Spatial mapping of greenhouse gases using laser absorption spectrometers at local scales of interest

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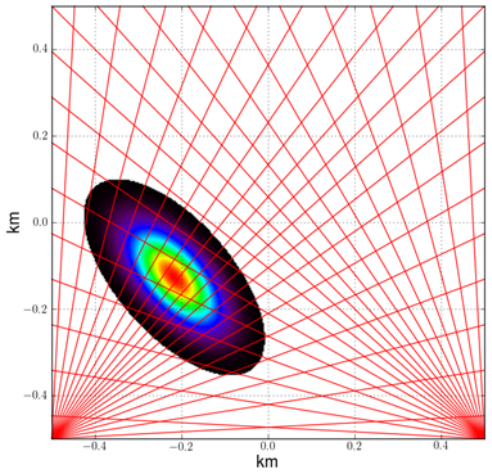
Overview

- Greenhouse gas Laser Imaging Tomography Experiment (GreenLITE)
- Background
- Measurement technique
- Instrument overview
- Algorithm review
- System testing
  - Local
  - Zero Emission Research and Technology site
  - Illinois Basin – Decatur Project
  - Boulder Atmospheric Observatory
- Summary and future plans

Program Objectives Greenhouse gas Laser Imaging Tomography Experiment - GreenLITE

- Original system developed for the DOE under cooperative agreement DE-FE0012574
- Addresses this DOE Program Goal:
  - *"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."*

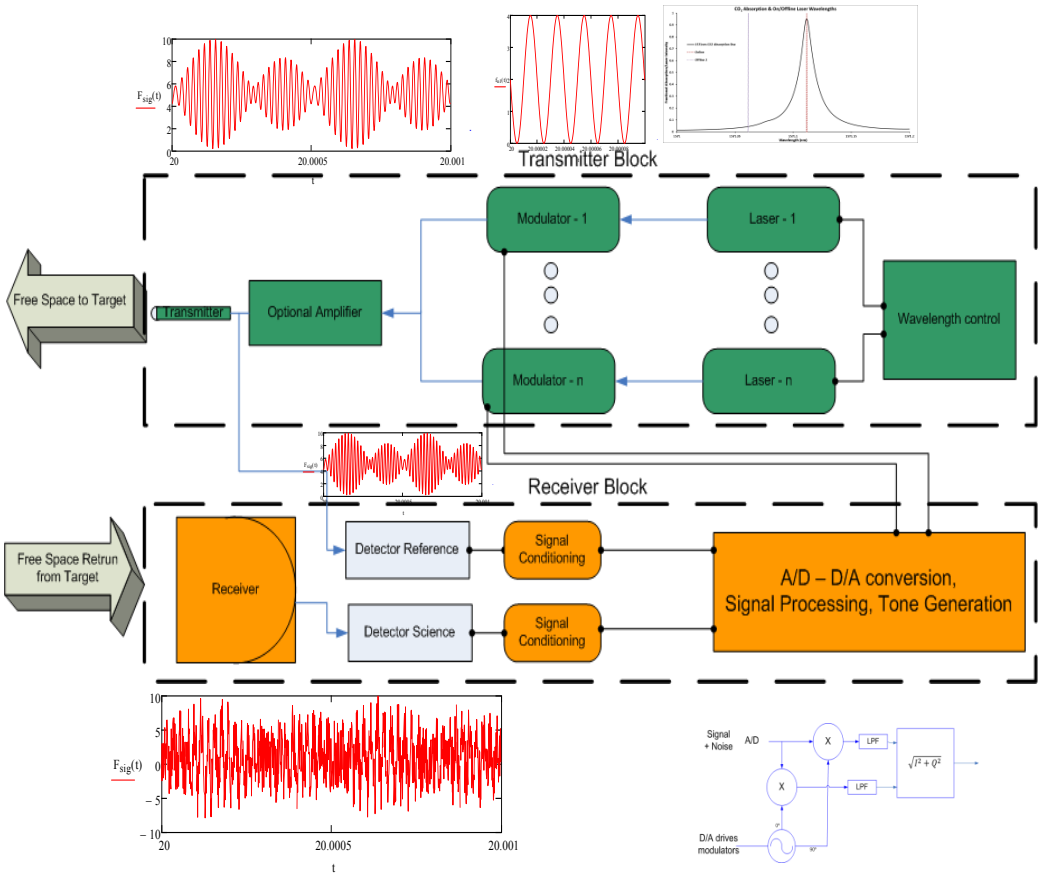


- 2 scanning Laser Absorption Spectrometer (LAS) instruments with a series of retro-reflectors. Real-time, continuous, unattended, remote operation. Robust open web user-friendly interface for remote access and monitoring of site data.

- Test performance locally and validate at the Zero Emissions Research and Technology (ZERT) facility (Bozeman, MT)
- Demonstrate the system over an extended period at an operational Ground Carbon Storage (GCS) site

Intensity Modulated Continuous Wave (IM-CW) Laser Absorption Spectroscopy

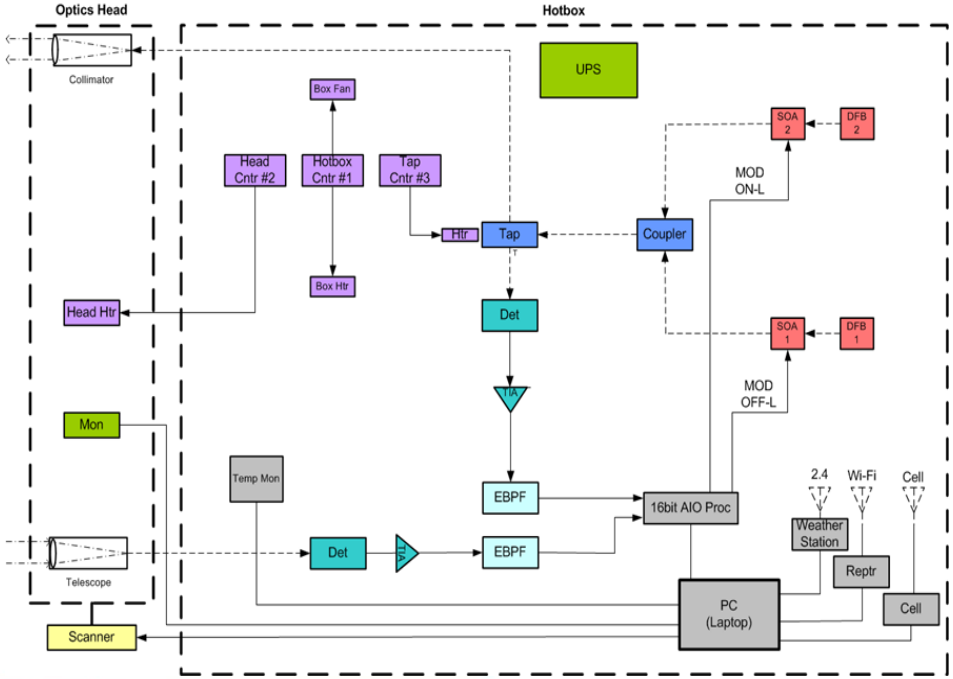
- 2 or more fixed optical wavelength lasers
- Unique amplitude modulation for each channel
- Simultaneous transmission of all wavelengths
- Optional amplification post combining
- Reference signal tapped off
- Return signal contains modulated waveform and noise
- Converted to electrical signal after collection
- Signal is digitized and a digital lock-in amplifier is used to separate wavelength components
- Ratio of transmit signal normalized returns gives differential transmission



- Differential transmission is used to estimate dry air mole fraction using radiative transfer

GreenLITE Instrument Overview

- **Designed for autonomous long-term remote operations**
- **Simultaneous transmission of on and off λ**
- **Eye-safe 1571 nm, 5mW CW transmitter**
- **Measures differential transmission and range**
- **3G/4G wireless data streaming**
- **Interfaced directly with local weather station**



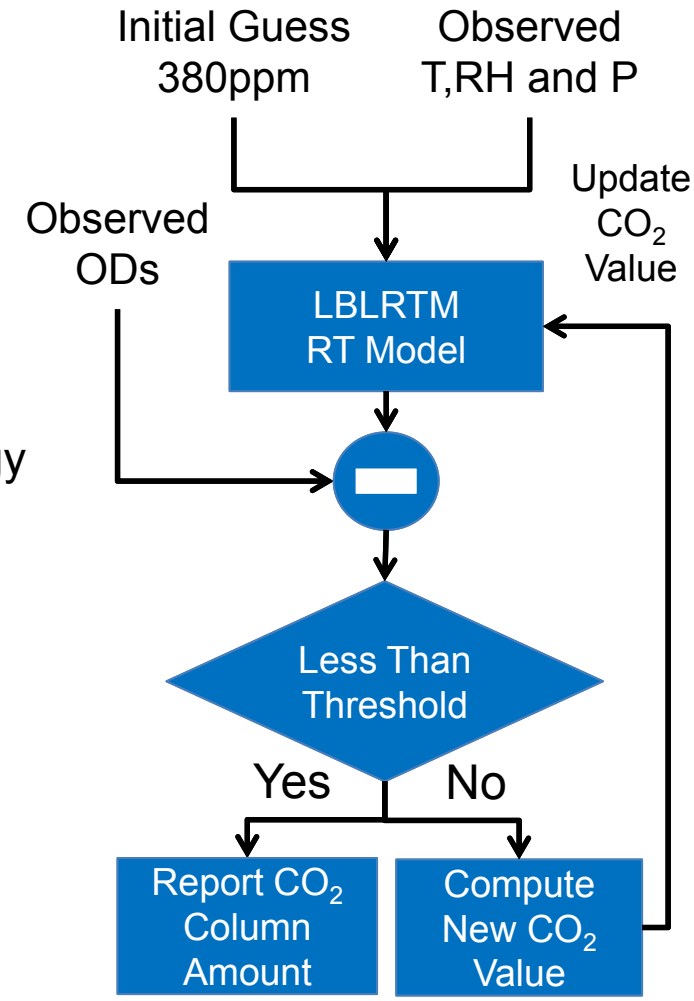
Online Wavelength	1571.1129 nm
Offline Wavelength	1571.0629 nm
Optical Transmit Power	5 mW (2.5 mW per ch.)
Modulation Rate	19.2 – 24.6 kHz
Modulation Waveform	sinusoidal
Sampling Rate	1.0 MHz
Sampling Resolution	16 bits
Transmitter Optics	25 mm
Receiver Optics	25 mm
Optics Configuration	biaxial, fiber-coupled
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
Current design range	1 km

Control & Acquisition Software

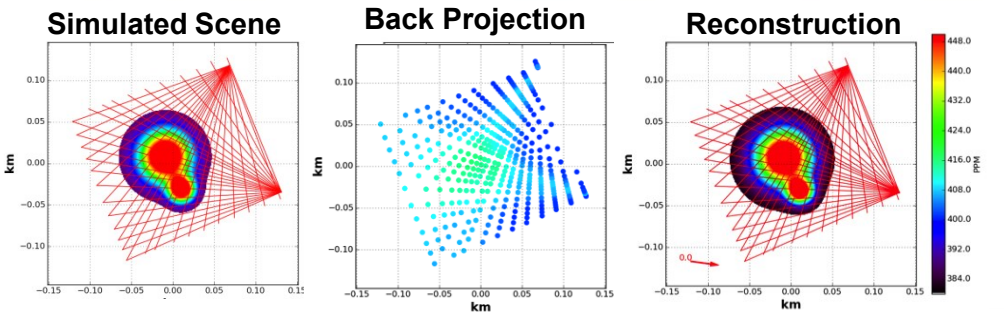
- All hardware control, data acquisition, and data transmission to server is LabVIEW-based.
- Left image shows main program, right image shows pan-tilt positioner (scanner) control & status.

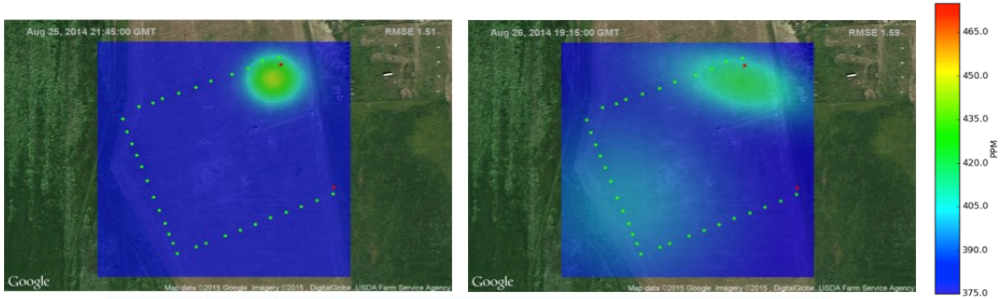
Retrieving CO2 Concentrations from Optical Depth Measurements

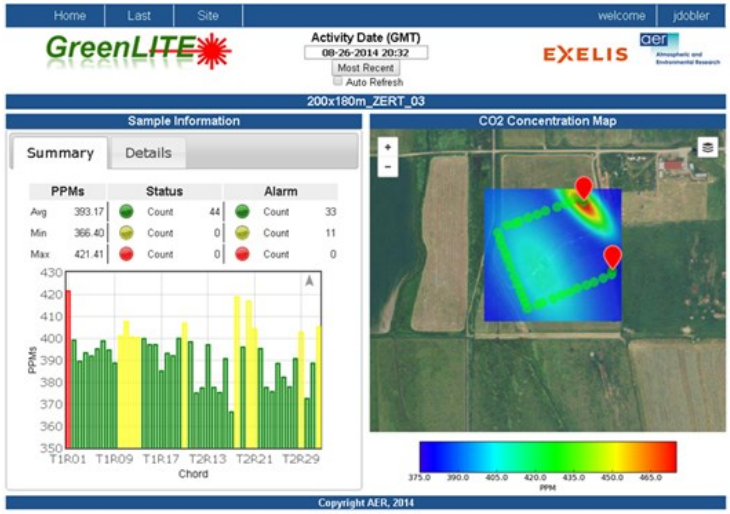
- Algorithms developed by our partners at Atmospheric and Environmental Research, Inc.
- Iterative Radiative Transfer-based approach is used to estimate chord concentrations
  - Ingest
    - Observed optical depths
    - In situ measurements of surface meteorology (T, RH and P)
  - Model expected optical depth given path configuration and T, RH and P
  - Assess difference between model and measured values
  - Adjust CO_2 column amount based on gradient so that model best matches measured values
  - Approach has been demonstrated for both airborne and ground implementations



2D Reconstructions





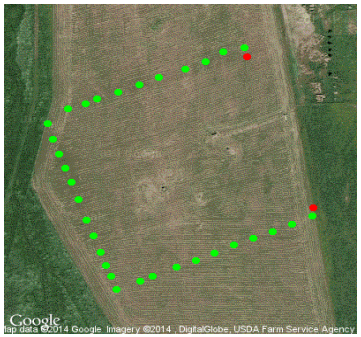


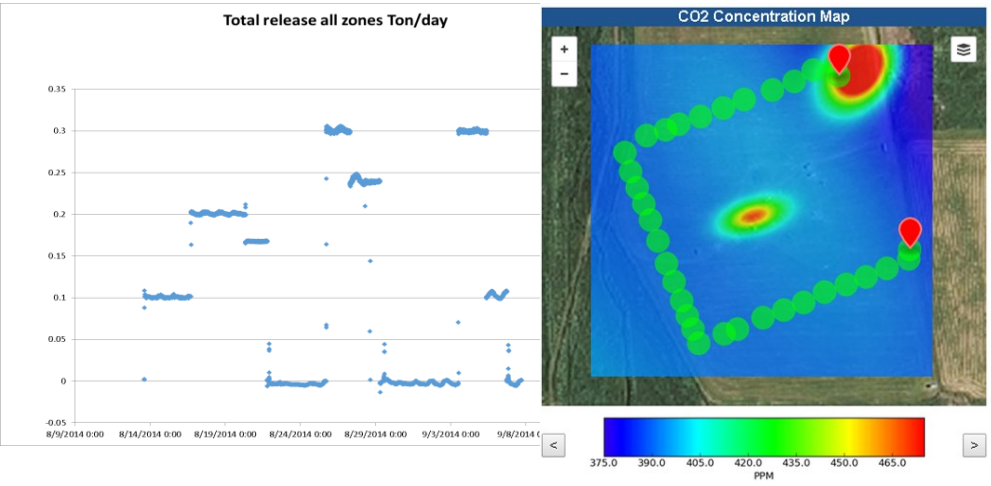
- Objective
  - Employ simplified gradient and idealized plume model to describe 2-D field distribution
- Challenges
  - Analytic model is only idealized estimate of wind driven plume and does not account for complex variations in background.
  - Small number of observed values under-constrains the reconstruction problem limiting ability to describe complex scenes
  - Natural variability in chord data makes precise fitting difficult
  - Non-standardized geometries of chord placement due to geographic constraints, e.g. road, buildings, provide sub-optimal samples.
- Solution
  - Extensive trade study performed to develop model constraints that enable generalized best fit over diverse set of environmental conditions
- Future
  - Explore *a priori* statistics to further constrain model and expected values to provide better site/application specific solutions

Initial Testing at Exelis Laser Test Range

- Sensor and system testing were performed at Harris' laser test facility in New Haven, IN.
- Initial testing was conducted spring and summer 2014
- Testing focused on system functionality from sensor to web interface while preparing for performance testing at instrumented test site in Montana.
- Follow on testing also validated performance of 2D reconstructions for localizing plumes by elevating specific chord concentrations
- Demonstrated remote operability under harsh winter conditions

System testing - ZERT



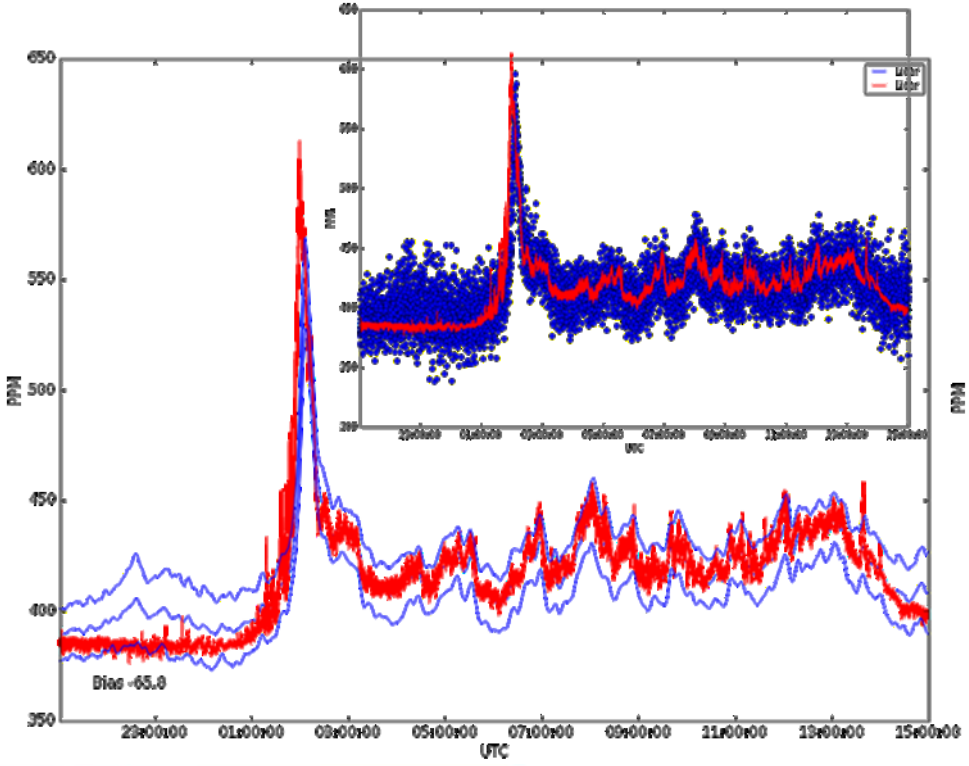


- Additional testing was performed at the Zero Emissions Research and Technology Facility operated by Montana State University, in Bozeman, MT 8/18/2014 – 9/9/2014
  - Horizontal well for controlled releases ~2m below the surface up to 0.3T/day from 70 m pipe split into 6 segments.
- Over 600 hours of data over a wide range of conditions were collected in Bozeman.
- System and software were designed, built, and deployed in 10 months
- Saw persistent features from ground release and other natural sources, even in the presence of varying background levels.
- Also made direct comparisons to independent onsite *in situ* measurements (next slide)

Comparison with Li-COR (West Systems)

Average of all chords (blue) closely matches trends of Li-COR-based system (red), capturing large respiration signal at sunset. However, spatial variation is seen in lidar data chords that an in-situ monitor can not capture.

05-06 September 2014



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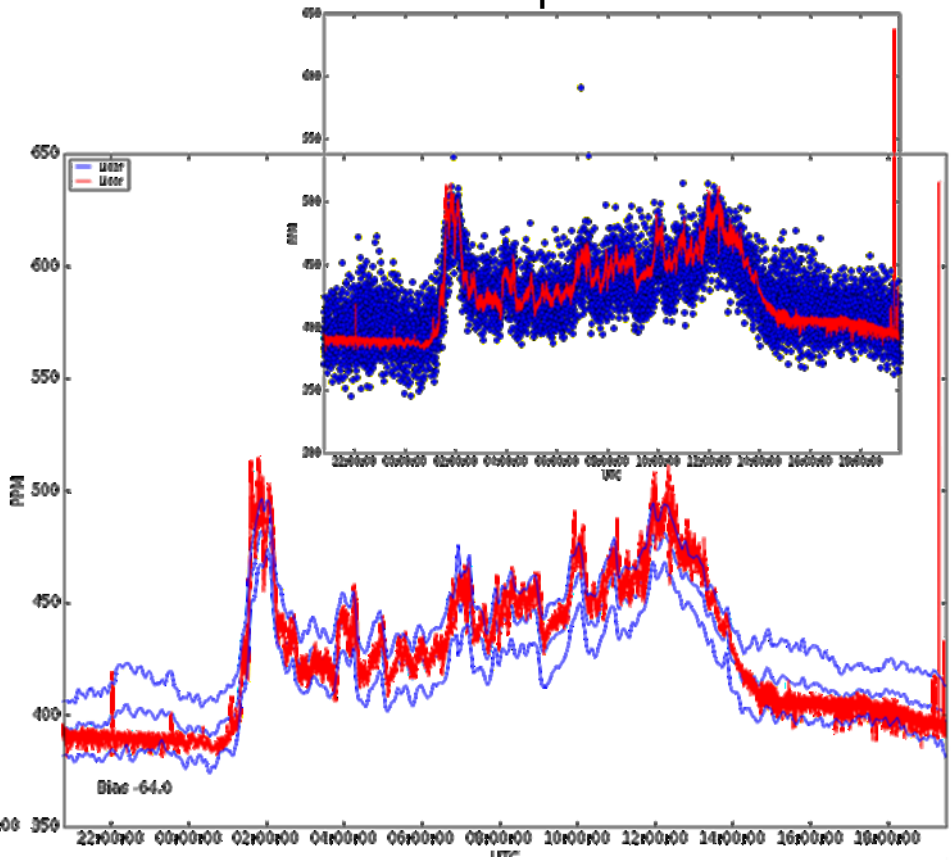
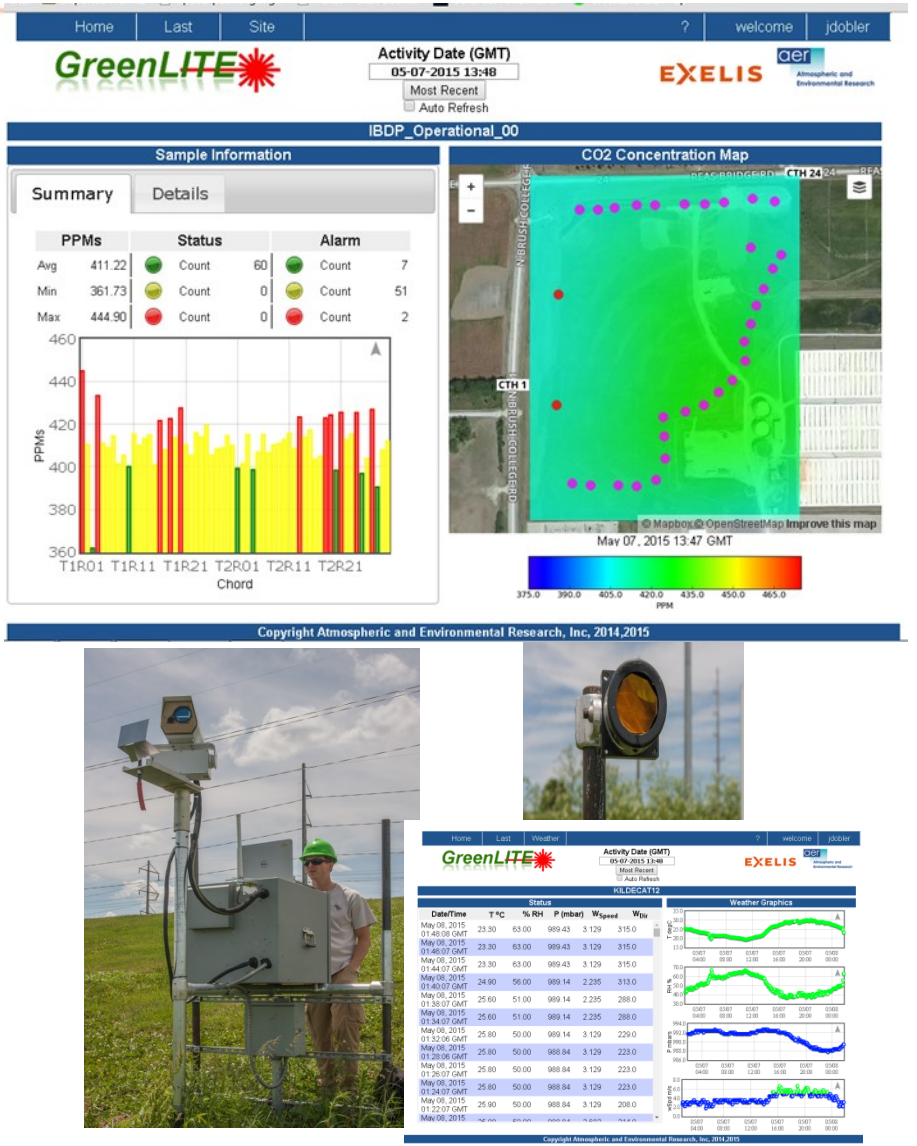
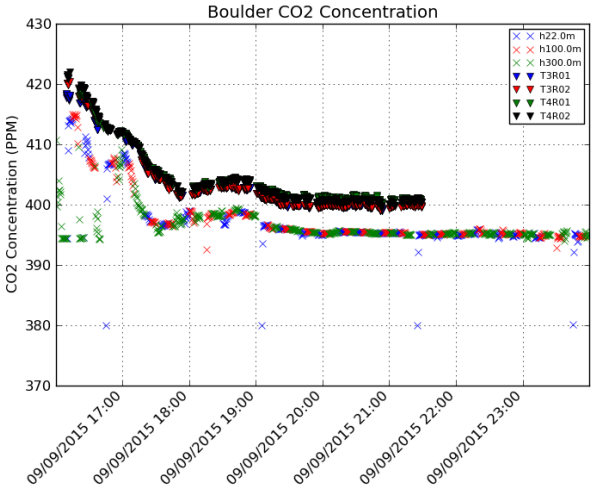


System testing - IBDP

- The Illinois Basin - Decatur Project is a large scale GCS project led by the Illinois State Geological Survey in partnership with Archer Daniels Midland
- GreenLITE was deployed on site in Feb 2015 and operated near continuously until early August 2015
- System Collected and displayed via a secure web-based user interface > 1.8M retrieved concentrations and 72 k 2D-reconstructions with a 90% uptime to down time duty cycle
- Only on site interaction was a monthly inspection and cleaning, all other interaction was performed remotely from Fort Wayne, IN



System testing - BAO



- System was upgraded for 5 km in 2015
  - 1” optics expanded to 6”
  - Laser power increased to ~25 mW
  - Larger Retro reflectors used
- Tests conducted 8/31 – 9/11 at the NOAA Boulder Atmospheric Observatory
- Placed 5 retro reflectors on the BAO tower
  - Located at 47, 75, 97, 145, 197 m AGL
- Collected ~5 hours worth of data from 2 km NW of tower
- Collected ~14 hours of data from 5 km NW of tower
- SNR of transmission ratio >6000 over 1 min interval, (6) – 10 sec measurements
- Preliminary data provided by NOAA from LI-COR based system at 22 m, 100 m, and 300 m
- Initial comparisons look promising
  - Trends match well temporally
  - We are currently seeing ~6 ppm bias between the tower data and the LAS data

Summary and future work

- A new measurement system has been developed for monitoring GHG over large spatial scales up to ~30 km^2.
- The initial system developed for the DOE was evaluated at multiple locations, and demonstrated the ability to detect small persistent sources within the field of regard, including underground sources as small as 0.3T/day.
- The 1 km system was also deployed for a long term autonomous demonstration at an active GCS site (~6 month) period during 2/23 – 8/10, 2015, and collected over 1.8 M + raw samples, 1.6 M retrieved samples and 72 k 2D-reconstructions
- The system has recently been expanded in 2015 to make measurements over >5 km.
- The longer range system was recently tested at the NOAA Boulder Atmospheric Observatory – Analysis is underway
- Next step is to test the full 5 km GreenLITE system in a 2D mapping capacity
  - Working with Laboratoire des Sciences du Climat et de l'Environnment (LSCE) to establish a demonstration in Paris, France late 2015

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Partners: T. Scott Zaccheo, Timothy Pernini, Christopher Botos

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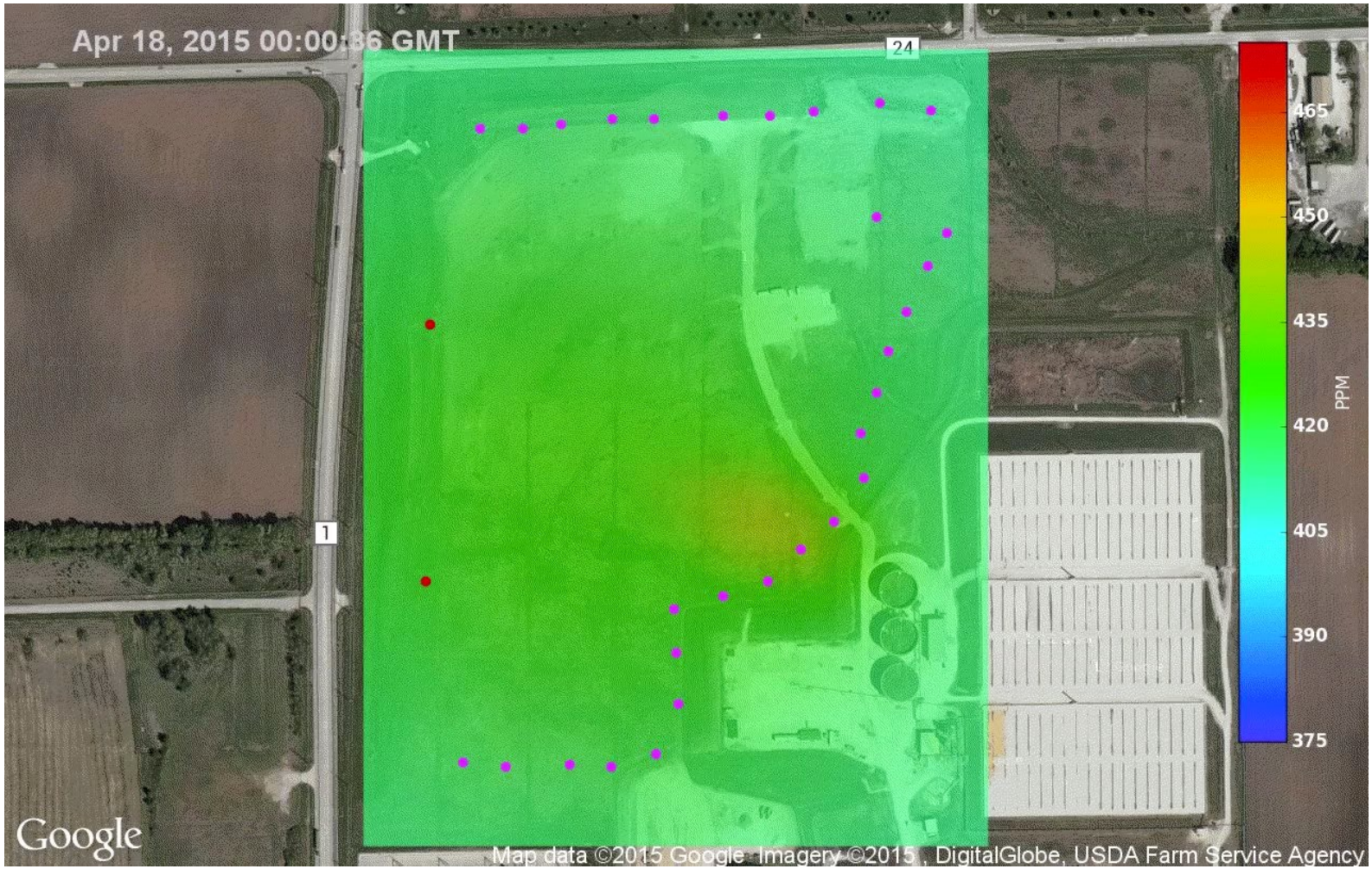
Access and support for BAO tower testing and *in situ* data for comparisons

Laura Dobeck, Lee Spangler

Questions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