A FIBER OPTIC ARRAY FOR THE DETECTION OF SUB-SURFACE CARBON DIOXIDE AT CARBON SEQUESTRATION SITES

by

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DEDICATION

This thesis is dedicated to my brother Zachary. It’s neither what happens to us nor what we are given which matters most; it’s what we choose to build.
ACKNOWLEDGEMENTS

First and foremost I would like to thank Dr. Kevin Repasky, my advisor, for his relentless hard work and dedication in helping me work towards my degree and the completion of this project. Big thanks as well to Dr. John Carlsten for always being able to explain things in a way that I can understand, and for being a continual source of good ideas. Finally, thank you to my mother and father for all their support.

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A fiber sensor array for sub-surface CO₂ concentrations measurements was developed for monitoring geologic carbon sequestration sites. The fiber sensor array uses a temperature-tunable distributed feedback (DFB) laser outputting a nominal wavelength of 2.004 μm. Light from this DFB laser is directed to one of the four probes via an in-line 1x4 fiber optic switch. Each of the probes is placed underground and utilizes filters that allow only soil gas to enter the probe. Light from the DFB laser interacts with CO₂ within the probe before being directed back through the switch. The DFB laser is tuned across two CO₂ absorption features where a transmission measurement is made, allowing the CO₂ concentration to be retrieved. This process is repeated for each probe, allowing CO₂ concentration measurements to be made as a function of time for each probe. The fiber sensor array was deployed for fifty-eight days at the Zero Emission Research Technology (ZERT) field site and for a twenty-eight day period at the Kevin Dome geologic carbon sequestration site. Background measurements indicate the instrument can monitor background levels as low as 1,000 parts per million (ppm). During a thirty-four day sub-surface CO₂ release, elevated CO₂ concentrations were readily detected by each of the four probes with values ranging to over 60,000 ppm.
INTRODUCTION

Rise in Atmospheric Carbon Dioxide

The average atmospheric concentration of carbon dioxide CO$_2$ has been monitored continuously at the Mauna Loa Observatory in Hawaii since 1957.$^{1,2}$ The average atmospheric concentration of CO$_2$ has risen over the past fifty five year observation record from a mean value of 315.97 parts per million (ppm) in 1959 to more than 400 ppm in 2014. Furthermore, the rate of change of the atmospheric concentration of CO$_2$ has increased from an average value of 0.85 ppm/year between 1960 and 1969 and 2.05 ppm/year between 2004 and 2013. Records of CO$_2$ concentrations from other sites around the globe show similar results.$^2$

The increasing level of atmospheric CO2 is due to anthropogenic activity including the burning of fossil fuel and land use changes.$^3$ The CO$_2$ emission from fossil fuel combustion was 7.9 gigatonnes of carbon (GtC) per year in 2005 while the CO$_2$ emission from land use changes, mainly clearing of land, was 1.5 GtC per year in 2005.$^6$ Atmospheric CO$_2$ is estimated to contribute approximately 63% of the gaseous radiative forcing responsible for anthropogenic climate change. The increasing atmospheric concentration of CO$_2$ resulting from anthropogenic sources including fossil fuel consumption and land use changes, is causing international concern regarding the effects on the climate system.$^7$ This concern is due to the fact that the earth acts a blackbody radiator at around -20 °C and emits infrared light, originally absorbed from the sun, in a range of wavelengths from ~ 3-50 µm. This emitted infrared light corresponds directly
with a number of absorption bands for CO$_2$, specifically at 12 and 14 µm in wavelength. Energy radiated by the earth is being absorbed by atmospheric CO$_2$ at these wavelengths, and is causing an overall heating of the earth which is in-turn affecting the climate system.

Carbon sequestration$^{16-21}$ is one method for mitigating the emission of carbon dioxide from power generation facilities. Carbon sequestration captures the CO$_2$ at sources such as coal-fired power plants and then injects the CO$_2$ into geologic formations to minimize the CO$_2$ emissions into the atmosphere. Furthermore, injection of CO$_2$ can be used for Enhanced Oil Recovery (EOR), extending the production lifetime of oil wells. A variety of carbon sequestration projects on the commercial scale are under way, including the Sleipner Saline Aquifer Storage Project$^{22}$ currently storing CO$_2$ beneath the North Sea and the Weyburn Project in Canada,$^{23,24}$ which is using injected CO$_2$ for EOR to extend the life of the oil fields. Furthermore, in the United States, seven regional Carbon Sequestration Partnerships$^{25}$ are working to develop the science and technology needed for successful and safe carbon sequestration and EOR.

Monitoring instrumentation is one of many areas of technology development needed to ensure both the integrity of carbon sequestration sites and public safety.$^{26-33}$ This instrumentation will be needed for both tracking the fate of the CO$_2$ once it is injected requiring monitoring technology based on seismic detectors, and instrumentation that can be placed down monitoring wells, such as pressure and temperature monitors. Furthermore, detection techniques and instrumentation for near-surface monitoring are needed as well for ensuring both carbon sequestration site integrity and public safety. A
variety of monitoring tools and techniques need to be developed to encompass the wide variability in the carbon sequestration sites. One specific group of detection tools currently in development utilize the light from a tunable distributed feedback (DFB) laser to monitor molecular absorption of ambient air, allowing CO$_2$ concentrations to be found. In this thesis, the development and demonstration of a 1 x 4 fiber sensor array operated with a DFB laser for sub-surface monitoring of CO$_2$ is presented.

The 1 x 4 fiber sensor array utilizes a single DFB laser operating in the continuous wave (cw) mode with a nominal operating wavelength near two microns to make integrated-path differential absorption (IPDA) measurements of sub-surface CO$_2$ concentration. The light from the DFB laser is directed by a 1 x 4 fiber optic switch to the first of 4 probes that are placed underground. The light interacts with the sub-surface CO$_2$ and is then directed back through the switch to a transmission detector. The DFB laser is scanned over CO$_2$ absorption features allowing sub-surface CO$_2$ concentrations to be retrieved. The fiber optic switch then addresses the second probe and this process is repeated until measurements at all 4 probes have been completed at which point the process is repeated.

The predecessor to this 1 x 4 array was tested in the years prior to the 2012 test of this instrument. The previous instrument did not incorporate a fiber switch and used only a single sub-surface sensor. Four probes were chosen as a tractable means to test the scalability of the system as pertinent for use at commercial or large-scale sequestration sites.
This 1 x 4 sensor array offers a variety of advantages for commercial and scientific use. The send/call geometry of the programming allows the fiber array to be scaled to $N$ probes in a cost-effective manner by utilizing a single laser, two detectors, and one fiber optic switch, which are the expensive components, while designing the probes to be low cost. Commercial switches with up to 1 x 50 are available,$^{39}$ allowing this technology to scale up to a 1 x 50 array leading to a low-cost sensor array since the cost of each fiber probe is minimal. Comparable point sensor arrays for CO$_2$ can easily add an order of magnitude in terms of cost for a system of the same size. Furthermore, because the instrument uses all fiber optic components, the sensor can be configured easily for field deployment and is not affected by adverse weather conditions. The system is also designed to run completely autonomously for extended periods of time, and only requires personnel for data retrieval. Finally, even operating with a very low-power DFB laser, and short-length, free-space cells, sub-surface CO$_2$ fluctuations due to microbial activity can be monitored. Integration of a second DFB laser and a multiplexer could allow for measurements of sub-surface oxygen (O$_2$) levels, and allow for conclusions to be drawn on changes in soil gas content and its causes.

This thesis is organized as follows. A brief discussion of integrated-path differential absorption (IPDA) spectroscopy is presented in the rest of this section. In section II, a description of a 1 x 4 fiber sensor array is presented. Data from a fifty-eight day field deployment at a controlled subsurface release of CO$_2$ at the Zero Emission Research Technology (ZERT) field site$^{40,41}$ is presented in section III along with data
from the Kevin Dome deployment. Finally, some brief concluding remarks are presented in section IV.

Integrated Path Differential Absorption Spectroscopy

The atmospheric concentration of a molecular species can be related to the transmission of light by considering the optical depth, $\alpha L$, where $\alpha$ is the absorption per unit length for the molecular species of interest and $L$ is the length the light interacts with the molecular species of interest. It is notable that losses due to scattering are ignored for these sub-surface probes. The optical depth can be related to the molecular line strength, $S$, and the normalized line shape parameter, $g(\nu - \nu_0)$, by the relationship

$$\alpha L = S g(\nu - \nu_0) N P_a L$$

(1)

with $N = N_L \frac{296}{T_a}$ is the total number of molecules, $N_L = 2.479 \times 10^{19}$ molecules/(cm atm) is Loschmidt’s number, $T_a$ is the temperature in K, and $P_a$ is the partial pressure of the molecule of interest in atm. The number density of the molecules of interest is $NP_a$ whereas the total number density of molecules is $NP_T$ where $P_T$ is the atmospheric pressure in atm. The concentration of molecules of interest is thus

$$C = \frac{NP_a}{NP_T} = \frac{P_a}{P_T}$$

(2)

Using Beer’s law, which expresses the transmission as a function of the optical depth as $T = e^{-\alpha L}$ for a gas of uniform concentration, and the above two equations, the concentration for the molecular species of interest is

$$C = \frac{-\ln(T)}{S g(\nu - \nu_0) N L \left(\frac{296}{T_a}\right) P_T L}$$

(3)
Values for the line strength, $S$, and normalized line shape parameter, $g(v - v_0)$, are tabulated in the HIgh-resolution TRANsmision molecular absorption (HITRAN) database.\textsuperscript{42} With measurements of the transmission for a known path length, and known temperature and pressure, a retrieval of the molecular concentration can be completed using eq.(3).

The subsurface concentration of CO$_2$ can range up to 10,000 ppm depending on soil moisture, temperature, and microbial activity. A plot of the transmission as a function of wavelength is shown in Figure 1 for a path length of $L = 1$ m with a total atmospheric pressure of $P_T = 1$ atm, and an ambient temperature of $T_a = 288$ °K. The solid black line (dashed blue line, dotted red line) represents the transmission spectrum for a 2,000 ppm (10,000 ppm, 60,000 ppm) CO$_2$ concentration. These values of CO$_2$ concentration were chosen as representative of the range of sub-surface CO$_2$ concentrations expected at a geologic sequestration site. The maximum expected absorption for the line centered at 2.00402 μm for a CO$_2$ concentration of 2,000 ppm (10,000 ppm, 60,000 ppm) is 2.9% (13.6%, 57.8%). The transmission measured by the instrument, and the resulting calculated CO$_2$ concentrations will be based around the 2.00402 μm absorption line. Values for the wavelength, line strength, and line shape parameter for the eight strongest CO$_2$ absorption features in the 2.001 to 2.005 μm wavelength range are presented in table 1.
Figure 1 Transmission as a function of wavelength for a 1 m pathlength, a temperature of 288 K, and a pressure of 1 atm. The black solid line (blue dashed line, red dotted line) represents calculations based on a CO$_2$ concentration of 2,000 ppm (10,000 ppm, 60,000 ppm). This range of CO$_2$ concentration represents the expected subsurface CO$_2$ concentration that will be seen at a geologic sequestration site, with background levels typically between 2,000 ppm and 8,000 ppm depending on microbial activity and meteorological conditions.
Table 1 The wavelength, line strength, and normalized line shape for the eight strongest CO$_2$ absorption features in the 2.001 µm to 2.005 µm wavelength range. The two absorption lines used in the experiment described in this paper are highlighted.

<table>
<thead>
<tr>
<th>Wavelength µm</th>
<th>Line strength $10^{-21}$ cm/molecule</th>
<th>Normalized Line shape cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.001 102 0</td>
<td>0.811 2</td>
<td>1.160 0</td>
</tr>
<tr>
<td>2.001 557 7</td>
<td>0.931 6</td>
<td>1.151 6</td>
</tr>
<tr>
<td>2.002 025 5</td>
<td>1.048</td>
<td>1.140 1</td>
</tr>
<tr>
<td>2.002 505 7</td>
<td>1.153</td>
<td>1.130 4</td>
</tr>
<tr>
<td>2.002 998 0</td>
<td>1.241</td>
<td>1.116 1</td>
</tr>
<tr>
<td>2.003 502 6</td>
<td>1.302</td>
<td>1.102 2</td>
</tr>
<tr>
<td>2.004 019 2</td>
<td>1.332</td>
<td>1.084 2</td>
</tr>
<tr>
<td>2.004 548 2</td>
<td>1.322</td>
<td>1.0653</td>
</tr>
</tbody>
</table>

**Differential Error Analysis**

In order to gain insight into the accuracy of the instrument a differential error calculation on the concentration calculation was performed. It is apparent from equation (3) the concentration is dependent on a number of constants but three main variables: the temperature, the pressure and the measured transmission. The pressure was not specifically monitored by this instrument, but during field deployment a separate weather station run by the Optical Remote Sensor Laboratory did take constant meteorological measurements. These measurements show that the average pressure varied only by several millibars within any given 24-hour period. During the month of July, 2012 (month of field deployment at ZERT site), the average pressure was 850.8 mb, with maximum and minimum measured pressures at 858 mb and 841 mb, respectively. In
order to calculate the effect of this change on the calculated concentrations of CO$_2$, a differential calculation is made on equation (3) based on the pressure $P_T$, becoming

$$dC = \frac{-\ln(T) \cdot dP_T}{S_g(v - v_0)N_L(\frac{v}{T_a})p_T^2L}.$$  

(4)

Due to the error in the transmission measurement and its large effect on the calculated concentration this error from the pressure is taken to be negligible, and the pressure in the concentration calculation is set to a constant 850mb.

![Figure 2](image_url)

Figure 2  Plots of the error introduced into the concentration calculation from a 10 mb pressure error. The plot on the left is the error from a calculated concentration of 4000 ppm or a transmission of ~95%. The plot on the right is for a concentration of 50,000 ppm or ~50% transmission signal.

The temperature at the probes was monitored by a 10k thermistor wired into the nose of probe 3. The temperature at the probes stayed relatively constant at their buried depth of ~1m. Over the entire month of July 2012, the average subsurface temperature was around 290 K, with a variation of less than ±3K. For each scan then, taking only
minutes, the variation in temperature was far less than 1 K, so the temperature was taken as a constant for each individual probe scan before being inserted into the concentration calculation. It follows that the error from the temperature based on this slight variation is negligible. Equation 5 shows the differential error of the concentration based on temperature.

$$dC = \frac{-\ln(T) \cdot dTa}{S_g(\nu-\nu_0)N_L(296)P_TL}$$  \hspace{1cm} (5)

This error is independent of the actual ambient temperature, but has dependence only on the error in measured temperature (a constant) and the transmission (assuming already that the error from pressure is also negligible).

As mentioned, the greatest error in the concentration came from the error in the transmission. The differential error for transmission derived from equation (3) becomes

$$dC = \frac{dT}{T \cdot S_g(\nu-\nu_0)N_L(296)P_TL}$$  \hspace{1cm} (6)

To simplify this, the differential error for the transmission was taken to be constant for each fiber probe based on its peak transmission signal as this number varied from probe to probe. The normalized transmission errors for probes 1-4 are 3%, 7%, 5%, and 5% respectively. These variations constitute random fluctuations in the measured transmission voltage on the detector at no more than 5 mV. Figures 3 and 4 show the error introduced from the subsurface temperature measurement and the error introduced from the transmission signal measurement, respectively.
Figure 3  Plot of the error introduced from the temperature for the sub-surface probes for a range of transmission values corresponding to a range of CO$_2$ concentrations.

Figure 4  Plot of the error introduced in the concentration calculation from the measured error in the transmission signal at a constant value of 5%. This error is approximately a factor of 10 or higher than the error from temperature and pressure.
THE 2μm SUB-SURFACE FIBER ARRAY

Laser Diode Characteristics

The laser diode used in this instrument is a Nanoplus 2004nm, Fiber-coupled, DFB laser. This laser source was originally used in the predecessor of the 1 x 4 fiber sensor array, and did display characteristics of degeneration over repeated use which will be discussed in more detail in following section on optical power. Table 2 shows some of the specified characteristics of the laser diode.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>λ</td>
<td>nm</td>
<td>2003</td>
<td>2004</td>
<td>2005</td>
</tr>
<tr>
<td>Optical Power</td>
<td>$P_{opt}$</td>
<td>mW</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Operation Temperature</td>
<td>$T$</td>
<td>°C</td>
<td>25</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Temperature Tuning Rate</td>
<td>$C_T$</td>
<td>nm/K</td>
<td>.18</td>
<td>.20</td>
<td>.22</td>
</tr>
<tr>
<td>Threshold Current</td>
<td>$I_{th}$</td>
<td>mA</td>
<td>20</td>
<td>25</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 2 Given characteristics of the 2004μm DFB laser.

Temperature Tuning

The operating principle of this instrument relies on wavelength tuning of the DFB over selected molecular absorption features of the CO₂ molecule. This tuning was accomplished using a constant current while tuning the temperature over a range of about 33-39 °C. This corresponded to a wavelength range of 2003.15 μm to 2004.25 μm which
encompassed the two selected absorption features discussed in the previous section. Each wavelength scan then covered 1.1 nm with 100 steps, thus giving a wavelength step size of 0.011 nm. Exactly why these wavelengths were chosen involved the use of the laser controller and the associated digital-to-analog converter (DAC) card and will be discussed in more detail in the programming section.

**Laser Control**

The laser temperature and current were regulated using a Wavelength Electronics dual laser driver and TEC controller (LDTC0520). This unit has the option for both onboard and remote control capability. The laser current was run at a constant 60mA using an onboard trimpot. The laser temperature was controlled remotely by the computer for tuning over the desired range. This operation requires a DAC to convert the digital program commands to analog voltage signals for input into the temperature controller. The actual temperature of the laser was monitored in real time with feedback from the built-in laser thermistor. Before field deployment, the laser wavelength was calibrated to specific temperatures. Based on this calibration, the temperature was scanned through a range of temperatures containing the absorption features of interest. In this way the actual TEC temperature, and thus the laser wavelength, can be monitored and controlled from a single panel in the Labview control program.

One issue with the highly compact and portable LDTC0520 was lack of an interlock between the laser anode and cathode when the unit was off. This is of concern for a field-deployed instrument, as power outages or other errors were common. To solve
this problem, a printed circuit board (PCB) was manufactured, utilizing a relay switch to allow for an interlock in laser control. The original power plug was rerouted into this PCB, to which the LDTC0520 was mounted and otherwise functioned as normal. When the system is powered down, intentionally or not, a short between the anode and cathode is achieved and no potential damage from static build up can occur. A schematic of the relay circuit and the mounted LDTC0520 can be seen in Figures 5 and 6.

![Schematic of the relay circuit used for the laser node shorting/laser protection during power outages.](image)

**Figure 5** Schematic of the relay circuit used for the laser node shorting/laser protection during power outages.

![Image of the LDTC0520 mounted on the relay circuit PCB.](image)

**Figure 6** Image of the LDTC0520 mounted on the relay circuit PCB.
During field deployment, very little change in wavelength was observed in laser operation. Minor shifts were expected to occur in the laser output wavelength due to age or extreme environmental temperature changes, but these effects were minimally observed. Any slight change in the temperature-wavelength correlation of the laser was mitigated by the analysis programming, which always seeks out the minima of the returned intensity and assigns it to the proper absorption feature (by wavelength). Long-term study of the change in laser wavelength due to extended use would be useful for further understanding of system performance.

Detectors

For both the transmission and reference detectors, two New Focus model 2034 IR InGaAs photoreceivers were used. At the 2µm wavelength used, the responsivity of the detectors is approximately 1A/W with a transimpedance gain of $2 \times 10^3$ V/A on the low gain setting.

Any voltage measured by the detectors from the laser can be converted into an optical power by the equation:

$$P_{in} = \frac{V}{RG}$$  \hspace{1cm} (7)

where $P_{in}$ is the optical power, $V$ is the measured voltage on the detectors, $R$ is the responsivity, and $G$ is the transimpedance gain for the detector.
Optical Power

The typical voltage of the 14-pin laser diode directly out of the connecting fiber was 630 mV, which corresponds to a power of 315 µW out of the laser. The specified optical power for the DFB operating at ~25 °C or 10kΩ is 1 mW. It is expected that at a higher operating temperature, the output optical power would decrease. It is of note that over the course of several years the output power dropped considerably from around 0.5 mW. It is likely that the change in optical power of the laser diode was the result of deformations or cracks in the laser cavity, possibly due to the repeated stress of temperature tuning and the fluctuations of the operating temperature during field deployment in previous years. The resulting laser output, regardless of its denigration in power, was still stable in wavelength and power (at a given temperature) and could still be utilized for the field deployment.

System Layout

A schematic of the fiber sensor array is shown in Figure 7. A distributed feedback (DFB) laser operating at 2.004 µm was mounted in a 14 pin butterfly package with a fiber pigtailed output. The DFB laser is a continuous wave (CW), tunable source that has an internal thermoelectric cooler (TEC) that allows temperature tuning of the DFB laser. The DFB laser is mounted in a commercial mount from ILX Lightwave that provides a second TEC that is used to stabilize the ambient temperature in which the DFB laser operates. This second TEC is important during field operations where temperatures can range between a low of 0 °C at night to a high of 35 °C during the day.
The fiber-coupled output from the DFB laser is non-isolated and directly incident on an in-line fiber splitter, which uses 62.5µm multi-mode optical fiber, with 50% of the light from one port directed to a reference detector. The remaining 50% of the light from the second port is directed to an in-line 1 x 4 fiber optic switch. The in-line opto-mechanical fiber optic switch has an insertion loss of less than 0.6 dB with a cross talk of less than -60dB. Each of the four fiber-coupled output ports is connected via a multi-mode fiber optic cable to a probe that is placed into the ground. The fiber optic cables are all 62.5µm, FC/PC multimode fibers approximately three meters in length. At the probes the light is collimated and allowed to interact with the CO₂ that diffuses into the buried probes through Millipore filters placed at the top and bottom of the probes. These filters allow the soil gas to diffuse into the probes but keep out dirt and water. The light is then re-coupled into the multi-mode optical fiber where it is directed back through the fiber optic switch and is again incident on the in-line fiber splitter where light from one port is directed to a transmission detector. The reference and transmission detectors are monitored using a multichannel voltmeter that can be read by a computer via a GPIB interface.
Figure 7 Schematic of the 1 x 4 fiber sensor array.

Figure 8 Schematic of the fiber probe is shown on the left and four completed fiber probes shown on the right.
A schematic of the fiber probes is shown in Figure 8. The optical fiber from the 1 x 4 fiber optic switch is a multi-mode optical fiber with a core diameter of 62.5 µm (Opteqip A20134) with angled physical contact (FC/APC) connector. This connector couples to the fiber probe via a keyed FC/APC connector mounted in the top-end cap of the probe. The light exiting the fiber is collimated with an aspheric, fiber coupled, collimator which has a focal length of \( f = 11 \text{ mm} \) and a reflectivity of <3%. The collimated light travels to the mirror mounted in a commercial optical mount that reflects the light back through the collimating lens and back into the optical fiber. The mirror mount has a resistive heater attached to ensure that condensation does not form on the mirror when the fiber probe is buried for extended periods of time. A thermistor is also placed in the fiber optic probe to allow temperature measurements needed for the data inversion discussed in section II. Millipore filters in both the top end cap and bottom end cap allow soil gas to move into and out of the fiber probe when the fiber is buried while keeping out dirt and water. The overall length of the fiber probe is 60 cm with a 50 cm free space path length where the light and CO\(_2\) can interact. The diameter of the end caps are 5.0 cm while the diameter of the narrower central tube is 3.8 cm. The fiber probes are made out of aluminum and were machined by the author. A picture of the four completed probes is shown in Figure 8. During field deployment each of the four probes was buried in large diameter PVC tube that had been perforated with 3/16 inch holes to allow for soil gas to pass through the tube unimpeded. This was done to allow for easy access to the probes once buried. In the event the return signal was lost the probes could
easily be removed from the ground for inspection and maintenance. However, during field testing, the probes did not require removal once placed in the ground. Originally the probes were also designed with piezo-electric transducers mounted behind the mirror to help peak up the return signal after an undesired strain or stress on the probe caused some loss in return intensity. Once it was realized that the fiber probes remained at peak signal for long durations of time, the piezos were removed from the system.

**Programming and Instrument Control**

The instrument is operated using software developed in the Labview programming environment. Data is collected in the following manner. Once the channel to the desired probe is set the programming begins a digital ramp to slowly tune the laser by stepping its operating temperature. This is a basic positive ramp function that outputs a voltage to a DAC in which the user can set the step size and start/stop values of the function. At each step of the voltage ramp the DAC converts the value to its analog counterpart and outputs it to the laser TEC controller. This, in turn, causes small positive change in temperature for the diode and thus a small increase in wavelength. During each step of the temperature, the computer records a reference signal value (voltage) from the laser, a transmission signal from the probe, and the subsurface temperature. The reference and transmission signals are actually recorded several times per step and the median value is recorded for that temperature (wavelength) step. This is done to help mitigate any noise or modulation while the laser stabilizes to that temperature. The dwell time at each step, the step size, and the time between each reference and transmission
measurement are all defined by the user. Experimental measurements show that the laser requires at least one second to settle into each temperature and stabilize the output wavelength. During the actual field testing of the instrument each temperature step took about four seconds allowing ample time for the laser wavelength to stabilize and the computer to monitor accurately the reference and transmission signal. Figure 9 shows a simplified block diagram of the system programming scheme.

Figure 9 Chart demonstrating the flow of data collection for the fiber array in the Labview programming.
As was discussed in the section on temperature tuning, the laser is tuned between 2003.15 µm to 2004.25 µm. This range was selected for a very specific set of reasons. The DFB contained a built-in 10k thermistor for feedback on the laser temperature set by the TEC. The LDTC0520 utilized a voltage input, from 0 -1 V that corresponded to a specific temperature on the TEC. Thus the tuning wavelength needed to be converted to a temperature, which could be converted to a resistance in kΩ on the TEC, and finally converted to a voltage for input into the LDTC0520 via the Labview programming. The approximate start-stop wavelengths corresponded to a temperature range of 33 -39 °C, measured by the Bristol wavelength meter. Figure 6 shows the relationship between the DFB set temperature and the set resistance in kΩ. The nearest whole-number values for the TEC resistance that captured the desired absorption features fell between 7-5.5kΩ; this resistance range gives the exact wavelength tuning range from 2003.15 to 2004.25 µm. As mentioned, the LDTC0520 utilized a voltage input. To convert the TEC set resistance to a voltage, a simple conversion is done using the bias current on the feedback sensor, in this case, a 100 µA thermistor. The input voltage on the LDTC0520 ranged from 0-2 V; this, combined with a 12-bit DAC card ranging from 0-5 V, meant that the minimum voltage resolution was approximately 1.2 mV. Using 100 steps between the selected voltage range of 0.7-0.55 V for input meant the system would have 1.5V/step, just above the DAC voltage resolution and enough points per scan to clearly define any absorption features.
A plot of the actual DFB temperature versus the TEC set point in kΩ. The black vertical line indicates the start of the selected temperature scan range at 7 kΩ scanning down to 5.5 kΩ or about 39.3 °C laser temperature.

A single scan for a probe takes about seven minutes, contains 100 points of measurement for the reference/transmission signals (mean values), and moves the laser through a temperature range of 33.42-39.33 °C. Once a scan is completed, the transmission is normalized and the molecular concentration can be calculated using the results discussed in section I, and the program moves on to the next probe to repeat the entire process.
The Zero Emissions Research and Technology (ZERT) field site\textsuperscript{35,36} is a controlled CO\textsubscript{2} release facility located on the western edge of Montana State University (MSU) in Bozeman, MT (45°39’N, 111°04’W) at an elevation of 1,495 m. The ZERT site has a buried horizontal release pipe that was developed to simulate a longitudinal CO\textsubscript{2} leak source, such as a geologic fault or a weakness in a geologic capstone atop a subsurface reservoir, for the development and testing of near-surface and surface monitoring tools for carbon sequestration. The site is on a relatively flat alluvial plain that consists of thick sandy gravel deposits overtopped by several meters of silts, clays, and topsoil. The buried release pipe is 98 m long, with an inner diameter of 10.16 cm, and is oriented 45° east of true north. The central 70 m of the pipe is perforated to seep CO\textsubscript{2} during injection. A series of eight packers were placed within the release pipe to assist in dispersing the gas evenly along the slotted portions of the release pipe with each of the eight sections of pipe plumbed with its own flow controller. The pipe was buried using a horizontal drilling technique that minimized disturbance to the surface environment; however, the pipe installation was deflected from a perfectly straight path because of cobble in the gravel layer underground.
Figure 11 The ZERT field site is shown in the left hand figure with the subsurface pipe location and below ground fiber instrument locations marked. The fiber sensor probe deployed at the ZERT site is shown in the right hand figure.

A thirty-four-day release experiment was performed beginning July 10, 2012. The CO₂ release rate for this experiment was 0.15 tons CO₂/day, about the equivalent to two idling cars, evenly distributed over the eight sections of the underground pipe. The flow rate was chosen in the following manner. Approximately $4 \times 10^6$ tones CO₂/year can be captured from a 500 MW fossil fuel burning power plant. Over a 50 year period, this would result in a total of $200 \times 10^6$ tones CO₂ which could be sequestered. Assuming that the injection area is approximately 1% of a typical geologic fault in size, the flow rate was chosen so that the seepage would mimic less than 0.01% through a typical fault. This implies that the flow rate chosen mimics the levels that need to be monitored and observed at geologic sequestration sites.

**Data Collection**

A plot of the normalized transmission as a function of wavelength is shown in Figure 12. The solid red line represents the normalized transmission measured using one of the four probes during the release experiment. The Labview program used to collect
and process the data, which was described in section II above, returned a CO$_2$ concentration of 50,926 ppm. The dashed blue line in figure 5 is a plot of the transmission as a function of wavelength based on this CO$_2$ concentration resulting from the HITRAN database. Good agreement between the measured and expected results indicates the fiber sensor probe and corresponding software are working properly.

Figure 12 A plot of the normalized transmission as a function of wavelength. The solid red line represents the normalized transmission measured using one of the four probes during the release experiment. The calculated CO$_2$ concentration from this measured transmission was 50,926 ppm. The dashed blue line is a plot of the transmission as a function of wavelength based on this CO$_2$ concentration resulting from the HITRAN database.

The fiber sensor probe was operated for a fifty-eight day period, proving subsurface CO$_2$ concentration measurements from each of the four probes. A plot of the CO$_2$ concentration as a function of time for each of the four probes between July 5 and July 9, 2012 period is shown in Figure 13. This data was collected before the subsurface CO$_2$
injection began thus providing background data. During this four-day period, the CO₂ concentration ranged between 1,000 and 7,000 ppm. A diurnal cycle is evident in figure 13, with a maximum CO₂ concentration occurring around 1:00 pm Mountain Daylight Time (UTC -6 hrs). There is a general decline in measured CO₂ concentrations after this time, leading to a general minimum about twelve hours later.

![CO₂ Concentration Chart](image)

Figure 13 A plot of the CO₂ concentration as a function of time for each of the four probes measured over a four day period before the beginning July 5, 2012, before the sub-surface CO₂ release began. A diurnal cycle of subsurface CO₂ concentration is seen by each of the four probes with CO₂ concentrations ranging between 1,000 ppm and 7,000 ppm. This cycle is most likely due to microbial activity and meteorological conditions.

This diurnal cycle is related to the subsurface microbial activity as well as the surface meteorological conditions and soil moisture. Secondary peaks do occur at a couple of points in the last two days shown in Figure 13, which most likely correspond to changes
in wind speed, or air pressure due to inclement weather. These changes in surface
condition can drastically affect how CO$_2$ rises from the soil. This data shows the each of
the four fiber probes is able to monitor background CO$_2$ concentration levels.

A plot of the CO$_2$ concentration as a function of time for each of the four probes
over a fifty-eight day period is shown in Figure 14. The four probes were located
roughly on the corners of a rectangle with an area of about 1 m$^2$. The front two probes
were placed closest to the pipe at a 0.5 m perpendicular distance with a maximum depth
of approximately one meter. The remaining two were shifted back by about another 0.5
m. All four probes were buried at 45$^\circ$ angles with respect to the horizontal surface. The
CO$_2$ release began at 12:00 pm local time on July 10, 2012 and lasted until August 13,
2012, with the release start time and stop marked in Figure 14 with vertical lines. Data
were collected twenty two days before the start of the release to ensure the instrument
was able to monitor background levels. During this first twenty one days, the
background CO$_2$ concentrations fluctuated between 1,000 ppm and 7,000 ppm showing a
daily diurnal cycle. After the start of the release, the sub-surface CO$_2$ concentration
began to rise in each of the four probes after approximately one day.
Figure 14  A plot of the sub-surface CO$_2$ concentration as a function of time for each of the four probes over a fifty-eight day period. The start and stop of the controlled sub-surface CO$_2$ release are indicated by the solid vertical lines. A rise in the sub-surface CO$_2$ concentration by over a factor of six over background levels indicate that the fiber sensor array can detect changes in subsurface CO$_2$ concentration at the level needed for geologic carbon sequestration.

This delay in the measured rise in sub-surface CO$_2$ concentration results from the time it takes for the CO$_2$ to move from the release pipe to the location of the fiber sensor probes. About two days into the release experiment, a lightning strike caused a power outage and damaged the flow controllers, causing the CO$_2$ flow to be stopped. This is clearly seen in the data as the drop in CO$_2$ concentration until about six days after the start of the release, at which time the CO$_2$ flow started again and each of the four probes measured a rapidly rising CO$_2$ concentration that reached peak levels of about 65,000 ppm for three of the four probes until the release was stopped. The other probe registered values greater than 70,000 ppm during the release. Once the release was stopped, it took
approximately three days for the subsurface CO$_2$ concentration values to fall back to their steady-state background levels.

**Kevin Dome Deployment**

During the summer of 2013 the fiber array was deployed in the field at the location known as the Kevin Dome in northern Montana.$^{45}$ The Kevin Dome is an 1800 square km subsurface, geologic formation that has both naturally occurring CO$_2$ and porous rock areas that would allow for storage of CO$_2$. In order to test the viability of carbon sequestration the naturally occurring CO$_2$ will be pumped from a production well along a 6 mile pipeline to an injection well where it will be sequestered at a depth of ~4000 ft.

The fiber sensor array was deployed at a point at the Kevin Dome field site and allowed to collect surface background data over seventeen nights during July and August. Due to a lack of constant electric power to run the system at the remote location, the array was operated intermittently for several hours per day. Figure 15 shows the measured CO$_2$ concentrations from the fiber array at the Kevin Dome field site for the four probes. Because the system was operated for smaller intervals instead of a continual 24-hour cycle, the measured CO$_2$ concentrations were averaged for each nightly interval during which the instrument was operating; the nightly average for each probe was plotted against each night of operation. These background measurements show similar concentrations to the measurements taken at the ZERT site the year before indicating a typical background level. The overall average for the CO$_2$ concentration does seem
slightly elevated, especially for night time operation when microbial activity is expected to decline and reduce sub-surface CO₂. This change in measured CO₂ may be due to a higher transmission voltage noise during the Kevin Dome deployment, due to a decrease in laser power and stability as was previously discussed. This means that the instrument was most likely measuring near the overall noise floor of ~5000 ppm. Reduction of system noise and the continual monitoring of subsurface CO₂ levels through a variety of techniques will be of interest as the actual transport and sequestering of CO₂ takes place over the life of the project.

Figure 15  Plots of the background CO₂ measured during the Kevin Dome deployment.
CONCLUSION

A fiber optic sensor array for sub-surface CO₂ concentration measurements has been demonstrated at the ZERT controlled sub-surface release facility over a fifty eight day period. This 1 x 4 fiber sensor array utilizing a send/call configuration uses a single tunable DFB laser and fiber optic components to make sub-surface CO₂ concentration measurements based on integrated path differential absorption techniques. This instrument was successfully deployed over a fifty-eight day period measuring background CO₂ concentrations over twenty one days, measuring the changing sub-surface CO₂ concentrations in each of the four probes resulting from a thirty four day sub-surface controlled release, and finally monitoring the relaxation back to background levels for the three days after the injection was stopped. Background CO₂ concentrations ranged between 1,000 ppm and 7,000 ppm while the release was designed to mimic the conditions needed for successful geologic sequestration site monitoring with concentrations ranging over 70,000 ppm.

The 1 x 4 fiber optic sensor array can be scaled in a cost effective manner for monitoring larger areas. In-line fiber optic switches based on the same technology used by the 1 x 4 switch employed in this demonstration instrument are available in a number of geometries with up to 50 output ports. The part count for the expensive components including the DFB laser, detectors, and fiber optic switch does not increase as the number of probes increases and the probes have been designed to be made inexpensively. This allows the fiber sensor array to be scaled inexpensively with the added benefit that the
fiber probes can be placed as needed and easily moved providing for a reconfigurable sensor.

The fiber sensor array is currently used for sub-surface CO$_2$ detection. The ability to monitor other sub-surface gases including methane (CH$_4$) and oxygen (O$_2$) can provide process based information that can help determine the origin of the CO$_2$\textsuperscript{44}. For example, if photosynthesis is occurring, the ratio of the change in CO$_2$ will be related to the ratio of the change in O$_2$. The ability to monitor other soil gasses with a similar geometry can be incorporated through adding tunable DFB lasers at the appropriate wavelengths and using wavelength division multiplexers to allow for spectroscopy of multiple species in a single probe. Future research efforts may be aimed at achieving this goal.
REFERENCES CITED


[43] Optical Remote Sensor Laboratory, Dr. Joseph Shaw, Montana State University, Electrical and Computer Engineer Department. http://orsl.eps.montana.edu/weather/


APPENDICES
APPENDIX A

INSTRUMENT SCHEMATICS
#1-72 Tapped Hole
- Depth of 40, .6 on front end,
  .4 on back end, \( R = 0.0075 \)

4 x #0-80 Tapped Hole
- Depth of .160, \( R = 0.4300 \)
6 x #1-72 Tapped Hole at 60 degree spacing for attachment to nose
R.9375

Well for O-ring Width/depth=.20/.050
Ø 1.0510

2.00

4 x #1.72 counterbore for attachment to probe center tube
R.275
R.6575

Wall for .030 o-ring Width/depth=.20/.050

4 x #4-40 Tapped Hole
R.60
Ø 1.5875
Ø .4375

3 x Gas through-punts Radius/depth=.035
120 degree starting separation rotated through 90 degrees both directions

Nose Adapter

Title

Size
A
2nd Gen.

Rev

Scale: 2:1
Weight:

Sheet 1 of 1
Piezo Brace
Fiber Probe Nose

- Ø1.55
- 3/32 Through all
- Ø0.75 Through all

6 x #0-80 tapped hole for washer attachment
Depth of .20 and at Radius of .5625
Exploded Assembly
APPENDIX B

PROGRAMMING FOR DATA COLLECTION AND ANALYSIS
Coding for the concentration and error
% First, retrieve the index file with all scan timestamps for specific probe and load into matlab
%C:\Research\2013\Data\Probe #\Probe #_Index.dat -actual file
Probe = 'Probe 1'; %set the probe # you are working with
date = '1-16 to 1-26'; %set the date range you are working with
dT=.05; % set the trasmission error...this will change depending on the probe
time =.25:.25:272.75; % set the time vector "8 hours between each probe scan" for my scans - this number can change so beware
path = strcat('C:\Research\2014\Data\',Probe,'\',Probe,'_Index.dat'); %make sure you set your 'year' correctly
index_all = load(path);

%Now create new index file with iterations of 100 (this number is arbitrary and simply determines how many points you wish to do an error analysis on)
y = size(index_all,1);
    month_day = zeros(y,1); %y is the total number of scans
    hour_min_sec = zeros(y,1);

    month_day(:,1) = index_all(:,1); %makes two separate files containing
    hour_min_sec(:,1) = index_all(:,2); %the month/day/year and
    Hr/Min/Sec from the index file

    Conc = zeros(size(index_all,1),1); %initialize the arrays for the concentration and the errors
    C = zeros(size(index_all,1),1);
    dCT = zeros(size(index_all,1),1);
    %% BEGIN THE CONCENTRATION CALCULATION FOR THE 2 LINES AND TAKE THEIR AVERAGE

    for q = 1:size(index,1) %for each scan (100 points) a single concentration and error will be calculated
        MDY = sprintf('%08d',month_day(q,1)); % creating file path to load scans
        HMS = sprintf('%06d',hour_min_sec(q,1));

        % C:\Research\2013\Data\Probe #\MDY\HMS
        file_name = strcat('C:\Research\2014\Data\',Probe,'\',MDY,'\',HMS,'.dat');
        %file_name = strcat('C:\Research\2013\Data\Probe 1\',07222012,'\',000331.dat');
        scan_file = load(file_name);

        %file now loaded
    %first define all constants for concentration calculation
    N=2.479*10^19; %Loschmidt's number (mol/cm^3*atm)
P = .850; %pressure in atmospheres
$L = 100; \text{ \%cell length in centimeters}$

$S(1) = 1.302 \times 10^{-21}; \text{ \%linestrengths (cm/mol)}$

$S(2) = 1.332 \times 10^{-21};$

$\text{FWHM}(1) = 0.1444; \text{ \%FWHM of absorption lines}$

$\text{FWHM}(2) = 0.1468;$

$g = \text{zeros}(1,2);$

$g(1) = 1/(\pi \times ((\text{FWHM}(1))/2)); \text{ \%lineshapes (1/cm)}$

$g(2) = 1/(\pi \times ((\text{FWHM}(2))/2));$

% Temperature factor

$\text{Tambient} = (\text{mean}(\text{scan\_file(:,5)))) \times (-0.0019) + 316.84;$

$\text{Treference} = 296;$

$\text{Tfactor} = \text{Treference}/\text{Tambient};$

$\text{for i}=1:\text{size}(\text{scan\_file},1);$  

$\text{scan\_file(i,6)} = \text{scan\_file(i,3)}/\text{max}(\text{scan\_file(:,3))};$

$\text{end}$

%%%----------------------------------------------------------

% Beginning data sorting to calculate concentration
% Find indeces corresponding to peak minima

$\text{for i} = 11:38$

$\text{if i} == 11$

$\text{min1} = 1;$  

$\text{end}$

$\text{min1} = \text{min}(\text{min1},\text{scan\_file(i,6))};$

$\text{if min1} < \text{scan\_file(i,6)}$

$\text{min\_index} = \text{min\_index; \#ok<ASGSL>}$

$\text{else}$

$\text{min\_index} = i;$  

$\text{end}$

$\text{end}$

$\text{for i} = 60:85$

$\text{if i} == 60$

$\text{min2} = 1;$

$\text{end}$
min2 = min(min2, scan_file(i,6));

if min2 < scan_file(i,6)
    min2index = min2index;  %#ok<ASGSL>
else
    min2index = i;
end

%%
% Find center of maxima and corresponding
% normalized transmission value

for i = 1:10
    if i == 1
        max1 = scan_file(i,6);
        max1index = i;
    end

    max1 = max(max1, scan_file(i,6));

    if max1 > scan_file(i,6)
        max1index = max1index;  %#ok<ASGSL>
    else
        max1index = i;
    end
end

for i = 90:101
    if i == 90
        max3 = scan_file(i,6);
        max3index = i;
    end

    max3 = max(max3, scan_file(i,6));

    if max3 > scan_file(i,6)
        max3index = max3index;  %#ok<ASGSL>
    else
        max3index = i;
    end
end

%%
% find the maximum between the two absorption features
max2index = round((min1index + min2index)/2);

max1value = (scan_file(max1index,6) + scan_file(max1index + 1,6) + ...
              scan_file(max1index + 2,6))/3;
max2value = (scan_file(max2index - 2, 6) + scan_file(max2index - 1, 6) +
... + scan_file(max2index, 6) + scan_file(max2index + 1, 6) +
... + scan_file(max2index + 2, 6))/5;
max3value = (scan_file(max3index - 2, 6) + scan_file(max3index - 1, 6) +
... + scan_file(max3index, 6))/3;

% Build vectors of max values and indeces
x = zeros(1, 3);
x(1, 1) = max1index;
x(1, 2) = max2index;
x(1, 3) = max3index;

y = zeros(1, 3);
y(1, 1) = max1value;
y(1, 2) = max2value;
y(1, 3) = max3value;

% Build linear approximation for polyfit framework
x1 = zeros(1, x(1, 3));
y1 = zeros(1, x(1, 3));

for p = x(1, 1):x(1, 2)
    m1 = (y(1, 2) - y(1, 1))/(x(1, 2) - x(1, 1));
x1(1, p) = p;
y1(1, p) = m1 * x1(1, p) + y(1, 1) - m1 * x(1, 1);
end

for p = x(1, 2):x(1, 3)
    m2 = (y(1, 3) - y(1, 2))/(x(1, 3) - x(1, 2));
x1(1, p) = p;
y1(1, p) = m2 * x1(1, p) + y(1, 2) - m2 * x(1, 2);
end

T = zeros(1, 2);
T(1) = scan_file(min1index, 6)/y1(min1index);
T(2) = scan_file(min2index, 6)/y1(min2index);

% CALCULATE CONCENTRATION
C = zeros(1, 2);
for i = 1:2
    if T(i) < 1
        C(i) = (-log(T(i)))/(S(i) * g(i) * N * Tfactor * P * L) * 10^6;
    else
        C(i) = 0;
    end
end

% 2-line nonzero average concentration (PPM)
if ~ isempty(C)
    Conc(q,1) = round(mean(nonzeros(C)));
else
    Conc(q,1) = 0;
end

%% this is the end of the 2-line concentration calculation
%% CALCULATING THE ERROR IN THE CONCENTRATION \( \delta C \)
% now begin the error calculation to attach to each concentration value calculated
% Errors --- Probe 1 = .03, Probe 2 = .07, Probe 3 = Probe 4 = .05 -
% again
% these values will change as the system does
% error in the transmission moved to first frame
dC = zeros(1,2);

    for i = 1:2 %error for each of the absorption lines
        dC(i) = ((dT*10^6)/(S(i)*g(i)*N*Tfactor*P*L*T(i)));
    end

dCT(q,1) = (dC(1,1) +dC(1,2))/2; %average of the error.

end

%% CREATING ARRAYS FOR PLOTTING THE CONCENTRATION
% this is entirely up to you.
averaged(:,1) = filter(1,6,Conc(:,1)); %3 point running average on concentration values
averaged(:,2) = dCT(:,1); %error and averaged concentration in one array "averaged" the error is in column 2
Total(:,1) = Conc(:,1); %"Total" is the non-averaged concentrations and errors
Total(:,2) = dCT(:,1);
%creating arrays with the error bar spacing (errordist), the errors at each
%point (errors), and the concentration at that point (errorconc)
%Ben - August 2014 still needs work
delta =100; %this is the spacing between the errors bars you can choose

errodist = zeros(floor(length(time)/delta),1);
errors = zeros(floor(length(time)/delta),1);
errorconc = zeros(floor(length(time)/delta),1);

% CREATING ARRAYS FOR ERROR BAR PLOTTING
p = 1:delta:floor(length(time));
for q = 1:floor(length(time)/delta);
    errodist(q,1) = time(1,p(q));
    errors(q,1) = averaged(p(q),1);
    errorconc(q,1) = averaged(p(q),2);
end;
errortotal(:,1) = errors(:,1);
errortotal(:,2) = errorconc(:,1);

%% FRAME SETS MINIMUM TO ZERO IF THE ERRORS ARE LARGER THAN THE MEASURED VALUE
%This sequence basically creates a vector that will not allow the errors to go below zero
% do this for either the entire number of files or just the ones selected by delta - choose to run this frame or the next...not both
low =zeros(length(index_all),1);
for q = 1:length(index_all)-1
    if averaged(q,1)>averaged(q,2)/2
        low(q,1)=averaged(q,2)/2;
    else
        low(q,1)=averaged(q,1);
    end
end

%% FRAME SETS MINIMUM TO ZERO IF THE ERRORS ARE LARGER THAN THE MEASURED VALUE
low =zeros(length(errortotal),1);
for q = 1:length(errortotal)
    if errors(q,1) > errortotal(q,2)/2
        low(q,1) = errortotal(q,2)/2;
    else
        low(q,1) = errortotal(q,1);
    end
end;

%% THIS FRAME ALLOWS FOR PLOTTING OF THE DATA AND THE ERRORS

figure = errorbar(errodist,errors,low,'r');
hold on
plot(time, averaged(:,1));
figure_title= strcat(Probe,' Concentration', date,' (MATLAB)');
title(figure_title) % --or whatever probe you are on
ylabel('PPM');
xlabel('Time (Hours)')
hold off
%% clear;
%% ANYTHING AFTER THIS IS PROGRAMMING THAT CAN BE USED TO SAVE THE DATA AUTOMATICALLY OR IS LEGACY
% PROGRAMMING THAT MAY OR MAY NOT BE USEFUL.

% saving the individual Concentrations calculated and the errors.
Also,
% saving plots.
    %write_file_name=strcat('C:\Research\2013\7-11 to 7-12\',Probe,'\Total_\',Probe);
    %write_file_name_1=strcat('C:\Research\2013\7-11 to 7-12\',Probe,'\averaged_\',Probe);
    %write_file_name_2=strcat('C:\Research\2013\7-11 to 7-12\',Probe,'\low_\',Probe);
    %write_file_name_3=strcat('C:\Research\2013\7-11 to 7-12\',Probe,'\time_\',Probe);

%write_file_name=strcat('C:\Research\2014\',date,'\',Probe,'_variables');
%figure_name=strcat('C:\Research\2014\',date,'\',Probe,'_plot');
    %dlmwrite(write_file_name, Total, delimiter, '\t');
    %dlmwrite(write_file_name_2, averaged);
% save(write_file_name);
    % save(write_file_name_1, averaged);
    % save(write_file_name_2, low);
    % save(write_file_name_3, time);
% saveas(figure, figure_name);
% extra coding
for q = 1:length(data1)
    if P1averaged(q,1)>P1averaged(q,2)/2
        low(q,1)=P1averaged(q,2)/2;
    else
        low(q,1)=P1averaged(q,1);
    end
end
% low2=low;
P2averaged(:,3)=P2averaged(:,2);
figure = errorbar(data4,P4averaged(:,1),low4,P4averaged(:,3)/2);
% title('CO2 Concentration July-Aug. 2013');