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Report Title:
Development of a 1 x N Fiber Optic Sensor Array for Carbon Sequestration Site Monitoring

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Principal Author
Dr. Kevin Repasky

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Montana State University
Electrical and Computer Engineering
Cobleigh Hall Room 610
Bozeman, MT 59717

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Abstract

A fiber sensor array for sub-surface CO_2 concentrations measurements was developed for monitoring geologic carbon sequestration sites. The fiber sensor array uses a single temperature tunable distributed feedback (DFB) laser operating with a nominal wavelength of 2.004 μm. Light from this DFB laser is direct to one of the 4 probes via an in-line 1 x 4 fiber optic switch. Each of the 4 probes are buried and allow the sub-surface CO_2 to enter the probe through Millipore filters that allow the soil gas to enter the probe but keeps out the soil and water. Light from the DFB laser interacts with the CO_2 before it is directed back through the in-line fiber optic switch. The DFB laser is tuned across two CO_2 absorption features where a transmission measurement is made allowing the CO_2 concentration to be retrieved. The fiber optic switch then directs the light to the next probe where this process is repeated allowing sub-surface CO_2 concentration measurements at each of the probes to be made as a function of time. The fiber sensor array was deployed for fifty-eight days beginning June 19, 2012 at the Zero Emission Research Technology (ZERT) field site where sub-surface CO_2 concentrations were monitored. Background measurements indicate the fiber sensor array can monitor background levels as low as 1,000 parts per million (ppm). A thirty four day sub-surface release of 0.15 tones CO_2/day began on July 10, 2012. The elevated subsurface CO_2 concentration was easily detected by each of the four probes with values ranging to over 60,000 ppm, a factor of greater than 6 higher than background measurements. The fiber sensor array was also deploy at the Big Sky Carbon Sequestration Partnership (BSCSP) site in north-central Montana between July 9th and August 7th, 2013 where background measurements were made in a remote sequestration site with minimal infrastructure. The project provided opportunities for two graduate students to participate in research directly related to geologic carbon sequestration. Furthermore, commercialization of the technology developed is being pursued with five different companies via the Department of energy SBIR/STTR program.

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Executive Summary

The goals of the research project were to develop and demonstrate a fiber optic based sensor array capable of monitoring carbon sequestration sites to ensure site integrity and public safety. The fiber sensor array utilized a central laser transmitter and receiver that directed light at 2.00 μm via optical fibers to a series of probes that are placed underground to measure the sub-surface carbon dioxide (CO_2) concentration. The send/call geometry of the fiber sensor array allows for cost effective scaling to a large number of probes by minimizing the cost of each probe via a simple passive probe design. The single laser transmitter and receiver combined with the low cost probes offer a cost effective approach for monitoring. The fiber sensor array can be scaled up to fifty probes using a single laser transmitter and receiver, can be used to monitor several square kilometers, and is easily reconfigurable.

The fiber sensor array uses an integrated path differential absorption (IPDA) measurement technique to determine the sub-surface CO_2 concentration. This measurement is achieved by tuning the laser transmitter over several absorption features associate with CO_2 near the 2.00 μm spectral region where CO_2 has strong absorption features. By keeping track of the change in transmission as the laser transmitter tunes over the absorption features, the CO_2 concentration can be calculate with knowledge of the absorption line strength and lineshape.

The fiber optic sensor array was demonstrated using a 1 x 4 geometry. First, the fiber probes were designed and machined using the Montana State University Electrical Engineering machine shop. Next, the laser transmitter was assembled and characterized and each of the four probes was aligned. Once the assembly of the fiber sensor array was completed, software was developed to operate the fiber sensor array by first directing the laser transmitter to a single probe then tuning the laser over the absorption features of interest and measuring the transmitted and return signal. Once these signals were measured, the software calculated a normalized transmission signal and found the minimum transmission associated with each absorption feature. The CO_2 concentration was then calculated for each absorption feature then averaged yielding a final concentration measurement. The software then switched to the next probe and the process is repeated until the user interrupts the program.

The fiber optic sensor array was tested at the Zero Emission Research Technology (ZERT) field site. The ZERT field site allows CO_2 to be released below the water table via a perforated well that is separated into eight different sections via packers. Each section of the pipe has a dedicated flow meter allowing a known quantity of CO_2 to be released. During the field experiments, the CO2 flow rates were chosen to mimic the CO_2 concentrations needed for successful monitoring of carbon sequestration sites. The fiber sensor array was successfully deployed at the ZERT field site making continuous measurement over a fifty eight day period measuring CO_2 concentrations between approximately 2,000 parts per million (PPM) up to 60,000 PPM. The fiber sensor array was able to easily detect the elevated CO_2 concentrations associated with the release indicating this instrument is capable of successfully monitoring carbon sequestration sites.

The fiber sensor array was deployed during the final summer of the project at the Big Sky Carbon Sequestration Partnership site located in north central Montana. The instrument successfully operated at this remote field site for a thirty day period. With the successful demonstration of the fiber sensor array, commercialization is being pursued through the SBIR/STTR programs with several small businesses.

I. Introduction

The goal of the research effort was to develop and deploy a fiber based sensor array for monitoring subsurface carbon dioxide at carbon sequestration sites. During this project a 1 x 4 fiber sensor was developed and demonstrated at both a controlled subsurface release facility and at the Big Sky Carbon Sequestration Partnership site. The project was funded through the American Reinvestment and Recovery (ARRA) act and also had as part of its goals the development of the workforce needed for successful carbon sequestration and commercialization. Two graduate students have worked on this project which directly addresses the workforce development. Commercialization of the fiber sensor array is being conducted through the Department of Energy SBIR/STTR program. To date, two Phase I project has been funded, one Phase I project has been declined, and three Phase I projects are pending.

The goals for the research project are encapsulated in a statement of the project objects. These project objectives, as stated in the original proposal, will lead to the development and demonstration of a 1 x 4 fiber sensor array for carbon sequestration site monitoring. The proposed fiber sensor array is a low cost, reconfigurable sensor that has the potential for large area coverage based on the number of fiber probes that can be accessed using one laser and two photo-detectors in the call/receive geometry. To reach this overall objective, the proposed project contains three phases. The objective of the first phase is to develop a single channel fiber optic sensor including the development of the fiber probe. The objective of the second phase is to refine the design of the fiber probe based on the experience gained during the first phase of the project and develop a 1 x 4 fiber sensor array. The objective of the third phase of the proposed work is to test the fiber sensor array at the ZERT site. Each of these project objects, as discussed below, have been met.

This final report is organized as follows: Section II contains a brief summary of the project highlights. Section III presents the technical aspects of the project. Finally some brief concluding remarks are presented in Section IV.

II. Project Summary

Students:

Graduate Student I: Graduate Student in Physics. He worked on the initial probe design and testing. He is currently working towards a Ph.D. in physics in the areas of optical spectroscopy.

Graduate Student II: Graduate student in Electrical and Computer Engineering. He worked on improving the fiber probe designs and deploying the instrument at the Zero Emission Research Technology (ZERT) controlled sub-surface release facility and the Big Sky Carbon Sequestration Partnership site. This work will form the basis of his master's thesis. He will continue working towards his Ph.D. in electrical engineering where his Ph.D. thesis will be based on deploying monitoring technologies and techniques as part of the Big Sky Carbon Sequestration Partnership project.

Journal Papers:

"Field demonstration of a 1 x 4 Fiber Sensor Array for Sub-Surface Carbon Dioxide Monitoring for Carbon Sequestration", Benjamin Soukup, Kevin S. Repasky, John L. Carlsten, and Geoff Wicks, Journal of Applied Remote Sensing, V8, 083699-1 – 083699-13, 2014.

Conference Talks:

<u>Contributed:</u>

“Sub-Surface Carbon Dioxide Concentration Measurement Using a Fiber Based Sensor in a Send/Call Geometry for Carbon Sequestration Site Monitoring”, Geoffrey Wicks, Benjamin Soukup, Kevin S. Repasky, John L. Carlsten, Jamie L. Barr, and Laura Dobeck, American Geophysical Union Meeting, San Francisco, California, 2010.

“Development of a 1 x N fiber sensor array for monitoring geologic carbon sequestration sites”, DOE ARRA Geolgic Sequestration Training and Research Project Yearly Review Meeting, Pittsburg, PA, February 23-25, 2011.

“Development of a 1 x N Fiber Optic Sensor Array for Carbon Sequestration Site Monitoring”, Kevin S. Repasky, John L. Carlsten, Benjamin Soukup, and Geoff Wicks, Carbon Storage R&D Project Review Meeting, Pittsburgh, PA, August, 2012.

“Development of a 1 x N Fiber Optic Sensor Array for Carbon Sequestration Site Monitoring”, Kevin S. Repasky, John L. Carlsten, Benjamin Soukup, and Geoff Wicks, Carbon Storage R&D Project Review Meeting, Pittsburgh, PA, August, 2013.

<u>Invited:</u>
“Optical Tools and Techniques for Large Area Surface Monitoring of Carbon Sequestration Sites”, Kevin S. Repasky, William Johnson, Benjamin Soukup, John L. Carlsten, Rick Lawrence, and Scott Powell, Optical Society of America Energy and the Environment, Tucson, AR, 2013

Commercialization Efforts:
The commercialization of the fiber sensor array is progressing through the Department of Energy (DoE) SBIR/STTR programs. Currently one phase I proposal has been funded and four phase I proposals are pending these proposal are listed below:

<u>Funded:</u>
“Fiber Optic O_2/CO_2 Sensor to Monitor Atmospheric Leakage at CO_2 Injection Sites**”** Department of Energy Phase I SBIR

“Development of a novel IR detector for improved CO_2 subsurface sequestration monitoring” Department of Energy Phase I SBIR.

<u>Pending</u>:
“Development of a nBn detector for carbon cycle and other related green house gas measurements” Department of Energy Phase I SBIR.

“Wireless subsurface gas optical monitoring system” Department of Energy Phase I SBIR.

“Broad area monitoring of CO2 release” Department of Energy Phase I SBIR.

<u>Declined:</u>
“Fiber Optic Sensor Array for Carbon Sequestration Monitoring” Department of Energy Phase I SBIR.

III. Technical Report

The atmospheric concentration of a molecular species can be related to the transmission of light by considering the optical depth, αL, where α 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. The optical depth can be related to the molecular linestrength, S, and the normalized lineshape, $g(\upsilon - \upsilon_0)$, by the relationship

$$\alpha L = Sg(\nu - \nu_0)NP_aL \quad (1)$$

with $N = N_L \frac{296}{T_a}$ the total number of molecule where $N_L = 2.479 \times 10^{19}$ molecules/cm atm is Loschmidt's number and T_a is the temperature in K. 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 thus

$$C = \frac{NP_a}{NP_T} = \frac{P_a}{P_T} \quad (2)$$

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

$$C = \frac{-\ln(T)}{Sg(\nu - \nu_0)N_L(\frac{296}{T_a})P_T L} \quad (3)$$

Values for the linestrength, S, and normalized lineshape, $g(\upsilon - \upsilon_0)$, are tabulated in the HITRAN database. With measurements of the transmission for a known pathlength, and know temperature, and pressure, the molecular concentration can be calculated 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 pathlength 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 rage of sub-surface CO_2 concentrations expected at a geologic sequestration site. The maximum absorption at the 2.004 02 μm wavelength is 2.9% (13.6%, 57.8%) for the CO_2

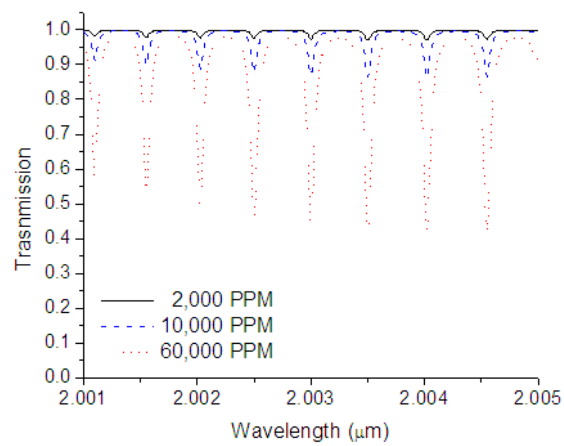

Figure 1 Transmission as a function of wavelength for a 1 m pathlength, a temperature of 288 K, and a pressure of 1 atm. The black solid line (blue dashed line, red dotted line0 represents calculations based on a CO_2 concentration of 2,000 ppm (10,000ppm, 60,000 ppm). This range of CO_2 concentration represents the expected subsurface CO_2 concentration that will be seen at a geologic sequestration site. Background levels typically range between 2,000 ppm and 8,000 ppm depending on microbial activity and meteorological conditions.

concentration of 2,000 ppm (10,000 ppm, 60,000 ppm). Values for the wavelength, linestrength, and lineshape for the eight strongest CO_2 absorption features in the 2.001 to 2.005 µm wavelength range are presented in table 1.

A schematic of the fiber sensor array is shown in figure 2. A distributed feedback (DFB) laser operating at 2.004 µm is mounted in a 14 pin butterfly package with a fiber pigtailed output. The DFB laser has an internal thermoelectric cooler (TEC) that allows temperature tuning of the DFB laser. The DFB laser is mounted in a commercial mount that provides a second TEC cooler 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 couple output from the DFB laser is incident of an in-line fiber splitter, which uses 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 are connected via a multi-mode fiber optic cable to a probe that is place into the ground. These probes allow the light to interact with the carbon dioxide (CO_2) that diffuses into the buried probes through Millipore filters place at the top and bottom of the probes. These filters allow the soil gas to diffuse into the probes but keeps out dirt and water. The light is then re-coupled into the multi-mode optical fiber where it is then directed back through the fiber optic switch and is again incident on the in-line fiber splitter where light from one port is direct 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.

Wavelength mm	Linestrength 10^{-21} molecules/cm	Normalized Lineshape Cm
2.001 102 0	0.811 2	1.160 0
2.001 557 7	0.931 6	1.151 6
2.002 025 5	1.048	1.140 1
2.002 505 7	1.153	1.130 4
2.002 998 0	1.241	1.116 1
2.003 502 6	1.302	1.102 2
2.004 019 2	1.332	1.084 2
2.004 548 2	1.322	1.0653

Table 1 The wavelength, linestrength, and normalized lineshape 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 ZERT field experiment are highlighted.

The laser temperature and current are regulated using a Wavelength Electronics dual laser driver and TEC controller (WTC0520). This unit has the option for both onboard and remote control capability. The laser

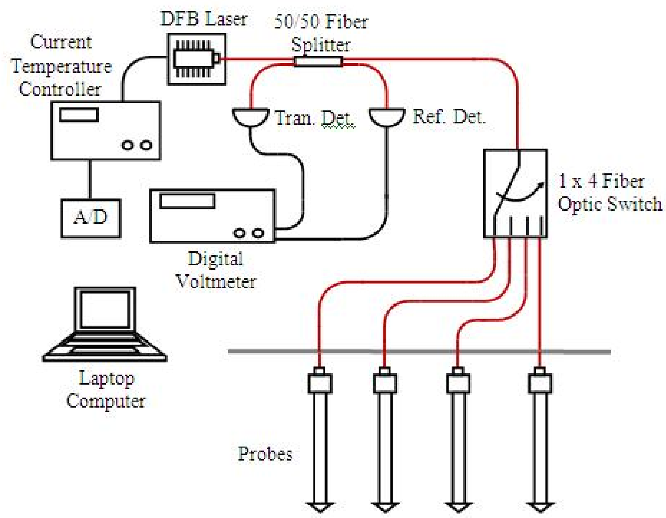

Figure 2 Schematic of the 1 x 4 fiber sensor array.

current is run at a constant 50mA using an onboard trimpot. The laser temperature is controlled remotely from the computer for tuning over the desired range. This operation requires a digital to analog converter (DAC) to convert the digital program commands to analog voltage signals for input into the temperature controller. In this way actual TEC temperature, and thus the laser wavelength, can be monitored and controlled from a single panel in the Labview control program.

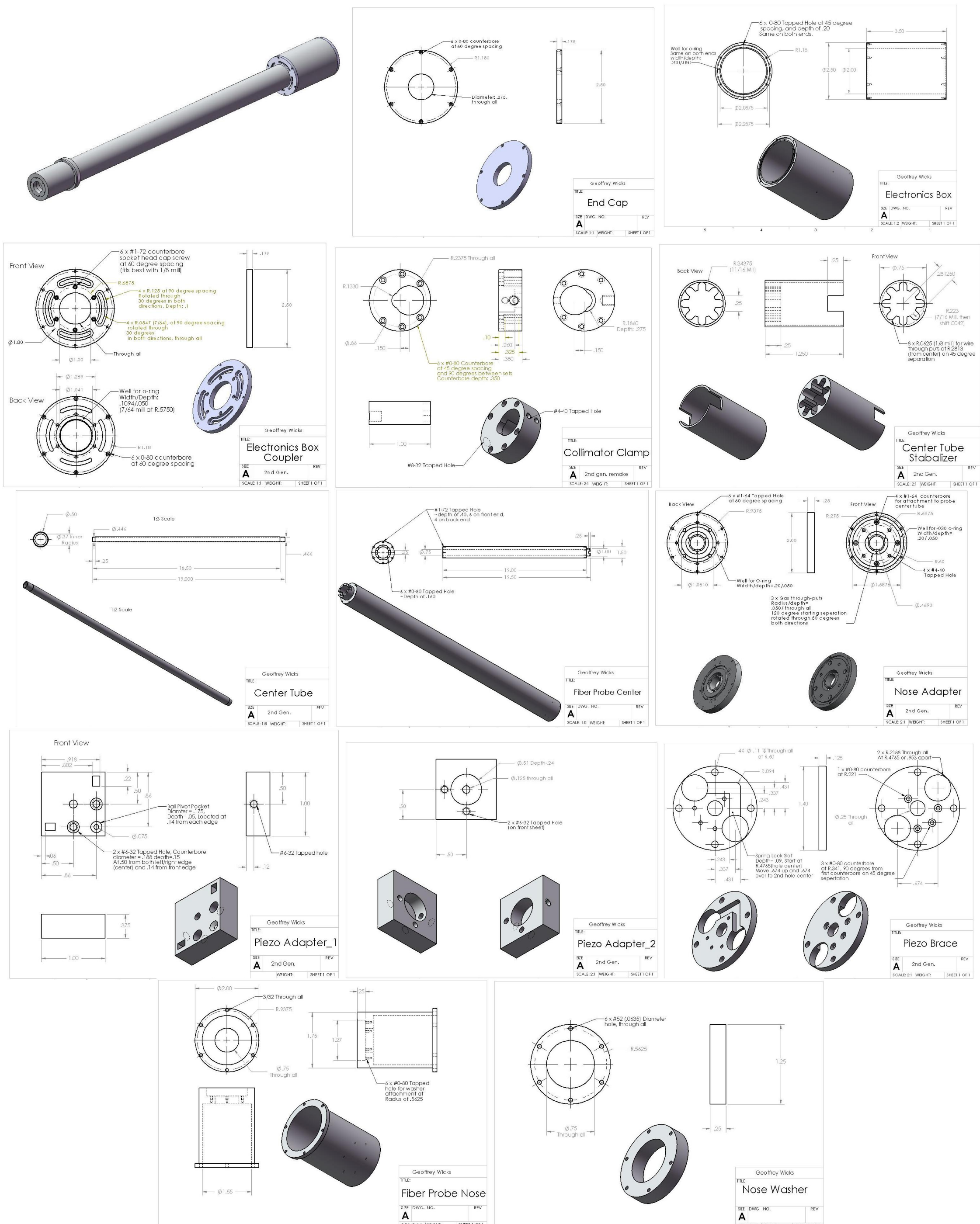

Figure 3 The assembly and machine drawings completed in SolidWorks CAD software for the second generation fiber probes.

The fiber probes where designed and machine drawing developed using the Solidworks CAD software package. This design process involved the development of an initial design for a fiber probe. After testing this first probe, design modifications and improvements to the fiber probe design where incorporated leading to the final set of assembly and machine drawings shown in figure 3.

A schematic of the fiber probes is shown in figure 4. 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 (Optequip 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 using a lens with a focal length of f = 11 mm. 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. A picture of the four completed probes is shown in figure 4.

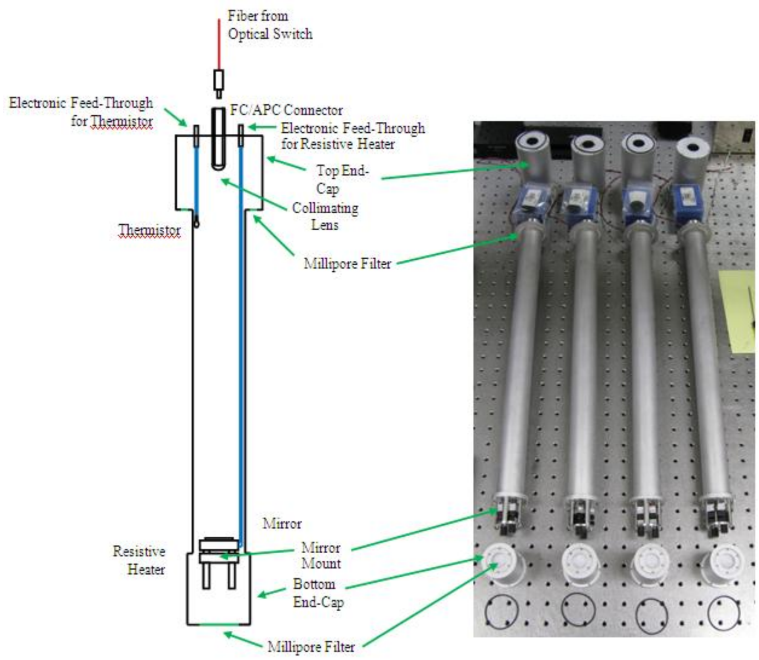

Figure 4 Schematic of the fiber probe is shown on the left and four completed fiber probes shown on the right.

The instrument is operated using software developed in the Labview programming environment. A screen capture from the front panel of the Labview program for a single channel is shown in figure 5. The upper left plot shows the reference detector voltage while the upper right plot shows the transmission detector voltage. The bottom left plot shows the normalized transmission which is calculated by dividing the two transmission plots. Once this is done, the Labview program determines the minimum transmission values for each of the transmission features scanned which are then marked with a red circle. Then the Labview program calculates the baseline by looking at point midway between the transmission minima and then normalizes the transmission plot These baseline values are marked with the green diamonds. The concentration for each transmission feature is then calculated and averaged to produce a CO_2 concentration which is then displayed as a time series in the lower right hand plot. The four channel Labview program is similar, but displays the results for each of the four probes along with a switch status.

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 ramping its operating temperature.

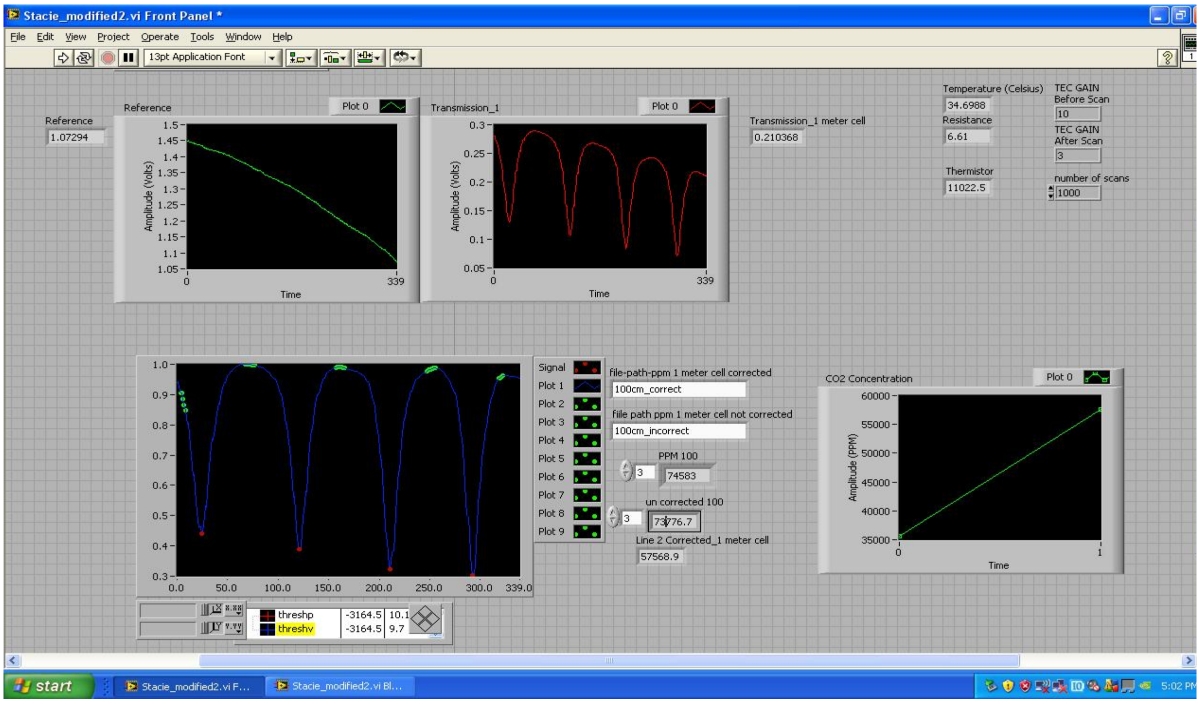

Figure 5 The front panel of the Labview program for a single channel. The upper left plot shows the reference detector voltage while the upper right plot shows the transmission detector voltage. The bottom left plot shows the normalized transmission with the green diamonds showing the baseline measurement and the red dots showing the minimum transmission used to calculate the CO_2 concentration. The concentration time series is shown in the lower right hand plot.

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 the laser requires at least a 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. 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 from 33-39^{o} F. Once a scan is completed the transmission is normalized and the molecular concentration can be back calculated using the results from above, and the program moves on to the next probe to repeat the entire process.

Initial testing of the fiber sensor array was completed in a laboratory setting using dry ice to mimic the elevated subsurface CO_2 concentrations to be expected in the field. The packaging allowed for active temperature control in the enclosed housing, continuous monitoring of the laser thermoelectric cooler (TEC) status monitoring because of power outages at the field site, and the ability to remotely monitor the status of the fiber sensor array. A picture of the completed 1 x 4 fiber sensor array is shown in figure 6. The weather proof electronics house is the white box at the top of figure 1 while the four fiber probes can be seen in the lower part of the figure. The electronics box contains a line voltage fan that is controlled using a cooling thermostat. When the temperature of the box exceeds a user defined temperature, the fan circulates ambient air to keep the temperature within the box within the working range for the instruments contained within the box. A picture of the electronics contained within the box is shown in figure 7. The distributed feedback (DFB) laser, detector, and fiber optic switch are labeled in this figure.

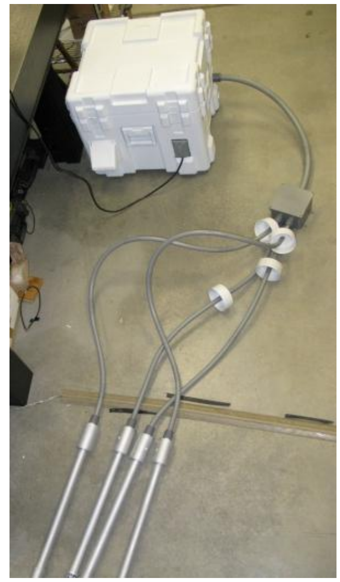

Figure 6 The assembled 1 x 4 fiber sensor array.

The software updates in preparation for the summer field deployments were in part in response to issues run into during the summer 2010 field experiment. First, due to multiple power outages last summer that shut the laser and TEC cooler off, the scanning software was modified to check the status of the laser and TEC after each scan. This allows a warning to be sent indicating that a power interruption has shut off the laser. Next, to minimize the time required to be in the field and to begin preparing the instrument for long term unattended operations, the Labview software has been modified to include the ability to monitor the instrument via a remote desktop. The instrument operator can now monitor the status of the instrument from any internet available computer.

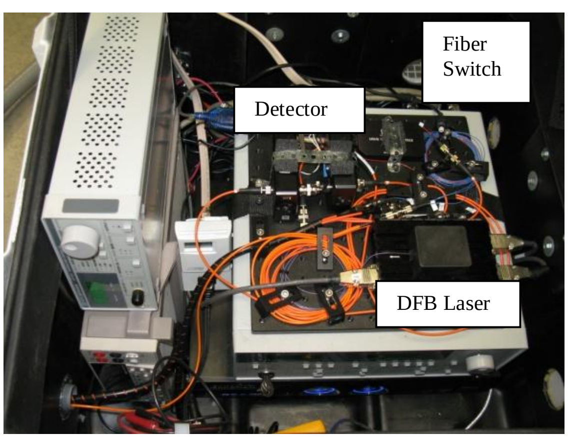

Figure 7 The optical layout and electronics housed in the weather proof box.

A plot of the CO_2 concentration as a function of scan number is shown in figure 8 for a single fiber probe. Data shown in figure 8 was collected over a 20 hour period with the rapid rise in the CO_2 concentration resulting from the introduction of the dry ice and the slower fall in the CO_2 concentration resulting from the melting of dry ice. This data indicated that the instrument was working properly. Once this initial test was completed, data collected using all four of the probes was collected to ensure the successful operation of the fiber sensor array. This data is shown in figure 9 for a 12 hour period.

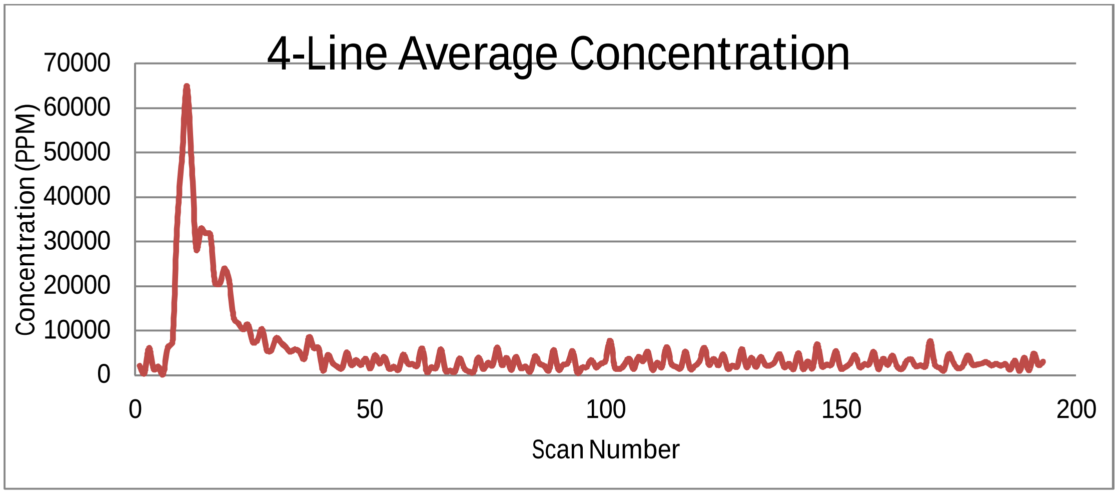

Figure 8 The CO_2 concentration measured using a single probe over a twenty hour period. The concentration was calculated using the average value calculated from the four CO_2 absorption features scanned by the DFB laser.

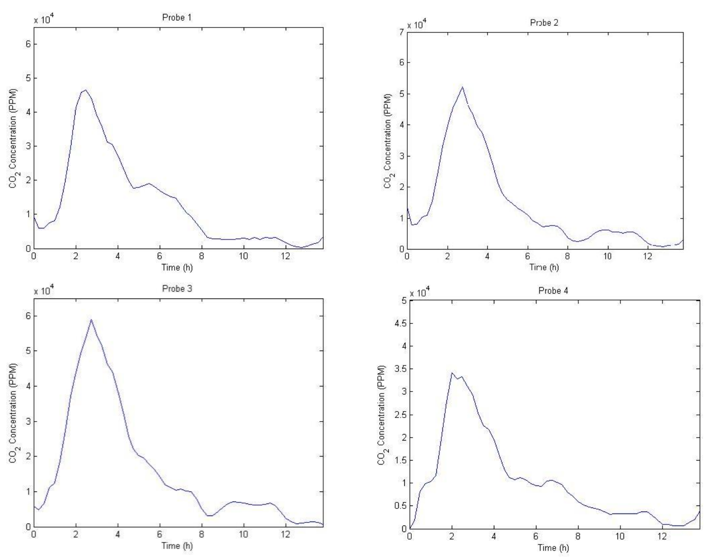

Figure 9 Data collected over twelve hours using the four probes.

With the completion of the laboratory testing, the fiber sensor array was deployed at the Zero Emissions Research and Technology (ZERT) field site, shown in figure 10. The ZERT field site is a controlled CO_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_2 leak source,

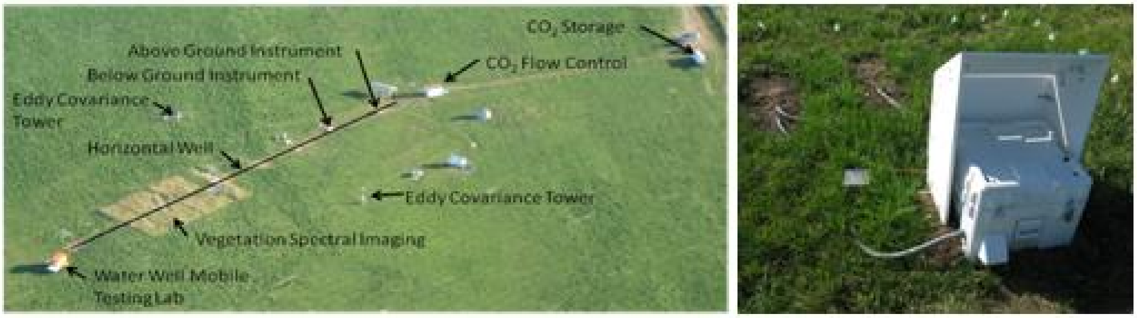

Figure 10 An aerial view of the ZERT field site is shown in the left hand figure while the deployed instrument is shown in the right hand figure.

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 topped by several meters of silts, clays, and topsoil. The well 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 well is perforated to inject CO_2. A series of eight packers were placed within the well to assist in dispersing the gas evenly along the slotted portions of the well 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 well installation was deflected from a perfectly straight path because of cobble in the gravel layer underground.

A thirty four day release experiment was performed beginning July 10, 2012. The CO_2 release rate for this experiment was 0.15 tons CO_2/day, about the equivalent to two idling cars, evenly distributed over the eight section of the well. The flow rate was chosen in the following manner. Approximately 4 x 10^6 tones CO_2/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 200x10^6 tones CO_2 which could be sequestered. Assuming that the injection area is approximately 1% of a typical fault size, the flow rate was chosen so that the seepage would mimic less that 0.01% through a typical fault. This implies that the flow rate chosen mimics the levels that need to be monitored at geologic sequestration sites.

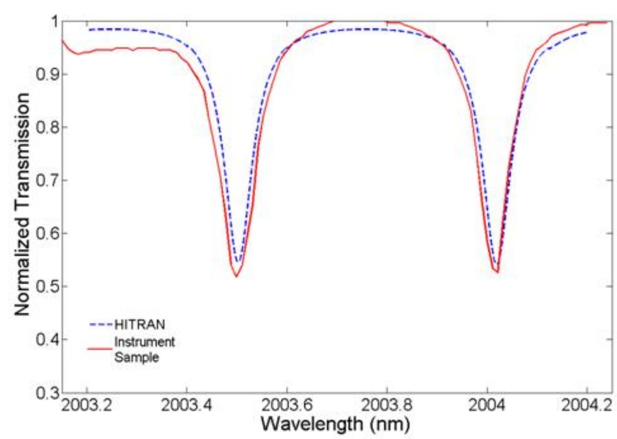

Figure 11 The solid red line represents transmission measurements made with the fiber sensor while the blue dashed line represents the expected transmission based on the HITRAN database.

A plot of the normalized transmission as a function of wavelength is shown in figure 11. 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 above, returned a CO_2 concentration of 50,926 PPM. The dashed blue line in figure 11 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.

The fiber sensor probe was operated for a fifty-eight day period proving subsurface CO_2 concentration measurements from each of the four. 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 12. This data was collected before the subsurface CO_2 began providing background data. During this four day period, the CO_2 concentration ranged between 1,000 and 7,000 PPM. A diurnal cycle is evident in figure 6 with a maximum CO_2 concentration occurring around 1:00 pm local time and a minimum occurring approximately twelve to fifteen hours after the maximum value. This diurnal cycle is related to the subsurface microbial activity as well as the surface meteorological conditions and soil moisture. This data shows the each of the four fiber probes is able to monitor background CO_2 concentration levels.

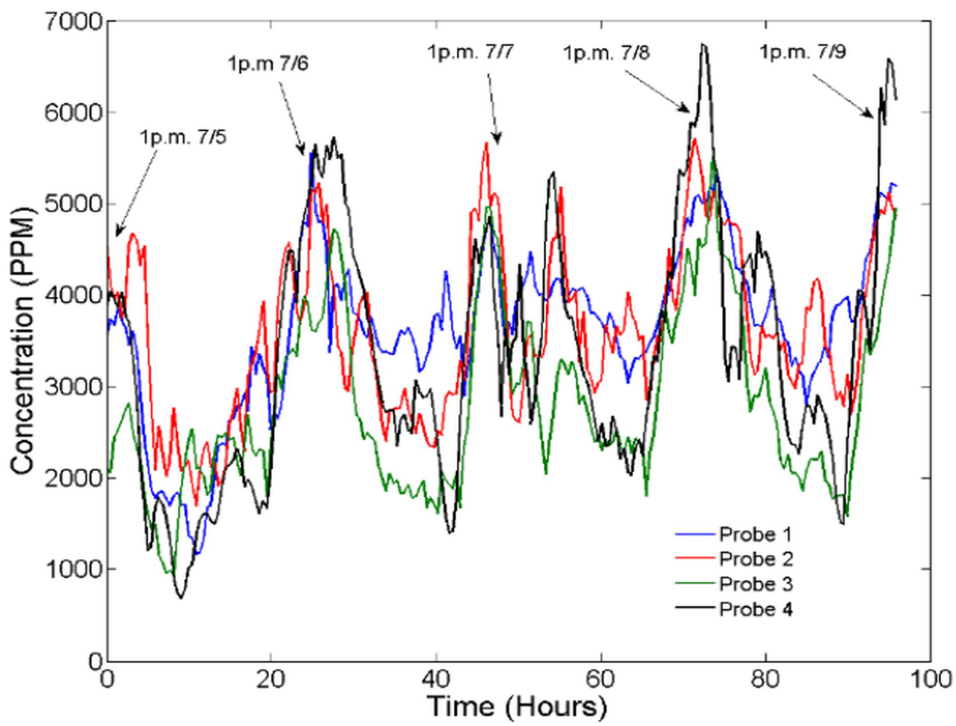

Figure 12 A plot of the CO_2 concentration as a function of time for each of the four probes measured over a four day period before the beginning July 5, 2012 at 1:00 pm local time. This data was collected before the beginning of the controlled sub-surface CO_2 release and providing background measurements A diurnal cycle of subsurface CO_2 concentration is seen by each of the four probes with CO_2 concentrations ranging between 1,000 ppm and 7,000 ppm. The diurnal cycle is most likely due to microbial activity and meteorological

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 13. The four probes were located roughly on the corners of a rectangle with an area of about $1m^2$. The front two probes were placed closest to the pipe at a 0.5 m perpendicular distance with a max depth of about one meter. The remaining two were shifted back by about another 0.5 m. All four probes were buried at 45^o 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 8, 2012 with the release start time and stop marked in figure 13 with vertical lines. Data was collected twenty two days before the start of the release to ensure the instrument was able to monitor background levels. During this first twenty two 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. 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 well 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 in 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 which reached a steady state value of about 50,000 ppm until the release was stopped. 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.

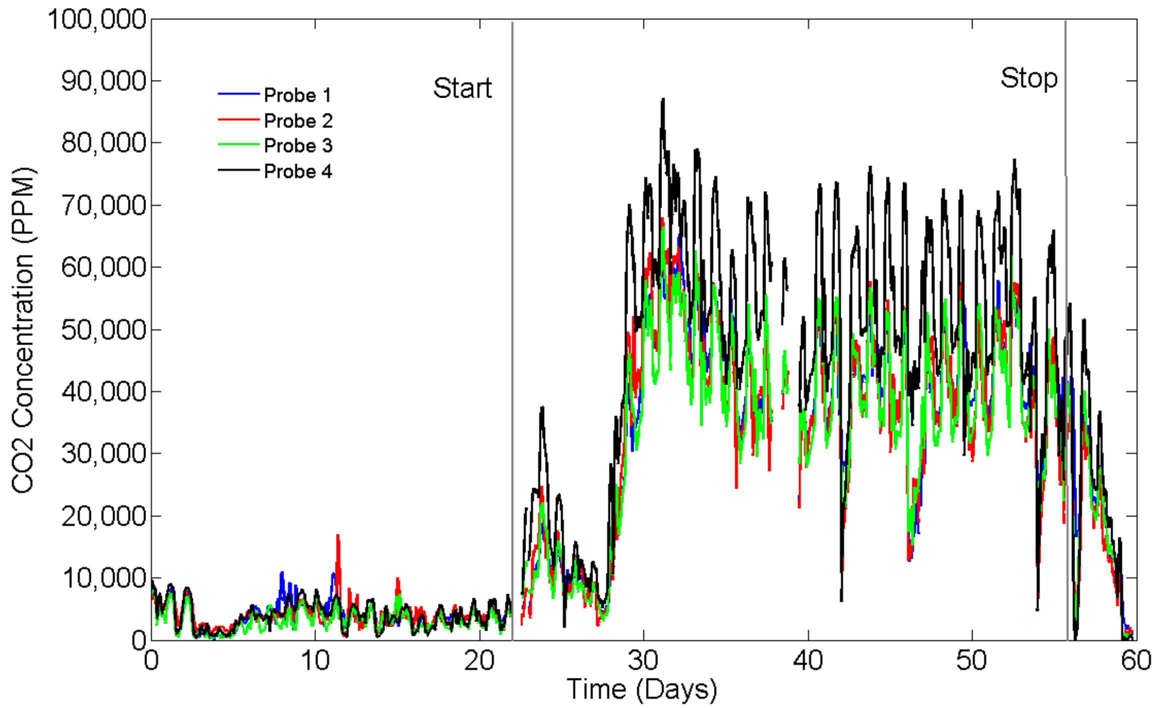

Figure 13 A plot of the sub-surface CO_2 concentration as a function of time for each of the four probes over a fifty-eight day period. The start and stop of the controlled sub-surface CO_2 release are indicated by the solid vertical lines. A rise in the sub-surface CO_2 concentration by over a factor 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.

A fiber optic sensor array for sub-surface CO_2 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 CO_2 concentration measurements based on integrated path differential absorption techniques. This instrument was successfully deployed over a fifty-eight day period measuring background CO_2 concentrations over twenty two days, measuring the changing sub-surface CO_2 concentrations in each of the four probes resulting from a thirty four day sub-surface controlled release, and finally monitoring the decrease of CO_2 to background levels for the three days after the injection was stopped. Background CO_2 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 60,000 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 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 inexpensively scale up with the added benefit that the fiber probes can be placed as needed and easily moved providing for a reconfigurable sensor array.

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 . 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 are aimed at achieving this goal. The successful deployment of the fiber sensor array at the ZERT field site during the summer of 2012 indicated that this detector has the potential to monitor carbon sequestration sites. During the summer of 2013, the fiber sensor array was deployed at the Big Sky Carbon Sequestration Partnership (BSCSP) site in north central Montana. The location of the BSCSP site is indicated on the map in the left hand map in figure 14. The right hand map is

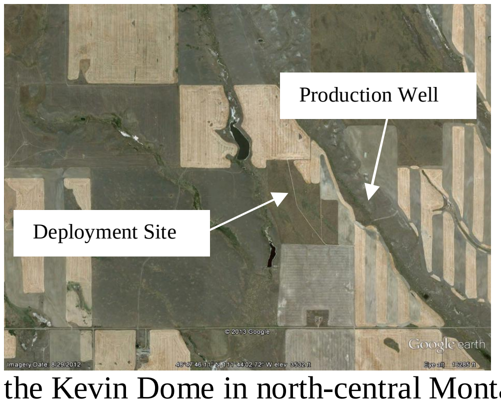

Figure 14 The location of the BSCSP site located at the Kevin Dome in north-central Montana is shown on the map on the left. The Google image on the right shows the location of the production well and deployment site.

a Google image with the location of the production well and the approximate field site shown. It was hoped that the production well would be in place for the field deployment. However due to delays resulting from permitting, the BSCSP was unable to begin drilling the production well. Because of the permitting delays, there was no infrastructure available so electricity for the fiber sensor array was provided by a 2.0 kW portable generator. A picture of the fiber sensor array deployed at the field site is shown in the left hand picture in figure 15 and the optical and electronic components housed in the weatherproof container are shown in the right hand figure. Data was collected for a few hours each day due to the limited operating time of the generator with a limited fuel supply. Plots of the CO_2 concentration measured by each of the four fiber probes are shown in figures 16 below. The Fiber sensors each measured CO_2 concentrations of approximately 2,000 PPM which corresponds to background levels seen at the Zero emission field site. The fiber probes were designed to have a minimum detection of approximately 1,000 ppm so these background measurements are at the lower end of the instruments dynamic range. The error bars shown in figure 16 results from a differential error analysis as discussed below.

Figure 15 The fiber sensor array deployed at the field site is shown in the left hand image and the optical and electronic components housed in the weatherproof container are shown in the right hand image.

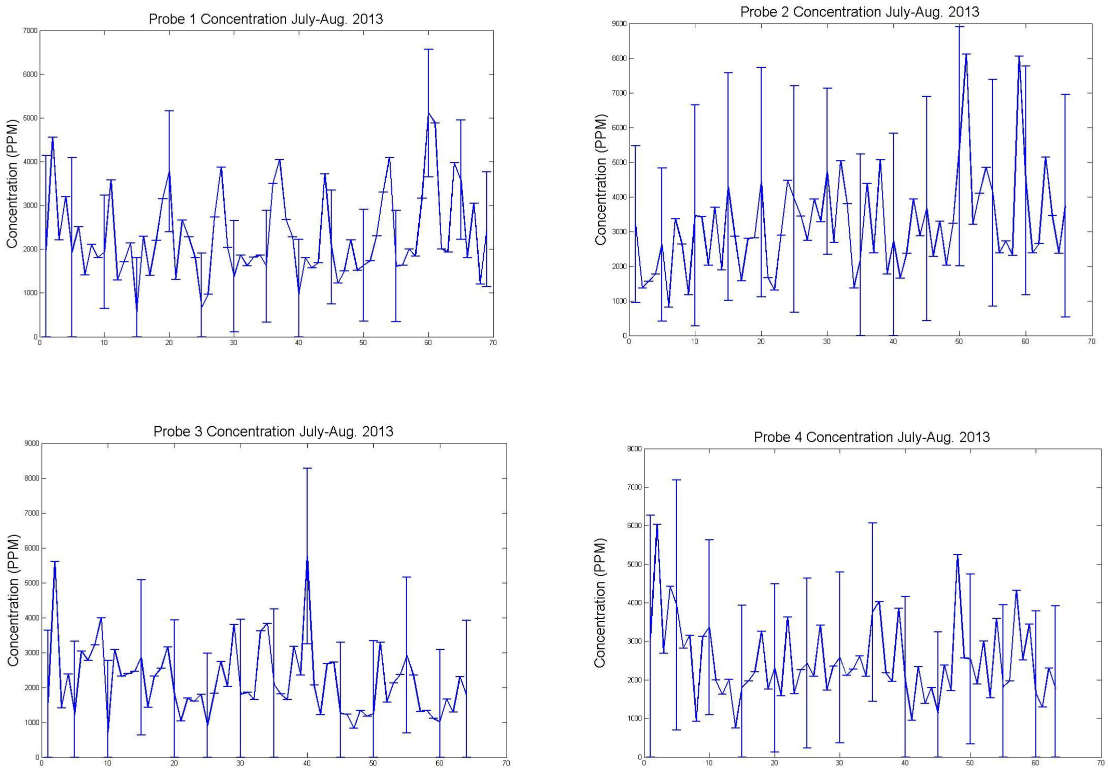

Figure 16 The CO_2 concentration measured between July 9th and August 7th at the Big Sky Carbon Sequestration Partnership site.

The diffenretial error analysis begins with the integrated path differential absorption (IPDA) equation that allows calculation of the CO_2 concentration (C) as a function of the measured transmission, T. The IPDA equation is

$$C = \frac{-\ln(T)}{Sg(\nu - \nu_0)N_L(\frac{296}{T_a})P_T L} \quad (4)$$

The linestrength (S), lineshape (g(v-v$_o$)), Loschmidt's number (N_L), and the pathlength (L) are all constant inputs into the equation. The atmospheric pressure, P_T, has also been regarded as a constant up to this point as it varies by only ~.01atm during the course of a day according to the ZERT weather station. The remaining two variables, transmission (T) and ambient temperature (T_a), are analyzed independently to give an estimate on the error for the concentration. Mathematically, this error is represented by

$$dC = \frac{dC}{dT}dT + \frac{dC}{dT_a}dT_a \quad (5)$$

where dT and dT_a are the quantified noises on the transmission signal and temperature reading respectively. Taking the partial derivatives, the error in the retrieved concentration is

$$dC = \frac{-1}{Sg(v-v_o)N_L\frac{296}{T_a}P_T L T}dT + \frac{-\ln(T)}{Sg(v-v_o)N_L 296 P_T L}dT_a \qquad (6)$$

The concentration retrieval will utilize the measured transmission to determine the dT term used in the above equation and will provide a plot of the CO_2 concentration as a function of time for each probe along with an error estimate.

The CO_2 probes were designed to have a dynamic range so that measurements can be made starting at background levels of 2000 parts per million (PPM) through 100,000 PPM. The smaller amount of absorption at the lower concentrations will result in the highest uncertainties in CO_2 concentration measurements. The results of the error analysis for data collected over 14 hours for data collected on June 11, 2012 is shown in figure 17 and include the results of the error analysis. This data shows the error for subsurface CO_2 concentrations near the minimum

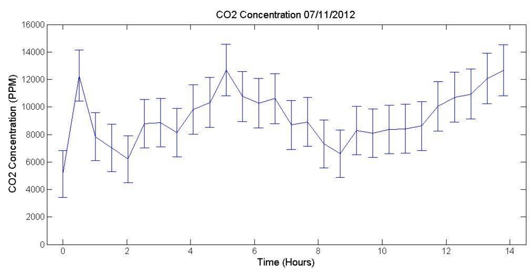

Figure 17 CO_2 concentration and measurement uncertainty near minimum detectable CO_2 concentrations.

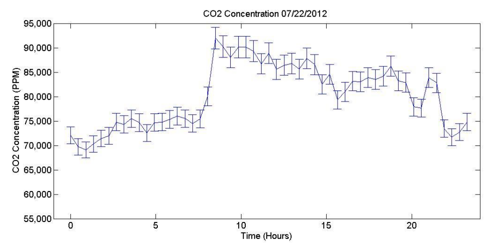

Figure 18 CO_2 concentration and measurement uncertainty at higher CO_2 concentrations from later in the controlled release experiment.

detection level. A plot of the CO_2 concentration from later in the controlled release experiment at the ZERT site is shown in figure 18. The error associated with the higher concentrations is reduced due to the large absorption.

V. Conclusions

The major research goals for the project involved developing and demonstrating a fiber sensor array for sub-surface CO_2 monitoring. The fiber sensor array developed is capable of monitoring subsurface CO_2 concentrations ranging from 2,000 ppm to 100,000 ppm. This instrument has been demonstrated at the ZERT controlled subsurface release facility and was able to easily detect the elevated subsurface CO_2 concentrations needed for successful sequestration site monitoring. This instrument has also been deployed at the BSCSP site in north-central Montana and has provided background CO_2 measurements. This instrument will continue to be deployed over the next several years as part of the monitoring strategy at the BSCSP site.

The project provided opportunities for two graduate students. The first graduate student is a Ph.D. candidate in the Electrical and Computer Engineering Department and this work will for the basis for his master's thesis. This student will continue working towards his Ph.D. that will focus on monitoring tools and strategies for carbon sequestration site monitoring. The second graduate student is a Ph.D. candidate in the Physics Department. This work launched his graduate studies focusing on developing spectroscopic tools and techniques. The graduate student training is helping to develop the workforce needed for successful carbon sequestration.

This project was funded through an ARRA grant and had as one of its program goals a path towards commercialization of the developed technology. Researchers at Montana State University are working with several small businesses through the Department of Enengy's SBIR/STTR program to move this technology into the commercial section. To date, two phase I project has been funded, three phase I projects are pending, and one phase I project declined. This SBIR/STTR activity includes proposal development with five small businesses.

Appendix A
Papers

"Field demonstration of a 1 x 4 Fiber Sensor Array for Sub-Surface Carbon Dioxide Monitoring for Carbon Sequestration", Benjamin Soukup, Kevin S. Repasky, John L. Carlsten, and Geoff Wicks, Journal of Applied Remote Sensing, V8, 083699-1 – 083699-13, 2014.

Field demonstration of a 1×4 fiber sensor array for subsurface carbon dioxide monitoring for carbon sequestration

Benjamin Soukup,[a] Kevin S. Repasky,[a] John L. Carlsten,[b] and Geoff Wicks[b]

[a]Montana State University, Department of Electrical and Computer Engineering, Cobleigh Hall Room 610, Bozeman, Montana 59717
repasky@ece.montana.edu

[b]Montana State University, Department of Physics, EPS 264, Bozeman, Montana 59717

Abstract. A fiber sensor array for subsurface CO_2 concentration measurements was developed for monitoring geologic carbon sequestration sites. The fiber sensor array uses a single temperature-tunable distributed feedback (DFB) laser operating with a nominal wavelength of 2.004 μm. Light from this DFB laser is directed to one of the four probes via an inline 1×4 fiber optic switch. Each of the four probes is buried and allows the subsurface CO_2 to enter the probe through Millipore filters that allow the soil gas to enter the probe but keeps out the soil and water. Light from the DFB laser interacts with the CO_2 before it is directed back through the inline fiber optic switch. The DFB laser is tuned across two CO_2 absorption features, where a transmission measurement is made allowing the CO_2 concentration to be retrieved. The fiber optic switch then directs the light to the next probe where this process is repeated, allowing subsurface CO_2 concentration measurements at each of the probes to be made as a function of time. The fiber sensor array was deployed for 58 days beginning from June 19, 2012 at the Zero Emission Research Technology field site, where subsurface CO_2 concentrations were monitored. Background measurements indicate that the fiber sensor array can monitor background levels as low as 1000 parts per million (ppm). A 34-day subsurface release of 0.15 tones CO_2/day began on July 10, 2012. The elevated subsurface CO_2 concentration was easily detected by each of the four probes with values ranging over 60,000 ppm, a factor of greater than 6 higher than background measurements. [DOI: 10.1117/1.JRS.8.083699]

Keywords: carbon dioxide; fiber optic applications; absorption.

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1 Introduction

The average atmospheric concentration of carbon dioxide (CO_2) has been monitored continuously beginning in Mauna Loa Observatory in Hawaii since 1957.[1,2] The average atmospheric concentration of CO_2 has risen over the past 55-year observation record from a mean value of 315.97 parts per million (ppm) in 1959 to 391.57 ppm in 2011. 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 to 1.96 ppm/year between 2000 and 2009. Records of CO_2 concentrations from other sites around the globe show similar results.[2]

The increasing level of atmospheric CO_2 is due to anthropogenic activity including the burning of fossil fuel and land-use changes.[3–5] The CO_2 emission from fossil fuel combustion was 7.9 gigatones of carbon (GtC) per year in 2005, whereas 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 climatic 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 their effects on the climatic system.[7–15]

Carbon sequestration[16–21] is one method for mitigating the emission of CO_2 from power generation facilities. Carbon sequestration captures the CO_2 at the source, 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 is 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 lifetime 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 the many areas of technology development needed for successful carbon sequestration.[26–33] This instrumentation will be needed for both down-well and near-surface measurements for tracking the fate of the CO_2 once it is injected, and for ensuring both carbon sequestration site integrity and public safety. These needs will require monitoring technology based on seismic detectors and down-well sensors for both pressure and temperature. A variety of monitoring tools and techniques will need to be developed to encompass the wide variability in the carbon sequestration sites. One specific group of detection tools currently in development utilizes the light from a tunable distributed feedback (DFB) laser to monitor molecular absorption of ambient air, allowing CO_2 concentrations to be found.[34–38] In this article, the development and demonstration of a 1×4 fiber sensor array operated with a DFB laser for subsurface monitoring of CO_2 are presented.

The 1×4 fiber sensor array utilizes a single DFB laser operating in the continuous wave mode with a nominal operating wavelength near 2 μm to make integrated path differential absorption (IPDA) measurements of subsurface CO_2 concentration. The light from the DFB laser is directed by a 1×4 fiber optic switch to the first of four probes that are placed underground. The light interacts with the subsurface 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 subsurface CO_2 concentrations to be retrieved. The fiber optic switch then addresses the second probe, and this process is repeated until measurements at all four probes have been completed, at which point the process is repeated.

The predecessor to this 1×4 array was tested in the years prior to the 2012 test of this instrument. This previous instrument did not incorporate a fiber switch and used only a single subsurface 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 1×4 sensor array offers a variety of advantages for commercial and scientific uses. 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 1×50 are available[39] which allows this technology to scale up to a 1×50 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 utilizes all fiber optic components, the sensor can be easily configured 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, subsurface CO_2 fluctuations due to microbial activity can be monitored. Integration of a second DFB laser and a multiplexer could allow for measurements of subsurface oxygen (O_2) levels and conclusions to be drawn on changes in soil gas content and its causes.

This article is organized as follows. A brief discussion of IPDA spectroscopy is presented in Sec. 2. In Sec. 3, a description of a 1×4 fiber sensor array is presented. Data from a 58-day field deployment at a controlled subsurface release of CO_2 at the Zero Emission Research Technology (ZERT) field site[40,41] are presented in Sec. 4. Finally, some brief concluding remarks are presented in Sec. 5.

2 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, αL, where α is the absorption per unit length for the molecular species of interest and L is the length of the light that interacts with the molecular species of interest. The optical depth can be related to the molecular line strength, S, and the normalized lineshape, $g(v - v_0)$, by the relationship[26]

$$\alpha L = Sg(v - v_0)NP_aL, \tag{1}$$

with $N = N_L(296/T_\alpha)$ is the total number of molecules, where $N_L = 2.479 \times 10^{19}$ molecules/cm atm is Loschmidt's number and T_a is the temperature in K. 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

$$c = \frac{NP_a}{NP_T} = \frac{P_a}{P_T}. \tag{2}$$

Using Beer's law, which relates the transmission as a function of the optical depth by $T = e^{-\alpha L}$, and the above two equations, the concentration for the molecular species of interest is[26]

$$c = \frac{-\ln(T)}{Sg(v - v_0)N_L\left(\frac{296}{T_a}\right)P_TL}. \tag{3}$$

Values for the linestrength, S, and normalized lineshape, $g(v - v_0)$, are tabulated in the high-resolution transmission molecular absorption (HITRAN) database.[42] With measurements of the transmission for a known pathlength, 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 Fig. 1 for a pathlength 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 and dotted red line) represents the transmission spectrum for a 2000 ppm (10,000 ppm and 60,000 ppm) CO_2

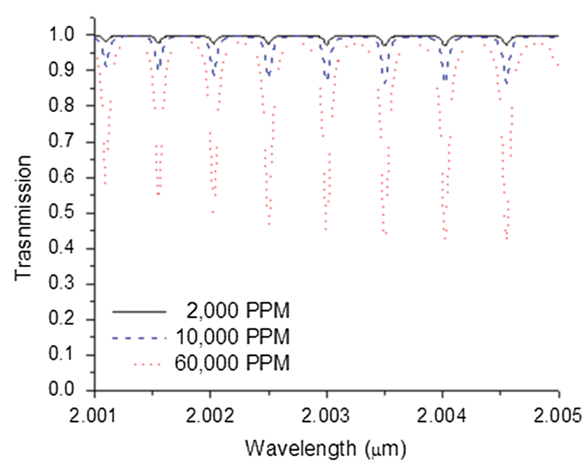

Fig. 1 Transmission as a function of wavelength for a 1-m pathlength, a temperature of 288 K, and a pressure of 1 atm. The black solid line (blue dashed line and red dotted line) represents calculations based on a CO_2 concentration of 2000 ppm (10,000 ppm and 60,000 ppm). This range of CO_2 concentration represents the expected subsurface CO_2 concentration that will be seen at a geologic sequestration site with background levels typically between 2000 and 8000 ppm depending on microbial activity and meteorological conditions.

Table 1 The wavelength, linestrength, and normalized lineshape for the eight strongest CO_2 absorption features in the 2.001- to 2.005-μm wavelength range. The two absorption lines used in the experiment described in this article are highlighted.

Wavelength (μm)	Line strength 10^{-21} (molecules/cm)	Normalized lineshape (cm)
2.0011020	0.8112	1.1600
2.0015577	0.9316	1.1516
2.0020255	1.048	1.1401
2.0025057	1.153	1.1304
2.0029980	1.241	1.1161
2.0035036	1.302	1.1022
2.0040192	1.332	1.0842
2.0045482	1.332	1.0653

concentration. These values of CO_2 concentration were chosen as the representative of the range of subsurface 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 2000 ppm (10,000 ppm and 60,000 ppm) is 2.9% (13.6% and 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, linestrength, and lineshape for the eight strongest CO_2 absorption features in 2.001- to 2.005-μm wavelength range are presented in Table 1.

3 Instrument Description

A schematic of the fiber sensor array is shown in Fig. 2. A DFB laser operating at 2.004-μm is mounted in a 14 pin butterfly package with a fiber-pigtailed output. The DFB laser has an internal thermoelectric cooler (TEC) that allows temperature tuning of the DFB laser. The DFB laser is mounted in a commercial mount 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 nonisolated and directly incident on an inline fiber splitter, which uses multimode 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

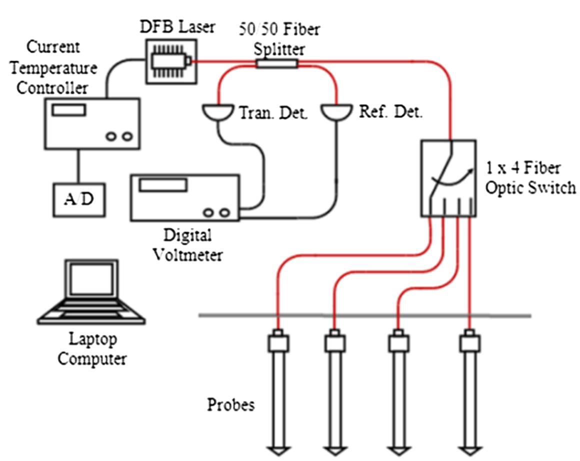

Fig. 2 Schematic of the 1 × 4 fiber sensor array.

directed to an inline 1 × 4 fiber optic switch. The inline opto-mechanical fiber optic switch has an insertion loss of less than 0.6 dB with a crosstalk of less than −60 dB. Each of the four fiber-coupled output ports is connected via a multimode fiber optic cable to a probe that is placed into the ground. These probes collimate the light and allow it to interact with the CO_2 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 recoupled into the multimode optical fiber, where it is directed back through the fiber optic switch, and is again incident on the inline fiber splitter, where light from one port is directed to a transmission detector. The reference and transmission detectors are monitored using a multi-channel voltmeter that can be read by a computer via a GPIB interface.

The laser temperature and current are regulated using a Wavelength Electronics dual laser driver and TEC controller (WTC0520). This unit has the option for both onboard and remote control capability. The laser current is run at a constant 50 mA using an onboard trimpot. The laser temperature is controlled remotely by the computer for tuning over the desired range. This operation requires a digital to analog converter (DAC) to convert the digital program commands to analog voltage signals for input into the temperature controller. The actual temperature of the laser is monitored in real time with feedback from the built-in laser thermistor, but is not used as feedback to control the laser temperature. Before field deployment, the laser wavelength was calibrated to specific temperatures. Based on this calibration, the temperature is scanned through a range of temperatures containing the absorption features of interest. In this way, actual TEC temperature, and thus the laser wavelength, can be monitored and controlled from a single panel in the Labview control program.

During field deployment, very little change in wavelength was observed in the 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 programming, which always seeks out the minima of the returned intensity and assigns it to the proper absorption feature. Long-term study of the laser change in wavelength due to use would be useful for further understanding of system performance.

A schematic of the fiber probes is shown in Fig. 3. The optical fiber from the 1 × 4 fiber optic switch is a multimode optical fiber with a core diameter of 62.5 μm (Optequip 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 $f = 11$ 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 the 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 Sec. 2. 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 pathlength where the light and CO_2 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. A picture of the four completed probes is shown in Fig. 3. During field deployment, each of the four probes was buried in large diameter PVC tube that had been perforated with 3/16 in. 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 and 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 piezzo-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 piezzos were removed from the system.

The instrument is operated using software developed in the Labview programming environment. Data are collected in the following manner. Once the channel to the desired probe is set, the

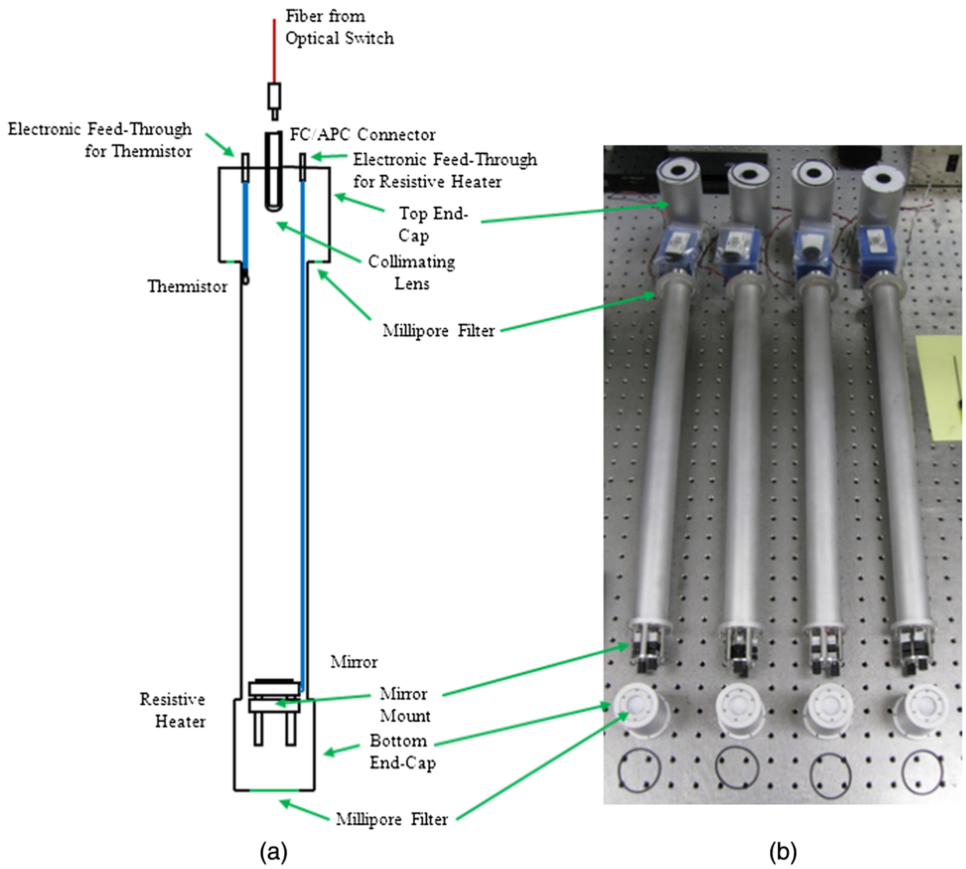

Fig. 3 Schematic of the fiber probe is shown in (a) and four completed fiber probes are shown in (b).

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 a 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 measurements are all defined by the user. Experimental measurements show that the laser requires at least 1 s to settle into each temperature and to stabilize the output wavelength. During the actual field testing of the instrument, each temperature step took about 4 s, allowing ample time for the laser wavelength to stabilize and the computer to monitor accurately the reference and transmission signals.

A single scan for a probe takes about 7 min, contains 100 points of measurement for the reference/transmission signals (mean values), and moves the laser through a temperature range from 33 to 39°C. Once a scan is completed, the transmission is normalized and the molecular concentration can be back calculated using the results in Sec. 2, and the program moves on to the next probe to repeat the entire process.

4 Controlled Subsurface Release Experiment

The ZERT field site[35,36] is a controlled CO_2 release facility located on the western edge of Montana State University in Bozeman, Montana (45°39′N, 111°04′W), at an elevation of

1495 m. The ZERT site has a buried horizontal release pipe that was developed to simulate a longitudinal CO_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. A picture of the ZERT field site is shown in Fig. 4 along with a picture of the fiber array instrument deployed at the sight. 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 deg east of true north. The central 70 m of the pipe is perforated to seep CO_2 during injection. A series of eight packers was 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.

A 34-day release experiment was performed beginning from July 10, 2012. The CO_2 release rate for this experiment was 0.15 tons CO_2/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 4×10^6 tones CO_2/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 200×10^6 tones CO_2 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 that 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.

A plot of the normalized transmission as a function of wavelength is shown in Fig. 5. 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 Sec. 3 above, returned a CO_2 concentration of 50,926 ppm. The dashed blue line in Fig. 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 that the fiber sensor probe and corresponding software are working properly.

The fiber sensor instrument was operated for a 58-day period, providing 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, periods is shown in Fig. 6. This data were collected before the subsurface CO_2 began providing background data. During this 4-day period, the CO_2 concentration ranged between 1000 and 7000 ppm. A diurnal cycle is evident in Fig. 6 with a maximum CO_2 concentration occurring around 1:00 pm local time. There is a general decline in measured CO_2 concentrations after this time leading to a general minimum about 12 h later. 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 2 days shown in Fig. 6, which most likely correspond to the changes in wind speed or air pressure due to inclement weather. These changes in

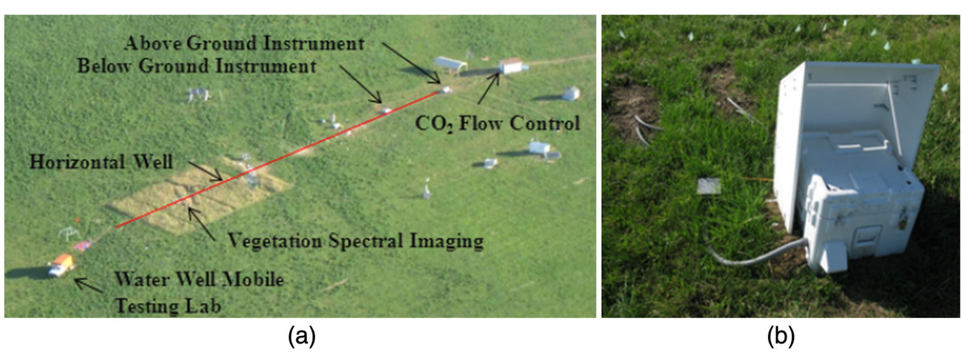

Fig. 4 The Zero Emission Research Technology (ZERT) field site is shown in (a) with the subsurface pipe location and below ground fiber instrument locations marked. The fiber sensor probe deployed at the ZERT site is shown in (b).

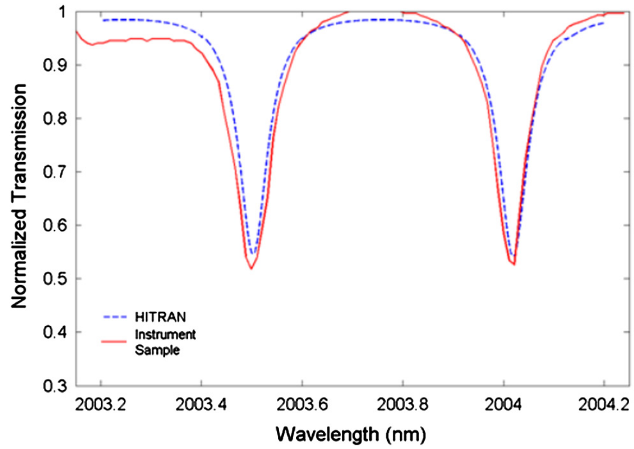

Fig. 5 A plot of the normalized transmission as a function of wavelength. The solid red line represents the normalized transmission measured using one of the four probes during the release experiment. The calculated CO_2 concentration from this measured transmission was 50,926 ppm. The dashed blue line is a plot of the transmission as a function of wavelength based on this CO_2 concentration resulting from the high-resolution transmission molecular absorption (HITRAN) database.

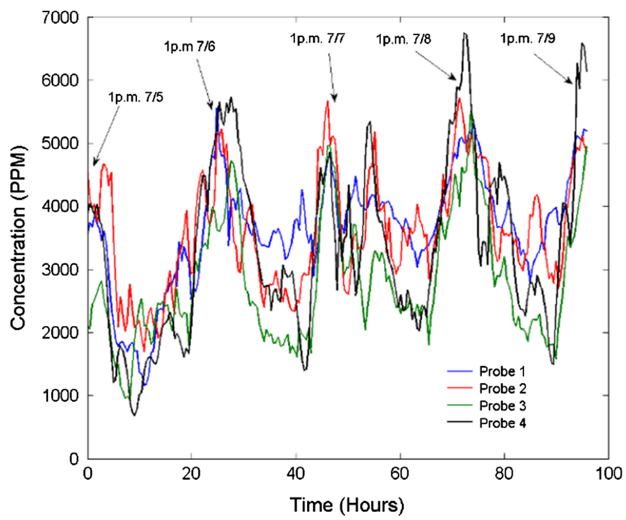

Fig. 6 A plot of the CO_2 concentration as a function of time for each of the four probes measured over a 4-day period before the beginning from July 5, 2012, at X:XX pm local time. These data were collected before the beginning of the controlled subsurface CO_2 release and providing background measurements. A diurnal cycle of subsurface CO_2 concentration is seen by each of the four probes with CO_2 concentrations ranging between 1000 and 7000 ppm. The diurnal cycle is most likely due to microbial activity and meteorological conditions.

surface condition can drastically effect how CO_2 rises from the dirt. This data show that 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 58-day period is shown in Fig. 7. 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 about 1 m. The remaining two were shifted back by about another 0.5 m. All four probes were buried at 45-deg 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 Fig. 7 with vertical lines. Data were collected 22 days before the start of the release to ensure that the instrument was able to monitor background levels. During this first 21 days, the background CO_2 concentrations

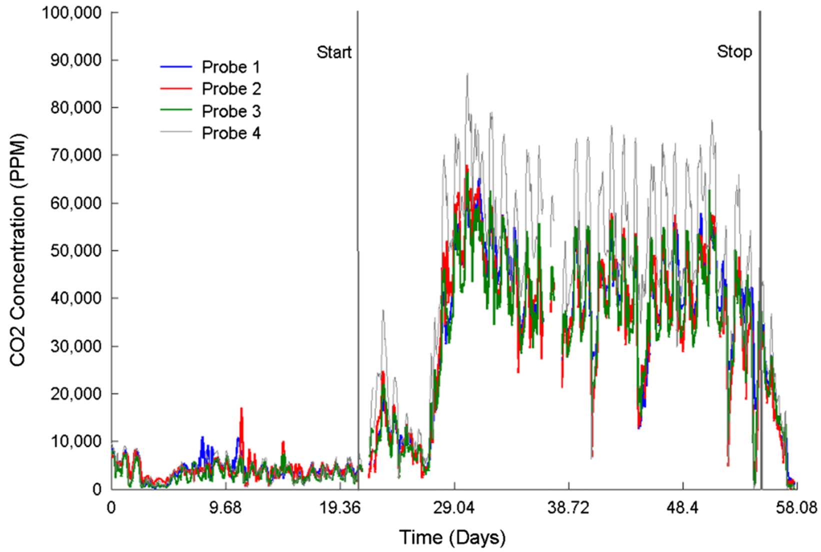

Fig. 7 A plot of the subsurface CO_2 concentration as a function of time for each of the four probes over a 58-day period. The start and stop of the controlled subsurface CO_2 release are indicated by the solid vertical lines. A rise in the subsurface CO_2 concentration by over a factor of 6 over background levels indicates that the fiber sensor array can detect changes in subsurface CO_2 concentration at the level needed for geologic carbon sequestration.

fluctuated between 1000 and 7000 ppm showing a daily diurnal cycle. After the start of the release, the subsurface CO_2 concentration began to rise in each of the four probes after approximately 1 day. This delay in the measured rise in subsurface 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 2 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 in the drop in CO_2 concentration until about 6 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 which 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 3 days for the subsurface CO_2 concentration values to fall back to their steady-state background levels.

5 Conclusions

A fiber optic sensor array for subsurface CO_2 concentration measurements has been demonstrated at the ZERT-controlled subsurface release facility over a 58-day period. This 1 × 4 fiber sensor array utilizing a send/call configuration uses a single-tunable DFB laser and fiber optic components to make subsurface CO_2 concentration measurements based on IPDA techniques. This instrument was successfully deployed over a 58-day period, measuring background CO_2 concentrations over 21 days, measuring the changing subsurface CO_2 concentrations in each of the four probes resulting from a 31-day subsurface controlled release, and finally monitoring the relaxation back to background levels for the 3 days after the injection was stopped. Background CO_2 concentrations ranged between 1000 and 7000 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 × 4 fiber optic sensor array can be scaled in a cost-effective manner for monitoring larger areas. Inline fiber optic switches based on the same technology used by the 1 × 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 the subsurface CO_2 detection. The ability to monitor other subsurface gases including methane (CH_4) and oxygen (O_2) can provide process-based information that can help determine the origin of the CO_2.[43] For example, if photosynthesis is occurring, then 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 are aimed at achieving this goal.

Acknowledgments

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Benjamin Soukup earned a BS degree in physics from Montana State University in 2011, and he is currently working on his MS in electrical engineering. His research is focused on the development and testing of optical remote sensing instruments for carbon dioxide detection. This includes instruments utilizing both the IPDA technique and range resolved measurements using a DIAL.

Kevin S. Repasky received a BE in mechanical engineering from Youngstown State University 1987, and his MS and PhD in physics from Montana State University in 1992 and 1996. He is currently an associate professor in the Electrical and Computer Engineering Department at Montana State University and has recently been appointed a visiting scientist at the National Center for Atmospheric Research. His research interests include laser and photonic development, nonlinear optics, optical remote sensing, and atmospheric science.

John L. Carlsten holds a BS degree in physics from the University of Minnesota (1969) and MS and PhD degrees in physics from Harvard University (1974). Currently, he holds the position of regents professor of physics at Montana State University. Previously he has held positions at the University of Colorado (1974 to 1979) and the Los Alamos National Laboratory (1979 to 1984). Currently he is collaborating with Prof. Kevin Repasky of the Electrical and Computer Engineering Department on lidar applications to water vapor DIAL, aerosol measurements, and carbon dioxide monitoring. He is a fellow in the American Physical Society and is a fellow in the Optical Society of America.

Geoffrey Wicks is a physics graduate student at Montana State University, and is currently performing research in the field of femtosecond molecular spectroscopy, specifically making high-accuracy measurements of the two-photon absorption (2PA) cross section spectra of chromophore molecules. He is interested in direct measurements of intramolecular charge transfer and analysis of its behavior in different molecular environments, and 2PA measurements of molecular series with systematically varied structural and electronic properties provide access to this delicate information. In his spare time he enjoys camping, biking, and destroying electronics with his two sons.

Appendix B: Presentations

"Sub-Surface Carbon Dioxide Concentration Measurement Using a Fiber Based Sensor in a Send/Call Geometry for Carbon Sequestration Site Monitoring", Geoffrey Wicks, Benjamin Soukup, Kevin S. Repasky, John L. Carlsten, Jamie L. Barr, and Laura Dobeck, American Geophysical Union Meeting, San Francisco, California, 2010.

"Development of a 1 x N fiber sensor array for monitoring geologic carbon sequestration sites", DOE ARRA Geolgic Sequestration Training and Research Project Yearly Review Meeting, Pittsburg, PA, February 23-25, 2011.

"Development of a 1 x N Fiber Optic Sensor Array for Carbon Sequestration Site Monitoring", Kevin S. Repasky, John L. Carlsten, Benjamin Soukup, and Geoff Wicks, Carbon Storage R&D Project Review Meeting, Pittsburgh, PA, August, 2012.

"Development of a 1 x N Fiber Optic Sensor Array for Carbon Sequestration Site Monitoring", Kevin S. Repasky, John L. Carlsten, Benjamin Soukup, and Geoff Wicks, Carbon Storage R&D Project Review Meeting, Pittsburgh, PA, August, 2013.

"Optical Tools and Techniques for Large Area Surface Monitoring of Carbon Sequestration Sites", Kevin S. Repasky, William Johnson, Benjamin Soukup, John L. Carlsten, Rick Lawrence, and Scott Powell, Energy and the Environment, Optical Society of America, Tucson, AR, November, 2013.

Sub-Surface Carbon Dioxide Concentration Measurement Using a Fiber-Based Sensor in a Call/Return Geometry for Carbon Sequestration Site Monitoring

Geoffrey R. Wicks, Benjamin Soukup, Kevin S. Repasky†, John L. Carlsten, Jamie L. Barr, Laura Dobeck*

*Corresponding Author Address: Geoffrey Wicks, EPS 338 Montana State University, Bozeman, MT 59717
†Corresponding Author Address: Kevin S. Repasky, Electrical and Computer Engineering Department, Cobleigh Hall
Room 610, Montana State University, Bozeman, MT 59717, e-mail repasky@ece.montana.edu, phone (406) 994-6082

Abstract

Geologic carbon sequestration is a means to mitigate the increasing atmospheric concentration of carbon dioxide (CO2) by capturing the CO2 at a source such as a power generation facility and storing the captured CO2 in geologic formations. Many technologic advances will need to occur for successful carbon sequestration including near surface monitoring tools and techniques to ensure site integrity and public safety. Researchers at Montana State University (MSU) are developing a scalable fiber sensor array in a call/return configuration for monitoring near sub-surface CO2 concentrations.

The low cost fiber sensor array being developed at MSU for sub-surface CO2 detection for monitoring carbon sequestration sites will utilize a series of fiber probes connected to a detector and a 1 x N fiber switch that can direct the light to one of the N fiber probes. The fiber sensor array will utilize a single tunable distributed feedback (DFB) diode laser with a center wavelength of 2.004 µm to access CO2 absorption features. The fiber sensor array can easily be reconfigured by simply moving the fiber probes. Low cost is achieved by using inexpensive passive components in the fiber probes while limiting the number of the more expensive components including the DFB laser, the detector, and the 1 X N fiber switch.

A single probe fiber sensor system was tested over a thirty day period at the Zero Emission Research Technology (ZERT) facility that was developed for testing surface and near surface carbon sequestration monitoring instrumentation using a controlled underground CO2 release. In this presentation, the design of the single probe fiber sensor system will be presented, along with the system performance during the thirty day controlled underground CO2 release.

Operational Theory

The concentration C of a molecular species as a function of ambient absolute temperature, total atmospheric pressure, and normalized transmission of light through a path length L (cm) is given as[1]:

$$C = \frac{-\ln(T)}{Sg(\nu-\nu_0)\left[N_L(296/T_a)\right]P_T L},$$

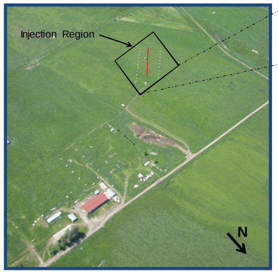
where T is the normalized transmission, S (cm/molecule) is the molecular line intensity, $g(\nu-\nu_0)$ (cm) is the normalized line shape for predominantly pressure-broadened transitions, $N_L = 2.479 \times 10^{19}$ (molecules/cm^3 atm) is Loschmidt's number at 296 K, T_a is the ambient temperature in Kelvin, and P_T is the total atmospheric pressure in atm.

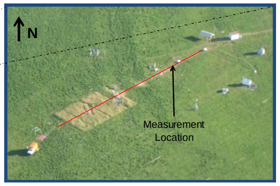
The molecular line intensities and normalized line shapes for the CO_2 absorption features of interest, obtained from the HITRAN database[2], are:

Wavelength (µm)	Wave Number (cm^{-1})	Line Intensity (10^{-21} cm/molecule)	Normalized Line Shape (cm)
2.0040192	4989.9722	1.33200	5.1590
2.0045482	4988.6553	1.32200	5.0686
2.0050895	4987.3085	1.27000	4.9697
2.0056428	4985.9327	1.17300	4.8597

The distributed feedback laser diode is temperature-tuned over the CO_2 transitions of interest (25˚C-35˚C), while reference and return signal intensity measurements are taken (see schematic). These data are used to create a normalized transmission profile of the CO_2 features. The transmission values at line center are then inserted into the above equation in order to produce a concentration value for each of the four lines. These concentration values are then averaged in order to obtain time-resolved concentration measurements.

Aerial Views of ZERT Controlled Release Facility

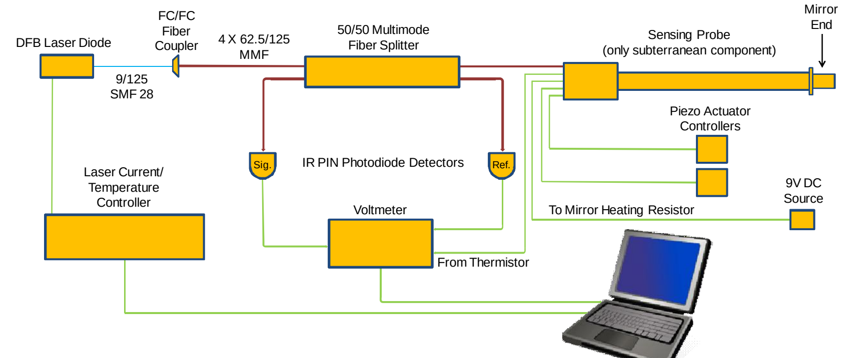




Above: Close-up of ZERT Controlled Release Facility with the underground release pipe indicated in red

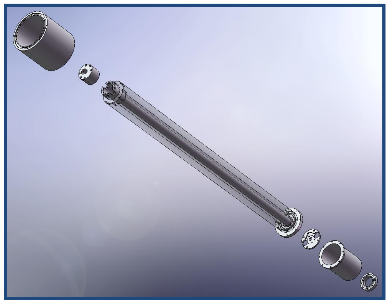
Left: ZERT Controlled Release Facility

System Schematic

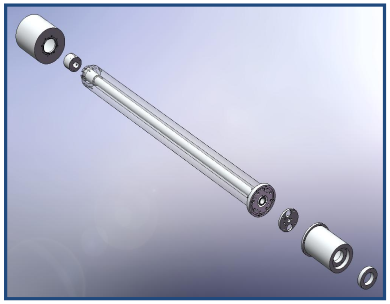


A schematic of the fiber sensor system utilizing a send/call geometry is shown in the figure above.

Sensor Probe Design: Exploded Views

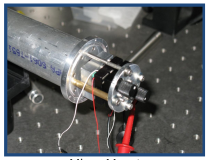


View from connector end with transparent center housing



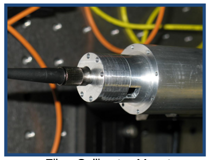
View from mirror end with transparent center housing

Probe and System Design Pictures

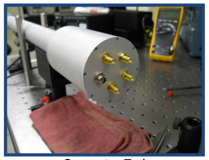


Mirror Mount

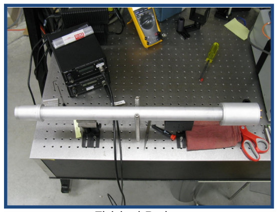
Nose End With Micropore Filter



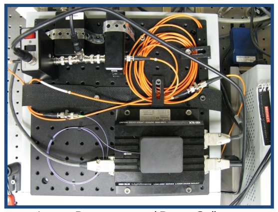
Fiber Collimator Mount



Connector End



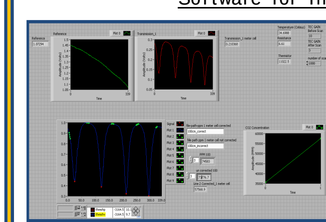
Finished Probe



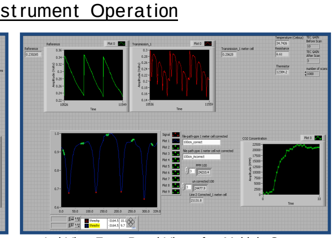
Laser, Detectors, and Beam Splitter

Deployed System

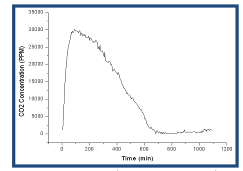
Software for Instrument Operation



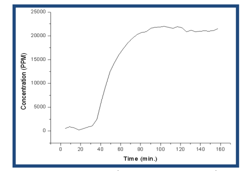
Single Scan Screenshot of LabView Front Panel



LabView Front Panel View after Multiple Scans

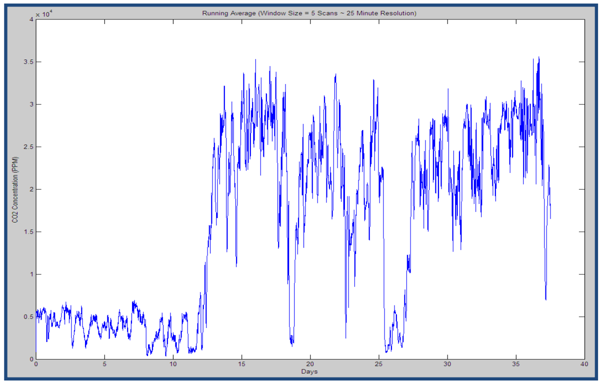


CO_2 Concentration Data From Lab Injection 1



CO_2 Concentration Data From Lab Injection 2 (delayed 30 min.)

Results from the 30 Day Controlled Release Experiment



Scan data collected during a total of 38 days. The CO_2 was injected at a constant rate of 0.15 metric tons per day for the thirty days 07/19/2010 through 08/19/2010.

Concluding Remarks

Researchers at Montana State University are currently developing a suite of remote sensing instruments to be used for measurements of greenhouse gas concentrations. The data in this presentation show the quality of CO_2 subterranean concentration measurements that can be obtained with the fiber probe sensor system described herein. These data are the culmination of the first phase of development for this system.

The project is currently in its second phase of development, whereby the incorporation of a fiber switch will facilitate the obtainment of an array of four subterranean measurements as a proof of concept for a similar system expanded to N fiber sensor probes.

Acknowledgements

This research was kindly supported by DOE Grant DE-FE0001858.

References

1. *Differential Absorption Measurements of Carbon Dioxide Using a Temperature Tunable Distributed Feedback Diode Laser,*
Kevin S. Repasky, Seth Humphries, John L. Carlsten
Review of Scientific Instruments **77**, 113107 (2006)

2. HITRAN-PC 3.0, University of South Florida, (2000)

DOE-ARRA Geologic Sequestration Training and Research
2011 Yearly Review Meeting

Project DE-FE0001858
Title: Development of a 1 x N Fiber Optic Sensor Array for Carbon Sequestration Site Monitoring

Montana State University
Presenter: Dr. Kevin Repasky, Electrical and Computer Engineering
February 23-25, 2011

Project Participants

- Kevin Repasky, Electrical and Computer Engineering, Montana Staet University, (PI)
- John Carlsten, Physics, Montana State University, (Co-I)
- Geoffrey Wicks, Graduate Student, Physics
- Benjamin Soukup, Undergraduate Student, Physics
- Laura Dobeck, Zero Emission Research and Technology (ZERT) Field Site Manager, Montana State University
- Lee Spangler, Director ZERT and Big Sky Carbon Sequestration Partnership, Montana State University

Introduction

- Near surface monitoring of sequestration sites is needed to ensure the sequestration site integrity and public safety.
- The proposed 1 x N fiber sensor array provides a potentially low cost reconfigurable instrument for large area monitoring for sequestration sites.

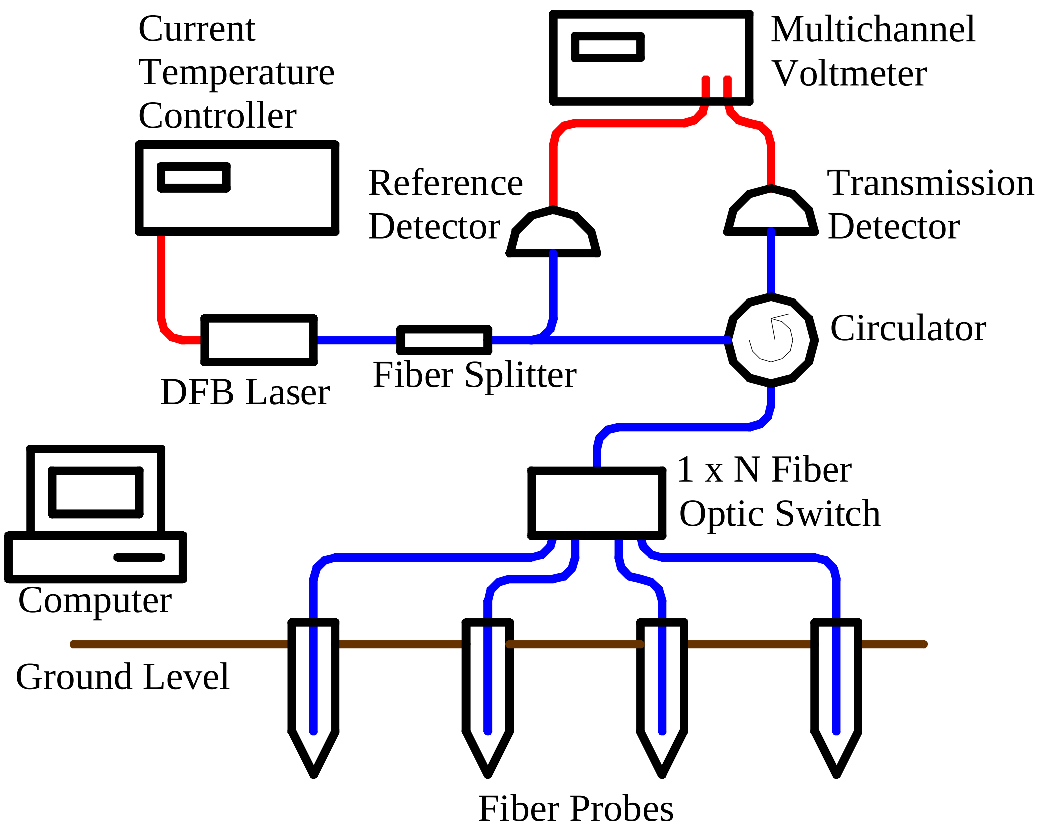
Project Objectives

- The objective of the proposed work is to develop and demonstrate a 1 x N fiber sensor array for near surface sequestration site monitoring.
- Provide educational opportunities for undergraduate and graduate students in carbon sequestration.

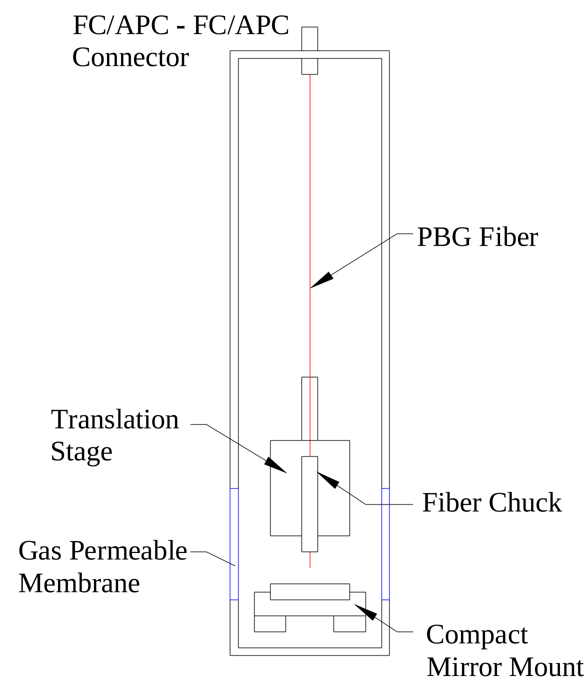
Project Funding

- Total Project Cost: $299,203
- DOE Share: $299,203
- Non-DOE Cost Share: $0

Highlights of Project to Date

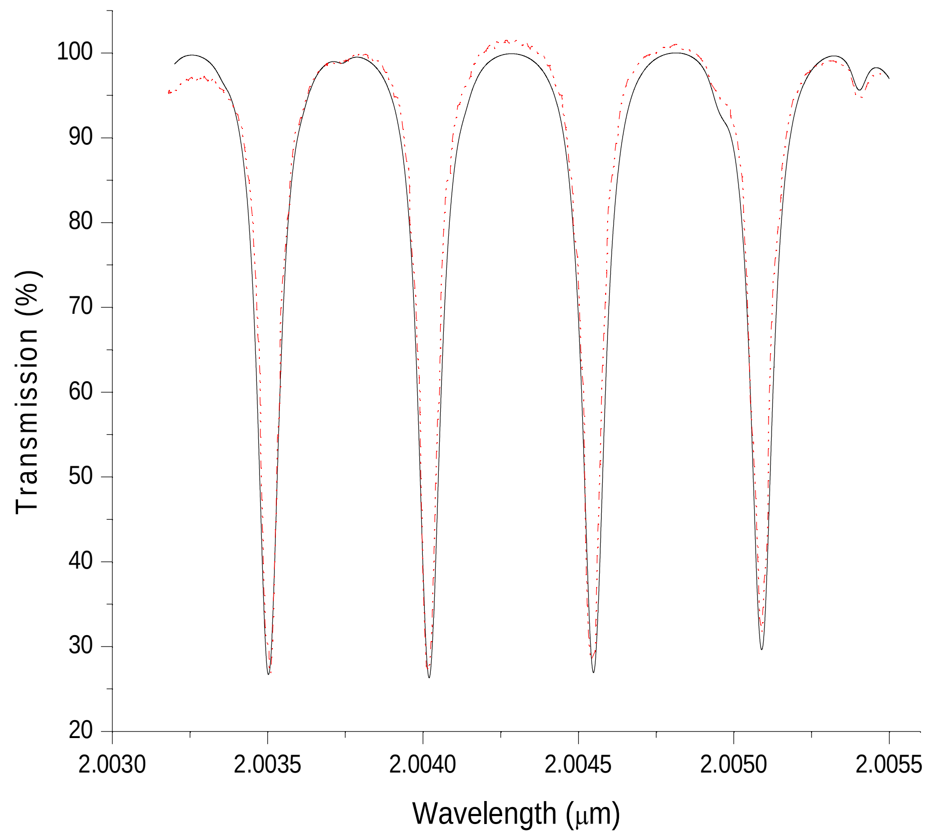


Schematic of the 1 x N fiber sensor array



Schematic of the fiber sensor probe.

Highlights of Project to Date

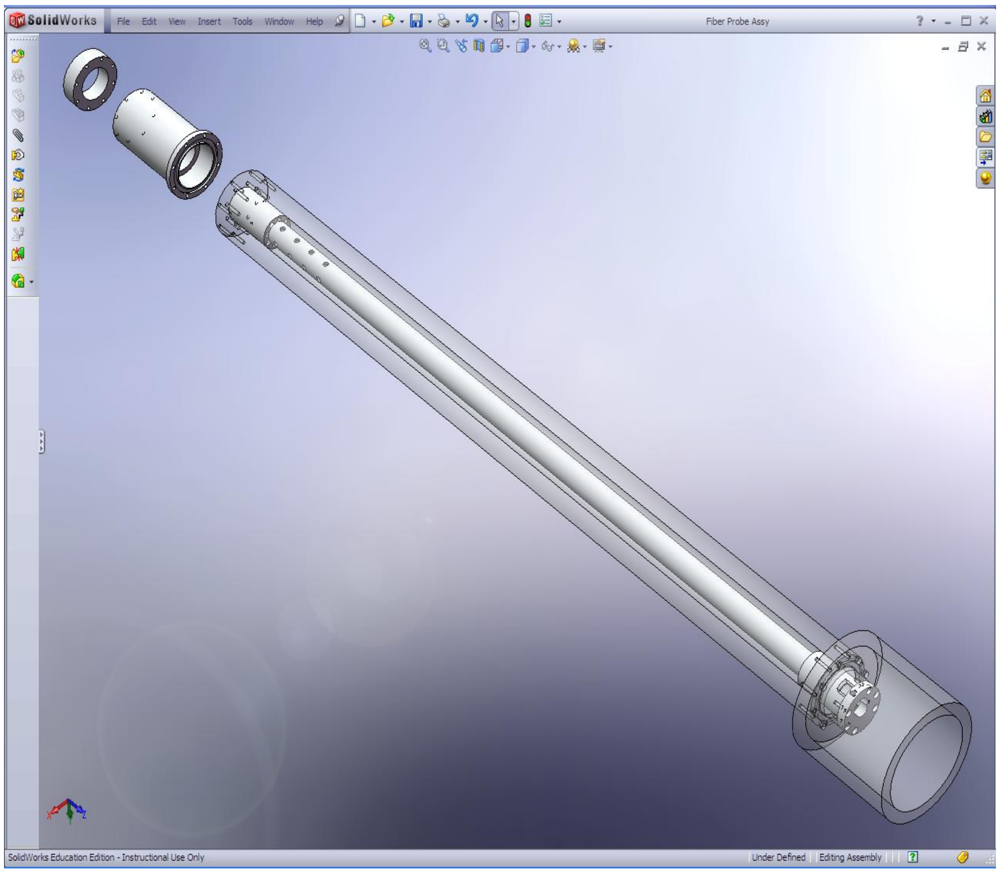


The black line represents the expected transmission as a function of wavelength while the red line represents the measured transmission as a function of wavelength for CO_2 absorption features near 2 μm.

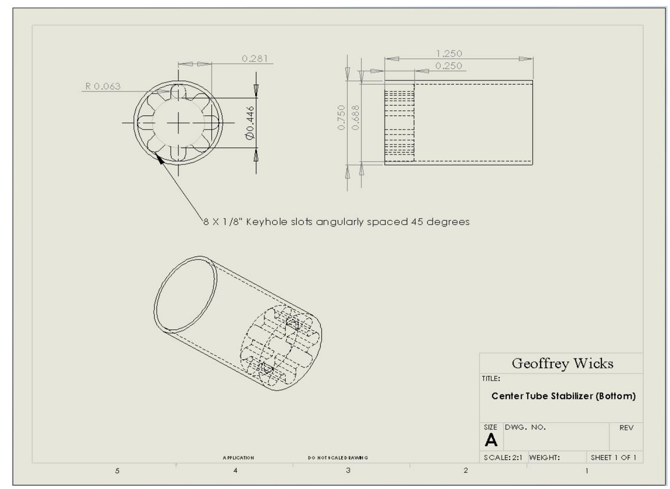
$$C = \frac{P_a}{P_T} = \frac{-\ln(T)}{Sg(\nu - \nu_0)N_L\left(\frac{296}{T_a}\right)P_T L}$$

The concentration, C, can be calculated by measuring the transmission, T.

Highlights of Project to Date

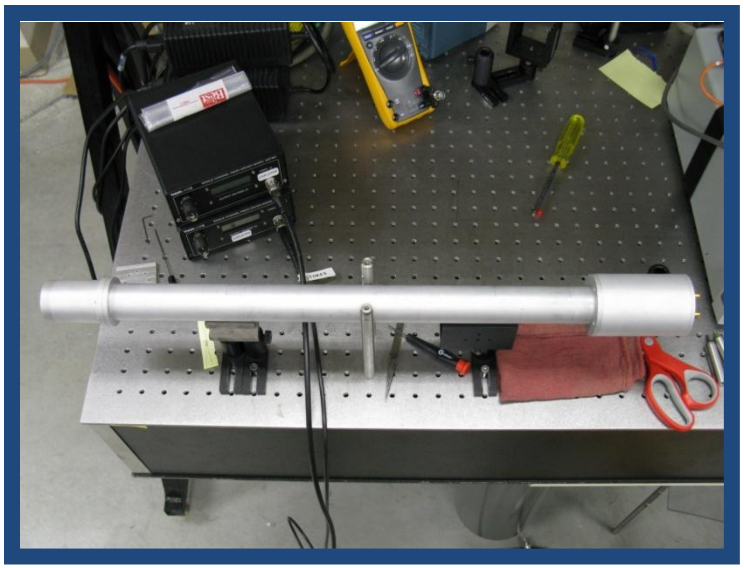


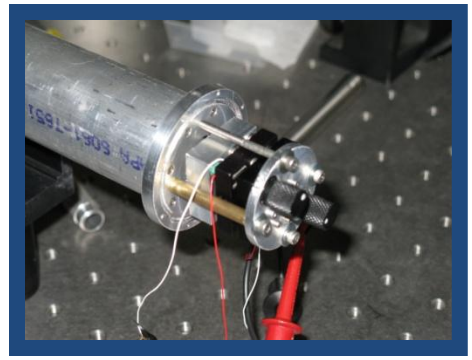
The exploded assembly drawing of the 1st generation fiber probe.

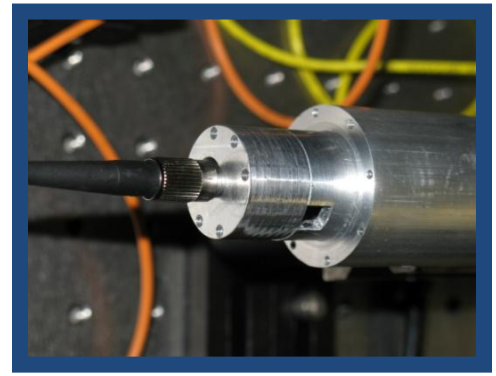


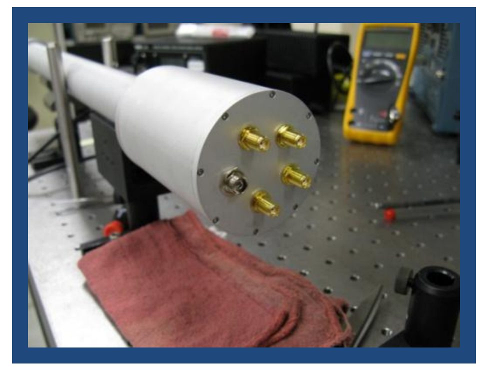
Machine Drawings for the 1st generation fiber probe

Highlights of Project to Date



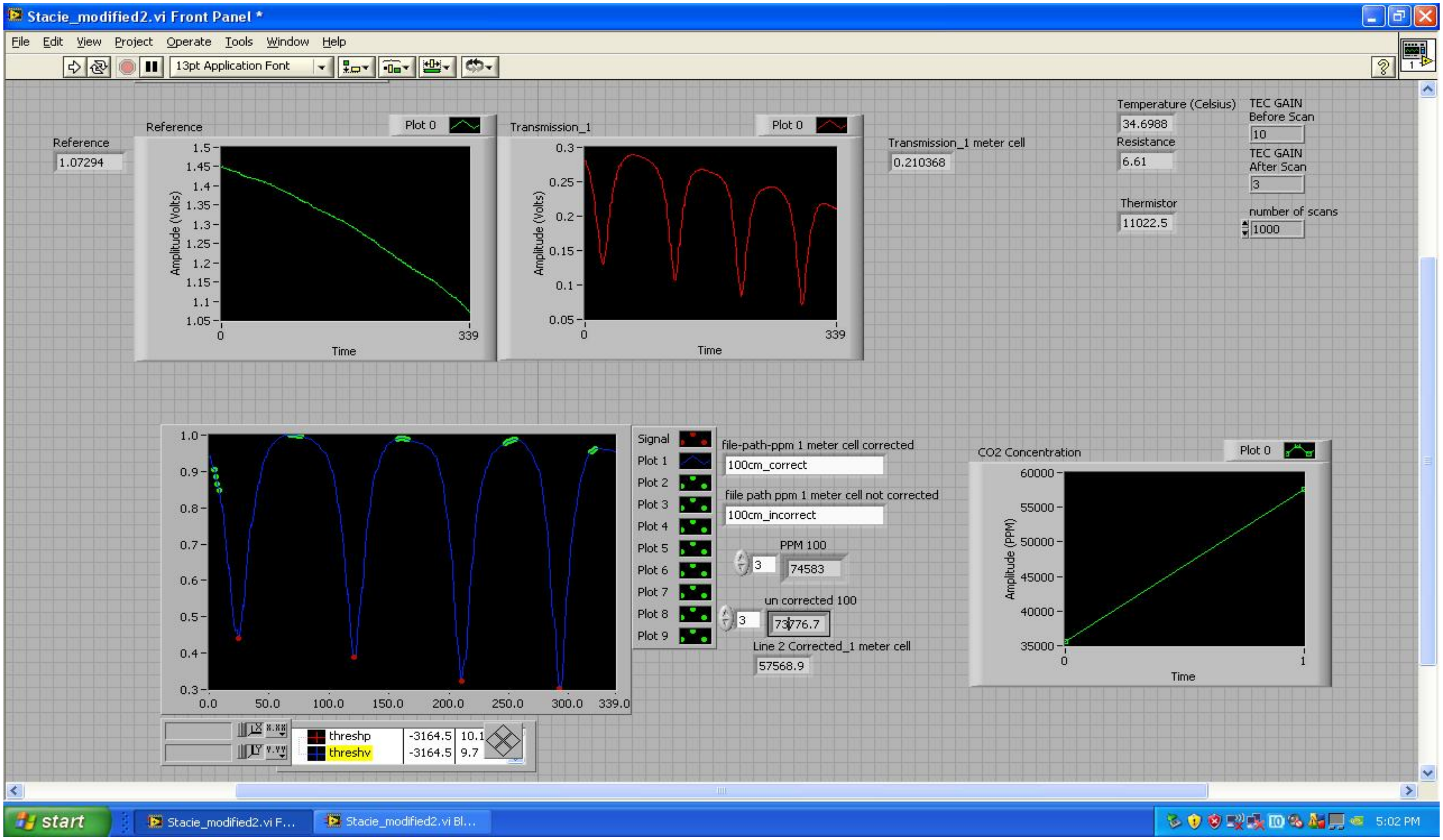






Machined, assemble, and aligned first generation fiber probe

Highlights of Project to Date

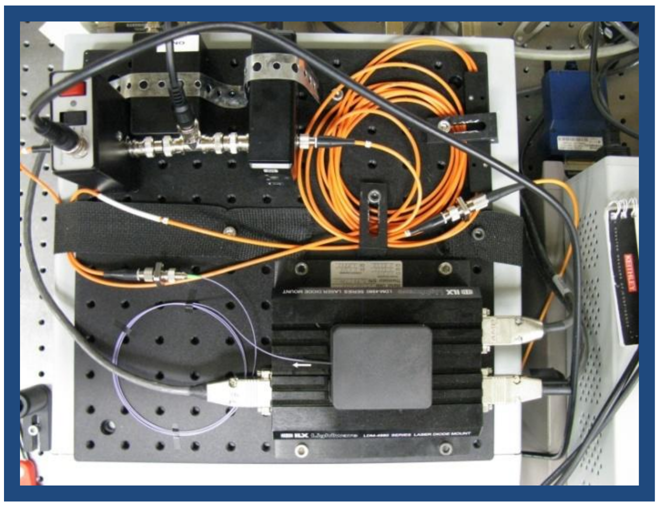


Front panel of the Labview program for operating the fiber sensor.

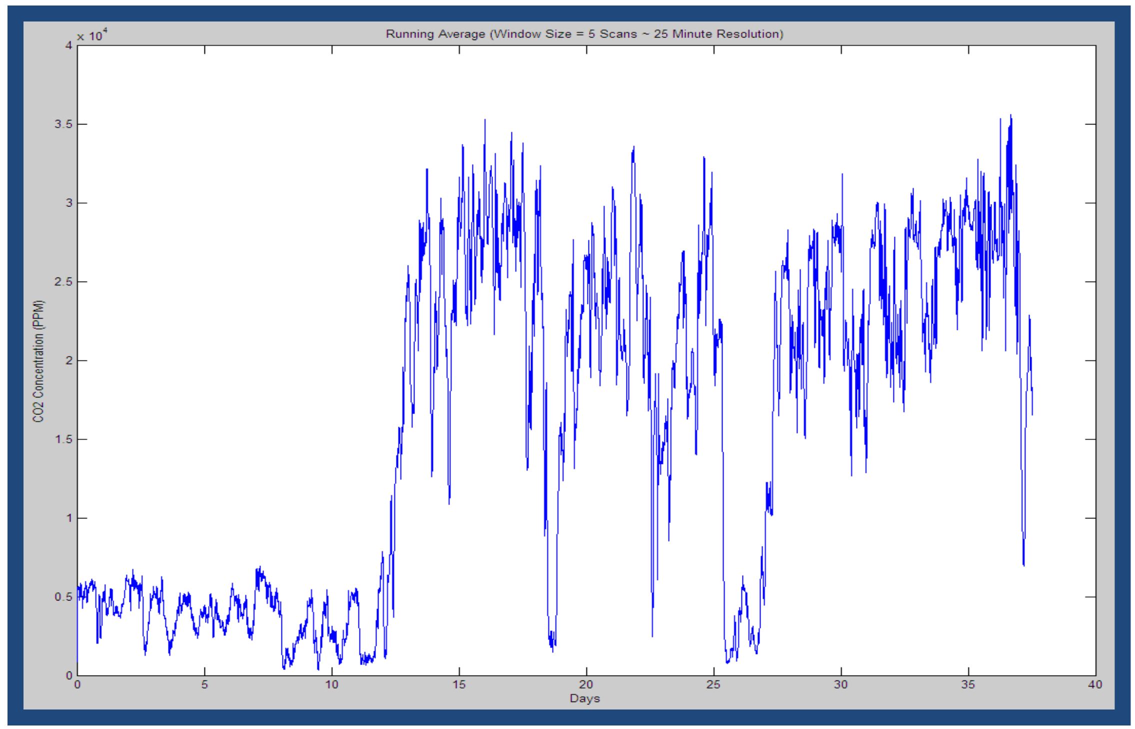
Highlights of Project to Date

Aerial view of the ZERT controlled underground release facility for testing near surface and surface monitoring instrumentation.

Highlights of Project to Date

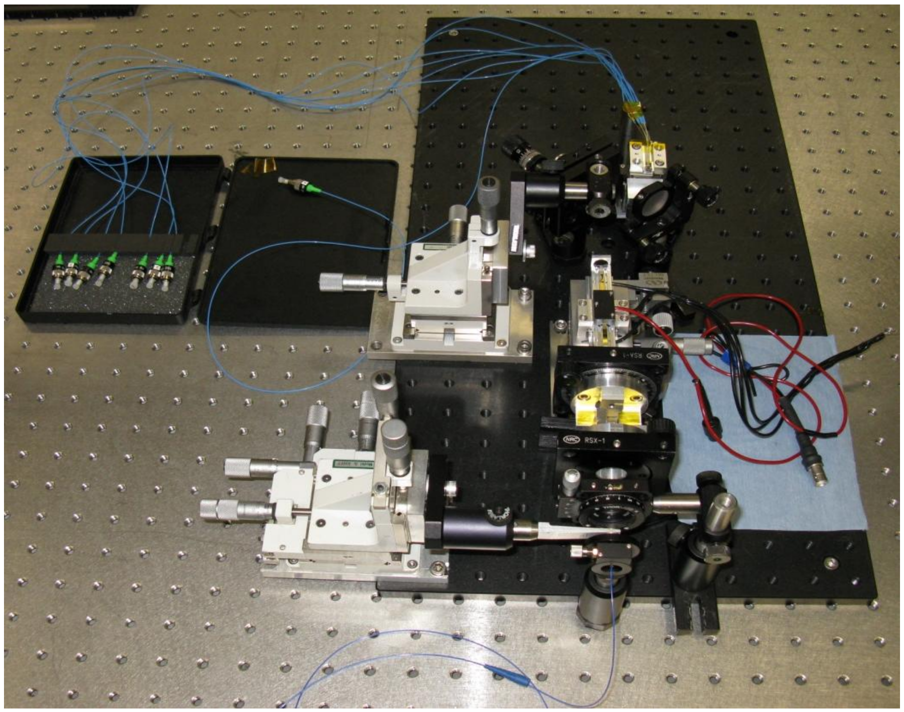


Laser,detectors, and computer housed in a weatherproof field deployable box.



CO_2 number density as a function of time for the 2010 summer controlled thirty day release.

Highlights of Project to Date



1 x 100 Electro-Optic switch under development

Commercialization Efforts

- Phase I EPA SBIR with ADVR, a Bozeman Montana based Photonics Company
- Phase II EPA SBIR is Pending

Tasks – Overview

Task No.	Task Description	Task Duration	Task Funding
1	Project Management and Planning	12/01/2009 – 11/30/2012	$27,407
2	Develop a single channel fiber sensor	12/1/2009-11/30/2010	$108,856
3	Develop a 1 x 4 fiber sensor array	12/1/2010-11/30/2011	$75,677
4	Field testing of the fiber sensor array	12/1/2011-11/30/2012	$87,263

Project Schedule

Project Milestone Description	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Planned Start Date	Planned End Date	Actual Start Date	Actual End Date
Project Managerment Plan	x	x	x	x	x	x	x	x	x	x	x	x	1-Dec-09	30-Nov-12	1-Dec-09	
Negotiate Management Plan	x												1-Dec-09	28-Feb-10	1-Dec-09	28-Feb-10
Prepare Reports	x	x	x	x	x	x	x	x	x	x	x	x	1-Dec-09	30-Nov-12	1-Dec-09	
Develop a Single Channel Fiber Sensor	x	x	x	x									1-Dec-09	30-Nov-10	30-Dec-10	30-Sept-10
Develop CAD drawings	x	x											1-Dec-09	30-Jul-10	1-Dec-09	28-Feb-10
Construction of the fiber probe		x	x										1-Mar-10	29-Oct-10	1-Feb-10	30-Sep-10
Develop control software			x	x									1-Jun-10	28-Dec-10	1-Mar-10	30-Sep-10
Laboratory Testing of Single Channel Fiber Sensor				x									1-Sep-10	30-Dec-10	1-Mar-10	30-Sep-10
Develop 1 x 4 Fiber Sensor Array					x	x	x	x					1-Dec-10	30-Nov-11	1-Sep-10	
Modify CAD drawings					x	x							1-Dec-10	28-Jun-11	1-Sep-10	1-Dec-10
Construction of the four fiber probes						x	x						1-Mar-11	31-Aug-11	1-Oct-10	
Develop control software for the 1 x 4 fiber sensor array							x	x					1-Jun-11	28-Nov-11		
Laboratory testing of the 1 x 4 fiber sensor array								x								
Field Testing of the Fiber sensor Array									x	x	x	x	1-Dec-11	30-Nov-12		
Field Testing of the Fiber sensor Array									x	x	x	x	1-Dec-11	30-Nov-12		

Discussion – Task 2

- Task Name/Goal: Develop a single channel fiber sensor
- Key Subtasks:
  - Develop CAD drawings
  - Construction of the fiber probe
  - Develop control software
  - Laboratory testing of the single channel fiber sensor
- Responsible parties (including students): Kevin repasky, John Carlsten, Geoffrey Wicks, Benjamin Soukup
- Task Status: 100% complete
- Major accomplishment: Demonstrated single channel fiber sensor over a thirty seven day period.
- Major issues/problems: None

Discussion – Task 3

- Task Name/Goal: Develop the 1 x 4 fiber sensor array
- Key Subtasks:
  - Modify CAD drawings
  - Construction of the four fiber probes
  - Development of the control software for the 1 x 4 sensor
  - Laboratory testing of the 1 x 4 fiber sensor array
- Responsible parties (including students): Kevin repasky, John Carlsten, Geoffrey Wicks, Benjamin Soukup
- Task Status: 25% complete
- Major accomplishment: CAD drawings complete and machine is finished.
- Major issues/problems: None

Project Milestones

Milestone	Planned Completion Date	Actual Completion Date
1. Development of CAD drawings of the proposed sensor probe and detector equipment.	7/30/2010	3/31/2010
2. Construction of the single fiber sensor probe.	10/29/2010	9/30/2010
3. Development of the computer code to operate the detector system.	12/28/2010	9/30/2010
4. Construction and laboratory testing of the single channel fiber sensor and probe in the call/return geometry.	12/30/2010	12/30/2010
5. Modify the CAD drawings for the four second generation fiber probes	6/28/2011	Active

Project Milestones

Milestone	Planned Completion Date	Actual Completion Date
6. Construction of the Four fiber sensor probes and detection system.	8/31/2011	Active
7. Modify the computer code to operate the detector system for four probes.	11/28/2011	
8. Construction and laboratory testing of the 1 x 4 fiber sensor array.	12/30/2011	
9. Testing the 1 x 4 fiber sensor array at the ZERT field site.	11/30/2012	

Anticipated Efforts for the Coming Year

- Activity 1: Modify CAD drawings for the four fiber sensor probes.
- Activity 2: Construction and alignment of the four fiber probes.
- Activity 3: Modification of the software to operate the 1 x 4 fiber sensor array.
- Acivity 4: Laboratory testing of the 1 x 4 fiber sensor array.
- Activity 5: Pursue avenues of commercialization.

PI Contact Information

- If you have any questions or would be interested in collaboration please contact
- repasky@ece.montana.edu (for instrument development and deployment)
- dobeck@chemistry.montana.edu (for information regarding the ZERT sub-surface controlled release facility.
- Spangler@montana.edu (for information regarding ZERT and the Big Sky Carbon Sequestration Partnership.

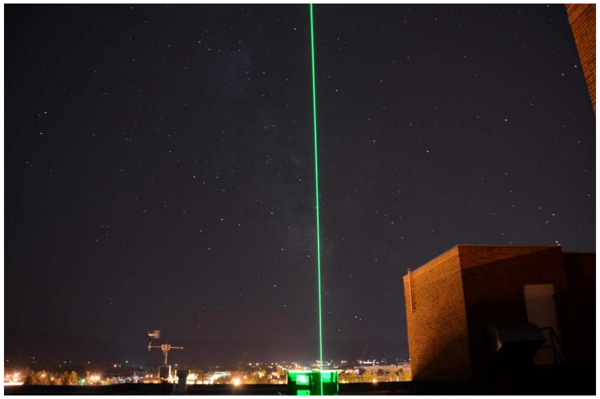
Development of a 1 x N Fiber Optic Sensor Array for Carbon Sequestration Site Monitoring

Project Number: DE-FE0001858

Kevin S. Repasky

Electrical and Computer Engineering, Cobleigh Halll Room 610,
Montana State University, Bozeman, MT, 59717

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the
Infrastructure for CO_2 Storage
August 21-23, 2012



Presentation Outline

- Program and Project Benefits
- Technical Status
  - Brief Introduction to integrated path differential absorption concentration measurements
  - 1 x N fiber sensor array description
  - Experimental results
- Program accomplishments and summary

Benefit to the Program

- Program Goals Addressed:
  - Develop technologies to demonstrate that 99% of CO_2 remains in the injected zones.
  - Conduct field tests for site operations (monitoring/verification/accounting)
- Project Benefits

  The research project is developing a scalable, cost effective, reconfigurable fiber sensor array for large sub-surface monitoring of CO_2. This technology contributes to the Carbon Storage Program's effort to ensure 99% CO_2 storage permanence in the injection zones.

Project Overview: Goals and Objectives

- The project objectives for the proposed work include the development, testing, and deployment of a 1 x N fiber sensor array for subsurface CO_2 monitoring.
  - Relates to the development of technologies to demonstrate that 99% of CO_2 remains in the injected zones.
  - Success criteria: Demonstration of instrument from a laboratory setting.
- Testing of the instrument will be conducted to determine the performance of the fiber sensor array at the Zero Emission Research Technology (ZERT) field site during a controlled release experiment.
  - Relates to conducting field tests for site operations.
  - Success criteria: Demonstration of instrument during a ZERT controlled release experiment.

Technical Status: Integrated Path Differential Absorption (IPDA) Technique

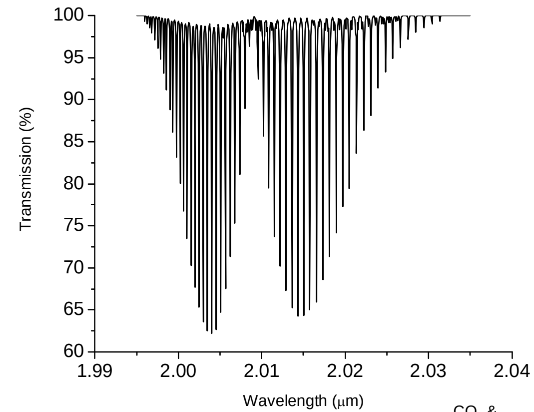
- The number density for carbon dioxide is related to the amount of light absorbed as a function of wavelength.

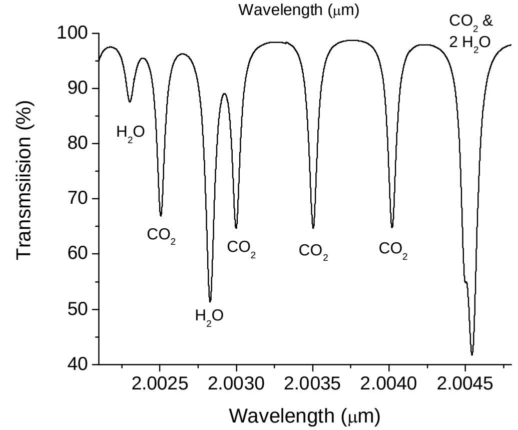
- Working near the 2 μm wavelength provides strong absorption features which allow subsurface CO_2 concentration measurements to be made in as little as 0.5 m.

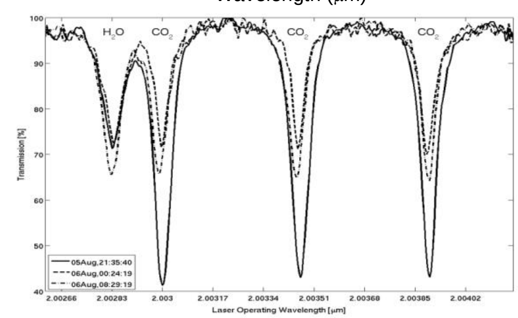
- Measuring the normalized transmission allows on to calculate the number density.

- Using the line strength and line shape parameters, the concentration can be calculated from the IPDA equation:

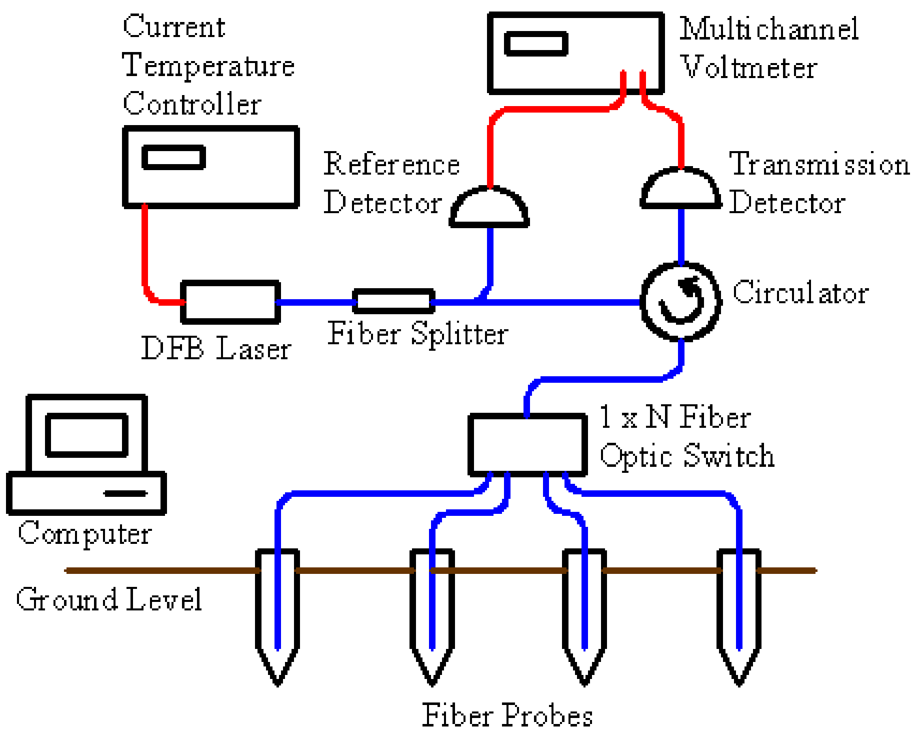
$$C = \frac{-\ln(T)}{Sg(\nu - \nu_0)\left[N_L(296/T_a)\right]P_T L},$$

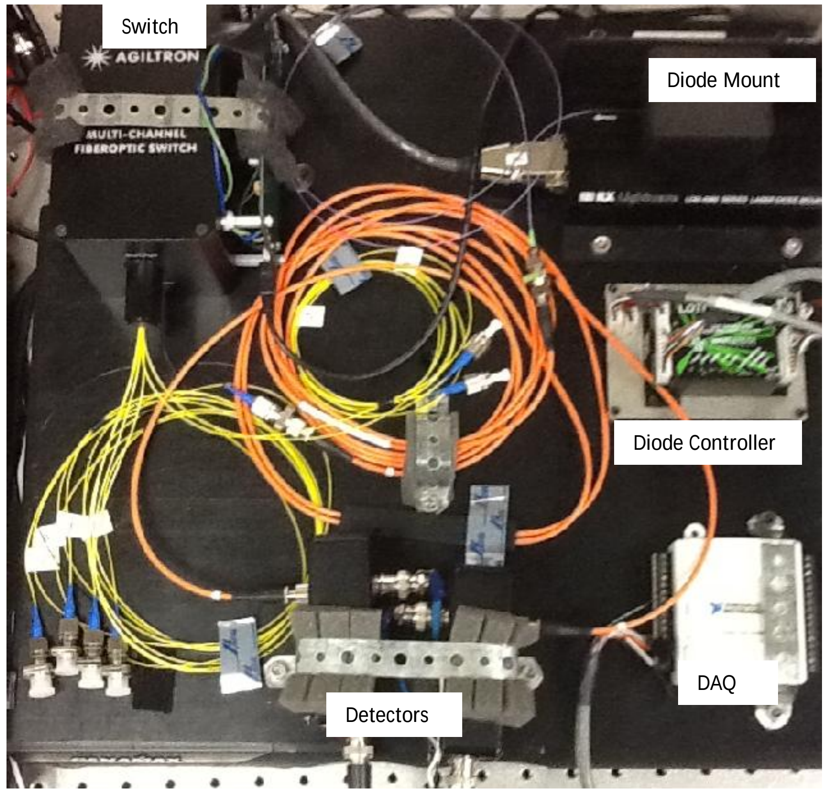




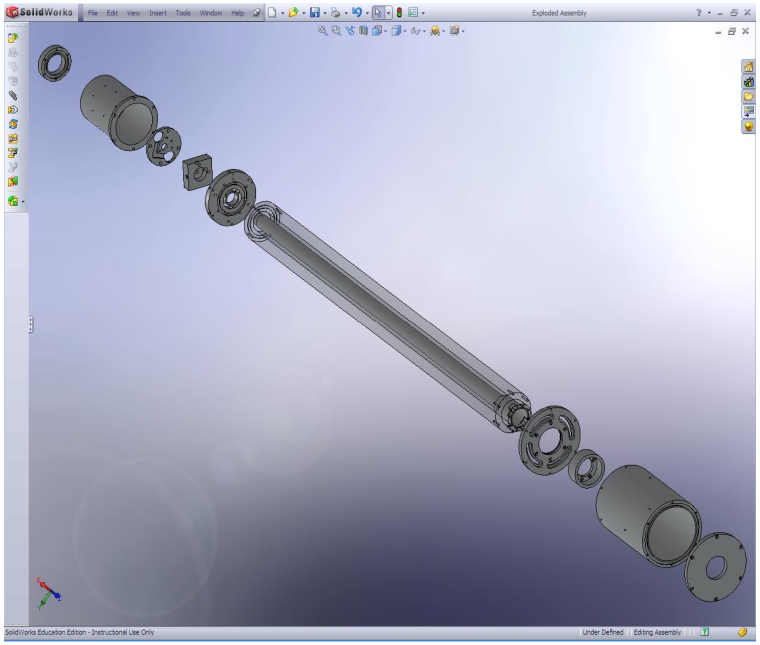


Technical Status: Instrument Design

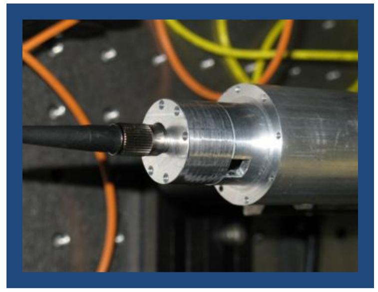




Technical Status: Probes

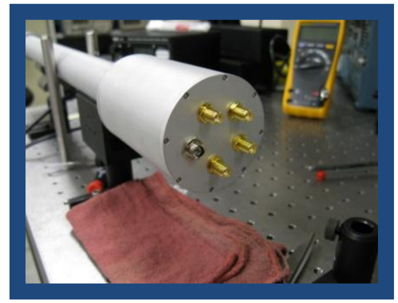


Solidworks CAD drawing of the probe design. The probe was designed to contain all passive optical components and is inexpensive to manufacture.



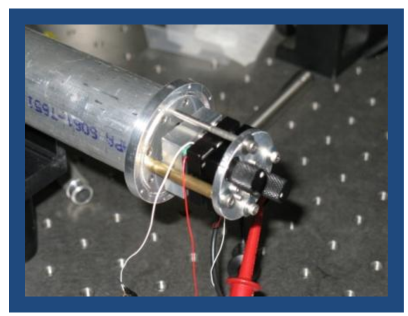
Fiber coupler details

Electronic Feed-through



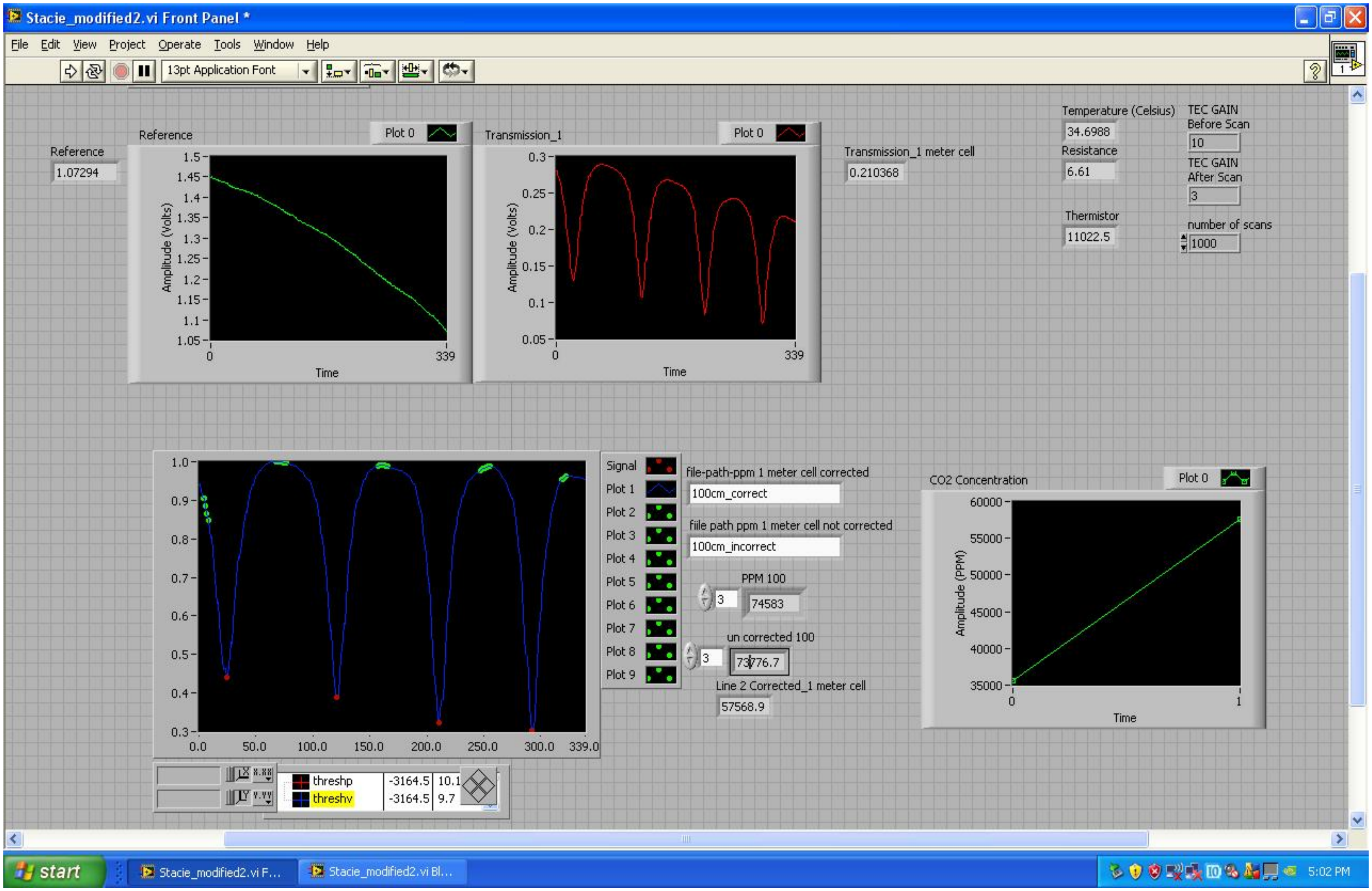
Gas permeable membrane

Retro-reflector details

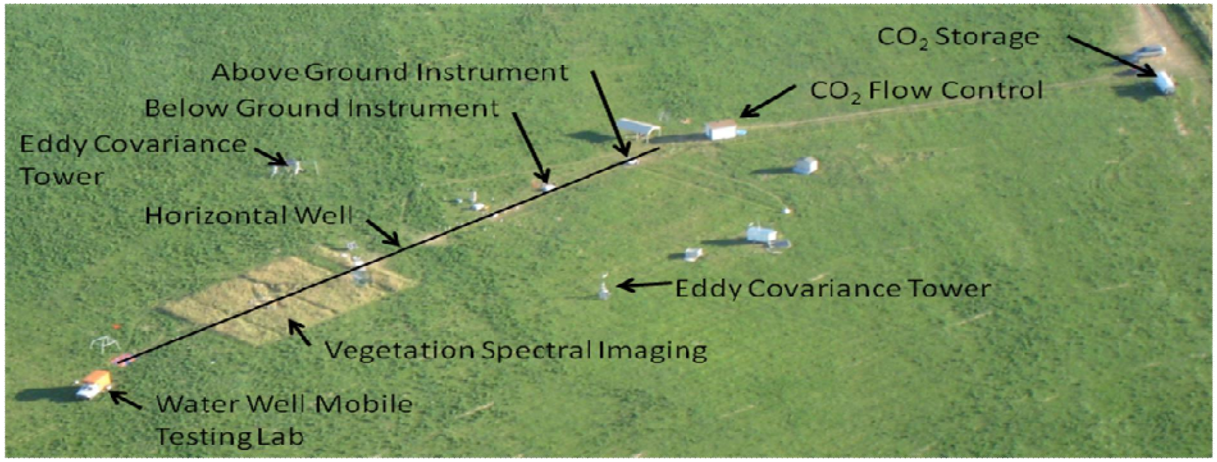


Four completed fiber probes

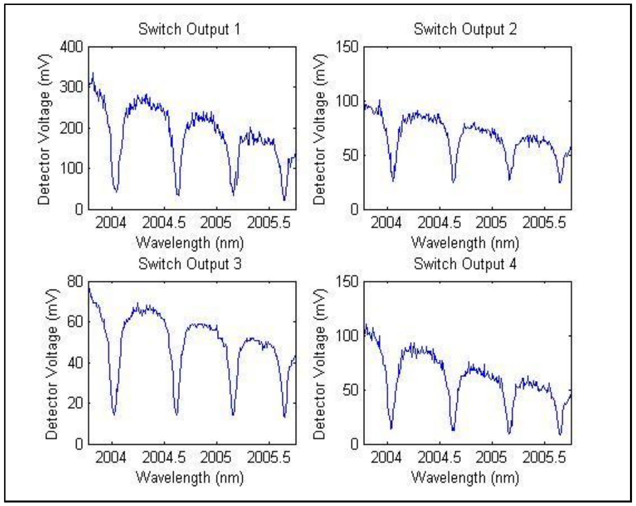
Technical Status: Data Acquisition Software



Technical Status: Field Experiment



Aerial view of the ZERT controlled release site.

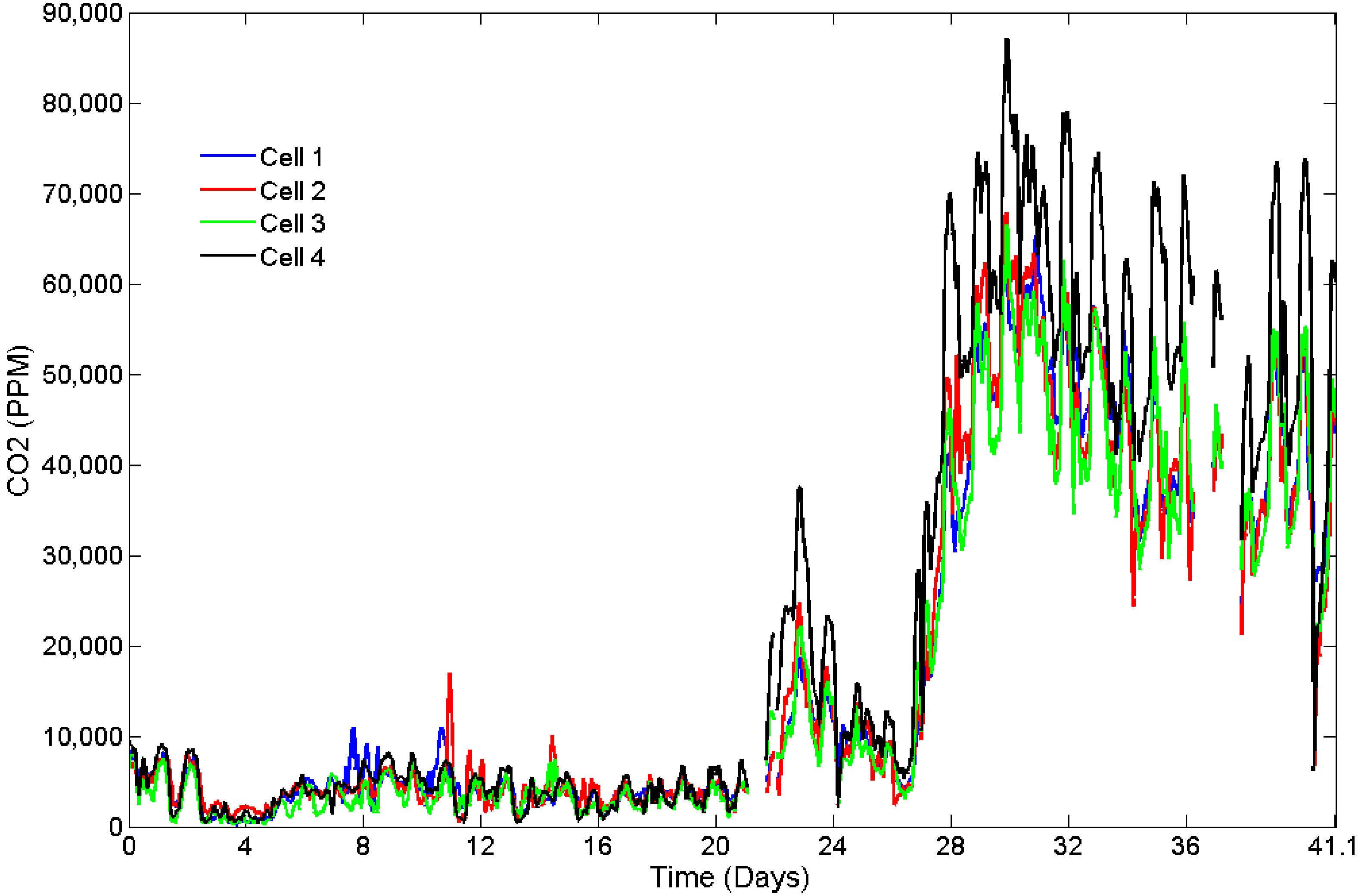


Transmission data from the four probes (un-normalized).

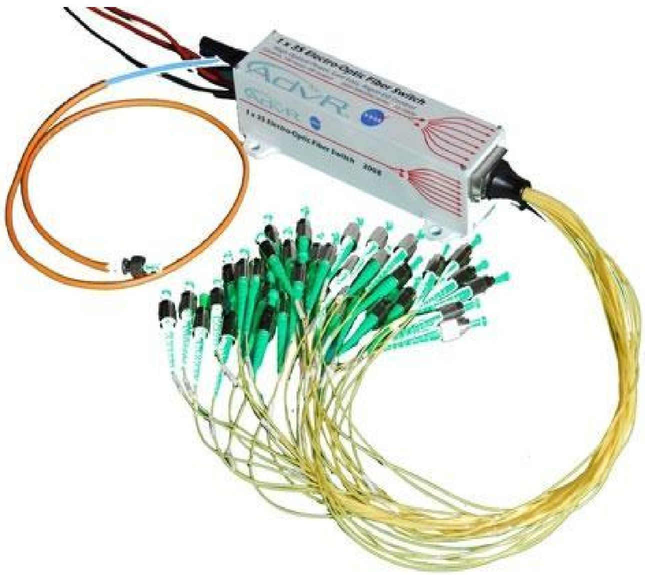
Electronics and optics packaged in a weatherproof enclosure for field studies.

Instrument deployed at the ZERT site with sun shade.

Technical Status: ZERT Field Data



Scalability and Large Area Coverage



A commercial 1 x 100 fiber optic switch allows up to 100 probes to be deployed. Using standard telecommunications fiber, these 100 probes can be located up to 1 km away from the central electronics box.

Because the cost of the probes is kept low, scaling to 100 probes will not greatly increase the cost providing a cost effective sensor array.

Accomplishments to Date

- A 1 X N fiber sensor array architecture has been developed.
- Subsurface CO_2 concentration measurements have been made continuously for over 40 days.
- Instrument has been demonstrated at the ZERT field site where the elevated subsurface CO_2 concentration from the subsurface release is clearly evident.

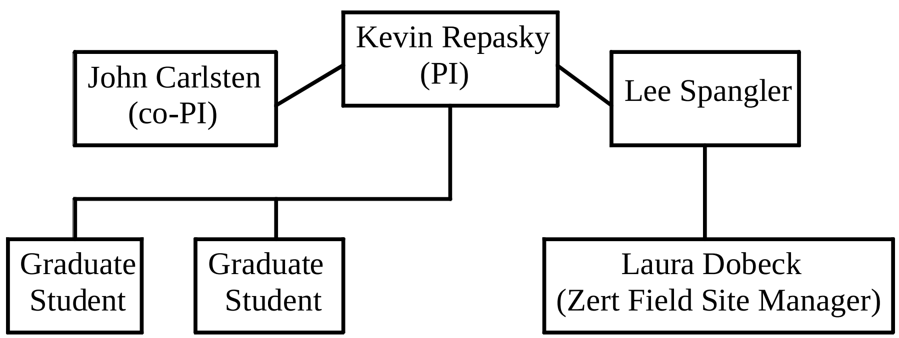
Summary

- The fiber sensor array has been successfully deployed at the ZERT controlled release experiment.
- The fiber sensor array offers a scalable, reconfigurable, cost effective monitor for large area coverage with autonomous operations.
- Future Plans
  - Include a second DFB laser for sensing oxygen to provide the potential to distinguish sources of subsurface CO_2.
  - Working with Advr and starting discussions with Lambda Inc. to transfer technology into the commercial market.

Thanks Kindly for Your Time

Appendix: Organization Chart

Organizational Chart



- Kevin Repasky: (PI) responsible for overall project.

  John Carlsten: (Co-PI) work with Dr. repasky to manage project and students.

  Lee Spangler: Head of ZERT and BSCSP. Coordinate field work

  Laura Dobeck: Coordinate ZERT field experiments.

figure 5.

Appendix: Gantt Chart

Month	3	6	9	12	15	18	21	24	27	30	33	36
Phase 1 Develop a single channel fiber sensor	←	—	—	→								
Task 1.1 Project management and planning	↔											
Task 1.2 Development of a fiber sensor probe	←	—	→									
Task 1.3 Development and testing of a single channel fiber sensor			←	→								
Phase 2 Development and initial testing of a 1 x 4 fiber sensor array					←	—	—	—	—	→		
Task 2.1 Design and construction of four fiber sensor probes					←	—	→					
Task 2.2 Construction of the 1 x 4 fiber sensor array							←	—	—	→		
Phase 3 Field testing the 1 x 4 fiber sensor array											←	→
Task 3.1 Field testing the fiber sensor array											←	→

figure 5.

Appendix: Presentations and Publications

- Presentations:
  - "Large area detection of CO2 for carbon sequestration", IEAGHG: Environmental Impacts of CO2 Storage Workshop, Bozeman, MT, July 2012 (invited).
  - "Subterranean Carbon Dioxide (CO_2) Concentration Analysis Utilizing an Optical Fiber Probe Array for Carbon Capture and Storage (CCS) Site Monitoring", Benjamin Soukup, Kevin S. Repasky, and John L. Carlsten, American Geophysical Union, San Francisco, California, 2011.
  - "Sub-Surface Carbon Dioxide Concentration Measurement Using a Fiber Based Sensor in a Send/Call Geometry for Carbon Sequestration Site Monitoring", Geoffrey Wicks, Benjamin Soukup, Kevin S. Repasky, John L. Carlsten, Jamie L. Barr, and Laura Dobeck, American Geophysical Union Meeting, San Francisco, California, 2010.
- Papers:
  - "Development of a 1 X N fiber sensor array for subsurface carbon sequestration site monitoring", Benjamin Soukup, Geoffrey Wicks, Kevin S. Repasky, and John L. Carlsten, in preparation for submission to the Journal of Applied Remote Sensing.

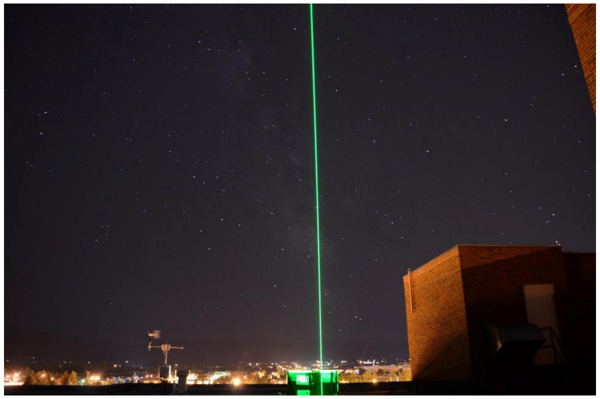
Development of a 1 x N Fiber Optic Sensor Array for Carbon Sequestration Site Monitoring

Project Number: DE-FE0001858

Kevin S. Repasky, John L. Carlsten, Benjamin Soukup, and Geoff Wicks

Electrical and Computer Engineering, Cobleigh Halll Room 610, Montana State University, Bozeman, MT, 59717

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage
August 21-23, 2012



Presentation Outline

- Program and Project Benefits
- Technical Status
  - Brief Introduction to integrated path differential absorption concentration measurements
  - 1 x N fiber sensor array description
  - Experimental results
- Program accomplishments and summary

Benefit to the Program

- Program Goals Addressed:

  Develop and validate technologies to ensure 99% storage permanence.

- Project Benefits

  The research project is developing a scalable, cost effective, reconfigurable fiber sensor array for large sub-surface monitoring of CO_2. This technology contributes to the Carbon Storage Program's effort to ensure 99% CO_2 storage permanence.

Project Overview: Goals and Objectives

- The project objectives for the proposed work include the development, testing, and deployment of a 1 x N fiber sensor array for subsurface CO_2 monitoring.
  - Relates to the development of technologies to demonstrate that 99% of CO_2 remains in the injected zones.
  - Success criteria: Demonstration of instrument from a laboratory setting.
- Testing of the instrument will be conducted to determine the performance of the fiber sensor array at the Zero Emission Research Technology (ZERT) field site during a controlled release experiment and at the Big Sky Carbon Sequestration Partnership Site.
  - Relates to conducting field tests for site operations.
  - Success criteria: Demonstration of instrument during a ZERT controlled release experiment and for a one month deployment at the BSCSP site.

Technical Status: Integrated Path Differential Absorption (IPDA) Technique

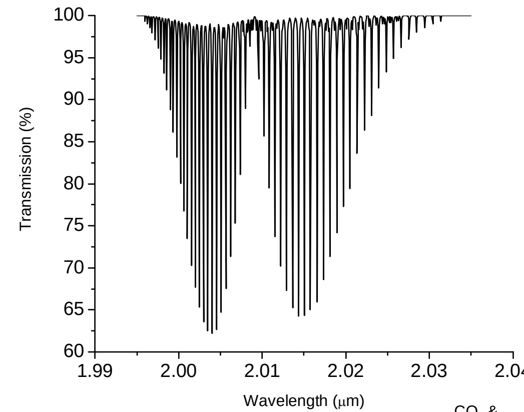
- The number density for carbon dioxide is related to the amount of light absorbed as a function of wavelength.

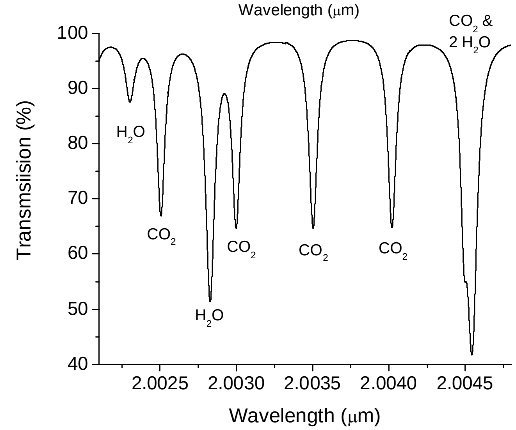
- Working near the 2 μm wavelength provides strong absorption features which allow subsurface CO_2 concentration measurements to be made in as little as 0.5 m.

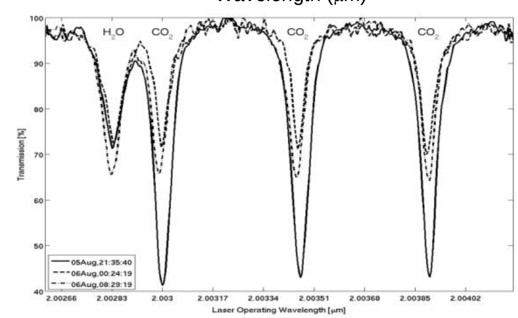
- Measuring the normalized transmission allows on to calculate the number density.

- Using the line strength and line shape parameters, the concentration can be calculated from the IPDA equation:

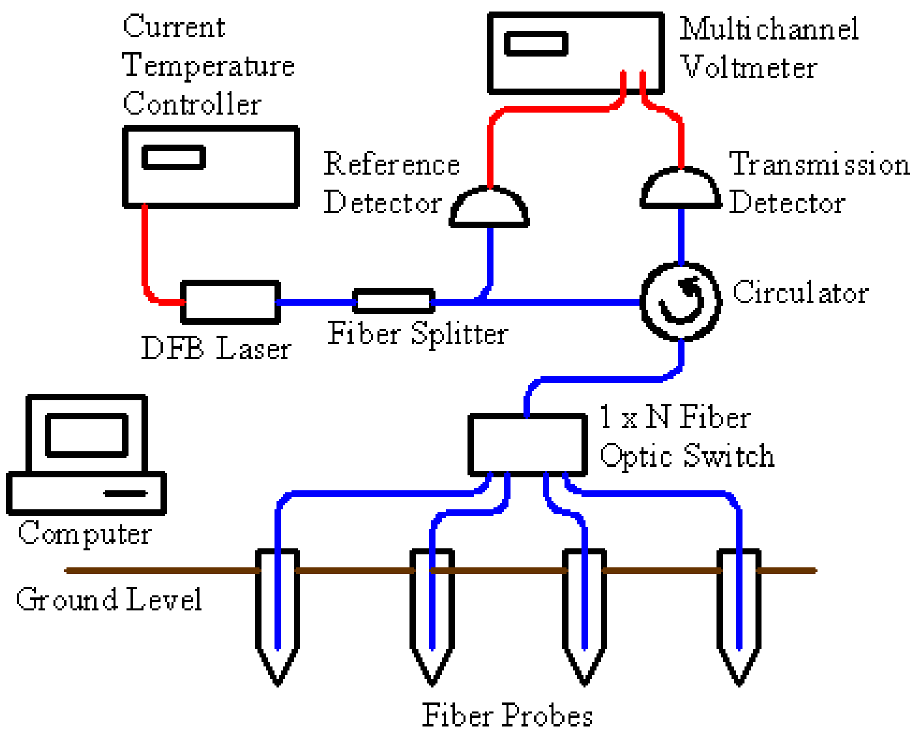
$$C = \frac{-\ln(T)}{Sg(\nu - \nu_0)\left[N_L(296/T_a)\right]P_T L},$$

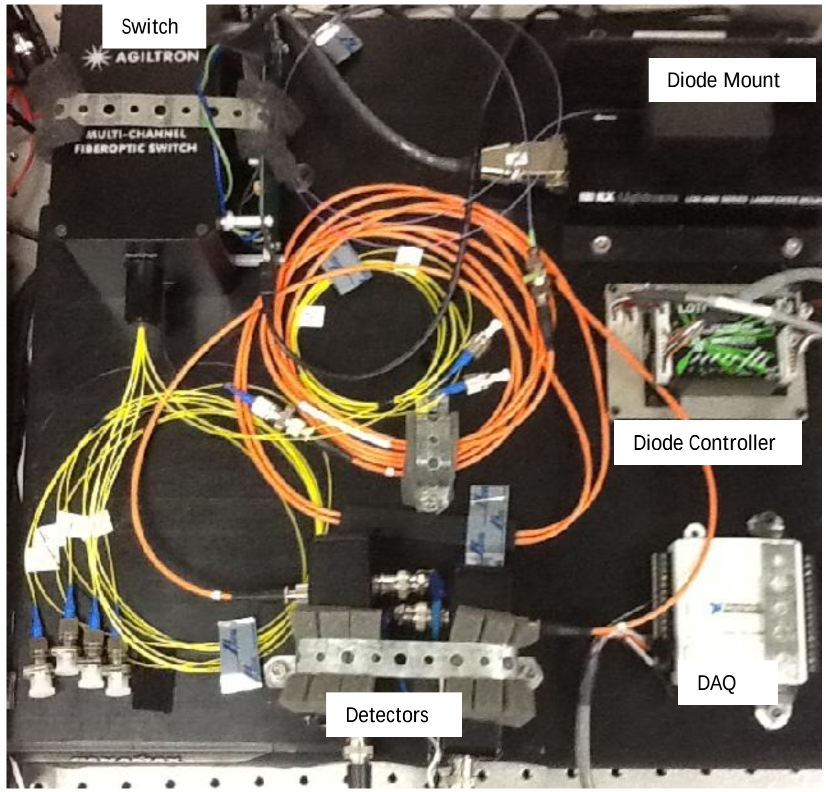




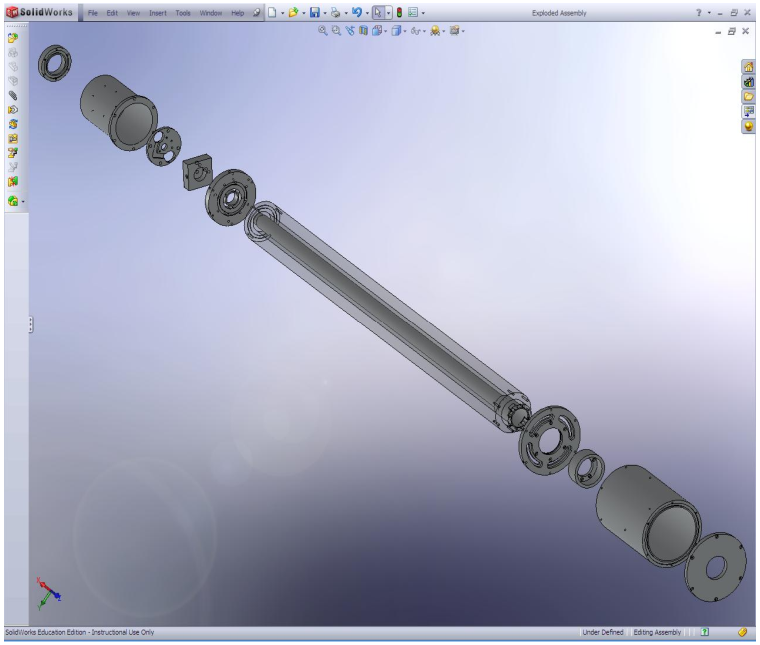


Technical Status: Instrument Design

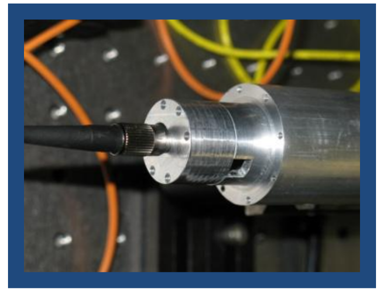




Technical Status: Probes

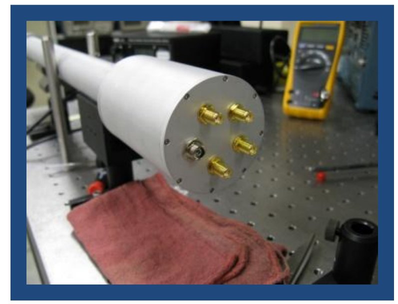


Solidworks CAD drawing of the probe design. The probe was designed to contain all passive optical components and is inexpensive to manufacture.



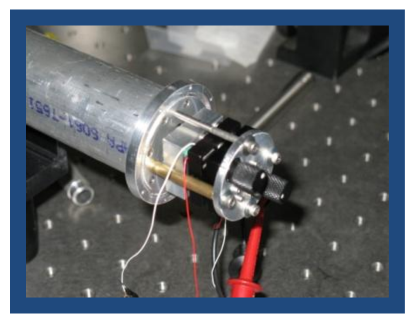
Fiber coupler details

Electronic Feed-through



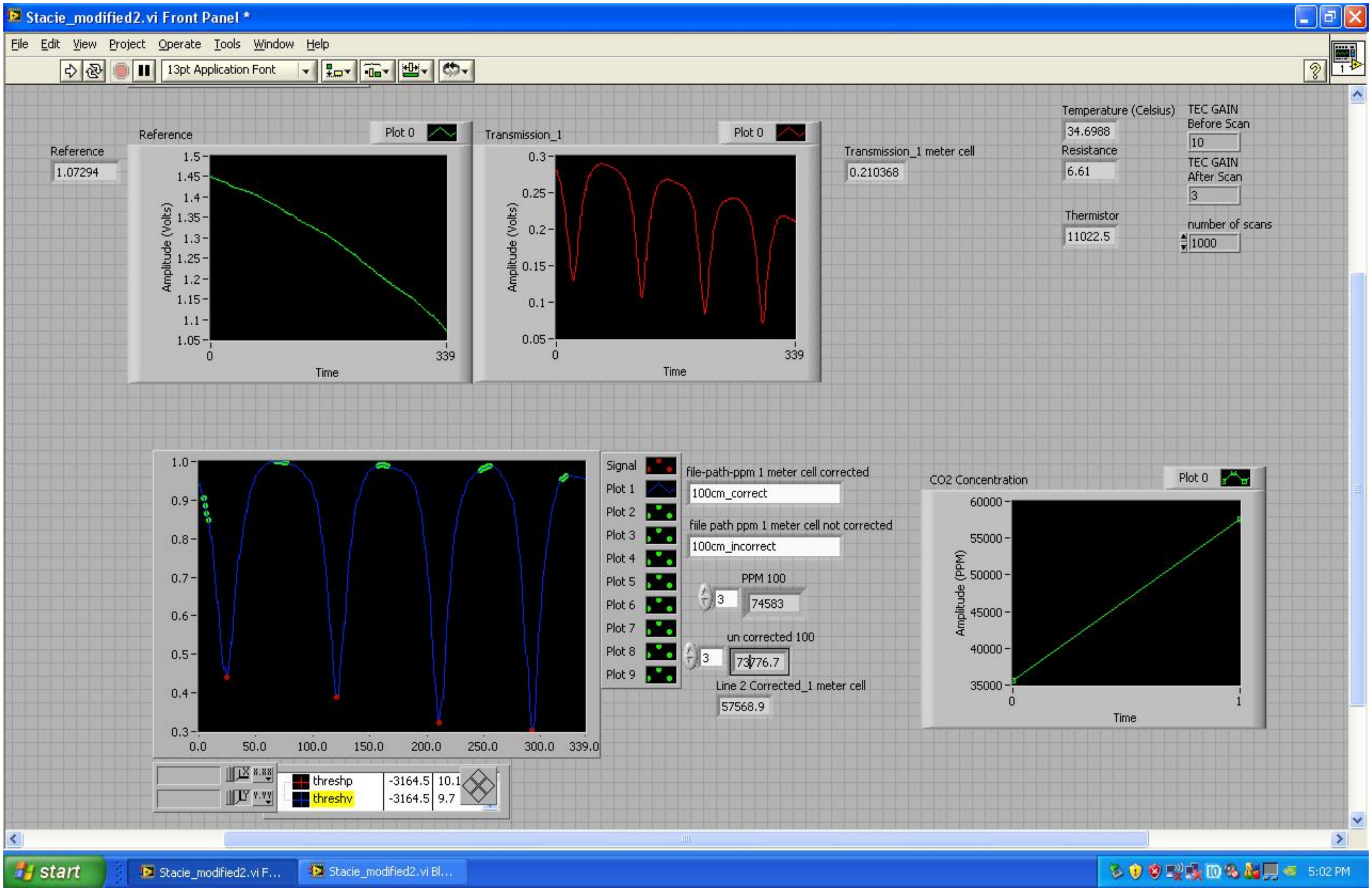
Gas permeable membrane

Retro-reflector details

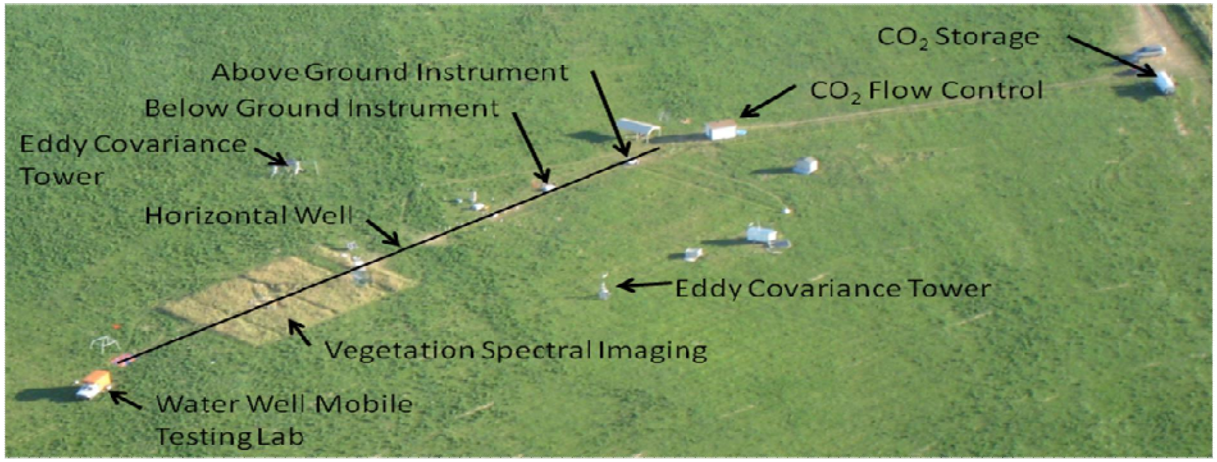


Four completed fiber probes

Technical Status: Data Acquisition Software



Technical Status: Field Experiment



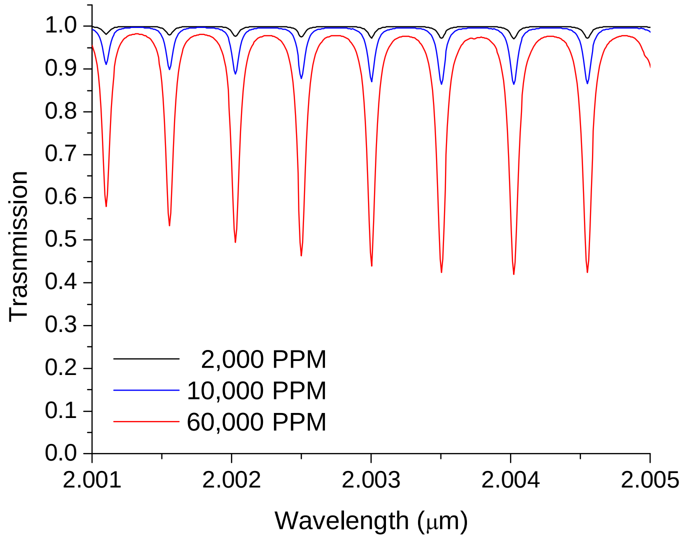
Aerial view of the ZERT controlled release site.

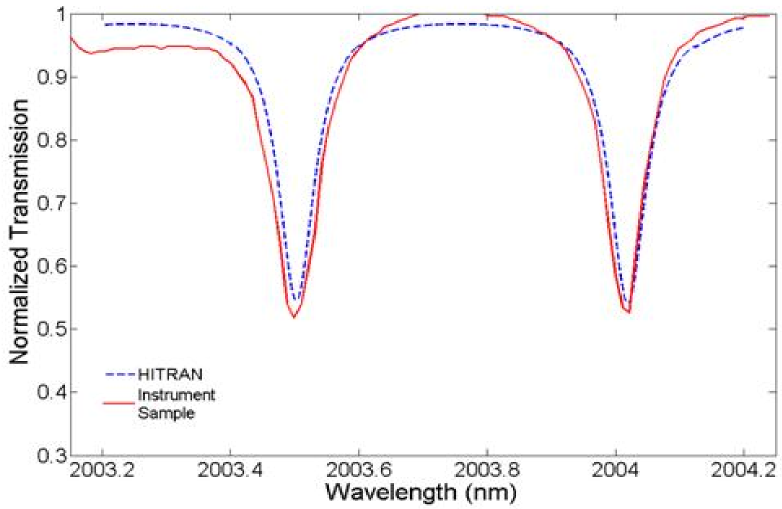
Electronics and optics packaged in a weatherproof enclosure for field studies.

Instrument deployed at the ZERT site with sun shade.

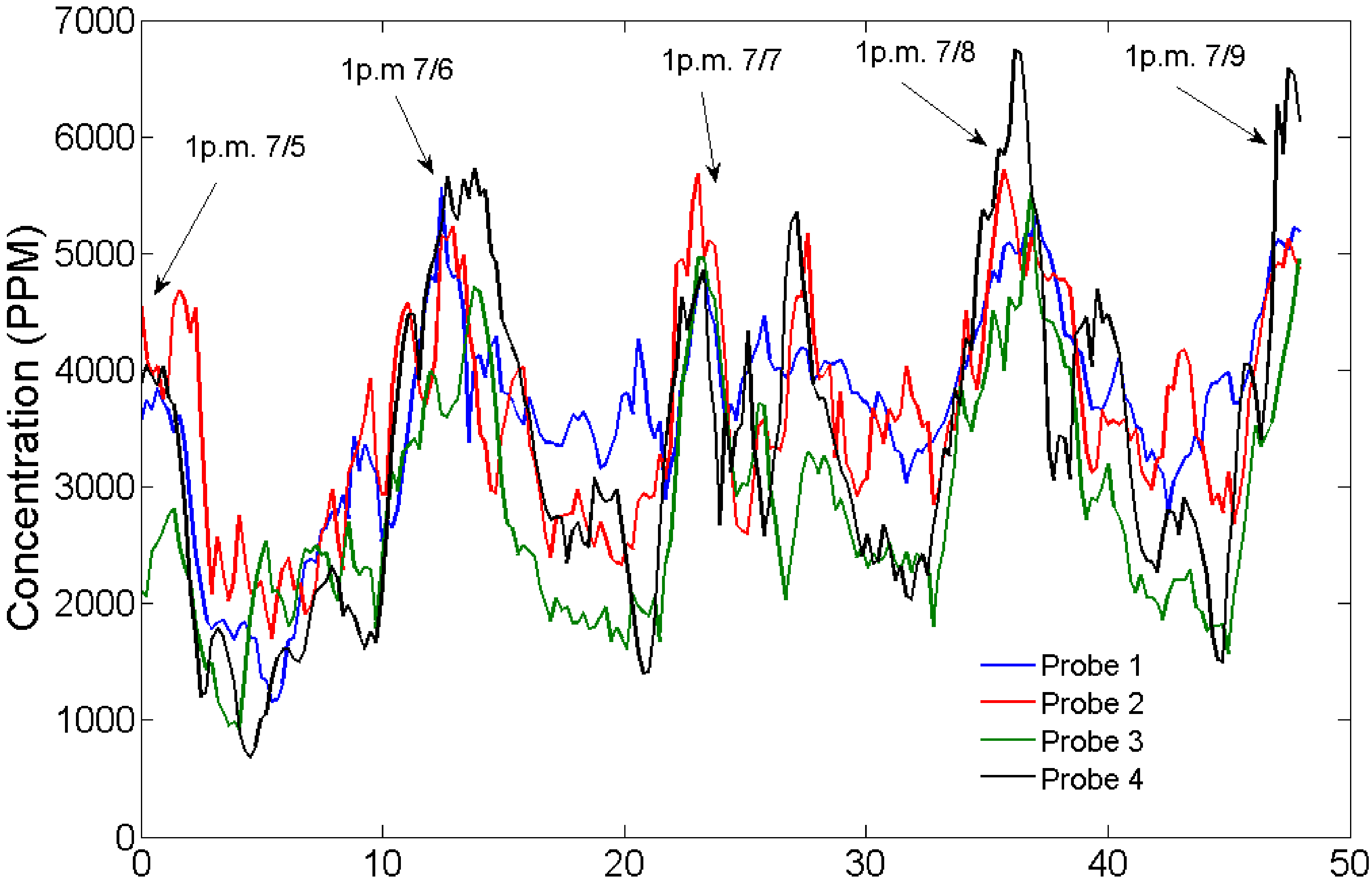
Technical Status: ZERT Field Data

Wavelength mm	Linestrength 10^{-21} molecules/cm	Normalized Lineshape Cm
2.001 102 0	0.811 2	1.160 0
2.001 557 7	0.931 6	1.151 6
2.002 025 5	1.048	1.140 1
2.002 505 7	1.153	1.130 4
2.002 998 0	1.241	1.116 1
2.003 502 6	1.302	1.102 2
2.004 019 2	1.332	1.084 2
2.004 548 2	1.322	1.0653

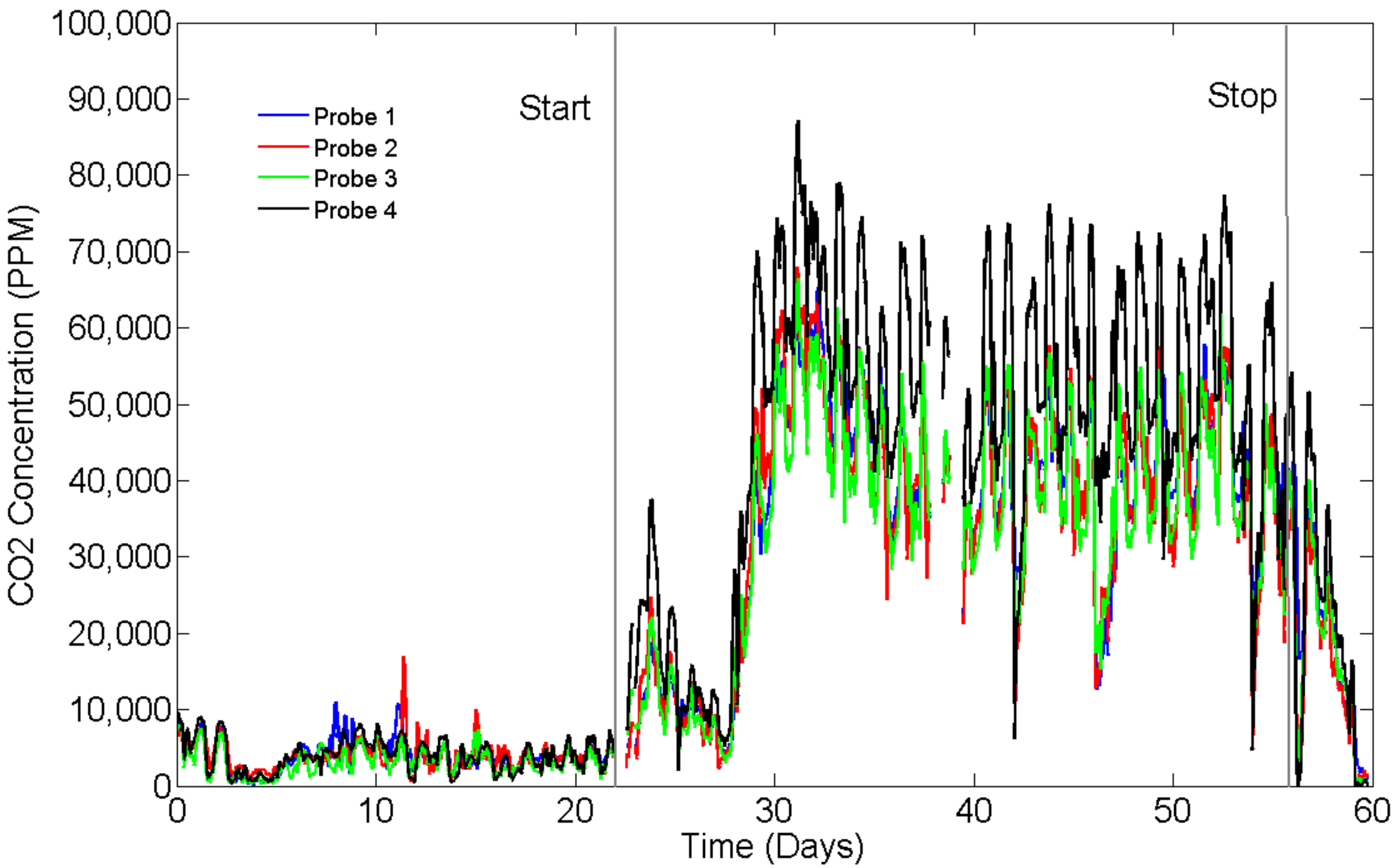




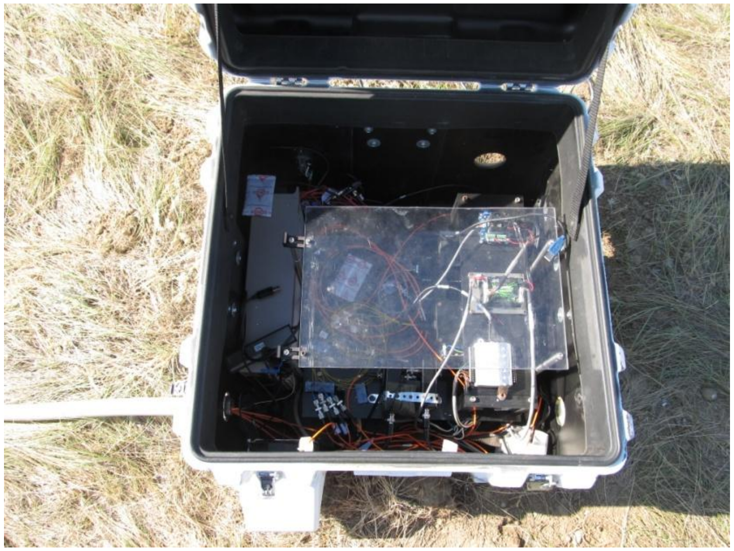
Technical Status: ZERT Field Data

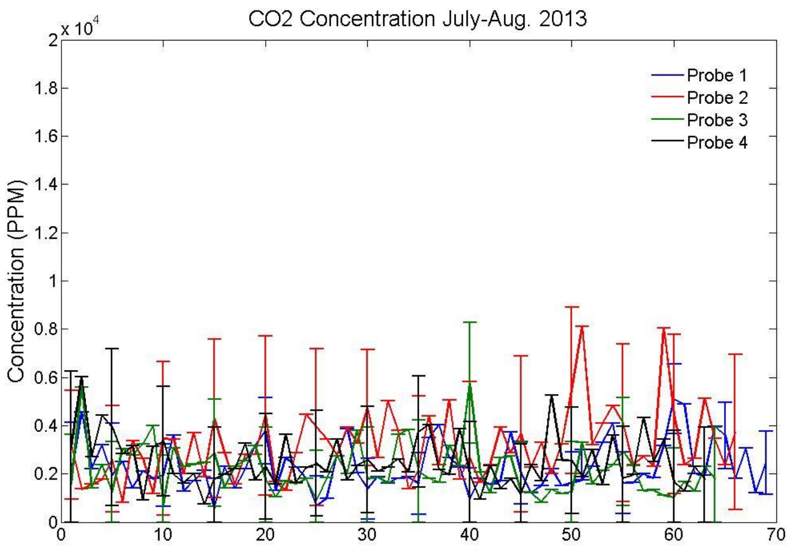


Technical Status: ZERT Field Data

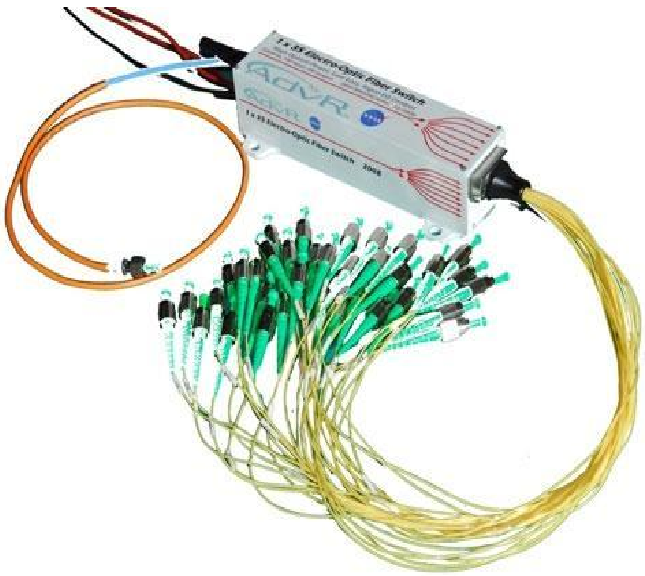


Technical Status: BSCSP Field Data





Scalability and Large Area Coverage



A commercial 1 x 100 fiber optic switch allows up to 100 probes to be deployed. Using standard telecommunications fiber, these 100 probes can be located up to 1 km away from the central electronics box.

Because the cost of the probes is kept low, scaling to 100 probes will not greatly increase the cost providing a cost effective sensor array.

Accomplishments to Date

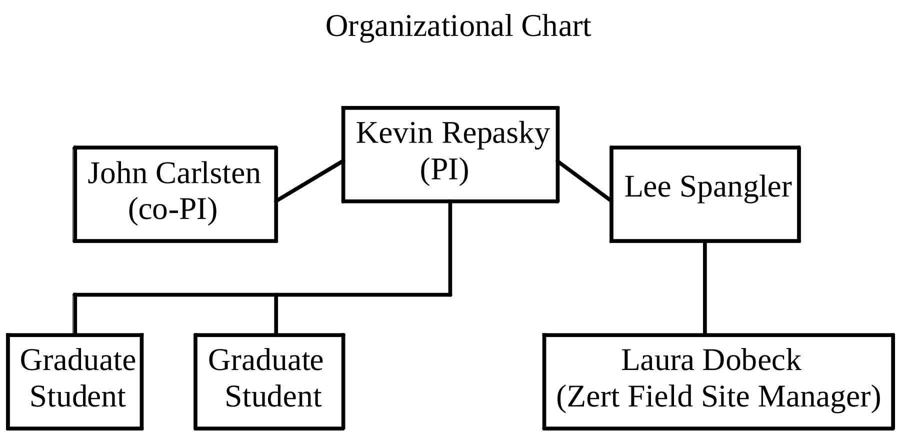
- A 1 X N fiber sensor array architecture has been developed.
- Subsurface CO_2 concentration measurements have been made continuously for over 40 days.
- Instrument has been demonstrated at the ZERT field site where the elevated subsurface CO_2 concentration from the subsurface release is clearly evident.
- Instrument has been successfully deployed at the BSCSP site.

Summary

- The fiber sensor array has been successfully deployed at the ZERT controlled release experiment.
- The fiber sensor array offers a scalable, reconfigurable, cost effective monitor for large area coverage with autonomous operations.
- Future Plans
  - Include a second DFB laser for sensing oxygen to provide the potential to distinguish sources of subsurface CO_2.
  - Working with Integrated Optical Systems on transfer technology of fiber sensors into the commercial market.

Thanks Kindly for Your Time

Appendix: Organization Chart



- Kevin Repasky: (PI) responsible for overall project.

  John Carlsten: (Co-PI) work with Dr. repasky to manage project and students.

  Lee Spangler: Head of ZERT and BSCSP. Coordinate field work

  Laura Dobeck: Coordinate ZERT field experiments.

figure 5.

Appendix: Gantt Chart

Month	3	6	9	12	15	18	21	24	27	30	33	36
Phase 1 Develop a single channel fiber sensor	◄─	──	──	─►								
Task 1.1 Project management and planning	◄►											
Task 1.2 Development of a fiber sensor probe	◄─	──	─►									
Task 1.3 Development and testing of a single channel fiber sensor			◄─	─►								
Phase 2 Development and initial testing of a 1 x 4 fiber sensor array					◄─	──	──	──	──	─►		
Task 2.1 Design and construction of four fiber sensor probes					◄─	──	─►					
Task 2.2 Construction of the 1 x 4 fiber sensor array							◄─	──	──	─►		
Phase 3 Field testing the 1 x 4 fiber sensor array											◄─	─►
Task 3.1 Field testing the fiber sensor array											◄─	─►

figure 5.

Appendix: Presentations and Publications

- Presentations:
  - “Large area detection of CO2 for carbon sequestration”, IEAGHG: Environmental Impacts of CO2 Storage Workshop, Bozeman, MT, July 2012 (invited).
  - “Subterranean Carbon Dioxide (CO_2) Concentration Analysis Utilizing an Optical Fiber Probe Array for Carbon Capture and Storage (CCS) Site Monitoring”, Benjamin Soukup, Kevin S. Repasky, and John L. Carlsten, American Geophysical Union, San Francisco, California, 2011.
  - “Sub-Surface Carbon Dioxide Concentration Measurement Using a Fiber Based Sensor in a Send/Call Geometry for Carbon Sequestration Site Monitoring”, Geoffrey Wicks, Benjamin Soukup, Kevin S. Repasky, John L. Carlsten, Jamie L. Barr, and Laura Dobeck, American Geophysical Union Meeting, San Francisco, California, 2010.
- Papers:
  - “Development of a 1 X N fiber sensor array for subsurface carbon sequestration site monitoring”, Benjamin Soukup, Geoffrey Wicks, Kevin S. Repasky, and John L. Carlsten, in preparation for submission to the Journal of Applied Remote Sensing.

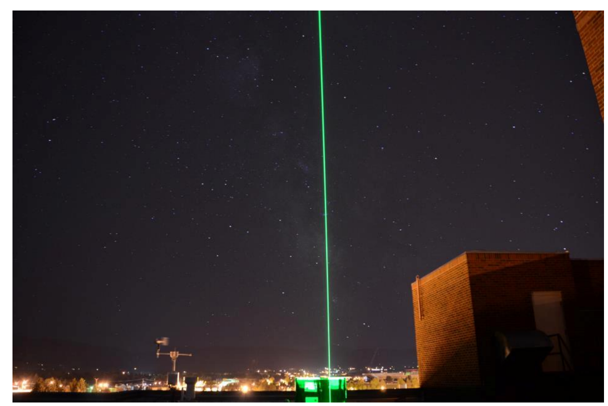
Optical Tools and Techniques for Large Area Surface Monitoring of Carbon Sequestration Sites

Kevin S. Repasky, William Johnson, Benjamin Soukup, John L. Carlsten, Rick Lawrence, and Scott Powell
Electrical and Computer Engineering, Cobleigh Halll Room 610, Montana State University, Bozeman, MT, 59717

Montana State University Bozeman

ZERT Zero Emissions Research and Technology

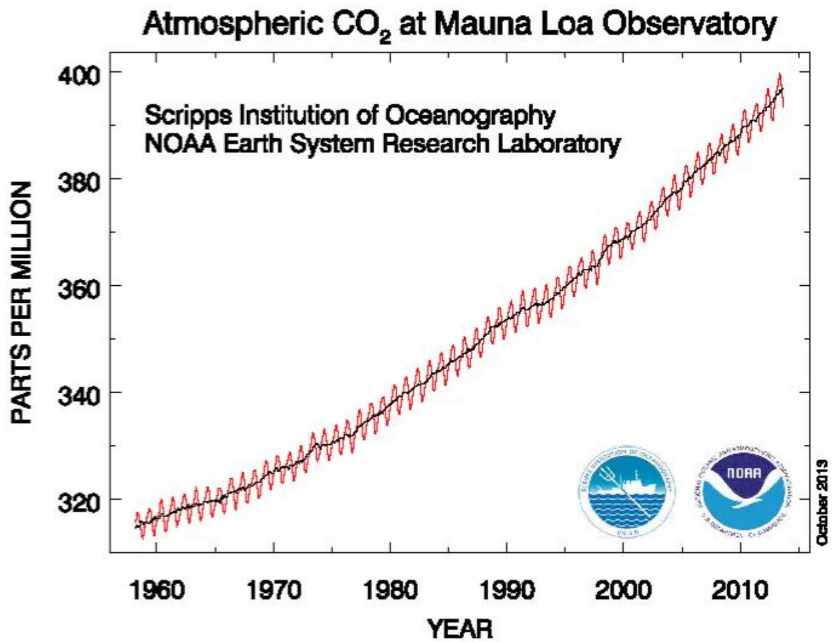
Big Sky Carbon Sequestration Partnership



Talk Outline

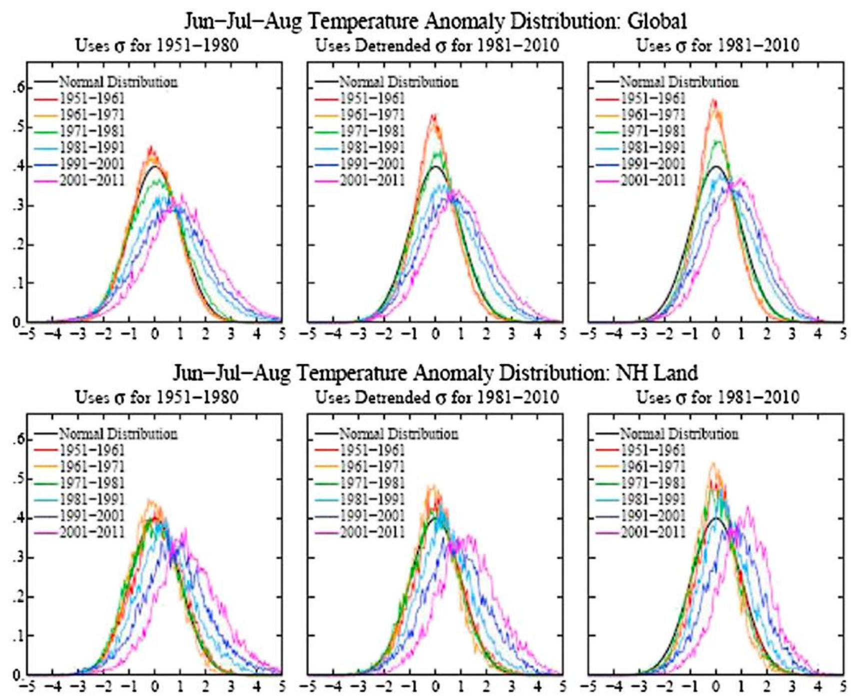
- Introduction to Carbon Capture Utilization and Storage (CCUS).
- Surface monitoring based on a differential absorption lidar (DIAL).
- Near sub-surface integrated path differential absorption fiber sensors.
- Flight based hyperspectral imaging.

Carbon Capture Utilization and Storage (CCUS)

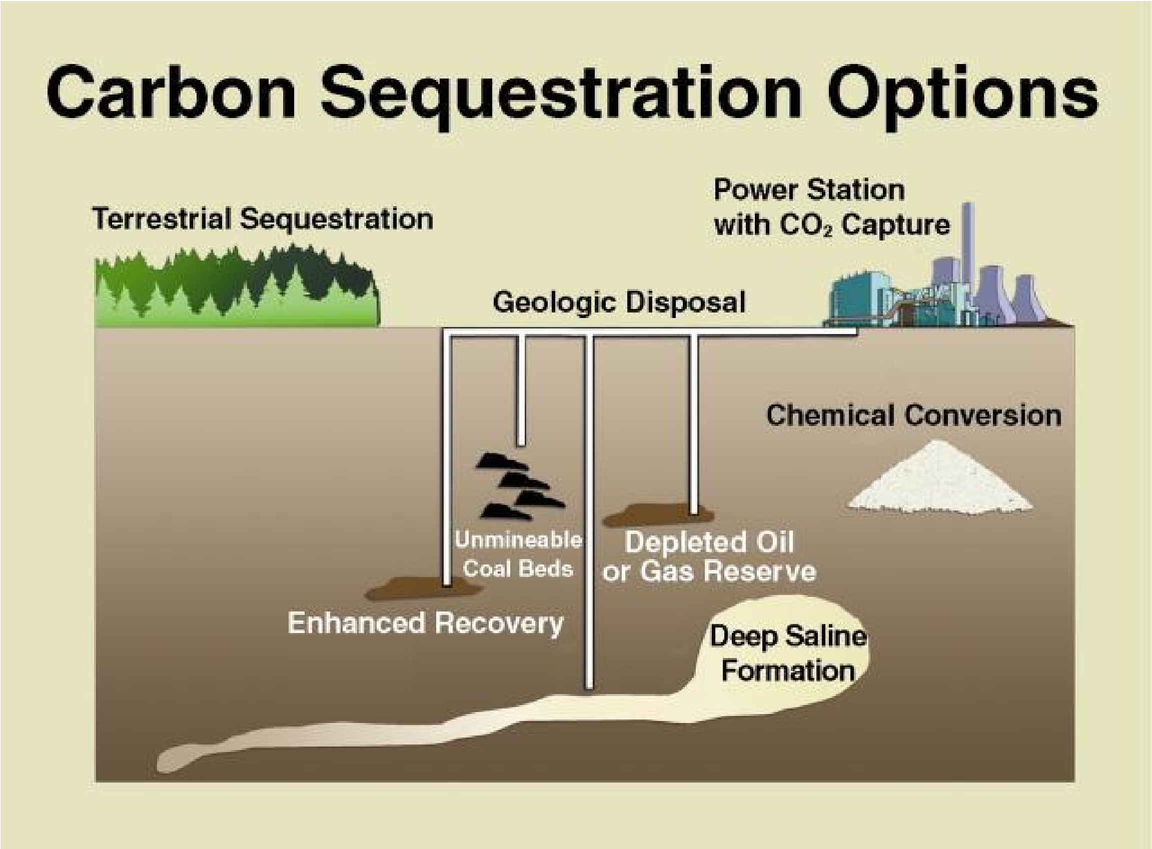


- CO_2 levels have risen from 316 ppm in 1959 to 395 ppm in 2013
- The rate of increase of the atmospheric concentration has increased from 0.85 ppm/year between 1960 and 1969 to 1.96 ppm between 2000 and 2009
- The emissions of CO_2 in 2005 dues to fossil fuel consumption was estimated at 7.9 Gigatonnes/year

- The atmospheric concentration of CO_2 affects the Earth's energy balance by trapping more thermal radiation.
- The increase levels of CO_2 are impacting the global climate leading to international efforts to decrease the emission of CO_2 and other green house gases.



Carbon Capture Utilization and Storage (CCUS)



Carbon capture utilization and storage utilizes CO_2 captured at a point source such as a power generation facility. The CO_2 is then compressed and pumped underground where it may be used for enhanced oil recovery and/or stored in geologic formations.

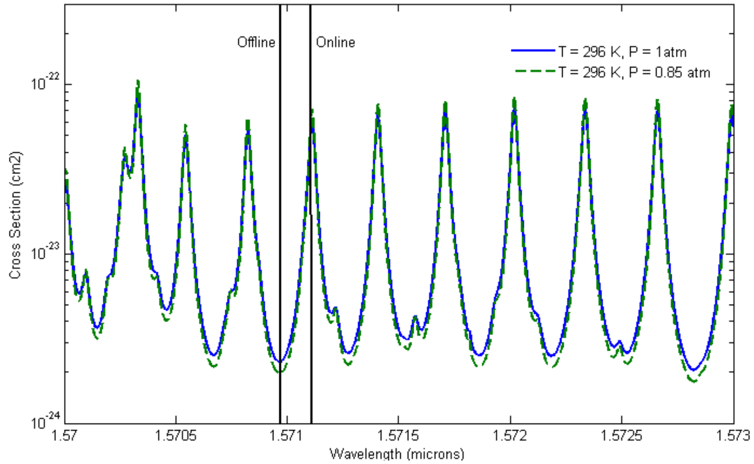
- Large localized emitters of carbon dioxide, which make up 39.6 percent of the total United States carbon emissions as of 2010, capture CO_2 gas at their emission point.
- The current estimated viable carbon sequestration capacity of identified sequestration type formations in the United States and parts of Canada alone is 12.9 metric Petatons.
- There are 83 active carbon sequestration projects worldwide as of February 2013 and 32 announced sites are under active development.

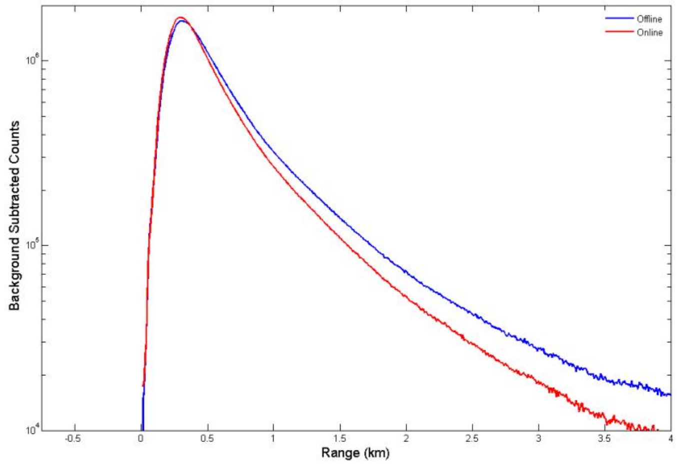
Carbon Capture Utilization and Storage (CCUS)

- The Department of Energy is implementing eight large-scale (one million metric tons or more total) geologic storage and utilization projects that will demonstrate the long-term, effective, and safe storage and utilization of CO2 in the major geologic formations throughout the United States and portions of Canada through seven regional carbon sequestration partnerships (RCSP's).
- The goals of these RCSP projects are to:
  - Provide scientific data to validate the capacity estimates to within +30% for deep saline formations, where little data currently exists.
  - Assess the effects of reservoir heterogeneity on the performance of the storage operations to contact the pore space and maintain injectivity.
  - Validate the reservoir models against field data; implement mitigation strategies to reduce potential hazards; and verify the fate of the injected CO2 using the most advanced monitoring networks applied to date.
  - Finally, these projects will demonstrate that the projects are representative of the regional geology to store large volumes of CO2 emissions generated from major point sources
- To achieve these goals, many technological advances must be realized including monitoring and verification tools that can help ensure site integrity and public safety. This talk will focus on three monitoring technologies being developed at Montana State University.

Differential Absorption Lidar (DIAL) Technique

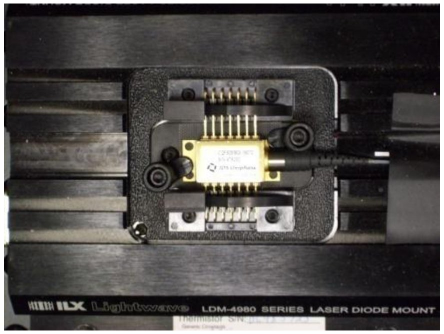
- The DIAL technique uses two closely spaced wavelengths and does not rely on an instrument calibration.
- The difference between the return signal for the two closely spaced wavelengths is related to the molecular number density.
- The number density can be calculated using the DIAL equation.

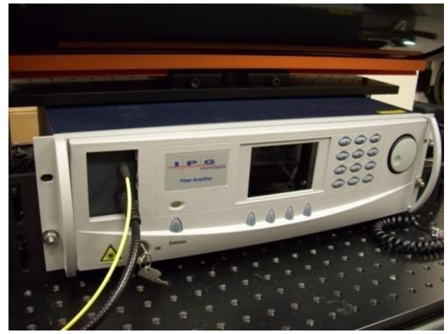


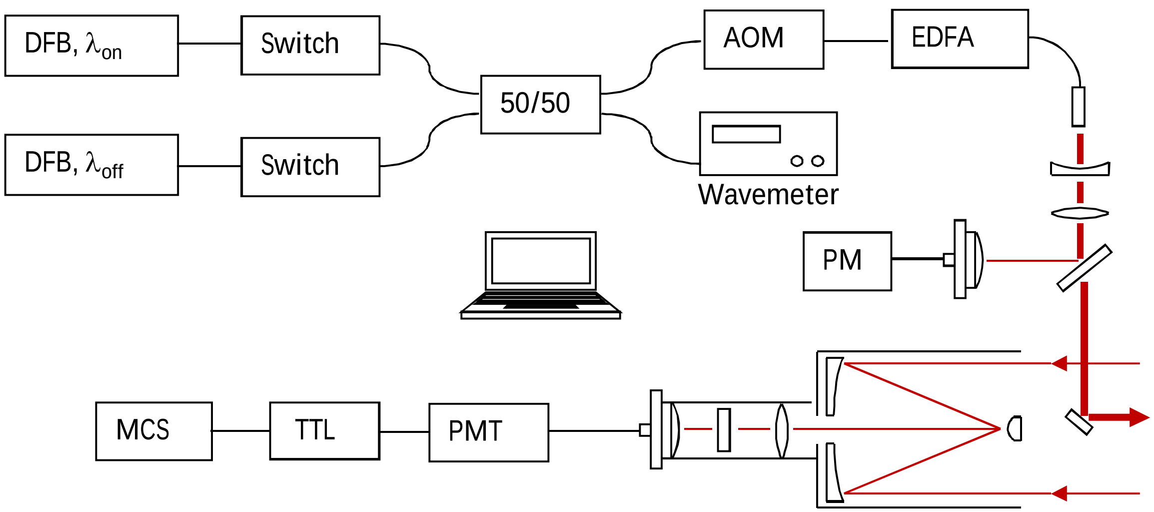


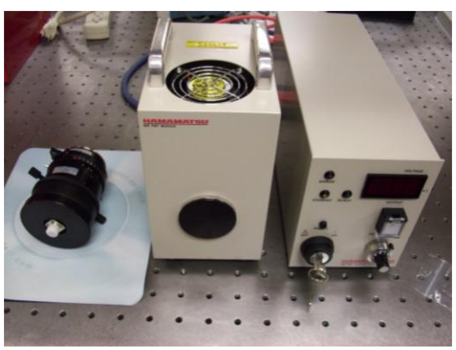
$$N(r) = \frac{1}{2\Delta r(\sigma(\lambda_{on}, r) - \sigma(\lambda_{off}, r))}\left[ln\left(\frac{P(\lambda_{on}, r)P(\lambda_{off}, r + \Delta r)}{P(\lambda_{on}, r + \Delta r)P(\lambda_{off}, r)}\right)\right]$$

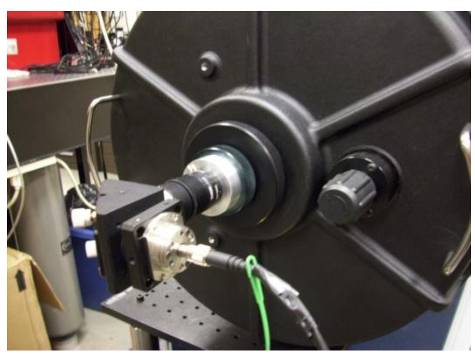
DIAL Instrument Schematic









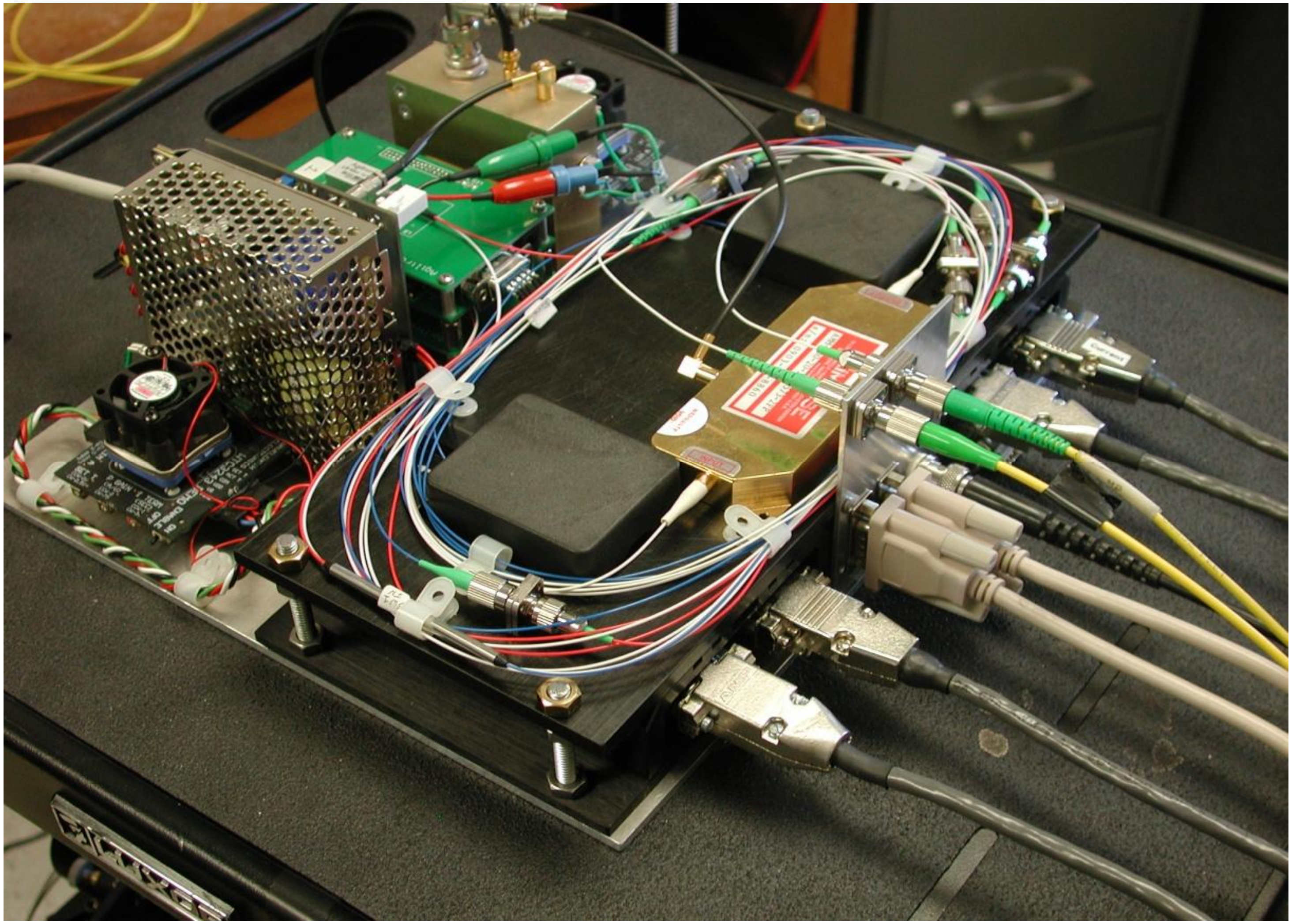


DFB Lasers	
Manufacturer	Eblana
Packaging	14 pin
Output Power	10 mW
Linewidth	<2 MHz
Side Mode Suppression	>40 dB

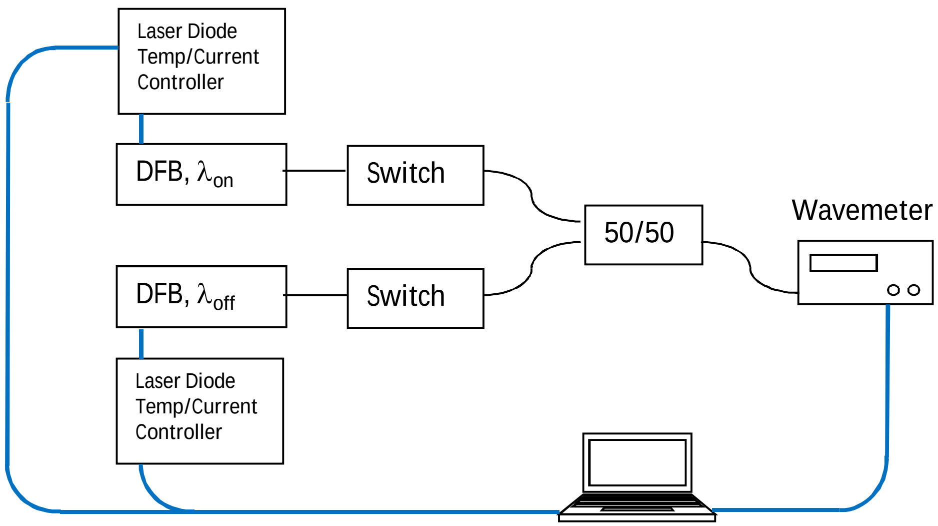
EDFA	
Manufacturer	IPG Photonics EAR-0.5K-1573-MT
Max. Output Power	1 W
Power Stability	0.54%
Wavelength Range	1.570 – 1.575 μm

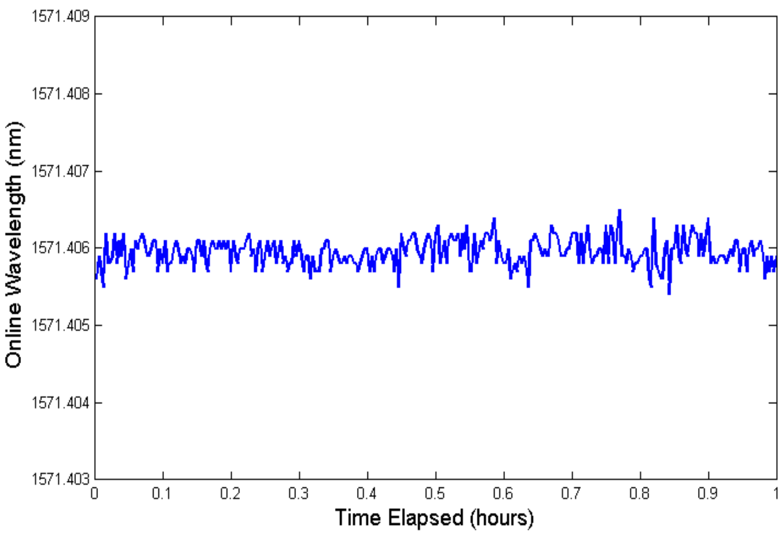
PMT	
Manufacturer	Hamamatsu H10330-075A
Wavelength	0.95 – 1.70 μm
Gain (@-800 V)	$1X10^6$
Dark Current	300 nA
Quantum Efficiency	2%
Operating Temp.	TEC Cooled to -60 C

DIAL Laser Transmitter



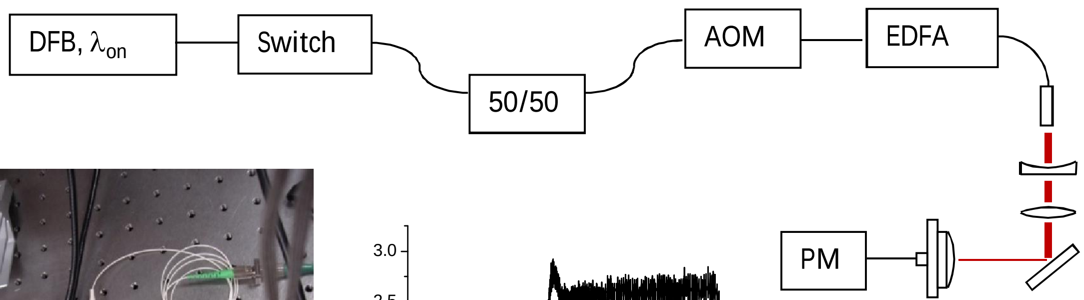
Wavelength Control



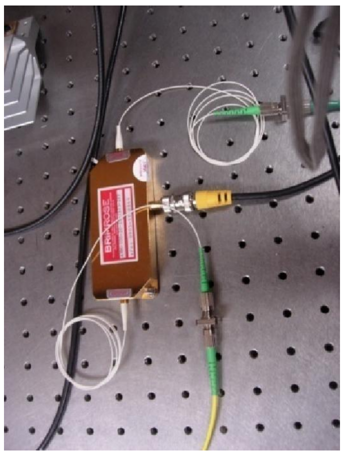


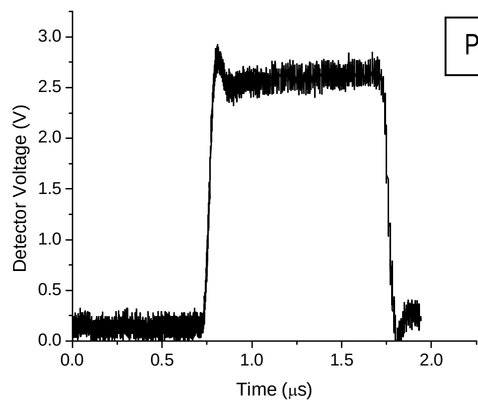
- A two laser scheme was developed so that switching times between on-line and off-line can be on the order of seconds.
- This locking scheme always ensures seed power to the EDFA to prevent damage due to stimulated Brillioun scattering.
- This locking is robust, operating unattended over a period of 12 hours with this instrument and up to seven days on a water vapor DIAL.
- Locking stability is +/- 0.18 pm (+/- 20 MHz)

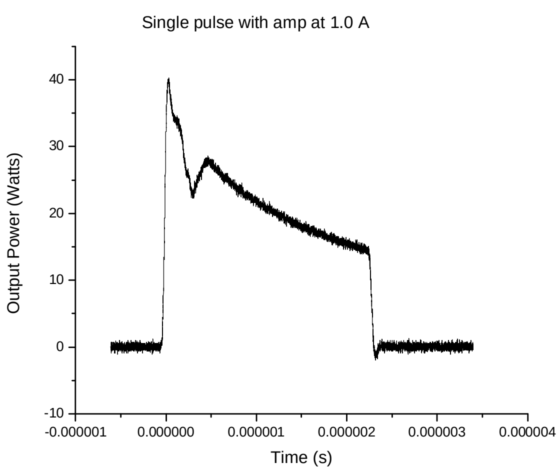
Pulse Generation

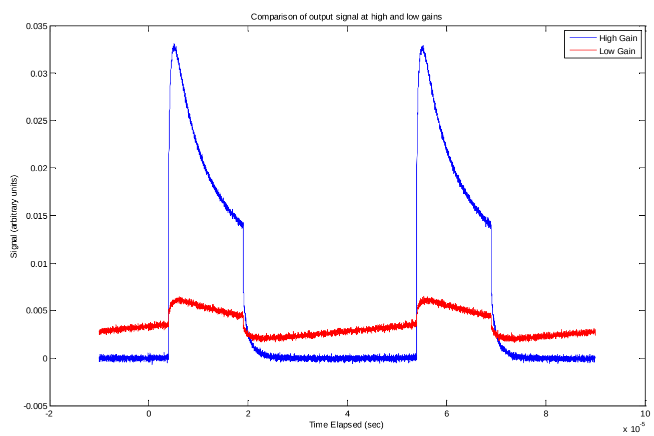


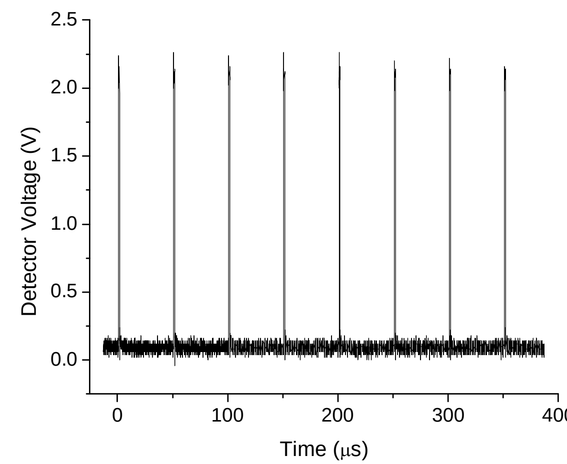
- Pulses between 0.2 and 2 μs generated using the AOM.
- Pulse repetition frequency of up to 25 kHz demonstrated.
- A pulse repetition frequency of 15 kHz provides a maximum range of 10 km.









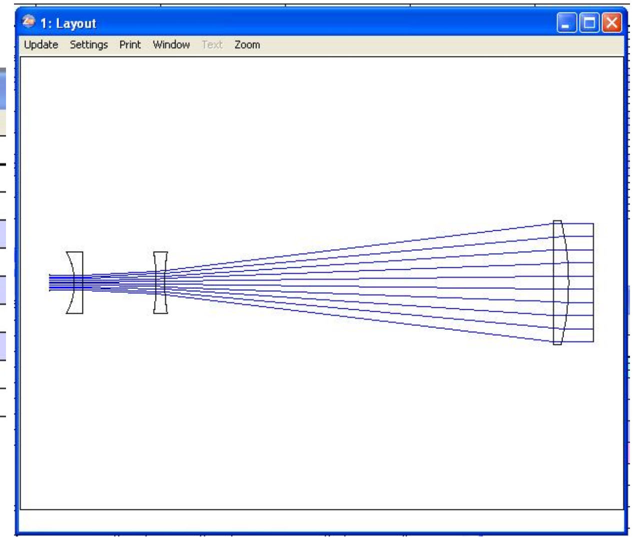


Optical Modeling

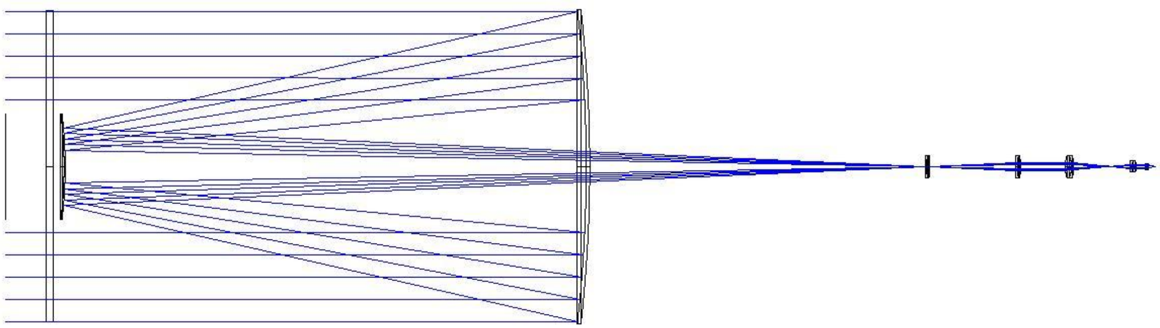
Lens Data Editor

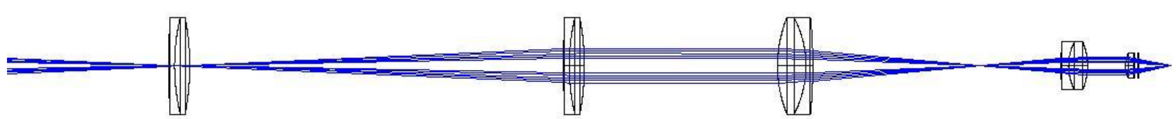
Edit Solves View Help

Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	Conic
OBJ	Standard		Infinity	Infinity		0.000	0.000
STO	Standard	input beam	Infinity	10.000		2.900	0.000
2*	Standard	expander	-25.700	3.500	N-BK7	12.500 U	0.000
3*	Standard		Infinity	30.020 V		12.500 U	0.000
4*	Standard		-77.900	3.500	N-BK7	12.500 U	0.000
5*	Standard		77.900	159.298 V		12.500 U	0.000
6*	Standard	collimator	Infinity	6.200	N-BK7	25.400 U	0.000
7*	Standard		-103.360	10.000		25.400 U	0.000
IMA	Standard		Infinity	-		24.334	0.000



Collimation of the outgoing beam is key to achieving accurate on-line and off-line returns. Measuring the M^2 and beam diameter of the outgoing beam, a collimation optical train was designed.

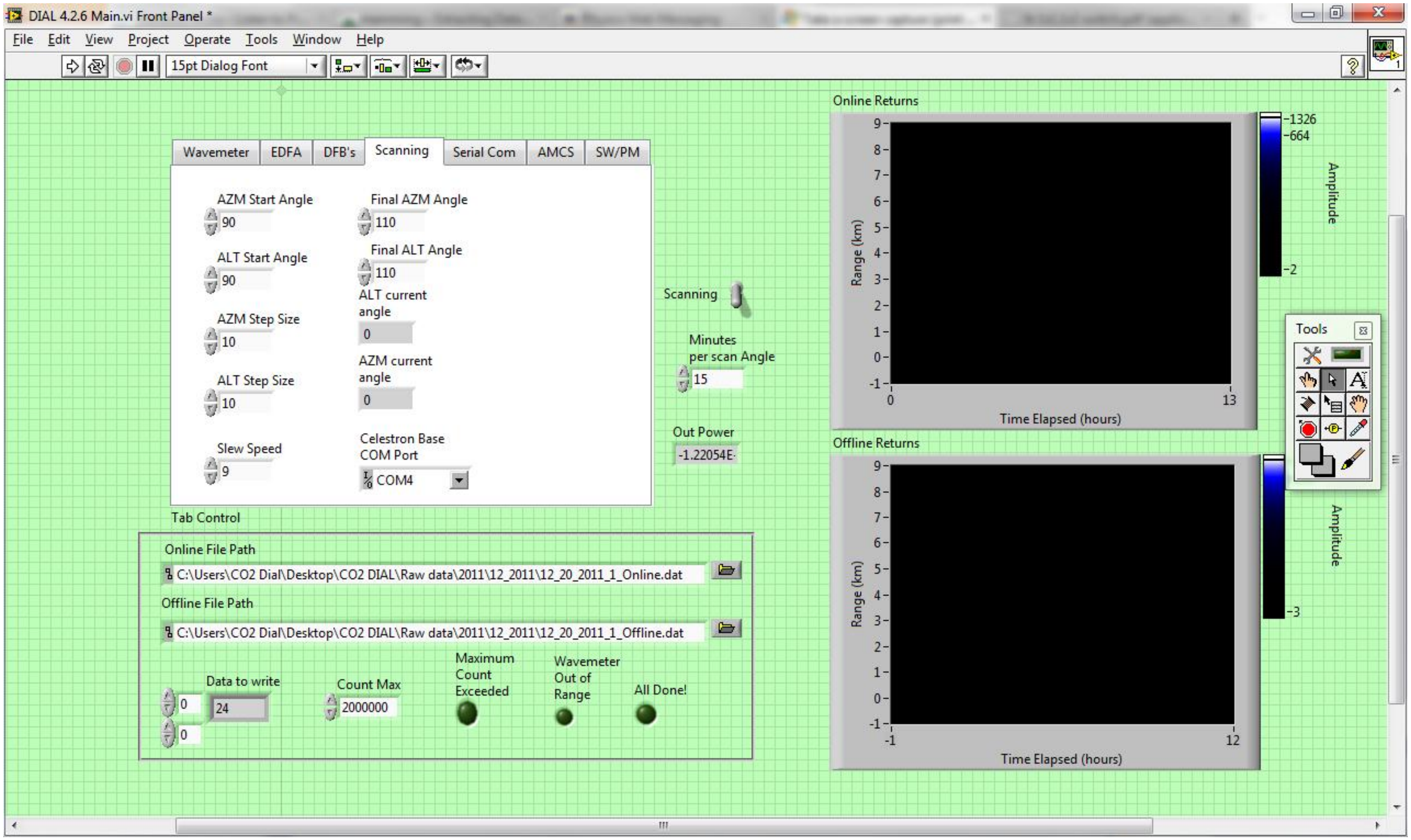




The receiver optical train images the telescope focus at the fiber input which acts as the receiver field stop.

Range, overlap, and signal to noise performance depends on a well executed receiver design.

Labview Control Program



Technical Status: CO_2 DIAL -- Scanning

Using existing telescope mount with motor drives provides a stable scanning method.

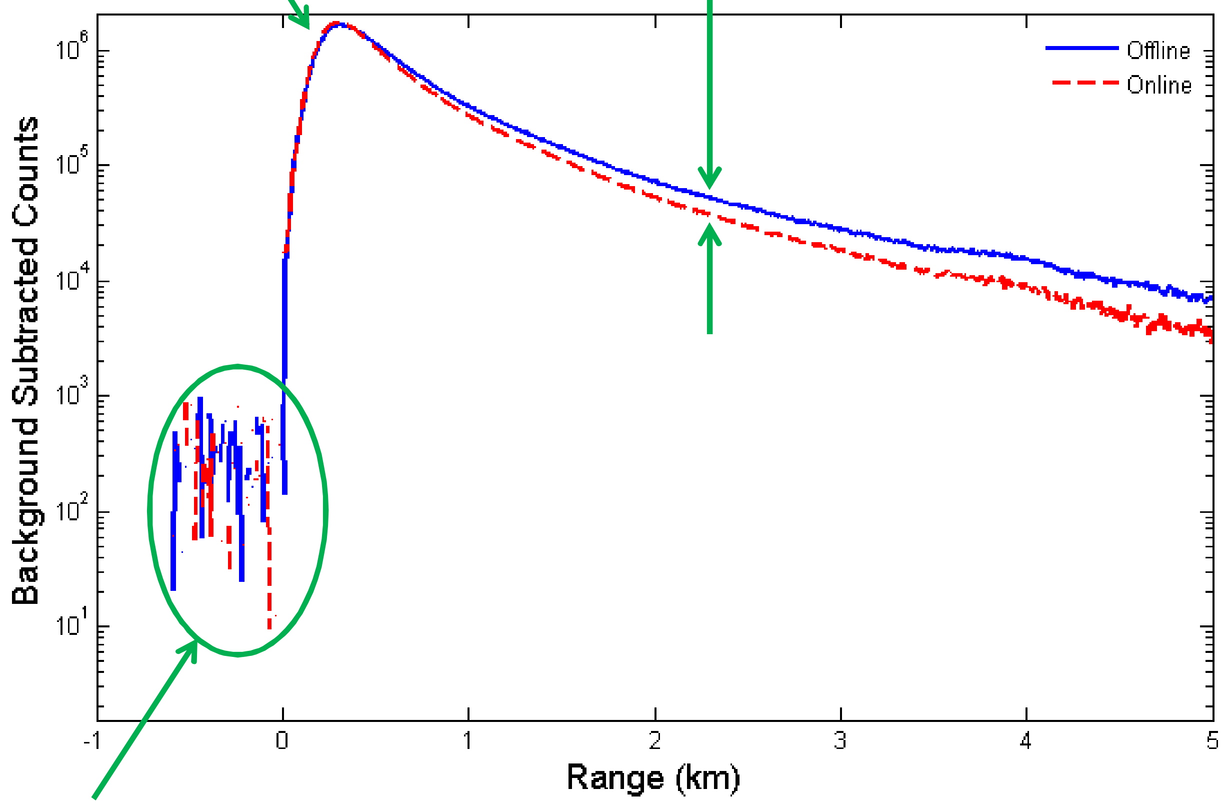
DIAL instrument, supporting electronics, and data acquisition computer in the cargo trailer at the ZERT site.

On-line and Off-line

Initial overlap

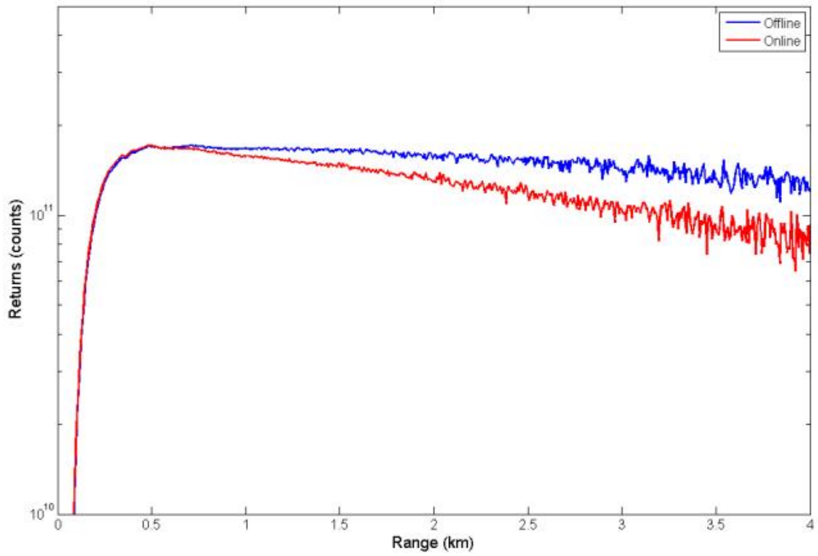
Difference in return signal is directly related to the CO_2 number density

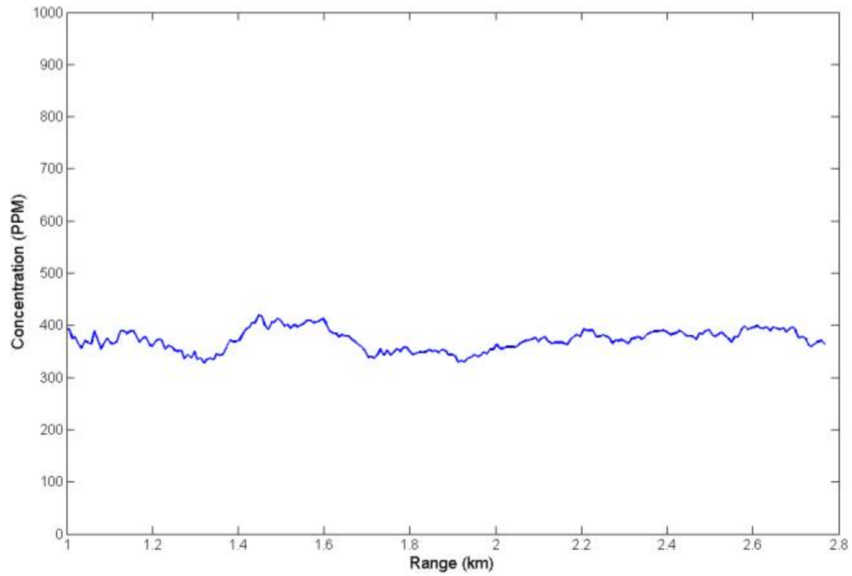
Shown on a log scale to remove the $1/r^2$ dependence

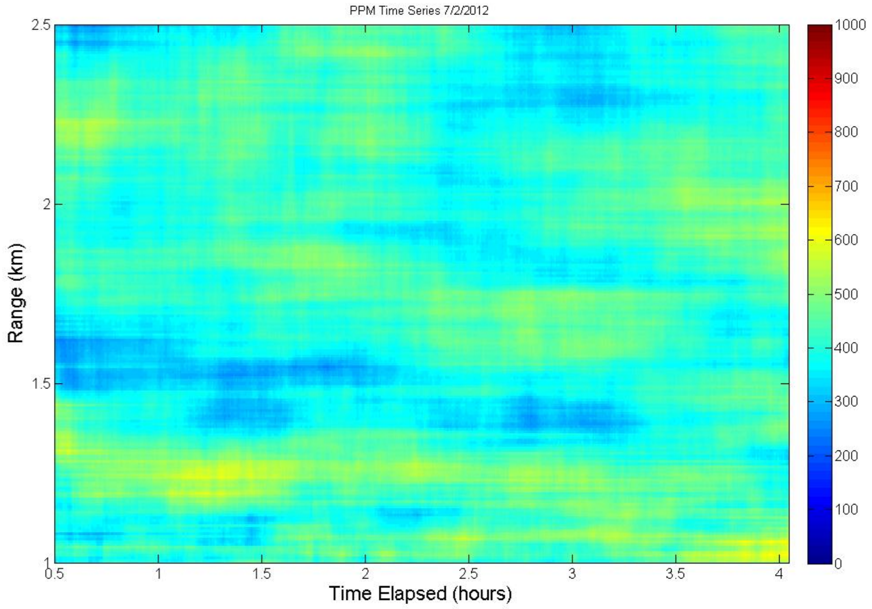


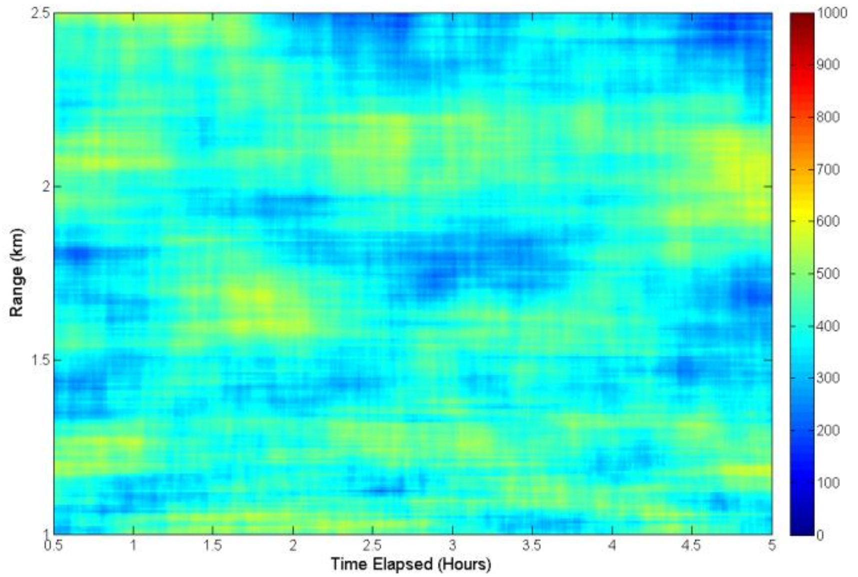
4 μs of background collected before laser pulse fires. Used for background subtraction

Initial Data









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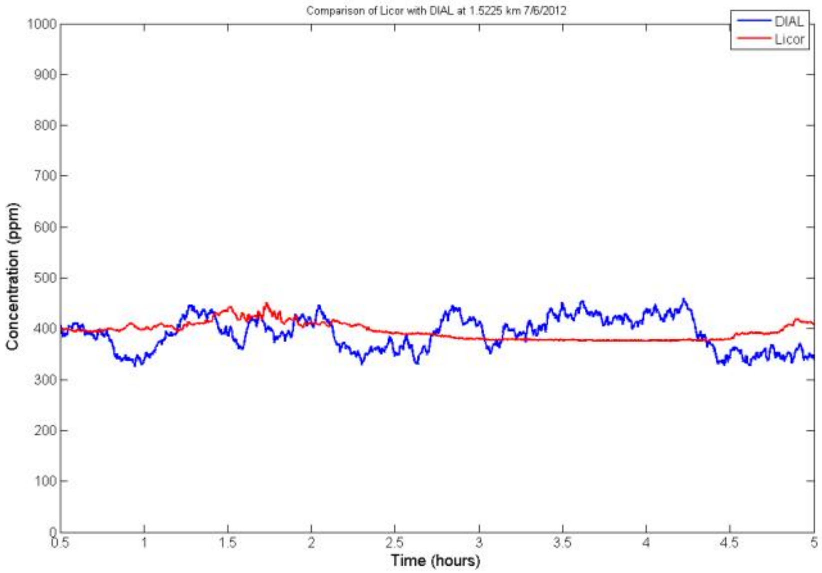
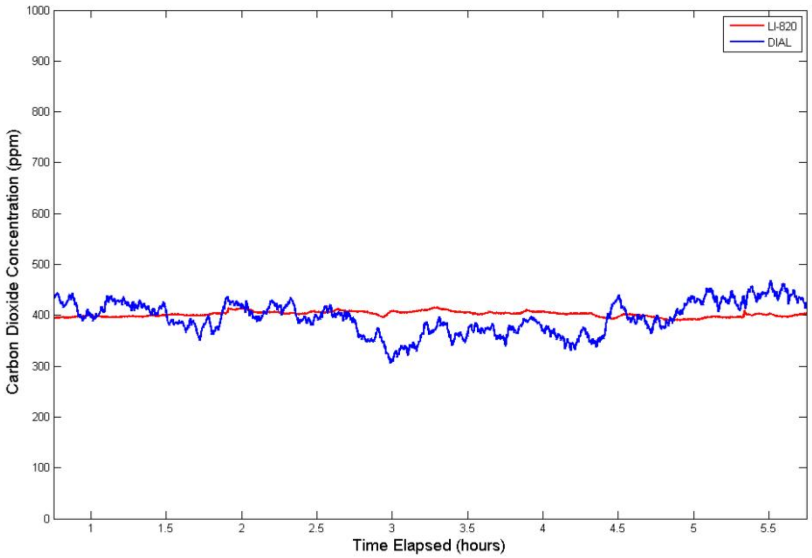
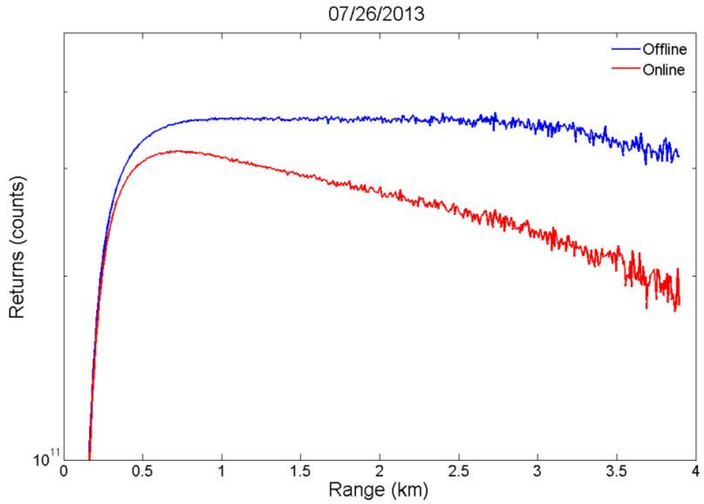
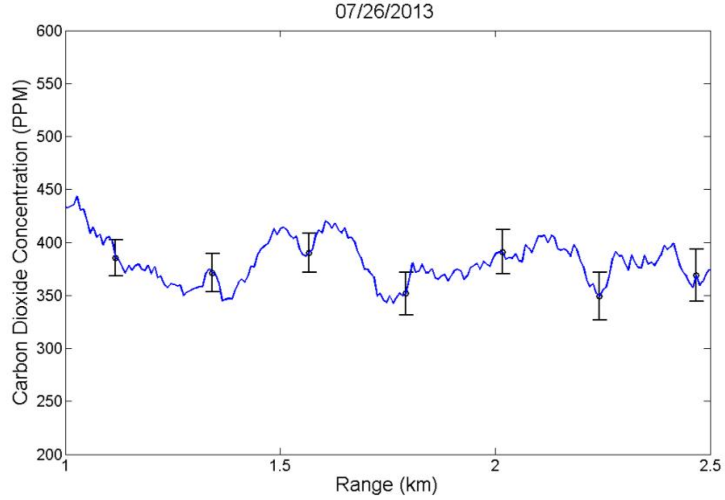


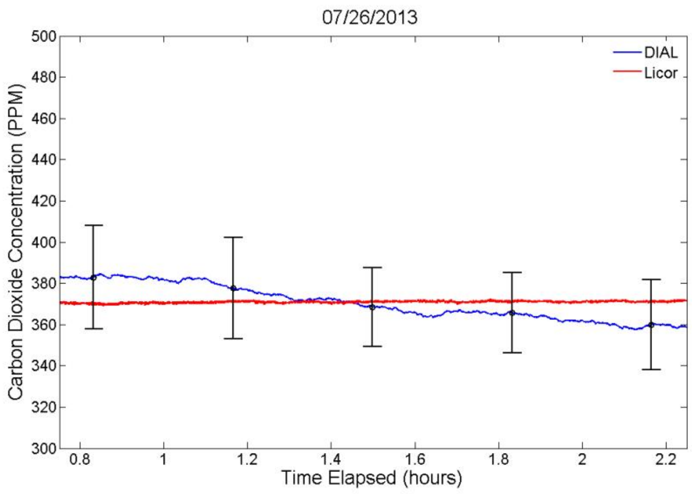


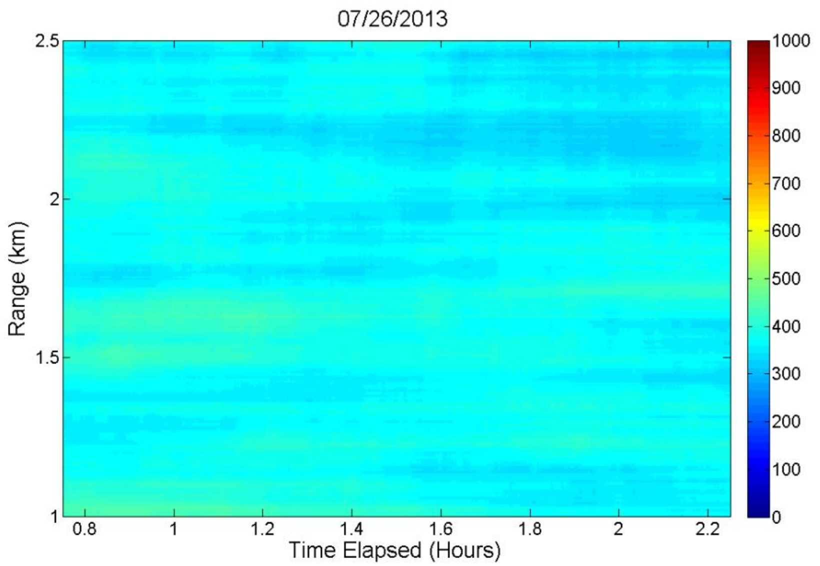
Deployment at the Big Sky Carbon Sequestration Site

Data from thenBig Sky Carbon Sequestration Site

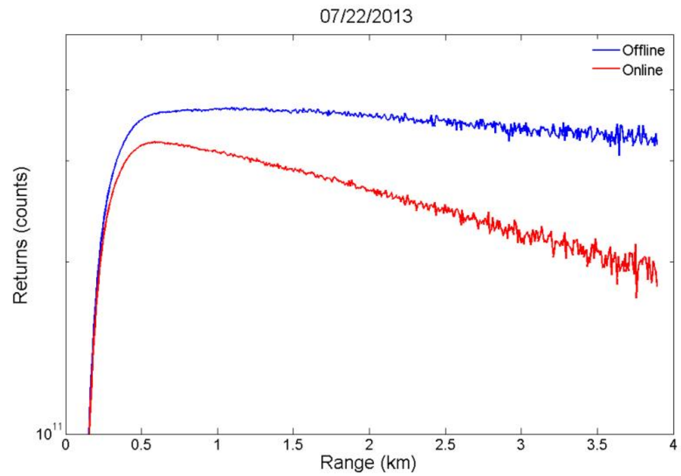


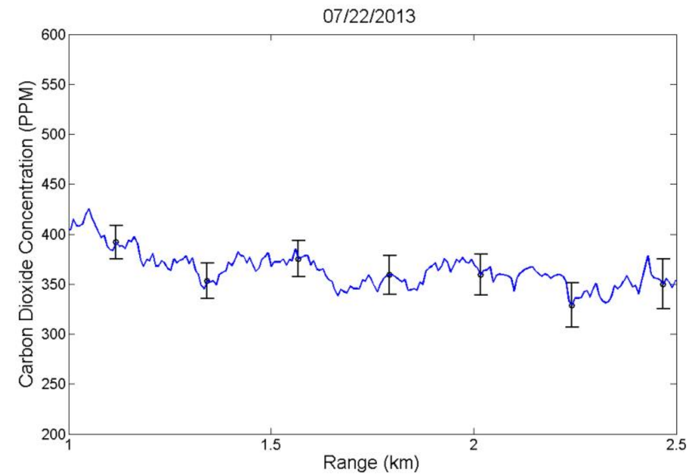


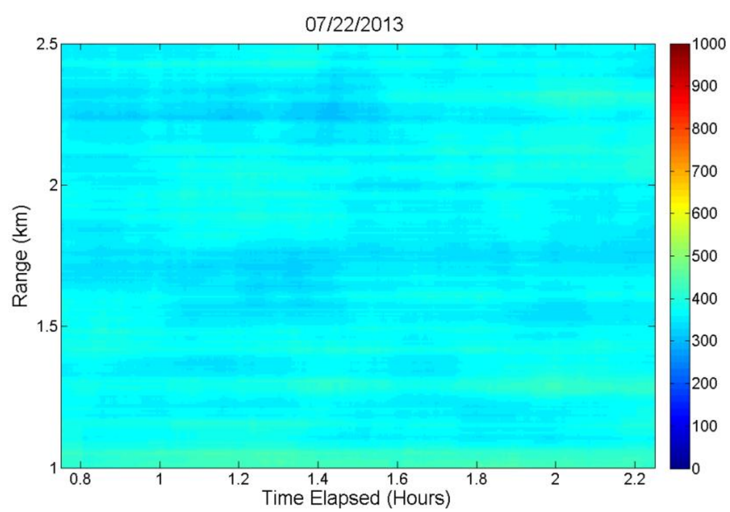


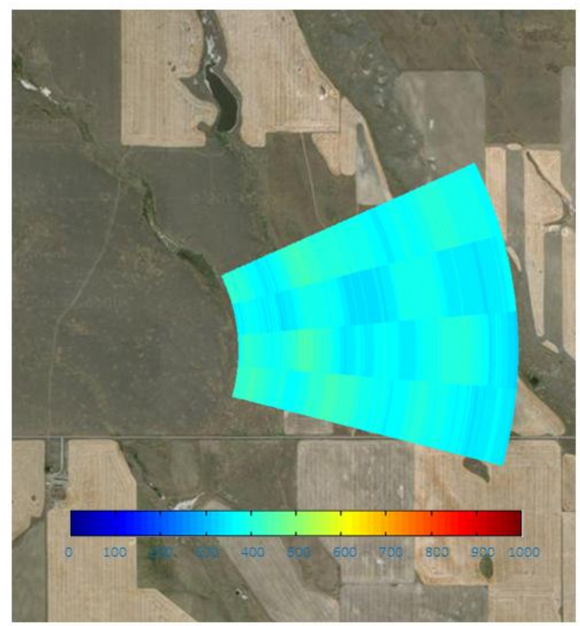


Data from the Big Sky Carbon Sequestration Site









Integrated Path Differential Absorption (IPDA) Technique

MONTANA STATE UNIVERSITY BOZEMAN

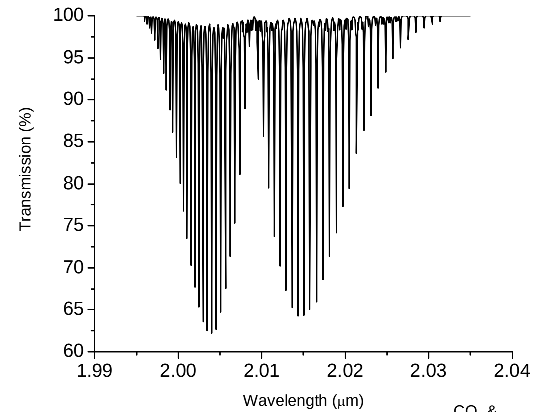
- The number density for carbon dioxide is related to the amount of light absorbed as a function of wavelength.

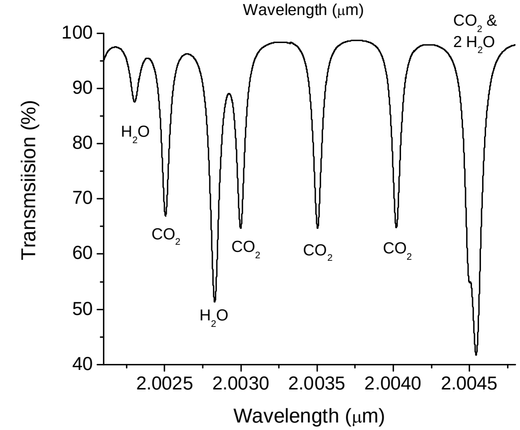
- Working near the 2 μm wavelength provides strong absorption features which allow subsurface CO_2 concentration measurements to be made in as little as 0.5 m.

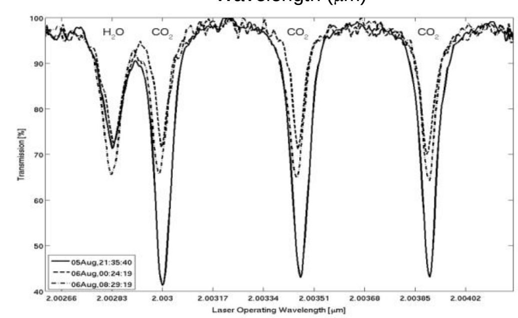
- Measuring the normalized transmission allows one to calculate the number density.

•Using the line strength and line shape parameters, the concentration can be calculated from the IPDA equation:

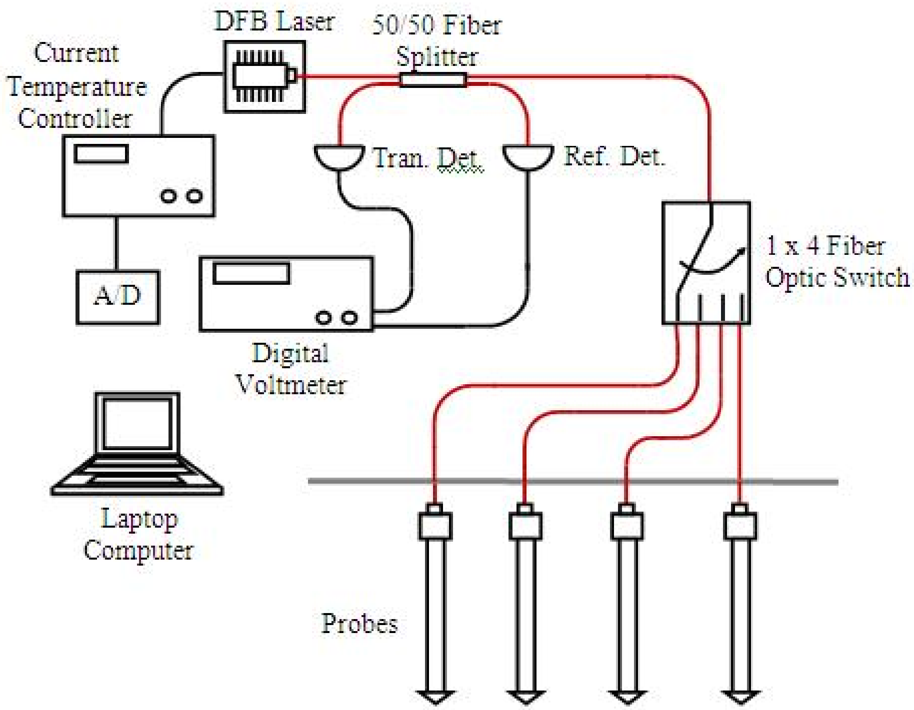
$$C = \frac{-\ln(T)}{Sg(\nu-\nu_0)\left[N_L(296/T_a)\right]P_T L},$$

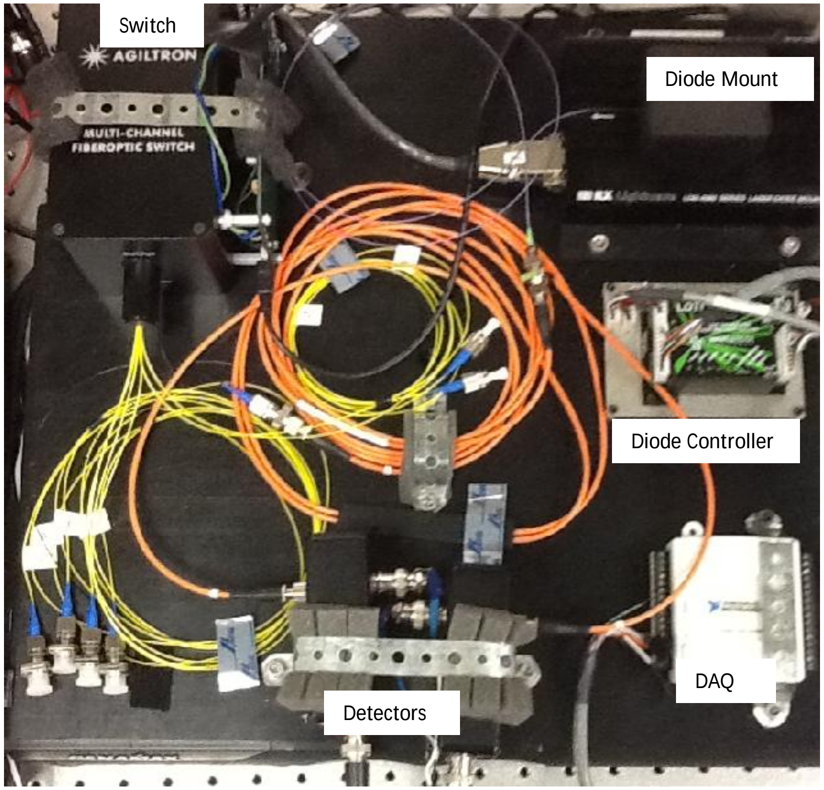




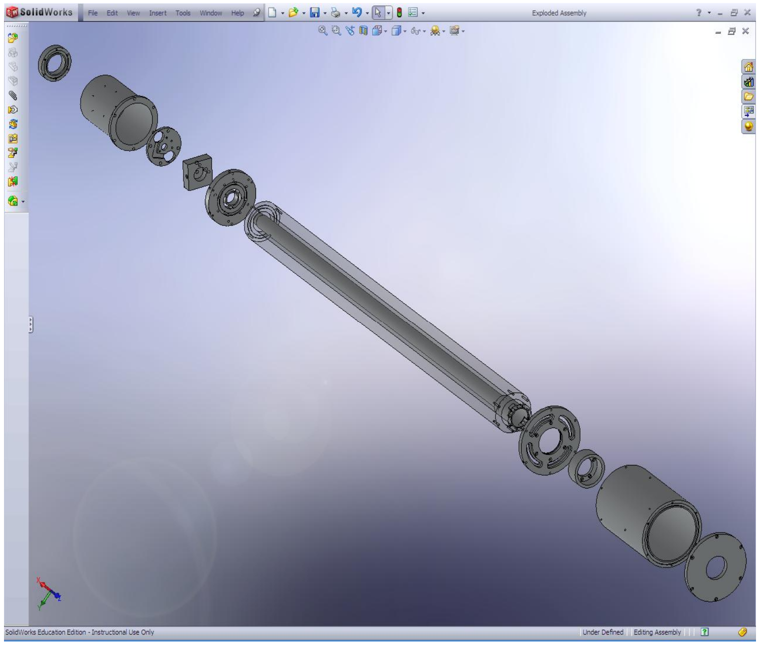


Instrument Design

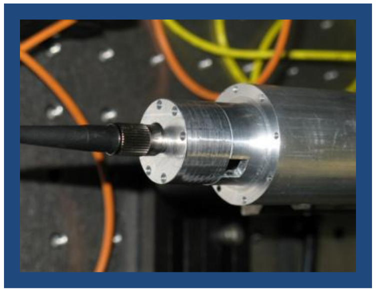




Probes

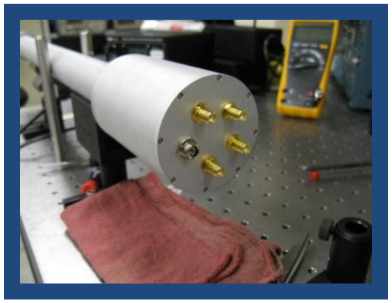


Solidworks CAD drawing of the probe design. The probe was designed to contain all passive optical components and is inexpensive to manufacture.



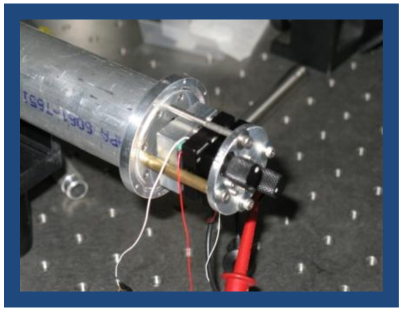
Fiber coupler details

Electronic Feed-through



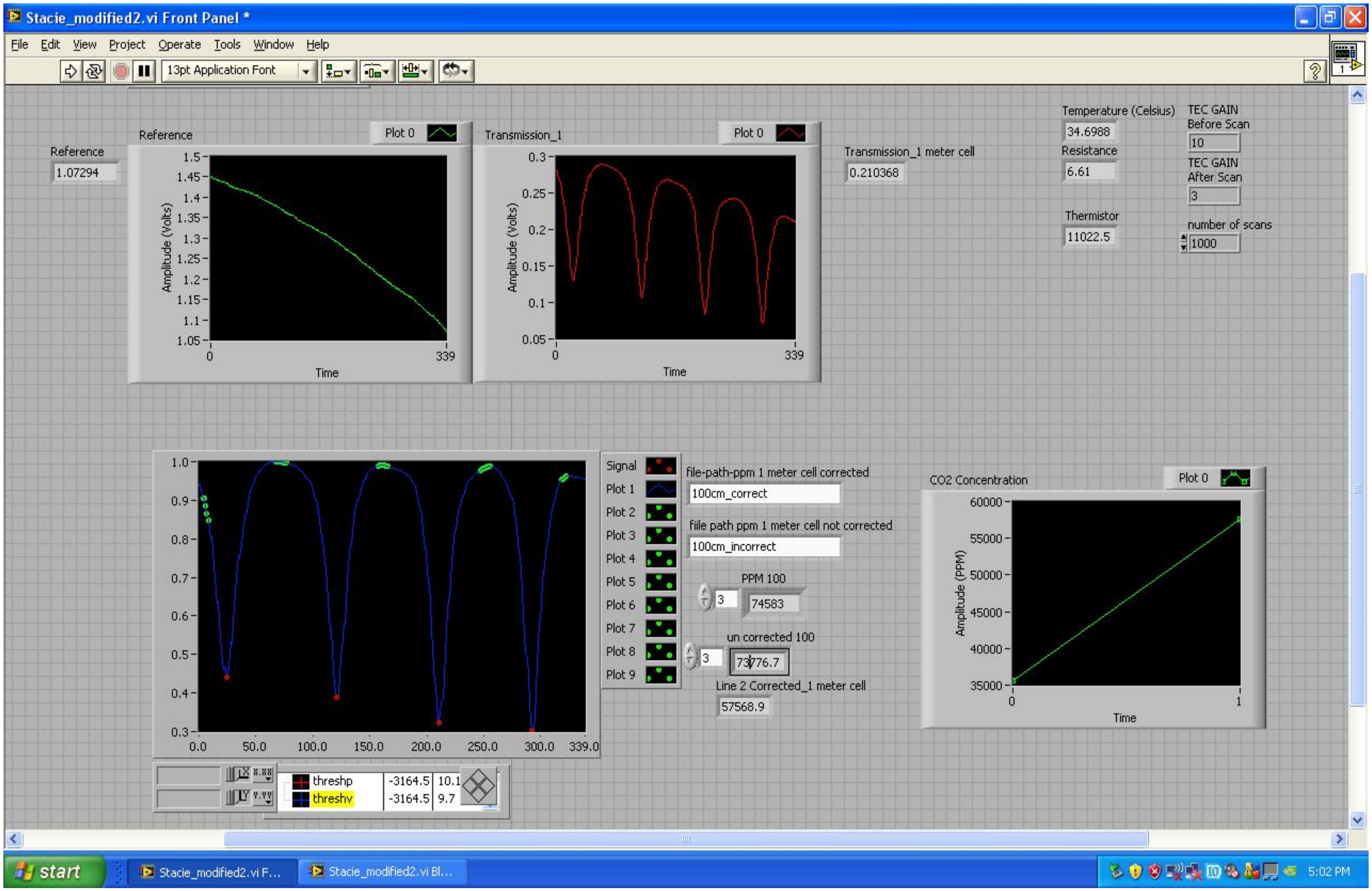
Gas permeable membrane

Retro-reflector details

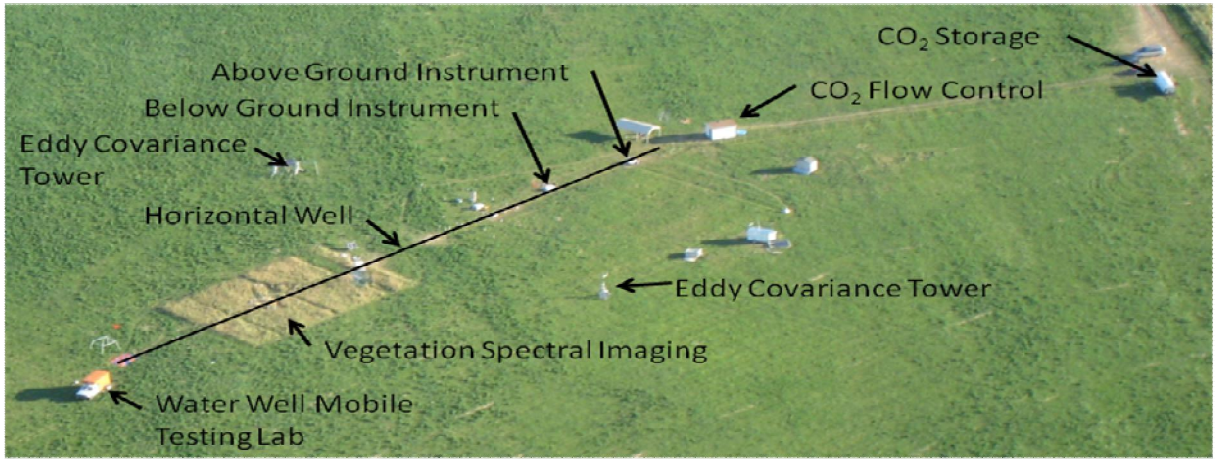


Four completed fiber probes

Data Acquisition Software



Field Experiment



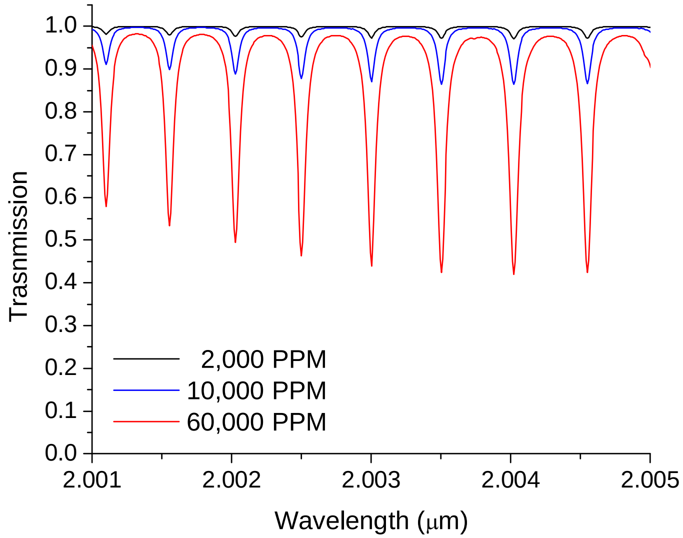
Aerial view of the ZERT controlled release site.

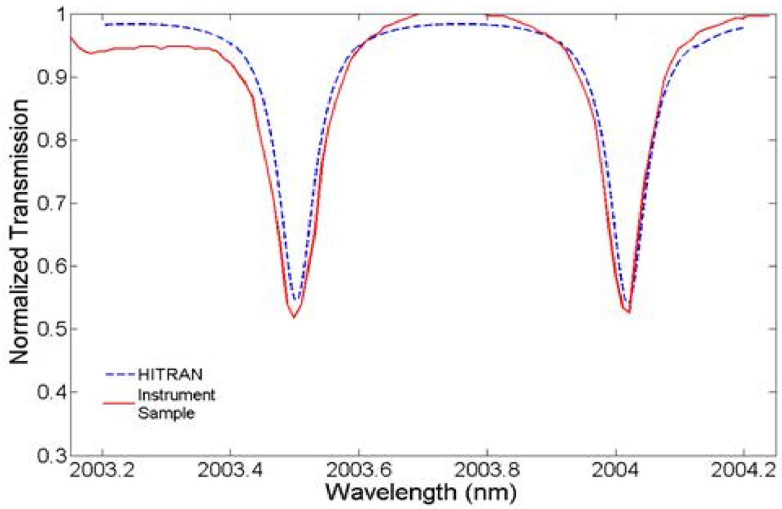
Electronics and optics packaged in a weatherproof enclosure for field studies.

Instrument deployed at the ZERT site with sun shade.

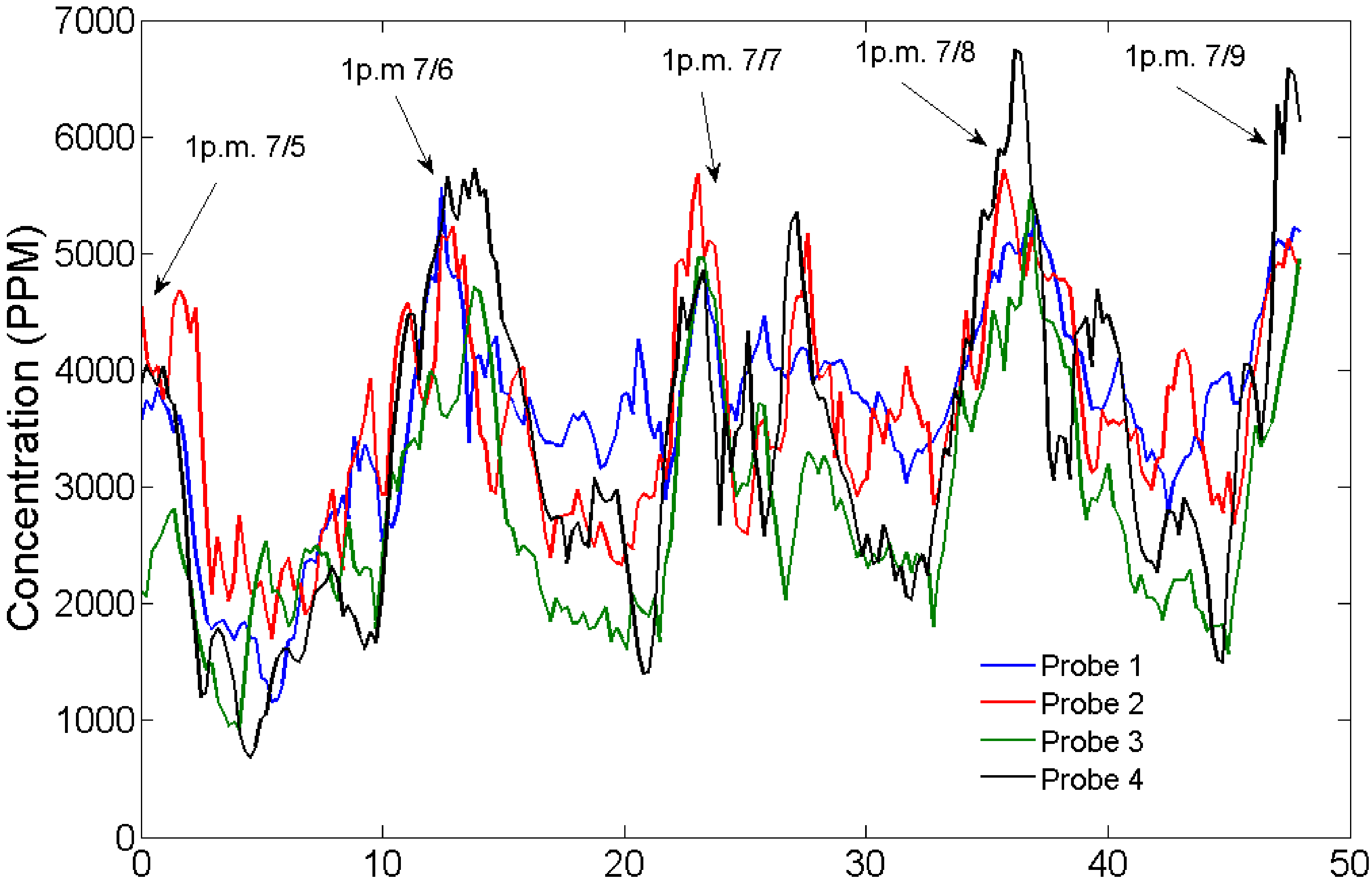
ZERT Field Data

Wavelength mm	Linestrength 10^{-21} molecules/cm	Normalized Lineshape Cm
2.001 102 0	0.811 2	1.160 0
2.001 557 7	0.931 6	1.151 6
2.002 025 5	1.048	1.140 1
2.002 505 7	1.153	1.130 4
2.002 998 0	1.241	1.116 1
2.003 502 6	1.302	1.102 2
2.004 019 2	1.332	1.084 2
2.004 548 2	1.322	1.0653

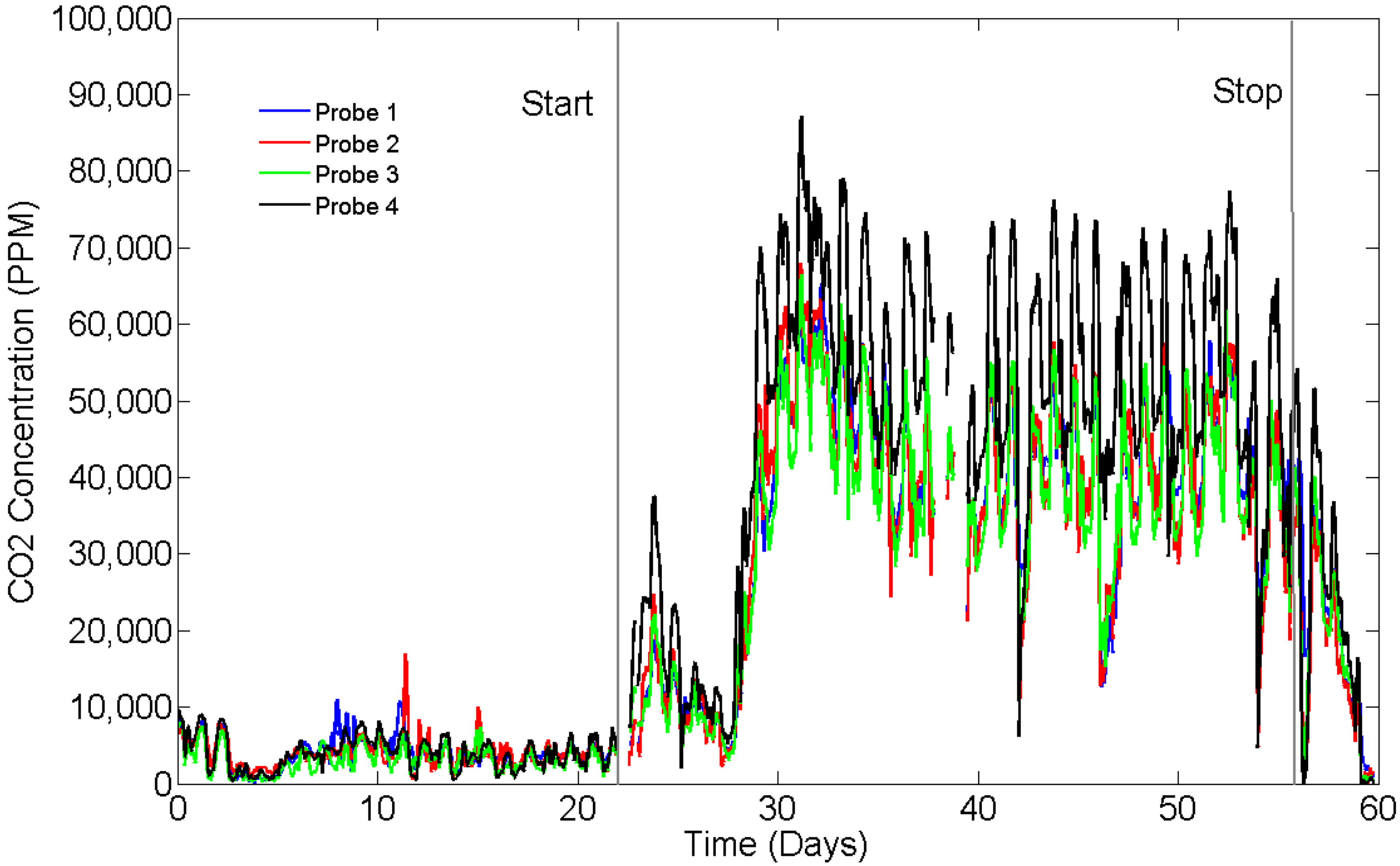




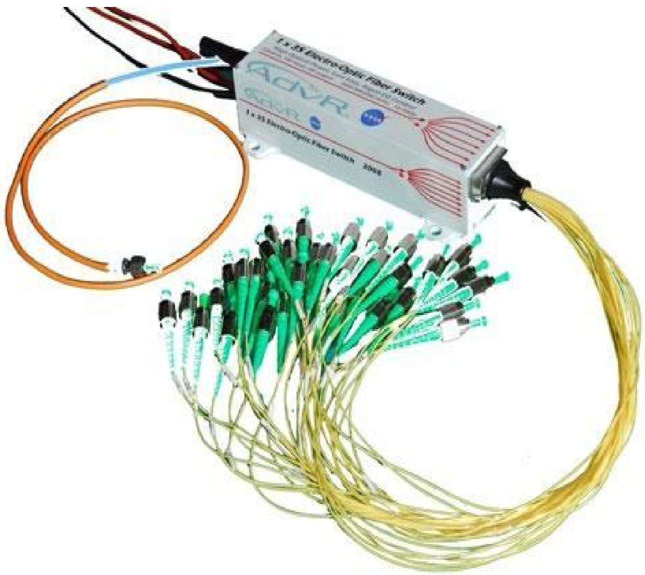
ZERT Field Data



ZERT Field Data



Scalability and Large Area Coverage



A commercial 1 x 100 fiber optic switch allows up to 100 probes to be deployed. Using standard telecommunications fiber, these 100 probes can be located up to 1 km away from the central electronics box.

Because the cost of the probes is kept low, scaling to 100 probes will not greatly increase the cost providing a cost effective sensor array.

Hyperspectral Imaging

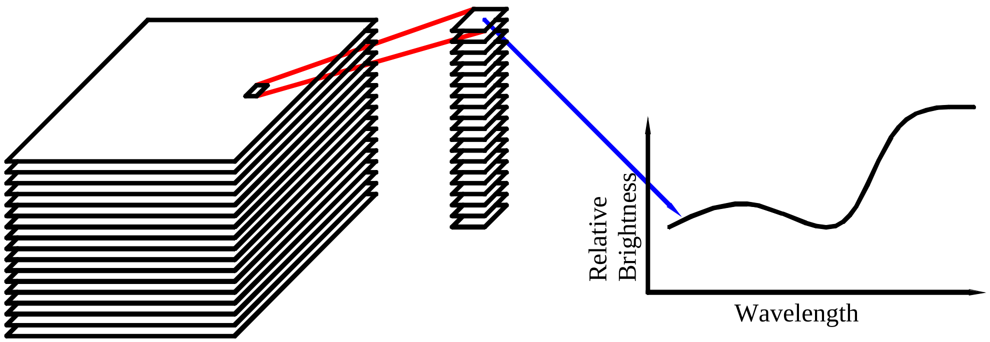
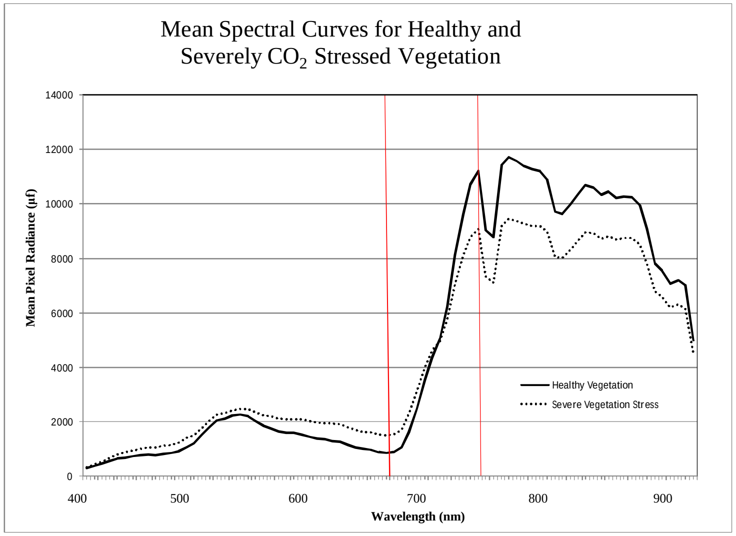


Image simultaneously acquired in many narrow adjacent wavelength bands

For each spatial pixel, a brightness value is defined for each wavelength band

For one spatial pixel, the brightness value for each wavelength band is plotted as a function of wavelength to create a reflectance spectrum

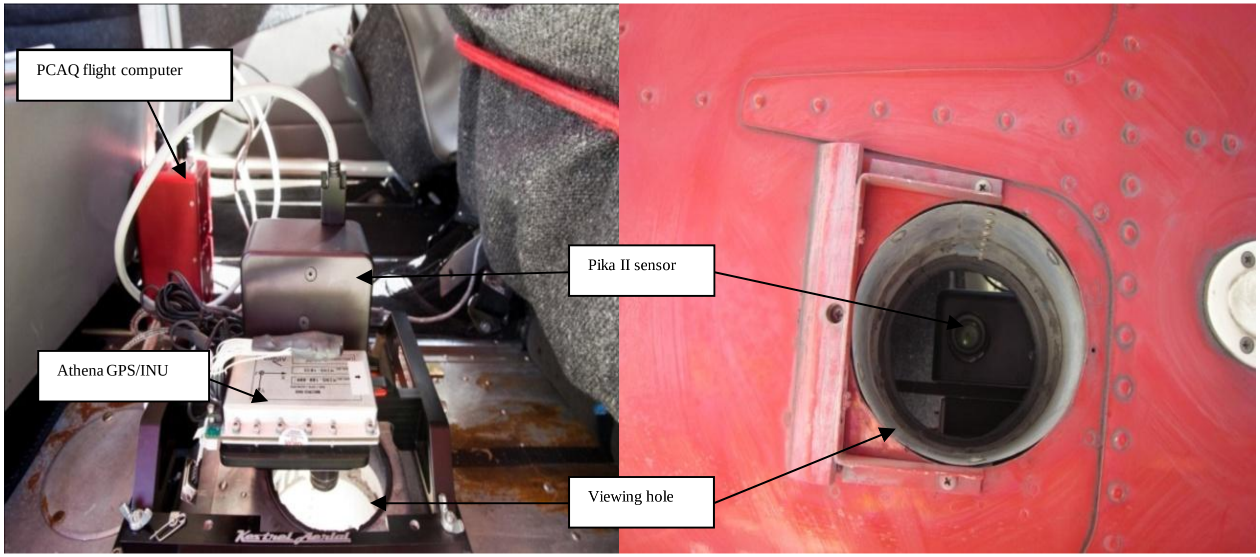


For each pixel in the image, a reflectance spectra – amount of light reflected as a function of wavelength -- is generated

Stressed vegetation can be detected be detected using subtle changes in the reflectance spectra resulting from plant physiology

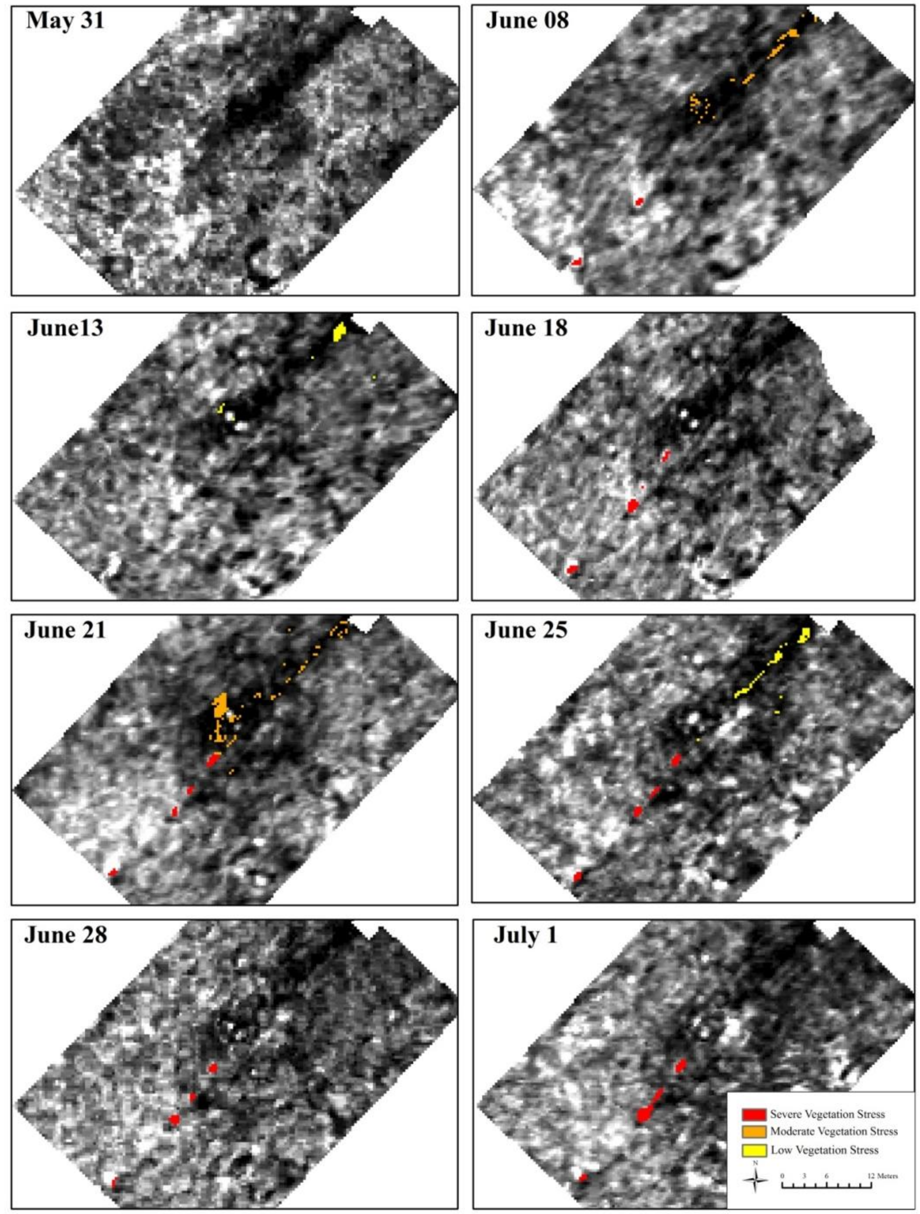
Hyperspectral Imaging

Flight based hyperspectral imaging allows large area monitoring needed for carbons sequestration sites



Hyperspectral Imaging

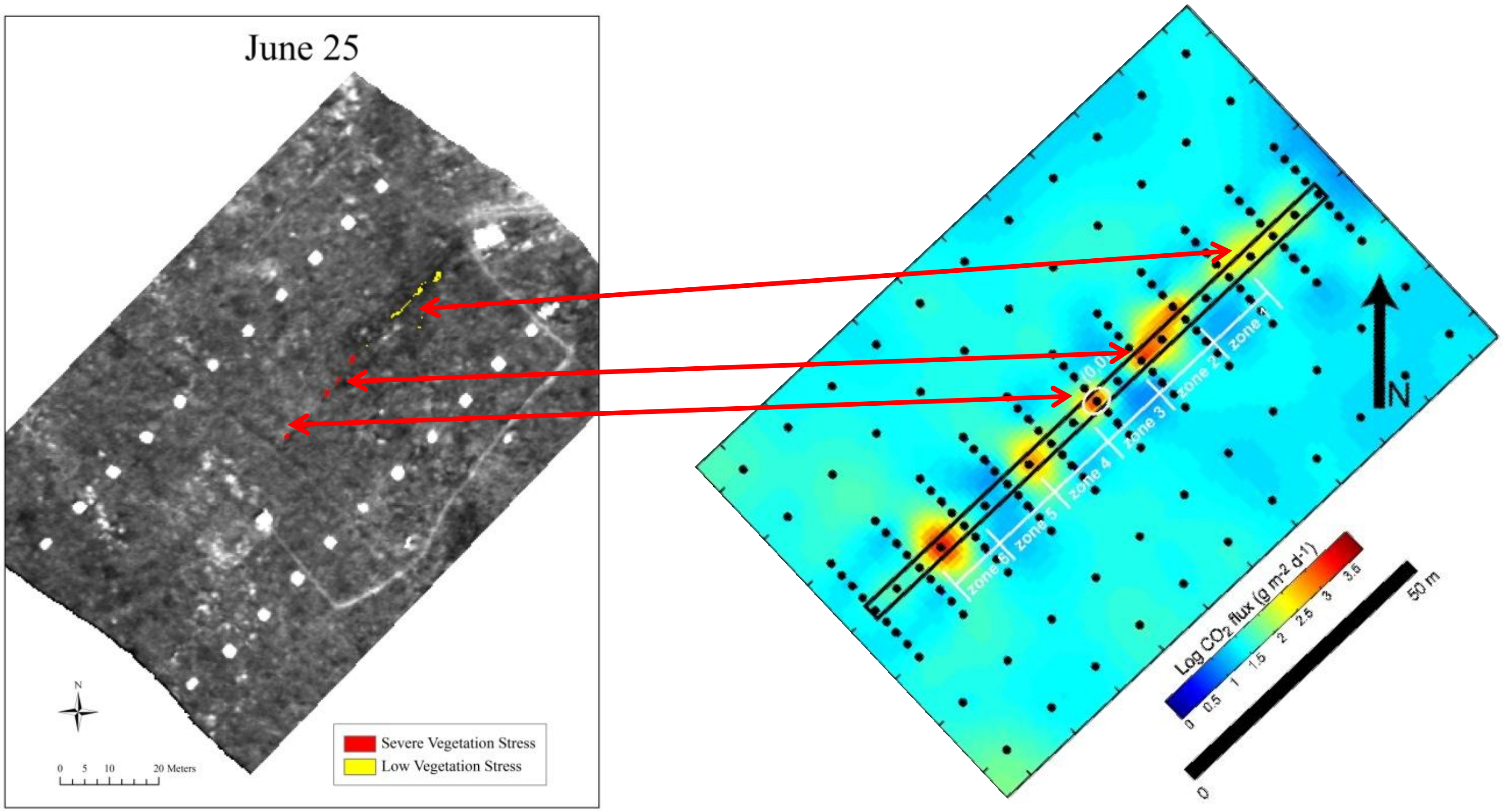
Aerial view of the ZERT field site



Evolution of the vegetation stress over the course of a month long sub-surface release at the ZERT field site.

Hyperspectral Imaging

The stress vegetation correlates with chamber measurements of carbon dioxide providing a validation of this method.



Note: CO_2 inject only in first three zones.

Concluding Remarks

- CCUS requires the development of many key pieces of technology including monitoring tools.
- A variety of monitoring tools and techniques will be required for the wide array of sequestration site environments.
- DIAL:
  - Provides large area coverage using a direct detection technique.
  - Work is ongoing to improve the signal to noise performance.
- Fiber Sensor Array:
  - Provides point measurements in a scalable and reconfigurable sensor array using a direct detection technique.
  - Working to commercialize through the DoE SBIR program.
  - Work is ongoing to incorporate FM spectroscopy measurements for isotope ratios of $C^{12}O_2$ and $C^{13}O_2$ for sourcing of the CO_2.
- Flight Based Hypserspectral Imaging:
  - Large area surveys using an indirect detection technique.
  - Utilizes commercial hyperspectral imaging systems.

Thanks Kindly for Your Time

- This work was supported by grants through the Department of Energy and the Montana Board of Research Commercialization Technology (MBRCT).
- Thanks to Lee Spangler and Laura Dobeck for their development and operation of the ZERT field site.