A Methane Lidar for Greenhouse Gas Measurements

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Outline

• Motivation - Why measure Methane?
• GSFC Measurement Approach
• Technology and Challenges
• Current Status
• Airborne Campaign
• Summary
Why measure Methane?

Methane Trend since 1975

February 2016 was the warmest February in 136 years of modern temperature records. That month deviated more from normal than any month on record.

Source: www.esrl.noaa.gov/gmd/agci/agci.html

Source: http://www.giss.nasa.gov/research/features/201603_gistemp/
Methane Lifetime

<table>
<thead>
<tr>
<th>Gas</th>
<th>Estimated 1750 tropospheric concentration\textsuperscript{1}</th>
<th>Recent tropospheric concentration\textsuperscript{2}</th>
<th>GWP\textsuperscript{3} (100-yr time horizon)</th>
<th>Atmospheric lifetime\textsuperscript{4} (years)</th>
<th>Increased radiative forcing \textsuperscript{5} (W/m\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrations in parts per million (ppm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide (CO\textsubscript{2})</td>
<td>278\textsuperscript{6}</td>
<td>397.2\textsuperscript{7}</td>
<td>1</td>
<td>\sim 100-300\textsuperscript{4}</td>
<td>1.91</td>
</tr>
<tr>
<td>Concentrations in parts per billion (ppb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane (CH\textsubscript{4})</td>
<td>722\textsuperscript{8}</td>
<td>1823\textsuperscript{2}</td>
<td>28</td>
<td>12\textsuperscript{4}</td>
<td>0.50</td>
</tr>
<tr>
<td>Nitrous oxide (N\textsubscript{2}O)</td>
<td>270\textsuperscript{9}</td>
<td>327\textsuperscript{2}</td>
<td>265</td>
<td>121\textsuperscript{4}</td>
<td>0.19</td>
</tr>
<tr>
<td>Tropospheric ozone (O\textsubscript{3})</td>
<td>237\textsuperscript{1}</td>
<td>337\textsuperscript{2}</td>
<td>n.a.\textsuperscript{3}</td>
<td>hours-days</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Source: DoE \url{http://cdiac.esd.ornl.gov/} and IPCC Chapter 8

CH\textsubscript{4} is removed from the atmosphere by a single process, oxidation by the hydroxyl radical (OH), but the effect of an increase in atmospheric concentration of CH\textsubscript{4} is to reduce the OH concentration, which, in turn, reduces destruction of additional methane, effectively lengthening its atmospheric lifetime.
Sources of Methane

Source: http://icp.giss.nasa.gov/education/methane/intro/cycle.html
Arctic Methane

Katey Walter Anthony Univ. of Alaska Fairbanks https://www.youtube.com/watch?v=YegdEOSQotE

FEATURE 20 May 2015

Methane apocalypse? Defusing the Arctic’s time bomb
Methane “Arctic Time Bomb” requires year-round observations

- “Large quantities of organic carbon are stored in frozen soils (permafrost) within Arctic and sub-Arctic regions. A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases carbon dioxide and methane. This feedback can accelerate climate change, but the magnitude and timing of greenhouse gas emission from these regions and their impact on climate change remain uncertain...” E. A. G. Schuur, et.al., *Nature*, Vol 520, 9 April 2015, 174

- “Here, we report year-round CH$_4$ emissions from Alaskan Arctic tundra eddy flux sites and regional fluxes derived from aircraft data. We find that emissions during the cold season (September to May) account for ≥50% of the annual CH$_4$ flux, with the highest emissions from noninundated upland tundra.” Donatella Zona et.al., “Cold season emissions dominate the Arctic tundra methane budget”. PNAS, January 5, 2016, vol. 113, no. 1, 40–45
The 23 October 2015 blowout of a well connected to the Aliso Canyon underground storage facility in California resulted in a massive release of natural gas. Analysis of methane (CH$_4$) and ethane (C$_2$H$_6$) data from dozens of plume transects from 13 research aircraft flights between 7 Nov 2015 and 13 Feb 2016 shows atmospheric leak rates of up to 60 metric tonnes of CH$_4$ and 4.5 metric tonnes of C$_2$H$_6$ per hour. At its peak this blowout effectively doubled the CH$_4$ emission rate of the entire Los Angeles Basin, and in total released 97,100 metric tonnes of methane to the atmosphere.” S. Conley et.al. Science 25 Feb 2016, pp. DOI: 10.1126/science.aaf2348
“Reducing methane emissions is a powerful way to take action on climate change; and putting methane to use can support local economies with a source of clean energy that generates revenue, spurs investment, improves safety, and leads to cleaner air. That is why in his Climate Action Plan, President Obama directed the Administration to develop a comprehensive, interagency strategy to cut methane emissions.”

White House Climate Action Plan – Strategy to Cut Methane Emissions (March 2014)
Comparison of actual OCO-2 coverage (left) vs. simulated ASCENDS coverage for December 16-31 2015. The sparse sampling OCO-2 coverage at high latitudes is a major drawback of passive remote sensing missions. (Simulation provided by Dr. Stephan R. Kawa, GSFC).
GSFC CH$_4$ IPDA Lidar

- **Transmitter (Laser) Technology**
  - Current (optimum) Wavelength for CH$_4$ Earth Detection: ~1.64-1.66 µm
  - Optical Parametric Oscillators (OPO) and Optical Parametric Amplifiers (OPA) are the “baseline” solutions for the transmitter.
  - Other options (Er:YAG and Er:YGG) now possible.
- **Receiver (Detector) Technology**
  - DRS e-APD

![Diagram of CH$_4$ IPDA Lidar](image-url)

- **Transmitter**
  - Pump Laser 1.06 µm
  - Seed Laser 1.65 µm
  - OPA/OPO
  - Transmit Optics
  - Trace Gas (CH$_4$) Absorption
  - To surface

- **Electronics**
  - Detector & Filters

- **Receiver**
  - Receiver Optics
  - Reflection from surface

![Graphs of Transmittance](image-url)
GSFC CH$_4$ Lidar with Integrated Path Differential Absorption Lidar (IPDA)
CH$_4$ Laser Transmitter: OPO-OPA

OPO

OPA

$\begin{align*}
I_1(t) & \quad \text{Seed(s)} \\
I_2(t) & \\
I_1(1) & \\
I_1(2) & \\
I_1(i) & \\
n_2(t) & \\
\end{align*}$

DFB:

DBR:

Yb fiber, Nd:YAG or hybrid

OPO (cavity)

Idler, Residual Pump

Signal $I_1$ Methane Line

Burst Pulse

$\sim 100$ µs separation

Burst Pulse

20-40 pulses

$\sim 3-50$ ns pulses

Single Pulse

$\sim 50$ ns pulses
## Current GSFC Power scaling options OPA/OPO

<table>
<thead>
<tr>
<th>Approach</th>
<th>#1. OPA with smaller burst pulses</th>
<th>#2. OPA with large pump pulse</th>
<th>#3. OPO with large pump pulse</th>
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<tbody>
<tr>
<td><strong>Seed laser</strong></td>
<td>Existing DFB lasers are OK but would prefer a DBR laser and higher power</td>
<td>High seed power <strong>needed</strong> Would prefer a DBR</td>
<td>Existing DFB laser is OK would prefer a DBR laser and higher power</td>
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<td><strong>Parametric stage</strong></td>
<td>Single OPA stage possible but currently at low energy.</td>
<td>Need multiple OPA stages to achieve high power</td>
<td>Need for cavity locking &amp; step tuning</td>
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**Er:YAG and Er:YGG**
Other transmitter options: Er:YAG and Er:YGG

• Why consider other transmitter options?
  – OPAs and OPOs are parametric conversion techniques. They are complex and difficult to implement are sensitive to vibration.
  – Size/mass of airborne instrument needs to reduced.
  – Erbium Yttrium-aluminum-garnet (YAG) 1.645 nm
  – Erbium Yttrium-gallium-garnet (YGG) 1.651 nm

• Potential for “simpler” and more efficient transmitter technology.

• Tuning remains an issue.
OPO

~122 cm

~33 cm
2015 Airborne Demonstration

- Flight Test Methane LIDAR Instruments:
  - GSFC Methane Sounder (20-l OPA and 5-l OPO)
  - GSFC Picarro
  - COSS-HSC Optec Solutions
  - In-situ CO2 (LaRC G. Diskin)

- Conduct several test flights from NASA’s Armstrong Science Aircraft Integration Facility (SAIF) in Palmdale, CA:
  - 1 Engineering flight
  - 2 science flights
  - Approximately 12 hours of flight time in mostly in CA/NV

- Compare OPO-OPA performance
- Assess detector performance
- Assess CH₄ LIDAR measurements over Western US
- Evaluate derivation of XCH₄ from LIDAR observations and compare with in-situ and calibrations sites whenever possible.

CH₄ emissions in CA. Source: EPA
CH$_4$ Airborne Instrument

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (OPA/OPO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center I</td>
<td>1650.9 nm</td>
</tr>
<tr>
<td>Number of I</td>
<td>20/5</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>~700/80 ns</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>~30/250 µJ</td>
</tr>
<tr>
<td>Bin width</td>
<td>4 ns</td>
</tr>
<tr>
<td>Divergence</td>
<td>~150 µrad</td>
</tr>
<tr>
<td>Receiver diam.</td>
<td>20 cm</td>
</tr>
<tr>
<td>Field of view</td>
<td>300 µrad</td>
</tr>
<tr>
<td>Receiver BP</td>
<td>0.8 nm (FWHM)</td>
</tr>
<tr>
<td>Averaging time</td>
<td>1/16 s *</td>
</tr>
<tr>
<td>Detector Resp.</td>
<td>~1-1.5 x 10$^9$ V/W</td>
</tr>
</tbody>
</table>

*Data analysis uses 1s averages
Flight Conditions

- Clouds
- Cultivated/Urban/Landfill
- Varying Topography

- Desert/Spirals
- Ocean
- Evening/Night
Data is filtered for Ground Returns. 1 s averaging. No DRS non-linearity correction. No GPS correction. Model assumes uniform CH4 1900 ppm.
Science Flight 1 CH$_4$ mixing Ratio
OPA Precision 1s averaging

<table>
<thead>
<tr>
<th></th>
<th>N total</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4</td>
<td>1242</td>
<td>1938.91262</td>
<td>7.59609</td>
</tr>
</tbody>
</table>

~0.4%
OPO Precision 1s averaging*

Descriptive Statistics

<table>
<thead>
<tr>
<th></th>
<th>N total</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>KNCH4</td>
<td>536</td>
<td>1.97477</td>
<td>0.01008</td>
</tr>
</tbody>
</table>

~0.5%

*Using K. Numata’s retrievals
DRS e-ADP works very well at 1651 nm.
Responivity is close to what we have for CO$_2$ but there is still some uncertainty on the actual value.
DRS is linear over at least two to three orders of magnitude.
Signal strength (link margin) during flight is roughly what we expected. Return signal estimation is complicated by burst pulse shape of the OPA and the high OPO energy and clouds/topography.
Both OPA and OPO worked better than expected.
Best precision for: OPA ~ 0.4% and OPO ~ 0.5%.
20 wavelengths (OPA) produced better fits than 5 (OPO) but OPA was extremely sensitive to LMA fiber and cabin temperature fluctuations and does not have adequate energy for space unless external amplifiers are used and/or the present OPA laser is improved.
OPO cavity is sensitive to temperature and pressure but still worked well.
OPO has the required (high) energy but the OPO flight was complicated by our inability to effectively attenuate the laser.
OPO energy was more stable than OPA during flight.
Summary

- Many different approaches and options for power scaling investigated.
- Leveraged IRAD & ACT programs.
- Demonstrated two viable architectures for a CH$_4$ transmitter using OPA and multi-wavelength OPO.
- Demonstrated power scaling to 250-290 µJ.
- Demonstrated and validated CH$_4$ airborne measurements using the two lidar transmitters.
- Other laser transmitter options being investigated.
- We would like to thank ESTO and GSFC IRAD for their support.
Setup for 5-wavelength OPO
OPA Open-path measurement setup

Fibertek laser head
Fiber amplifier stage #5

Data acquisition system
Chiller
Stage #1~4

DFB laser
Tuning signal

Computer
Boxcar averagers

976nm
1064nm

HWP

MgO·PPLN

DM

W

Filter

CH4 cell

DET

Telescope

Far target
**CH$_4$ Laser Transmitter Components**

**Pump:** a high power, single frequency, narrow linewidth fiber or solid state laser at 1064 nm

**Seed:** a low power, single frequency diode laser at 1651 nm.

Optical Parametric Oscillator (OPO) or Optical Parametric Amplifier (OPA). A non-linear crystal that amplifies the seed laser to the energy needed for space (250-300 µJ) **without** degrading the spectral characteristics.

**Used OPO/OPAs to measure CH4 at near and mid IR, CO2, H2O and CO**
CH4 Transmitter Technology - OPA

**OPA:** Easy to align, easy to tune, power scaling hard to achieve while maintaining narrow linewidth.

*OPA samples the CH₄ line at several wavelengths using a single, continuously tuned seed laser*
OPO: Complicated to align and tune; power scaling easier to achieve while maintaining narrow linewidth. OPO samples the CH$_4$ line at several discrete wavelengths using multiple seed lasers. All lasers must be locked.
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<th>#3. OPO with large pump pulse</th>
</tr>
</thead>
</table>
| Pump laser    | 1. Burst mode laser. Need to achieve higher energy and pulse uniformity. Hybrid shown to work.  
                 2. Burst mode fiber MOPA with Waveguide Amplifier shows promise | 1. High power Yb fiber laser (1030 nm).  
                 2. Planar Wave Amplifier with commercial laser as Master Oscillator.  
                 2. High power Yb fiber laser (1030 nm). |
| Seed laser    | Existing DFB lasers are OK but would prefer a DBR laser and higher power | High seed power **needed** Would prefer a DBR | Existing DFB laser is OK would prefer a DBR laser and higher power |
| Parametric stage | Single OPA stage possible but currently at low energy.            | Need multiple OPA stages to achieve high power                   | Need for cavity locking & step tuning                            |

**Er:YAG and Er:YGG**