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Title: Low Cost Open-Path Instrument for Monitoring Surface Carbon Dioxide at Sequestration Sites

SHEETA Global Technology Corporation

Phase I SBIR Final Report

Sheeta Global Technology Corporation

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PROJECT SUMMARY

COMPANY NAME: SHEETA GLOBAL TECHNOLOGY CORPORATION
PROJECT TITLE: Low Cost Open-Path Instrument for Monitoring Surface Carbon Dioxide at Sequestration Sites
Topic number: DEVELOPMENT OF TECHNOLOGIES AND CAPABILITIES FOR COAL ENERGY RESOURCES
Subtopic Letter: b
PRINCIPLE INVESTIGATOR: Sheng Wu

Statement of the problem addressed

Large scale geological sequestration of CO2 requires a low cost sensor that could address the following challenges --- easy deployment over large area; low cost in terms of deployment and maintenance over large CO2 stream and reservior; must address the risk, safety, and economic considerations to the type of geological sequestration reservior.

General Statement of how the problem is being addressed

We propose that an open-path instrument can be designed and built that will have the required performance to measure the carbon dioxide concentrations near ground level over a tens of square kilometers of area or more, and cost under $40k. In phase I, we perfected the research prototype we built before in terms of both hardware for field deployment and also simulation software. We have worked out a joint field test plan with BEG of SECARB at their phase III carbon sequestration site. In phase II, we will first built and deploy a full field-ready networked sensor system in first 6 months, and then deploy at SECARB site for early background data collection before the start of their shallow injection. In the 2nd year, we will continue the data collection as SECARB already started their shallow injection, the data from our instrument before and after the injection will be analyzed jointly with SECARB's other monitoring instruments.

Commercial Applications and other benefits

The proposed sensor could also address other interesting gases, e.g. CH4 and N2O. The ability to cover long distances and networking feature will find applications, such as pipeline safety monitoring, dump site and other sequestration site green house gas monitoring and verification, and also many pollution monitoring applications over large metro areas.

Key Words

CO2 monitor, sequestration site, large area, surface and subsurface monitoring

Summary for Members of Congress

Public confidence in safety is a prerequisite to the success of carbon dioxide (CO2) capture and storage for any program that intends to mitigate greenhouse gas emissions. In that regard, this project addresses the security of CO2 containment by undertaking development of what is called "an open path device" to measure CO2 concentrations near the ground above a CO2 storage area.

FINAL REPORT

1. Identification and Significance of the Problem and Opportunity

Proposed Project Represents an Important Advancement for DOE Goals

Large scale deployment of geological carbon sequestration technologies requires monitoring and verification that carbon storage is efficient and environmentally acceptable in the long-term (decades or even centuries). This means the requirements to monitor such a project are quite daunting, both in the ***length of time*** and the ***wide area*** involved (Conway, 1994). Because the typical oilfield gas injection project typically has many wells spread out over many square kilometers, this suggests that a monitoring program to locate any significant leakage of the injected carbon dioxide at and surrounding a sequestration project would also encompass a very large surface area (Shuler, 2004; Tang Associate, 2002). Also, the instrument must have a minimum speed in updating the CO2 concentration measurement, this is because the dispersion of point leaks could be fast when there is wind, and in order to precisely locate the leaking source the speed of update has to be once several minutes for each direction (HTTP://WWW.ARL.NOAA.GOV/READY/PGCLASS.HTML).

Current technologies cannot address this huge area monitoring challenge cost-effectively. The immense area of a sequestration would make it not practical and too costly to rely on a whole network of individual detection carbon dioxide infra-red (IR) detection probes scattered about the site and then having to be networked together. While the cost of individual IR probes could be as cheap as a few hundred dollars, a thousand such probes per square kilometer would be required if each probe is to sample a 10 meter square and cost to collect the data from the network is even much higher. A more efficient technology for trace gas monitoring over large areas is long-open-path optical absorption spectroscopy. A laser is tuned to a certain wavelength that is subject to absorption by the gas of interest. The laser beam is sent out across many meters to a retro-reflector (a “mirror”) that sends the attenuated signal back to a sensor. Thus, a single laser instrument can monitor the CO2 concentration over area as large as several square kilometers. A much smaller number of these devices put together in a network technically could monitor the carbon dioxide concentration near the ground level of a large sequestration site successfully.

Our proposal is designed to address this carbon dioxide monitoring carbon dioxide challenge in a more cost-effective manner. We believe that an open-path instrument can be designed and built that will have the required performance to measure the carbon dioxide concentrations near ground level ***over a tens of square kilometers of area or more***, and cost under $40k. We propose to commercialize the technologies for open-path gas detection developed at California Institute of Technology with STTR support from DOE.

The proposed work meets the DOE specific solicitation objective of Subtopic 4b which is to promote the development of novel CO2 monitoring devices/sensors for detection of low levels of CO2 in the surface air. Other desirable attributes of our design are 1) device is easy and cost effective to deploy and maintain, and 2) device is safe to use (1.57μm is eye-safe and beam will be spread out in large areas in propagation), and 3) amenable to reliable, long-term, unattended operation.

The Probability of Technical and Economic Success

The proposed project is based on modification and integration of existing technologies to achieve the desired outcome, thereby increasing the probability of success versus a project that starts with a totally novel concept. More specifically, the new instrument is based on the same general proven concept of using lasers to perform open-path analysis of concentrations of different gases in air. By focusing on the single purpose of analyzing carbon dioxide concentration from 300 – 500 ppmv in the atmosphere the design and operation of the laser-based device becomes much simpler. Furthermore, we will use the already tested technology for long-range open-path gas developed at Caltech, which include the designs of electronic circuits and optical and mechanical components. Phase I of the proposed project will involve minor extensions of the Caltech tunable diode laser detection technology, a theoretical study of its performance at a sequestration site and cost analysis. Phase II, if approved, will involve construction of a commercial field deployable instrument.

The other inherent advantage in our proposed instrument design is that at this wavelength of 1.57 microns there are several low cost lasers and fiber optics components available from the telecom industry. These commercial off the shelf (COTS) components could give us great leverage in reducing the cost, improve the reliability and simplify the design.

2. Significant Benefits of Proposed Instrument versus Current Technology

The primary advantage of the proposed instrument is that it can cover a large area and does not require deployment of large power and data retrieval grids. There are several techniques for measuring CO_2 concentrations (see Appendix A for commercial companies offering CO_2 sensors). The most often used CO_2 sensor is based on Mid-IR absorption by CO_2 at 4.26μm. The absorption by CO_2 at this wavelength is the strongest, and therefore most sensitive for detecting CO_2. However, it is too strong to be used in long path detection as we propose to conduct here. Even with the brightest light source available today (e.g. Quantum Cascade lasers), we could only achieve the dynamic range of 1000ppm over ~1m path. 4 μm wavelength is only used in local CO_2 sensors. Although local CO_2 censors are available for as little as $1,000 a piece the cost of the large number of such sensors will be much larger than the cost of the proposed instrument. We aim to cover 10 km^2 area with a single long-open-path sensor. If we were to deploy a network of ***local sensors*** in a 3x3 km area spaced every 100x100 meter we would need 900 sensors at a cost of ***$900,000***. In addition, we would need to deploy a power grid and data network to power and log the sensors. And an engineer checking on the sensors would need to visit 900 sites, thus the maintenance cost of such a network of sensors would also be large.

There are also CO_2 sensors that uses wavelength at around 1.4μm to 2μm where absorption is 4 orders of magnitude weaker compared to 4.26μm. Because of the availability of diode lasers at these wavelengths, it is possible to measure CO_2 concentration with the desired dynamic range over a relatively long open path. For example, a system from Boreal Laser (GasFinderMC) with multi-channel (8 channels) capability is advertised to work over distances up to 1km and cost over $150k. Obviously, an instrument with such a high cost is not practical for large area deployment. Several factors are limiting the measurement length of this instrument. First, due to the limited diode laser power, measurement over distances larger than 1 km could be challenging. This is because of the relative high concentration of CO_2 in the air (~400 ppm). This could be mitigated easily with a high power diode laser or an amplifier as we proposed and demonstrated in phase I of this project. The second ***major obstacle*** besides power budget for optical loss is the hot air fluctuations during a sunny hot day, i.e. scintillation (SZAJOWSKI, 1998, Kim, 1997). Hot air pockets fluctuations create phase distortions in the beam and therefore cause interference noise in the signal received in the detector. Scintillation causes the signal received over long open paths to fluctuate easily over an order of magnitude. This is especially severe for lasers with narrow spectral bandwidth such as the single frequency diode lasers used in modulation spectroscopy. Fluctuations caused by scintillation could be happening on a time scale fast enough (as fast as several *ms*) that the stable measurement of the modulation side band beat signal is difficult. We have chosen to use large aperture launching and collection optics to minimize this problem.

There are two reasons we can achieve a major cost reduction versus commercial open-path instruments: 1) Existing instruments are designed to work at shorter distances (hundreds of meters). They use lower power laser diodes (power ~10mW) and small aperture optics. We propose and used the recently developed high-power (60 mW) diode lasers and large aperture transceivers to extend the operating range of the open-path gas sensor to several kilometers. If deployed in the center of the monitoring site, this could potentially monitor an area of $10km^2$ or larger. This is over 10 times increase in performance compared to the state of the art technology available now. 2) Existing instruments have a complex design in order to be multi-purpose instruments (measure concentration of several gases over a wide range of concentrations). We propose to design, construct, and test an instrument whose only purpose is to measure carbon dioxide concentration in air over the likely range of interest (300 – 500 ppmv). 3) Existing instruments use multiple laser and detector pairs to pointing at different directions. We propose to use single laser source (a diode laser) and single detector circuitry, and with built-in, commercial off-the shelf (COTS) switching and splitting fiber optics and high speed electronics to route the direction of laser probing beams, and signal channels. This approach simplifies the design requirements, while improves the reliability and reduces the cost greatly. This approach is possible due in part from recent advances in the fiber optical telecommunication technologies. A prototype of a low-cost open-path CO2 monitor built at our STTR subcontractor site (PEER, Caltech) demonstrated that large aperture optics allows one to extend the operating range of the open path instruments to 1.5 km (one way, or 3 km round trip). Using a high power diode laser will enable us to extend the operating range further by a factor of 2 or 3. The total bill of materials for the prototype of a one-directional CO2 monitor was $20,000. The proposed instrument will extend the capability of the prototype instrument to enable multi-directional monitoring. A fiber optic multiplexer and extra sets of transceivers and retroreflectors will add only $2,500 per channel to the price of the instrument. We have successfully demonstrated the operation of the fiber optic multiplexer and networking software that integrate multiple channels.

Development and Demonstration of Concept is Feasible

Again, per above discussion, the proposed project to create a new instrument is based on modification and integration of existing technologies to achieve the desired outcome. This approach increases the feasibility in completing the project with a finished working prototype instrument, and that this prototype device will have the expected performance characteristics.

The principles behind this project are:

1. Tunable laser FM modulation absorption spectroscopy, this is a well developed technology as we discussed in the technical section below.
2. Open path application of the above technique, this has been demonstrated over 1km path length by commercial instrument (see discussion below), and here we propose to boost the path length to over 3km, which means ***boosting the performance/price ratio up to 10 times.***
3. Our proposed techniques to extend the path length have been used and been demonstrate in free space optical communication where high speed data link has been established using laser beams.

3. Technical Objectives and Proposed Approaches

Objectives outline

Detection of trace gases in the long open path atmosphere by absorption spectroscopy could be a complicated task compared to small volume gas sample measurement in the laboratory. The difficulties include:

- It is difficult to perform measurements of absolute absorption as it is impossible to remove the target gas from the optical pass and measure zero-absorption signal.
- Concentration of interfering species cannot be controlled and can vary significantly.
- It is also impossible to control the temperature in the beam path, and variation in temperature affects the absolute concentration measurement.

Open-air long-path absorption spectroscopy (100 meter and longer) has additional challenges when compared to short-path gas sampling in the field, and these challenges are also the objectives of the proposed research instrument could solve:

- Fluctuations of the refractive index, due to hot air pockets, and atmospheric transmittance, due to rain and fog, lead to very large fluctuations of the amplitude of the received signal. In the long path length, the fluctuations are further enhanced. Power fluctuations by two orders magnitude on the millisecond time have been observed in free space optical telecommunications due to hot air pockets alone. Thus, conventional absorption spectroscopy used in the laboratory cannot be directly used at such long path lengths without taking care of these fluctuations.
- Atmospheric turbulence also leads to phase fluctuations of the laser beam banning the conventional phase-sensitive frequency modulation (FM) spectroscopy.
- High power laser source is needed as the power losses due to diffraction, scattering and mechanical instabilities grow.
- Finally, easy deployment is a must for the proposed instrument. Traditional FM spectroscopy using phase sensitive detection will require exact adjustment of phase depending on the working distances, and therefore is not suitable for this application.

The instrument that this project will develop will have to solve the following 4 major challenges in order to carry out reliable and accurate CO_2 monitoring over a long path length, e.g. up to 3km:

1. Immunity to power fluctuations and phase jitter in long open air path.
2. Relatively large field of view, so it is insensitive to opto-mechanical instabilities.
3. Interferences from other gases in the long-path open air.
4. Easy deployment, without complicated adjustment of phase parameters to the instrument during deployment and maintenance.

In section 4, we will give our proposed work plan that will make our instrument closer to commercialization. We will also present the results we achieved in phase I of this project. In section 5, we will discuss our previous results at our STTR subcontractor and provide evidences that these objectives are met.

4. Phase I Work and Results

Our STTR contractor has accomplished significant milestones in the prototype design and testing, and the results provide the foundation here for our proposal. However, there are still several issues need to be addressed in phase I of this STTR proposal that will make our proposed instrument closer to the real world, and enhance its potential in commercial success.

The first issue is to fully characterize the specifications of the prototype developed at PEER, Caltech. The specifications should be done by PEER group at Caltech with high power lasers as proposed below, and such data as *maximum working distance, measurement frequency and signal to noise ratio* will help us simulate the real cost of the instrument during field deployment. PEER group will also include the fiber optic switch in the system and verify the cellular network cellular capability of the prototype, this is one more step that push the instrument closer to the full deployment stage.

The second issue is to fully simulate the cost and deployment strategy by conducting CO2 leakage simulation at sequestration site. The work will be carried out by Sheeta Global Technology Corp. (SGTC), and lead by Steve L. Palm. With his expertise in fluidic mechanics, Steve will simulate how a CO2 leakage plume will develop under different diffusion models and then optimize the deployment strategy based on the latest specifications from the prototype at PEER group. The simulation results will confirm the ultimate goals of the project, and calculate the cost to achieve these goals.

Results from Phase I

At PEER Caltech, we have carried out the following tasks over the 9 months period for this proposal as subcontractor to Sheeta Global Technology Corp (SGTC).

Task I. Add fiber optical beam switch module to the CO_2 sensor system, demonstrate that the networked sensor system could function as proposed.

Subtask 1. We integrated the fiber optical switch into the system with commercial-off-the-shelf fiber optics.

Subtask 2. We reprogrammed our software to log the data of the additional channels.

Task II. Use high power diode laser to test the limit of the instrument's working range.

Subtask 1. We replaced our current low power diode laser (10mW) with a 40mW diode laser.

Subtask 2. We characterized the extended the range of the system, and also improved signal to noise ratio due to power increase.

The tasks above make the prototype system more mature for field deployment and provide data for SGTC to carry out their commercialization simulation work and plan.

Work accomplished by Sheeta Global Technology Corp. --- simulation of field deployment

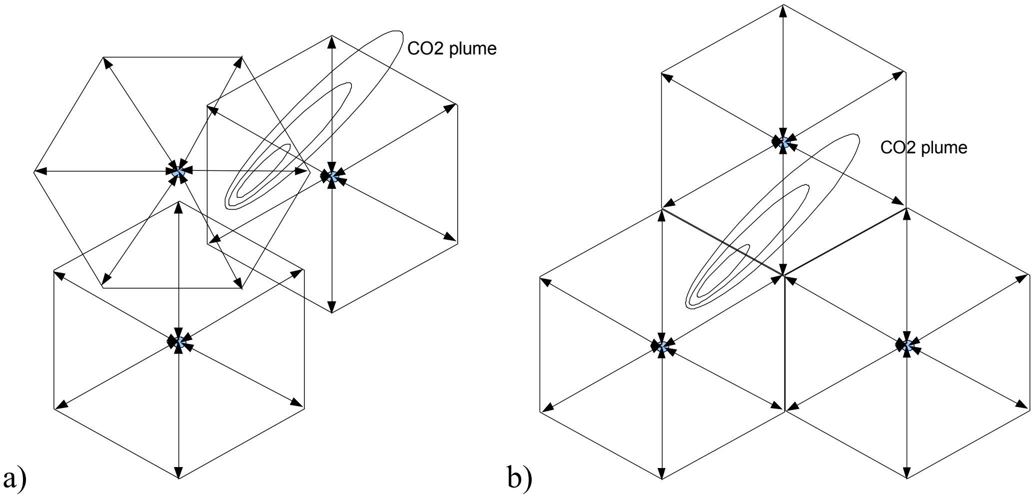


Figure 1. Sensitivity of long-range open-path monitors will depend on deployment scenario, i.e. the monitor density, number of directions etc.

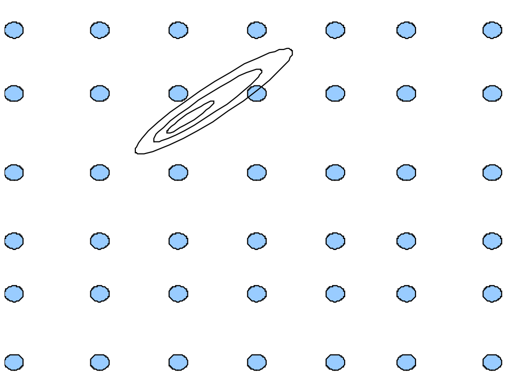


Figure 2. Network of local sensors. If a leak occurs between sensors by the time the plume reaches a sensor the concentration may drop below the background CO2 level.

Simulation of the long-range sensor sensitivity to CO2 leaks under different deployment scenarios

Diffusion of pollutants in the atmosphere is a rather complex phenomenon and the response of sensor networks to CO2 leaks can largely vary. The behavior of CO2 plume will depend on the wind direction and strength, vertical gradient of wind velocity and character of the terrain. Let us consider a simple model of gas plume, so-called, Gaussian slender plume model. According to this model, the concentration, *c*, in a plume propagating in the direction of the x-axis is expressed

$$c(r) = \frac{q}{2\pi u \sigma_y \sigma_z} \exp(-y^2 / 2\sigma_y) \exp(-z^2 / \sigma_z),$$

where q is the emission rate, u is the wind speed along the x-axis, and σ_y and σ_z are the dispersion parameters along y- and z- axes. It can be seen from this equation that the
local concentration of CO2 rapidly drops as the distance from the leak source increases. The density of the sensors has to be high enough to be able to detect an increase of CO2 level above the background.

We would like to emphasize that if long-open path detection is more sensitive to random leaks in the area being monitored. This follows from Beers law. The intensity of light, $I(\lambda)$, transmitted through a gas column of length l, follows the law:

$$I(\lambda) = I_0(\lambda) \exp(-c\sigma(\lambda)l),$$

where c is the gas concentration, λ is the wavelength of light, and $I_0(\lambda)$ is the intensity of the light source. Local CO2 sensors usually employ mid-IR absorption spectroscopy at 4 micron. The distance between the light source and detector in such a sensor is a few centimeters, which is much smaller than the dimensions of the plume. However, in the case of long-open path absorption spectroscopy $c\sigma(\lambda)l$ in the above equation should be replaced with an integral over the plume cross section $\int_l c(y)\sigma(\lambda)dy$. For example if the plume width, when it crossed the laser beam, is 10 meters, then for the long-range open path sensor the optical density will be at least two orders of magnitude larger than the one measured by the local sensor.

To estimate the performance characteristics of the proposed long-range open path sensor and compare it with performance of a network of local sensors we will perform numerical simulations of sensor response toCO2 leaks. We will model propagation of a typical CO2 plume on a CO2 sequestration site and calculate the absorption strength produced by it. The sensitivity to leak under different deployment scenarios will be evaluated by randomly choosing the location of leaks and wind direction.

Locating field test sites with potential regional partnerships

In phase I of the project, we already started discussion with local regional carbon sequestration partnerships. We first contacted with West Regional Carbon Sequestration partnership led by Dr. Larry Myer at Lawrence Berkeley National Lab, University of California. We agree to discuss the field test once their Phase III field injection test starts, possibly after 2010. Similar situation and schedule were discussed with Dr. Robert Finley of the Illinois Central regional partnership and Great Mountain regional partnership, they also agree to host our prototype instruments at their ongoing field trials, however the size of their injection are still in the small scale and no shallow injection is planned where a possible leak is a great concern.

Dr. Katherine Romanak from the Bureau of Economical Geology (BEG), Texas from the Southwest regional partnership (SECARB) also discussed our prototype and they have committed test sites for our prototype in their phase III field test. BEG scientists are planning a shallow injection at their Cranfield site in Natchez, Mississippi. The detailed proposal is given in the work plan for Phase II of the STTR project (see Phase II proposal).

5. Conclusions

We have successfully accomplished the proposed work in our phase I project, i.e. by adding fiber optical switch and high power diode laser systems, and characterizing the instrument performance over longer distances. We have also conducted simulation of the instrument based on the experimental results.

The test and simulation results support our proposed monitoring system, i.e. the performance of the instrument itself, operational and deployment costs are all within the proposed specifications.

We have also planned our phase II field test with our partner at BEG, Texas (see Phase II proposal).

The commercialization potentials for the instrument are also explored and proven to be positive; we have initiated marketing research in applications such as gas/oil pipe line safety monitoring, environmental monitoring at swine and dump site.

The reviewer for our phase II proposal also have positive reviews about our phase I research results, and the main objection came from the proposed phase II simulation injection at the proposed test site.

6. Recommendations

Although our proposed phase II research was not funded, the results from phase I provide us with a better understanding of the pros and cons of this low cost open-path instrument. We still consider the current market condition for such an instrument at sequestration site to be premature at the moment due to the unpredictable near term schedule for carbon sequestration. ***It therefore strongly recommended that we prepared to take the technology and products developed from this project for other market and research.*** Below we give a summary of the technologies we developed and hope this gives the project officers and public a better understanding that tax dollars have realized its major goal, i.e. to empower small business like us to grasp and be ready to apply the cutting edge technologies for the real world. Although the directly intended purpose for the products and technology developed here might not be applied for the short coming years, the contractors will be ready to apply them to other more practical and ready market.

Technologies Developed for open path FM spectroscopy

Electronics for open path FM spectroscopy

Frequency (or wavelength) modulation (FM) spectroscopy is a proven technique that allows to greatly improve the sensitivity of tunable diode laser spectrometers. FM spectrometers demonstrated the sensitivity of 10^{-7} fractional absorption units in the lab, and 10^{-5} in the field. FM spectroscopy involves modulation of the laser frequency at a radio frequency, Ω, with subsequent detection of the signal at harmonics of that frequency. In the laboratory, this can be performed by using general purpose frequency generators and lock-in amplifiers. Such commercial electronic instruments are large, heavy and expensive (thousands of dollars). Electronic circuits used in field sensor need to be compact and cheap to manufacture. Usually they are custom designed for each particular sensor. The STTR subcontractor of this proposal at Caltech has developed and tested compact and inexpensive electronic circuits for two-tone FM spectroscopy. It includes modulation and demodulation circuits, laser current driver and temperature controller (Figure 3 to 5).

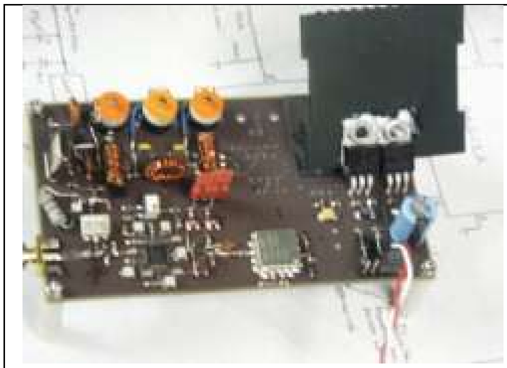


Figure 3. Two-tone modulation board.

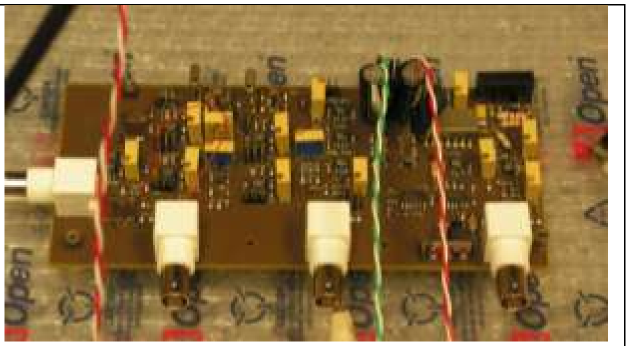


Figure 4. Demodulation board.

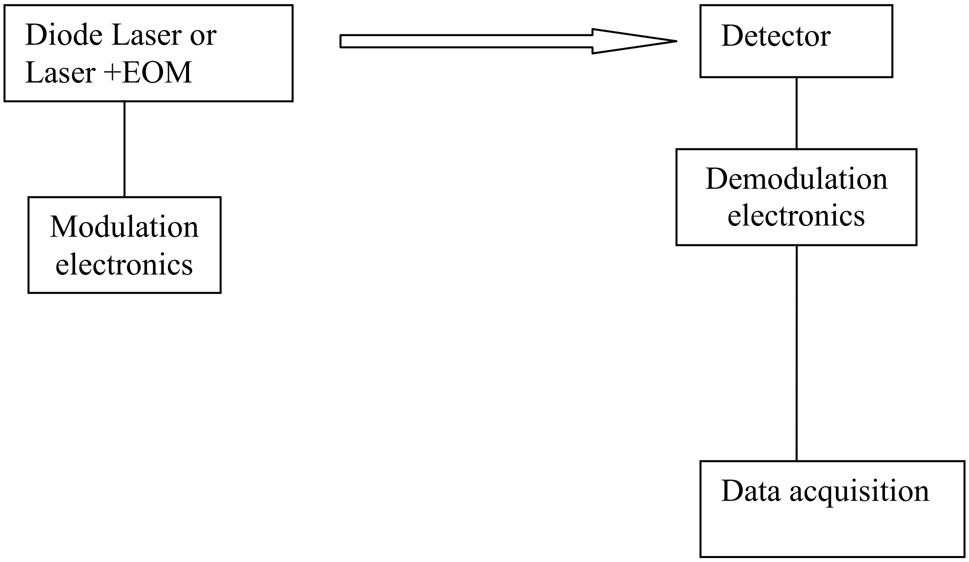


Figure 5. Block diagram of FM spectroscopy.

Optics

A laser beam always has non-zero divergence because of diffraction on the collimation optics which leads a growth of the beam diameter as a function of distance. In addition, fluctuations of the refractive index in the atmosphere ("hot" air flows) can deflect the beam from the original direction. Thus, instruments with longer optical paths require optics with larger apertures to improve collection efficiency and minimize the fluctuations of the received laser power. The Caltech team built a low-cost set of optics for optical gas monitoring in a single direction. The transceiver and retroreflector were assembled using low-cost commercial off-the-shelf components. In Phase I a couple of additional transceiver/retroreflector sets will be built using the same design to demonstrate multi-directional operation of the gas detector. In Phase II these components will be partially redesigned to make them more robust and increase their life time in the field.

Retroreflector

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 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.

Figure 6. Retroreflector array

Fig. 9 show the retroreflector array used in the Caltech instrument. The retroreflector that was built for the initial open-air experiments consists of 22 2.7”-diameter corner cube prisms. The current size of the array is approximately 14x15”. The array size can be easily varied by adding or removing the corner cube elements

Transceiver

To minimize the power loss over long distance due to the diffraction divergence the infrared radiation is collimated into an approximately 20-mm diameter beam. The collimator lens diameter is chosen be 25.4 mm (1 inch) to minimize the collimator footprint. A commercial reflector telescopes 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 is used to detect the near-infrared radiation. The detector is mounted in the eyepiece housing. The optical launcher is mounted in front of the collection telescope.

Figure 7. 8” Large aperture transceiver based on a commercial telescope.

Wavelength selection for detecting CO_2 over long paths

There are several techniques for measuring CO_2 concentrations (see Appendix A for commercial companies offering CO_2 sensors). The most often used CO_2 sensor is based on Mid-IR absorption by CO_2 at 4.26μm. The absorption by CO_2 at this wavelength is the strongest, and therefore most sensitive for detecting CO_2. However, it is too strong to be used in long path detection as we propose to conduct here. Even with the brightest light source available today (e.g. Quantum Cascade lasers), we could only achieve the dynamic range of 1000ppm over ~1m path.

Table 1. Relative absorption strength of CO2 at different IR wavelengthsTable 1.

Wavelength(µm)	Relative Absorption strength
1.432	1
1.570	3.7
2.004	243
2.779	6800
4.255	69000

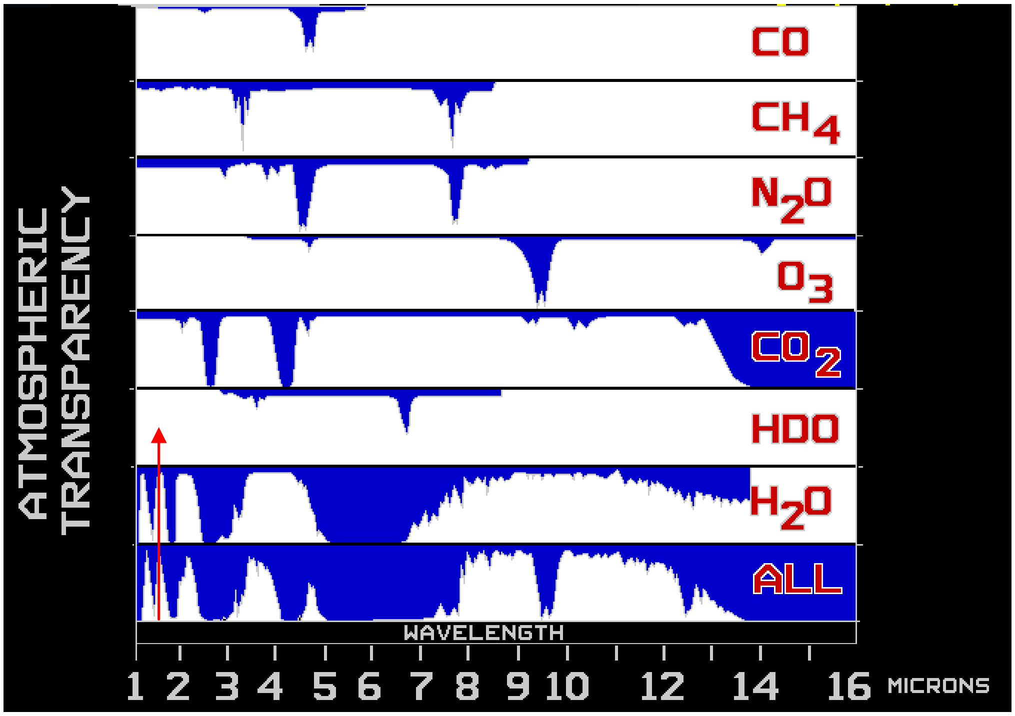


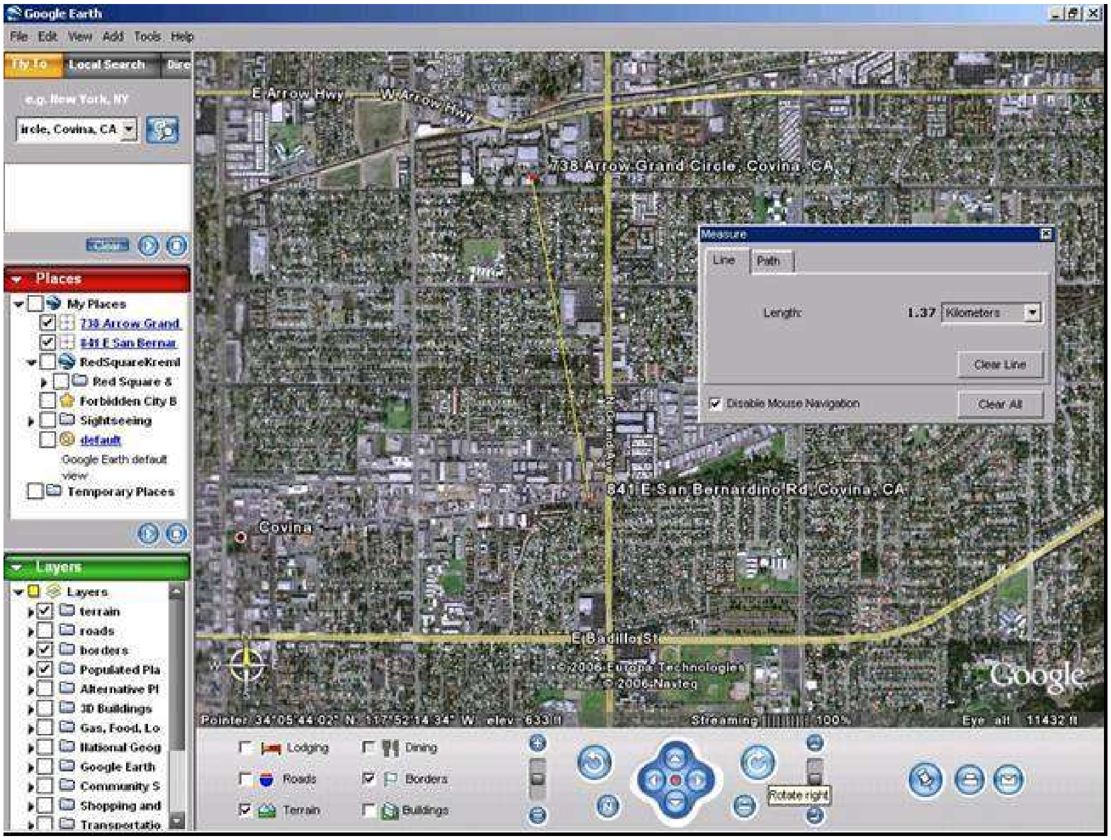
Figure 8. http://www.meto.umd.edu/~owen/CHPI/IMAGES/transir.html

Table 1 lists the relative absorption strength of CO_2 at different wavelengths in the IR. Also, from figure 6 showing the atmospheric transmission, we could see that the window at 1.57µm (indicated by red arrow) is also free of absorption from other atmospheric gases, this gives detection at 1.57µm high availability (e.g. less interference from H2O vapor). According to our discussion above, the absorption at 1.57μm is best suited for CO_2 detection because the weaker absorption, almost free of interference from other gases. Optics and detectors are commercial off the shelf for constructing multi-channel CO_2 monitoring systems

Because 1.57μm wavelength is located in the region used for the optical fiber communications (L-band, 1565nm to 1610nm), there are many commercial off the shelf (COTS) lasers, optics and detectors for this application. The lasers, optics and detectors not only deliver the power, and sensitivity needed by the experiment, they also have field-proven reliability, i.e. passing Bell Core standards. For example, IPG Photonics (www.ipgphotonic.com) could offer L-band EDFA with power well exceeding 1W; Oplink (www.oplink.com) could supply fiber 1xN(N=8, 4, 2) optic switches and 1x4 fiber optic splitters at this band; and there are also many other companies that could supply or build customized fiber optic modules with reliability passing Bell-core standards. All these COTS components give us great leverage in bringing down the cost, improving the reliability.

Preliminary field test results

The prototype built by Caltech was briefly tested on the roof of their laboratory in Covina, CA. The retroreflector was placed on the roof of another building 1.37 km away from the instrument.



Length: 1.37 Kilometers

☑ Disable Mouse Navigation

Pointer: 34°05'44.02" N 117°52'14.34" W elev 633 ft Streaming 100% Eye alt 11432 ft

Figure 9. The location of the initial field test of the instrument.

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 8 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.

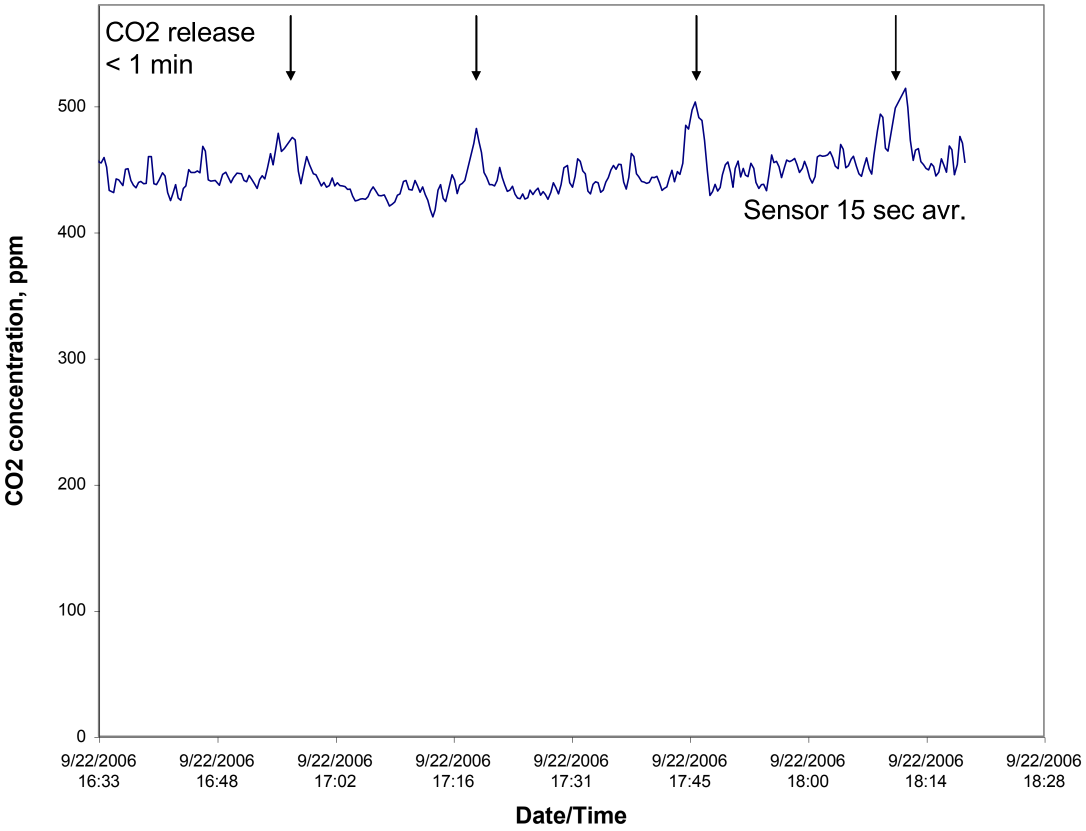


Figure 10. Sensitivity of the instrument to small CO2 leaks.

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8. APPENDIX A

Cost/Performance of Selected Fixed Point Commercial Carbon Dioxide Instruments

Source	Model Number/Description	Specifications	Approx. Price	Comments
Air Instruments Measurements	8800 Series Open-Path Ambient Air Analyzer			Available as dispersive IR, UV, or FTIR analyzer. IR is recommended.
Air Instruments Measurements	Model 7111 single gas analyzer	0 – 10000 ppm good to 1 ppm CO2		NDIR (non-dispersive IR)
Boreal Laser	Gas Finder	Path Length < 1 m to >1000 m good to 1 ppm CO2	$40K	Laser light/reflector Single channel unit
Boreal Laser	Gas FinderMC	Path Length < 1 m to >1000 m good to 1 ppm CO2	$150K	Laser light/reflector Up to 8 channels
W.E.Kuriger Associates	AirSense Model 310 Sensor	0 – 2000 ppm +/- 5% accuracy	$400 - $500	IR detection. Diffusion or duct sampling
W.E.Kuriger Associates	Model 301A-1 Carbon Dioxide Detector	0 – 2000 ppm +/- 5% accuracy	$400 - $500	Smaller size version of Model 310
MSA Instruments	Model 3600 Infrared Gas Monitor	Available ranges 0 to 0.2% CO_2 0 to 1.0% CO_2 0 to 5.0% CO_2	$1605 Note is $4065 for explosion proof	IR detection. Capable of remote sampling from 300 feet
MSA Instruments	Model 3630 Infrared Gas Monitor	Long term stability of +/5% 0 to 0.2% CO_2	$520	IR detection. Designed especially for indoor use. Capable of remote sampling/300 feet
RKI Instruments	Spectralert D/DR InfraRed Gas Detector	CO2 version: 0-2000, 5000, 10,000,50,000 ppm Accuracy +/-2% fsd on all ranges		Remote sensor option up to 50 meters Offshore stainless steel construction.
RKI Instruments	Beacon 800 Model	Carbon dioxide Range 0 – 1.0%	$1995	Permits from one to eight sensor transmitters. Beacon 800 can be wired to alarms, etc. Diffusion and sample draw heads available.
RKI Instruments	GD-K77D Series Sensor/Transmitter with Readout	Carbon dioxide Range 0 – 1.0	$1975	Electrochemical cell
Scott / Bacharach	4679-IR GasPlus Carbon Dioxide Gas Transmitter	0 – 2%, 0 – 5% Repeatability is +/- 2% below 40% full scale, otherwise +/- 5%	$1632	Dual wavelength detector, non-dispersive IR (NDIR)
Scott / Bachrach	CO_2 Continuous Monitor 2850	Available ranges 0 to 5.0% CO_2		Dual wavelength infrared carbon

				dioxide sensor
Sierra Monitor Corporation	Model 4102 Series Carbon Dioxide Sensor Modules	Accuracy of +/-5% of full scale 4102-80 0-2000 ppm 4102-85 0-5000 ppm 4102-86 0 – 20% 4102-89 0-2000 ppm	\$1100 - \$1500	Non-dispersive IR (NDIR) detection. Diffusion gas sampling. Models for wall mount and locating in ducts.
Topac Instruments	Guardian plus CO_2 Monitor	Carbon dioxide Ranges 0 – 3000ppm, 0 - 1%, 0 – 3%, 0 – 5 %, 0 – 10% Accuracy +/-2% of range	\$1700	Special non dispersive dual wavelength IR sensor. Remote sensing possible up to 90 feet waay.
Veris Industries, Inc.	CX Series CO_2 Sensors	Carbon dioxide Range 0 – 2000 ppm Accuracy +/- 20 ppm Range 0 – 5000 ppm Accuracy +/- 50 ppm	\$700 – \$850	Dual wavelength detector, non-dispersive IR (NDIR)
Li-Cor	LI-800	Carbon Dioxide 0 – 2000 ppm Accuracy +/-2%	\$2550	Dual wavelength detector, non-dispersive IR (NDIR)
Li-Cor	LI-62XX series	Accuracy to <1 ppmv	\$8360	NDIR type; used in aircraft
Li-Cor	LI-7500 Open Path	Accurate <1 ppmv	\$12,900	12 cm open path