \mu\text{J}$ produces a pulse energy density of $3.36 \mu\text{J}/\text{cm}^2$ resulting in a nominal ocular hazard distance of 0 meters.

A maximum exposure time of 10 seconds was assumed in making the eye safety calculations, as this is the expected maximum exposure time per the ANSI guidelines for non-visible beams where an individual would be visually unaware they are under the exposure of potentially hazardous radiation. The fiber output of the EDFA is attached to

a fiber collimator optical assembly which nominally collimates the output beam to a diameter of 5 mm. The radiation emitted from the EDFA is too high in irradiance to be considered eye safe. To correct this, a 10x beam expander was employed to increase the beam diameter from 5 mm to 50 mm. The EDFA fiber collimator assembly was connected to the beam expander with a custom machined mount (Figures 25-28)

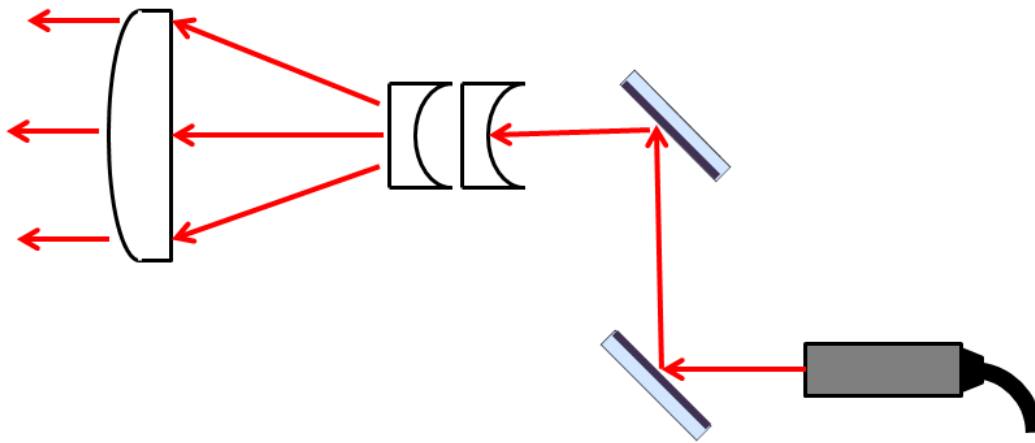


Figure 25: Schematic for the beam expander setup used to fire a 10x expanded beam coaxially with the receiver telescope. The EDFA fiber collimator output is steered up to fire coaxially and then expanded 10x to an eye-safe diameter.

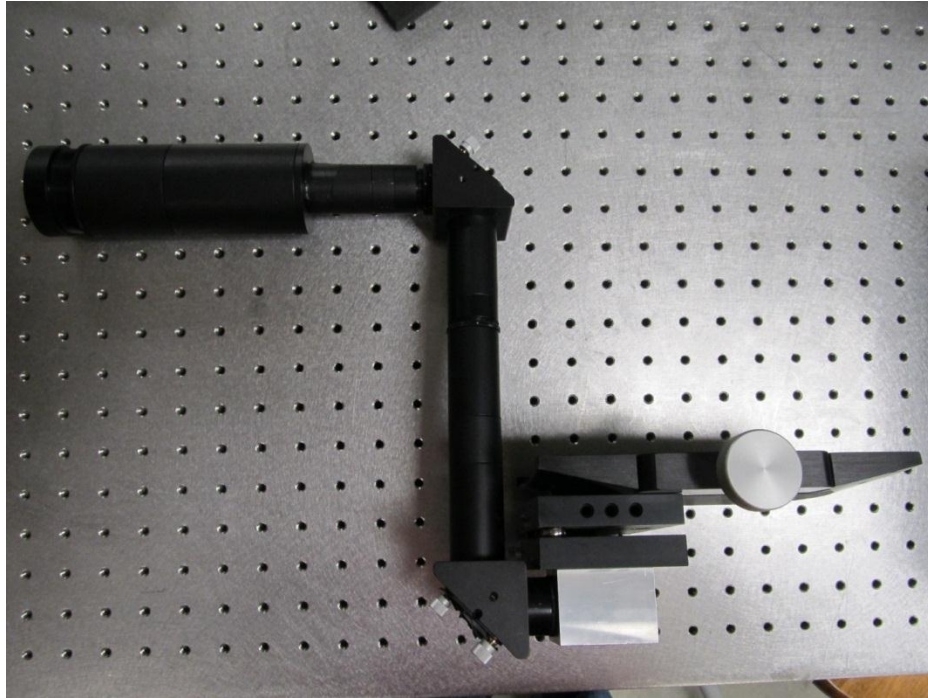


Figure 26: Photo of the beam expander. The assembly mounts directly to the telescope mounting bracket so that the beam expander moves with the telescope during scanning.

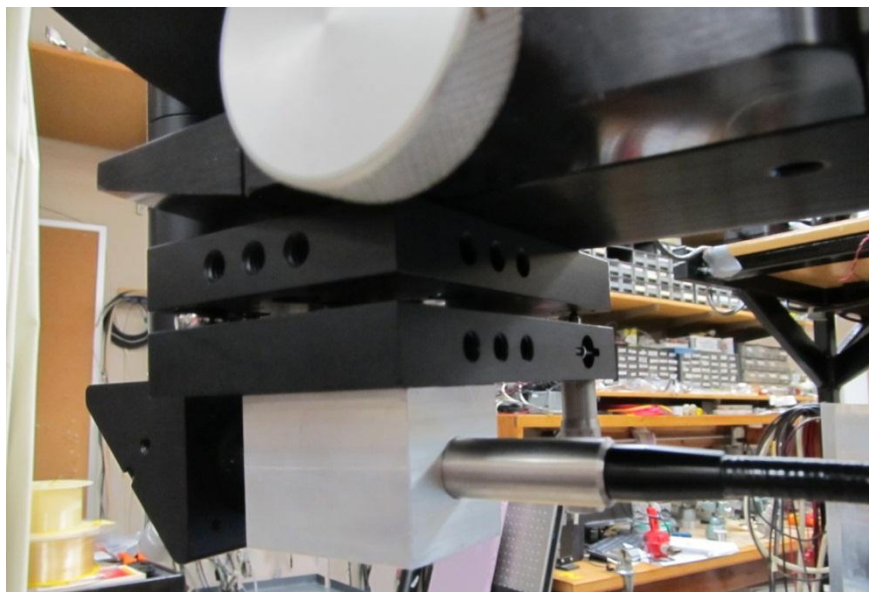


Figure 27: Photo of the beam expander mounted to the telescope with the EDFA fiber collimator output keying in to the beam expander assembly.



Figure 28: Another photo of the beam expander mounted to the telescope. The beam is entirely contained within SM1 optical tubing until it has been expanded to an eye-safe diameter of 5 cm.

At this new diameter, the DIAL pulses are reduced to $3.36 \mu\text{J}/\text{cm}^2$, which is within the eye safe guidelines. The beam expander consists of a -50 mm focal length plano-convex lens and a -25 mm plano convex lens paired together for achieving fast beam divergence. Another 200 mm focal length plano convex lens is employed to collimate the DIAL output at an eye-safe diameter.

The form of the beam expander was chosen for several reasons. First, it was desirable for transmitted pulses to be fired coaxially with the optical axis of the receiver. When the pulse first exits the DIAL, it is possible depending on the optical configuration to have a large initial burst of stray light be captured by the receiver. This is undesirable

for the low light level detectors employed for photon counting, as the magnitude of this initial burst of light can be large enough to cause damage in PMT's. When the light is launched coaxially, the obscuration of the secondary mirror on the Schmidt-Cassegrain telescope used reduces this initial flash to manageable levels.

The beam expander is mounted on a tip tilt stage to align the outgoing beam with the optical axis of the receiver. The tip/tilt stage was mounted to the side of the telescope because it was found that using the alignment screws on the final turning mirror of the expander altered the received lidar signal used for alignment since the user's arm partially obscures the receiver aperture while they are making the screw adjustments. To correct this, the beam steering adjustments were placed outside of the receiver's field of view so that during transmitter alignment, the user could make alignment adjustments without obscuring any of the receiver's field of view. The turning mirrors used were silver coated instead of dielectrically coated mirrors to reduce polarization sensitivity of the transmitted pulse energy. The EDFA uses non-polarization maintaining fiber, which causes the output polarization of the amplifier to drift during operation, especially during the first several minutes of operation when the amplifier is settling in to a thermal steady state.

Receiver

Once the DIAL pulse has been transmitted into the atmosphere, it is then up to the DIAL receiver hardware to measure and log the backscattered lidar signals. The overall layout of the optical components of the DIAL receiver are shown in Figure 29

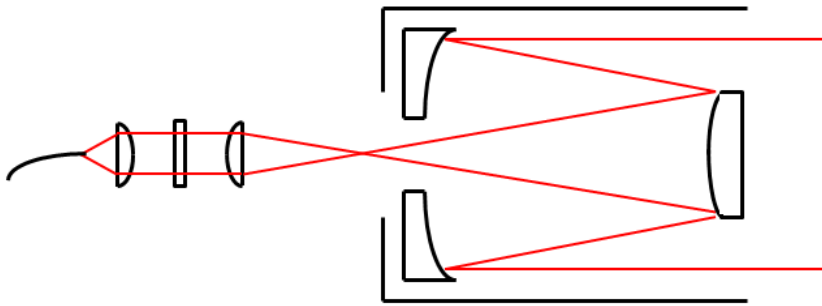


Figure 29: Diagram of the DIAL receiver optical components. A plano-convex lens collimates the light collected by the telescope for optical filtration. A second aspheric lens couples the filtered light in to an optical fiber.

FIELD OF VIEW	1.6 mRad
RECEIVER APERTURE	28 cm
DISTANCE TO FULL OVERLAP	830 m
OPTICAL PASSBAND	0.9 nm (FWHM)

Table 3: DIAL receiver optical parameters.

The receiver portion of the DIAL begins with an 11 inch Schmidt-Cassegrain telescope made by Celestron (CGE-XLT-11). The Schmidt-Cassegrain style was selected primarily for its compact form which was better suited to field deployment than larger forms such as the Newtonian telescope. A plano-convex lens acts to collimate the light collected by the telescope for optical filtration. After the collimating lens, a narrow band optical filter (Barr Associates) with an optical transmission full width half maximum of 0.9 nm (Figures 30 and 31)

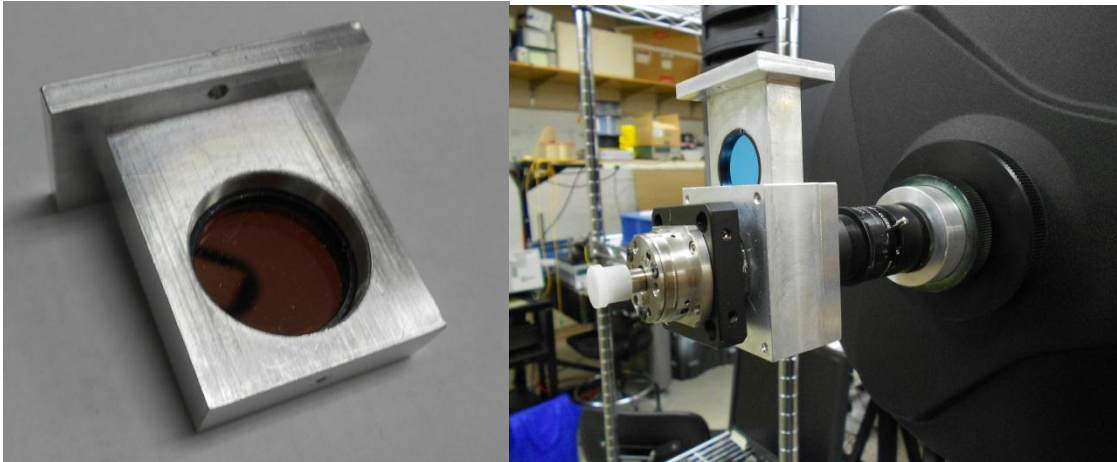


Figure 30: The narrowband optical filter in its housing (left) that can be removed for alignment of the DIAL from the receiver optical train (right)

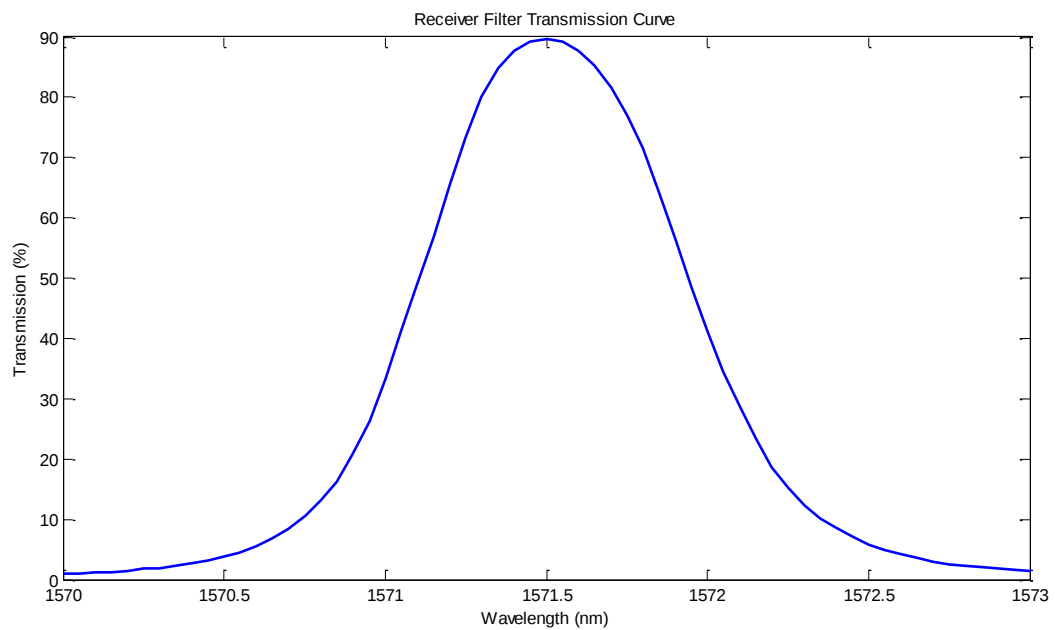


Figure 31: Transmission curve of the narrowband filter used to filter EDFA amplified spontaneous emission and ambient light.

This filter serves to improve the optical signal to noise ratio by suppressing the out of band light that would otherwise be incident on the detector from both the atmosphere and the ASE from the EDFA. After the received light is filtered, it is fiber

coupled with an aspheric lens module (Thorlabs PAF-11-X-APC) in to a 1000 mm fiber for the PMT detector or a 105 micron diameter fiber for the APD module (Figure 32).

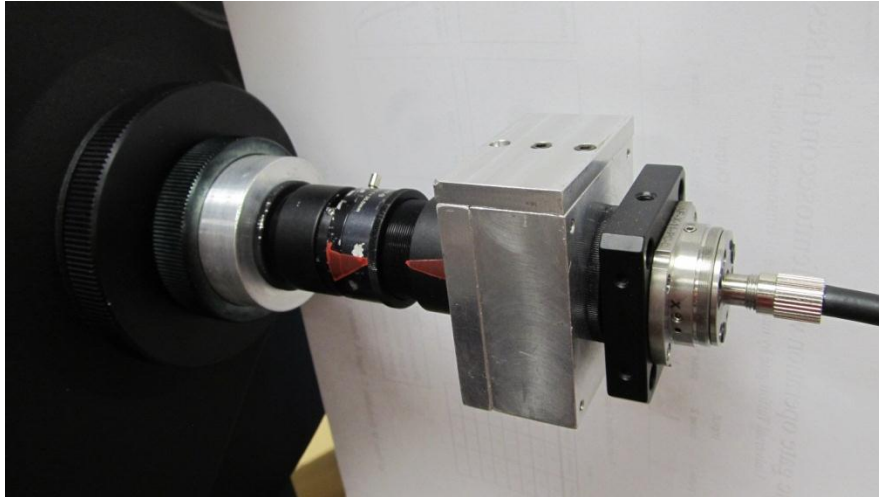


Figure 32: Receiver optical train. The freespace optical components are all mounted in SM1 optical tubing for stray light suppression and ease of mounting to the telescope.

The 1000 mm multimode fiber used for the PMT module is made by Ocean Optics and this large core diameter was selected to ease initial alignment and data collection with the DIAL. The drawback of using such a large core fiber is that it opens the field of view of the telescope allowing more background light to be collected by the receiver, but, for nighttime data collection the background light signal never exceeded 1 kHz. However, using the 1000 micron fiber for day time data collection proved to be impossible due to the background light levels being above the damage threshold of the detector.

The detector used with the 1000 micron core fiber is a near infrared photomultiplier tube (PMT) module made by Hamamatsu Corporation (H10330-075A, Figure 33).



Figure 33: H10330-075A Hamamatsu NIR PMT module used for measuring the DIAL signals.

For DIAL data collection, the PMT is operated in the Geiger mode where it measures individual photons captured by the DIAL receiver. To reduce the dark count rate to 200 kHz on average the module cools the photocathode to -50 degrees Celsius. For normal operation, the PMT was adjusted to operate at 800 volts for photon counting. When a photon triggers a photoelectron cascade within the PMT, the signal output of the PMT contains a small voltage spike generated by the photoelectron avalanche. This spike is captured by a Hamamatsu C9744 photon counting module (Figure 34) that generates a 50 ns duration square 5 volt pulse at its output to signal the detection of a photon if the voltage spike is above a user controlled discrimination voltage level, normally 200 mV. This unit operates as an interface between the PMT whose output is analog, and the data acquisition device used for DIAL data collection which measures digital signals.



Figure 34: Hamamatsu C9744 photon counting unit used to convert the analog voltage spike corresponding to a measured photon at the signal output of the PMT to a TTL pulse that can be counted by the AMCS-USB

For DIAL data collection, the output of the C9744 is monitored and recorded by a multi-channel scaler card (Sigma Space Corporation AMCS-USB, Figure 35).

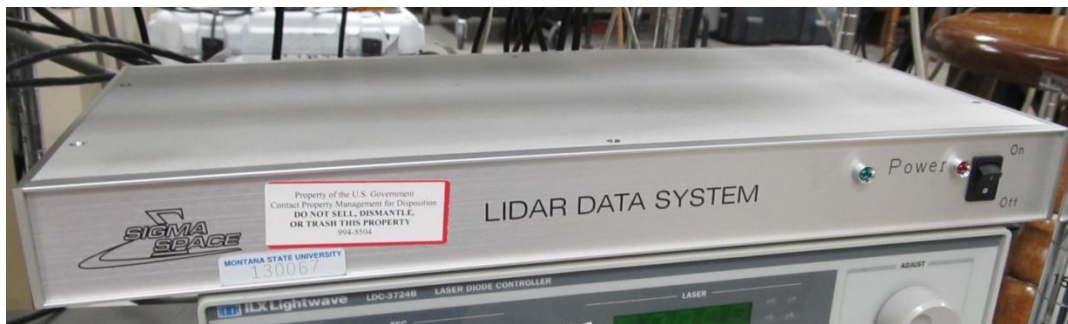


Figure 35: AMSC-USB multi-channel scaler card by Sigma Space Corporation.

The lidar signals vary rapidly on time scales of 10's of ns, and the DIAL often monitors the atmosphere for temporal periods of several hours. If this was recorded directly, this would generate tremendous amounts of data to process and store. To reduce the amount of data to more manageable levels, the scaler card performs inboard range binned averaging over many thousands of laser shots and transfers the averaged single

data set to the PC, reducing the amount of data to manage considerably. On a given laser shot, the scaler card is triggered 3 microseconds before the AOM is enabled by the same pulse train generator used to generate the control modulation signal for the AOM. After identifying the trigger pulse, the scaler card counts rising edges of digital pulses and bins the counts in time bins of 50 ns. The number of range bins worth of data to collect is set by the user. When the next trigger pulse is registered by the scaler card, the scaler again counts and range bins the measured pulses adding them to the recorded range binned data from the previous laser shot. This process of adding the next laser shot's photon counts to the previous laser shots' continues for a user specified number of accumulation cycles. When the number of laser shots is equal to the number of user specified number of accumulates, the scaler card writes the data to a buffer to be read over a USB connection by a PC.

There is a limitation for using a single data acquisition channel on the scaler card in that if the DIAL operating wavelength is switched in the middle of an accumulation cycle, the integrated data set that is transferred to the PC will be a mix of online and offline returns, making this data useless for computing CO₂ concentrations. If the online and offline wavelengths are switched frequently, which is usually the case, these wasted accumulation cycles can significantly tax the percentage of accumulated data that is not contaminated, requiring longer real time acquisition periods to get good signal to noise from temporal averaging. To bypass this limitation, an RF signal switch (Mini-Circuits ZX80-DR230-S+) is employed to route the output of the C9744 to either channels one or

two of the scaler card with channel one dedicated to accumulating online data and channel two dedicated to accumulating the offline data (Figures 36 and 37).

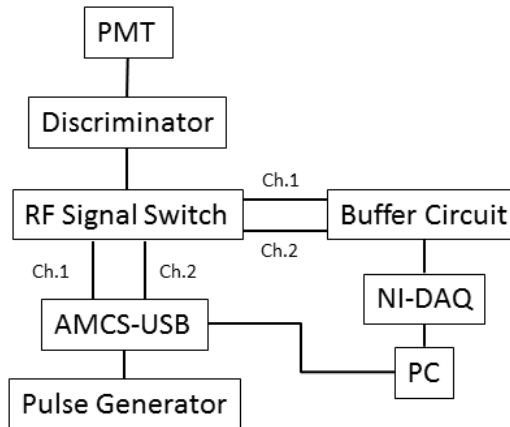


Figure 36: Block diagram for the RF signal routing switch.

The output from the C9744 discriminator is routed to either channel 1 if online signals are being collected or channel 2 if offline signals are being collected.

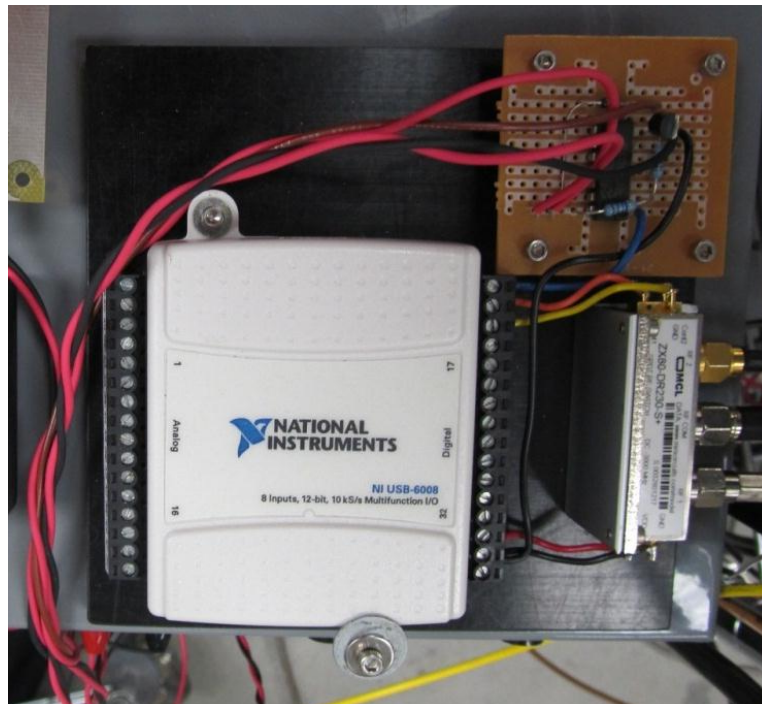


Figure 37: Photo of the RF signal switch, buffer circuit, and NI-DAQ control card.

The routing of the data is controlled by Labview with a National Instruments IO card (National Instruments, NI USB-6008). The IO card was found to not be capable of sourcing enough current to fully engage the RF signal switch channels on and off, so a buffer circuit was introduced between the IO card and the RF signal switch to supply the additional control current.

When switching between the online and offline wavelengths, there is a brief period where both wavelengths are seeding the DIAL system as described in the previous sections. When this is occurring, both RF signal switch outputs are set to the off position, so no data is accumulated during this brief period. Use of this switch allows the user to switch wavelengths at arbitrary rates, regardless of the settings and accumulation periods of the scaler card.

All hardware control, data acquisition, and system monitoring is handled by two Labview virtual instrument programs written for the DIAL system (Figure 38).

These programs allow the user to set the desired operating wavelengths, scanning angles, and data acquisition periods and then by simply running the programs, the DIAL accumulates as much scanning data as the user desires autonomously.

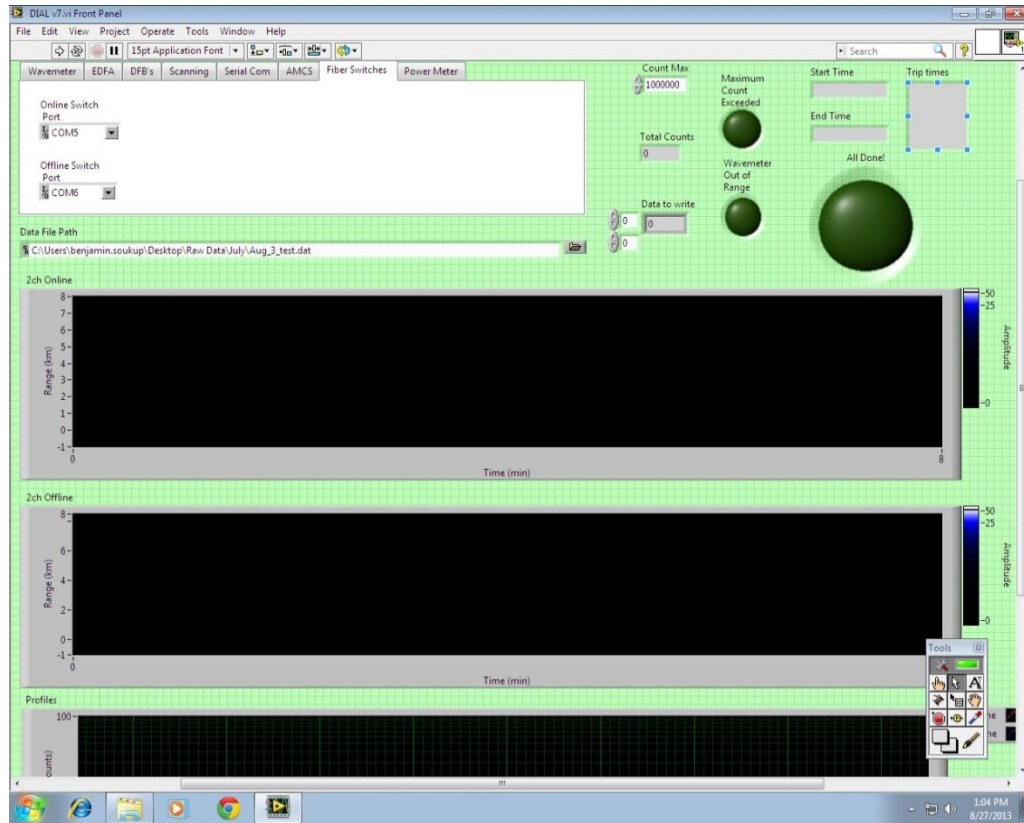


Figure 38: Screen shot of the Labview VI that controls the DIAL data acquisition.

Scanning Operation

A major advantage of using a DIAL system for monitoring CO₂ concentrations is that by simply pointing the system in different directions and repeating the range resolved measurement, a DIAL system has the ability to scan over very large field site areas with a single instrument. For the DIAL system discussed in this thesis, the scanning is accomplished with the commercial motorized scanning tripod that the telescope is mounted on. Since all of the DIAL receiver and transmitter optics are fiber coupled, the bulk of the instrument weight can be located on a separate rack next to the free space transmitter/receiver optics attached to the telescope. The output fiber of the EDFA and

the receiver fiber that goes to PMT are fairly flexible, allowing the freespace optics to be maneuvered with the tripod base without degradation in system performance. The tripod base has the option of accepting computer commands via a serial interface on the hand controller (Figure 39).



Figure 39: Hand controller that interfaces the Labview control with the motorized telescope base for PC controlled scanning of the DIAL's pointing direction.

The Labview control program was configured to write scanning instructions over a serial connection to the base to aim the system in whatever directions for user specified data accumulation period for autonomous scanning. Use of the commercial tripod for scanning instead of typically large gimbal mounted scanning mirrors reduces the cost, weight, and system complexity considerably.

Data Collection/Processing

The data collection and saving for later analysis is handled by the Labview programs written to control the DIAL system. Post processing is handled with an analysis program written in Matlab. To process the DIAL data, the raw data saved from the Labview program is first parsed in to a two dimensional array with each column representing individual accumulation cycles read from the scaler card. Two arrays are generated for the online and offline data which represent a lidar signal time series. Often when accumulating lidar data, a temporary hard target will float through the beam, generating a large signal spike in one scaler card accumulation cycle. These floating hard targets are believed to originate from insects or smoke and dust. These spurious signal spikes are detrimental to making DIAL measurements, because they often are only in the online or offline channels, which means that when a comparative absorption calculation is made, the spike in one channel biases the concentration away from the true value. To filter these spikes out of the data, a median filter is applied across the rows of the raw data arrays, equivalent to shot and pepper noise filtering in digital image processing.

After the median filtering, the individual columns have their background signals subtracted from them by subtracting the average of the few microseconds of background signal accumulated before each laser shot. After background subtraction, the data is then windowed in time typically with 60-90 minute windows. This time averaging is necessary to get adequate signal to noise ratio signals for making the CO₂ concentration calculations with a precision capable of identifying carbon sequestration site leakage. As discussed in chapter 1, expected carbon sequestration site leakages are expected to persist

for much longer than the time averaging window, so the DIAL should have sufficient temporal resolution to identify a leakage.

After temporal windowing, the data is still typically too noisy to make CO₂ concentration measurements with any useful level of precision. To address this, the data is also windowed spatially to improve the smoothness of the data. For near field signals such as those from 1km away along the line of sight of the DIAL, minimal spatial windowing is necessary since the signal is fairly large. Lidar signals from farther ranges such as those from 2 to 3 km away are significantly smaller, requiring larger spatial window sizes to get reasonable data. For the DIAL data processing, a variable spatial window is employed for smoothing the temporally windowed data. The user specifies a starting window size and initial range to apply this window. A final window size is specified for the end range of interest that is larger than the initial window size. The DIAL processing program then generates a linearly varying window size to be applied for all ranges between the initial and final windowed ranges (Figure 40).

Spatial windowing in general limits the spatial resolution of the DIAL, which limits the minimum leakage size that the DIAL would be sensitive to at a sequestration site. Using this variable window size allows for good spatial resolution in the near field where the signal is still large, while at the same time allows some lower resolution information to be extracted from the farther ranges that would otherwise be too noisy with small window sizes.

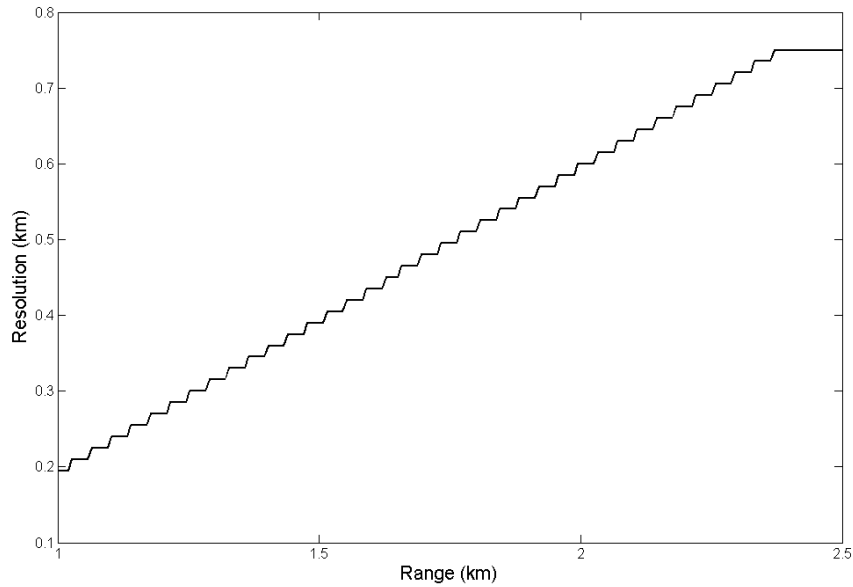


Figure 40: Variable spatial resolution employed to spatially filter the DIAL data. At closer ranges where the lidar signal is strongest, smaller spatial windows are employed to maximize spatial resolution. At larger ranges, where the signals are too small to measure carbon dioxide with reasonable precision, larger spatial windows are employed to get better precision at the cost of reduced spatial resolution.

After the spatial windowing, the final concentration as a function of range is calculated column by column in the time and range windowed data to generate a time series of the CO_2 number density as a function of range with the DIAL equation. Data concerning CO_2 gas concentrations is commonly stated in mixing ratios instead of number densities. To scale the number density to a mixing ratio, the data is rescaled using equation 14 from chapter 2 using the average ambient temperature and pressure of the air over the data acquisition period. The end result is a time series of the CO_2 mixing ratio versus range when no scanning is used. When scanning the DIAL, the user typically specifies a set of scan angles to be sampled over a data acquisition period. Usually these angles are sampled for 60-90 minutes individually. For the data

processing, the CO₂ profile for each scan angle is calculated with all of the same filtering and windowing as described above with all of the data per scan angle averaged together to generate a single concentration profile for a given scan angle. The final plot for the scanning action is a polar plot of the CO₂ concentration vs. range vs. scan angle (See Chapter 4).

For any calculated concentration calculation such as those shown in chapter 4, an error on the calculation is calculated based on a differential error analysis⁵¹. Starting

$$\text{from equation (9) in chapter 2 } N_d(r) = C * \ln \left(\frac{N(\lambda_{online}, r) N(\lambda_{offline}, r + \Delta r)}{N(\lambda_{online}, r + \Delta r) N(\lambda_{offline}, r)} \right) \quad (1)$$

the error in the number density is calculated below, where dN_d^2 represents the error squared in N_d as a function of $N(\lambda_{online}, r)$, $N(\lambda_{offline}, r + \Delta r)$, $N(\lambda_{online}, r + \Delta r)$, and $N(\lambda_{offline}, r)$

$$\begin{aligned} dN_d [N(\lambda_{online}, r), N(\lambda_{offline}, r + \Delta r), N(\lambda_{online}, r + \Delta r), N(\lambda_{offline}, r)]^2 = \\ \left(\frac{\partial N_d}{\partial N(\lambda_{online}, r)} dN(\lambda_{online}, r) \right)^2 + \left(\frac{\partial N_d}{\partial N(\lambda_{offline}, r + \Delta r)} dN(\lambda_{offline}, r + \Delta r) \right)^2 + \\ \left(\frac{\partial N_d}{\partial N(\lambda_{online}, r + \Delta r)} dN(\lambda_{online}, r + \Delta r) \right)^2 + \left(\frac{\partial N_d}{\partial N(\lambda_{offline}, r)} dN(\lambda_{offline}, r) \right)^2 \end{aligned} \quad (2)$$

evaluation of the partial derivatives gives

$$\begin{aligned} dN_d^2 = \\ C^2 \left[\left(\frac{dN(\lambda_{online}, r)}{N(\lambda_{online}, r)} \right)^2 + \left(\frac{dN(\lambda_{offline}, r + \Delta r)}{N(\lambda_{offline}, r + \Delta r)} \right)^2 + \left(\frac{dN(\lambda_{online}, r + \Delta r)}{N(\lambda_{online}, r + \Delta r)} \right)^2 + \left(\frac{dN(\lambda_{offline}, r)}{N(\lambda_{offline}, r)} \right)^2 \right] \end{aligned} \quad (3)$$

Assuming that the error in each signal measurement is photon counting error i.e.

$dN(\lambda_{online}, r) = \sqrt{N(\lambda_{online}, r) + B(\lambda_{online}, r)}$ where $B(\lambda_{online}, r)$ is the dark count and background noise in the range bin for $N(\lambda_{online}, r)$, then equation (3) simplifies to

$$dN_d^2 = C^2 \left[\frac{N(\lambda_{online}, r) + B(\lambda_{online}, r)}{N(\lambda_{online}, r)^2} + \frac{N(\lambda_{offline}, r + \Delta r) + B(\lambda_{offline}, r + \Delta r)}{N(\lambda_{offline}, r + \Delta r)^2} + \dots \right] \quad (4)$$

$$\left[\dots + \frac{N(\lambda_{online}, r + \Delta r) + B(\lambda_{online}, r + \Delta r)}{N(\lambda_{online}, r + \Delta r)^2} + \frac{N(\lambda_{offline}, r) + B(\lambda_{offline}, r)}{N(\lambda_{offline}, r)^2} \right]$$

the dark and background counts for each range bin and wavelength are estimated based on the average count value in the window of time prior to the laser firing.

LI-820 Data Logger

It was desirable to make comparisons of the DIAL's measurements against an in situ sensor to characterize the DIAL's performance. To accomplish this, a Licor LI-820 (Figure 30) was used to monitor ambient CO₂ levels at different sampling positions below the DIAL's line of sight.



Figure 41: LI-820 gas analyzer made by LICOR used for carbon dioxide measurements to compare to the DIAL.

Sampling of the air was done by pumping air through the LI-820 with a small aquarium air pump with the air pump mounted roughly 8 feet off of the ground to help reduce sampling small localized pockets of carbon dioxide that were found to be prevalent at ground level. The air pump pushes air through the LI-820 at less than 1 liter per minute. The LI-820 makes concentration measurements once per second and streams the measurement data over a serial port connection. Normally this data would be read and saved by a PC, but it was desirable to be able to operate the LI-820 with any support data logging electronics off of a battery power supply so that the measurements could be made at arbitrary locations regardless of the availability of local power. To replace the high power consumption PC, a data logging circuit was constructed to record and time stamp the LI-820's measurements to a USB memory stick (Figure 42).

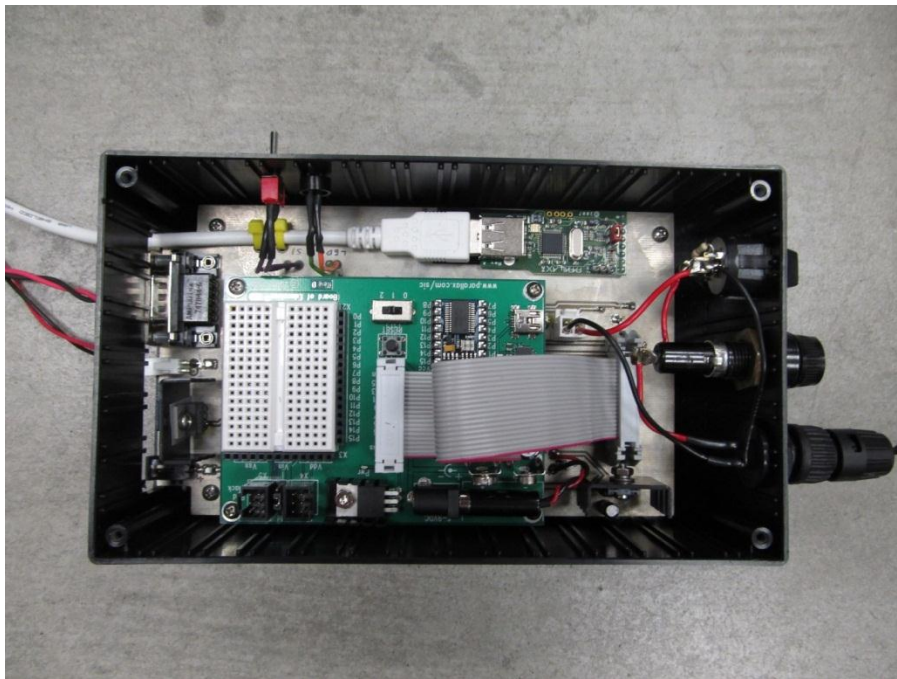


Figure 42: Picture of the data logger circuit used to store LI-820 measurements on to a USB memory stick

The data logger circuit uses a Parallax Basic Stamp 2px programmable microcontroller to record the streaming serial data from the LI-820. The microcontroller was programmed to also record the time from a (SparkFun Real Time Clock Module, DS1307 real time clock chip) real time clock circuit and store the time stamp and concentration measurements to the attached memory stick with a Memory Stick Datalogger accessory made by Parallax. The logic polarity and magnitude used by the LI-820 was different from that used by the microcontroller. To correct this, a simple logic converter circuit was also added to convert the LI-820's output data signal to a polarity and amplitude that the microcontroller could read (Figure 43). The total power consumption of the data logger is very low, allowing the LI-820 and the data logger to operate for multiple days continuously if desired off of the deep cycle marine battery used to power the setup.

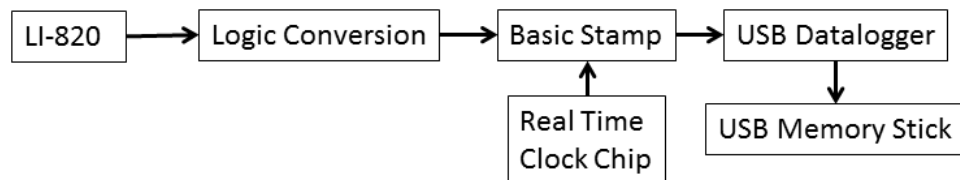


Figure 43: Diagram of the LI-820 datalogger circuit.

The LI-820, battery, and data logger circuit were contained within a weather tight container when acquiring field data (Figure 44).



Figure 44: LI-820, data logger circuit and battery all within the weatherproof container used for remote CO₂ measurements

Typically, prior to initiating DIAL data collection, the in situ sensor unit was positioned as close to directly beneath the DIAL's line of sight as was reasonably possible at ranges between 1 and 2 km from the DIAL system and the data collection with the LI-820 was initiated. An effort was made to position the LI-820 as far from any large CO₂ sources, which proved to be difficult in the Bozeman area. After the DIAL data acquisition period ended, the LI-820 data collection was stopped, and the data recorded with the LI-820 compared to the DIAL system's measurements over the same time period (See chapter 4).

EDFA

A variety of system characterization measurements were made of the DIAL system during its development to verify operating parameters as well as to troubleshoot and identify problems with the DIAL. A parameter of concern with all EDFA's is the Stimulated Brillouin Scattering threshold. Stimulated Brillouin Scattering (SBS) is a non-linear optical effect where a forward propagating light wave can generate an acoustic Bragg grating in the fiber core that can completely backscatter all of the originally forward propagating optical energy. The backscattered energy is often in the form of high peak power pulses which are capable of destroying optical components⁵². SBS requires a minimum light intensity before the process can generate sufficiently large acoustic gratings to be a problem. This minimum light intensity is the SBS threshold, and for fiber optic cables that confine optical beams to very small areas, this threshold can be less than 1 mW⁵³. To measure the threshold of the EDFA, the setup depicted in Figure 45 was employed.

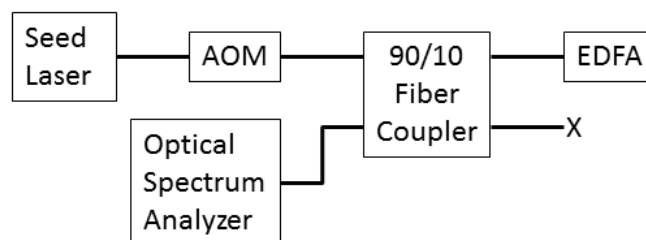


Figure 45: Block diagram for the measurement of the SBS threshold

The measurement uses a fiber coupler to measure the spectral content of any backreflected light coming out of the input of the EDFA. When SBS occurs, the backscattered light is redshifted from the incident light by roughly 10 GHz, which is typical for silica glass fibers⁵³. This allows discrimination between input light that has been backreflected by Fresnel reflections at fiber junctions and light that has been scattered through SBS processes. The optical spectrum of the backscattered light was measured while either the gain of the amplifier or the magnitude of the seed laser power was gradually increased. Well below the SBS threshold, the spectrum consists only of the seed wavelength (Figure 46).

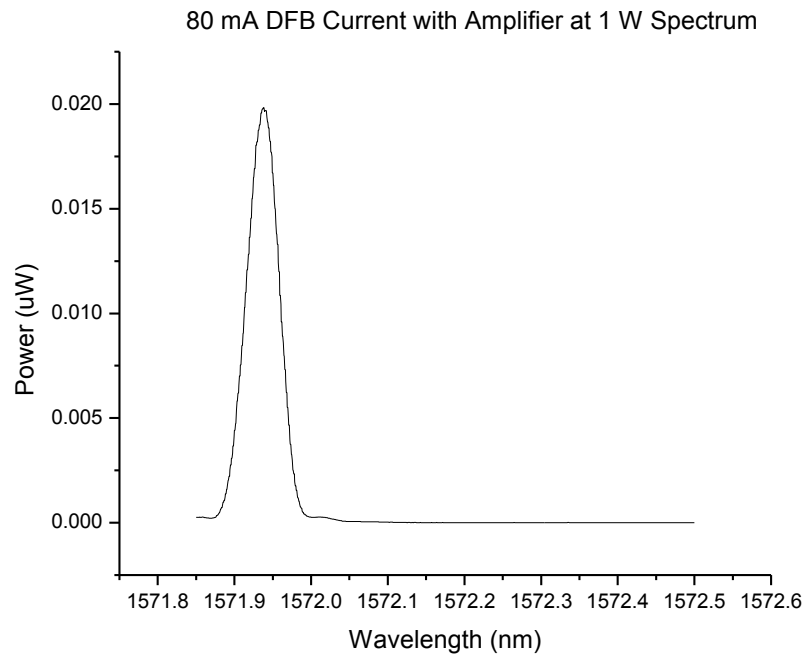


Figure 46: Measured signal with setup shown in Figure 45. Below the SBS threshold only the seed laser wavelength is present.

Approaching the SBS threshold, a small shoulder occurs offset from the peak on the red side by 10 GHz (Figure 47). Normal DIAL operation is safely below this SBS threshold to protect the optical components from potential damage.

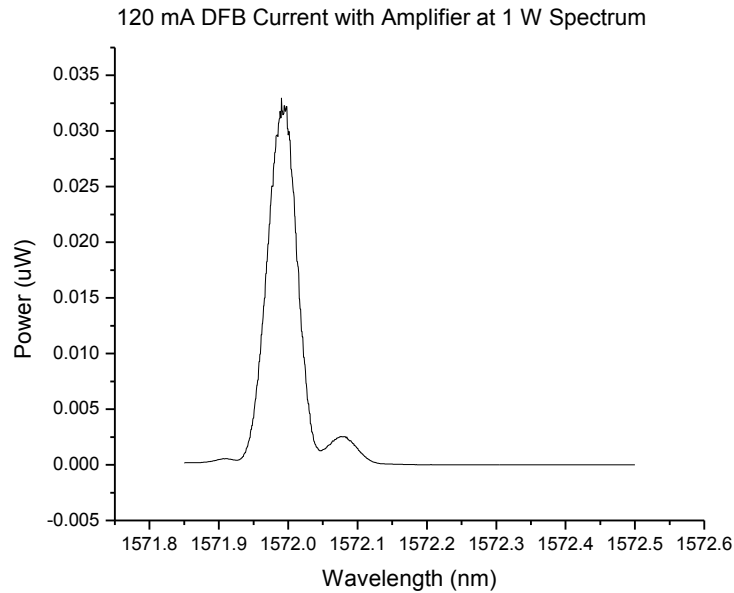


Figure 47: When the SBS threshold is crossed, red-shifted backscattered light is observed as a shoulder on the long wavelength side of the seed laser signal.

Another problem identified with the EDFA was the temporal and spectral content of the output. Ideally, the amplifier would simply produce an amplified version of the input signal. In practice, this was not found to be the case. The output pulse train was found to have a non-zero temporally varying amplified spontaneous emission (ASE) output in between pulses. The severity of the problem depended heavily on the gain of the amplifier (Figure 48). Too low of a gain and the majority of the optical power at the output was ASE based. At higher gains the problem was lessened.

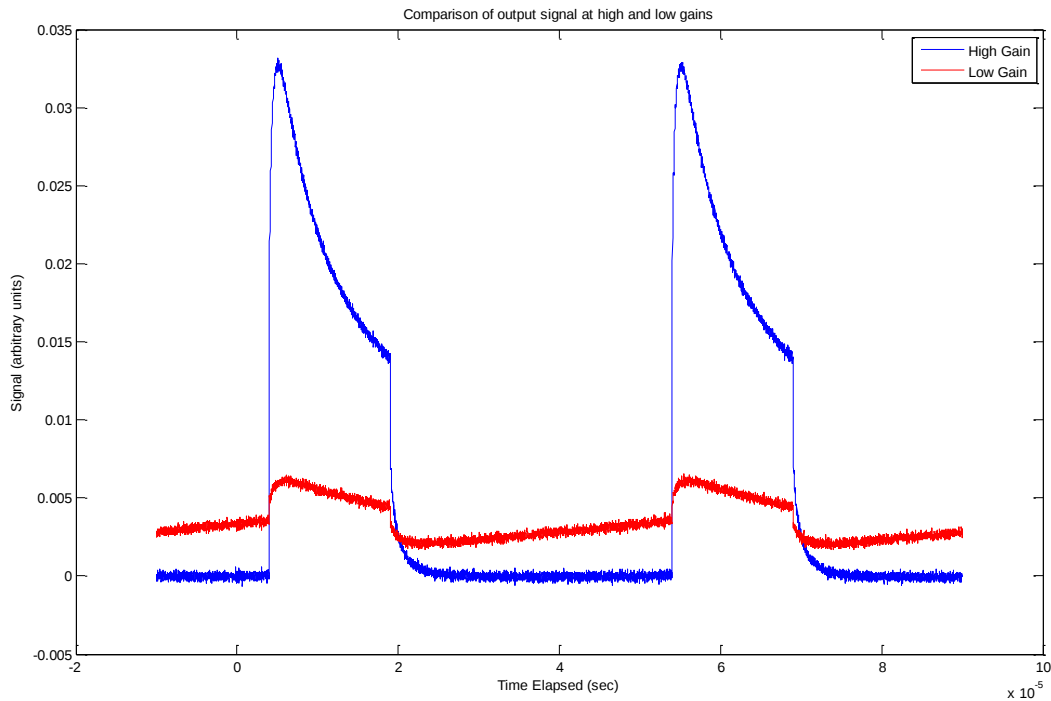


Figure 48: Optical signal emitted from the EDFA at high and low gain settings. At lower gains, ASE emission dominates (red curve). At higher gains this problem is reduced (blue curve)

This type of output was found to be highly disruptive to accurate DIAL measurements, as it introduced a time varying background noise on top of the backscattered signal which was impossible to completely remove in the data processing. To minimize this output in between pulses, the gain was adjusted until the output between pulses was found to be as small as possible. This occurred at a pump diode current setting of 1.50 A. The remaining ASE in between pulses was measured to be nearly completely filtered by the narrow band filter in the DIAL receiver (Figure 49). This was attributed to the fact that the EDFA ASE spans the EDFA's gain spectrum which ranges from 1571-1575 nm, while the filter has a full width half maximum

transmission of only 0.9 nm and is centered at 1571.52 nm at room temperature which is at the lower end of the EDFA's gain spectrum.

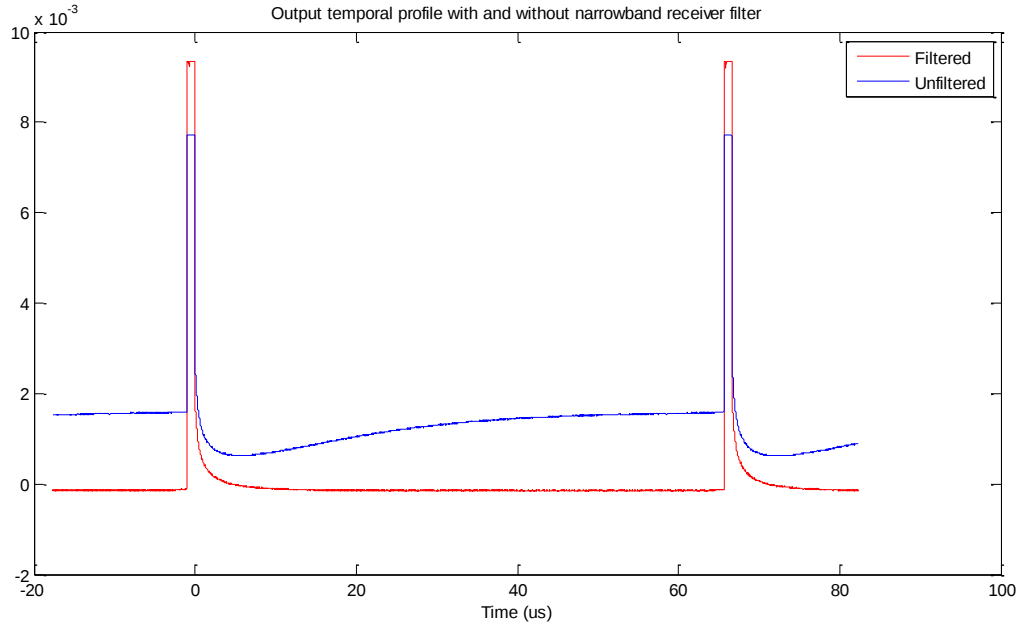


Figure 49: Filtered (red curve) and unfiltered (blue curve) output of the EDFA.

Seed Lasers

The initial seed lasers used by the DIAL were found to have insufficient side mode suppression ratios to maintain the necessary spectral purity to make a reliable DIAL measurement. Replacements with side mode suppression ratios of 40 dB were ordered and installed in the DIAL and their linewidth's measured with the delayed self-heterodyne technique⁵⁴ (Figure 50) with a 5223 meter long delay fiber so that the delay was longer than the seed laser coherence time.

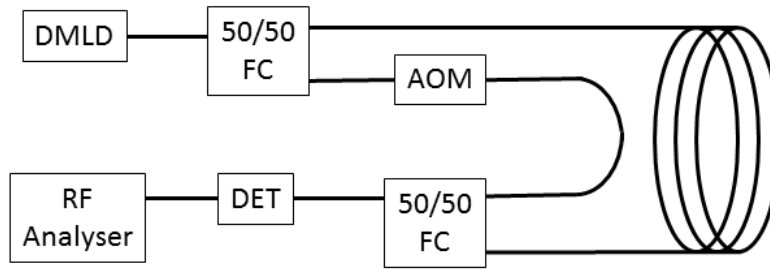


Figure 50: Diagram of the delayed self-heterodyne technique. A long delayed fraction of laser light is mixed with a frequency shifted portion of itself. The half width half max of the RF beat note on the RF analyzer is the full width half maximum linewidth of the laser.

When measured, the two lasers were found to have effective linewidths of 5 MHz (Figures 51 and 52) and 100 MHz, which was larger than the factory specified linewidth of 2 MHz. It is believed that the reason for this discrepancy lies in the fact that each of the laser diodes' wavelengths were not actively controlled beyond wavelength monitoring with a wavemeter. While the inherent linewidth of the lasers may have been consistent with the factory specifications, wavelength stability on the order of a MHz or less usually requires active locking of the diode laser to a wavelength reference standard such as an optical cavity or the absorption line of a gas⁵⁵⁻⁵⁷. The measured linewidths represented then not just the inherent laser diode linewidth but, also the jitter of the laser diode's frequency in the absence of active frequency locking. The 5 MHz linewidth laser was sufficiently narrow to serve as the online seed laser as it was still much narrower than the CO₂ absorption linewidth of 4.3 GHz. The wider 100 MHz linewidth laser was used for the offline laser as the offline measurement is less as linewidth critical than the online measurement.

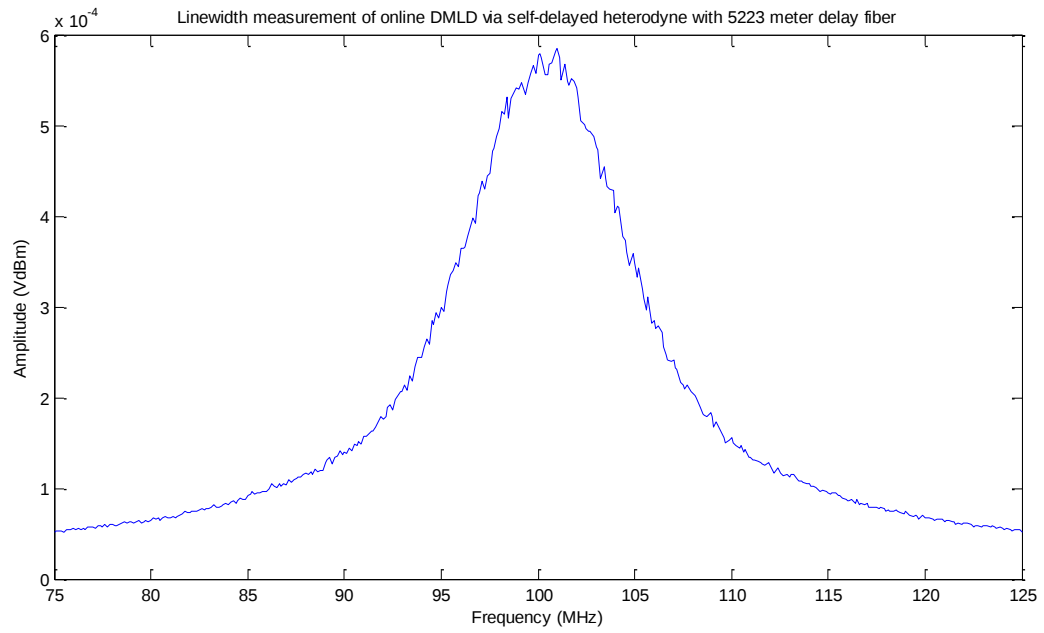


Figure 51: RF spectrum of the delayed self-heterodyne measurement of the online laser using a 5223 meter long delay fiber.

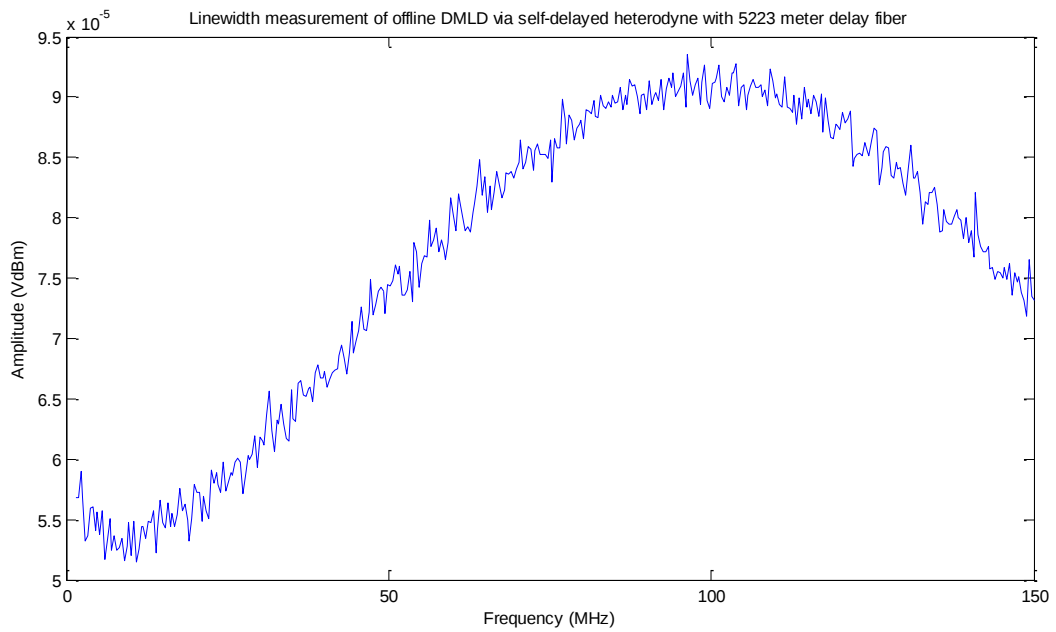


Figure 52: RF spectrum of the delayed self-heterodyne measurement of the offline laser using a 5223 meter long delay fiber.

Initial Dial Data

The DIAL began reliably making range resolved measurements of carbon dioxide in the summer of 2011. During this time, measurements were first made with the DIAL firing horizontally Westward out of a 6th floor window in Cobleigh Hall (Figure 53).



Figure 53: Picture of the system in Cobleigh Hall

During data acquisition periods the DIAL measures the lidar signals of the online and offline wavelengths as shown in Figure 54.

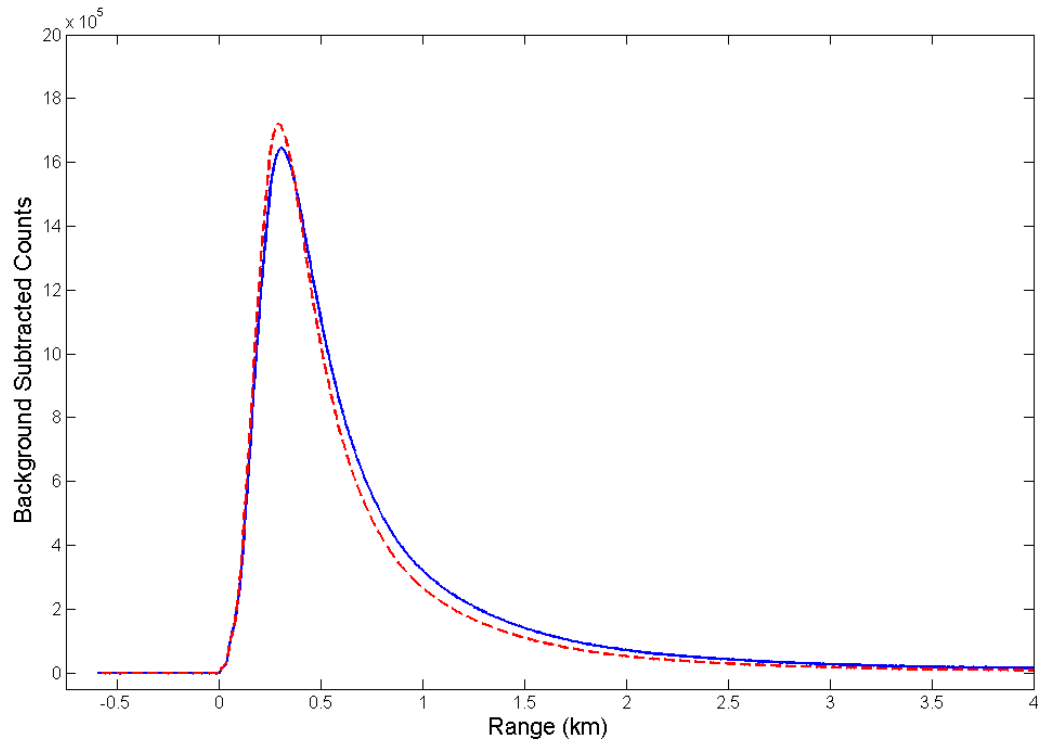


Figure 54: A plot of the background subtracted return signal as a function of range for the online (red dashed line) and offline (blue solid) wavelengths averaged over a thirty minute time period.

As can be seen in Figure 54, while the online signal is stronger at closer ranges, as the two wavelengths propagate away from the DIAL, the greater attenuation experienced by the online wavelength due to molecular absorption causes the online signal to quickly attenuate to a smaller signal than the offline wavelength. These offline and online signals are processed by the methods described in chapter 3, and the result is a range resolved measurement of CO_2 as shown in Figure 55.

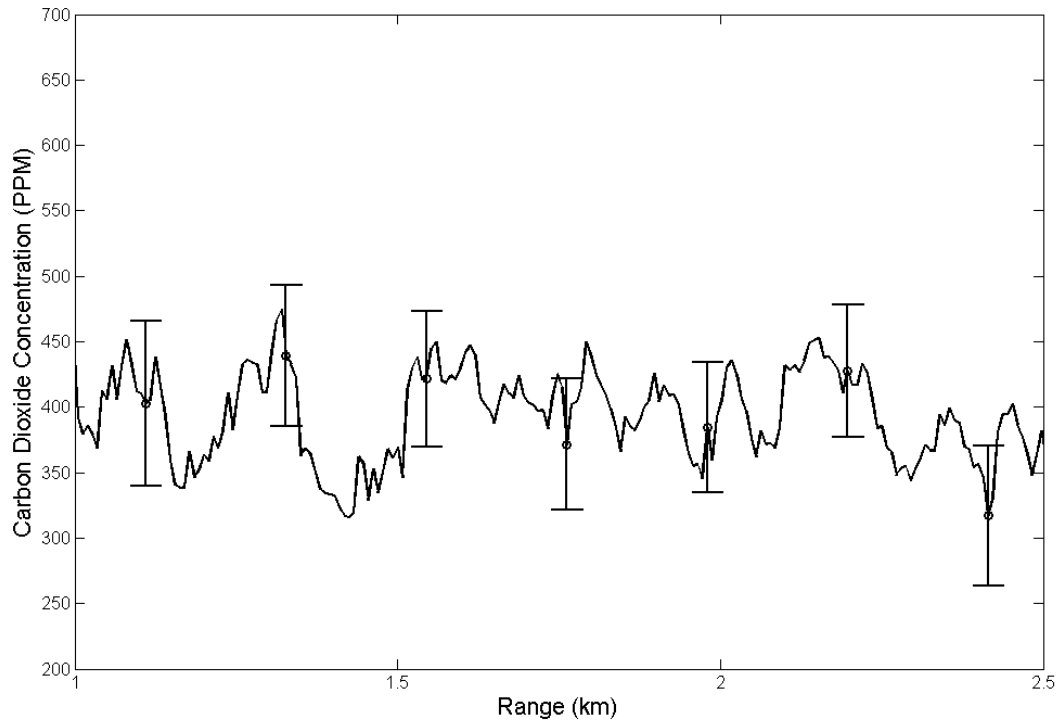


Figure 55: A plot of the CO₂ concentration profile as a function of range. The data was collected over a period of 60 minutes.

The profile was made averaging over a period of 60 minutes. The DIAL ran from 10:59 pm to 4:40 am on July 6th, 2012. A time series of the range resolved CO₂ measurements made by using a running time average over the course of the evening is shown in Figure 56.

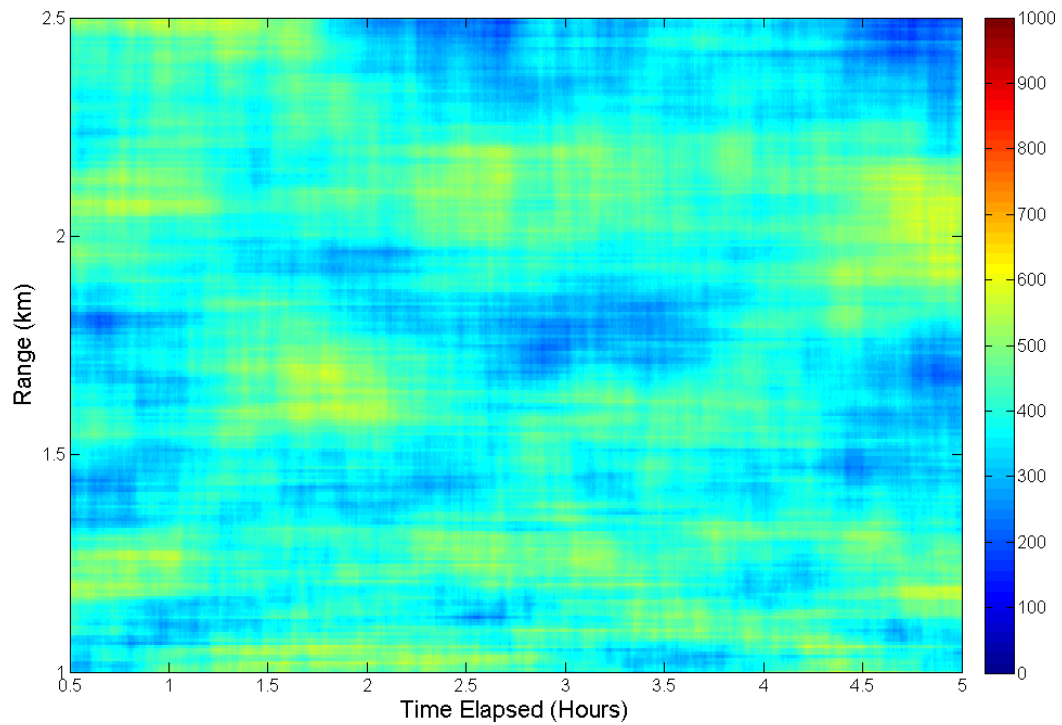


Figure 56: Plot of the CO₂ concentration as a function of range and time over a five hour period.

While the DIAL was firing, measurements were also made with the LI-820 which was located on the ground 1.5 km away from the DIAL, as close to directly below the DIAL's line of sight as was reasonably achievable on accessible land that was not too close to a local source of CO₂. The LI-820's measurements are shown in comparison with the DIAL's measurements at 1.5 km in Figure 57.

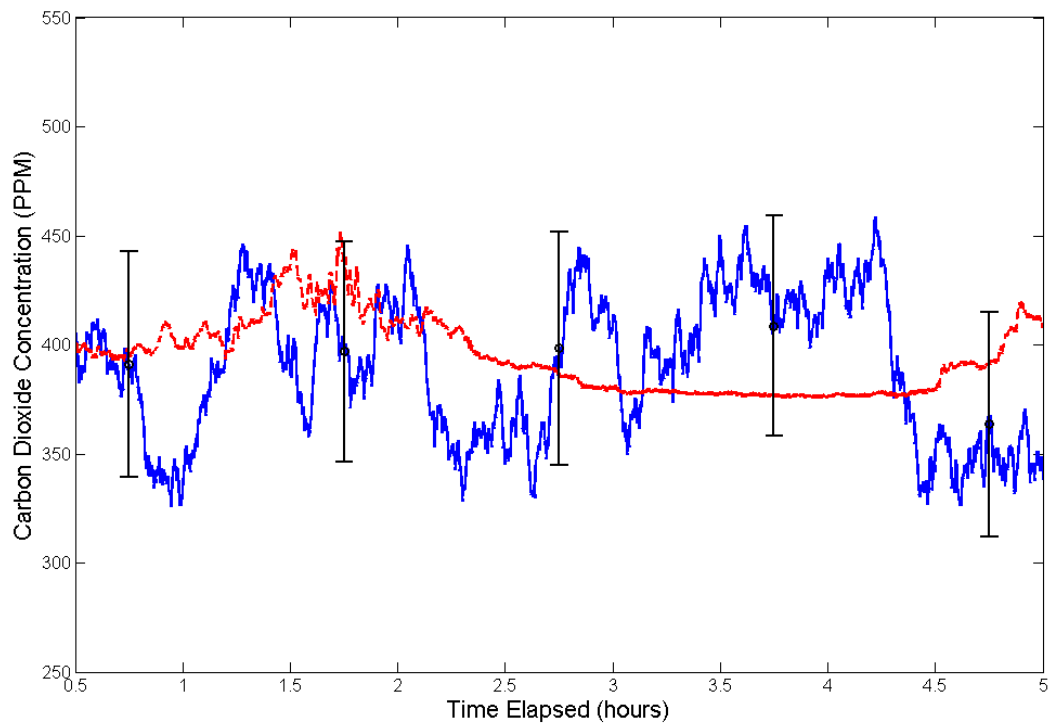


Figure 57: A plot of the CO₂ concentration as a function of time for the 1.5 km range is shown as the solid blue line. The CO₂ concentration measured with a collocated Licor LI-820 Gas Analyzer place 1.5 km away from the DIAL is shown as the red dashed line.

The data shown in Figures 55-57 showed enough agreement to within the error of each instrument to give confidence that the DIAL was making accurate low precision measurements of CO₂ in the atmosphere over its working range during a period of many hours. The DIAL's low precision prevents any meaningful statistical correlations to be made between the DIAL and the LI-820 beyond simple verification that the two systems measure CO₂ to within the error of each instrument.

Bozeman Field Measurements

Since the DIAL's purpose is to monitor sequestration sites, the next step in proving the DIAL instrument was to make outdoor field site type measurements. To accomplish this, the DIAL was put in to a small cargo trailer in a field West of Montana State University's campus (Figure 58).



Figure 58: Picture of the dial trailer out in the field with the DIAL within it

The DIAL operated in the trailer from 7/17/2012 to 8/7/2012 firing eastward. During this time, more range resolved measurements were made with the DIAL such as those made on 8/7/2012 in Figures 59-63.

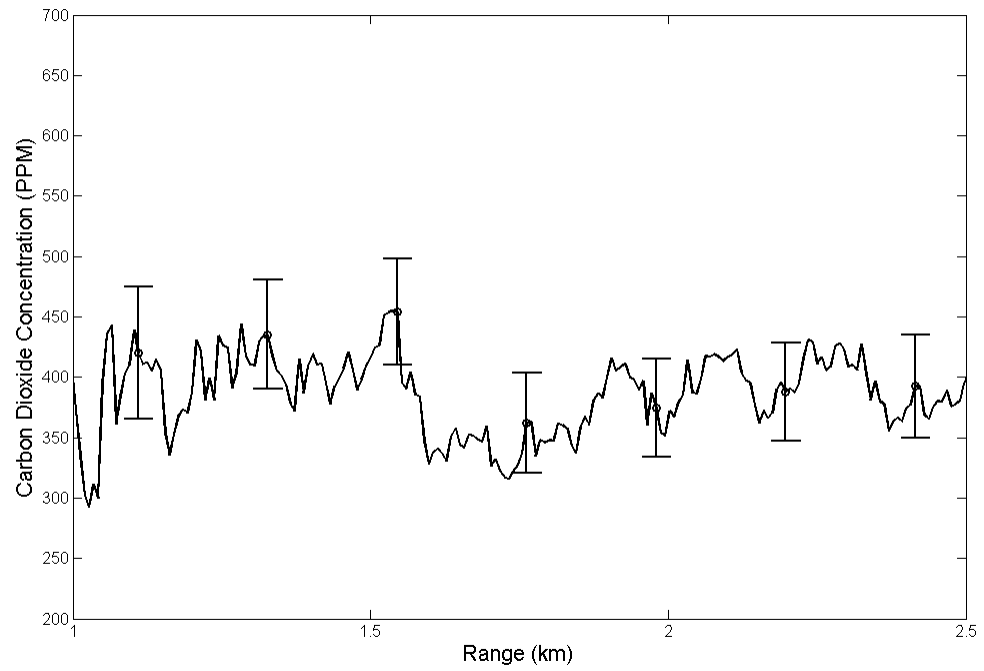


Figure 59: A plot of the CO₂ concentration profile as a function of range. The data was collected over a period of 60 minutes firing from the cargo trailer shown in Figure 58.

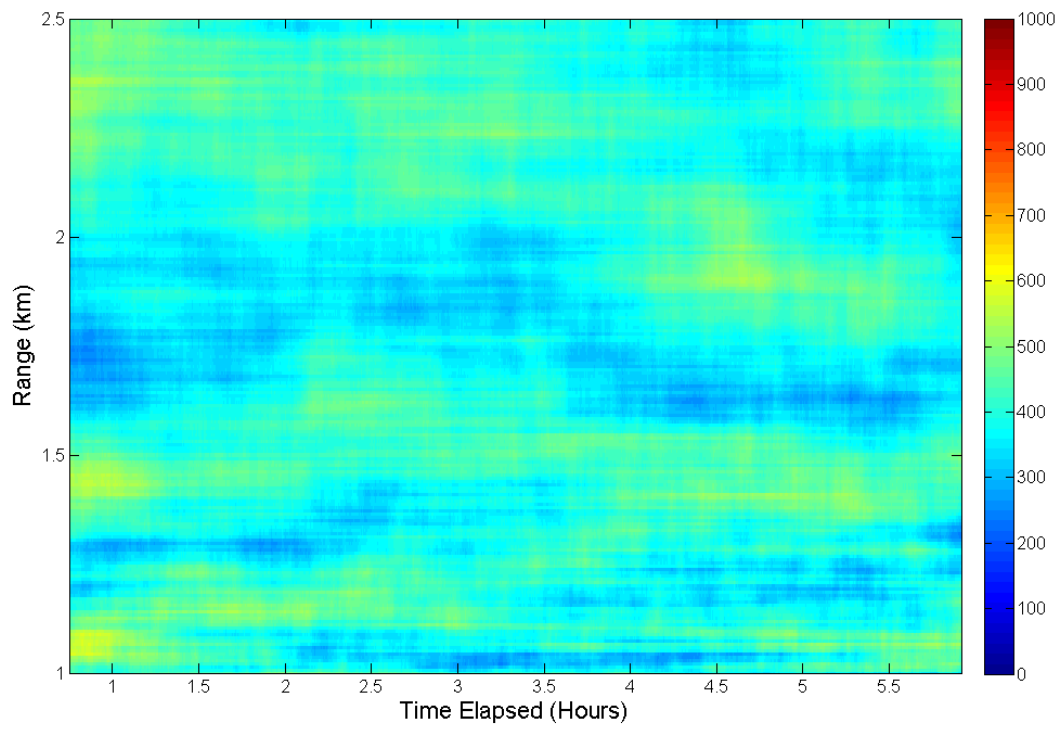


Figure 60: The CO₂ concentration as a function of range and time over a six hour period.

While in the trailer, measurements were again made in tandem with the LI-820 which was again located close to directly below the line of sight of the DIAL, only this time located at a range of 1.0 km away from the DIAL (Figures 61 and 62). Comparison of the LI-820's measurements with the DIAL's measurement of CO₂ at 1.0 km are shown in Figure 63.



Figure 61: Satellite snapshot of the location of the DIAL trailer location and the location of the LI-820 and the approximate beam path of the DIAL.



FIGURE 62: Picture of the LI-820 in the field. The LI-820 was run off of a battery in a weatherproof box. Air was pumped through the LI-820 with a small electric air pump elevated off of the ground.

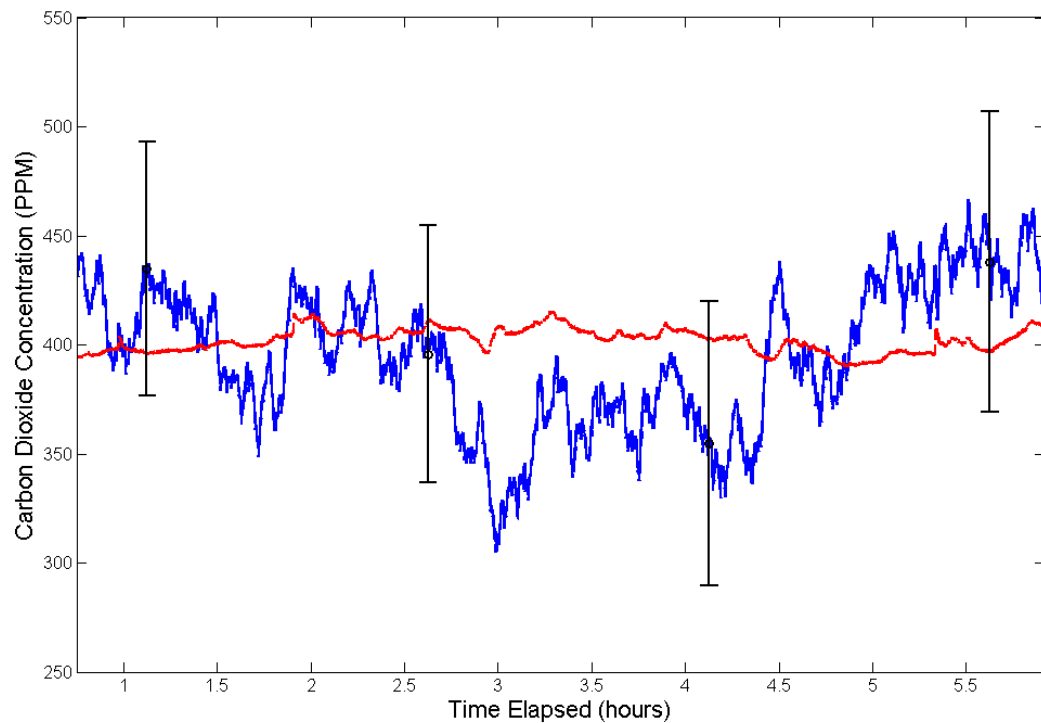


Figure 63: A plot of the CO₂ concentration as a function of time for the 1.0 km range is shown as the solid blue line. The CO₂ concentration measured with a collocated Licor LI-820 Gas Analyzer place 1.0 km away from the DIAL is shown as the red dashed line.

Data shown in Figures 59, 60, and 63 shows the DIAL performance under field conditions in comparison with the LI-820 sensor was nearly identical to the DIAL measurements shown in Figures 55-63 under non-field conditions. The DIAL's measurements agreed with those of the LI-820 to within the error of each instrument, the precision of the DIAL was still too low to measure any meaningful correlations with the LI-820.

Kevin Dome Field Measurements

In the Summer of 2013, the DIAL was taken to the Kevin Dome sequestration site in Oilmont Montana to demonstrate that it was capable of making routine monitoring measurements of a sequestration site over many weeks (Figure 64).



Figure 64: Pictures of the DIAL at the field site.

The DIAL operated at the Kevin Dome site from July 11th to August 4th of 2013 and made measurements during 17 nights during this time period. Examples of measurements made at the Kevin Dome site are shown in Figures 65-78.

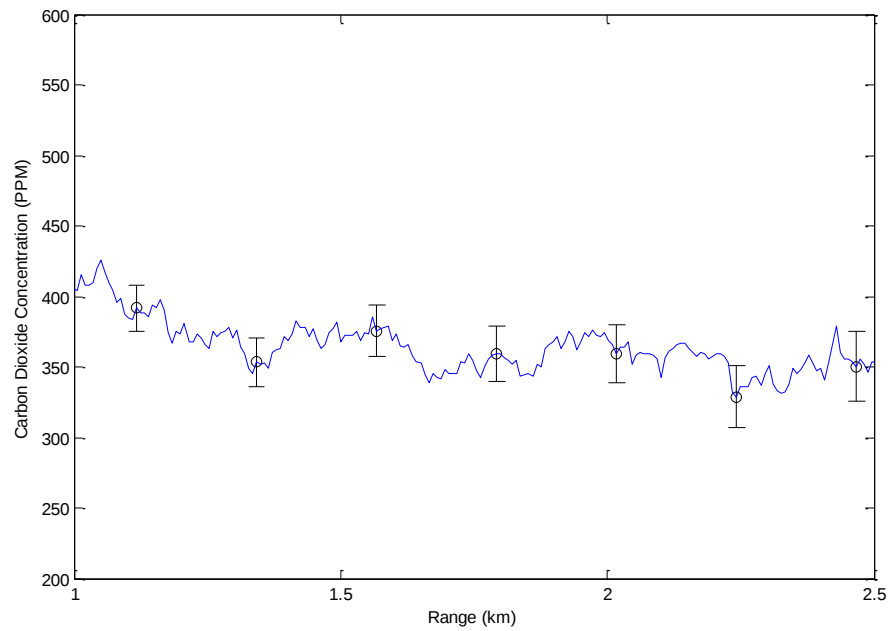


Figure 65: A plot of the CO₂ concentration profile as a function of range. The data was collected over a period of 90 minutes on 7/22/2013.

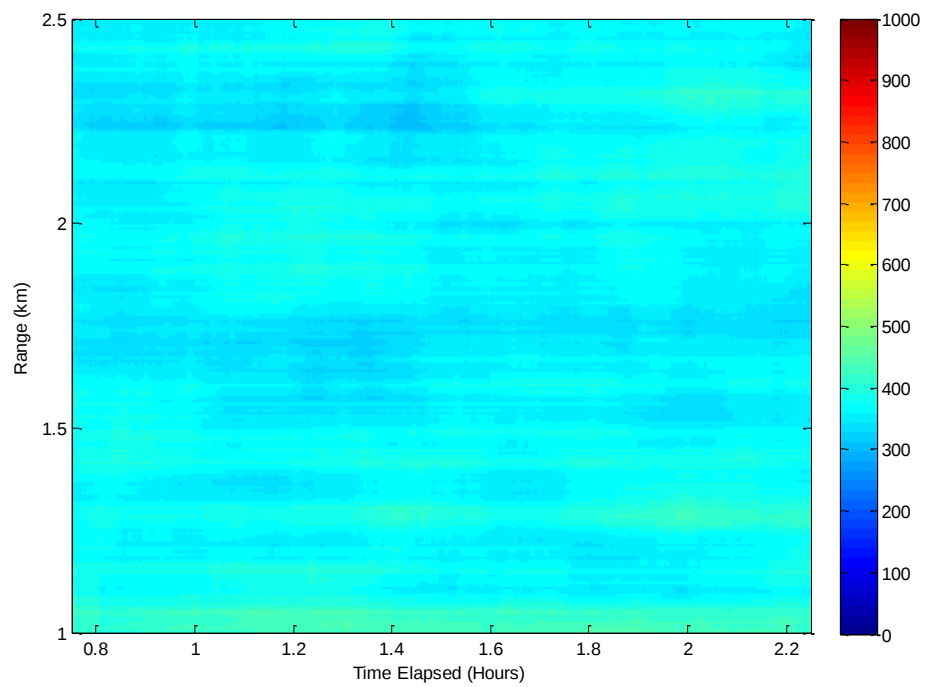


Figure 66: The CO₂ concentration as a function of range and time on 7/22/2013

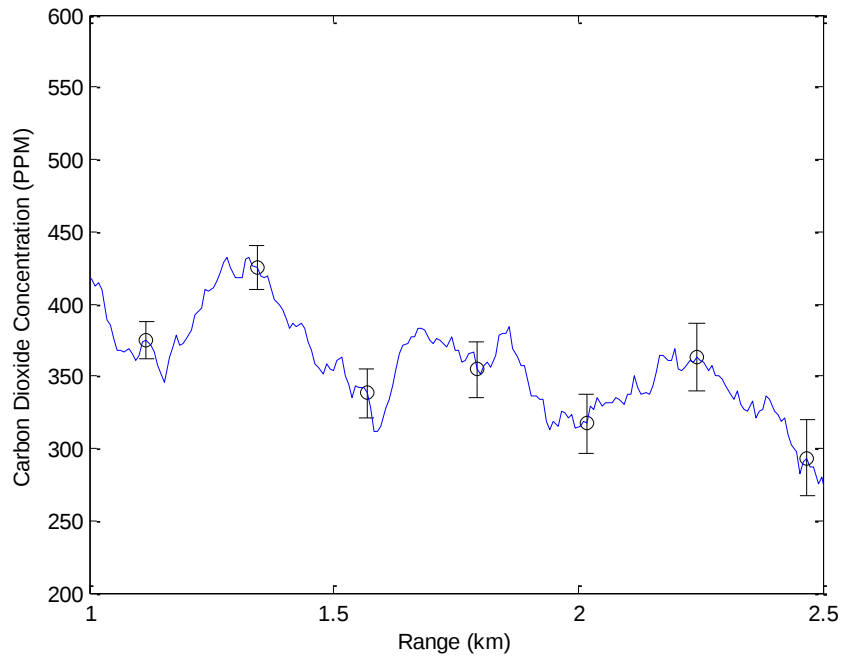


Figure 67: A plot of the CO₂ concentration profile as a function of range. The data was collected over a period of 90 minutes on 7/23/2013.

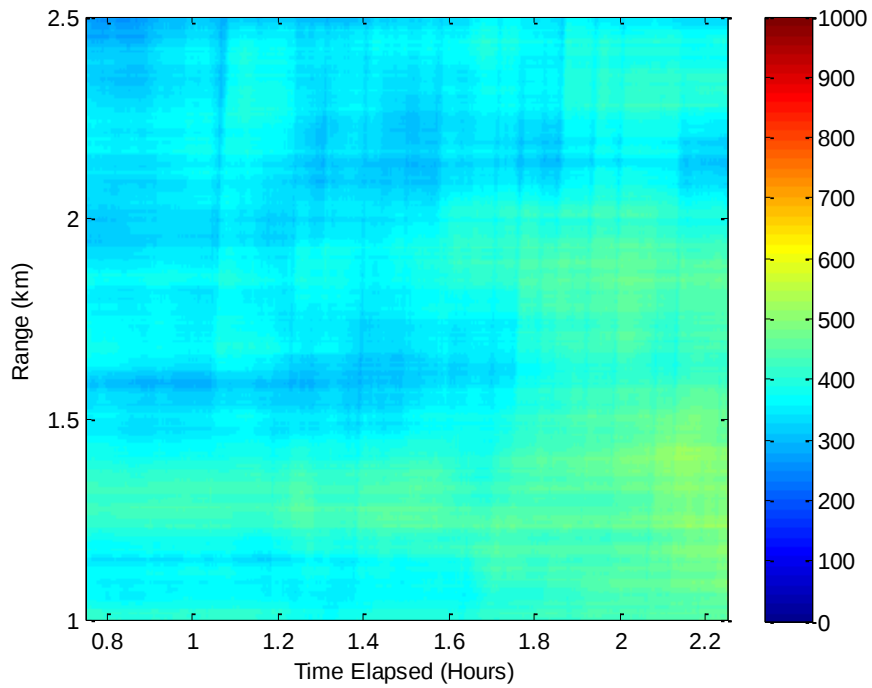


Figure 68: The CO₂ concentration as a function of range and time on 7/23/2013

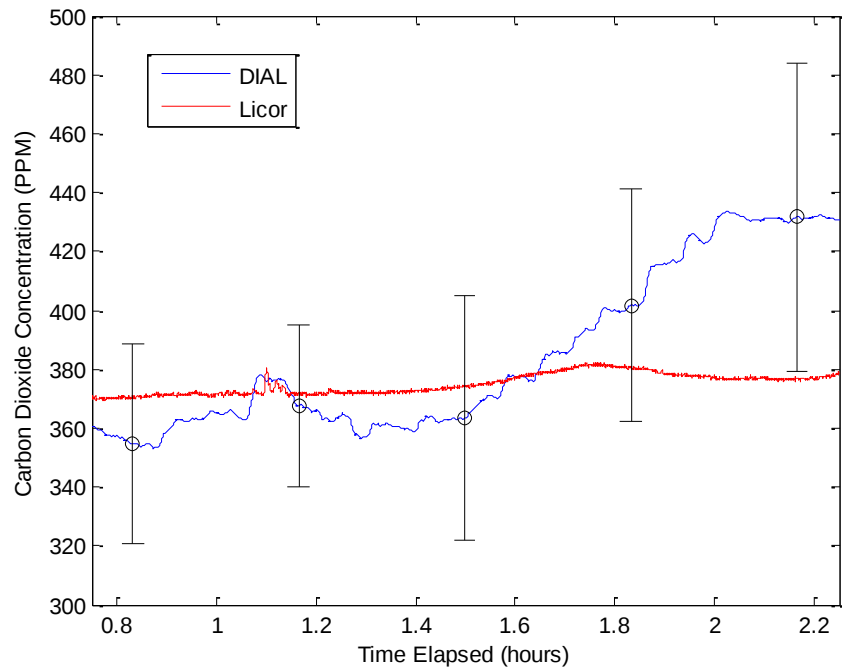


Figure 69: Comparison of the average CO₂ concentration from 1 to 2.5 km measured with the DIAL vs. time and the LI-820's measurements on 7/23/2013.

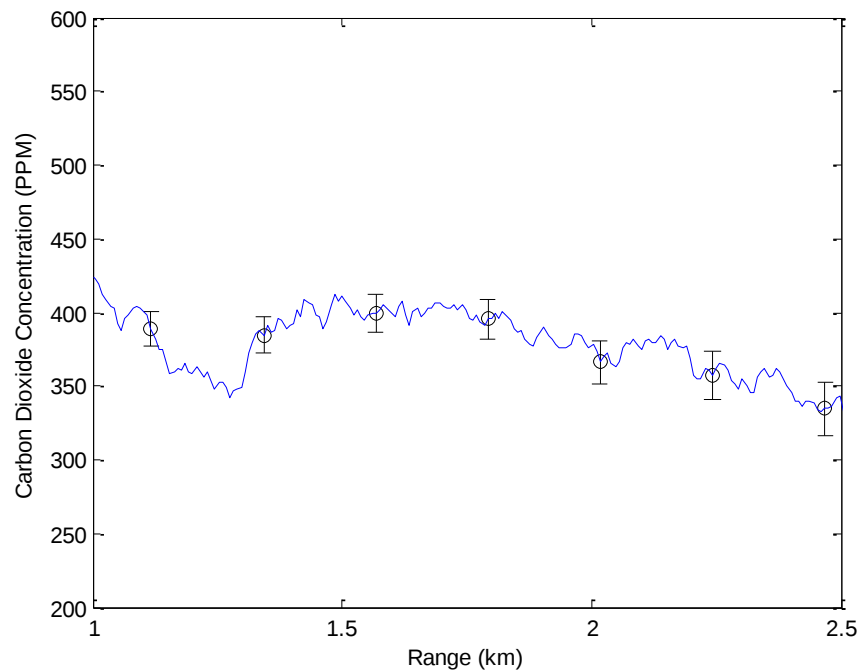


Figure 70: A plot of the CO₂ concentration profile as a function of range. The data was collected over a period of 90 minutes on 7/25/2013.

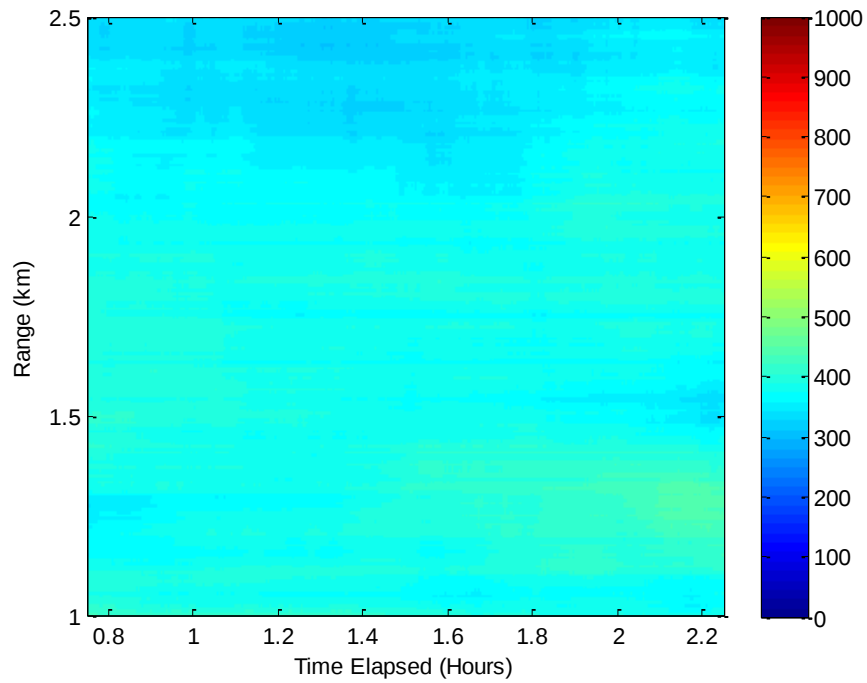


Figure 71: The CO₂ concentration as a function of range and time on 7/25/2013

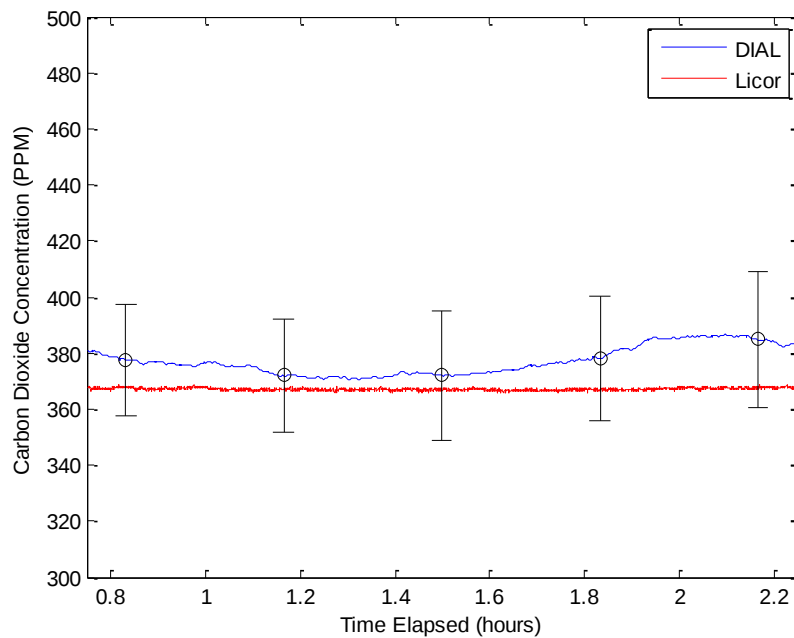


Figure 72: Comparison of the average CO₂ concentration from 1 to 2.5 km measured with the DIAL vs. time and the LI-820's measurements on 7/25/2013. Note that the LI-820's measurements are very constant due to strong persistent winds during the measurement period.

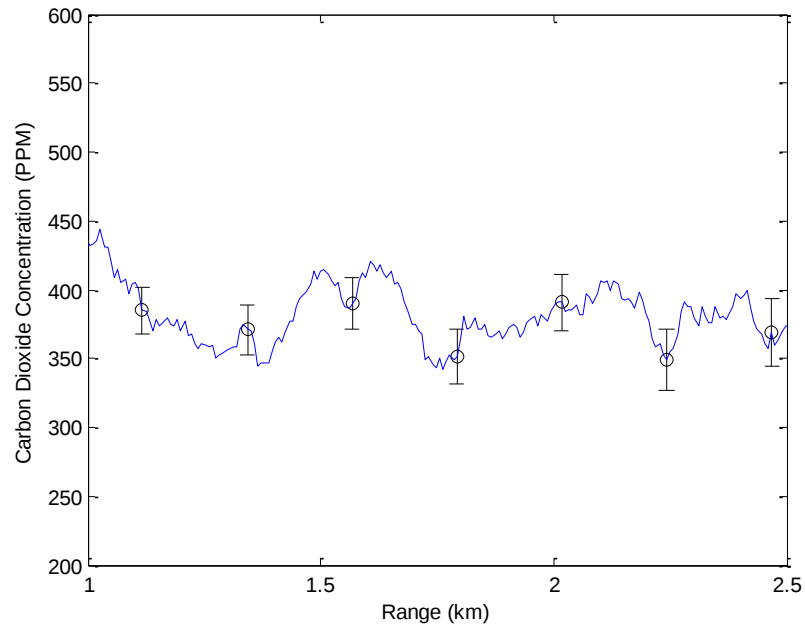


Figure 73: A plot of the CO₂ concentration profile as a function of range. The data was collected over a period of 90 minutes on 7/26/2013.

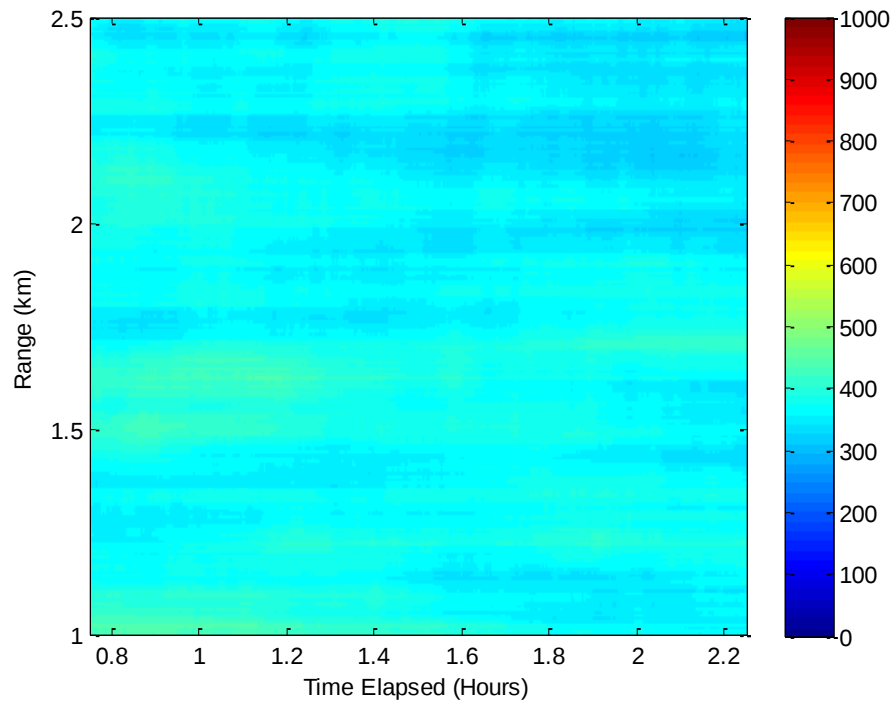


Figure 74: The CO₂ concentration as a function of range and time on 7/26/2013

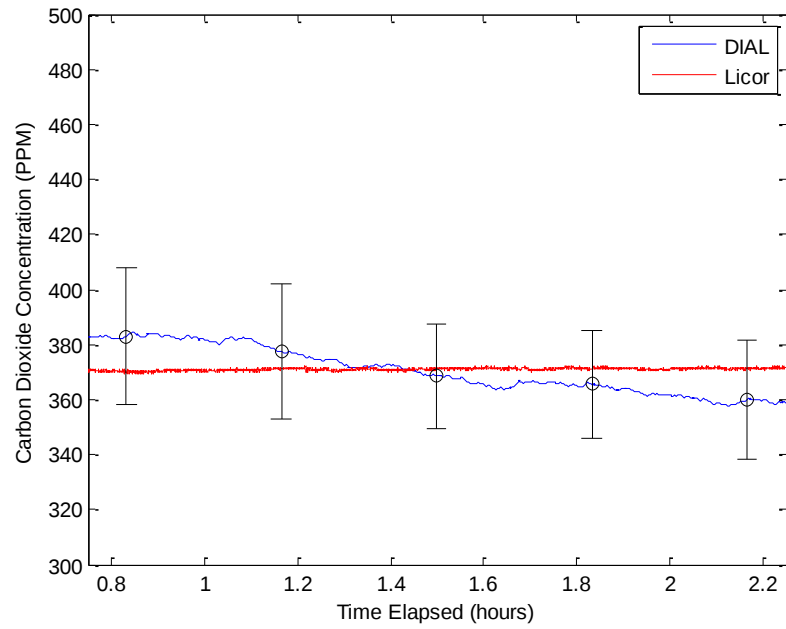


Figure 75: Comparison of the average CO₂ concentration from 1 to 2.5 km measured with the DIAL vs. time and the LI-820's measurements on 7/26/2013

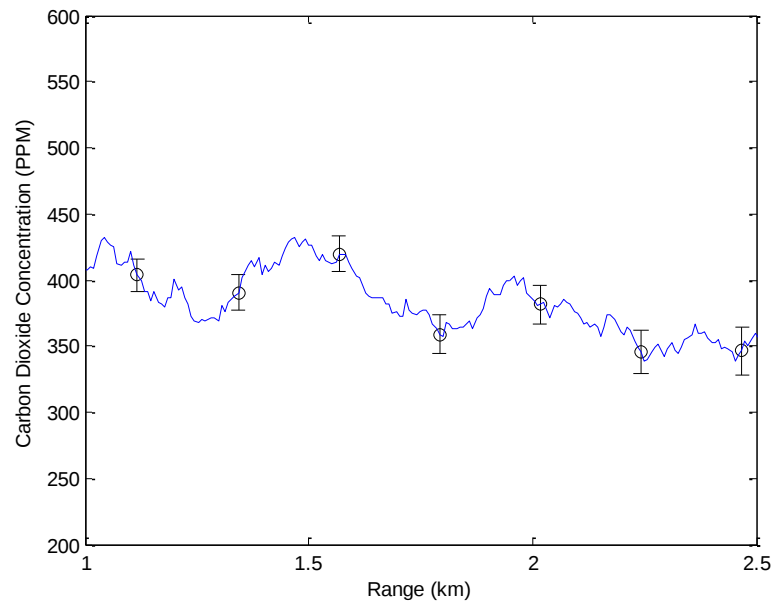


Figure 76: A plot of the CO₂ concentration profile as a function of range. The data was collected over a period of 90 minutes on 7/27/2013.

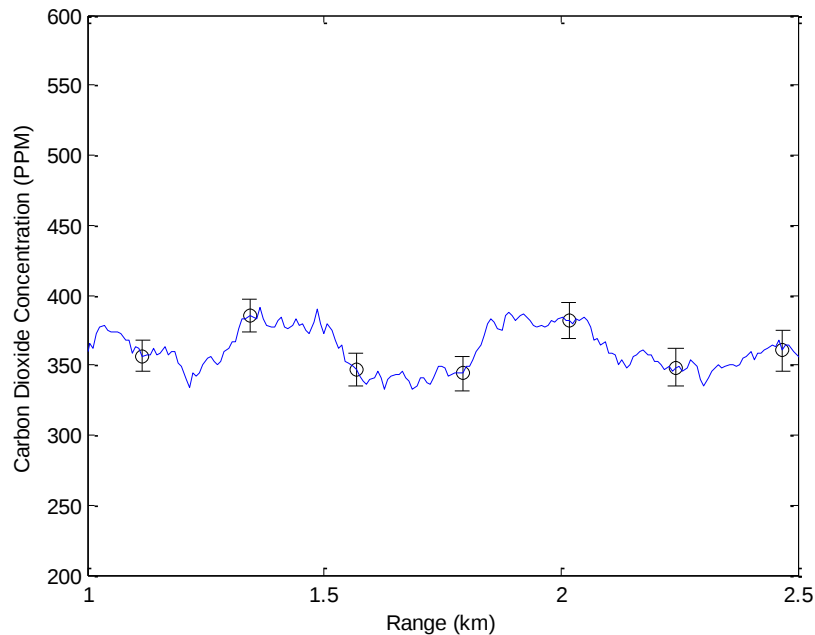


Figure 77: A plot of the CO₂ concentration profile as a function of range. The data was collected over a period of 90 minutes on 7/30/2013.

In general, the data taken at the Kevin Dome site shown in Figures 65-77 shows the DIAL's ability to make repeatable single line of sight measurements over the course of many different evenings. Limited by the noise of the PMT, the DIAL's precision is too high to measure any meaningful correlation between the LI-820's measurements and those of the DIAL. However, the DIAL's repeatable range resolved measurements of CO₂ for multiple hours each night over a period of multiple weeks under field conditions show that DIAL is robust enough to operate at remote sequestration sites for extended periods of time with a minimum of user supervision.

In addition to these single line of sight measurements, the DIAL also demonstrated autonomous scanning operation over the nights of 7/27/2013 and 7/30/2013. On the night of 7/27/2013, the DIAL took 90 minutes of data at a 0 degree

angle pointing roughly 100 degrees East of North, then automatically reoriented its firing direction to take an additional 90 minutes of data firing 90 degrees East of North. Two nights later on 7/30/2013, the DIAL took 90 minutes of data firing 80 degrees East of North, then again automatically reoriented its firing direction to take an additional 90 minutes of data firing 70 degrees East of North. The results of this scanning are shown in Figure 78.

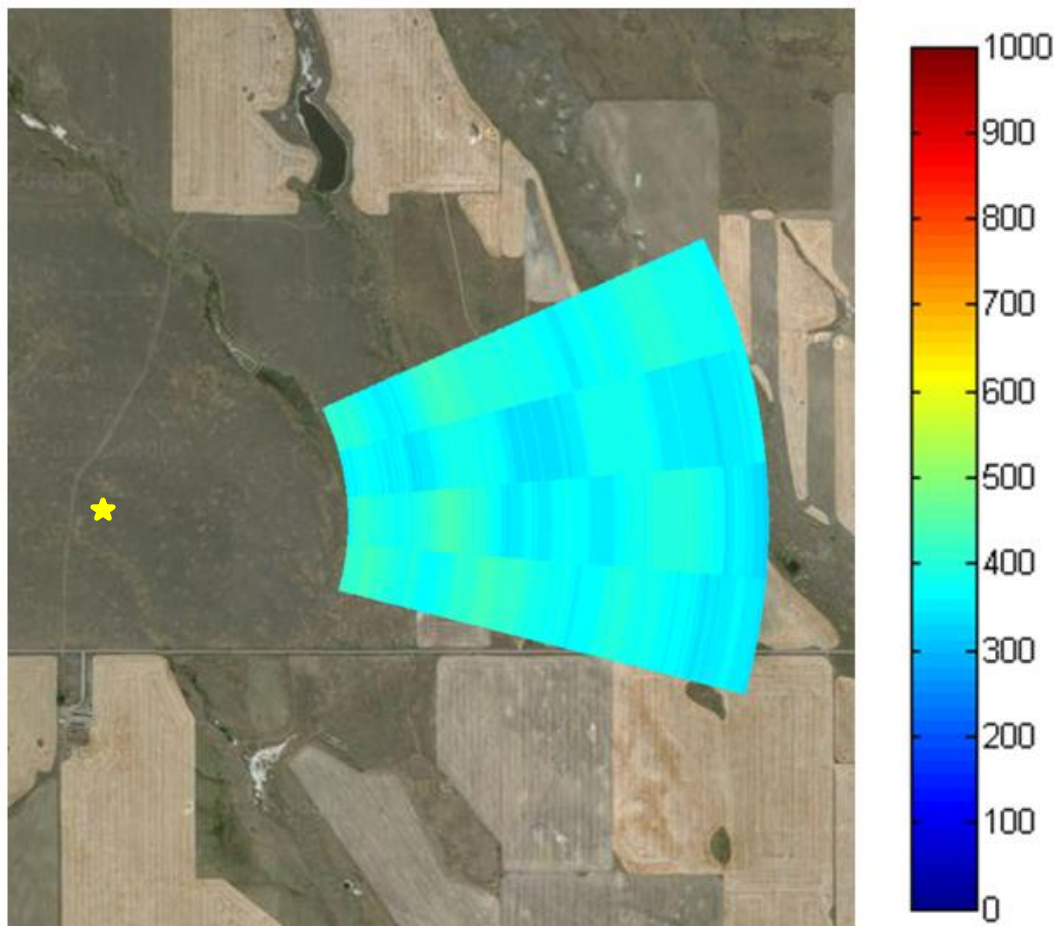


Figure 78: Range resolved CO₂ measurements made with the DIAL scanning horizontally over a 40 degree range.

The DIAL scanned an area of 1.83 km² over the course of these two evenings, demonstrating that it is capable of autonomous scanning operation over the course of multiple evenings. Maps such as Figure 78 could eventually be used by those monitoring carbon sequestration sites to identify potential leakages at different areas of the site, as well as for verifying that the above ground concentrations of CO₂ are at safe levels for those working in and around sequestration sites.

IPDA WORK

In the Spring of 2012 work began at NASA Langley Research Center developing a 2 micron integrated path differential absorption lidar (IPDA) for measurement of carbon dioxide from an aircraft. As described in chapter 3, the integrated path measurement is distinct from the DIAL measurement in that the measurement uses the signal from a hard scattering target to measure the average concentration of a trace gas of interest between the transmitter and the scattering target.

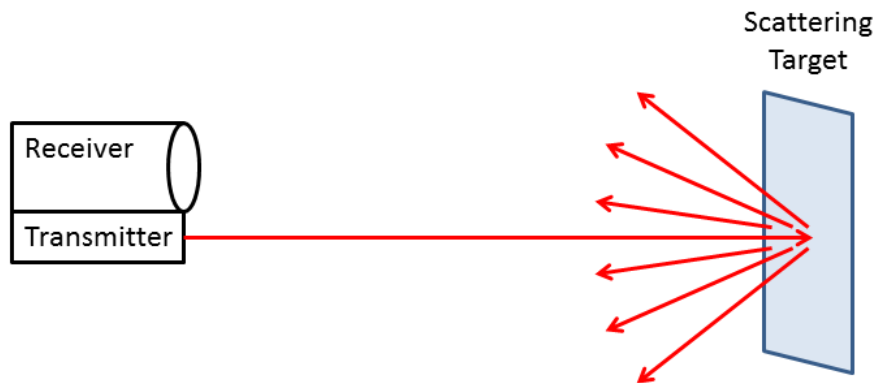


Figure 79: Diagram of the IPDA measurement. Laser light projected from a lidar transmitter scatters off of a hard target and is collected by a receiver for analysis.

When this measurement is made from an aircraft, a gas concentration measurement error is introduced by the fact that since the aircraft is moving, the online and offline laser pulses do not scatter from the exact same section of ground (Figure 80).

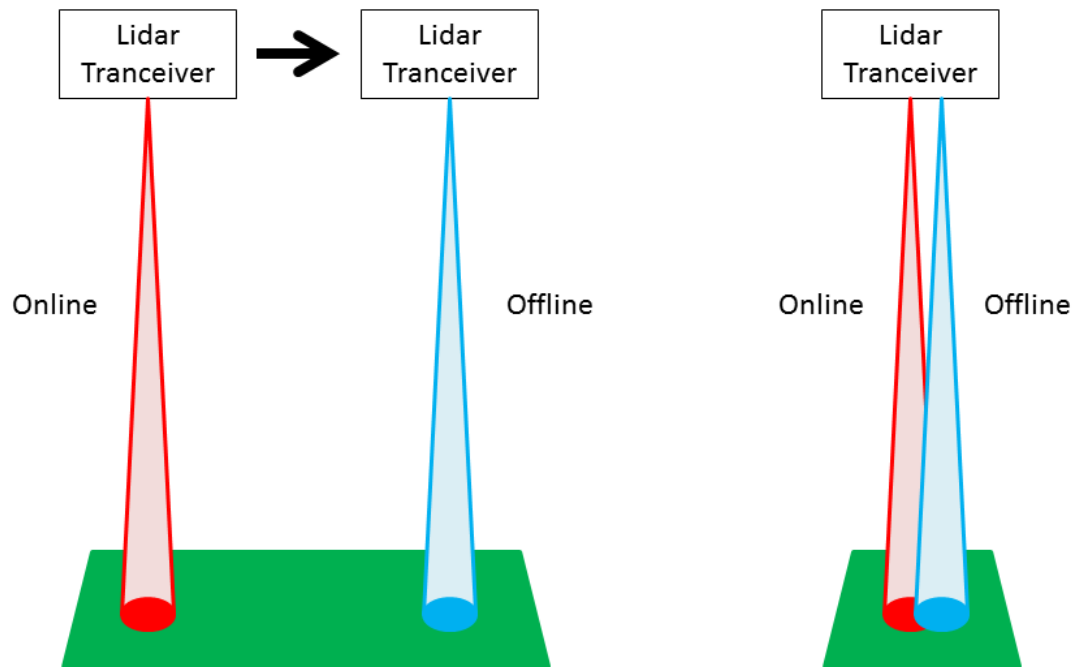


Figure 80: When making the IPDA measurement from a moving platform such as an aircraft, an error is introduced in the measurement by the fact that the backscattered signal came from different footprints on the ground. Shorter delays between the online and offline as depicted on the right reduce the error by having the two beams' footprints have a large overlap.

This error can be reduced by firing the offline laser pulse as quickly as possible after the online laser pulse to maximize the overlap of the two laser pulse spots on the ground (Figure 81)

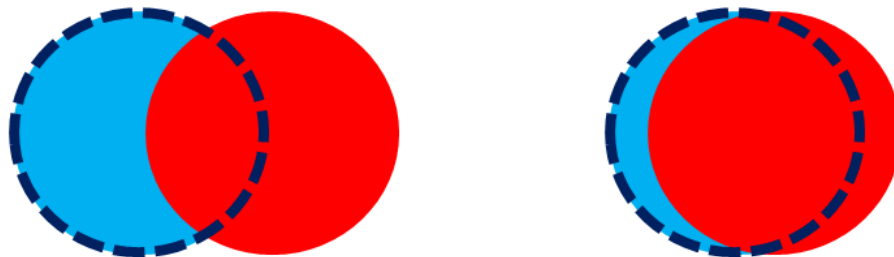


Figure 81: The closer the online (red) and offline (red) laser shots occur together, the greater the overlap on the scattering target which reduces the CO₂ measurement error.

The 2 micron IPDA utilizes a double pulsed Hm:Tm:YLF laser capable of firing a second laser pulse 100 us after the first pulse to produce a ground spot overlap of 95% at typically cruising altitudes and speeds.

Wavelength Control Unit

Carbon dioxide absorption lines in the 2.05 micron band are roughly an order of magnitude stronger than those at 1.57 microns. As a result, the IPDA online wavelength is detuned from the absorption line center 2-6 GHz in order to optimize the optical depth of the air column being measured (Figure 82).

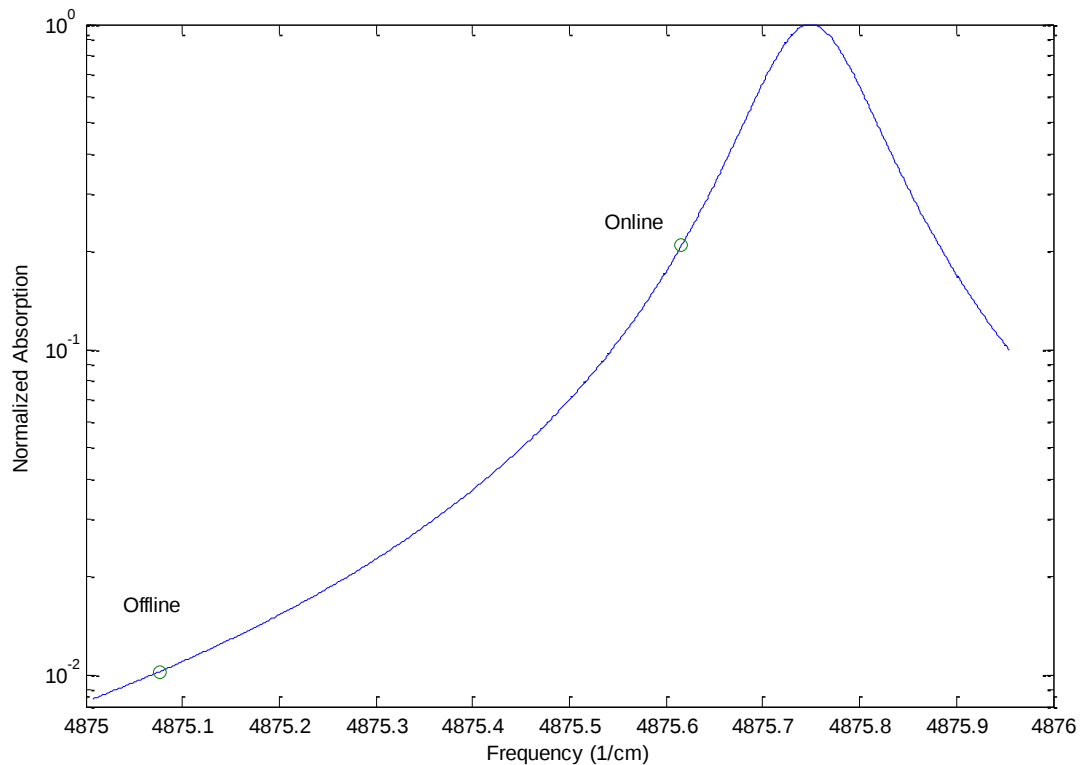


Figure 82: Normalized absorption line used for the IPDA measurement with the Online and Offline positions marked.

In order to meet the target precision of less than 1 ppm error on the column integrated concentration measurement, the online wavelength needs to be held to at least ± 1 MHz of the set wavelength. To hold the online laser to this precision, a wavelength control unit was constructed for robust self-contained control of the lasers that seed the laser cavity (Figure 83).



Figure 83: Photo of the wavelength control box

The wavelength control unit contains three Hm:Tm:YLF seed laser sources that rest on a water cooled platform. The first laser is used as a reference laser source that is locked to the center of the CO₂ absorption line with a partially evacuated CO₂ gas cell with the Pound-Drever Hall technique (Figure 84).

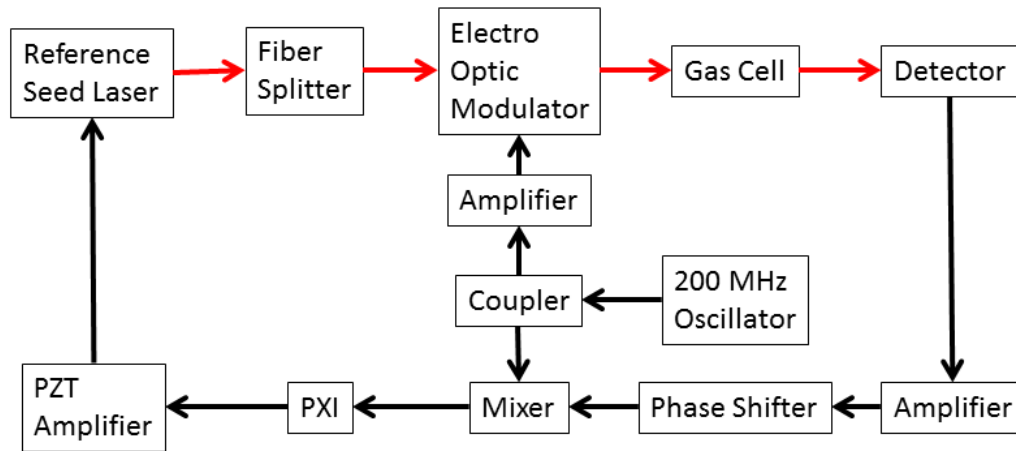


Figure 84: Schematic of the reference laser locking system used in the wavelength control unit.

This scheme provides an electronic error signal used to quantify the deviation of the laser wavelength from the absorption line center (Figure 85).

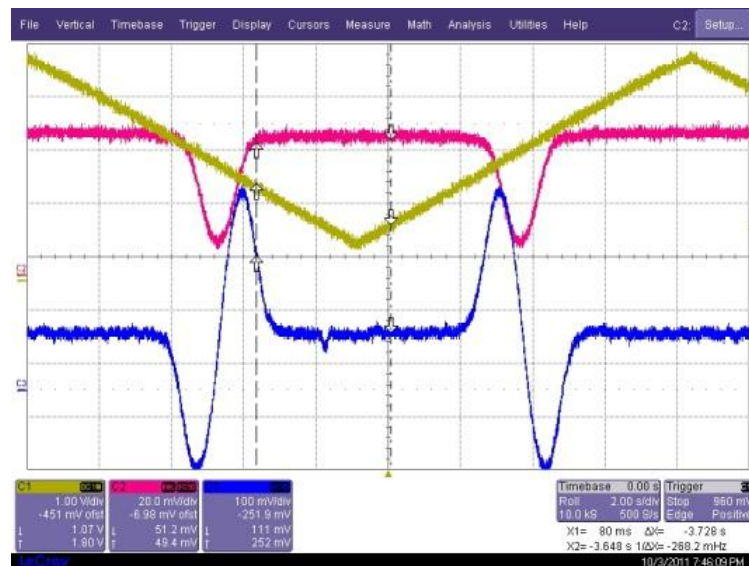


Figure 85: As a control signal (Yellow curve) tunes the wavelength of the reference laser over an absorption line, the transmitted signal intensity (Pink Curve) traces out the absorption line shape. With the system shown in Figure 6, an error signal is generated (Blue curve) that provides information regarding the position of the reference laser's wavelength relative to the line center. This signal is used to control the reference laser, holding it to the center of the absorption line.

This error signal is monitored with a Labview program on a National Instruments PXI unit (Figure 86) which measures the error signal, and generates a control signal with a PID control loop that is amplified by a Piezo-electric amplifier/controller (Figure 87). The amplifier adjusts a piezo-electric element within the seed lasers for fine adjustment of the operating wavelength.

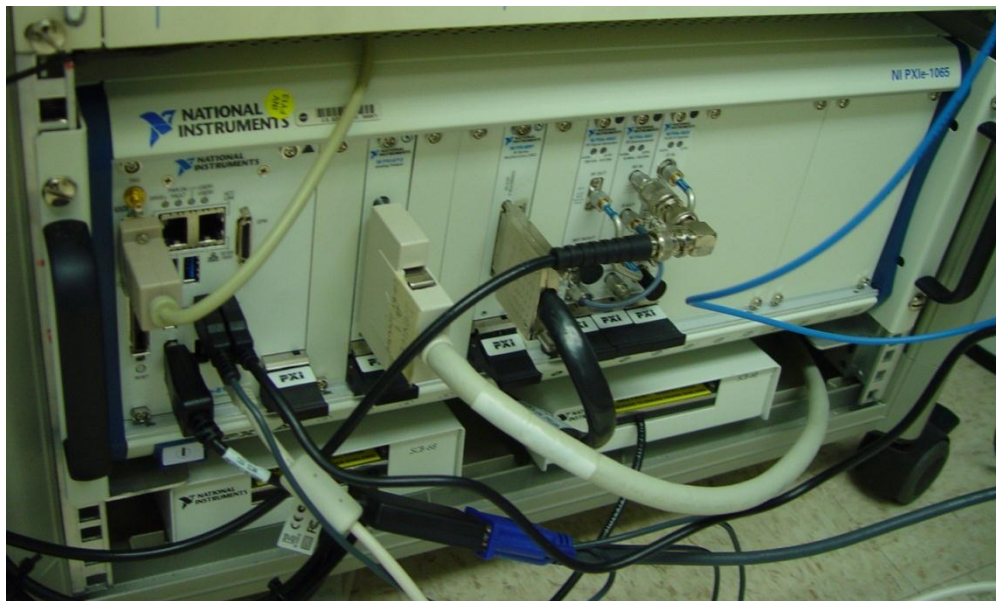


Figure 86: Picture of the PXI unit used for controlling the seed laser sources

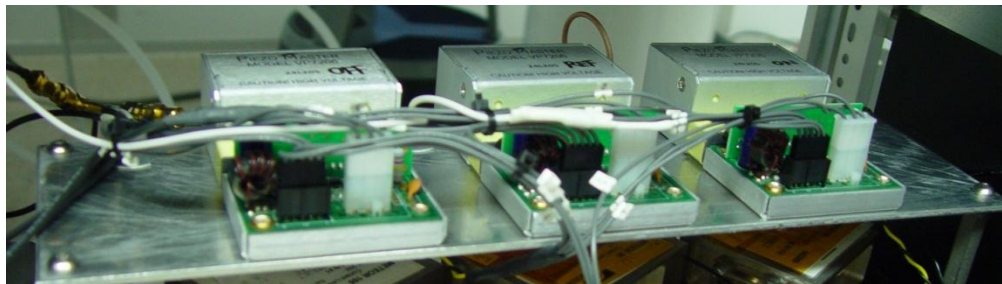


Figure 87: Picture of the piezo-electric amplifiers/controllers

With the reference locked to the absorption line center, the online wavelength can then be locked to the reference laser. This is achieved by first mixing the two optical

signals with a fiber coupler. The mixed optical signal is then measured with a fast optical detector. The frequency spectrum of the electronic signal output of the optical detector is measured with an RF downconverter within the PXI unit. Within the frequency spectrum is a peak centered at the difference in optical frequencies of the reference and online lasers. The beat frequency is measured and a control signal from a PID software loop within the same Labview VI controlling the reference laser is amplified by another Piezo amplifier to adjust the online laser's frequency to the desired offset from the absorption line center, typically ranging from 2-6 GHz.

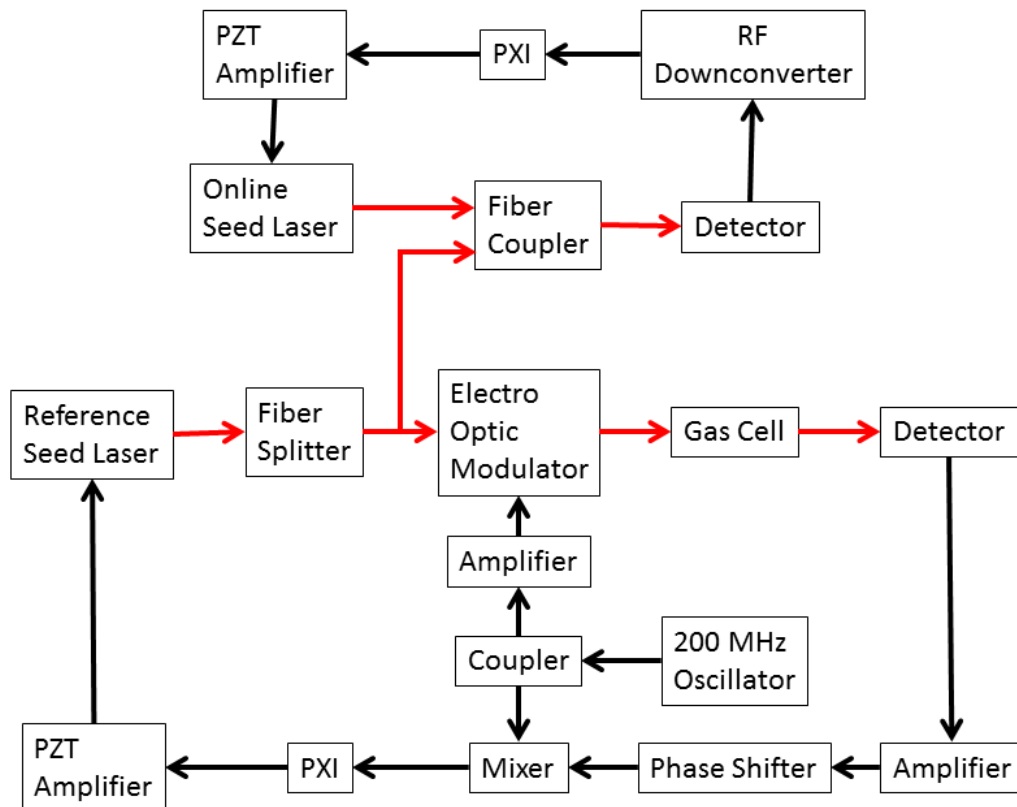


Figure 88: Diagram showing the components used to lock the online laser a set frequency offset from the reference laser.

The third seed laser within the wavelength control unit is held to the offline wavelength by measuring its wavelength with a Bristol 621 Wavemeter. The difference between the offline laser's actual wavelength from the desired wavelength is calculated and a control signal is generated to adjust the offline laser based on a PID control loop within a Labview VI on the PXI unit. The control signal is amplified with a third piezo amplifier connected to the piezo control connection on the offline laser. The locked online and offline laser signals are each connected to the input of a 2x1 electro-optic switch. The switch allows the operator to switch seed wavelengths between the first and second laser pulse of the IPDA's pulse pair output. The output of the switch seeds the laser cavity that generates the pulse pair for the IPDA measurement.

Laser Transmitter

The output of the wavelength control unit seeds the laser cavity which generates the high energy pulse pair used for the IPDA measurement. The laser cavity is a ramp and fire Q-switched bowtie cavity (Figure 89) with a water cooled diode pumped Ho:Tm:YLF gain crystal. The cavity generates a pulse pair with characteristics described in Table 4.

Pulse Energy Offline/Online	40 mJ/100 mJ
Pulse Pair Repetition Rate	10 Hz
Pulse Pair Separation	200 μ s
Pulse Duration Offline/Online	600 ns/200 ns
Beam Diameter	18 mm
Laser Cavity Length	3 meters

Table 4: Laser transmitter characteristics

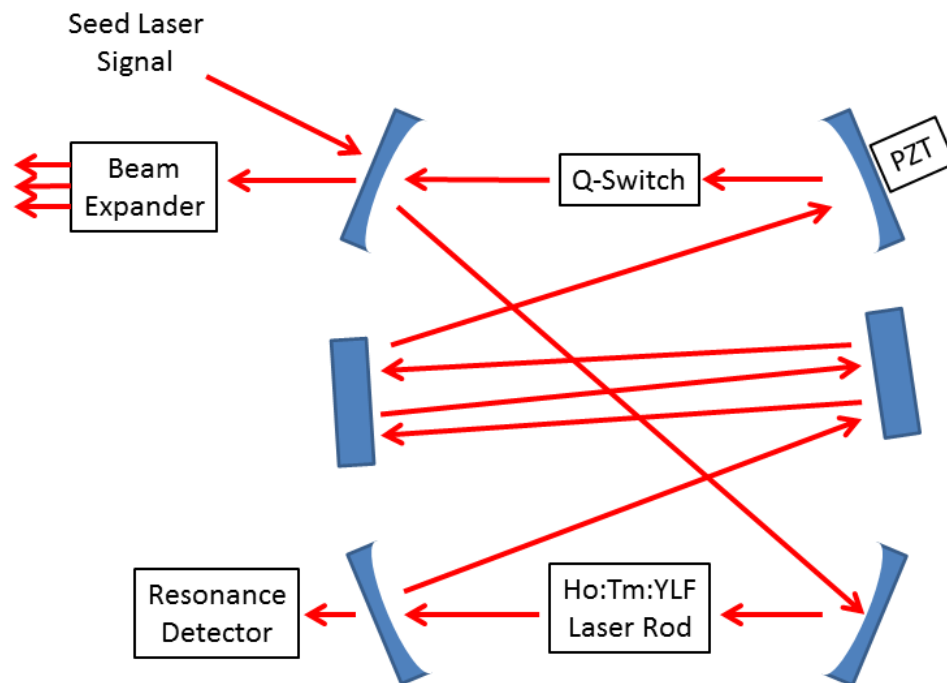


Figure 89: Diagram of the IPDA laser cavity

The output of the laser cavity is expanded by 6X to reduce the nominal ocular hazard distance (NOHD) of the IPDA to less than 500 meters. The entire laser cavity is mounted on a water cooled plate which is kinematically mounted to a hermetically sealed

housing to maintain laser alignment under flight conditions. Within the laser cavity housing is the energy monitoring detector used to measure the relative transmitted energies of the online and offline laser pulses. Each transmitted pulse profile measured with the energy monitor is recorded by a digitizer for later analysis.

Laser Receiver

Once the IPDA pulses have scattered off of the ground, a portion of the scattered light is collected by the IPDA receiver (Figures 90, 91).

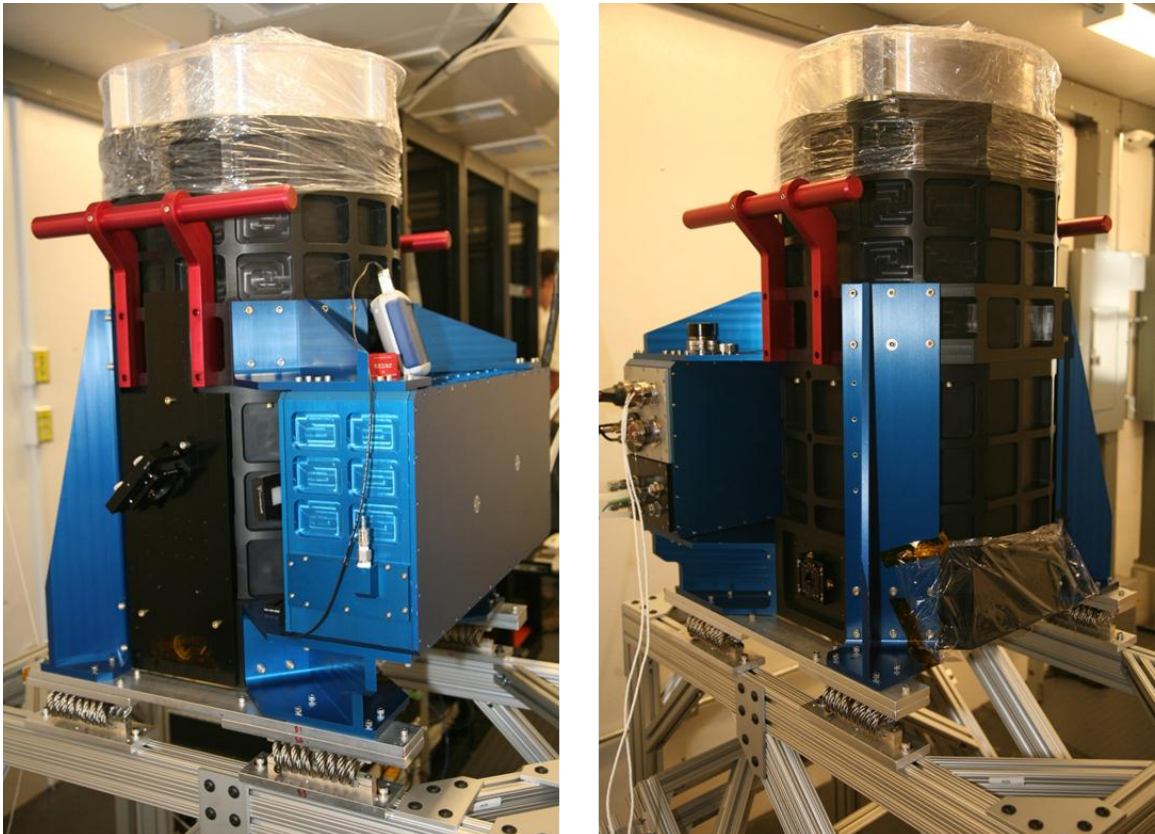


Figure 90: Photos of the IPDA receiver

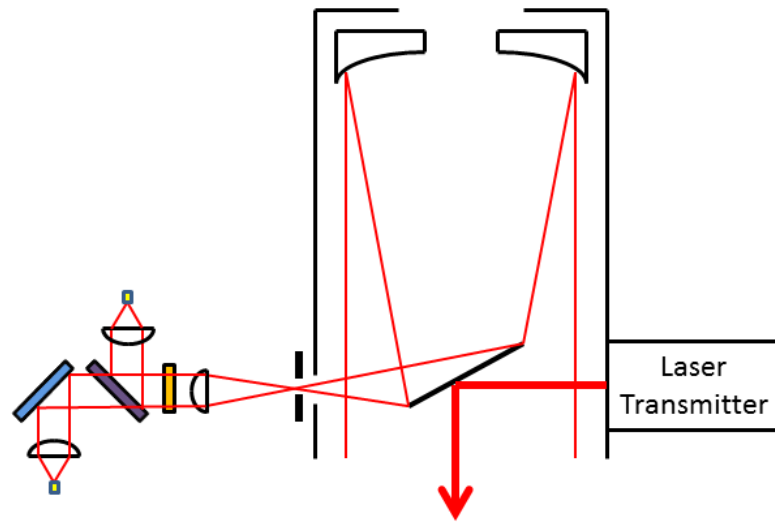


Figure 91: Diagram of the IPDA receiver

The receiver is Newtonian telescope made for the IPDA project. The light collected by the telescope is focused through a pinhole to set the IPDA's field of view. The light is then collimated with a lens and filtered with a narrowband optical filter. The filtered light is then split with a 90/10 beamsplitter in to a high and low gain channel to accommodate the range of reflectivities expected for the different ground targets. At the end of each channel, another lens focuses the signal light on to an optical detector. The measured optical detector signal is recorded with a digitizer for later analysis. The entire receiver is mounted on wire rope isolators for vibrational isolation of the instrument.

Ground Testing

Prior to flying the instrument, initial testing of the IPDA instrument was carried out in a climate controlled research trailer made for the IPDA (Figure 92).

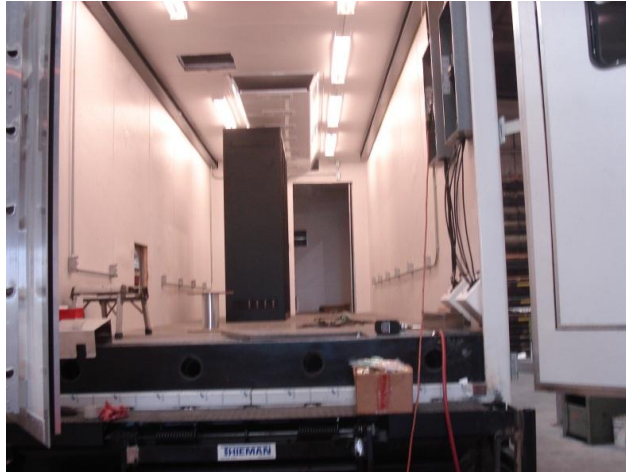


Figure 92: Photo of the inside of the research trailer used for ground testing.

The trailer is equipped with windows mounted in the roof and side for firing the IPDA vertically or horizontally. When fired horizontally, the IPDA was directed towards various hard targets including a set of reference targets built to simulate the reflectances of different ground targets such as ice, snow, water, and foliage for characterization of the IPDA's performance against these different targets. For data comparison, an LI-840A CO₂ and water vapor sensor (Figure 93) was deployed in the vicinity of the sampled air volume for comparison of the dry air mixing ratios measured with the IPDA.



Figure 93: Photo of the LI-840a

The LI-840A was calibrated with two point calibration against a NOAA reference standard cylinder of carbon dioxide used for the CO₂ global carbon monitoring network and a cylinder of dry nitrogen.

Flight Testing

The ultimate goal for the IPDA project is to make 20 hours of flight based IPDA measurements of CO₂. NASA Langley has a B200 aircraft equipped with nadir pointing window for lidar instruments (Figure 94).



Figure 94: Photo of the B200 aircraft used for the IPDA flight measurements

The IPDA transceiver will be mounted directly over this window during flight and its supporting systems mounted on three different racks attached to the aircraft (Figure 95)

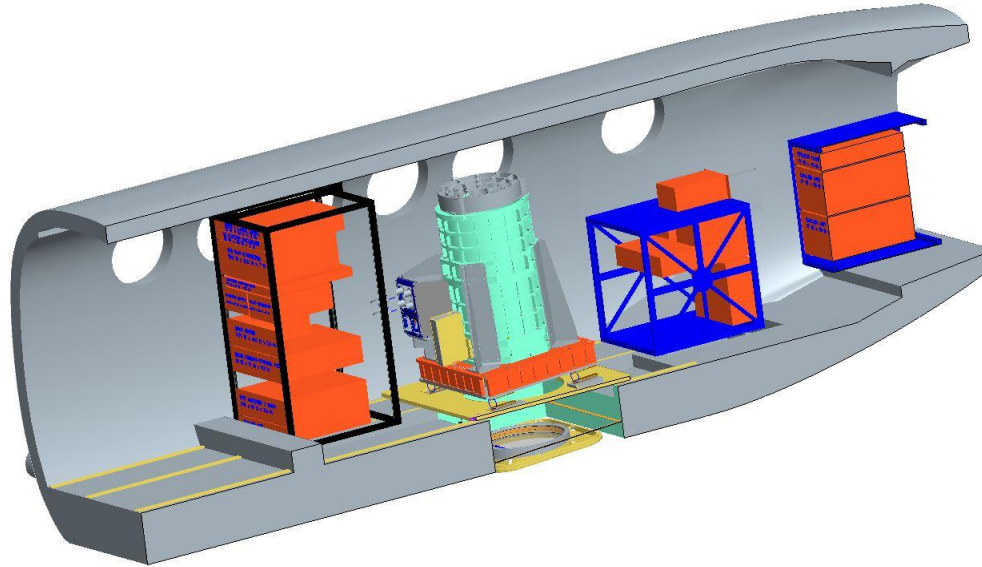


Figure 95: Diagram of the planned aircraft layout

While the IPDA measurements are being made during flight, in situ measurements of absolute pressure and temperature, relative humidity, GPS position will be made for later use during post processing for the IPDA data. The B200 will also be equipped with an inlet port mounted on the roof of the aircraft to sample the outside carbon dioxide and water vapor concentrations with the LI-840A sensor. Anticipated flight measurements are expected to occur in the first few months of 2014. These measurements will be carried out following flight paths in the Hampton area at an altitude of 28,000 feet.

CONCLUSIONS/FUTURE WORK

To date the DIAL constructed at Montana State University built for monitoring carbon sequestration site integrity has performed range resolved measurements of carbon dioxide with an eye-safe configuration using commercial off the shelf components. The DIAL has been deployed in the Bozeman area as well as the Kevin Dome sequestration site in Oilmont Montana. The system measures carbon dioxide concentrations with a typical precision of $\pm 15\%$ with 60 minute averaging times and a spatial resolution of 200-750 meters. While the DIAL meets the specification objectives for being able to potentially identify a carbon sequestration site leakage, there is considerable room for instrument improvement. These improvements include:

- 1) Replacing the slow electro-mechanical fiber optical switches with an electro-optic 2x1 switch
- 2) Replacing the AOM with an electro-optic modulator
- 3) Converting the online/offline switching to electronic control coupled to the RF signal switch signal router for shot to shot switching
- 4) Locking the online wavelength with a gas cell
- 5) Updating and optimizing the laser transmitter beam expander
- 6) Effectively implementing the NIR APD photon counting module
- 7) Replacing the ILX laser diode drivers with more compact OEM type laser diode drivers
- 8) Redesigning the DIAL receiver optics for near field optimization

- 9) Converting the amplifier to be polarization maintaining with a bare fiber output for improved output beam quality control
- 10) Powering the DIAL with a remote power system that does not emit carbon dioxide
- 11) Implementing a sum-frequency generation setup in to the DIAL receiver

Replacing the Slow Electro-Mechanical Fiber Optical Switches

The DIAL is limited in its switching speed agility by the use of the electro-mechanical fiber optic switches. These switches were originally chosen for their low transmission loss and low cost. However, fast electro-optic switches with tolerable levels of transmission loss and reasonable cost are becoming more and more commercially available (Figure 96).



Figure 96: A high performance commercial electro-optic switch

These switches are capable of switching between inputs in 10's of nanoseconds, allowing for laser shot to shot wavelength switching. This fast switching is also advantageous, in that it leaves a brief enough dead time between switching from one input to another to not introduce any deleterious spontaneous emission or stimulated Brillouin scattering induced from large upper energy level energy storage. Shot to shot switching is also advantageous, in that the DIAL calculations of range resolved gas

concentrations have reduced errors from atmospheric fluctuations: the shot to shot switching allows the online and offline wavelengths to have sampled a nearly identical atmosphere. Practically speaking, these electro-optic switches also only require a TTL electronic modulation signal to operate, unlike their acousto-optic counterparts which require RF acousto-optic drivers as discussed in Chapter 3. This would reduce the overall complexity of the DIAL.

Replacing the AOM with an Electro-Optic Modulator

In addition to the improvements seen in electro-optic switching technology in recent years, electro-optic intensity modulators have also progressed considerably. Such intensity modulators have much faster switching times than their acousto-optic counterparts (Figure 97).



Figure 97: A high performance electro-optic intensity modulator

The switch shown in Figure 97 is capable of producing pulses as short as a few nanoseconds. Pulses this short are shorter than the SBS buildup time in optical fibers. This means that while for longer pulses where SBS has time to build up and limit the total power transmitted through the fiber before SBS sets in, pulses shorter than 10 nanoseconds (the phonon coherence time in silica fibers) can be very large in intensity without being restricted by SBS thresholds. This would enable the DIAL to operate at

higher output powers which would improve signal to noise ratios in the measured lidar signals.

Converting the Online/Offline for Shot to Shot Switching

A subtle improvement to the DIAL's overall structure in the interest of reducing the demands on the controlling PC, especially with potential shot to shot wavelength switching, would be to connect electronically the RF signal switch to the electro-optic control signal (Figure 98) or a set of AND logic gates (Figure 99) for online/offline signal routing. Electronic coupling of the seed laser switching to the data acquisition channels would alleviate requirements that the PC always switch the data routing circuit at the same time that the seed wavelength is switched.

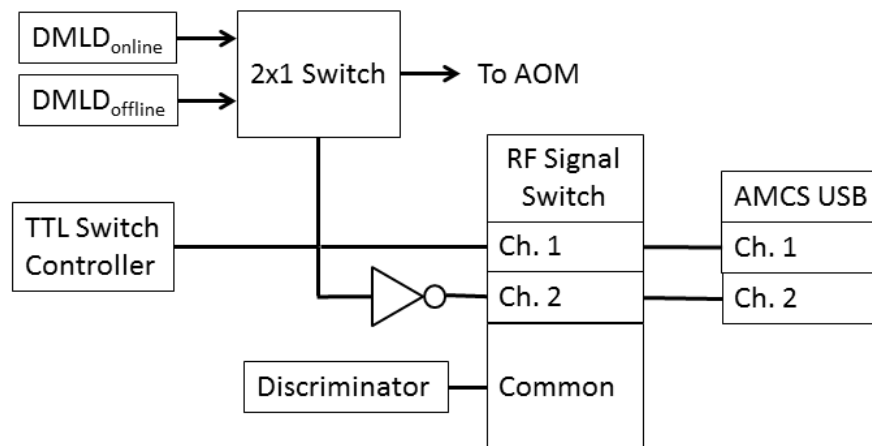


Figure 98: Electronics schematic showing the coupling of the laser wavelength switching with the data acquisition routing using the RF signal routing switch

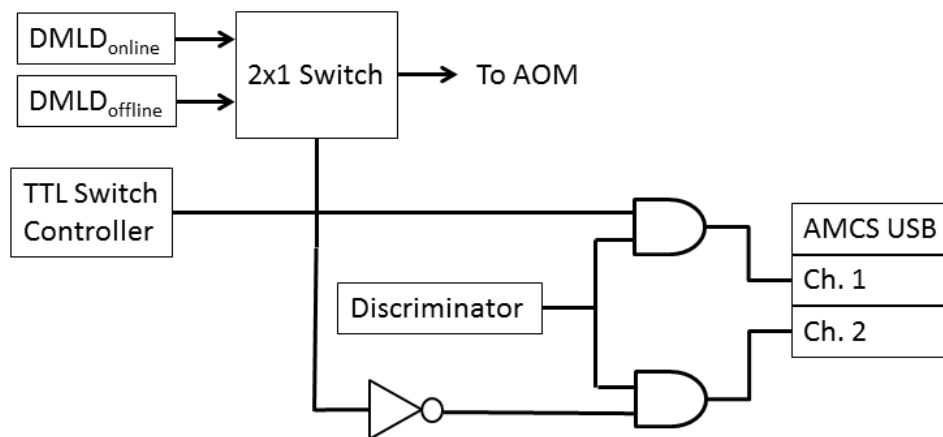


Figure 99: Electronics schematic showing the coupling of the laser wavelength switching with the data acquisition routing using NOT and AND logic gates

To date, the data acquisition with the AMCS significantly taxes PC resources to a point where considerable effort was undertaken to ensure that the DIAL's Labview control software did not overstretch the PC. Using electronic control of the signal routing and laser wavelength switch would allow wavelength switching rates up to shot to shot switching without imposing any demands on PC. This would enable the PC to only need to handle data acquisition and saving, as well as other basic hardware control.

Locking the Online Wavelength with a Gas Cell

Currently the online laser wavelength is maintained with a wavemeter which to date holds the online wavelength to a precision of 37 MHz. This could be improved with the addition of an absorption cell locking scheme as described in Chapter 5 for locking the IPDA's online wavelength. This locking has been accomplished on other 1.5 micron

CO₂ DIAL systems⁵⁸ (Figure 100) which have achieved wavelength locking precision of 0.3 MHz.

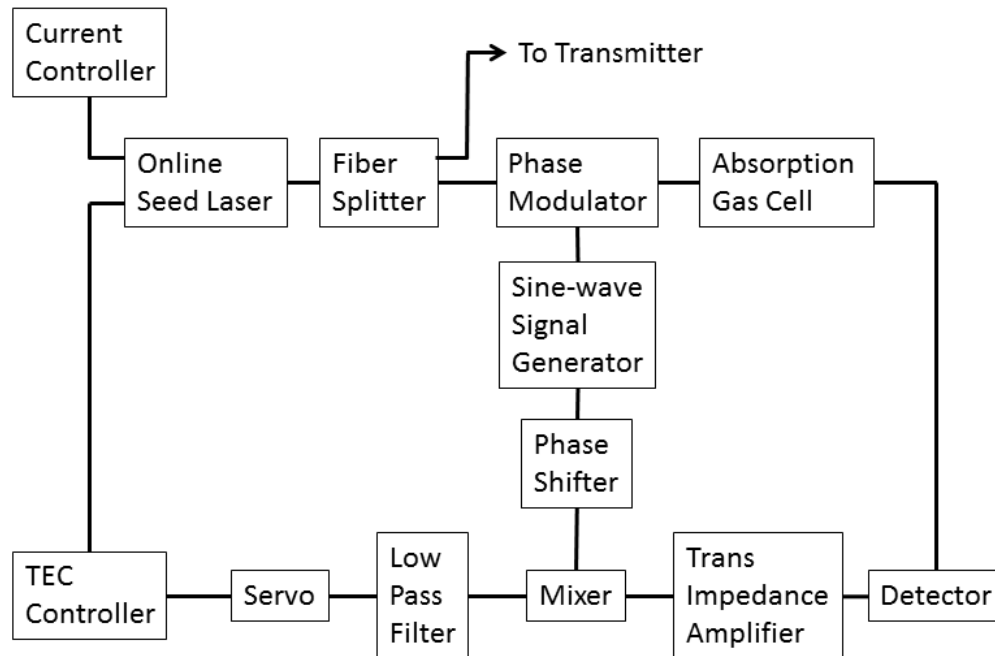


Figure 100: Schematic for the absorption gas cell based laser locking scheme as described in reference 1.

Updating and Optimizing the Laser Transmitter Beam Expander

To date the DIAL expands the transmitted beam to an eye safe diameter with a combination of plano convex and plano concave spherical lenses. This approach, instead of using a commercial beam expander, was done due to the EDFA's output beam diameter being larger than most commercial beam expander's input apertures. The transmitted beam on the DIAL suffers from considerable aberration. This is believed to be in part to the use of spherical lenses. A potential improvement, at least for the

diverging lens would involve using a large aperture short focal length aspheric lens for diverging the beam while maintaining the same beam expander length.

Effectively Implementing the NIR APD Photon Counting Module

In the Spring of 2013, a near infrared free running photon counting avalanche photodiode module was purchased to eventually replace the PMT module (Figure 101)

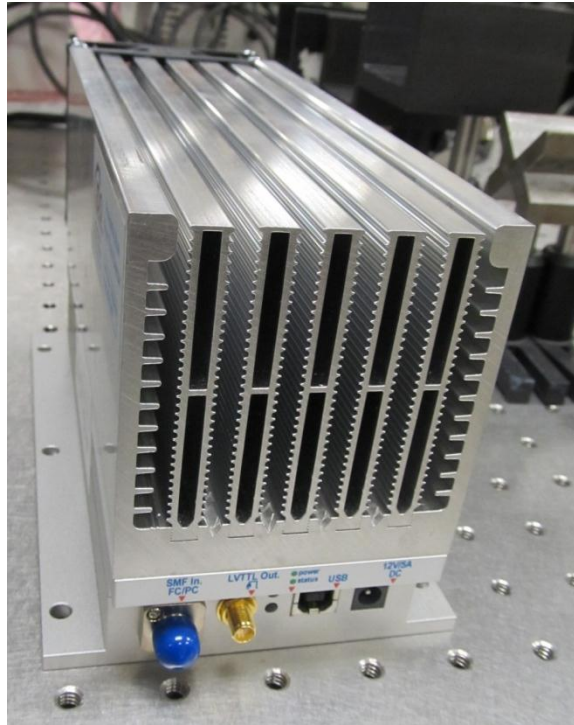


Figure 101: Photo of the ID220 NIR APD photon counting module from IDQuantique
The pertinent performance specifications compared to the PMT module are detailed in Table 5

	PMT	APD
Dark Count Rate	200 kHz	2 kHz*
Dead Time	NA	10 μ s
Maximum Count Rate	1 MHz	100 kHz*
Active Area Diameter	18 mm	100 microns

*With 10 μ s dead time

TABLE 5: Comparison of the PMT and APD's specifications

From Table 5, one can see that nearly all of the APD's performance specifications far exceed those of the PMT module. The major disadvantage of the APD module is its small active area, which at 100 microns represents roughly the smallest reasonable fiber diameter achievable with the commercial optics used with the DIAL.

Replacing the ILX Laser Diode Drivers

Currently the seed lasers for the DIAL are driven with a pair of ILX 372B laser diode drivers. While reliable and easy to use, these units are bulky and do not reliably operate below ambient temperatures of 55 degrees Fahrenheit, which has been an issue especially during field experiments where the nighttime temperatures are often around 50 degrees or less. An alternative option would be to use two Wavelength Electronics combination laser diode and temperature controllers (Figure 102).



FIGURE 102: The proposed Wavelength Electronics combination laser diode and TEC controller replacement for the ILX laser diode drivers.

These laser controllers are small, robust, and operate over a larger ambient temperature range than the ILX drivers, making them ideal candidates for replacing the ILX drivers for the DIAL, especially under field conditions.

Redesigning the DIAL Receiver Optics for Near Field Optimization

The current receiver design for the DIAL could be improved by redesigning the receiver to be a telecentric pupil imaging system. While more complicated than the current optical layout, the different design approach has the advantage of reducing overlap issues associated with ground imaging lidar layouts like the one used on the current DIAL system.

Converting the Amplifier to be Polarization Maintaining with a Bare Fiber Output

Considerable improvement with the DIAL could also be achieved by replacing the current EDFA with an EDFA that is both polarization maintaining and has a bare fiber output instead of a collimated terminated output. The currently used EDFA is randomly polarized, meaning that the output polarization drifts with time, especially during the first 30 minutes of operation.

This unstable polarization axis is problematic if the user wishes to pickoff a portion of the transmitter beam for output power monitoring purposes. As the polarization drifts, the fraction of light monitored with a beamsplitter and detector varies due to polarization sensitivity of many beamsplitting optics. A fixed polarization would allow for a constant fraction of light to be picked off for output power monitoring. Using a bare fiber terminated output amplifier would be advantageous for improving transmitter beam quality. The current EDFA used has a measured M squared of 4, which makes collimation of the transmitter beam difficult. The problem seems to be with the

collimator attached at the end of the EDFA output. Using a bare fiber output amplifier in combination with higher quality fiber collimations optics would improve the transmitter beam divergence. This is of considerable importance, given that the DIAL, especially when using the smaller 100 micron core fibers, is very sensitive to transmitter beam divergence. If the transmitted beam diverges excessively, the focused spot size at the face of the fiber coupling the received light to the APD detector is larger than the fiber core diameter, meaning that the DIAL never comes in to full overlap which severely restricts the DIAL's ability to make quantitatively accurate carbon dioxide concentration measurements.

Remote Power (Solar/Wind)

For field deployments, the DIAL to date has operated off of a portable generator (Honda EU2000i, Figure 103)



Figure 103: The Honda EU2000i generator that has been used to operate the DIAL during field experiments.

The DIAL system only consumes around 500 watts of power, which is easily driven by commercial generator systems. There are disadvantages of using a generator. First, a generator requires routine attention in terms of servicing and refueling. This places logistical demands on the DIAL in terms of staffing, as someone must be in constant attendance of the system. Second, the generators themselves are emitters of carbon dioxide. While it is believed that they do not emit enough carbon dioxide to interfere with the DIAL measurements in any significant way, they do interfere with any in situ carbon dioxide sensors operating in the vicinity of the DIAL. Since many sequestration sites will employ a variety of monitoring technologies, some highly sensitive to false positives that generator emissions would cause, it would be desirable to upgrade the DIAL to run on a remote solar/wind based power system (Figure 104)



Figure 104: An example of a remote power system⁵⁹

The minimal power consumption of the DIAL system would allow a user to upgrade the DIAL to a remote off the grid power system for an initially estimated cost of 2,750 dollars. Such as system would require

Solar panels 1,000 dollars

Inverter: 250 dollars

Wind turbine: 1,000 dollars

Batteries: 500 dollars

Implementing Sum-Frequency Generation

The major limiting factor of the DIAL system and infrared active optical remote sensing instruments in general is the limited availability of single photon sensitive detectors in the infrared region. As an alternative to direct infrared photon detection, the use of sum-frequency generation (SFG) techniques could potentially be used to measure the infrared photons indirectly⁶⁰.

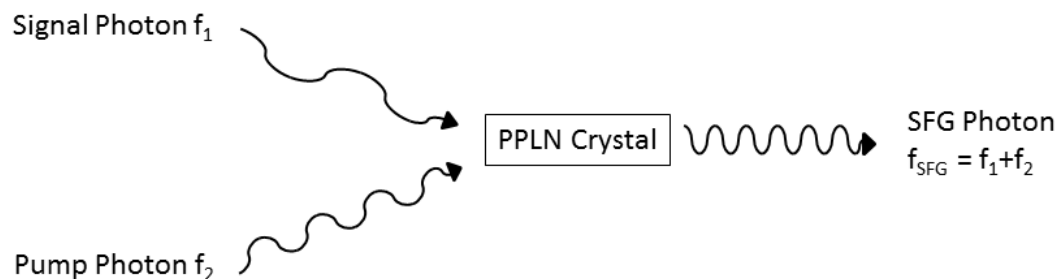


Figure 105: Sum frequency generation involving a PPLN crystal where a signal and pump photon combine to create a single photon whose frequency is the sum of the pump and signal photon frequencies.

Sum frequency generation involves the combining of two photons in to a single photon whose energy is equal to the sum of the original two photons. Using a pump laser source, the DIAL's collected signal would pass through a SFG setup to convert the 1.57 micron photons in to photons in the visible range that could be detected by more mature silicon based avalanche photodiode based photon detectors.

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