A Laser Absorption Spectrometry System for Monitoring the Spatial Distribution of CO_2 over Paris, France

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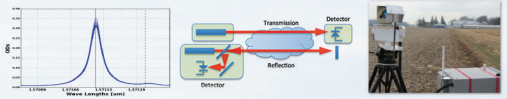
ABSTRACT

In 2015 Harris Corporation and Atmospheric and Environmental Research (AER) developed a system for directly monitoring the spatial distribution of CO_2 over large urban areas. The system uses a pair of Laser Absorption Spectroscopy (LAS) transceivers, based on the Harris Intensity Modulated Continuous Wave (IM-CW) approach, coupled with a series of retroreflectors in order to measure the atmospheric density of CO_2 over a large number of intersecting lines, or chords. Combining the LAS measurements with local temperature, pressure, and relative humidity, the CO_2 densities can be used to estimate the 2D spatial distribution within the area of coverage. The Harris IM-CW approach has been under evaluation from an airborne platform since 2004 and has demonstrated high accuracy and precision measurements of CO_2 in the 1.57 micron absorption band. (Dobler et al., 2013)

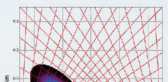
Starting in October 2013, Harris and AER developed a system known as the Greenhouse gas Laser Imaging Tomography Experiment (GreenLITE™) under a cooperative agreement with the Department of Energy's National Energy Technology Laboratory (NETL). GreenLITE™ was initially developed to monitor Ground Carbon Storage (GCS) sites, as part of a suite of measurements needed to verify 99% containment of these storage facilities. The GreenLITE™ system was evaluated over a range of conditions at multiple locations over the past years (2014-2015), with results directly compared to independent *in situ* systems. This evaluation has shown the GreenLITE™ system is capable of identifying and spatially locating sources within the field of regard (~1 km² for initial GreenLITE™ system), and the results demonstrate very strong correlation with the independent measurements.

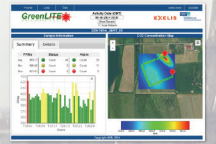
The GreenLITE™ system has now been expanded to work at a range of 5 km and to cover areas up to 25 km². The performance of the 5 km system was evaluated under a grant from the National Institute of Standards and Technology (NIST) at the NOAA Boulder Atmospheric Observatory (BAO) in August of 2015. The system was then deployed in Paris, France, with support from Enviroearth, the Laboratoire des Sciences du Climat et de l'Environnement (LSCE), and Laboratoire Atmospheres, Milieux, Observations Spatiales (LATMOS), in November 2015 and is still operational.

SENSING OF COLUMN CO_2



- **Approach:** Retrieve CO_2 (or other trace gas) column amount from active measurements of optical depths
  - Column amount is proportional to path length and molecular density
    - "On"-line wavelength λ (on absorption feature of interest)
    - "Off"-line λ+/-Δλ (in the continuum)
- **Instrument**
  - Employs telecommunication technology at wavelengths in a weak CO_2 feature (1.57um)
  - Designed to work in either Transmission or Reflection
    - *Transmission:* Eliminates partial column returns at cost of path length
    - *Reflection:* Increases path length, simplifies instrument and enclosure design
- **GreenLITE™ Concept**
  - The measurement approach is derived from the Harris-developed IM-CW airborne demonstrator for the ASCENDS mission
  - Initial development was aimed at monitoring ground carbon storage sites
  - This approach allows simultaneous transmission of multiple wavelengths, significantly reducing noise from the instrument and atmosphere in the differential measurement
  - The GreenLITE™ system consists of at least two transceivers and a series of retroreflectors to generate an interwoven grid of integrated path absorption measurements
  - Using the crossing paths of the measurement lines (chords) an estimate of the 2D spatial distribution can be derived using something similar to a sparsely sampled tomography approach
  - The system was designed to run autonomously and in near-real time while processing is done remotely and dissemination of the data is handled through a web-based interface





More information on the measurement approach can be obtained in the references below.

Dobler, Jeremy T., et al. "Atmospheric CO 2 column measurements with an airborne intensity-modulated continuous wave 1.57 μm fiber laser lidar." Applied optics 52.12 (2013): 2874-2892.

Dobler, Jeremy, et al. "Spatial mapping of greenhouse gases using laser absorption spectrometers at local scales of interest", Proc. SPIE 9645, Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing XI, 96450K (20 October 2015); doi: 10.1117/12.2197713

IN 2015, A MODIFIED GREENLITE™ SYSTEM WAS BUILT USING HARRIS AND AER DISCRETIONARY FUNDING TO EXPAND ITS RANGE FROM 1 KM TO 5 KM:

- Transmitted optical power was increased from approximately 5 mW to 25 mW. The same semiconductor optical amplifiers (SOAs) were matched with new custom controllers and drivers that are able to drive them closer to their capacity.
- Telescope diameter was increased from 1 inch (25.4 mm) to 6 inches (152.4 mm).
- Transmitter's collimator and receiver's telescope were reconfigured to mount them coaxially, to provide full overlap at any range.
- Diameter of retroreflectors was increased from 2 inches (50.8 mm) to 5 inches (127 mm).

VALIDATION OF EXPANDED-RANGE INSTRUMENT AT NOAA TOWER SITE

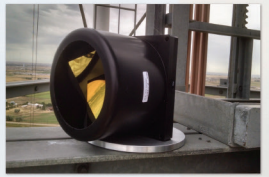
Initial testing of 5 km system was conducted at NOAA's Boulder Atmospheric Observatory (BAO) in September 2015. This 300-meter tower, located about 22 km east of Boulder, Colorado, is equipped with meteorological instrumentation at 7 heights. Harris personnel temporarily installed the new 127-mm retroreflectors on the tower, at heights of about 50, 75, 100, 150, and 200 meters. Two lidar transceivers were set up at a site ~2 km WNW of BAO, and then at a site ~5 km WNW of BAO.

Since data at each site was taken by two co-located instruments, there was no 2-dimensional grid of chord intersection points generated. Rather, the purpose of the experiment was to validate the instrument's operation at ranges up to 5 km. Among the specific objectives were:

- Verification that the system can be aligned with targets at a range of 5 km
- Verification of adequate signal-to-noise ratio (SNR) at this range
- Verification of proper scanner operation and repeatability, both horizontally and vertically
- Comparison of retrieved CO_2 concentrations, from slant-path measurements, with those from the NOAA LI-COR on the tower and Picarro *in situ* measurements

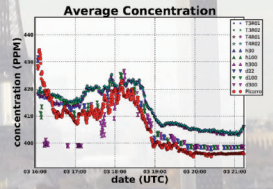
ALL OBJECTIVES WERE ACCOMPLISHED!

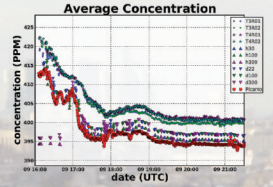
Both transceivers running side-by-side in Boulder, CO



New 5 inch retroreflector installed on BAO tower

GREENLITE™ DATA IN COMPARISON WITH NOAA TOWER DATA AND HIGH ACCURACY *IN SITU* DATA FROM A PICARRO CAVITY RING DOWN SPECTROMETER





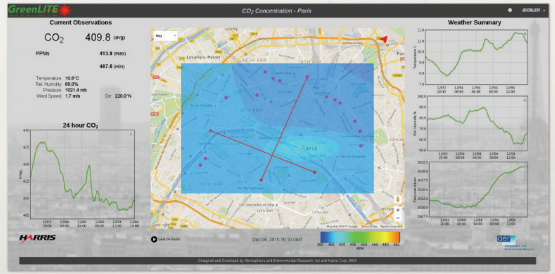
- Over 15 hours of data were collected
- GreenLITE™ measured higher than BAO by an average of 5.2 ppm with a 1σ stdev of 0.49 ppm
- We are investigating the source of this difference, it appears to be real and constant
- GreenLITE™ Transceiver to Transceiver agreed to 1.06 ppm on average with 1σ stdev of 0.56 ppm
- The laser measurement tends to be smoother than the in situ measurements as expected for an integrated path measurement

DEPLOYMENT TO PARIS

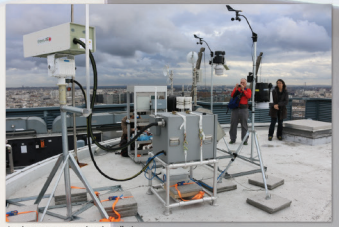
Initial discussions with LSCE for expanding the GreenLITE™ system to 5 km chords and deploying in Paris began in February 2015. Our subcontractor, Enviroearth, did an amazing job of obtaining permissions for operation in Paris, establishing collaborations with LATMOS, Montparnasse ICADE, Paris Habitat, Elogie and CESE, making arrangements to install the equipment, installing 15 reflectors, and getting the initial transceiver setup completed in a very short time.

The Harris and AER team performed exceptionally, in order to design and build the 5 km system in ~6 months and deploy to Boulder in August/Sept. The hardware required for mounting the system, compatible with each location, was then designed and shipped to Paris along with the instrument hardware during October for initial installation.

Harris completed the installation in the first week of November and the system saw first light on November 9th and has been running continuously 24 hours per day, 7 days a week since then, while displaying the data and 2D maps live on a web-based interface.



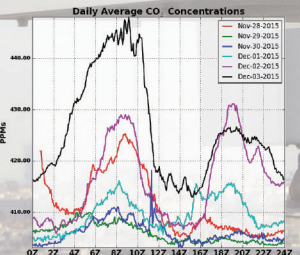
Typical reflector installation



Jussieu tower transceiver installation

As of 12/9/2015, we have collected over 450,000 raw samples, retrieved more than 300,000 ppm values, and generated >6000 2D reconstructions over Paris, France, in near-real time.

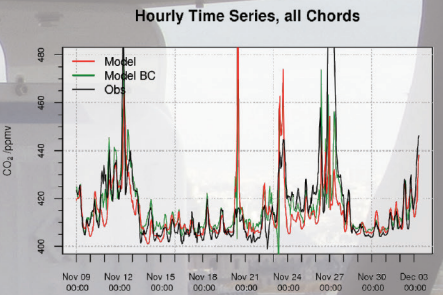
Comparisons with models and independent measurements are extremely promising. Some preliminary results are shown to the left and below. Please see our companion poster #285 "Real-Time Monitoring and Mapping of CO_2 Concentrations Over Extended Urban Area: Mapping the Two-Dimensional Distribution of CO_2 over Paris, France" presented in this session by Dr. Scott Zaccheo for more details on these initial comparisons.



On the left is an example of the variation of the daily diurnal cycle measured by the GreenLITE™ system over Paris.

On the right is a comparison of the CHIMERE Model run by LSCE and the GreenLITE™ data over the first 24 days of operation. The results in red are the model without constraints from the LSCE tower Picarro measurements in the southwest and northeast edges of Paris (upwind and down wind respectively), the green line is the model after inclusion of the Picarro measurements, and the black line is the GreenLITE™ observations.

Results are still preliminary but are very encouraging.



FUTURE WORK

- Continue to improve the GreenLITE™ implementation (e.g. implement locked lasers, replace mechanical scanners with optical scanner to enable 360° functionality, reduce size weight and power)
- Continue taking data in Paris and evaluate the potential for using GreenLITE™ data directly in the model inversions
- Demonstrate a GreenLITE™ system for CH_4 and CO_2 combined measurements

ACKNOWLEDGMENTS

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