A DIFFERENT VIEW OF ATMOSPHERIC CARBON MONITORING

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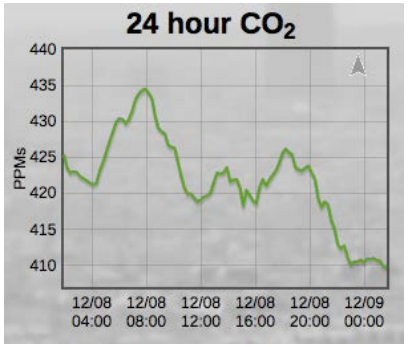
Greenhouse gas Laser Imaging Tomography Experiment - GreenLITE

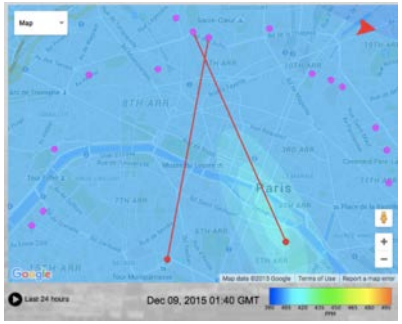
- Provides 24/7 real-time measurements
  - Near-surface concentrations
  - 2-D view of the concentration and distribution of near-surface CO_2.
- Collaboration between the Harris Corporation and Atmospheric and Environmental Research (AER)
- System Design:
  - Employs differential absorption spectroscopy to measure integrated column CO_2 concentrations for a set of user defined paths 200m – 5 km in length (transceivers to retro reflectors)
  - Constructs 2-D distribution using sparse tomography over 0.25 to >25 km^2
- Original system developed for the DOE for *detecting and measuring CO_2 leakage from geological storage sites*
- Field Deployments and Installations
  - Montana State University Zero Emissions Research and Technology (ZERT) facility
  - The Illinois Basin - Decatur Project : Large scale GCS project
  - NOAA Boulder Atmospheric Observatory (BAO) tower
  - Paris FR
- Ongoing work
  - Validation and extensions of approach to other trace gases, e.g. CH_4

Paris Deployment

Time Varying Average CO_2

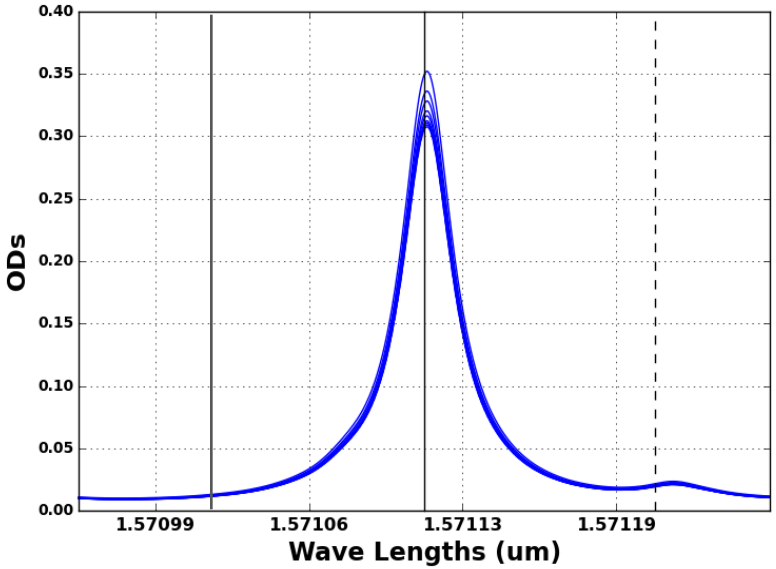


2-D Spatial Distribution



Estimating Column CO_2 via Differential Laser Absorption Spectroscopy (LAS)

- **Initially developed to monitor ground carbon storage sites**
- **GreenLITE Approach**: Retrieve CO_2 (or other trace gas) column amount from differences in observed optical depths for two closely spaced laser wavelengths over a defined atmospheric round trip path.
- Repeat for many overlapping paths spanning a plane.
- Use intersecting retrieved column values to estimate concentration distribution across the plane.



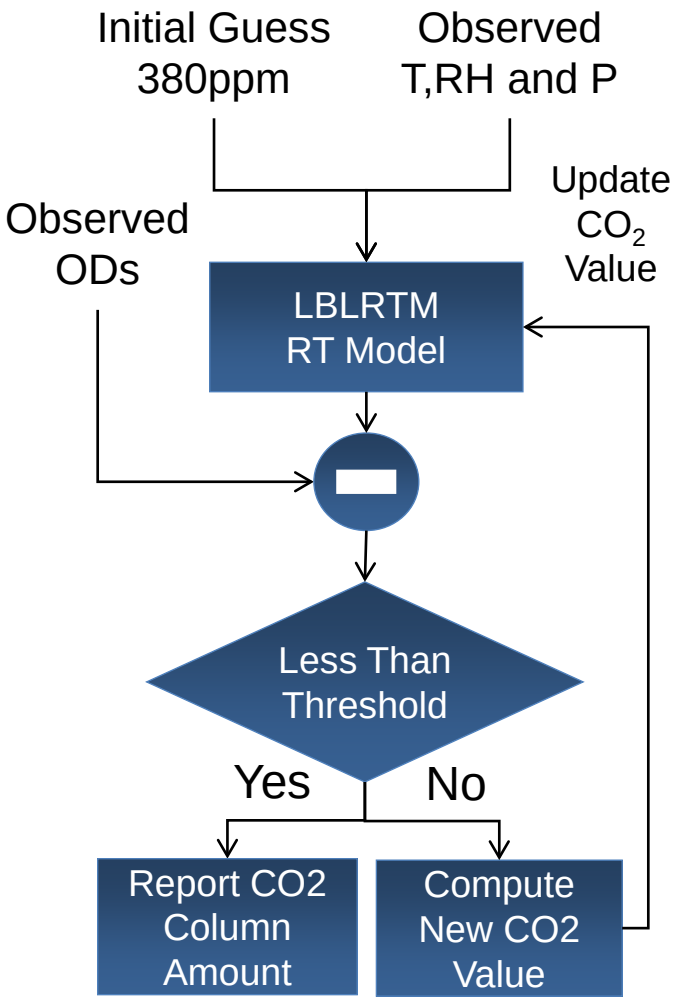
Basic Retrieval Recipe

1. Simultaneously measure absorption of “On”-line wavelength λ (on absorption feature of interest) and absorption of “Off”-line wavelength λ+ Δ (in the continuum)
2. Fit estimated column value XCO_2 to observed difference given path length and local atmospheric state
3. Retrieve spatial information through sparsely sampled tomography approach

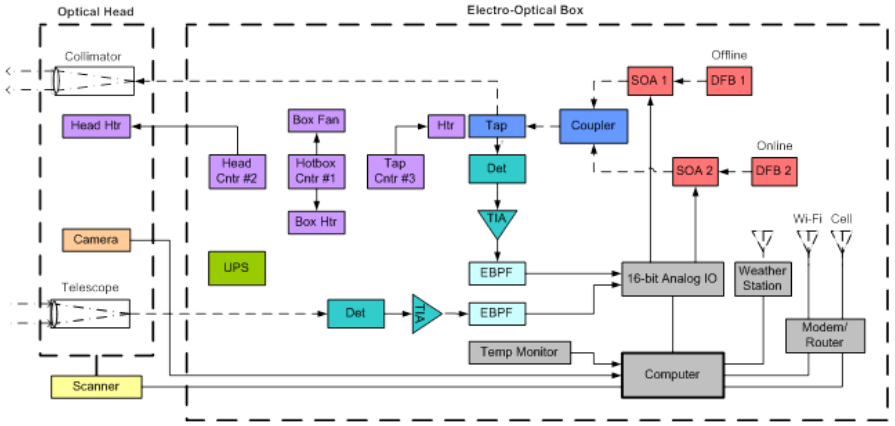
Retrieving CO_2 Concentrations from Optical Depth Measurements

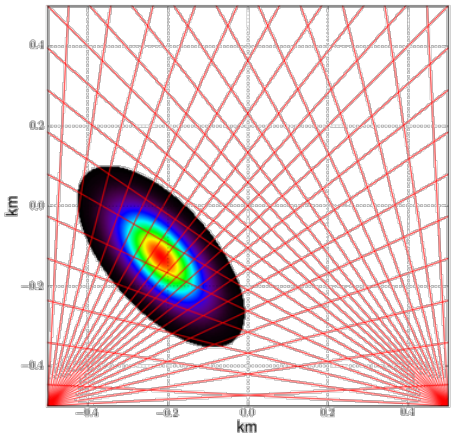
- **Basic iterative RT-based approach**
  1. Ingest
     - Observed optical depths
     - *In situ* surface observations (T, RH and P)
  2. Model expected optical depth given path configuration and T, RH and P
  3. Assess difference between model and measured values
  4. Adjust CO_2 column amount based on gradient
  5. Converge when model matches measured values
- **Extended approach for chord length > 1 km over varying topography**
  - Minimize fit for a sum of fixed sub-chord segments along the path with fixed lengths and varying atmospheric states.
- **Construct 2-D views using model-based tomographic reconstruction approach**
  - Describes underlying field as function of analytic features and simple 2-D background gradient

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



GreenLITE instrument concept overview of initial 1 km system





- **Autonomous, remotely operated set of transceivers with multiple reflectors**
- **Eye-safe 1571 nm, 5mW CW transmitter**
- **Measures differential transmission and range over multiple intersecting paths**
- **3G/4G wireless data streaming**
- **Interfaced directly with local weather station**
- **Retrievals to XCO_2 in near real-time on AWS**
- **Near-real-time data dissemination via web interface**
- **Multiple tests (Harris and ZERT) and 6+ month continuous deployment (IBDP)**

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
Lock-in Period	10 sec (adjustable)
Power	110 V, 60 Hz, 3 A
Current design range	1 km

Extended System Testing – Boulder Atmospheric Observatory

Online Wavelength	1571.1129 nm, 1571.1137 nm
Offline Wavelength	1571.0629 nm, 1571.0637 nm
Optical Transmit Power	25 mW (15 mW on 10 mW off)
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	152 mm
Optics Configuration	coaxial, fiber-coupled
Detector	InGaAs PIN
TIA Gain	10^5 or 10^6 (programmed)
Retroreflectors	127 mm
Lock-in Period	10 sec (adjustable)
Power	110 V, 60 Hz, 3 A
Current design range	1 km

- System was upgraded for 5 km in 2015
  - 1” receive optics expanded to custom 6”
  - Laser power increased to ~25 mW
  - Larger Retro reflectors used
- Tests conducted 8/31 – 9/11 at the NOAA Boulder Atmospheric Observatory – Funded by NIST
- 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 found an ~5 ppm bias between the tower data and the LAS data with a STDEV of 0.5 ppm – further evaluation in process
- Moving toward urban scales

Deployment to Paris

Initial discussions for expanding the GreenLITE™ system to 5 km chords and deploying in Paris began in February 2015.

Subcontractors Enviroearth, obtained permissions for operation in Paris, and establishing collaborations with LATMOS, Montparnasse ICADE, Paris Habitat, Elogie and CESE.

Harris/AER designed and built the 5 km system in ~6 months and deployed to Boulder in August/Sept.

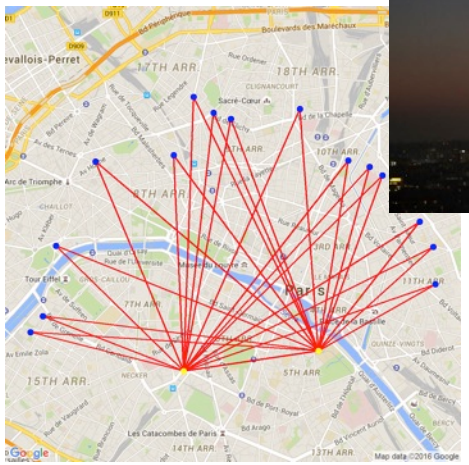
Mounting hardware compatible with the locations, was designed and shipped with the instrument for initial installation in Paris during October.

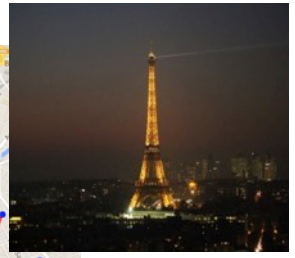
Harris completed the installation in the first week of November and the system saw first light on November 9th

Two transceivers and 15 retro reflectors were installed

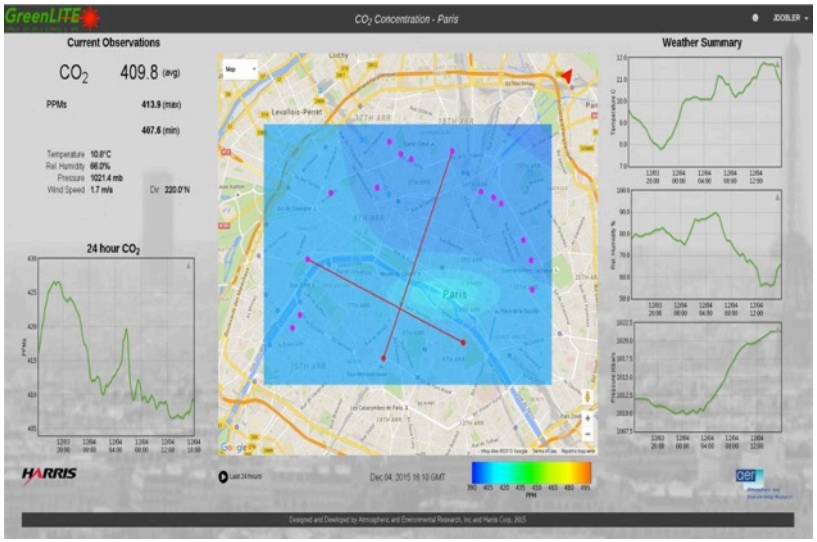
Typical reflector installation

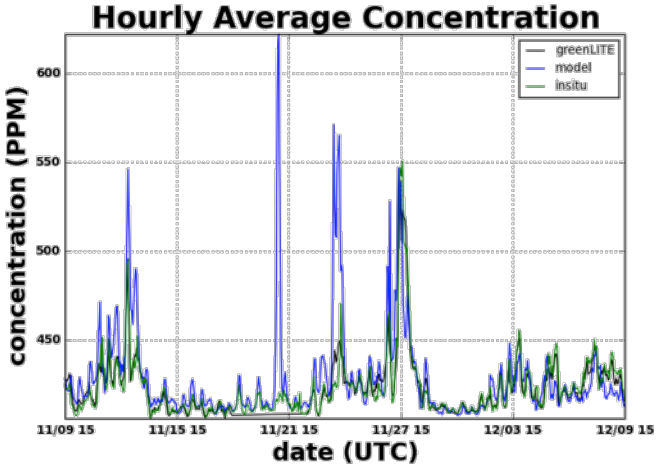
Jussieu tower transceiver installation

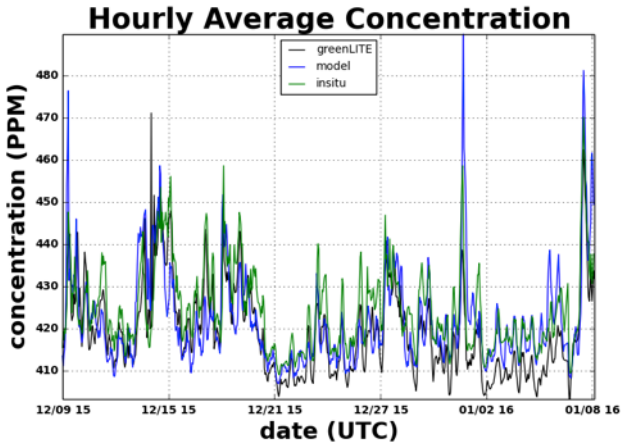




Paris Results Following COP21





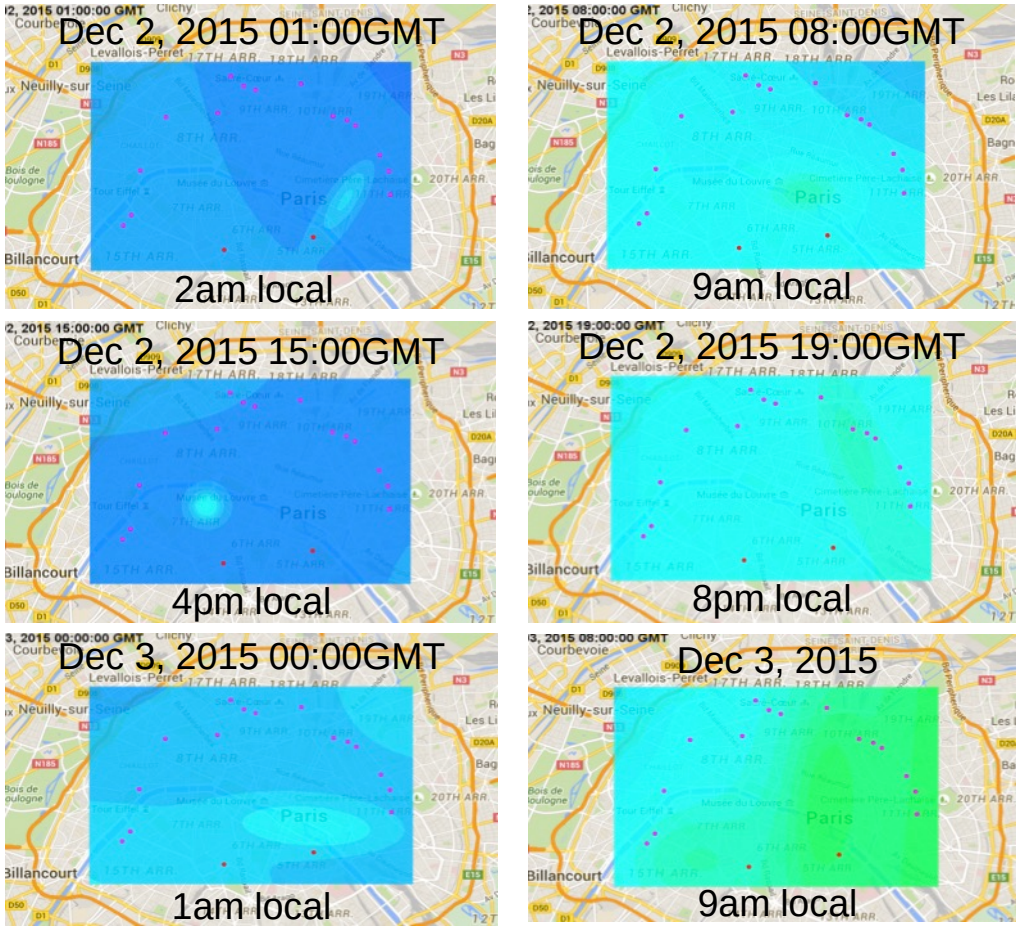


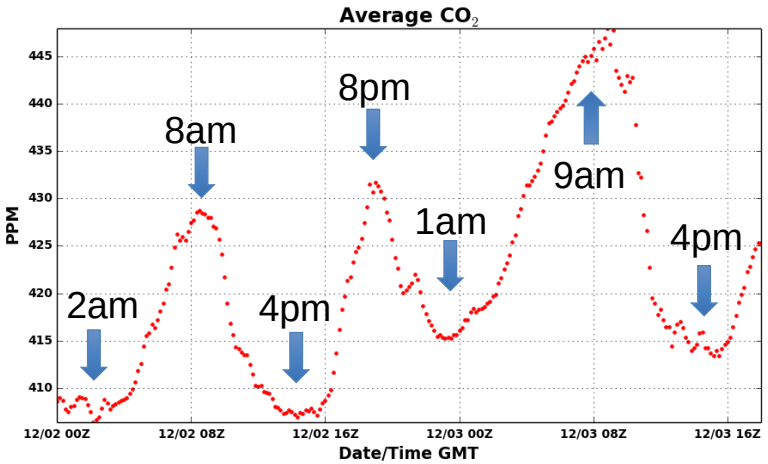
As of 5/9/2016, we have collected over 4M raw samples, retrieved more than 2.4M ppm values passing QC, and generated >50k 2D reconstructions over Paris, France, in near-real time.

Comparisons with a Picarro located within a park just outside of the GreenLITE™ footprint confirms the large excursions from the models seen by GreenLITE™ are real.

Picarro data made available by Cité des Sciences et de l'Industrie (Marc Jamous, Jean-Christophe Theisen, Didier Philippe, Michel Maintenant, Sylvain Aulombard et Michel Pérez) , and the staff from LSCE who helped to setup the analyzer (M.Ramonet, M.Delmotte and M.de Florinier)

Example: 36hr CO_2 Time Sequence over Paris France





Measurements and reconstructions provide real-time dynamic of complex environments

What is next?

Continuing operations in Paris until November 2016 – Results in a full year record and ability to evaluate diurnal and seasonal cycles – currently Harris funded

Working with LSCE and LATMOS for additional *in situ* measurements in Paris for system evaluations

Continuing evaluation of model comparisons and working toward inclusion of GreenLITE™ data in inversions

Working on integration of a locked laser to improve performance

Submitted CMS proposal with NOAA and OU to evaluate vertical column at BAO tower with augmentation from Picarro on elevator to resolve integrated column. Uses 1 km system developed for DOE

Also includes a null test at RRV Nevada for the 2-D reconstructions

Working on a methane version for first analysis under Harris funding in 2016

Proposal submitted for a combined CO2 and CH4 system for US city deployment

Questions