Dual frequency comb spectroscopy and atmospheric modeling for the detection of methane leaks at oil and gas production sites

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Outline

Background

Coupled measurement/inversion regional monitoring solution

Dual-frequency comb spectroscopy

Large Eddy simulations/Atmospheric Inversion

Synthetic data tests

Test site configuration

Outlook
Background

Atmospheric methane (CH$_4$)

Potent greenhouse gas

- 25x > CO$_2$ (100 yrs)

Natural and anthropogenic sources

- Landfills, agriculture, wastewater treatment, oil and gas systems, coal mining
- Sink: oxidation by OH

Accounts for 11% of all US GHG emissions

- >50% from anthropogenic sources
- 25% from natural gas systems

Background

Rapid growth in US natural gas production since 2007
• EPA released new rules for regulating \( \text{CH}_4 \) from oil and natural gas production systems (May 2016)

ARPA-E MONITOR Program
Develop new technology/techniques for sensing methane at oil and natural gas production sites
• Capable of determining size and location of methane leaks
• Competitive cost compared with current methods
• Provide efficient end user (industry) platform
Natural gas extraction east of Platteville Colorado. DCS could monitor over 100 sites from a central location. Overlapping fields could ensure complete coverage.
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Methane measurements

Dual frequency comb spectrometry
• High precision
• Robust
• Proven over kilometer scale open paths (Rieker et al., 2014, Optica)
Methane measurements

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A Frequency Comb = Stabilized Mode-Locked Laser

\[ T = \frac{1}{f_{\text{rep}}} \]
Methane measurements

Dual frequency comb spectrometry
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- Proven over kilometer scale open paths (Rieker et al., 2014, Optica)

A Frequency Comb = Stabilized Mode-Locked Laser

$$I(f)$$

$$f_0$$

>100,000 lasers
Methane measurements

Dual frequency comb spectrometry
- High precision
- Robust
- Proven over kilometer scale open paths (Rieker et al., 2014, Optica)

A Frequency Comb = Stabilized Mode-Locked Laser
Stabilize two degrees-of-freedom -> entire comb is stabilized

\[ f_n = n f_{\text{rep}} + f_0 \]

\( I(f) \)

Phase-lock (stabilize)
offset frequency, \( f_o \)

>100,000 well behaved lasers

Phase-lock (stabilize)
one tooth
to a reference laser
Coherent Dual-Comb Spectroscopy

Interfere signals from two coherently locked combs

Frequency Comb 1

Frequency Comb 2

Open path

Detector
Coherent Dual-Comb Spectroscopy

Interfere signals from two coherently locked combs

Frequency Comb 1

Frequency Comb 2

Open path

Detector

RF frequencies
Coherent Dual-Comb Spectroscopy

Portable DCS

Comb tooth linewidth: 2×10^{-8} nm

Wavelength accuracy: 1×10^{-6} nm

RF Power

2 kHz (2×10^{-8} nm)

Optical Frequency (THz)

184.03150  184.03160
Coherent Dual-Comb Spectroscopy

**Portable DCS**

**Comb tooth spacing:**

~0.002 nm

**RF Power**

- 200 MHz (0.002 nm)

**Optical Frequency**
Coherent Dual-Comb Spectroscopy

Portable DCS
105 nm wavelength span, 0.002 nm point spacing
100s of absorption lines - CH$_4$, CO$_2$, H$_2$O
650 μs acquisition time per spectrum - 7000 averages to reach SNR at right
Coherent Dual-Comb Spectroscopy

**Portable DCS**

- 105 nm wavelength span, 0.002 nm point spacing
- 100s of absorption lines
  - CH$_4$, CO$_2$, H$_2$O
- 650 µs acquisition time per spectrum
  - 7000 averages to reach SNR at right

Fit to retrieve integrated concentration of trace gases along light path
Proof of concept measurements

**Absorbance**

- CH$_4$ & H$_2$O features (+ weak CO$_2$)
- CO$_2$ features (+ weak H$_2$O, HDO, hotbands)

**Wavelength (nm)**

- 1650
- 1645
- 1640
- 1615
- 1610
- 1605
- 1600

**Wavenumbers (cm$^{-1}$)**

- 6060
- 6080
- 6100
- 6200
- 6220
- 6240

**Residual**

- 4 x 10$^{-3}$
- -4 x 10$^{-3}$
Proof of concept measurements

- 3 ppb CH$_4$ sensitivity in 5 minutes over 2 km
Methane precision: portable DCS vs POC

POC: 4ppb*km in 1000s
Methane precision: portable DCS vs POC

POC: 4ppb*km in 1000s
Portable: 1-4ppb*km in 100s
Methane precision: portable DCS vs POC

Proof-of-concept DCS (2 km path)
New DCS (2 km path)
New DCS (400 m path)
Idealized trends

CH$_4$ Precision (ppb*km)
Averaging Time (s)

POC: 4ppb*km in 1000s
Portable: 1-4ppb*km in 100s

Limited by atmospheric variability (not instrument)
High resolution simulation of atmospheric transport

- Software developed and maintained by the Engineering Laboratory at NIST
- Scalable, large-scale parallel computations
- Import wind speed / direction and meteorological parameter
- Import topography

### Low to moderate Wind Conditions
- Meteorological data from local station
- One minute temporal resolution
- 8 meter spatial resolution

### High Wind Conditions
Monitoring Solution Framework

- Spectrometer data
- Meteorological data
  - Transport Model
  - Influence Function
- Inversion
- Leak Location and Size
Synthetic data testing

- Spectrometer data
- Meteorological data
  - Transport Model
  - Influence Function
  - Inversion
- Measurements from BAO during FRAPPE 2014
  - Meteorological
  - CH₄ (for background)
- Leak Location and Size
Measurements from BAO during FRAPPE 2014

• Meteorological
• CH$_4$ (for background)

Synthetic data testing
Synthetic data testing

Measurements from BAO during FRAPPE 2014
  • Meteorological
  • CH$_4$ (for background)

Synthetic data

Meteorological data

Transport Model

Influence Function

Inversion

Leak Location and Size
Synthetic data testing

Initial test configuration
• 1km x 1km domain
• 1 “true” leak
• 4-8 possible leaks
Synthetic data testing

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ARPA-E target leak rate = 6 scfh
(\sim 3.5 \times 10^{-5} \text{ kg s}^{-1})
Synthetic data testing

Initial test configuration
- 1km x 1km domain
- 1 “true” leak
- 4-8 possible leaks
Test site configuration

Nearby wells (from Colorado Oil & Gas Conservation Commission)

BAO Tower

BAO site access

1 mile
Synthetic data testing (for BAO test site)

Realistic test configuration
- 2km x 2km domain
- 2 “true” leaks
- 52 wells (possible leaks)
Synthetic data testing (for BAO test site)

Realistic test configuration
- 2km x 2km domain
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- “TRUE” LEAKS
- SOLUTION MEAN ± 2*STDV
Test site configuration

Nearby wells (from Colorado Oil & Gas Conservation Commission)

BAO Tower

BAO site access

1 mile

1 mile
Test site configuration
Test site configuration

BAO ideally suited for remote CH$_4$ sensing
• Many other research studies have taken place here
  • Current trace gas sampling
• Offers a realistic background for oil and gas production sites
• Good for testing inversion modeling
Summary/Outlook

Built and tested a portable dual frequency comb spectrometer for measuring methane over kilometer scale open paths

Built out inversions to couple LES and line of sight DCS measurements

Demonstrated success in locating 1 and 2 leaks within the test domain

- Synthetic data runs
- Modeling domain actually larger than test site (included 52 active wells)

Infrastructure in place to start field testing dual-frequency comb

Begin coupling actual measurements into model

Start exploring other potential field test sites

- Cover different terrain, background CH$_4$, etc.
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NIST Boulder/Gaithersburg
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BAO site managers
Synthetic data tests use point source CH$_4$ measurements from 2014 as background, along with the winds that accompanied those measurements. Inversions consistently find signal south-east of BAO...
Synthetic data testing (for BAO test site)

- Leak strength of 1.5E-3 kg/s
- Divided by 3.9E-6 kg/s per cow (McGinn and Beauchemin, 2012)
- Estimated 390 ± 120 head cattle at Hulstrom
- Dairy farm with 400 head of cattle produces a ‘leak’ that is 50x greater than the MONITOR 6 scfh target