Continuous, regional approach to methane source detection and sizing using dual frequency comb laser spectroscopy and atmospheric inversions

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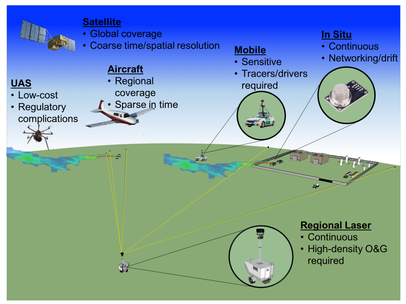
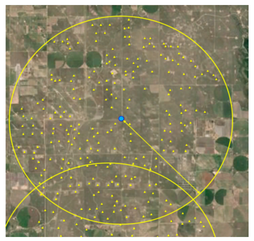
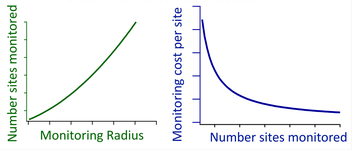
Overview

Goal: Regional leak detection service covering Oil & Gas infrastructure in 5-30 square mile regions





Monitor for leaks at 100s of sites from a central location



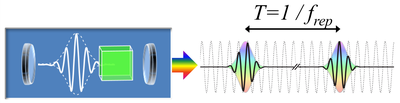
Leak Detection and Sizing

- To date, ability to find up to 2 leaks
- Ability to approximate source strength
- Coverage of areas up to 2km x 2km

Frequency Comb Technology

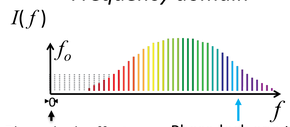
Frequency Comb: a stabilized mode-locked laser, output acts as **>100,000 well behaved CW lasers**

Time domain



Passively Mode-Locked Laser

Frequency domain

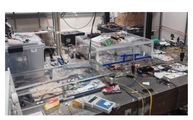


Phase-lock offset frequency, f_o

Phase-lock one tooth to fixed laser

Frequency Comb lasers are ready to move out of the laboratory:

Proof-of-Concept Dual Comb Spectrometer



- Sensitive mode-locking
- Stabilized optical table
- >$500,000

Fieldable Frequency Comb

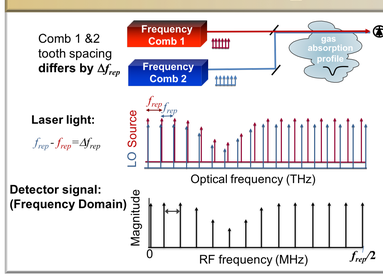
Sinclair *et al.*, Optics Express, **22**, 6996 (2014)

- 0.7 liter package
- Simple reproducible design
- FPGA control electronics

Our Combs

- Portable DCS
- Large cost reduction
- Ruggedized for field

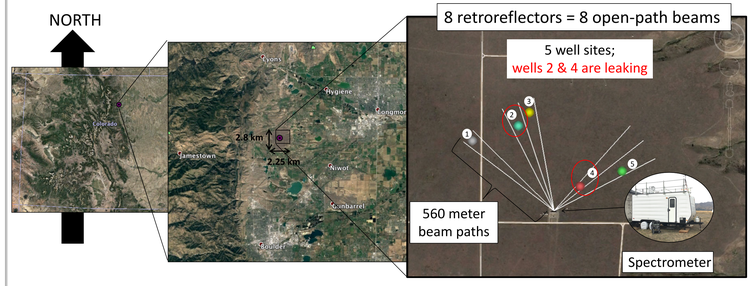
Dual Comb Spectroscopy (DCS)

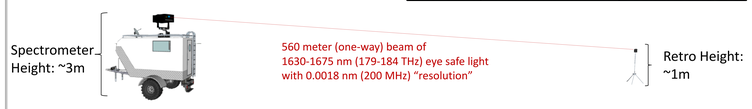


- Light from 2 frequency combs combined and passed through gas sample
- Difference in repetition rates leads to heterodyne beat frequency for each comb tooth pair
- Detectable with standard InGaAs fast photodiodes
- **Extremely sensitive, multispecies sensing with low instrument drift, intrinsic calibration**

Coddington *et al.*, PRL, **100**, 013902 (2008)

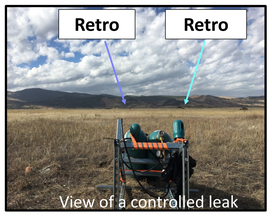
Field Deployment, Table Mountain





Field Site and Deployment:

- North-Central Colorado
- Flat-topped mesa, ~3 x 2 km across
- Few local methane sources
- Variable meteorological conditions
- Methane cylinders and flow controllers for testing sensitivity to two very small (8 scfh) leaks
- Wind sensors: Kestrel vane anemometer & 3D sonic anemometer

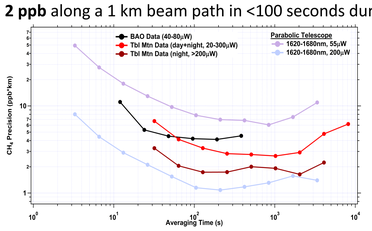


Retroreflectors ("retros"):

- Corner cube mirrors
- Can be located < 1-2 kilometers from spectrometer
- Refractive telescope launches / receives light
- 20x beam expander with 3" optics
- Return beam is coupled directly onto photodiode

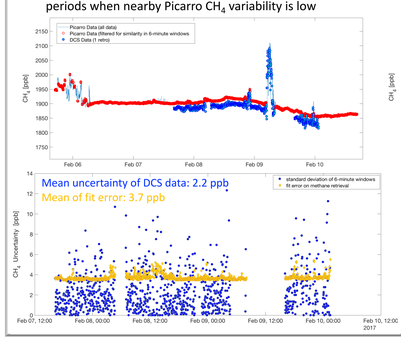
Measurement Precision:

2 ppb along a 1 km beam path in <100 seconds during stable conditions

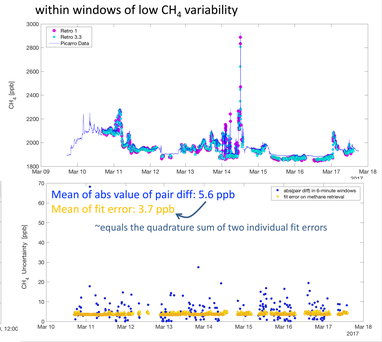


- Allen deviation shows that measurement precision improves with averaging time
- Noise increases after several minutes due to atmospheric CH_4 variability

Measurement repeatability one one retro:
DCS measurements compared in moving windows during periods when nearby Picarro CH_4 variability is low



Measurement repeatability on two retros:
Pairs of measurements taken from different retros within windows of low CH_4 variability



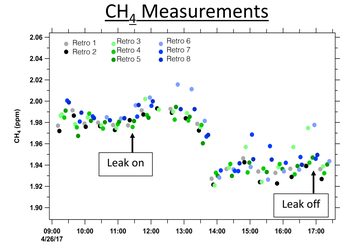
CH_4 Inversions for leak detection

Deployment and Leak Detection Testing at Table Mountain, Colorado

Goal: Detect two 10-15 scfh leak (0.1 -0.2 kg/hr) within one day
Method: place two 6 scfh leaks in field, sample beams upwind and downwind of leak as well as other potential leak locations (e.g., well pads)
Experiment: Use inverse model to determine presence of two leaks and leak rates

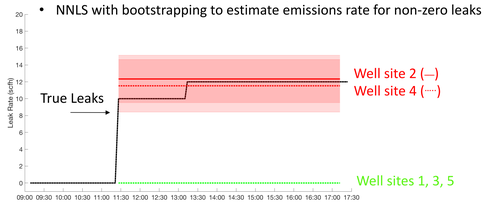
Can we size multiple leaks in an inversion with only one set of beams per well site?

CH_4 Measurements

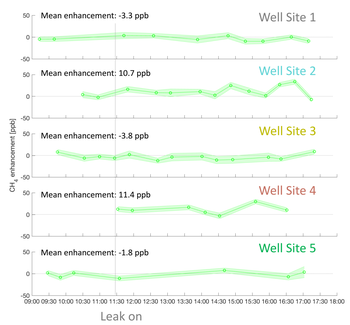


Least-squares fit for leak rate at each well site

- Non-zero minimum test to determine presence of leak
- NNLS with bootstrapping to estimate emissions rate for non-zero leaks



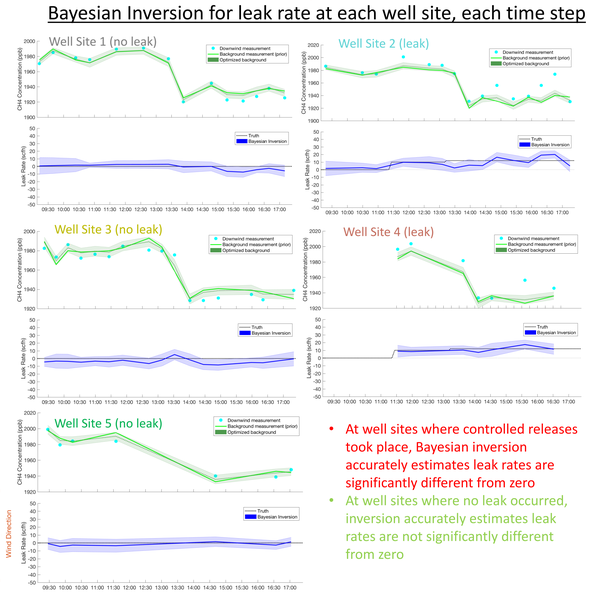
CH_4 Enhancements at each leak site



- Enhancements observed at no-leak sites (well sites 1, 3, and 5) are within uncertainty range of zero
- Enhancements observed at leak sites (well sites 2 and 4) are significantly different from zero

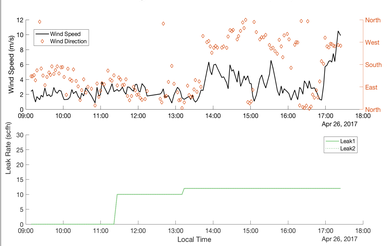
What if intermittency of leaks is unknown?

Bayesian Inversion for leak rate at each well site, each time step



- At well sites where controlled releases took place, Bayesian inversion accurately estimates leak rates are significantly different from zero
- At well sites where no leak occurred, inversion accurately estimates leak rates are not significantly different from zero

Meteorological conditions on 04/26/2017



- Background optimized in inversion
- Background prior uncertainty = msmt uncertainty
- Prior flux estimate = 0 scfh
- Prior flux uncertainty = 10 scfh
- Temporal flux covariance length scale = 6 minutes
- Temporal bkg covariance length scale = 2 minutes
- Inversion for a single potential point source. Information about shared likelihood of leaks between well & separator (for example) can be incorporated

Future Work

- **Future Goals**
  - Identify industry partners for testing DCS system at production sites
  - Test approaches to finding leak location on well pad to within 5 m
  - Expand applicability of observing system for other types of facilities, natural systems