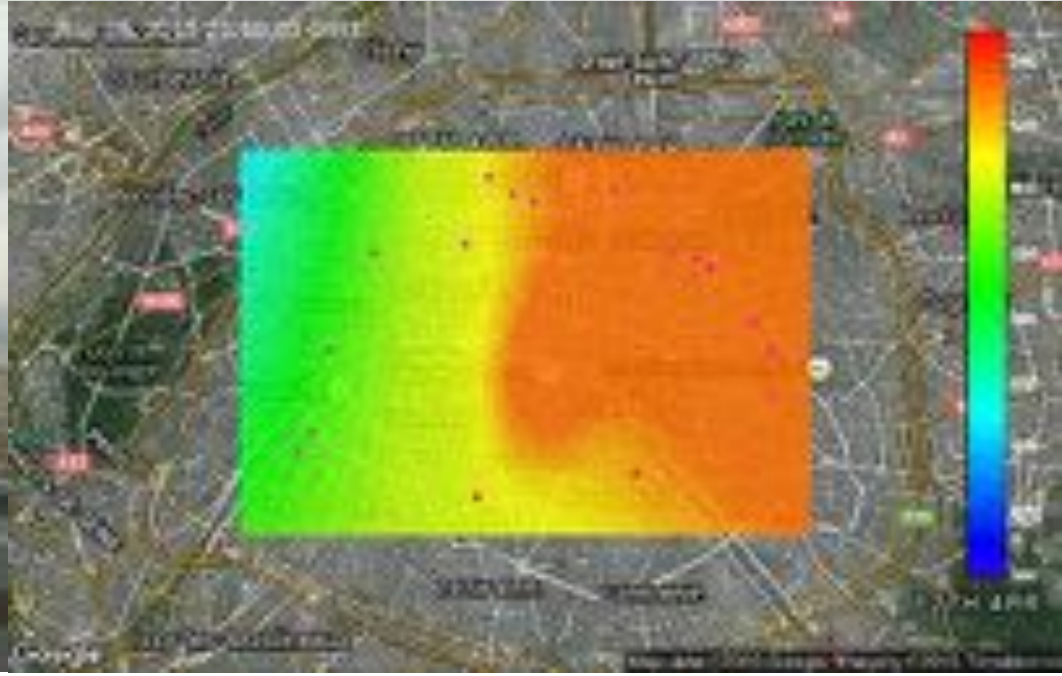

GREENLITE OVER PARIS: A NEW APPROACH TO URBAN SCALE MONITORING OF GREENHOUSE GAS

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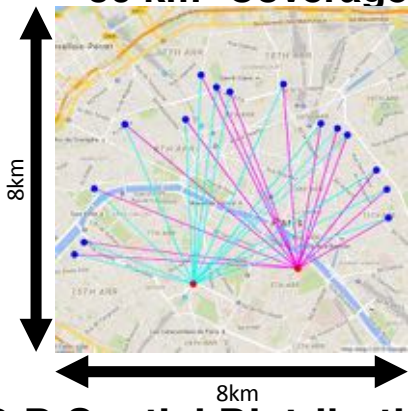
Greenhouse gas Laser Imaging Tomography Experiment – GreenLITE™ overview

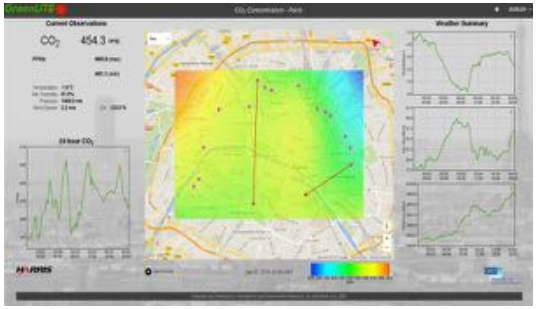
- System development was a collaboration between Harris Corporation and Atmospheric and Environmental Research (AER)
- Deployed in cooperation with LSCE, LATMOS, Enviroearth and many others
- System Design:
  - Employs a pair of Intensity Modulated Continuous Wave (IMCW) differential absorption spectroscopy transceivers
  - 15 retro reflectors used to create a set of user defined paths 2.5 – 5.3 km in length (transceivers to retroreflectors)
  - Measures differential transmission along each path ~10 sec each
  - Integrated with meteorological measurements (T, P, RH, wind speed and direction)
  - Cloud-based retrievals to convert to dry air mole fraction (XCO_2)
- Constructs 2-D distribution using sparse tomography over ~30 km^2 with spatial resolution of ~200 meters
- Provides 24/7 real-time measurements and data access
  - Web-based user access to data
  - Near-surface concentrations by path
  - Spatially averaged concentrations
  - Weather information
  - 2-D view of the concentration and distribution of near-surface CO_2.
  - Instrument and server telemetry

Paris Deployment

~30 km^2 Coverage

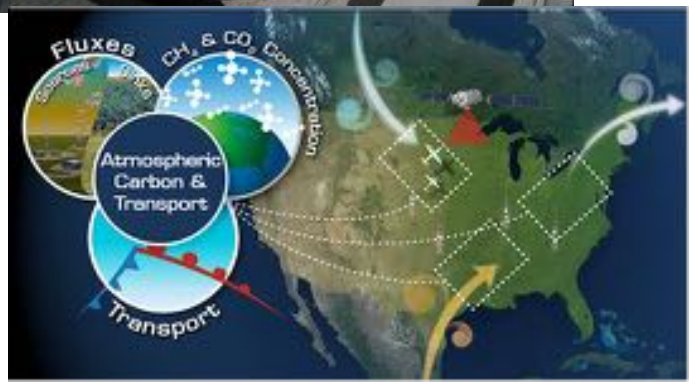


2-D Spatial Distribution



Estimating Column CO_2 via differential Laser Absorption Spectroscopy (LAS)

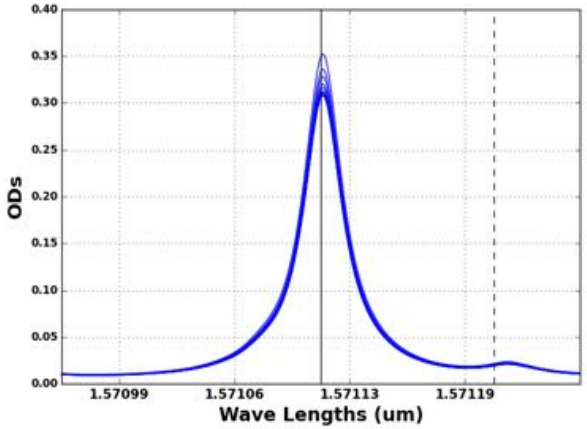
- **IMCW approach originally designed for airborne demonstrator for ASCENDS mission.**
- **Currently preparing to fly with ACT-America Earth Venture Mission**
- **Uses unique modulation on each wavelength to separate closely spaced fixed optical frequencies**
- **Reference channel measures transmitted power for each wavelength**
- **Science channel measures received power after transit through atmosphere, reflection and return to receiver**
- **Ratio of received over transmitted gives transmission of given wavelength via Beer-Lambert Law**
- **Ratio of channels gives differential transmission due to absorption**

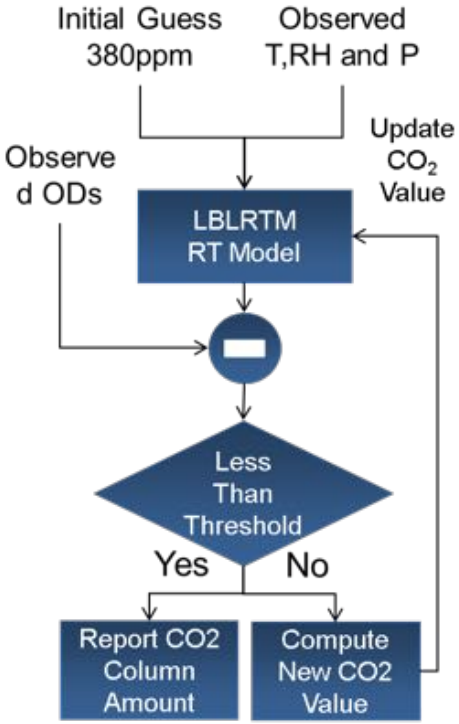


Retrieving CO_2 concentrations from optical depth measurements

Basic Measurement Approach

- Simultaneously measure Transmission of "On"-line wavelength λ and Transmission of "Off"-line wavelength λ+ Δ
- Convert to differential optical depth
- Package with meteorological data and send to cloud for storage, retrieval and dissemination.

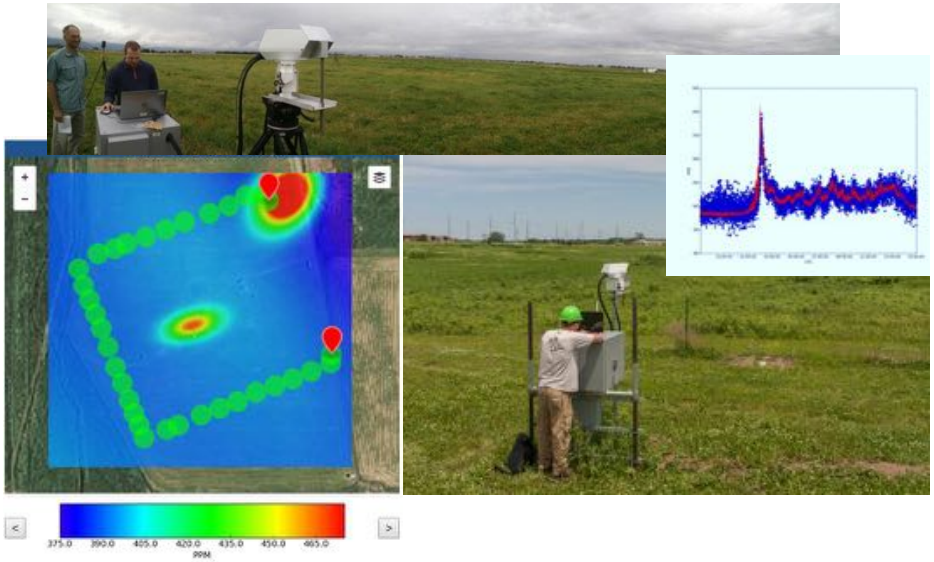




- **Extended approach for chord length > 1 km over varying topography**
  - Minimize fit for a sum of fixed sub-chord segments along the path with fixed lengths and varying atmospheric states.
- **Construct 2-D views using model-based tomographic reconstruction approach**
  - Describes underlying field as function of analytic features and simple 2-D background gradient

GreenLITE: the road to Paris

- Original GreenLITE was built for the Department of Energy National Energy Technology Laboratory to monitor geological carbon storage (GCS) sites and was designed for 1 km path lengths to cover up to ~1 km^2, and began in October 2013
- Tests were performed at the Zero Emissions Research and Technology facility in Bozeman, MT, in Sept 2014, validating concept
- The system was then deployed for a 6 month trial period over an actual GCS site Feb. – Aug. 2015 (over 3600 hours of data were collected)



- System was upgraded for 5 km in 2015
  - 25 mm receive optics expanded to custom 152 mm
  - Laser power increased from ~5 mW to ~25 mW
  - Larger retroreflectors used
- Tests conducted 8/31 – 9/11 at the NOAA Boulder Atmospheric Observatory – Funded by NIST
- Placed 5 retroreflectors 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 & ~14 hours of data from 5 km NW of tower
- Point comparisons at end of chord tracked well with ~5 ppm +/- 0.5ppm difference

GreenLITE: 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 with support from LSCE, 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.

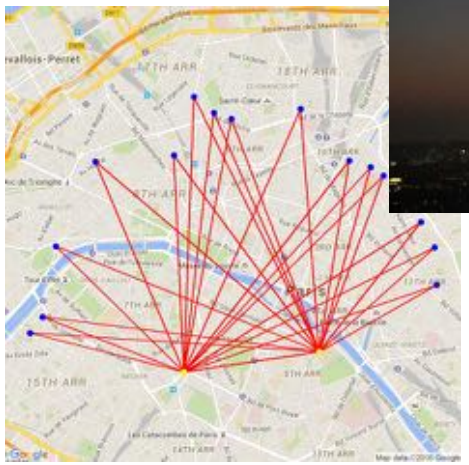
Mounting hardware compatible with the locations was designed and shipped with the instrument for initial installation in Paris during October.

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

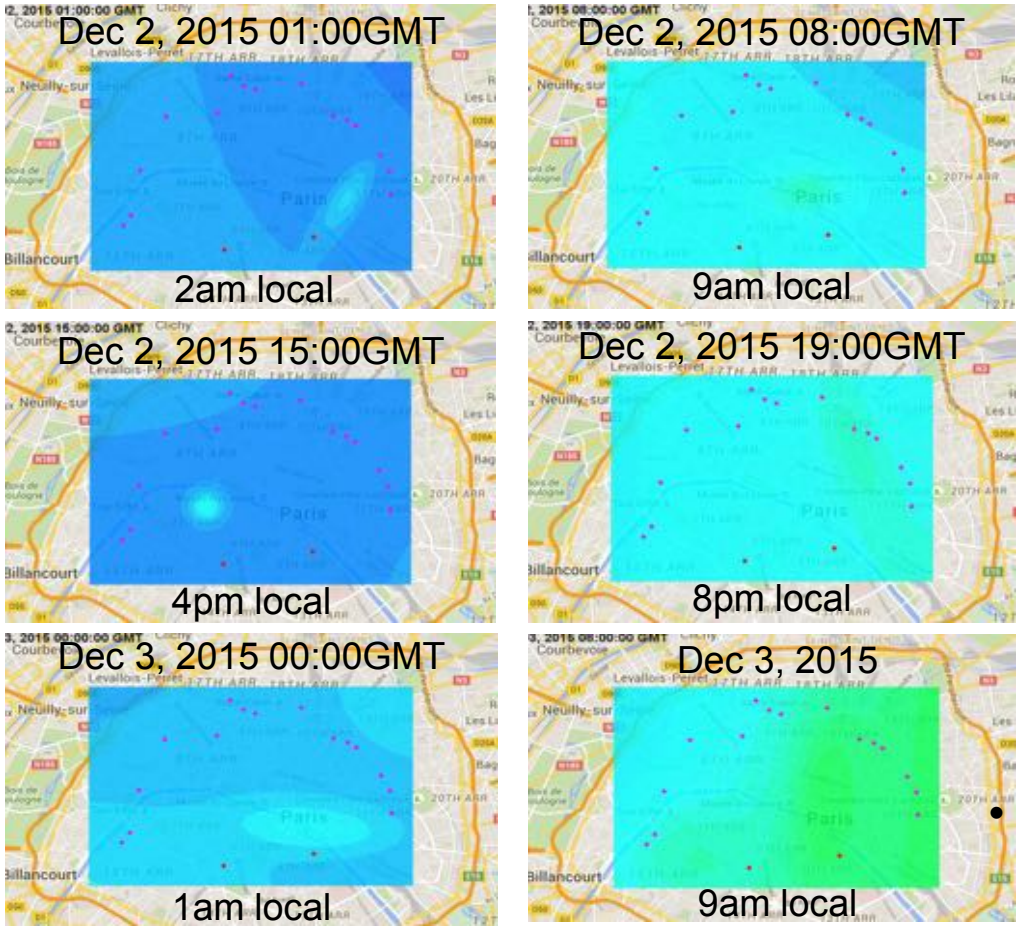
Two transceivers and 15 retroreflectors were installed.

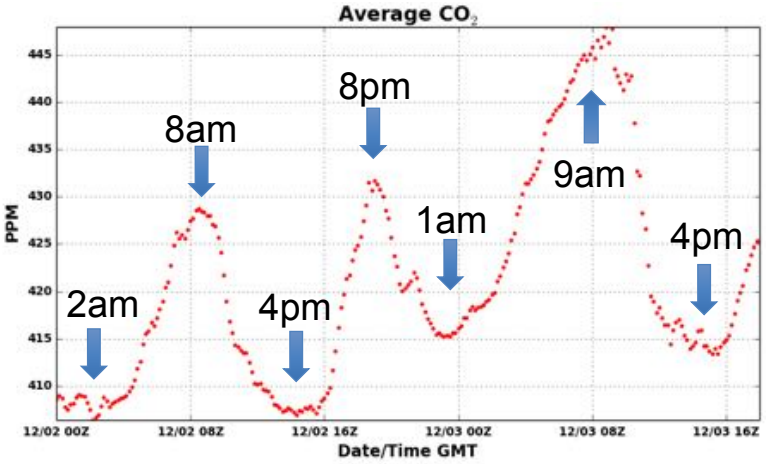
Typical reflector installation

Jussieu tower transceiver installation



Example: 36hr CO_2 time sequence over Paris, France





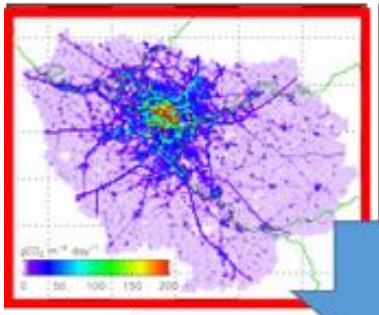
Measurements and reconstructions provide real-time dynamics of complex environments

- As of 5/28/2016, we have collected over 3.4M raw samples, retrieved more than 1.6M ppm values passing QC, and generated >42k 2-D reconstructions over Paris, France, in near-real time.

Models and in situ for verification

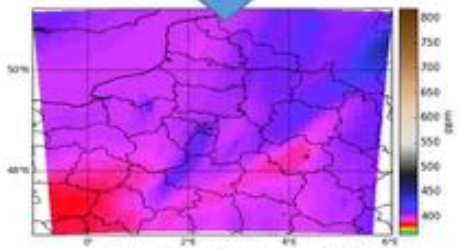
Modelling of CO2

CO2 - IER emissions
(hourly, 1 km x 1km)

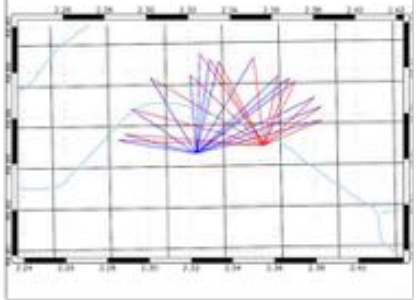


Input data

- Fossil fuel CO2 emissions (IER)
- Meteorology (ECMWF)
- natural fluxes of CO2 (C-TESSEL)



Modelled CO_2 field
2 km x 2 km, 20 m vertical (near surface)



Hourly integration along chords

In-situ observations of CO_2

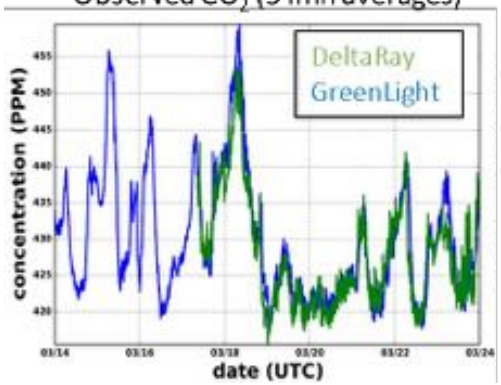
Jussieu (co-located)

Thermofisher DeltaRay:
- Reference every 30 mins
- Repatability ca. 0.01-0.09ppm

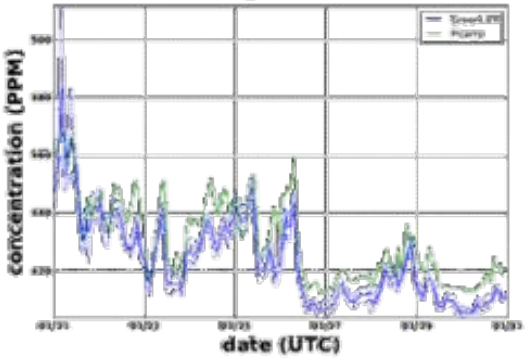
Cité des Sciences

Picarro CRDS G2301
- Reference every 11 hours
- Repatability 0.02 ppm

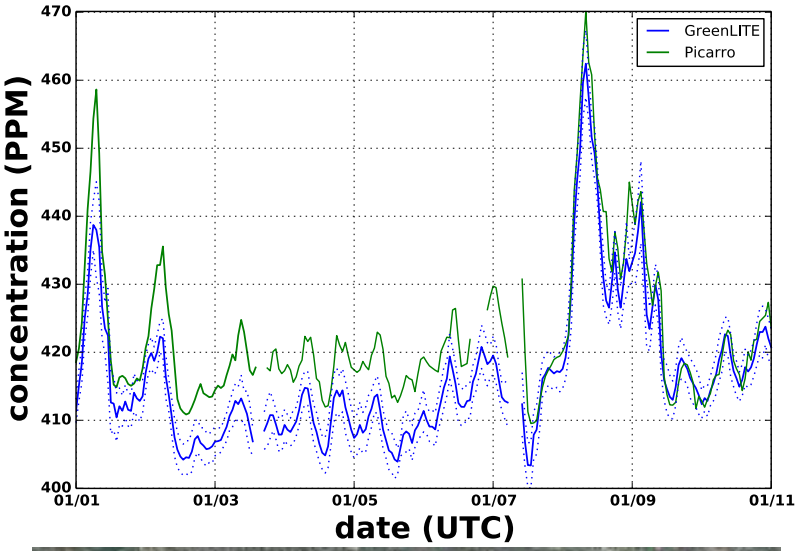
Observed CO_2 (5 min averages)

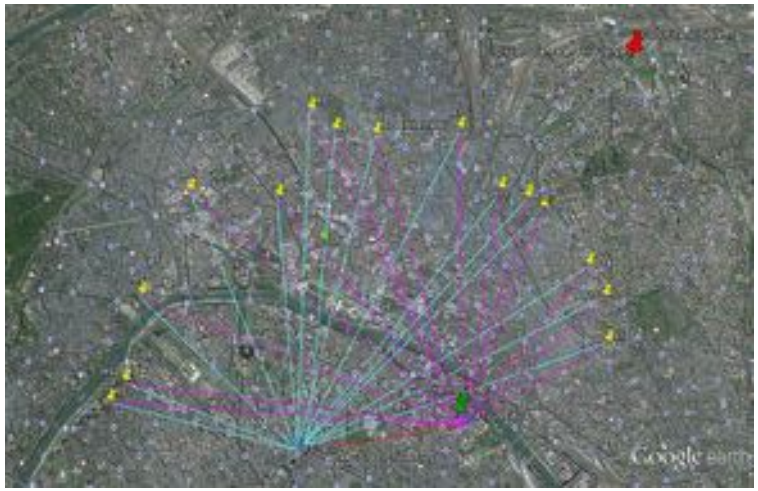


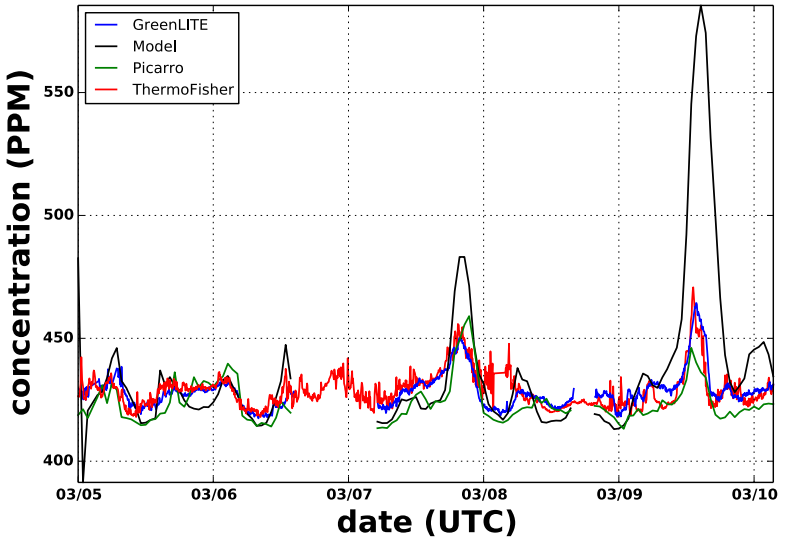
Observed CO_2 (1 hour averages)

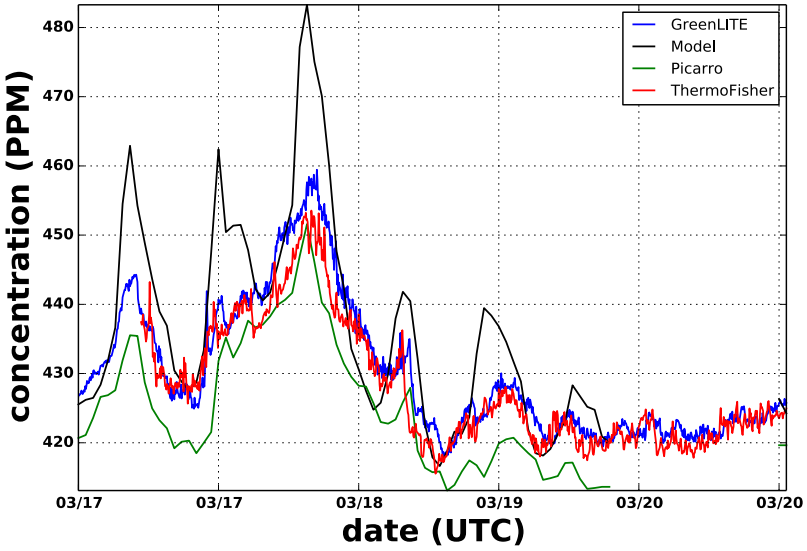


Picarro, model and ThermoFisher comparisons



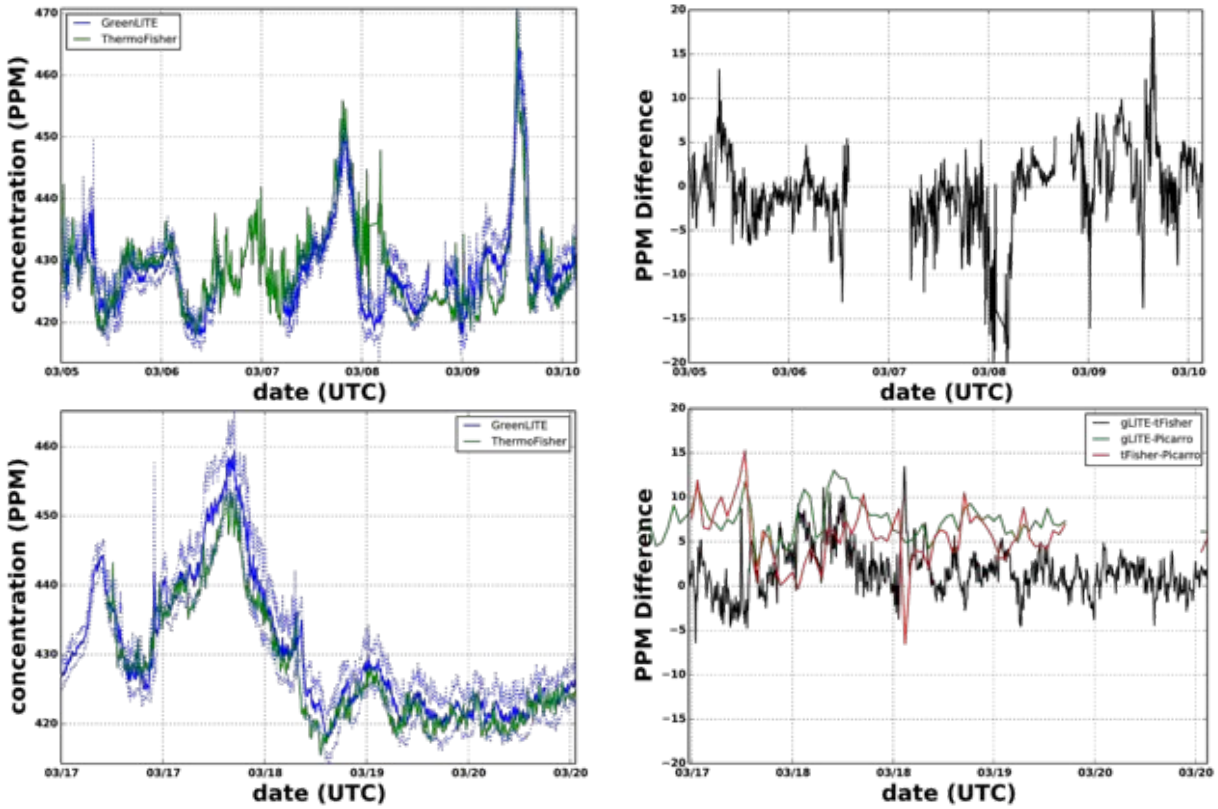






Picarro data made available by Cité des Sciences et de l'Industrie (Marc Jamous, Jean-Christophe Theisen, Didier Philippe, Michel Maintenant, Sylvain Aulombard et Michel Pérez) , and the staff from LSCE who helped to setup the analyzer (M.Ramonet, M.Delmotte and M.de Florinier)

Closer look at comparison with Thermo-Fisher and Picarro



- Comparisons to Thermo- Fisher instrument show exceptionally good results
  - Most likely driven by the location of the Thermo-Fisher instrument within the GreenLITE footprint.
- Picarro and GreenLITE track each other, but exhibit a time-varying bias
  - Most likely do to location of Picarro outside of GreenLITE field of view.

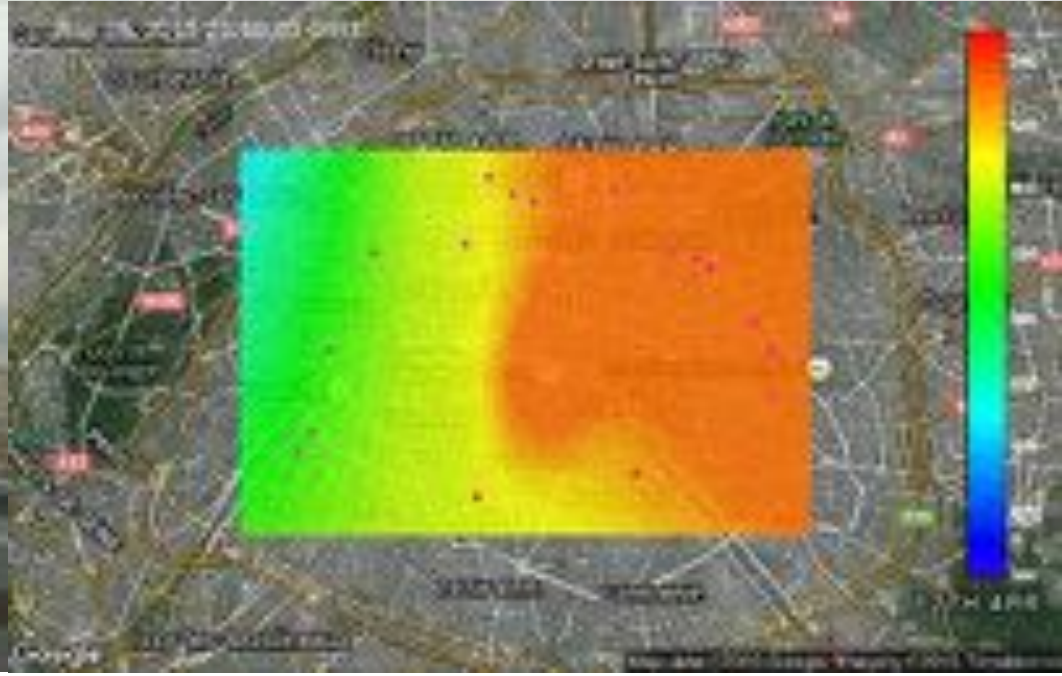
Conclusions and future plans

➢ Conclusions

- A new measurement approach has demonstrated the ability to measure CO_2 concentrations and 2-D spatial distribution over large areas
- Initial assessments of the measurement against in situ instrumentation and modeled values show very good agreement
- Initial measurements also show there can be significant variations across an urban environment
  - GreenLITE can provide spatially averaged measurements which may benefit model inversions

➢ Future Plans

- Continuing operations in Paris until November 2016 – Results in a full year record and ability to evaluate diurnal and seasonal cycles – currently Harris funded
- Work with LSCE and LATMOS for additional in situ measurements in Paris for further system evaluations
- Continuing evaluation of model comparisons and working toward inclusion of GreenLITE data in inversions
- Demonstrate a similar system capability for CH_4
- Evaluate benefits of spatial boundary layer information for improved calibration of space assets



QUESTIONS?

- Movie