Low Cost Open-Path Instrument for Monitoring Atmospheric Carbon Dioxide at Sequestration Sites

Final Technical Report

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Abstract

In the past 48 months of the project, we have accomplished all objectives outlined in the proposal.

In the first year, we demonstrated the technology for remote sensing on a bench top scale. The core electronics are designed and fabricated. We achieved results that will safely deliver the specifications outlined in the proposal.

In the 2nd year, 2 major technical tasks outlined in the Statement of Objectives, i.e. Build a field test ready prototype of a long-range CO2 monitor, and characterize its performance in the short term and demonstrate that the monitor characteristics meet the goals set in the initial proposal, have been accomplished. We also conducted simulation work that defines the different deployment strategies for our sensors at sequestration sites.

In the 3rd year, Specifications and Testing protocols have been developed for the CO2 monitor. 1% accuracy had been demonstrated in short period tests (~1 hour). Unattended system operation and stability over a period of a week has been demonstrated with and without EDFA (laser power amplifier). The sensitivity of the instrument to CO2 leaks has been demonstrated.

In the 4th no-cost extension year, we further field tested the system and the experience we accumulated give us a clear picture of what else are needed for final field deployment.

These results have shown all the objectives of the project have been fulfilled. In July 2008, along with our commercial partner we won the DOE STTR phase I award to commercialize the instrument developed in this project --- a testimony to the achievement of this research.
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Objectives

After prove of concept work in Phase I, the final objectives of the project are:

- Build a field test ready prototype of a long-range CO2 monitor,
- Characterize its performance in the short term (weeks) and demonstrate that the monitor characteristics meet the goals set in the initial proposal.

Performed work

Electronics

- **Demodulation board**
Second version of the FM detection board was designed, manufactured and populated. The new design included capability to switch between two input channels with separate pre-amplifiers, additional amplifiers and band-pass filter, and a new version of the rectifier circuit. The board were tested and debugged in the laboratory by supplying a 10.7 MHz sine wave generated by a frequency synthesizer to its inputs.

Figure 1. PCB of the second version of demodulation circuit.
• **Driver and temperature controllers for a DFB laser**

The wavelength of a DFB laser needs to be stabilized in the vicinity of a chosen CO2 absorption line and repeatedly scanned across the line at a frequency around 100-1000 Hz. The scanning range should be about 0.8 cm\(^{-1}\), or 24 GHz. The laser wavelength depends on the injection current and laser temperature. Thus, it is necessary to stabilize and control these parameters in order to control laser wavelength. The current tuning coefficient is about 0.03~0.04 cm\(^{-1}\)/mA. The injection current control provides fast and fine tuning of the laser wavelength in a range of about 1 cm\(^{-1}\). This requires a laser driver (LD) that could follow external ramp modulation. The temperature selection permits slow tuning of the wavelength in a region of about 10 cm\(^{-1}\), and therefore, selection of CO2 lines. The temperature tuning coefficient is about 0.1 nm/ºC or 0.4 cm\(^{-1}\)/ºC. Once a CO2 line is selected the laser temperature should be stabilized over long period of time. This is usually realized through a Peltier cooler with precise temperature control (TEC). A Peltier cooler is already incorporated in the package of the commercial telecom diode laser.

A LD + TEC driver based on Wavelength Electronics WLD3343 laser diode driver chip and the HTC1500 TEC controller were built. The WLD3343 has a bandwidth of 2 M Hz, sufficient for 100s Hz modulation. The HTC1500 TEC controller could control a total of 9 W of heat/cooling power to the Peltier element inside the DFB laser.
Figure 2. Laser driver and temperature control circuit.

Figure 3. CW DFB laser in a Thorlab DFB laser mount.
• **Ramp generator**

The CO2 monitor contains a distributed feedback (DFB) diode laser as a source of radiation. The wavelength of the laser can be tuned by varying its temperature and injection current. Therefore, the wavelength stability is also determined by the stability of these two parameters. To insure the accuracy of absorption measurement in the long run it is necessary to stabilize the laser wavelength at the peak of an absorption line of CO2 or repeatedly scan the laser wavelength over the line contour. In the latter case, the long term drift of the center frequency of the scan will not adversely affect the measurement as the shift of the line position can be monitored and taken into account. The latter approach was chosen as it does not require development of sophisticated electronic circuits and permits to monitor the noise due to fluctuations of the atmospheric transmittance.

The laser driver (LD) and temperature control (TC) circuits that were built can adjust the injection current proportionally to the control voltage applied to one on the pins of the LD chips. A simple ramp generator was needed to scan the laser wavelength. A single chip solution was chosen provided the required functionality. A circuit was designed to provide the power for the chip and permit adjustment of the waveform parameters. Printed circuit boards (PCB) for this circuit were designed, manufactured, populated (see Fig.1) and tested. The circuit generates saw-tooth and square waves with adjustable amplitude and duty cycle. The saw-tooth wave is used to ramp the laser current; the square wave triggers the data acquisition board.
Optics

- **Retroreflector**
Because the launcher and detector are located at the same place it is necessary to direct the laser beam back to the instrument once it passes over the monitoring area. Corner cube prisms are commonly used to return laser beams to their launch point because they reflect the incoming beams back parallel to themselves independent of the initial direction. It is not necessary to align the prism; such a retroreflector can be placed at a remote location and left unattended for a long period of time. It will only be necessary to make sure that the incoming beam overlaps with the retroreflector. Thus, all alignment can be performed on the transceiver side.

The deviation of the reflected beam from the initial direction is proportional to the deviation of the prism corner angle from 90 degrees. Thus, for long-range operation (kilometers) high precision prisms need to be used.
Since the laser beam expands as it propagates over a long distance a large area retroreflector is required to accommodate the beam. Because the cost of large prisms is very high an array of small corner cubes is the most cost effective design of a large area retroreflector. The array design also allows one to change the size and cost of the retroreflectors depending on the deployment scenario.
The retroreflector that was built for the initial open-air experiments consists of 22 2.7”-diameter corner cube prisms. The prisms are glued into cylinder aluminum holders which are mounted on an aluminum sheet (see Figure 1). The current size of the array is approximately 14x15”. The array size can be easily varied by adding or removing the corner cube elements.

**Launcher**
In the laboratory setup the fiber output was collimated with a 5mm diameter lens into 3mm diameter beam. To minimize the power loss over long distance due to the diffraction divergence the infrared radiation is launched in a approximately 20 mm diameter beam. The collimator is lens diameter was chosen to be 25.4 mm (1 inch) to minimize the collimator footprint; an achromatic doublet lens was used to minimize to reduce the spherical aberration.
• **Collection optics and detector**
A commercial reflector telescope is used to collect the light reflected back by the retroreflector. It provides 10” collection optics at very low cost ($500). An amplified InGaAs photodiode was used to detect the near-infrared radiation. The detector was mounted in the eyepiece housing. The optical launcher is mounted in front of the collection telescope.
As the distance between the transceiver and retroreflector increases the laser power loss grows very fast due to the beam divergence. For operation over distances of about 1km and beyond it is necessary to increase the power of the laser source. In the initial plan of work it was suggested to us an erbium-doped fiber amplifier (EDFA) to amplify the diode laser power for long-range operation. EDFAs are mature technology commonly used in the semiconductor industry. During Year II of the project suitably of the EDFA technology for frequency modulation spectroscopy was evaluated. A telecom EDFA was purchased and tested in different configurations within our instrument. Although it was found that the instrument can perform well over distances as large as 1.4 km with an un-amplified diode laser further extension of the operating range with require additional laser power.
EDFAs are commonly used in telecom industry for long-distance transmission. The tested EDFA can amplify the output of the DFB diode laser up to 500mW (more than 20 times). Since the proof of concept demonstration of the FM technique and laboratory testing of the electronics were performed without an EDFA it was necessary to verify that the detection scheme works with an EDFA in-line. Tests of modulation and detection scheme with an in-line EDFA were preformed using the reference cell optical path. It was discovered that the EDFA gain changed as the frequency of the laser was tuned by ramping the injection current. Although the changes in gain were small, the power gradient was picked up by detection electronics because the frequency modulation technique measures the gradient of transmittance or, in this case, gain. The EDFA is being used in the instrument is a standard telecom grade amplifier that does not maintain the polarization of the laser radiation. The EDFA has single mode fiber inputs and outputs. Although the single mode fiber does not maintain polarization it does not scramble it. Furthermore, the direction of polarization depends of the laser wavelength and even strain in the fiber.

Laboratory tests showed that the gain of the EDFA is polarization dependent, that is it is different for different polarizations of the light. The radiation of a DFB diode laser is linearly polarized. The polarization does not become scrambled; however, its direction in the fiber is unstable. When the laser wavelength is tuned the distribution of the laser power between the orthogonal polarizations changes. Since the polarizations have different gains the overall output power of the EDFA fluctuates as a function of the wavelength.

There are two ways of solving the problem with polarization dependent gain: 1) to use a polarization maintaining EDFA and 2) to scramble the polarization.

Although polarization maintaining EDFAs are commercially available they are not commonly used and, therefore, not stocked by the manufactures. The expected delivery time for an EDFA is approximately 3 months. We chose to use a polarization scrambler
from General Photonics. A polarization scrambler randomly rotates the polarization of light at kilohertz frequencies. If the measurement time constant is much longer than $1/f$ then the effective EDFA gain will be the average of the gains of both polarizations. The scrambler was inserted in the fiber line between the diode laser and the EDFA. Comparison of the signals with scrambler on and off showed that polarization scrambling stabilized line contours.

However, the use of a polarization scrambler does not eliminate the EDFA gain dependence on laser wavelength. Although the EDFA gain varies by only a few percent when the laser wavelength is tuned the change of the gain is comparable to the absorption loss. Moreover, the period of the gain fluctuations is comparable to the width of the CO2 absorption features. The fluctuations of the gain could possibly be taken into account by demodulating the laser power after the EDFA; however, this would require modification of the demodulation electronics. Another way to circumvent the EDFA gain fluctuations is to perform frequency (phase) modulation after the EDFA. In this case, when the laser light passes through the EDFA it does not have sidebands, and therefore, a gradient in gain does not produce amplitude modulation of the laser power. This method was implemented by modulating the laser radiation after the EDFA with the EOM used in our earlier experiments. Since the EOM contains a birefringent crystal it rotates polarization of the incoming light. If the input polarization is not fixed the output laser power will fluctuate because the angle between the polarization of the light leaving the crystal and output polarizer will vary. A polarizer aligned collinearly to the EOM output polarizer was inserted after the EOM to make sure that the polarization of the light that enters the EOM is aligned along the crystal axis. This method allowed us to eliminate fluctuations in the baseline of the demodulated signal. However, when the EOM was used for modulation the noise level was at least an order of magnitude worse than the one obtained by modulating the laser current, a possible reason for that being mixing between orthogonal polarizations in the crystal. The use of the EDFA in this scheme does not significantly improve the sensitivity of the instrument. The polarizers introduce significant power loss and the power after the second polarizer cannot be higher than the original DFB laser power by more than a factor of ten. However, when the EOM is used
the two-tone signal is weaker due to lower modulation depth and the noise is higher leading to a similar signal-to-noise ratio.

As it will be described below a standard telecom un-amplified DFB laser provides sufficient power for achieving the necessary sensitivity over distances below 1.5km. The tests show that it is possible to use an EDFA followed by an EOM for frequency modulation spectroscopy. The use of an EDFA will permit to extend the operating range of open-path gas detectors by a factor of 2-3. However, these components will increase the price of the instrument (by about $10,000) and its power consumption.

**System integration**

To ensure operation under harsh environmental conditions the instrument is packaged in watertight plastic enclosures (NEMA 4). The optics and modulation/demodulation electronics are mounted in a 30”x24”x10” case. The electronic components of the instrument require different DC supply voltages, therefore, the instrument requires several DC power supplies ranging from -12V to +15V. The DC power supplies are housed in a separate enclosure (Figure 4). The power supply unit contains linear 5V, +/-12V and 15V and switching 5V power supplies.
Figure 9. Instrument enclosure.

Figure 10. Power supply enclosure.
Temperature stabilization

While being tested on the roof of PEER Center the CO2 monitor is exposed to direct sunlight. This leads the temperature of the instrument rise 15-25°C above the temperature of the air. In summer the air temperature in Southern California often rises above 40°C, therefore the temperature inside the instrument enclosure can rise up to 60°C causing failure of electronic components. During the initial tests of the instrument several IC of the diode laser driver repeatedly failed. To reduce the temperature gradient between the instrument enclosure and atmospheric air the former was covered by tape that reflects 95% of incoming infrared and visible radiation. The tape significantly lowered the temperature inside the instrument enclosure and prevented further electronics failures.

Two coolers were installed on the cover of the instrument. The coolers are controlled by a temperature controller (Omega) installed inside the main enclosure. The cooling units are powered by an additional 12 V power supply installed inside the power supply enclosure. As the temperature swings of the enclosure can be as large as 20-40°C especially if the instrument is exposed to direct sunlight the cooling units are unable to maintain the stable temperature inside the enclosure during 24 hour operation. However, the plastic walls of the enclosure have low heat conductivity, therefore, the heat released by electronics and active optical components of the instrument will be trapped inside raising the temperature inside the instrument far above the temperature of the enclosure walls. The temperature above 60°C can lead to instability and failure of semiconductor electronic components.

The purpose of the Peltier coolers is to conduct the heat generated by electronics and active optical components of the instrument outside and keep the temperature inside several degrees below the temperature of the enclosure.

Instrument Control and Data Acquisition Software

Custom software based on Microsoft .NET technology was developed to perform data acquisition. The software acquires the data from both photodetectors and demodulation board. It has the capability to switch the input channels on the demodulation board and shut down the diode driver. The software performs integration of the signals from the
open-air and reference channels, baseline subtraction, power normalization and log the ratio open-air-to-reference ratio.

Figure 11. Screenshot of the interface of custom designed data acquisition software.

**Field test**

- **Short-range field test**
  A short-range field test of the detection technique was the first quarterly milestone of Year II of the project. It was performed in the parking lot of PEER center in Covina, CA in December, 2005. The laboratory instrument was tested with the long distance launcher/receiver over a distances of about 100 meters. The laboratory instrument that included the external cavity diode laser, EOM driver, demodulation board, oscilloscope and the power supplies was assembled on a cart and transported outside the building where its was coupled with the launcher/detector.
During the test the retroreflector was placed at distance of approximately 100 meter from the launcher and telescope.

For this test we used an external cavity diode laser (Newfocus). A fiber coupled visible laser light is used for alignment of the launcher and telescope. The alignment procedure of the telescope was performed with a green (532nm) continuous wave alignment laser. The laser was coupled into a multimode optical fiber which was connected to the launcher. The launcher was collinearly aligned with the telescope. An aiming telescope also mounted on the main telescope tube was used to point the launcher and main telescope to the retroreflector. The further alignment was performed by optimizing the intensity of the returning light. We discovered that the reflected back light formed a relatively uniform beam approximately 25 cm in diameter centered at the launcher. The spot size was smaller the beam size at the retroreflector. This effect occurs because each prism reflects the light back into the launcher thus the returning beam size at the launcher
is determined by the size of the prisms and not the total size of the retroreflector. To improve the light collection efficiency the launcher was moved to the front of the telescope.

Modulation of the laser light and demodulation of the detected signal was performed by the electronic circuits built during Year One of this project. The electronics setup was similar to the one used in the laboratory. The output of the tunable diode laser passed through a fiber-coupled electro-optical modulator (EOM). The radiation from the fiber was than collimated by the launcher and director to the retroreflector. The returning light was focused by the telescope and an additional 3mm focal length lens onto the detector. Two-tone 2GHz+/−5MHz wave with the amplitude 1-2V generated by the EOM driver was applied to the modulator. The detector signal was fed to the demodulation board that detected the signal at 10MHz, the second harmonic of the lower tone. The frequency of the diode laser was scanned over 2 cm\(^{-1}\) region by ramping the voltage on the piezoelectric actuator. The figure demonstrates that even after averaging 16 scans (0.1 sec) the signal-to-noise ration is sufficient for detection of CO2 with 1 ppm accuracy.
• **Long-range test**
  It was preferable to perform the initial long range tests of our instrument in the vicinity of our lab. This would provide fast and easy access to laboratory tools and instruments. The other building of PEER center is also located in Covina, CA, approximately 1.4 miles south of the main building. A number of trees were blocking the line of sight between the roofs of the buildings. Tests with a green laser at night and with helium balloons during the day showed that in order to have a line of sight between the launcher and retroreflector, it was necessary to raise the retroreflector at least 28 feet above the roof of the second lab. We managed to build a stable Power-Strut support for the retroreflector array to raise it to the necessary height. The line of sight between the launcher and the retroreflector has been tested with a green laser. The reflection of the beam launched
from the roof of the main site from the retroreflector array 1.4km away can be easily spotted with a naked eye.

Figure 14. The optical path between the instrument and retroreflector.
Figure 15. Optical transceiver and electronics enclosures on the roof of PEER Center
Figure 16. Retroreflector array mounted on the roof the second building of PEER center.
Figure 17. The CO2 monitor after installation of the Peltier coolers and reflective tape.
Figure 18. CO2 concentration in Covina, CA, 4 min. average

The instrument was tested 24/7 since mid August, 2006. It was found that the mechanical stability of the launcher and collection telescope, and the configuration of the focusing optics were crucial for stability of the received signal. The first few weeks were spent on improving mechanical stability of the telescope and launcher mounts and debugging electronics. In first three weeks in September, 2006 data acquisition algorithms were tested and improved and preliminary data were collected.

Below is a brief summary of results of the long-range tests:

- **Stability of the optical alignment**: The signal remained at an acceptable level over periods of about a week after initial alignment. (On several nights a significant drop in the signal was observed between 12 midnight and 8 am. The signal level could be restored by slightly adjusting the direction of the launcher and telescope. The night
deviation of the transceiver from the daytime alignment is probably caused by the
deformation of the wooden roof supporting the instrument.

-**Signal-to-noise ratio:** At night or during non-windy days the noise level is lower than
2% in 1 min and lower than 1% in 2 min. During windy days the noise level can be as
high as 10% of the signal. Several factors most likely contribute to the higher noise level
during windy day: obstruction of the laser beam path by the branches of the tree adjacent
to it, fluctuations of the refractive index, vibration of the transceiver caused by the wind
and natural fluctuations of CO2 concentration during the day. We believe the obstruction
of the laser beam gives the largest contribution to the noise level during windy days and
the noise level in an obstruction free environment should be a factor of 2-4 lower.

-**Software stability:** In-house instrument control and data acquisition software has been
developed for data logging. The software is written in MS Visual Basic.NET and runs on
MS Windows platform. The program was stable over a period of longer than a week
without reboot or slowdown.

-**Sensitivity to small CO2 leaks:** A small CO2 leak was simulated by flowing pure CO2
at the pressure of about 20psi through a ¼ inch diameter tubing around the laser beam. It
was difficult to characterize the size of the CO2 plume and its density in the optical path
as the released CO2 was constantly removed by wind and gravity. It is reasonable to
assume the size of the CO2 cloud was not larger than 0.5 meter in diameter. Figure 19
shows the instrument response to CO2 release. The integration time was set to 15s which
corresponded to about 5% noise level. It can be seen that the instrument can easily detect
such a small leaks with a response time less than a minute.
Figure 19. Sensitivity of the instrument to small CO2 leaks.

- Calibration with a local sensor: The current prototype of CO2 monitor was designed for a wide range of operating distances. As the received signal amplitude by more than an order of magnitude in the range of distances 100m-2.5km the demodulation board has separate adjustable gain pre-amplifiers for the “open-air” and reference channels. In this configuration the instrument needs to be calibrated with an external sensor. However, the commercially available low-cost sensors measure only the local CO2 concentration. Use of a local CO2 reading for calibration of the long-range CO2 monitor may lead to an error in its absolute calibration if CO2 emission in the area is inhomogeneous. This seems to be the case in metropolitan Los Angeles where CO2 is emitted along the freeways and busy streets. Parallel data logging of the reading of the long-range CO2 monitor and a local CO2 sensor was performed to test applicability of a local sensor for instrument calibration. Figure 20 shows that in late evening and at night the CO2 concentration measured by the two sensors behaved similarly (declined in the evening and was flat at
night). During the day the readings of the sensor behaved differently. The long range sensor registered a significant increase in CO2 concentration with peaks at around 9am and 4pm (Fig. 20) while the CO2 concentration measured by the local sensor was almost flat. The observed discrepancy can be attributed to CO2 emissions from vehicles on the streets crossing the laser beam. The observed maximums of the CO2 concentration correlate with “traffic hours” in the area.

The tests showed that a local sensor can be used for absolute calibration of the CO2 monitor when it is certain that CO2 emissions in the area are homogeneous.

The instrument can be easily modified to perform calibration using the known concentration of CO2 (or other trace gas) in the reference cell. However, for the current application of our gas sensor (CO2 leak detection) the accuracy of absolute calibration is not critical.
Comparison with a local sensor

Figure 20. Comparison of readings of the long-range monitor and a local sensor.

1. New optical link

In September, we established a new optical link for testing our instrument. The retroreflector was mounted on an advertisement board at the distance of 462 meters from the roof of PEER laboratory (see figure 1). This link is much shorter than the link used in our initial demonstration (1.4km). However, to establish the link used in our initial demonstration it was necessary to mount the retroreflector 10 meters above the roof of our second building in order to keep it above the trees and get the line of sight. The posts that were used for that purpose collapsed under strong winds in spring 2007 because it was a temporary setup. The purpose of the initial link was to demonstrate the maximum operating range and power budget of the instrument. We decided to not invest limited time and money into building and maintaining extra long optical link in this phase of the project. Our current goals: software development, instrument optimization and long-term testing can be achieved with a relatively shorter optical link.
2. Data acquisition and analysis software

Data acquisition and analysis software is a crucial part of a long-term data logging system. A field instrument may experience a variety of adverse effects and conditions during its deployment. For example, power loss due to light-of-sight obstruction, laser diode failure or temperature drift. Robust software must be able to identify and try to compensate such effects or report if it is not possible. In addition, the data collection procedures must be optimized to maximize the signal-to-noise ratio and minimize the data acquisition time.

We implemented the following changes of the electronics and software:

- Changed the laser current ramp profile.

In the past, the laser current was always positive. The signal baseline was measured once per 100-200 ramps but disabling the laser driver. Thus, the absorption signal and
its baseline were not measured exactly at the same time. Besides, that method had an
overhead time of about 2 seconds, the time it took for the laser temperature to
stabilize after the laser was turned on again. Currently the laser current is being
ramped during a half the cycle and kept zero during the other half. This allows us to
record the signal baseline once per ramp, shortly (less than 1 ms) after we record the
signal.

-Tested the possibility to use direct absorption spectroscopy for long-optical path
CO2 detection.
Absorption by CO2 in the air becomes relatively strong >=1% when the path length
exceeds several hundred meters. In a laboratory setting direct absorption spectroscopy
can reach the sensitivity of $10^{-4}$-$10^{-5}$ fraction absorption units. This would correspond
to 0.1-1% (4 ppm) sensitivity in terms of CO2 concentration. Of course, the laser
power fluctuations caused by atmospheric scintillation will reduce the detection limit;
however, since the fast response time is not necessary for long-term monitoring
longer averaging could reduce the power fluctuation noise.

In our initial tests we turned off the modulation and demodulation boards. The laser
current, and therefore, the frequency were ramped at the frequency of 500Hz, a full
wavelength scan was complete in a half of a cycle, i.e. 1 ms. The software was
modified to fit the observed peak to a Lorentzian line contour (figure 2). The
fluctuation shows that we could achieve the specified 1% detectivity after further
refinements (figure 3). This gives us another low cost approach to use high power
laser sources, e.g. Erbium Doped Fiber Amplifier (EDFA), to boost the working
distances and signal to noise ratio of our monitor system.
Figure 16. The lower window shows the open-air absorption signal and its fit to a Lorentzian line contour.

Figure 17. Short term test result of CO2 sensor in direct absorption mode. Average time 30s. The noise level is below 1-2%.
Figure 18. CO2 concentration measured in Covina, CA. Results of a 2 day instrument test. The short term noise level is within 1-2%.

Figure 19. Received laser power fluctuations during a 2 day period.
We also performed a short term test (2 days) of the instrument detecting direct absorption of CO2. The results are shown in Fig.4 and 5. Although the received laser power fluctuated by a factor of ten the noise in the measured CO2 concentration stayed within 1-2%.

Longer tests of the instrument over a period of a week were over conducted. The results are shown in Figures 6 and 7. During these test the instrument was operated without any interference. The instrument performance was monitored via a LAN to the data acquisition computer.

A CO2 release test was also conducted. CO2 was repeatedly released in the vicinity of the transceiver from a high pressure CO2 cylinder through a 0.25 inch tube. The release time was approximately 10s. The response of the CO2 monitor in this test is shown in Figure 8.

![Graph showing CO2 concentration over 9 days in Covina, CA.](image)

**Figure 20.** CO2 concentration recorded over 9 day period in Covina, CA. The radiation of the diode laser was not amplified.
Figure 21. CO2 concentration recorded over 6 day period in Covina, CA. Erbium-doped fiber amplifier (EDFA) was used to amplify the laser power by approximately a factor of 3.
Figure 22. CO2 concentration recorded by the instrument during a CO2 release test. The averaging time during the test was 10s.

- **Long-term field test**

In the 4\textsuperscript{th} no-cost extension year, we conducted long term field test by leaving the system on top of our roof over a 12 month period, and the systems are tested from time to time to check the health of the system. The purpose is to use the extra long time to test the field survival capability of the system, exposing weak links that might cause roadblocks for field deployment.

During this time, we found that the box developed leaks at the screws which forms the hinge of the door on the box. The leaks are caused by the weak sealant that seals the screw and the tapped holes, and the sealant epoxy obviously cracked over long term exposure to strong solar radiation, humidity and temperature variations.
**Simulation work**

We carried out simulation of multi-terrain and proforma monitor layout of the sensors developed at Geological Site. The above results from the field test give more detailed and realistic simulation for the system that will be deployed for real field use. For details of this work, please refer to the simulation report. Below, we give a summary of our findings.

**Background CO2 affect minimal detectable leakage**

We expect the variation of CO2 concentration at sequestration site to be large, e.g. 20% increase from baseline CO2 concentration, based past close-vicinity CO2 measurement at different geological sites.

Above, Figure 2 and 4 copied from reference 1 gave the seasonal and diurnal variations of near-surface atmospheric CO2 concentration within a residential sector of the urban CO2 dome of Phoenix, AZ, USA.

![Figure 2](image1.png)

**Fig. 2.** Daily maximum and minimum values of 30-min averages of near-surface atmospheric CO2 concentration over the course of year 2000.

![Figure 4](image2.png)

**Fig. 4.** Mean diurnal courses of near-surface atmospheric CO2 concentration (2-month averages of 1-min data) for the coldest two months of the year (December–January) and the warmest 2 months of the year (July–August).

Then, simulation of CO2 leakage at sequestration site is presented, we now have a model of estimate the CO2 increase as a result of CO2 leakage at different levels. Then, the deployment strategies for different geographic scenarios with certain CO2 leakage detection limit are discussed as well based on their cost and the leakage detection level.

**Deployment strategy could improve the minimal detectable leakage**

We come up with a deployment strategy that improves the minimal detectable leakage.
This strategy asks for an increase in the number of probing directions to maintain the maximum distance between the adjacent light beam paths. In this way, the minimal detectable leakage could be maintained while the size of the sensor cell increases (see figure below).

Based on this strategy, could detect leakage at an annual rate of less than 0.1% with the cost under our proposed budget. This 0.1% leakage is sufficient for ensure CO2 sequestration. Simulation results also indicate that it will save us cost of deployment and enable us to get further information about CO2 leakage locations and volume if we could integrate the analysis of the sensor information with weather conditions, such as time of the day, wind and rain etc.
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