A Methane Lidar for Greenhouse Gas Measurements

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Outline

• Motivation - Why measure Methane?
• GSFC Measurement Approach
• Airborne Campaign Results
• Current Status
• Summary
Why measure Methane?

Source: Saunois et al. 2016
Global Methane Budget

Global Methane Budget

TOTAL EMISSIONS

- 105 (77-133)
- 188 (115-243)
- 34 (15-53)
- 167 (127-202)
- 64 (21-132)

558 (540-568)

CH₄ ATMOSPHERIC GROWTH RATE
10 (9.4-10.6)

TOTAL SINKS

- 548 (529-555)
- 515 (510-583)
- 33 (28-38)

Sink from chemical reactions in the atmosphere
Sink in soils

EMISSIONS BY SOURCE

- Fossil fuel production and use
- Agriculture and waste
- Biomass burning
- Wetlands
- Other natural emissions (Geological, lakes, termites, oceans, permafrost)

In million-tons of CH₄ per year (Tg CH₄ / yr), average 2003-2012

Source: http://www.globalcarbonatlas.org
GSFC CH₄ IPDA Lidar

- **Transmitter (Laser) technology**
  - Current (optimum) Wavelength for CH₄ 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

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**Diagram: Transmitter**
- Pump Laser 1.06 µm
- Seed Laser 1.65 µm
- OPA/OPO
- Transmit Optics
- Trace Gas (CH₄) Absorption
- To surface

**Diagram: Receiver**
- Detector & Filters
- Receiver Optics
- Reflection from surface

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**Graphs:**
- Transmittance vs. Wavelength (nm) for H₂O and CH₄.
- Wavelengths: 1650.50 nm for H₂O, 1651.00 nm for CH₄.

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**Notes:**
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- Receiver (Detector) Technology
  - DRS e-APD
Why use multiple wavelengths?

“Ideal” Instrument – has only random noise which can be averaged indefinitely. Two wavelengths can adequately sample the lineshape. Averaging always helps.

Real Instrument – has random and non-random noise which can NOT always be averaged. Two wavelengths can NOT adequately sample the lineshape or reduce biases.
### CH$_4$ Airborne Instrument

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (OPA/OPO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center l</td>
<td>1650.9 nm</td>
</tr>
<tr>
<td>Number of l</td>
<td>20/5</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>~700/80 ns</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>~25/250 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*
2015 Airborne Demonstration Flight Tracks
Flight 1-OPA

Precision: 14.9 ppb or ~0.8%  
Slope = 0.98; offset = -0.007; $R^2 = 0.994$. 

- Slope: 0.98; Offset: -0.007; $R^2 = 0.994$. 
- Precision: 14.9 ppb or ~0.8%. 

Graphs showing data with annotations.
Flight 2-OPA

Precision: 13.4 ppb or ~0.7%

Slope = 0.998; offset = -0.007; R² = 0.990.
Flight 3-OPO

Precision: 21.4 ppb or ~1.1%

Slope = 1.01; offset = -0.003; $R^2 = 0.999$. 

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CH4 mixing Ratio-Raw (ppb)

1 sec Averaging

Lidar

1 sec Averaging

Theory
Airborne Demonstration Summary

✓ *Best* precision for:
  ✓ OPA ~ 6-9 ppb; overall 12-15 ppb
  ✓ OPO ~ 10-12 ppb; overall: 21 ppb

✓ 20 wavelengths (OPA) produced better fits than 5 (OPO).

✓ OPO correction needed for cross talk.

✓ DRS e-ADP works very well at 1651 nm and is linear over a remarkable range of signals and gain settings.

✓ New airborne instrument designed.
Current summary of laser efforts

Transmitter Requirements:
High Energy (~600 µJ)
Narrow linewidth
Tunable (10-20 wavelengths)
Robust
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/cost of airborne/space instrument needs to reduced.

• Potential for “simpler” and more efficient solid-state” laser transmitter technology.

• Tuning and lasing at the right wavelength remain an issue.
Er:YAG or Er:YGG?

- Spectroscopy (temperature dependence, line mixing, etc.)
- Interferences from $\text{H}_2\text{O}$ vapor.
- Power and Tunability requirements for the laser.
New Transmitters: Compact OPO and Er:YAG/Er:YGG

New compact OPO

Nonlinear crystal (MgO:PPLN)

Pump laser (Yb-fiber)

Seed $\lambda_s$

OPO

Signal $\lambda_s$

Idler $\lambda_i$

Er:YAG/Er:YGG

1651nm signal energy [\text{uJ}]

1030nm pump energy [\text{uJ}]

160923
Advalue Photonics fiber laser + OPO
Signal energy (unseeded)

Graph showing the relationship between 1030nm pump energy and 1651nm signal energy for a new compact OPO system.
Existing OPO (Er:YAG/YGG) Tuning

- 5 wavelength system for injection seeding
  - 5 lasers
  - 4 OPLLs
  - 4 optical switches
  - 4 fast detectors
New tuning concepts and monolithic OPO

- Simplify the existing multi-laser (wavelength) system
- Two proposed schemes:
  - Dual Sideband (DSB): requires Game Changing DBR deliverable
  - Single Sideband (SSB)
  - Both showing promising results
Both Er:YAG and Er:YGG require a wavelength-selecting element to lase at the right wavelength. Tuning becomes exceedingly complicated if we need to tune both the seed/cavity and the wavelength-selecting element.
New (improved) airborne sensor

- New transceiver uses Er:YAG/Er:YGG and new, compact OPO (AdValue pump laser)
- Two beams can be fired simultaneously (unlike the earlier version)
- Smaller than the earlier version but still too big to fly on small aircraft
- Vibration isolation maintained
Summary

✓ Demonstrated CH$_4$ airborne measurements using two lidar transmitters (OPA and OPO).

✓ Many different approaches and options for the laser transmitter are being investigated.

✓ Demonstrated power scaling with several options.

✓ Will incorporate Freedom Photonics seed laser deliverable and decide on final configuration.

✓ Looking for opportunities to fly!

• We would like to thank ESTO and GSFC IRAD for their support.
GSFC CH$_4$ Lidar with Integrated Path Differential Absorption Lidar (IPDA)
Setup for 5-wavelength OPO

Data acquisition system
- Computer
- Boxcar averagers

Pump laser Nd:YAG
- 1064 nm (pump)

CH4 cell (Vacuum tank)

Reflective target

1651 nm (Signal)

Telescope

Cavity length ctrl

Switch

SOA

COL

DM

DMs

BE

DET

Sig.

CH4

Phase modulator

OPO cavity lock

Beat with slave lasers

ODF-LD (Slave 1)
- \( \lambda_1 \)

ODF-LD (Slave 2)
- \( \lambda_2 \)

ODF-LD (Slave 3)
- \( \lambda_3 \)

ODF-LD (Slave 4)
- \( \lambda_4 \)

ODF-LD (Master)
- \( \lambda_0 \)

CH4 cell (Fiber coupled)

16FSR~102Hz

Slave 1
- \( \lambda_1 \)

Slave 2
- \( \lambda_2 \)

Master
- \( \lambda_0 \)

Slave 3
- \( \lambda_3 \)

Slave 4
- \( \lambda_4 \)

CH4 absorption

OPO cavity transmission
OPA Open-path measurement setup

Fibertek laser head
Fiber amplifier stage #5

Data acquisition system
- Computer
- Boxcar averagers
- Trigger 10kHz
- Tuning signal

DFB laser
- SOA

Far target

Telescope

CH4 cell

Periscope

Filter

MgO:PPLN

HWP

DM

976nm

1064nm

1651nm

W
CH\textsubscript{4} Laser Transmitter: OPO-OPA

Signal \textit{l}_1 \text{ Methane Line} \sim 1650 \text{ nm}