Greenhouse gas Laser Imaging Tomography Experiment (GreenLITE)

Final Technical Report

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ABSTRACT

This report describes the development and testing of a novel system, the Greenhouse gas Laser Imaging Tomography Experiment (GreenLITE), for Monitoring, Reporting and Verification (MRV) of CO_2 at Geological Carbon Storage (GCS) sites. The system consists of a pair of laser based transceivers, a number of retroreflectors, and a set of cloud based data processing, storage and dissemination tools, which enable 2-D mapping of the CO_2 in near real time. A system was built, tested locally in New Haven, Indiana, and then deployed to the Zero Emissions Research and Technology (ZERT) facility in Bozeman, MT. Testing at ZERT demonstrated the ability of the GreenLITE system to identify and map small underground leaks, in the presence of other biological sources and with widely varying background concentrations. The system was then ruggedized and tested at the Harris test site in New Haven, IN, during winter time while exposed to temperatures as low as -15 °CºC. Additional testing was conducted using simulated concentration enhancements to validate the 2-D retrieval accuracy. This test resulted in a high confidence in the reconstruction ability to identify sources to tens of meters resolution in this configuration. Finally, the system was deployed for a period of approximately 6 months to an active industrial site, Illinois Basin – Decatur Project (IBDP), where >1M metric tons of CO_2 had been injected into an underground sandstone basin. The main objective of this final deployment was to demonstrate autonomous operation over a wide range of environmental conditions with very little human interaction, and to demonstrate the feasibility of the system for long term deployment in a GCS environment.

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EXECUTIVE SUMMARY*

The Greenhouse gas Laser Imaging Tomography Experiment (GreenLITE™) was proposed in response to DE-FOA-0000798 specifically to address the DOE need *"Projects selected under this FOA will develop MVA tools, technologies, and/or methodologies that improve our ability to ensure that at least 99 percent of the injected CO_2 is stored permanently. In particular, the tools, technologies, and methodologies described in applications to this FOA should possess at least one of the following attributes:….The ability to detect potential or actual CO_2 leakage pathways with a high degree of accuracy, including remote sensing and satellite based systems for directly detecting and measuring CO_2 leakage from the storage formation(s) and/or quantifying CO_2 leakage across the storage field..*

The concept for the GreenLITE approach was born from a decade worth of work developing and fielding airborne and ground based laser absorption spectrometers for high accuracy CO_2 measurements. Just prior to the release of this FOA, Exelis had been investigating the potential of a ground based system to provide sparsely sampled tomographic mapping of CO_2 for volcanic monitoring applications.

The GreenLITE system utilizes two Intensity Modulated Continuous Wave (IMCW) laser absorption spectrometer (LAS) transceivers [1], coupled with a number of retroreflectors in a way that generates multiple overlapping lines (chords) across the field of interest. The interwoven differential transmission measurements are then sent via a wireless connection to a cloud-based storage and retrieval system. The differential transmission and knowledge of the transceiver and reflector locations is used along with local meteorological data to retrieve the dry air mole fraction (XCO_2), and then combined to constrain a sparsely sampled tomography reconstruction in order to generate a 2-D map of the concentation over the field.

Under this program the Exelis and Atmospheric and Environmental Research (AER) team took the concept and developed it into a unique, viable, monitoring system for Geologic Carbon Storage (GCS) facilities. Starting in October 2013, the team developed requirements, built the hardware and software elements, performed component level testing and deployed the system to a local test site by June 2014. After completing initial testing, the system was deployed to the Zero Emissions Research and Technology (ZERT) facility for quantitative demonstration. The ZERT site is located in Bozeman, MT, and has established a 6 section, 70 m long, underground pipe, permitted to release up to 0.3 T/day of CO_2 at ~2.5 m below the surface. The site was developed to test near surface Monitoring Reporting and Verification (MRV) technologies. During the deployment to ZERT the GreenLITE system demonstrated the ability to identify persistent sources, showed correlation with an independent CO_2 monitoring instrument of >0.93 over several days, and demonstrated the overall functionality and flexibility of the system to address different monitoring scenarios. In addition, the ZERT campaign demonstrated the ability of the system to be transportable and rapidly setup for temporary study applications.

Finally, in February 2015, the GreenLITE system was deployed to the Illinois Basin – Decatur Project for ~6 months in order to demonstrate the ability of the system to run autonomously in an operational GCS environment, and over a wide range of environmental conditions in a semi-permanent configuration. During the 5+ months that the GreenLITE system was operational at the IBDP site, more than 2 million raw samples of chord optical depth were collected, more than 1.8 million column CO_2 concentrations were retrieved, and approximately 72,000 2-D reconstructions were generated. The system collected data for approximately 3,800 hours with an up-time duty cycle of greater than 95%. The GreenLITE system operated in a wide range of environmental conditions, with temperatures ranging from -20 to 33 °C and wind gusts to 27 m/s. During this time period only 4 on-site (approximately monthly) visits were made to the site to clean optics and check on the general status of the system. All other interaction, including minor adjustments to alignment and monitoring system health, was performed remotely. The frequency of onsite visits could have been reduced to bi-monthly, but as this was an experimental deployment we were establishing that requirement. This particular site did require cutting the weeds down both before deployment and once during the deployment as they had grown very tall and were blocking a few of the chords that were closer to the ground due to topography of the site. However, the algorithms proved robust and were able to continue generation of 2-D reconstructions in the cases where a few chords were lost due to weeds or other interferences.

Overall the GreenLITE system was very successful and the development deviated little from the proposed plan. All milestones were met, and despite delay on a couple of early milestones, all subsequent milestones were completed on or ahead of schedule. A peer review was conducted late in the development process, but provided very useful feedback. The latter section of the report reviews the responses to the Peer Review team, and demonstrates the utility of the system.

Background

IMCW Laser Absorption Spectroscopy

In 2004 ITT Exelis built an airborne demonstration unit for remotely measuring CO_2 concentrations in the atmosphere. The airborne demonstration unit, or Multifunctional Fiber-Laser LIDAR (MFLL), is a suite of IMCW LIDAR instruments using all fiber construction for the transmitter and receiver (Fig. 1). The instrument suite consists of

- Unique patented multi-frequency single-beam synchronous-detection LAS for measuring the column amount of CO_2 between the sensor and the target
- Pseudo-Random Noise (PRN) altimeter for obtaining the CO_2 measurement column length and target reflectance
- Additional channel for remote measurement of column integrated O_2

The LAS instrument transmitter in this system consists of

- Three Distributed Feedback (DFB) lasers controlled to ± 0.2 pm (these are the signal lasers)
- Semiconductor Optical Amplifier (SOA) for each of the signal lasers used to impart a unique analog modulation to each of the transmitted wavelengths
- Erbium Doped Fiber Amplifier (EDFA) which amplifies the combined signal laser waveform to an average power of 5W with a reference tap to monitor the outgoing power
- High quality fiber collimator.

All of the wavelengths are transmitted simultaneously out of the same fiber collimator and thus have 100% spatial and temporal overlap. This eliminates sensitivity to highly varying surface reflectance as well as minimizing effects of atmospheric turbulence by making it common mode. The transmitter is all fiber-based and has no free space optics; this results in a rugged design that does not have many of the alignment issues of more complicated transmitter systems.

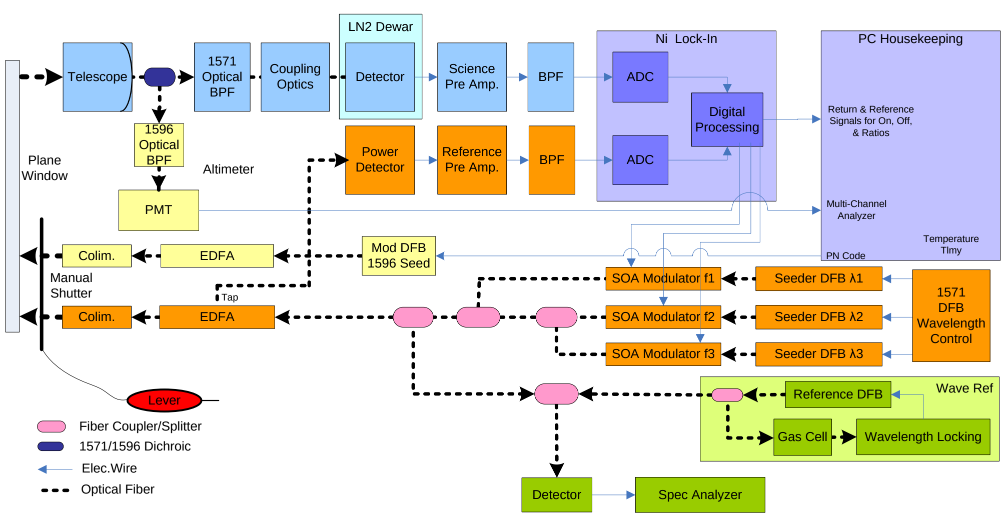


Figure 1 - Exelis' CO_2 LAS has been operationally validated via extensive ground and 13 aircraft campaigns.

The reflected light from the target is collected by the telescope and fiber coupled to a low excess noise 8×8 HgCdTe Avalanche Photodiode (APD) and Transimpedance Amplifier (TIA) to convert the optical signal to an analog voltage signal. A high resolution analog-to-digital converter is used to sample the analog waveform into a computer for processing. The fact that the optical and electrical path is common mode for all of the signal wavelengths leads to a significant reduction in sensitivity to instrument drift, and reduces noise from the atmosphere, target and sensor into a common mode term which is removed when the ratio of the signals is calculated.

A custom software-based lock-in amplifier then demodulates the signal by using the quadrature of the in-phase and out-of-phase components to yield the DC component of each of the three modulated signals. Once the reference signals and the signals that traveled from the aircraft to the target and back, have been separated, a ratio of the energy normalized signals is calculated to yield the differential transmission of the transmitted wavelengths.

By appropriately selecting the transmitted wavelengths at specific points of an absorption feature for a particular atmospheric species (e.g. CO_2 or O_2), the natural logarithm of the differential transmission is then related to the differential absorption, which is directly proportional to the column number density of the absorbing species. Other sources of atmospheric extinction are assumed to be equivalent given that the spacing of the transmitted wavelengths is very narrow (i.e. ~50 pm).

This LAS instrument was developed by Exelis in 2004 and has been extensively tested, matured, and thoroughly evaluated after thousands of hours of ground testing and >13 flight campaigns consisting of more than 75 aircraft sorties. The collection flexibility of the system is evident through the flight testing conducted over a variety of meteorological conditions, various land types, water, and during both days and nights. The instrument has been validated in conjunction with our partners at NASA Langley Air Research Center (LaRC), the University of New Hampshire and Atmospheric and Environmental Research, Inc. The instrument is housed in an aircraft rack that was designed to be compatible with the UC-12, P3 and DC-8 aircraft. Recent flights on the DC-8 aircraft have shown that the MFLL remote measurements compare with modeled results derived from onboard *in situ* measurements traceable to the World Meteorological Organization (WMO) on average to 0.67 ppmv with a standard deviation of 1.7 ppmv. [1]. To our knowledge, this accuracy and precision represents the highest quality remote airborne measurements of CO_2 reported to date.

Additionally, in 2011 Exelis developed a concept for using the IMCW approach in transmission. The concept was called the Laser Atmospheric Transmitter and Receiver-Network (LAnTeRN) [2]. The LAnTeRN system was designed to enable active measurements of CO_2 from a Geostationary orbit to receivers located on the ground. A prototype was built in 2011 to demonstrate this concept in a ground to ground configuration, in order to demonstrate the ability to separate the transmitter and receiver and make high quality measurements with very low signal power.

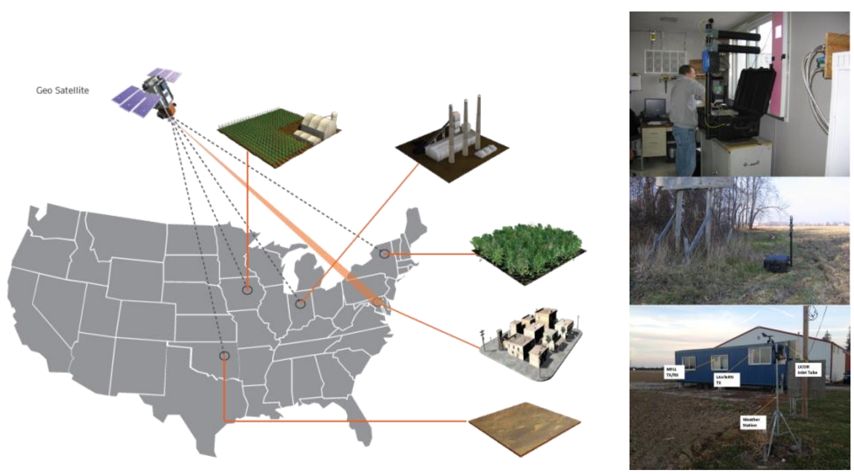


Figure 2. LAnTeRN concept shown on left with the ground-based demonstration unit shown on the right, at the Exelis Farm test site in New Haven, IN.

Overview of the GreenLITE System

The GreenLITE system leveraged the best of the MFLL and LAnTeRN systems with the goal of developing an autonomous, robust system for long term monitoring applications, such as detecting potential leaks at a GCS site. The GreenLITE system consists of two transceivers and a series of retroreflectors, in order to measure a number of overlapping CO_2 density lines, and enable an estimate of the 2-D spatial distribution.

Figure 3: GreenLITE transceiver hardware at Exelis Farm test site in New Haven. IN.

The transceivers consist of two main sections: a "hot box" and the optics head. The hotbox houses the electronics, lasers, modulators, computers and communications equipment; is water tight; and maintains everything at an ambient temperature of 38 °C. The optics head, which houses the transmit/receive optics and a camera, is also sealed and heated.

The optics head is attached to a mechanical scanner which points the transceiver at the specified retroreflector based on a map programmed at setup. The scanner is capable of being reprogrammed remotely. The optics head and the hotbox are connected by a watertight hose containing the electrical cables and optical fibers. An additional component is the calibration target which allows the system to take a zero path measurement, where the ratio of the channels should be one, in order to allow monitoring of the instrument stability over time.

The system is designed for continuous remote operation. A list of the key system parameters is included in Table 1.

An additional key component of GreenLITE, in terms of performance enhancements, is the real time web-based processing and user interface. These web-based tools allow remote autonomous deployment of the system and handle all data storage, processing and dissemination of the data to the user. The user can explore the 2-D reconstruction and individual chord data in real time, or scroll through a select period of time. Additionally, users can get information on the raw data and the instrument performance and health, either in real time or at selected times in the past.

Table 1: Key system parameters of GreenLITE system.

Online Wavelength	1571.1129 nm
Offline Wavelength	1571.0629 nm
Optical Transmit Power	5 mW (2.5 mW per ch.)
Modulation Rate	19.2 – 24.6 kHz
Modulation Waveform	sinusoidal
Sampling Rate	1.0 MHz
Sampling Resolution	16 bits
Transmitter Optics	25 mm
Receiver Optics	25 mm
Optics Configuration	biaxial, fiber-coupled
Detector	InGaAs PIN
TIA Gain	10^5 or 10^6 (programmed)
Retroreflectors	50 mm
Lockin Period	10 sec (adjustable)
Power	110 V, 60 Hz, 3 A

Development Philosophy

The overall goal for the GreenLITE development was to leverage the best aspects of Exelis' MFLL and LAnTeRN approaches, along with expertise in spectroscopic algorithms developed for this and other programs, in order to generate a cost effective, high accuracy measurement for a set of horizontal chords (transceiver to reflector and back) of the dry air mixing ratio XCO_2, and then to use these high quality density measurements in a sparsely sampled tomographic reconstruction process to estimate the 2-D spatial distribution.

The development philosophy for the hardware used to achieve this goal was:

- Develop a set of requirements for the system
- Establish Preliminary Design
- Flow requirements down to component level
- Specify commercial hardware able to meet developed requirements
- Identify parts for components not available and build
- Verify performance at component level
- Assemble
- Verify at transceiver level
- Verify requirements are met at full system level

The development philosophy for the software used to achieve this goal was

- Develop system requirements
- Establish platform and development tools
- Define interface between hardware, software and the user
- Flow those requirements to the instrument and database development
- Test software by component
- Test software integrated but local
- Test overall system software in cloud using virtual machines.

The philosophy was a fairly standard systems engineering approach where we began with a requirement to achieve a signal to noise ratio (SNR) of >1000 for a 1 km path length (chord), resulting in a precision of ≤2.5 ppm, for a standard atmosphere.

The Statement Of Project Objectives (SOPO) breaks this approach down in more specific detail, and the Budget Period 1 Interim Report details the work against each of the tasks leading up to final deployment of the system at the Illinois Basin - Decatur Project. The following sections provide a top level overview of the different design aspects of the project, followed by more specific results from testing the system, and then summarizing the accomplishments of the project in the conclusions section.

Experimental Methods:

GreenLITE System Development

Requirements Definition

The primary requirement was to be able to identify leaks in a GCS site in near-real-time at the levels required for 99% containment over 100 years. Some practical considerations were also considered up front in terms of desired operational environment, autonomous operation, schedule and budget. The requirements were broken down into environmental, power, performance for transmitter and receiver, and other ancillary considerations. From these a set of top level requirements were derived as follows:

Environmental

> 15 to 95 °F (-10 to 35 °C) ambient
> Day or Night operation
> Limited operation in light rain

- Survive heavy rain/snow (cleaning off may be required)
- Operation 3 m from surface (TBR – site specific)
- RH 10 - 80% non condensing
- Lifetime 6 months

Power

- Power – line 115 V 60 Hz
- UPS for >30 min

Performance

- Eye-safe at transmitter
- SNR >1000 for 10 s integration at 1 km range
- Some form of self-calibration
- Onboard processing to 0.25 s I and Q data
- Timing – computers synched over network

Transmitter

- Online – 1571.1120 nm, 2.5 mW
- Offline – 1571.070 nm (selectable), 2.5 mW
- Modulation – semiconductor optical amplifier (SOA), sinusoidal near 20 kHz
- DFB lasers (temp/current controlled)
- D/A – 16 bit, 1 MHz
- Electrical filter single pole
- Reference tap
- Beam divergence 1.6 mrad
  - ~5.25 feet at 1 km
  - Drivers: Scanner resolution, SNR, transmit power, other scatter sources

Receiver

- Eye-safe
- Step scanning 1 – 10 sec dwell time (co-located with receiver)
- Fixed TX/RX alignment
- Mounting platform
- Telescope – 1" Reflective
- FOV – 3.6 mrad full angle
- ~11 feet at 1 km
  - Drivers: Scanner, SNR, Filter properties, fiber coupled, fiber core
  - Optical BPF 2.4 nm Barr filters (TBR)
- TIA – Femto, digital gain selection
- Electrical HPF single pole
- A/D – 16 bit, 1 MHz
- Processor
- Communications (WiFi, 4G)
- Step scanning 1 – 10 sec dwell time

Ancillary

- Weather Station
  - Temp
  - Pressure
  - Wind – speed and direction
  - RH
- Web cam - streaming video, or images Shelter is required

> Mounting hardware to be determined by site- requires flexibility for experimental versus long term setup
> Remote restart
> Ability to remote desktop in to system.

From these requirements we began identifying commercial hardware for the system and identifying what items would need to be built custom. The next step, after acquiring hardware components and building the custom components, was testing of the critical components to ensure they met specification. All components were then integrated into the transceivers and testing at that level was completed. Finally, testing at the system level could be carried out.

Instrument Hardware Development & Test

Goals

The goal of the GreenLITE instrument hardware development was to leverage heritage from MFLL and LAnTeRN to generate a robust autonomous IMCW LAS transceiver. Additional constraints considered for this project included 1) create an optical design allowing for operation over the required area of interest, 2) provide means for protecting susceptible components from exposure to temperature and humidity extremes, 3) modularize the construction to ease the servicing of components and subsystems, and 4) provide some protection against short-term power failures while also insuring that the system could recover from long-term outages.

Objectives

The GreenLITE instrument hardware development objectives were selected to insure that the system would meet the performance, reliability, and durability requirements of the testing and deployment plans. The first objective was to develop an optical design capable of collecting adequate signal power at the design range of 1.2 km. Another objective was to identify a scanner with sufficient accuracy and resolution to allow accurate pointing of the optics at the retroreflectors. The next objective was to provide a stable thermal environment for delicate components such as lasers, optics and electronics. This environment would also need to protect the components from precipitation and high levels of humidity. The last objective of the hardware development was to separate the components into modular chassis with minimal external connections to simplify the process of removing components for service, repair, or upgrade.

Approach

The early stages of the hardware development effort focused on identifying appropriate optical components for the reflectors, the optics head window, and the transmitter/receiver optics. Several sizes and styles of retroreflectors of varying quality were tested to identify one capable of returning enough optical power to the receiver. Ultimately, a 50 mm hollow corner-cube retroreflector with 5 arcsec accuracy was selected. Several candidate optical windows were tested in front of the transmitter/receiver optics, and it was determined that a very high-quality optical grade wedged window with antireflection coating was required to prevent a degradation of the measurement. The window was specified with a 1.5 degree wedge, $\lambda/20$ surface quality and $<0.1\%$ reflectance for the anti-reflection coating, and was custom made by OptoSigma. Transmitter/receiver optical component testing first focused on inexpensive refractive optics, but it was determined that reflective optics were required to minimize distortion of the optical beam and allow for a high-quality measurement. The optical system as a whole was designed to allow for operation at path lengths up to 1.25 km, which is significantly more than was required at the IBDP site.

Several electronic and optical components were tested in a laboratory environment to determine their susceptibility to temperature variations. This was needed to aid in selecting temperature control requirements for the system. An insulated enclosure was modified to allow thermal control to within about 1° C over an ambient range of -18° C to 35° C.

Components were segregated roughly by transmitter and receiver functionality and packaged in two separate rack-mountable chassis, one for the transmitter components and the other for the receiver components. This packaging method allows for independent removal of each subsystem. A commercial uninterruptible power supply (UPS) was installed to provide protection against short-term power outages while also providing some ability to cycle power to components that might require occasional resetting.

A block diagram of the GreenLITE transceiver is shown below.

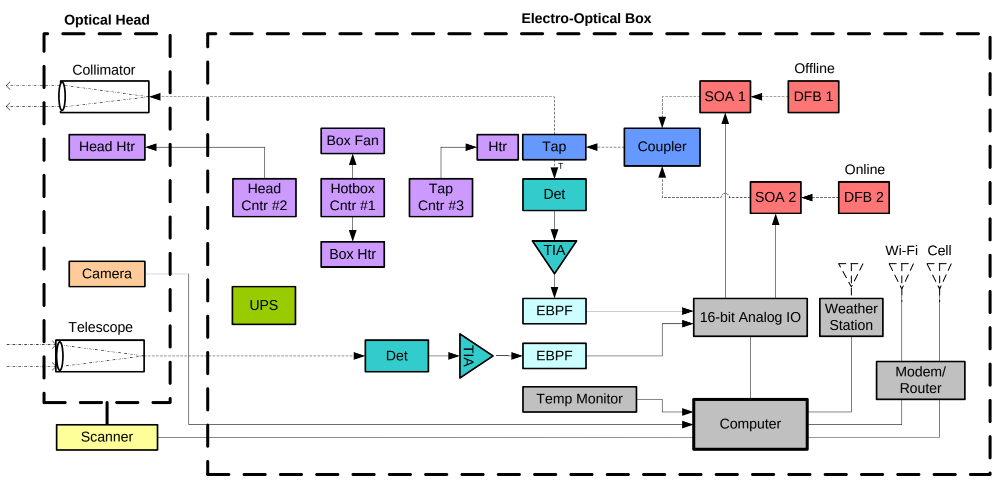


Figure 4. Functional block diagram of the GreenLITE system.

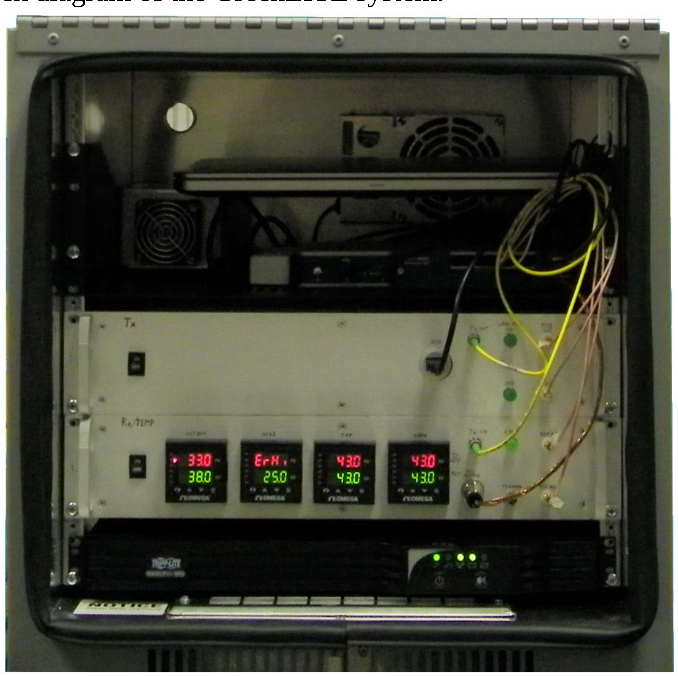


Figure 5. GreenLITE transceiver "hot box”.. Top shelf houses computer, DAC box, power distribution, and hubs. TX box houses lasers and modulators. RX box houses thermal control and detector chain for reference and science. Bottom shelf is the UPS.

The hot box was then connected to the optical head via flexible tubing that contained fiber optics and electrical connections. An additional cable between the hot box and the scanner was also required. The last parts added to the transceiver were the antenna for WiFi and 3G/4G connections. The WiFi enabled logging into the system from a local laptop, while the 4G connection was used to transmit the data to the database and to allow remote log in to the system when not onsite.

A photograph of a finished transceiver as deployed to IBDP is shown below in Figure 6.

Figure 6. Fully assembled transceiver with semi-permanent installation at the IBDP site.

Results and Discussions

The GreenLITE hardware design proved to be quite robust and reliable through multiple extended tests and deployments under a variety of conditions. In particular, the optical design was very stable and maintained alignment throughout the duration of the program, including a lot of handling during moves and shipments. The system was designed with enough margin that degradation of the retroreflector surfaces resulting in reduced return power did not result in the inability to make the measurement to the required accuracy after nearly 10 months of field deployments.

The mechanical scanner did exhibit some issues with long-term repeatability and had to be occasionally adjusted to maintain accurate pointing at the retroreflectors. All adjustments were able to be carried out remotely. This problem may have been exacerbated by the mounting structure used at IBPD, which was not built by the outside contractor as it was designed. Any movement of the platform due to ground shifting or swelling would result in a change in scanner alignment. For a permanent installation, care must be taken to insure a stable mounting solution for the scanner and optical head.

The thermal enclosure was able to maintain the proper operating environment in all but the coldest weather, when high winds were found to be forcing cold air through the vents in the enclosure. A modification to the enclosure, restricting direct airflow, improved the performance in cold, windy weather, and the temperature control performance was more than adequate for the environment in Illinois.

Future Considerations

The degradation of the retroreflector surfaces is believed to be due to exposure of the protective coating to outdoor weather. Possible solutions include working with the manufacturer to identify a more suitable coating or placing a protective window in front of the reflector to shield it from the elements.

The range or coverage area of the system can be increased by increasing the size of the receiver optics and retroreflectors, as has already been proven with the extended-range GreenLITE system Harris deployed to Paris, France, in late 2015 [4].

The optical head's range of motion was limited by the cable connecting it to the electro-optical box. A modified design with the cable exiting the optical head from the bottom near the axis of rotation will reduce the strain caused by the cable and allow for a greater range of motion for the optical head. Ideally, a future implementation would replace the mechanical scanner with an optical scanner and would allow 360 degree rotation without the need to run cables between the hotbox and optical head.

To reduce size, weight, and power, several of the commercial electronic components could be replaced with custom electronics. This would result in the ability to customize component packaging and make the system more compact. A reduction in size in weight and volume by 50% should be easily achievable with the proper commercial design.

Instrument Software Development

Goals

The goals of the GreenLITE instrument software development effort were to 1) Leverage prior software development for MFLL and LAnTeRN, 2) develop custom software to operate the GreenLITE instrument transceivers with operations including hardware control, data acquisition, preliminary data processing, and data communication, and 3) demonstrate through extensive testing that the software is robust and capable of extended-period autonomous operation with minimal operator interaction.

Objectives

The GreenLITE instrument software development objectives included all of the features and capabilities that would be required for extended, autonomous operation at the IBDP site. The first objective was the creation of a software concept for providing robust and reliable instrument operation while remaining flexible enough to accommodate future needs. The data format and communication protocol for transferring data to remote data processing and storage database were chosen to limit the storage and bandwidth requirements. The next objective was the implementation of the software concept in National Instruments' LabVIEW software programming environment. It was determined early in the development process that the software would need to provide both manual and autonomous operation modes with appropriate settings and controls for both. Another software design objective was to provide tools to aid in site configuration and setup as well as means for remote control and system administration.

Approach
The GreenLITE instrument software was developed incrementally, leveraging prior development where possible (modulation tone generation, ADC acquisition, lock-in processing, scanner control, event logging, error handling). Software modules were created, tested, and then integrated into the program. A software block diagram is shown in Figure 7.

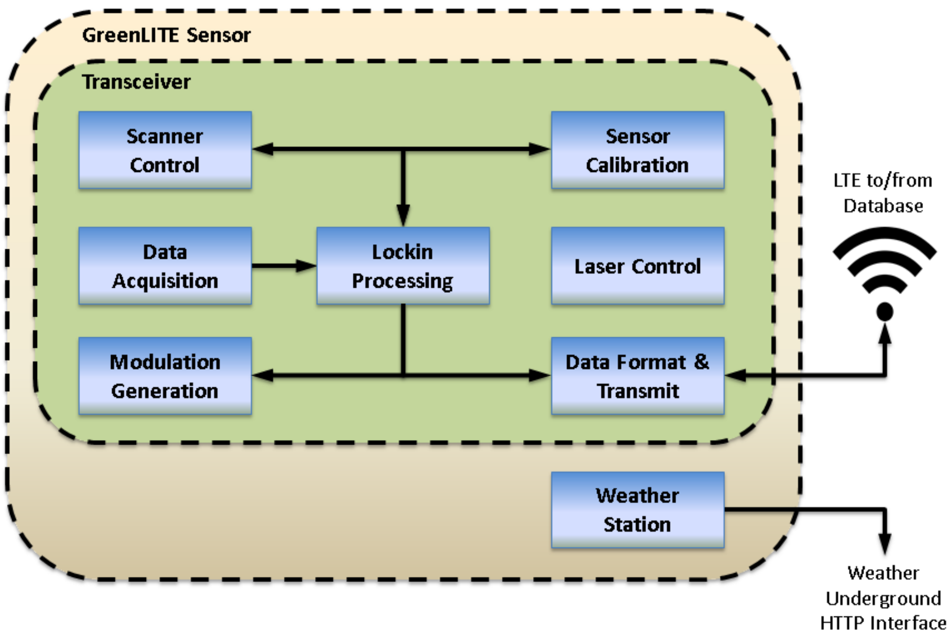


Figure 7. GreenLITE transceiver software block diagram.

A screenshot of the main software user interface is shown in Figure 8. All high-level and most other control actions are performed through this interface. Additionally, most pertinent status information is displayed on this screen as well.

Figure 8. Screenshot of primary GreenLITE software interface.

Actions and status information specific to the scanner are accessed through the scanner user interface, shown in Figure 9.

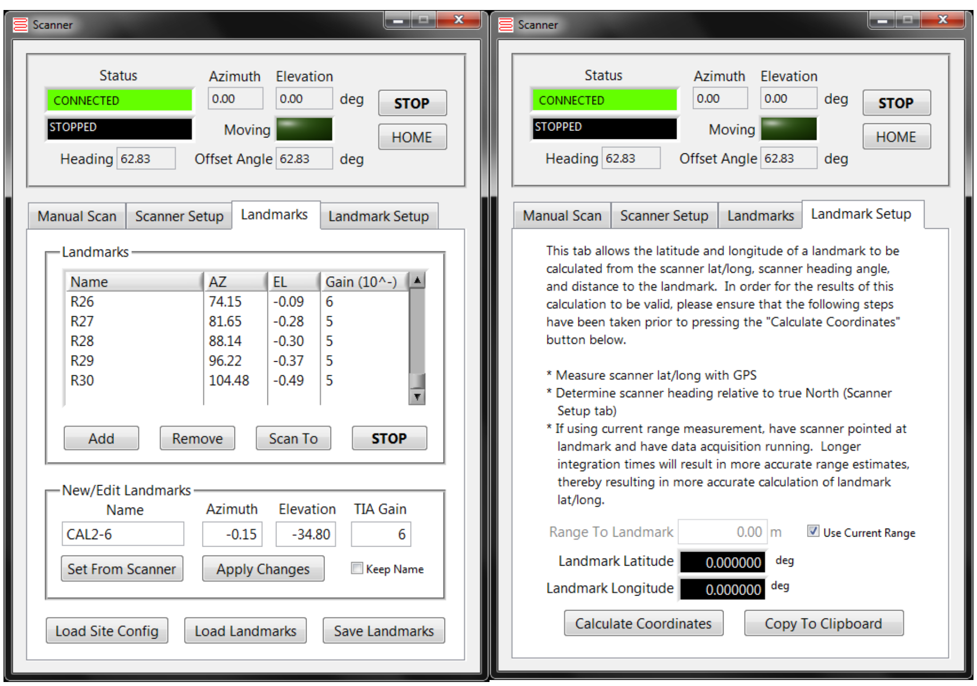


Figure 9. Screenshots of GreenLITE scanner software interface. Left: "Landmarks" tab where scanner coordinates can be loaded, edited, added, and saved. Right: "Landmark Setup" tab where reflector GPS coordinates can be calculated from the scanner pan angle and the measured optical path length.

Results and Discussions

The GreenLITE instrument software performed exceptionally well throughout the duration of the program, including local testing, ZERT testing, and the 6 month deployment at the IBDP site. Some features were added and improvements made as testing and development progressed, which was made possible by the selection of software architecture and modular implementation. IBDP site configuration was completed in just a few hours using the tools that had been developed and tested during local and ZERT testing.

Future Considerations

While the GreenLITE instrument software performed quite well and provided all required functionality, a few improvements could be made to further reduce the need for operator interaction. The first of these improvements would be to provide a method for automated scanner alignment to achieve maximum return power from the retroreflectors. If any shift in the scanner mounting occurs (such as from frost heave or strong winds in conjunction with saturated soil) the scanner pointing coordinates must currently be adjusted manually to ensure that the transmitter and receiver are still centered on the reflectors. This task could be implemented in software in an automated fashion to eliminate the need for an operator to perform the task.

Another software addition that might prove useful is a more sophisticated error notification system. The software can send e-mails and SMS messages to alert message subscribers for a couple of specific error conditions, but this could be expanded to include other conditions. For example, if any of the temperature controllers in the system is unable to maintain the target temperature or the software is unable to communicate with the scanner, a notification could be sent to subscribers to alert them.

Database, Processing and Dissemination Tools Development

Database

The overarching design of the GreenLITE database, data processing and data dissemination sub system hosted in a cloud based environment (Amazon Web Services) is illustrated in **Error! Reference source not found.**.

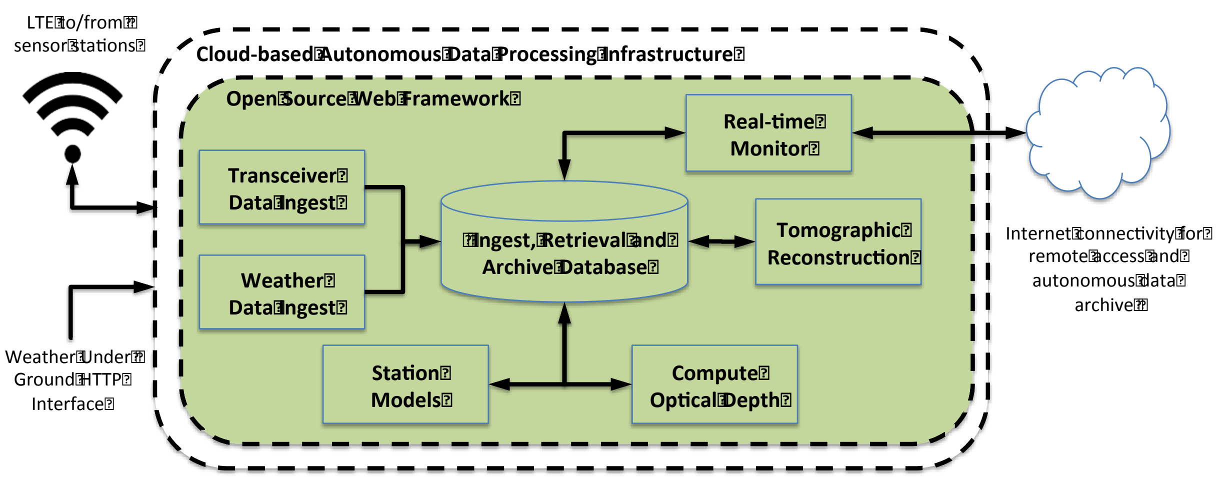


Figure 10. Overview of GreenLITE data processing and dissemination services hosted at part of remote cloud based deployment

This figure illustrates the external connections and the two major components, the GreenLITE ingest/ retrieval/archive database and the retrieval/reconstruction/dissemination software elements, and their sub systems. Both major subsystems are described below.

Goals

The database goal was to serve as the interface with the instrument, retrieval algorithms, 2-D reconstructions and user interfaces, while storing and archiving all pertinent information for later retrieval or further evaluation.

Objectives

The objective for the database was to be flexible, yet have clearly defined interfaces to the various external functions.

Approach

At the heart of this design is an off-the-shelf open source database implementation that acts as a standardized interface between the data collection Sites, the product generation algorithms and products, and the real-time monitoring display.

An initial estimation is that ten GBytes of local disk space will be required to accommodate a year's worth of on-site sample data collection in this database, which will be replicated via standard network protocols at AER/Exelis facilities for post-deployment analysis and off-site archiving.

The Django web framework provides a common database management and access abstraction layer that hides details of the underlying database implementation and can be used with many commonly used databases. The default built-in database is SQLite, which provides an environment for rapidly getting the application up and running. The underlying database may be changed later should SQLite be found insufficient for production purposes, with little or no modification to application code.

As part of the framework, Django defines a directory structure and data class model pattern for defining the database content. Each table in the database is represented as a class derived from a Django Model base class, whose class data members are the table's attributes. Additional behavior is defined by custom class methods.

Database Searchability

It is desirable for database storage and performance to minimize those data that are searchable. There are significant amounts of data in this application that do not need to be accessed as a function of their content, but rather carried along in records that contain data that are searchable. Non-searchable data are stored in the database as serialized atomic blobs, in the form of JSON objects. The *data definition document* classifies each data item as searchable or not.

Site Configuration

The Product Generation Subsystem database tables, or models, are functionally grouped by method of creation: static and dynamic. Static models are generally associated with a defined Site configuration instance, as well as software configuration. Content is manually defined.

Each Site configuration has a unique name, and location (center latitude, center longitude). This information is stored as an entry in a Site model table. Other configuration tables associated with a Site are Transceiver, Reflector, Chord (transceiver/reflector pair), Camera and WeatherStation. Thus the data model for a Site consists of:

- One entry, or row , with a unique SiteId in the **Site** table
- two entries in the **Transceiver** table,
- multiple reflector entries in the **Reflector** table,
- multiple chord entries in the **Chord** table, one for each paired transceiver/reflector,

- single entry in the **Camera** table,
- single entry in the WeatherStation table.

The Chord table contains TransceiverId and ReflectorId. Other tables contain the SiteId, in addition to other attributes.

Site configuration is to be initially defined with a standardized Excel spreadsheet, called a **Site Configuration Form**. The Product Generation Subsystem will read this form and from its contents populate the tables described above. If any attribute in the Site configuration changes, a new form is created and the Site configuration tables are populated with new entries. As such, there may be a Site configuration for multiple physical Sites, or multiple Site configurations for a single Site (can be used for multiple testing trials).

Site configuration data are needed by both the Product Generation Subsystem and the Site Subsystem software. To prevent accidental errors due to multiple data entry/sources, the Product Generation Subsystem will have a command-line driven utility to output a populated Site Configuration Form in CSV format that may be read by both systems.

Examples of how the utility may be invoked (*this is under review)* are:

- make site xls=<path to .xlsx> – populate a new database table from Site Configuration Form.
- make site csv=<path to .csv> – populate a new database table from a CSV Site configuration file
- make site-list – List all Site names and Site Ids from the database.
- make site-dump id=<Site Id> csv=<path to output .csv> – Create a CSV Site configuration file.

Results

The database has proved reliable throughout the GreenLITE project. It has enabled easy archiving and display of the data products and is extremely functional.

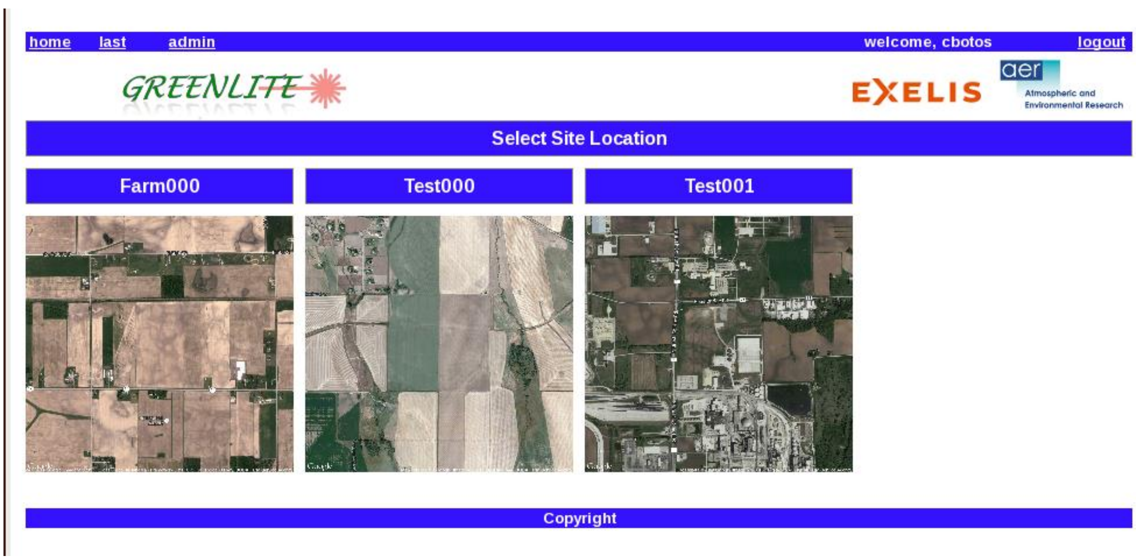


Figure 11. Example of the main page of the database web interface showing multiple sites that can be selected for query.

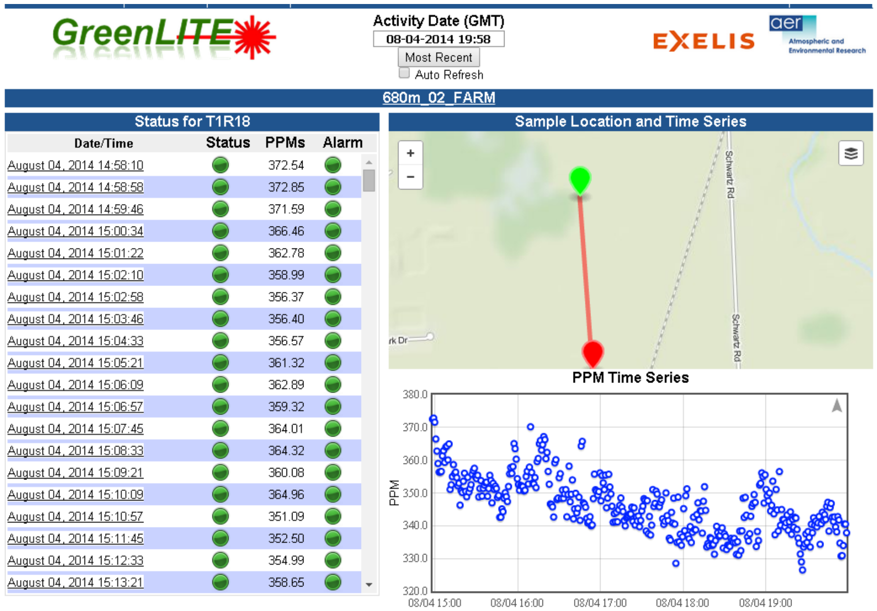


Figure 12. Example of deeper levels of the user interface, this level is looking at an individual chord.

Retrievals to XCO_2

The CO_2 lidar measurements and weather data (temperature, water vapor, and pressure) are used to calculate three quantities of interest: observed differential CO_2 optical depth (dOD), modeled CO_2 dOD, and CO_2 dry air mole fraction (XCO_2). Observed CO_2 dOD was calculated in a straightforward manner as the difference between the natural logarithm of online lidar measurements and offline lidar measurements along a given transceiver/reflector pair or "chord".

$$dOD_{obs} = \ln\left(e^{-OD_{\lambda_{off}}}\right) - \ln\left(e^{-OD_{\lambda_{on}}}\right) = OD_{\lambda_{on}} - OD_{off}$$

Next, AER's Line-By-Line Radiative Transfer Model (LBLRTM) is used to calculate modeled CO_2 dOD and retrieved CO_2 amount in conjunction using a conjugate gradient iterative approach. An initial CO_2 amount (~385 ppm) is used with measured weather data in LBLRTM to retrieve an initial dOD. The same is done for a delta XCO_2 amount (~ 4 ppm).

$$CO_2 = 385\ ppm \rightarrow LBLRTM \rightarrow dOD_{model}$$

$$delta\ CO_2 = CO2 + 4\ ppm \rightarrow LBLRTM \rightarrow delta\ dOD_{model}$$

The model CO_2 dOD and delta model CO_2 dOD will then be used with the observed dOD to adjust delta model dOD and calculate delta observed XCO_2:

$$\Delta OD_{model} = dOD_{model} - delta\ dOD_{model}$$

$$\Delta OD_{obs} = OD_{model} - OD_{obs}$$

The delta model dOD and delta observed dOD will be used to vary the delta CO_2 amount, and then used in LBLRTM to recalculate model dOD.

$$\Delta CO_2 = \Delta CO_2 * \frac{\Delta OD_{obs}}{\Delta OD_{model}}$$

$$CO_2 = CO_2 + \Delta CO_2$$

$$OD_{last} = dOD_{model}$$

$$CO_2 \rightarrow LBLRTM \rightarrow dOD_{model}$$

Lastly, model dOD and delta observed dOD will be recalculated. If delta observed OD is less than 0.0005, the model CO_2 amount and model dOD are reported; otherwise this process is iterated up to three more times to converge on a model CO_2 amount and model dOD that agree with the observed dOD, and the resulting XCO_2 is reported.

$$\Delta OD_{model} = dOD_{model} - dOD_{last}$$

$$\Delta OD_{obs} = dOD_{model} - dOD_{obs}$$

Algorithms for 2-D Reconstruction

The retrieved CO_2 concentration values are then employed in an additional minimization scheme that constructs two-dimensional models of the underlying field concentrations. In traditional tomographic applications, the number of back projections (chords) and angles should optimally approach or exceed the number of pixel elements in the resulting 2-D image, and often the scan geometry is optimized where possible to ensure high-fidelity, unconstrained reconstructions. In the GreenLITE case, the field is under-sampled, and the scan pattern is limited due to the number of deployed transceivers and reflectors, site topography, and both natural and man-made barriers. While a number of approaches have been proposed and implemented for a variety of similar applications [5] [6] [7] to optimally constrain this type of problem, the current baseline method models the underlying field concentrations as the sum of a set of analytical functions that are designed to describe the underlying CO_2 background distribution as well as a set of plume-like source terms. While a number of functional forms have been assessed as part of this work, the following analytical model describes the baseline 2-D field contained within the transceiver chord boundaries:

$$F_{CO_2}(x, y) = a + bx + cy + dxy + \sum_{n=0}^{N} \alpha_n e^{-\beta_n x_r^2} e^{-\gamma_n y_r^2} \quad (1)$$

where F(x,y) is the resulting CO_2 concentration as a function of the x/y location, and the linear model on the right-hand side describes the field elements. The first 4 terms in Equation 4 describe a basic background term that has a constant offset and is allowed to vary linearly as a function of x and y. The variable ***a*** describes the average background concentration, and the remaining elements describe a simple linear gradient across the field. The summation represents a set of simple Gaussian plumes to describe potential localized CO_2 sources. Each 2-D Gaussian is a function of a normalized set of x_r and y_r parameters defined as

$$x_r = \sqrt{(x - x_n) + (y - y_n)} \cos(\theta_n) \quad (2)$$

and

$$y_r = \sqrt{(x - x_n) + (y - y_n)} \sin(\theta_n) \quad (3)$$

where (x_n, y_n) is the plume center, and θ_n is the angle of rotation. The number of chords limits the number of supportable modeled plumes. The upper limit is defined as the number of chords minus the four background parameters, divided by the number of parameters. In this case each plume is defined by six parameters α_n, β_n, γ_n, x_n, y_n and θ_n. For example, a site with 42 intersecting chords limits the number of plumes to a maximum of 6 ([42 – 4]/6 = 6.3). In practice, the number of supportable plumes is on the order of 3-4 due to the ability of the minimization technique to uniquely assign values to each element. F(x,y) is constructed using an optimization scheme that minimizes the difference between retrieved CO_2 ppm values and modeled values constructed through discrete integration of F(x,y). This is achieved by minimizing the sum of the root-mean-square error (RMSE) differences between these values using a sequential least squares programming (SLSQP) optimization algorithm. SLSQP provides a standardized framework for minimizing a user-defined cost function given a set of additional parametric constraints. In this instance the cost function was defined as the sum of the squared differences between a set of observed chord values and modeled chord values created by averaging equally spaced samples along a given chord set for the model described in Equation 4. An additional weighting function was also placed on this overall metric so that the ratio of β_n to γ_n did not exceed some maximum, ensuring that plumes, irrespective of direction, had some finite width. As part of the overall minimization scheme, the model parameters were constrained 1) to ensure that the plumes were positive in nature and represented source and not sink terms, 2) to constrain plume source locations to the enclosed sampling space, and 3) to restrict plume source amplitudes to within physically realizable bounds for CO_2 emissions.

Figure 13 illustrates the results from a typical reconstruction based on synthetic data. In this example, the image on the left illustrates a typical synthetic field containing 2 centrally located Gaussian plumes on a constant background. The red lines indicate the chords associated with a typical two transceiver configuration with 10 reflectors on each of three sides. Next, the average concentration for each chord is computed based on discrete samples along each chord length. The plot in the center illustrates a simple back projection of the synthetic chord samples. Each dot in the resulting 2-D plot denotes the average value of all chord values that intersect the point of interest. While the resulting sparse back projection provides little information about the true distribution, it does provide a crude first guess at potential plume locations. Finally, the panel on the right describes the resulting reconstruction based on the synthetic data derived from the left hand panel and the reconstruction algorithm described above. This tomographic reconstruction method provides a robust mechanism for estimating well-defined plume-like sources.

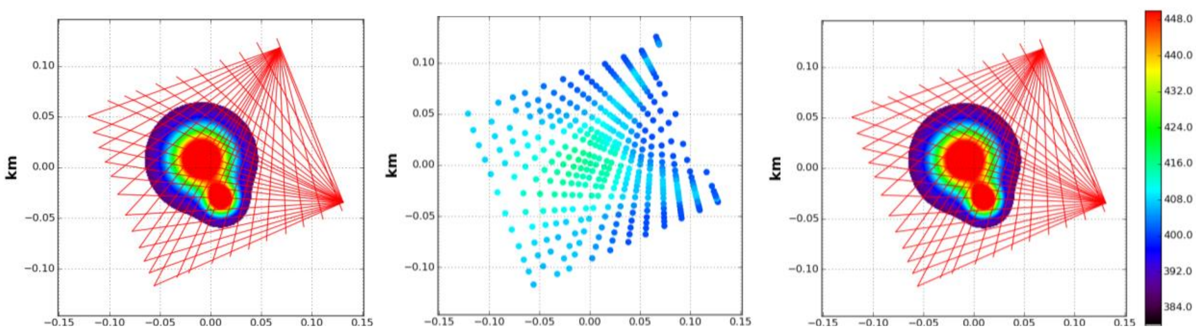


Figure 13. Simulated 2-D reconstruction. Image on the left depicts a synthetic scene and simulated chords for a typical two-transceiver configuration. The center plot depicts a simple back projection of the synthetic chord samples constructed from the field on the left, and the right hand panel illustrates the resulting reconstruction.

Results

The retrieval and reconstruction software provided on-site uptimes on the order of 98% and processed 1.3M raw samples resulting in greater than 1.2M retrieved samples and 58K 2-D reconstructions during the ~4 months of operational time at the IBDP site. In addition, the retrieved products were compared on a number of occasions to independent observations and fell well within expected margins of error (see discussion below).

Future Considerations

While the GreenLITE database, retrieval and reconstructions software performed quite well and provided all required functionality, a few improvements could be made to further enhance long term operability, maintenance and product performance. Some of these include software redesign and others are feature enhancements. Among the potential redesign task are: 1) Reorganization of database table and use of non-searchable metadata to enhance data retrieval/web performance, 2) Development of an integrated archive and retrieval system to enhance post-event analysis capabilities and reduce need for active online storage of the entire data record and 3) Develop/enhance defined user's roles to further tailor the web interface functionality. Additional topics/tasks that could be undertaken from a science/feature perspective are: 1) Development of enhanced 2-D reconstruction methods that incorporate a priori knowledge to enhance accuracy of provide 2-D distributions, 2) Explore combining concentration values with site specific inventory information and weather observations/model output to provide time/spatial varying absolute estimates of CO_2 flux or leak rates and 3) Development, in conjunction with the user community, a robust set of quality indicators or analytics that would enable real-time site specific monitoring by operational staff.

Results and discussions:

System Test Plans and Philosophy

The system level testing plan was to test incrementally as being built and in an "as will be operated" manner when possible. This begins at the component level in the laboratory, then to the transceiver level after the first transceiver is assembled. We used the lessons learned from the first transceiver to guide final assembly of the second transceiver, then, while testing the second transceiver, we modified the first transceiver. Once both transceivers were built and tested individually, we tested the two transceivers side-by-side over simple configurations to ensure they performed the same. In parallel to this we tested the algorithms using simulated data, until transceiver data was available, and then continued with the measured instrument data. After all of basic retrieval algorithms were tested and the transceivers had been verified to have similar performance meeting the defined requirements, we moved on to testing the system. System testing consisted of both transceivers, some number of retroreflectors, depending on the test, and validated all of the hardware and software interfaces and functionality. The last set of testing was for the 2-D reconstructions using a full system setup. The following sections review results from each of the incremental test periods leading to final system testing and deployment.

Component Level Testing

An example of some of the component level testing is provided in Figure 14 and Figure 15

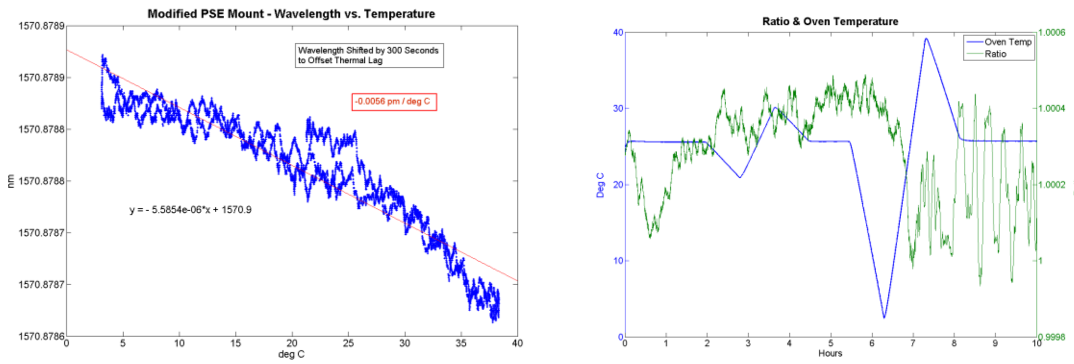


Figure 14: Examples of component level testing for stability over temperature, wavelength control left and impact on ratio of fiber components over temperature on right.

In some cases, like the multimode fiber used to collect the received light and get it to the detector, a number of different components had to be tested to identify the optimal solution. Some of the fibers initially specified had adverse impacts on the measured transmission ratio due to mode properties of the fiber.

Fiber			Ratio				
Part #	Core (um)	NA	Peak Power (W	Mean @ Peak	Mean @ 10%	Delta	Abs(Delta)
FG365LEC	365	0.22	1.32E-06	0.9999619	0.9996032	-0.0003587	0.000359
FG-550-LER	550	0.22	1.25E-06	1.0001161	1.0006467	0.0005306	0.000531
M21L05	600	0.39	1.21E-06	1.0001167	1.0007171	0.0006004	0.000600
BFL22-365	365	0.22	1.26E-06	1.0003287	0.9994908	-0.0008379	0.000838
M38L02	200	0.39	7.88E-07	0.9991963	1.0005843	0.0013880	0.001388
M17L05	200	0.22	7.37E-07	1.0017858	1.0001006	-0.0016852	0.001685
M25L02	200	0.22	8.81E-07	1.0015638	0.9998142	-0.0017496	0.00175
BFL-22-910	910	0.22	1.28E-06	1.0006795	1.0032957	0.0026162	0.002616
FT1000EMT	1000	0.39	1.14E-06	0.9980597	1.0022745	0.0042148	0.004215

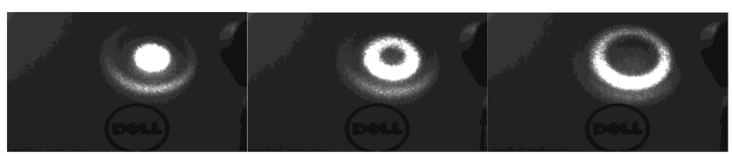


Figure 15: Example of component evaluations for multi-mode fiber options for receiver.

Other similar tasks included: comparing various fiber taps used for the reference channel to optimize the use of the 16-bit analog-to-digital converter while minimizing sensitivity to variations or drift due to temperature changes; evaluating retroreflector performance versus component cost, including the trades between different reflective tapes and true corner cubes of different angular accuracy.

System Level Testing

For terminology we typically refer to the transceiver testing as instrument tests and reserve the term system level testing to describe testing that occurred with both transceivers and some number of retro reflectors. This section includes discussion of both instrument and system level testing. System (instrument) level testing occurred following the integration of the first transceiver. Tests were conducted at the Exelis farm test site located in New Haven, IN, at the Zero Emissions Research and Technology (ZERT) facility in Bozeman, MT, and at the Illinois Basin- Decatur Project in Decatur, IL. The following sections describe the primary testing and results from all critical tests performed at these locations.

Farm Testing

The Exelis farm test site has been used by Exelis for testing many of our laser based systems since early 2000. The site has a work trailer, fully equipped with a wide range of test equipment designed for testing both optical and electrical functions (e.g. oscilloscopes, volt meters, optical power meters. wavelength measuring equipment, etc.).

The first testing conducted at the Exelis farm site was for evaluation of the first transceiver performance and to identify any issues before completing the second transceiver build. After this initial testing, lessons learned were applied to the second transceiver, and then implemented in the first transceiver during the testing of the second transceiver. Once both transceivers were operational and basic performance had been verified, both transceivers were tested side by side. After transceiver testing completed we moved into full system level testing, simulating the test configuration to be used at the ZERT site. Figure 16 illustrates a number of the test configurations that were used to evaluate the transceivers and full system tests at the Exelis farm test site.

Figure 16. Examples of the wide range of experimental arrangements conducted at the Exelis test range. Green dots are reflector locations, and red dots are the transceivers.

Transceiver Testing

The objectives of the transceiver testing were to verify they met the design requirement of SNR > 1000 for a 1.2 km range and to verify the pointing resolution and repeatability of the mechanical scanners under load. Additionally initial testing helped to identify some minor hardware issues and debug the software. Initial transceiver testing used a single retroreflector located ~680 m from the transceiver. This range was chosen due to the arrangement at the farm and easy access to the 680 m target we typically use for testing our laser-based systems.

Initial transceiver tested revealed the need for modification to some of the hardware. A pair of electrical bandpass filters was found to be responsible for crosstalk between signal channels due to inductive coupling. These filters were redesigned to eliminate the inductors and prevent crosstalk between them. The data acquisition module was designed for use in a laboratory environment at typical room temperature and did not respond well to being placed in the 38 °C thermal enclosure. The module was modified to include forced-air cooling. Testing of the first transceiver also showed that the refractive optics used in the original transmitter and receiver optical design did not result in satisfactory performance and were subsequently replaced with reflective optics. Lastly, we determined that the solar blocking filter included in the original optical design was unneeded and could be eliminated, simplifying the opto-mechanical design and reducing cost.

After completing the second transceiver integration, with the required modifications based on testing of the first transceiver, similar tests were conducted with this transceiver to verify performance. The first transceiver was modified as well and retested. When both transceivers had been tested individually they were set up to operate side by side for relative comparisons of collected return power, SNR, stability, and measured path length.

System Testing

System testing at the farm test site focused on integrating the transceivers with the back-end data processing infrastructure (CO_2 retrievals, 2-D reconstructions, database storage, website data display). A variety of site configurations were tested utilizing different numbers of reflectors and a wide range of path lengths. One such configuration closely matched the expected configuration at ZERT as a sort of "dry run" prior to testing the system at the ZERT site. Several software issues were resolved both in the transceivers and in the data processing system.

ZERT Testing

Overview

The Zero Emissions Research and Technology center maintains a field site on the Montana State University agricultural plot just west of the university in Bozeman, Montana. This site is directed by Dr. Lee Spangler, and managed by Dr. Laura Dobeck, and consists of an ~2.5 m depth horizontal well of approximately 70m in length divided into 6 segments that can be injected with CO_2 up to 0.3T per day total in a wide range of configurations.

Figure 17: Zero Emissions Research and Technology site outlined in Blue and the horizontal distribution pipe location for CO_2 injection illustrated in red.

After coordination with the ZERT facility personnel, deciding on site layout options and performing trade studies, along with planning for coordination with other researchers on site, release plan and all the logistics that go with implementing a remote field campaign, personnel staffing, transportation, shipping, lodging etc. the system was deployed to the ZERT site on August 18th, 2014.

The testing of the complete system at the ZERT leak detection test site in Bozeman, MT, was focused on demonstrating the ability to detect leaks of the size required to verify 99% containment over 100 years. On first arrival, another group from Stanford University was working on the site and had set the release schedule. Exelis used that opportunity to get setup and evaluate the initial data. When Stanford finished we had the release turned off over a weekend and data was collected for baseline establishment pre-release. We proceeded to collect ~200 hours of data over a wide range of quantified release scenarios over the course of a 3 week campaign under varying environmental conditions. This task resulted in a comprehensive data set that was used to verify the full system performance against a quantified leak and validate the 2-D concentration and flux map accuracy and precision. The arrangement of the grid at the ZERT site is shown in Figure 18 and was ~180m X 200m limited by the physical size of the site and the required angles for the retro reflectors. As can be seen in the figure the grid was pretty well centered over the horizontal well.

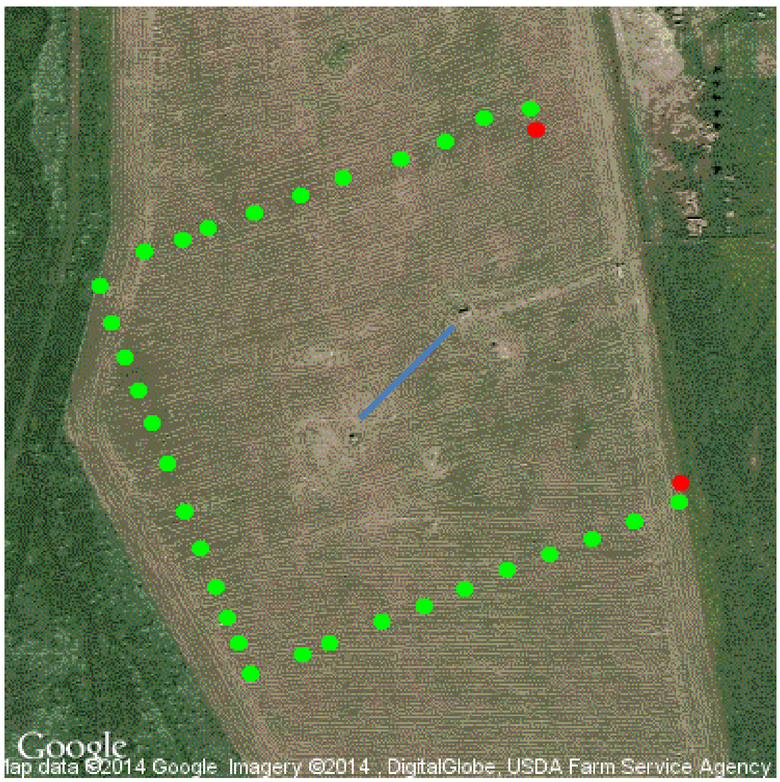


Figure 18: ZERT site configuration. Red circles are the transceivers and green circles are the retro reflectors. Blue line is the approximate location of the underground horizontal well. Note transceiver T1 is the northern transceiver, and transceiver T2 is the southernmost. The retro reflectors are numbered sequentially starting from the lower right of the image, R1, and continuing clockwise around the grid to R32.

Figure 19: Panoramic image of the ZERT site as seen from T2.

Figure 20 shows the various release rates for each section of the pipe over the course of the field campaign and Figure 21 shows the total combined release rate from all sections over the same period.

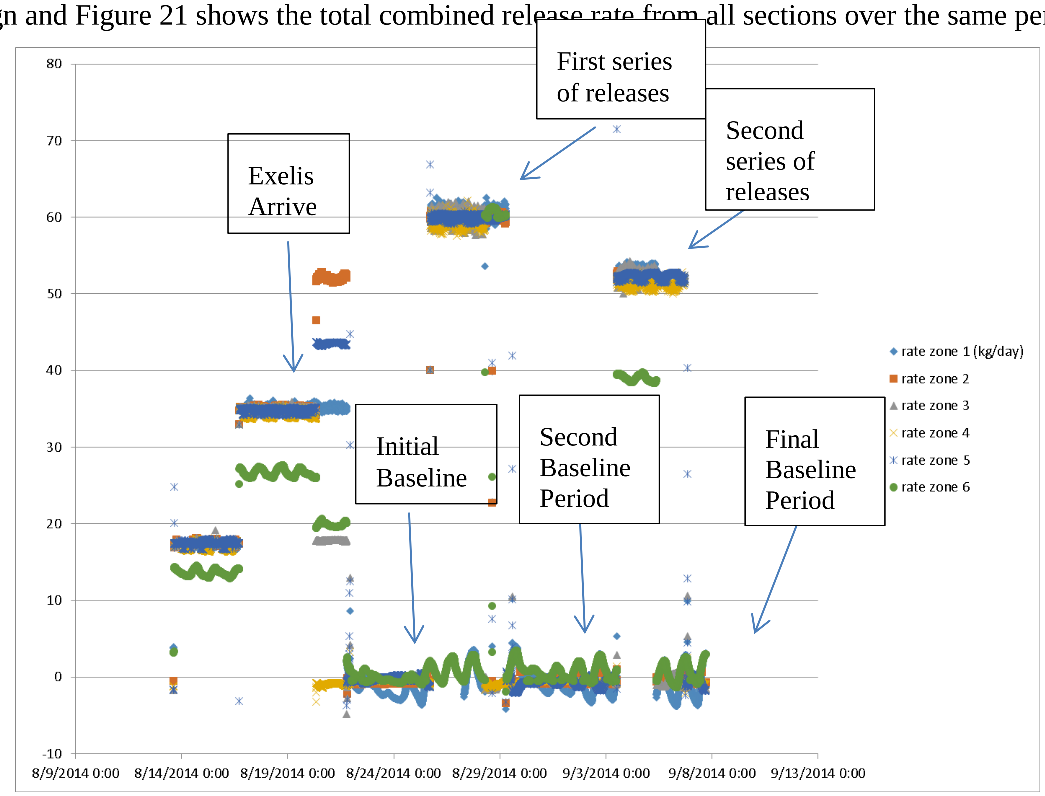


Figure 20: Release rate by Zone

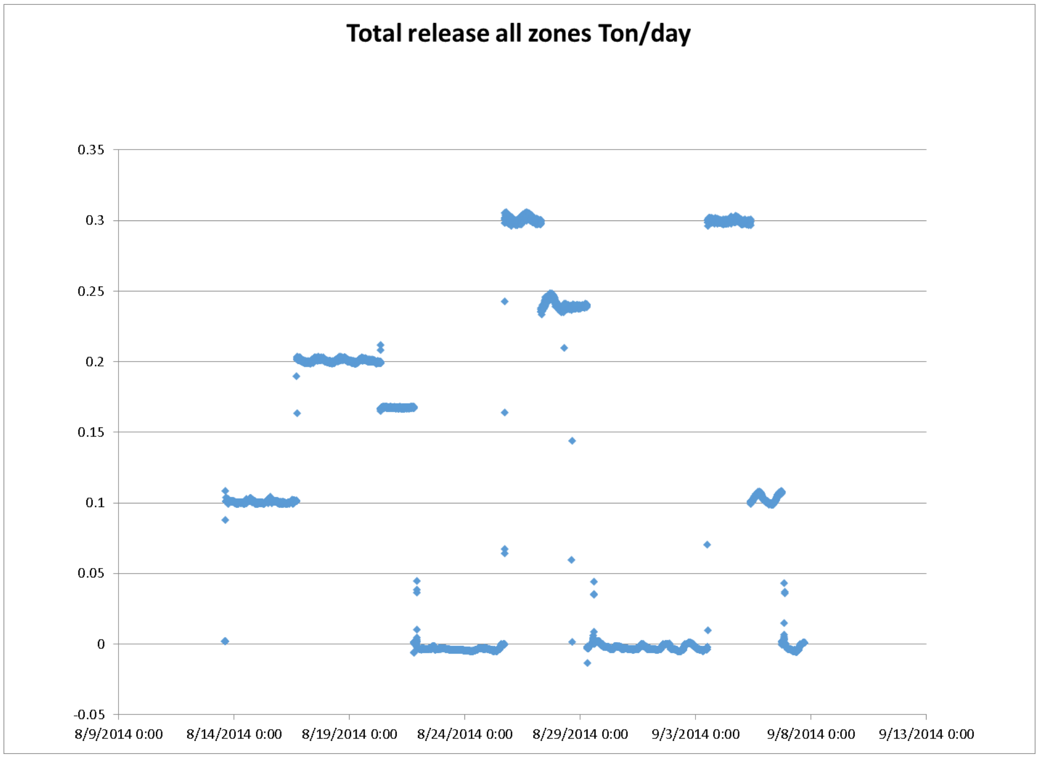
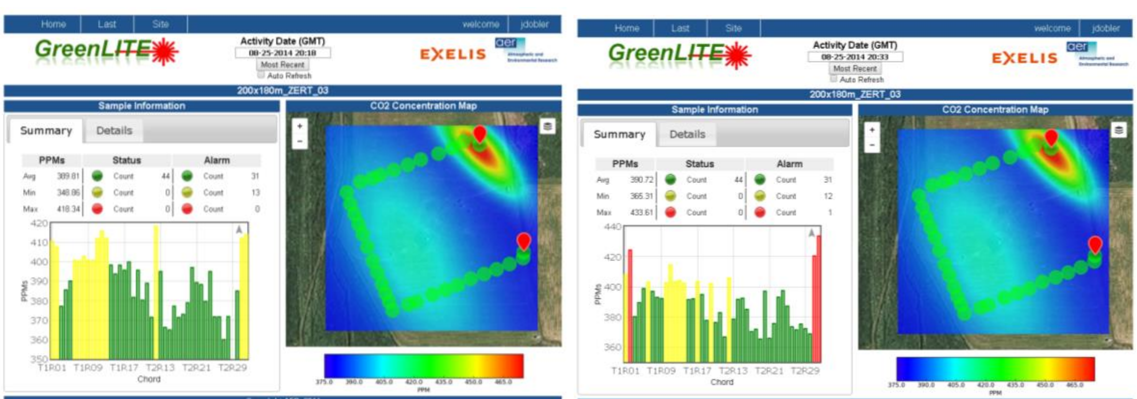


Figure 21: Total release rate all zones combined

Results

Analysis of the >200 hours of data collected from the controlled release site was used in quantifying the system performance for 1) single line CO_2 number density; 2) 2-D tomographic reconstructions; 3) flux mapping. All of the data for the entire campaign has been processed through the 2-D reconstructions. Only a summary of the data products is provided in this report. The full data set can be accessed via the database archive in the DOE data system.

The following figure shows the series of concentrations retrieved and the resulting 2-D concentration maps during a release, as seen from the cloud-based user interface.



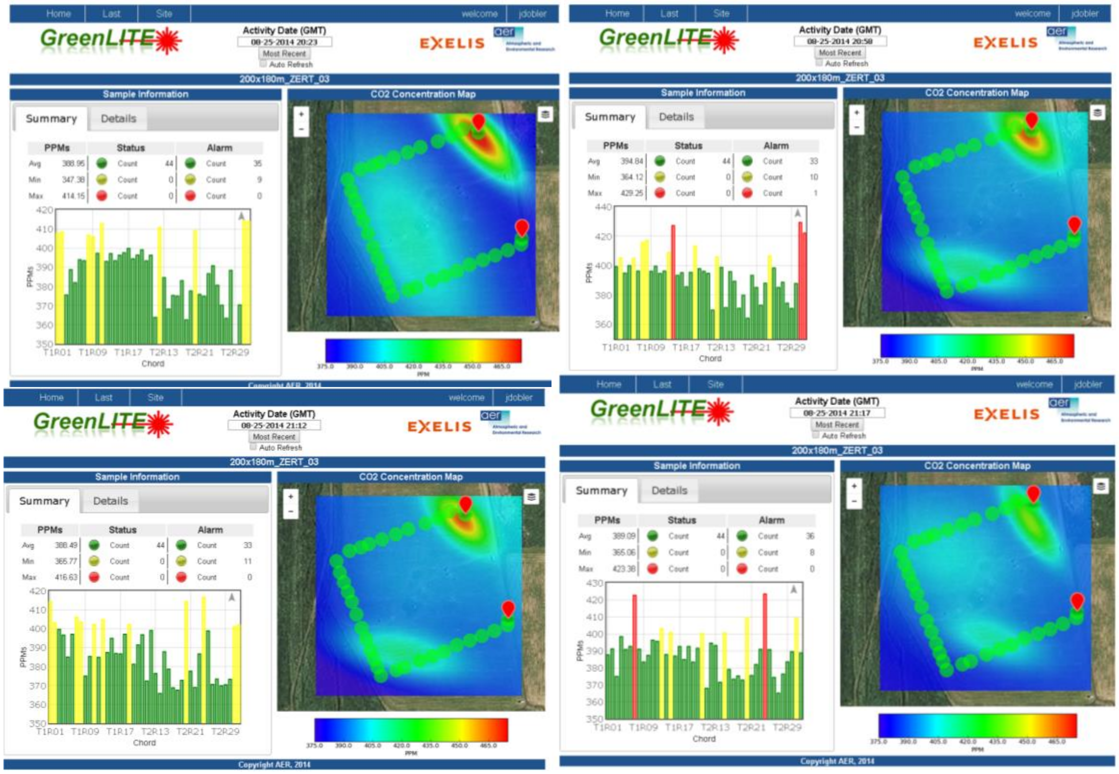


Figure 22: Time series of retrievals for concentration and the 2-D reconstructions during the ZERT testing. Note that the 2-D reconstructions are using half hour averages, but the entire field of chord data completes approximately every 4 minutes.

Note the source that consistently shows up near the Northern most transceiver is due to a large manure pile located just off of the ZERT facility where the north east corner of the 2-D overlay is. The CO_2 from the manure pile was measured using a West Systems Licor-based ground flux instrument and was found to be a constant source of 10's of ppm above background and to cause spikes in the CO_2 measured near the fence line of the ZERT site just east of T1 > 100 ppm, or ~10X the size of the spikes seen at a similar height from the ground release

Figure 23: CO_2 output from the manure pile was measured with the West system both in a static case (left) and using the hand held readout for initial assessment (right).

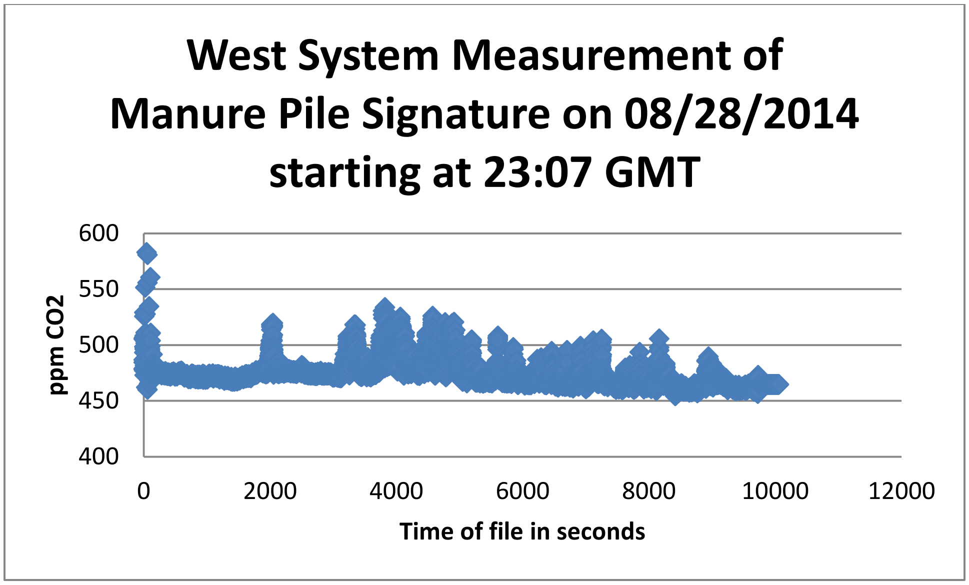


Figure 24: Example of variability in atmospheric CO_2 concentration generated from the nearby manure pile.

We also used the West System as an independent monitor of the CO_2 concentration at the ZERT site by locating it near the middle of the field on a pole as shown in Figure 25

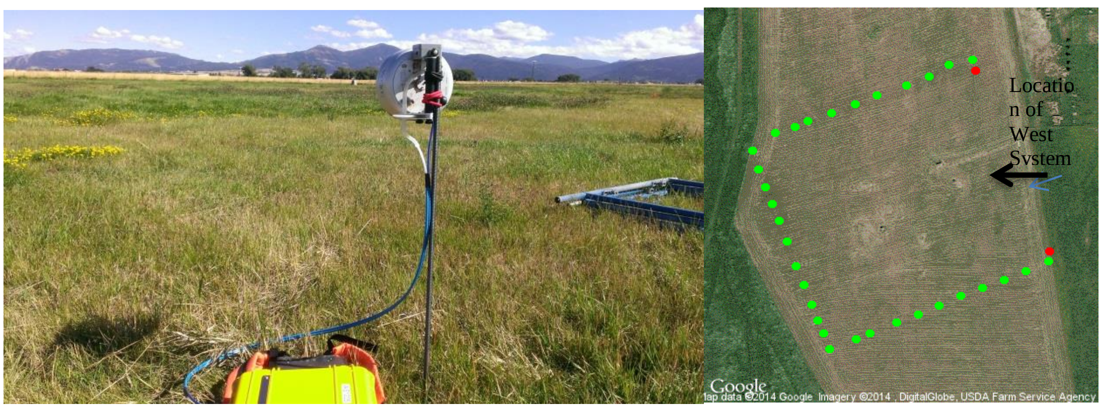


Figure 25: West System used to independently monitor CO_2 concentration at the ZERT site. System was used to monitor background levels and was located to minimize measurement of horizontal well.

Comparisons with the lidar were made, showing excellent agreement in the trends, but required a bias offset. Note that the west system is designed to measure surface flux with concentrations ranging from 200 ppm to 20000 ppm and is not designed for absolute atmospheric measurements. The concentrations measured from the lidar system tended to range from 380 – 420ppm during the day, and the West system tended to measure 65 – 70 ppm higher. The ranges measured by the lidar are more consistent with expected atmospheric concentrations and so the West system data was corrected for a DC bias relative to the lidar measurement. An example of the comparisons is shown in Figures 26 and 27.

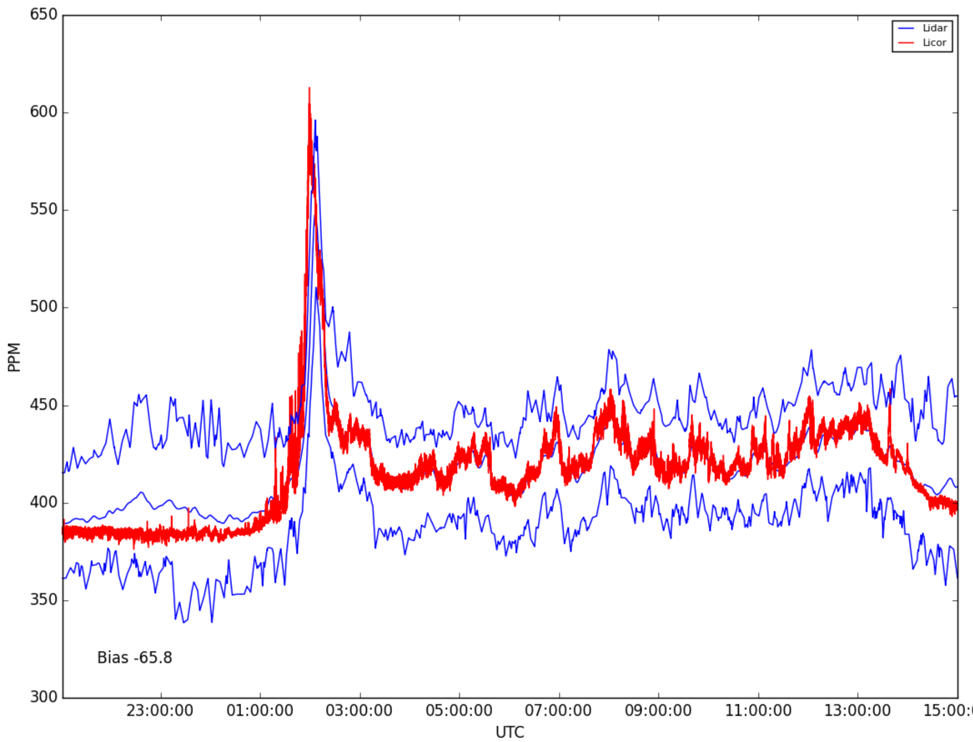


Figure 26: Comparison of West System Licor (red) in situ point measurement and the lidar data (blue). For the lidar data the average of all chords is shown in the middle and the min and max of the chord data are shown as well. The large peak around sunset is due to plant respiration.

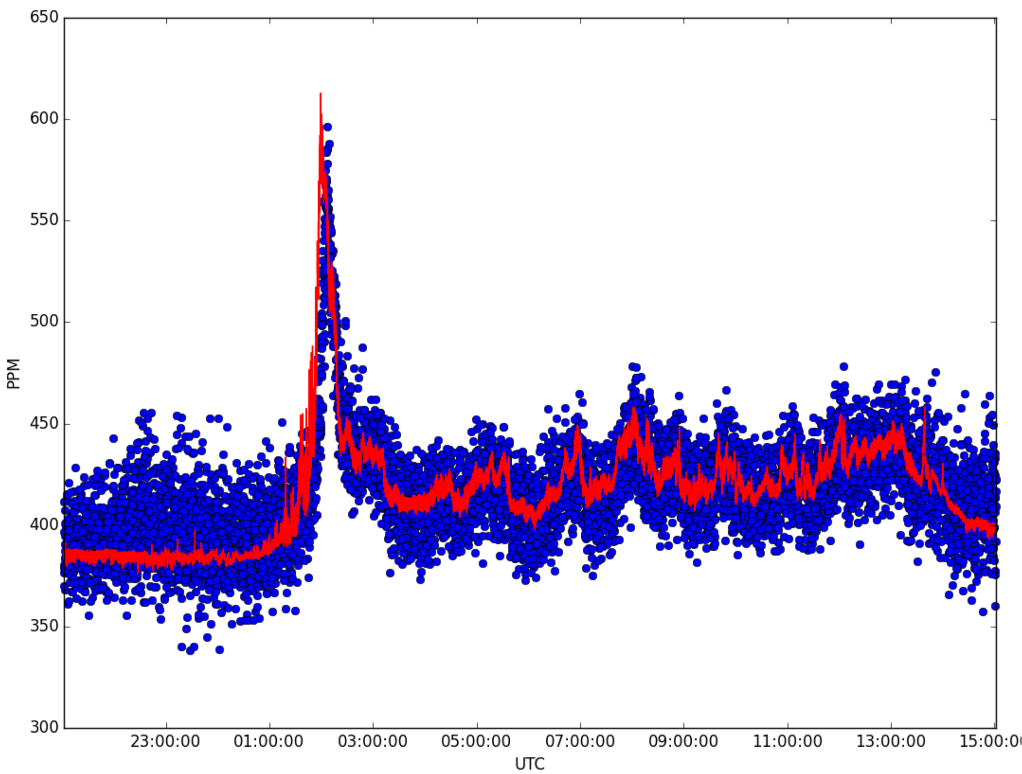


Figure 27: Lidar data compared to West System showing all chord data.

In addition to the West system there was also a LI-COR eddy covariance instrument on site. Unfortunately, the ZERT team was not able to provide overlapping data that passed quality control during the period we were operating. Eddy covariance data, like the lidar 2-D reconstructions is highly dependent on wind speed and direction. Bozeman, MT, provides a significant challenge in that regard; during the time of year the tests were conducted the winds were highly variable, likely limiting the value of the EC data.

System Operational Deployment Test

Illinois Basin - Decatur Project (IBDP)

Goals

The primary goal of the GreenLITE deployment at the IBDP site was to demonstrate the autonomous operation of the system in a real world GCS environment over an extended period of time and over a wide range of operating conditions to demonstrate the practicality of the measurement for this application. A secondary goal was to compare GreenLITE measurements of atmospheric CO_2 to point measurements of atmospheric CO_2 and chamber measurements of flux obtained by the Midwest Geological Sequestration Consortium (MGSC) lead by the University of Illinois – Illinois State Geological Survey (ISGS) Illinois Basin – Decatur Project (IBDP) site, a US Department of Energy-funded Regional Carbon Sequestration Partnership project.

Objectives

The first objective of the GreenLITE system deployment to the IBDP site was determining a site layout to maximize coverage area and minimize interference with site operations, while optimizing monitoring value. In addition the layouts were to be coordinated with the ISGS and Archer Daniels Midland (ADM; the IBDP host facility). Permanent or semi-permanent mounting structures needed to be designed and built for holding the transceivers and retroreflectors in fixed locations and orientations. Site preparation planning and contract implementation to an ADM approved contractor needed to be conducted. In order to demonstrate the ability of the system to operate over an extended period of time, a minimum operational period of three months was targeted as the baseline objective. Another objective was to make some qualitative comparisons of GreenLITE measurements to hand held and ISGS *in situ* data to verify that trends and changes in CO_2 concentration were not artifacts and for first order verification of GreenLITE results.

Approach

The initial plan during the proposal was to cover the full 0.8 by 0.8 km field. After some discussions with ISGS and ADM personnel and a visit to the IBDP site, the site layout shown in the left panel of Figure 28 was created. A similar layout was then tested at the Exelis New Haven, Indiana, test site. This configuration provided ~0.2 km^2 of coverage area and was largely determined by obstructions and site topography. The area covered much of the field area that is covered by the IBDP soil flux monitoring network grid. It did not cover the main injection well which had been capped since November 2014, when injection operations at the IBDP site were concluded. The GreenLITE coverage area did include the IBDP deep monitoring well known as Verification Well 1 (VW1). Mounting structures were designed, and site preparation requirements for power and equipment installation were determined. Site preparation plans were coordinated with IBDP and ADM and an ADM approved contractor was assigned site preparatory tasks. Two transceivers and 30 retroreflectors were installed Feb 24-25, 2015 by Exelis, with support from the IBDP team, and the system was brought online on Feb 25. The center and right panels of Figure 28 show a transceiver and retroreflector installed at the IBDP site. After a few weeks of monitoring and minor adjustments, the system was made fully operational on April 1, 2015. The system remained in operation until Aug 17, when it was shut down and removed from the IBDP site.

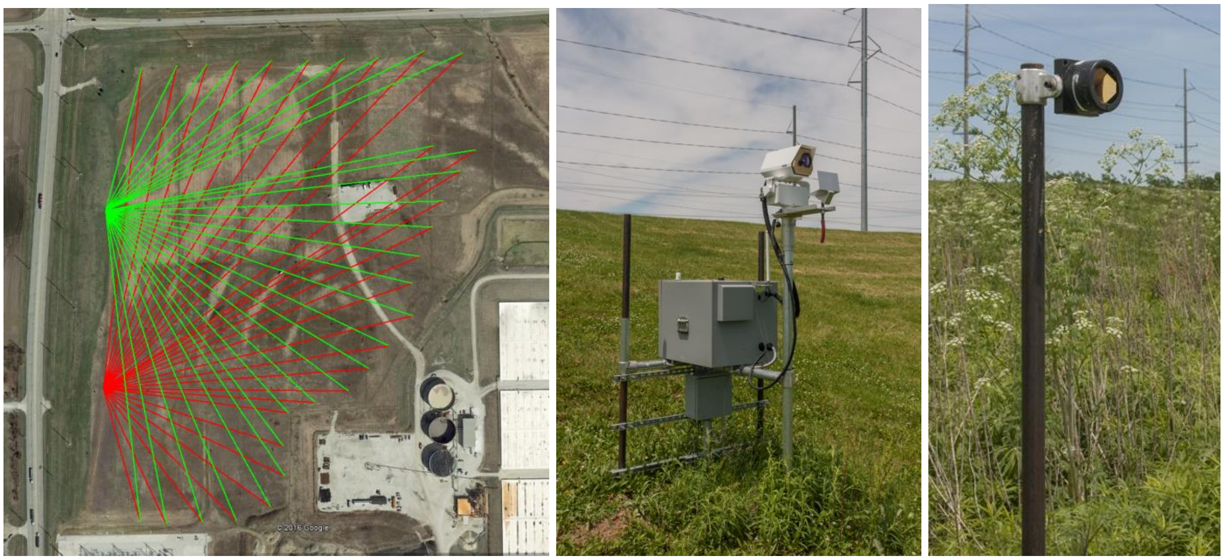


Figure 28. IBDP deployment images. Left: Site layout showing chords from transceivers to reflectors. Center: Photo of transceiver installed at IBDP site. Right: Photo of retroreflector installed at IBDP.

Results and Discussions

During the 5+ months that the GreenLITE system was operational at the IBDP site, more than 2 million raw samples of chord optical depth were collected, more than 1.8 million column CO_2 concentrations were retrieved, and approximately 72,000 2-D reconstructions were generated. The system collected data for approximately 3,800 hours with an up-time duty cycle of greater than 95%. The GreenLITE system operated in a wide range of environmental conditions, with temperatures ranging from -20 to 33 °C and wind gusts to 27 m/s.

In early July the system experienced a power outage resulting from a miscommunication with ADM. The original plan had the GreenLITE system being removed from the site in early July, and the extended deployment had not been conveyed to the ADM personnel responsible for managing the GreenLITE power supply. ADM cut power to the GreenLITE transceivers, and it took nearly two weeks for power to be restored. During this time, no data were collected by GreenLITE.

Four maintenance visits were made to the site during the deployment period, approximately 1 per month. At these times, transceiver optical windows were cleaned, retroreflector mirrors were cleaned, reflector pointing was checked and adjusted as needed, and vegetation was removed where it was obstructing the chord measurements.

Comparisons of the GreenLITE data to *in situ* data collected with a LI-COR based multiplexer operated by ISGS show that general trends track extremely well. The plots in Figure 29 show a representative comparison of GreenLITE and *in situ* CO_2 concentration measurements.

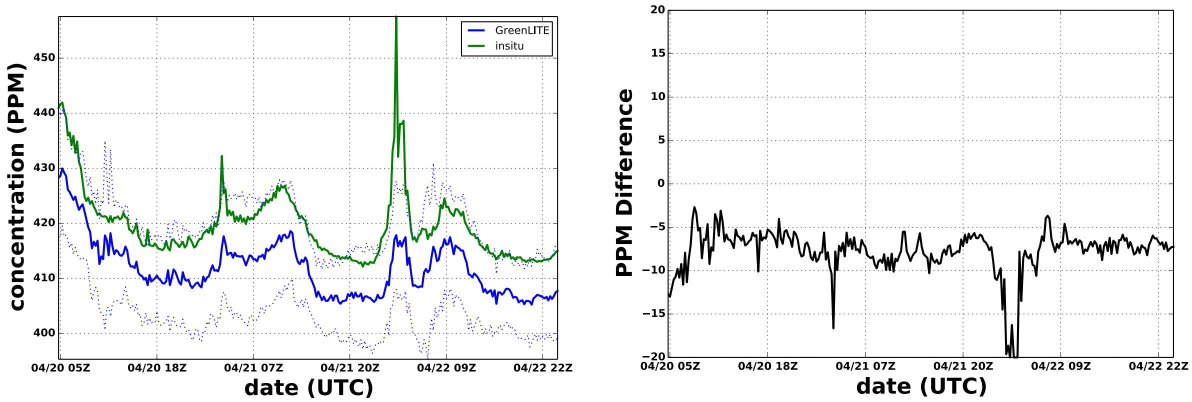


Figure 29. Comparison of ~3 day period of GreenLITE retrieved column CO_2 concentration (blue) and collocated in situ measurements (green) during IBPD deployment. Left: The solid blue line denotes the average GreenLITE concentration, while the dotted lines denote ± one standard deviation from the mean. Right: Average difference between GreenLITE and in situ data.

The GreenLITE data typically show a measured concentration that is 5-10 ppm lower than the *in situ* atmospheric concentration measurements made by the IBDP multiplexer. A number of factors may contribute to this difference; 1) The multiplexer is measuring at a single location (4 heights: 9 cm, 55 cm, 168 cm, and 255 cm and is unable to capture variations along the length of the chord that are captured by GreenLITE, 2) the height of the highest multiplexer measurement is 2.55 m while the GreenLITE chord is located approximately 3 m above the surface at the multiplexer location, and 3) the multiplexer is calibrated by the manufacturer but is not regularly calibrated using a gas standard and so absolute accuracy is unknown. Overall, the agreement is very good regarding measured trends and the offset is not unexpected. The differences at the peak are likely the result of the GreenLITE measurement being an integrated path measurement and thus it is less sensitive to hyper local fluctuations. Additional comparisons are shown in, Figure 30, and again the trends are well represented but the peaks in the GreenLITE data are averaged over the path resulting in the differences at the peaks. The top left plot shows cases where the GreenLITE data measured peaks that were not visible to the in situ instrument and the right and lower plot show cases where the integrated path averaged out higher concentrations seen at the spot of the in situ instrument.

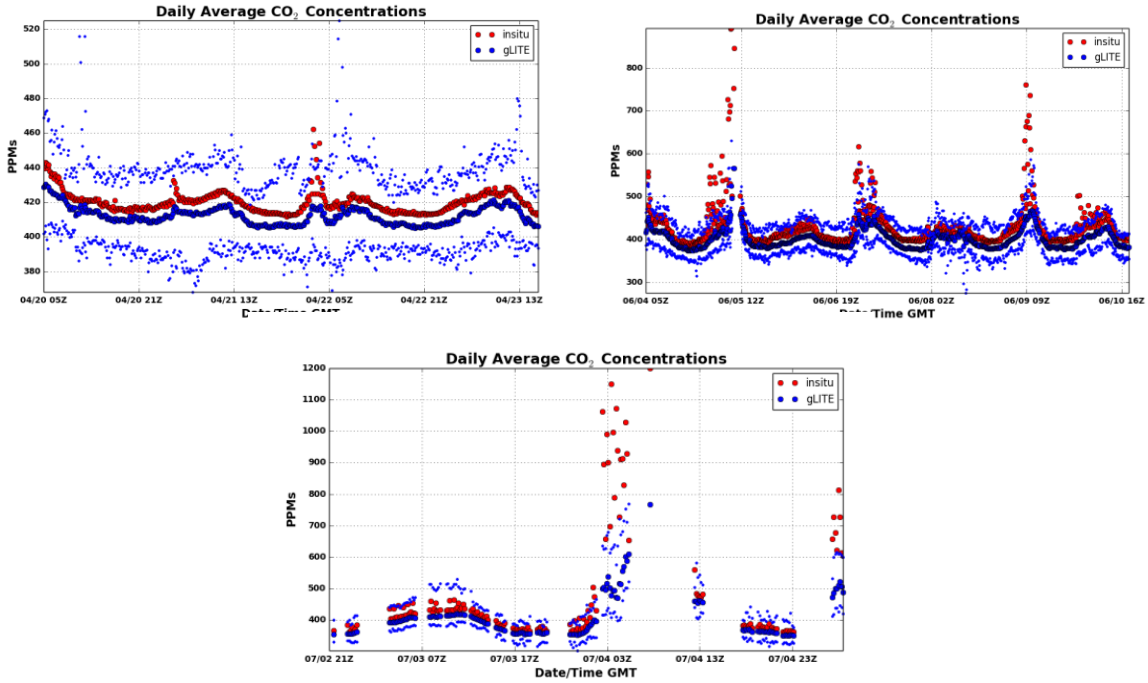


Figure 30 Comparison of IBDP in situ measurements and coincident GreenLITE samples. Red circles denote in situ measurements, blue circles illustrate GreenLITE measurements and blue dot depict the min/max GreenLITE chord values for sampling period.

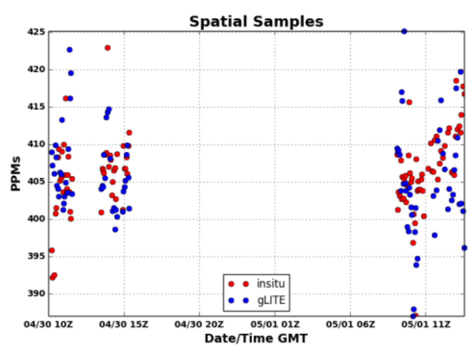


Figure 31. Plot of in situ soil flux concentration sample values and values extracted from GreenLITE reconstruction for same geographic location and time.

In addition to the multiplexer data, ISGS provided us with chamber measurements from the IBDP soil flux network across the site. The temporal measurements of the soil flux network make comparison between the two systems a little bit of a challenge as the points in the grid are measured over a 2 day period while the GreenLITE spatial data is generated approximately every 10 minutes. To compare the two measurement approaches as suggested by the Peer Review committee we sampled the 2-D reconstructions at the same locations and times as the flux chamber samples were taken as illustrated in Figure 32.

Figure 32. Illustrates the in situ flux monitoring locations on the left and values for initial CO_2 concentration in the flux chamber measured during the period of 4/31-5/1 2015 on the right. Red dot on the left denote sample positions within the GreenLITE reconstruction area, and the yellow dots show the position of those outside the GreenLITE reconstruction area.

Figure 33 shows the reconstructed fields along with the flux chamber measurements that occurred during the time the reconstruction was generated. Since the flux chamber collection spans a couple days this was the best way to compare the continuous 2-D reconstructions with the flux measurements. In an ideal scenario, all of the flux points would be measured simultaneously allowing for a better comparison of the 2-D maps.

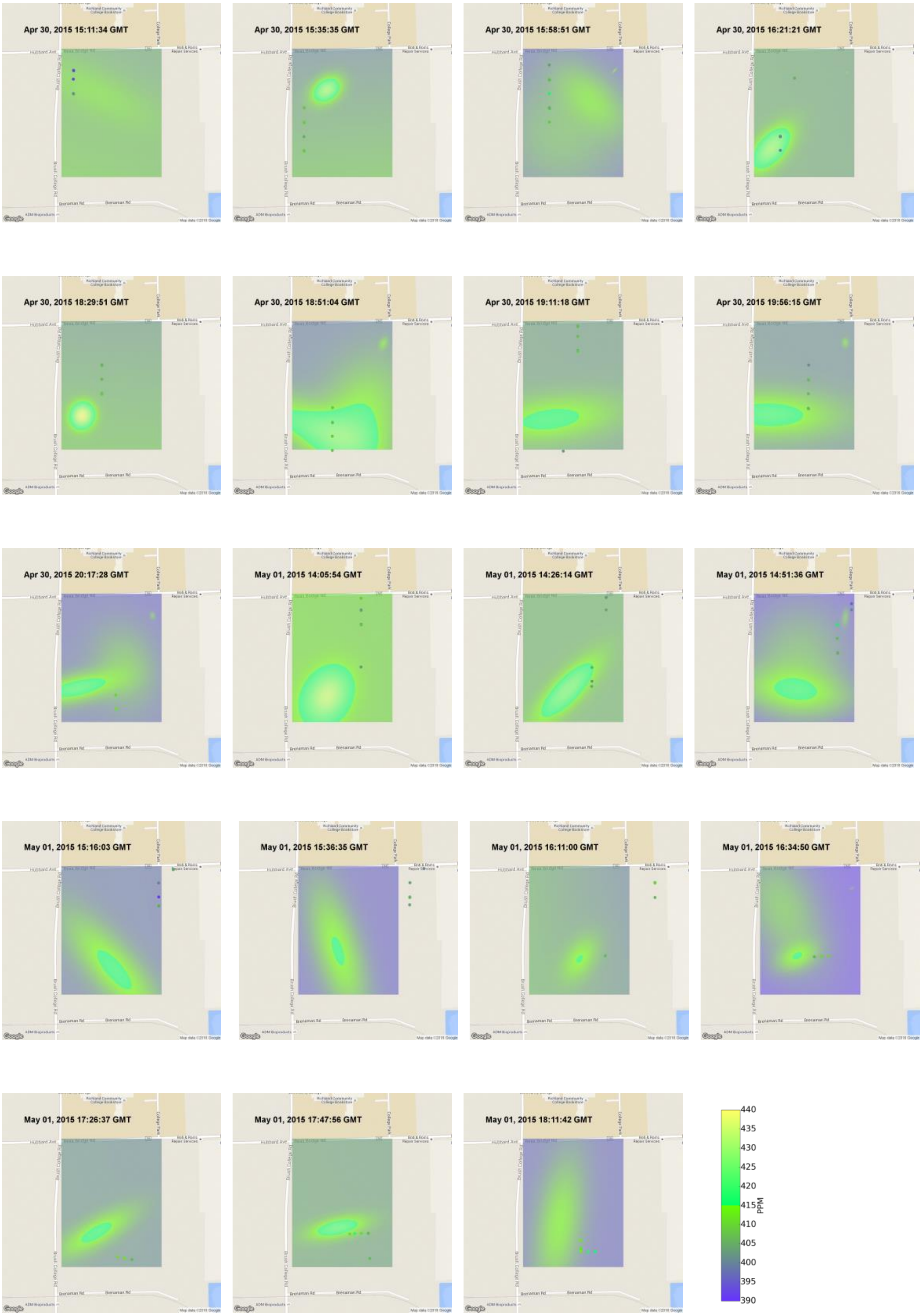


Figure 33. Over-plot of initial concentrations measured in the flux chambers (colored points) on temporally and geographically located reconstructions for IBDP site.

In addition to this approach we also compared the IBDP provided flux map to an average of all the 2-D reconstructions of concentration from GreenLITE during the same time period that the flux map samples were taken and the result is given in Figure 34.

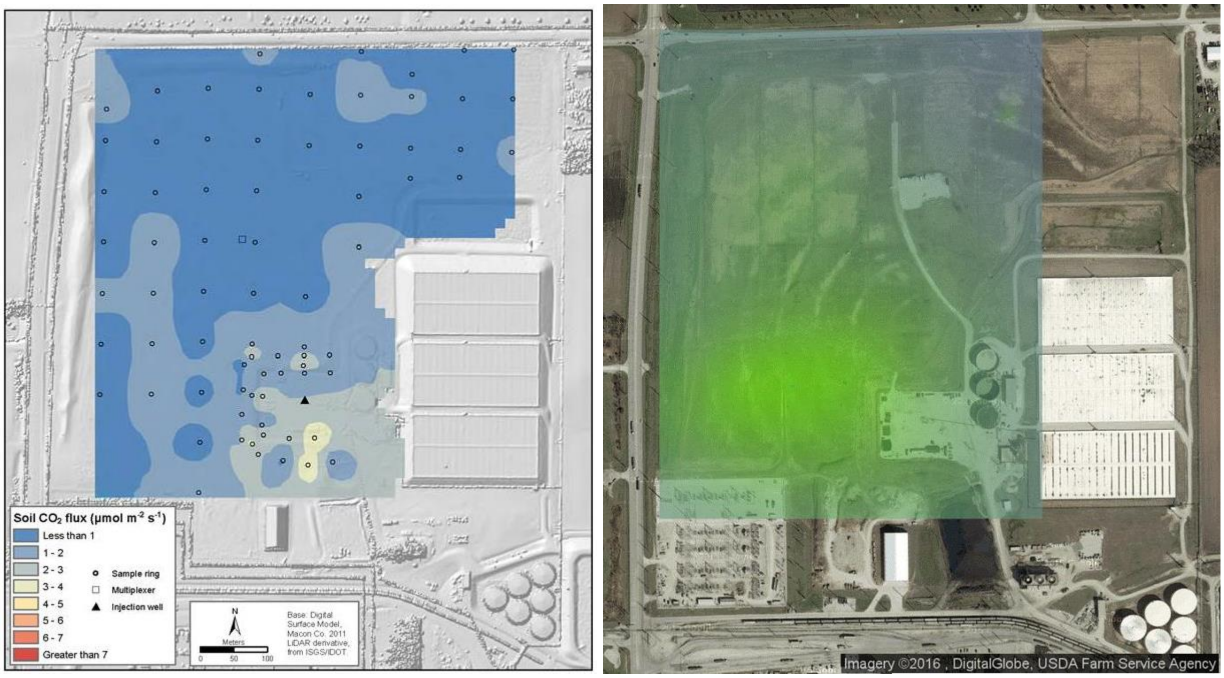


Figure 34. Comparison of a map generated from the IBDP flux monitoring network provided by ISGS (left) to the average GreenLITE 2-D reconstructions over the same time period as the flux measurements were made (right).

A full set of the average concentrations over the course of the deployment as measured from GreenLITE are included along with a full set of the 2-D reconstructions and chord data are included with the data archive.

Future Considerations

While the GreenLITE system performed quite well throughout its 5+ month operational deployment at IBDP, there are some improvements and enhancements that could be made to further increase the reliability, accuracy, and durability of the system while also broadening the range of potential applications. The addition of a locked laser source would improve accuracy by ensuring that the laser wavelengths do not drift and cause a bias in the measured CO_2 concentration. This was not determined to be an issue for this deployment, but it does add some uncertainty of up to a few ppm. Protective windows could be added to the retroreflectors to increase their useful lifetime. The manufacturer's protective coating did not fare well in the elements and caused the reflectivity of the reflectors to gradually decline over time by almost an order of magnitude over the deployment period. For this deployment we had sufficient margin that the loss in reflectivity did not cause the system to fall below the needed SNR of >1000 to maintain accurate measurements, but would likely have posed a problem if the setup was closer to the design range of 1 km path lengths. If windows were tested and required specialty glass that may add too much additional cost to the system, other coating materials could be considered that would be more robust.

Replacement of the mechanical scanner with an optical scanner could allow twice the coverage by enabling 360 degree rotation of the optical head. This was beyond the scope of the current program, but should be considered for future implementations.

The GreenLITE system could be used in a wider range of applications if it could also measure other gas species, such as methane. The system can be converted to measure methane through a straightforward switch of laser sources and modulators to those appropriate for the wavelengths needed to measure methane.

The system could be expanded to cover larger areas up to 50 or 100 km^2 using higher power amplifiers for the modulators and increasing the reflector and receiver aperture sizes, and combining that with the optical scanner 360 degree capability.

Another significant enhancement could be to optimize the electrical efficiency currently at about 220 W per transceiver during operation, and to develop alternate power (solar, wind, or hydro in some limited locations) sources to enable operating the system in more remote locations.

Additional automation of system alignment during setup and monitoring of telemetry data to notify the operator of potential issues could also be implemented to minimize the need for highly skilled operators in monitoring of the system.

Throughout the deployment period, persistent plumes were observed in certain areas of the measurement field. *In situ* measurements made with portable CO_2 sensors seemed to indicate that these plumes originated from nearby ethanol plant operations. For future deployments, characterization of nearby external sources would aid in interpretation of the 2-D reconstruction images.

Comparisons of the results with the IBDP measurements showed a strong correlation and further work should be done to evaluate the efficacy of this approach to replace other more labor intensive approaches. Ultimately, a number of measurement techniques will be required to meet the objective of verification of 99% containment over 100 years.

Other Potential Enhancements

In response to FY16Q2 - Carbon Storage Peer Review (FY15) - R2 we provide the following description of "design trades for site specific factors, distance between reflectors and transmitters, and potential for 3-D mapping capability (including vertical in addition to the horizontal measurements)."

First, it is important to note that there are restrictions on the sensor to reflector range both on the short and the long range side. For the shorter ranges high measurement precision requires much higher SNR from the instrument due to the very small value of absorption over the short path as illustrated in Figure 35. Very long ranges behave in the opposite way where the absorption signal is large, but the optical signal will become very small and makes achieving a high SNR challenging. For long paths higher SNR can be achieved by increasing the size of the receiver optics and retroreflectors, by transmitting higher powers, or by using specialized electronics and detectors, all of which drive cost.

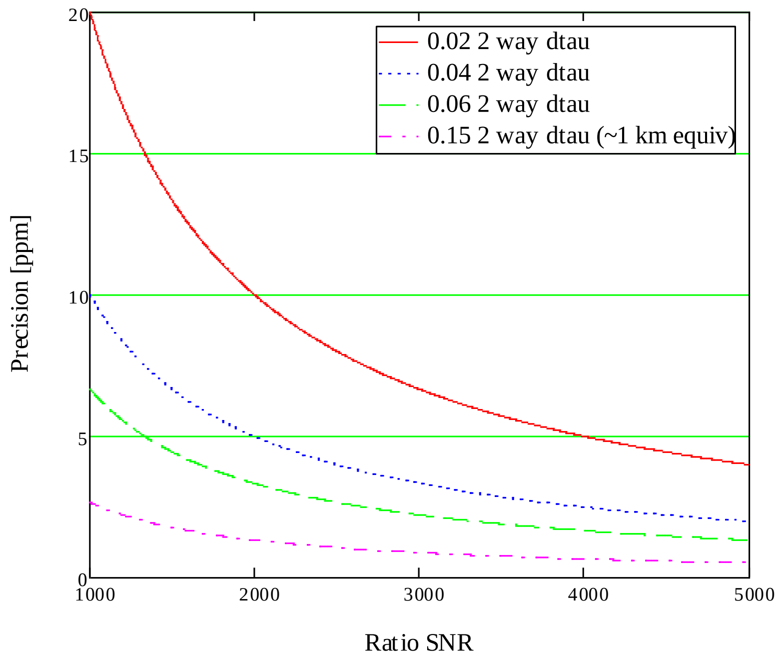


Figure 35. Example of measurement precision and required SNR as a function of optical depth (path length and concentration)

Our analysis indicates that the optimal operation is for ranges between 500 m and 5000 m. Below 500 meters the absorption is too low limiting precision and beyond 5000 meters the required optics, power, or detector scaling to maintain high SNR become cost prohibitive and grows exponentially. It is possible to extend the measurements out to 10 km path lengths or more, but the size of optics and complexity becomes prohibitive. With an optical scanner, as mentioned previously, a full 360 degree scan would be possible and would allow areas 0.5 km^2 to 50 km^2 to be covered with a GreenLITE system without significant impact on the design, cost or complexity of the system. Other restrictions still apply relative to the need for line-of-sight between a given transceiver and reflector.

With these limits in mind it is feasible to implement a 3-D GreenLITE system. For example, this could be done by using more than one reflector height and having multiple horizontal planes in a stack. Other possibilities include arranging the system as a box using 4 transceivers with towers at the corners, and reflectors in between. The benefit of this approach is it would be used along with wind information to monitor an entire facility and better estimate flux. It would require additional setup costs but could leverage existing infrastructure like the telephone poles that are around much of the IBDP site. A simple example is given in Figure 36.

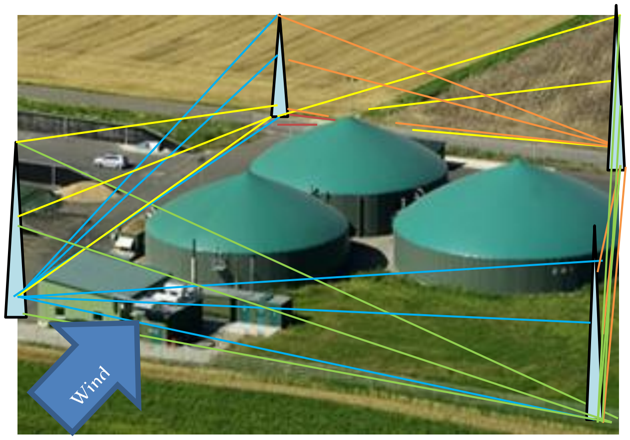


Figure 36. Simple example of a fence-line concept for determining flux from an isolated facility. Additional reflectors could be added across the sides to enable a 2-D cap in addition to the walls. Many other configurations are possible depending on the needs and site specific details.

The system is already capable of scanning in both the horizontal and vertical directions. The algorithms would have to be updated and it would have to be worked out if true 3-D reconstructions could be generated. It would be straight forward to apply the techniques demonstrated on this project to multiple 2-D planes at different heights that could then be used to generate a quasi-3-D representation of CO_2 concentration in a volume.

Conclusion:

GreenLITE was a novel concept envisioned as a potential key component of a long term solution for monitoring of GCS sites and verification of 99% containment. A big advantage of the GreenLITE system is the visualization that the 2-D mapping can provide. This capability enables live feedback to the operators and the public. The latter being a key factor in obtaining support for long term GCS operations. The program was executed very closely to the proposed plan and the system operated as proposed. A number of experiments were performed showing that the GreenLITE system is capable of producing quantified measurements across an entire carbon storage facility. A number of potential enhancements have been described that could further improve the utility of the GreenLITE system for GCS MRV activities. Another significant benefit of the GreenLITE system is the continuous, autonomous operation capability which has the potential to reduce long term labor requirements associated with other measurement approaches.

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LIST OF ACRONYMS AND ABBREVIATIONS

2-D - 2-Dimensional

A/D - Analog/Digital

ADC - Analog to Digital Converter

ADM - Archer Daniels Midland

AER - Atmospheric and Environmental Research

APD - Avalanche Photodiode

COTS - Commercial Off-The-Shelf

DAQ - Data Acquisition

DFB - Distributed Feedback

DOE - Department Of Energy

EDFA - Erbium-Doped Fiber Amplifier

FOV - Field Of View

GCS - Geological Carbon Storage

GPS - Global Positioning System

GreenLITE - Greenhouse gas Laser Imaging Tomography Experiment

HPF - High-Pass Filter

IBDP - Illinois Basin - Decatur Project

IMCW - Intensity Modulated Continuous Wave

ISGS - Illinois State Geological Survey

LAnTeRN - Laser Atmospheric Transmitter and Receiver-Network

LaRC - Langley Research Center

LAS - Laser Absorption Spectroscopy

LBLRTM - Line-By-Line Radiative Transfer model

MFLL - Multifunctional Fiber-Laser LIDAR

MRV - Monitoring, Reporting, and Verification

OD - Optical Depth

PRN - Pseudo-Random Noise

RH - Relative Humidity

RMSE - Root-Mean-Square Error

Rx - Receiver

SLSQP - Sequential Least Squares Programming

SNR - Signal-to-Noise Ratio

SOA - Semiconductor Optical Amplifier

SOPO - Statement Of Project Objectives

TIA - Transimpedance Amplifier

Tx - Transmitter

UPS - Uninterruptible Power Supply

ZERT - Zero Emissions Research and Technology

APPENDICES

NA