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

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

![Diagram of transmitter and receiver system](image)
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.
### CH₄ Airborne Instrument

**Parameter** | **Value (OPA/OPO)**
--- | ---
Center λ | 1650.9 nm
Number of λ | 20/5
Pulse Width | ~700/80 ns
Energy/pulse | ~25/250 µJ
Bin width | 4 ns
Divergence | ~150 µrad
Receiver diam. | 20 cm
Field of view | 300 µrad
Receiver BP | 0.8 nm (FWHM)
Averaging time | 1/16 s *
Detector Resp. | ~1-1.5 x 10⁹ V/W

*Data analysis uses 1s averages
Flight 1-OPA

Precision: 14.9 ppb or ~0.8%

Slope = 0.98; offset = -0.007; \( R^2 = 0.994 \).
Flight 2-OPA

Precision: 13.4 ppb or ~0.7%

Slope = 0.998; offset = -0.007; $R^2 = 0.990$. 

1 sec Averaging 

CH4 Mixing Ratio (ppb)

Time (UTC secs)

0 86000 88000 90000 92000 94000 96000 98000 100000

2000

1500

1000

500

0

Theory
- Picarro
- Lidar Mixing Ratio

DOD Lidar

DOD Theory

0.0 0.5 1.0 1.5 2.0 2.5

0.0 0.5 1.0 1.5

Linear Fit
Flight 3-OPO

Precision: 21.4 ppb or ~1.1%

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

Seed Laser
- DBR
- DFB
- Fast-tuned seed
- Seed Module (Tunable)

Pump Laser
- Solid State
- Fiber/Hybrid
- Pump
- Er:YGG/YAG
- OPO/OPA
- Final Design
• Why consider other transmitter options?
  – OPAs and OPOs are parametric conversion techniques. They are complex and difficult to implement and are sensitive to vibration.
  – Size/mass/cost of airborne/space instrument needs to be 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 H₂O vapor.
- Power and Tunability requirements for the laser.
New Transmitters: Compact OPO and Er:YAG/Er:YGG

![Experimental setup](image)

**Graph:**
- **1030nm pump energy [uJ]**
- **1651nm signal energy [uJ]**

- **Points:**
  - 160923: Advalue Photonics fiber laser + OPO
  - **Signal energy (unseeded)**

**Equipment:**
- **New compact OPO**
- **Nonlinear crystal (MgO:PPLN)**
- **Er:YAG/Er:YGG**
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 multilaser (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.
BACKUP
GSFC CH\textsubscript{4} Lidar with Integrated Path Differential Absorption Lidar (IPDA)
Setup for 5-wavelength OPO

Data acquisition system

Computer
Boxcar averagers

Pump laser
Nd:YAG

Trigger from FPGA

Cavity length ctrl

1064 nm (pump)

DFB-LD (Slave 1)

DFB-LD (Slave 2)

DFB-LD (Slave 3)

DFB-LD (Slave 4)

OPO cavity lock

Beat with slave lasers

Phase modulator

DFB-LD (Master)

CH4 cell (Vacuum tank)

1651 nm (Signal)

CH4 absorption

OPO cavity transmission

16FSR-10GHz

Reflective target

CH4

Telescope

Sig.

DET

IS

BE

DMs

DM

OPO

COL

SOA

Switch

Trigger from FPGA

Pump laser Nd:YAG

Cavity length ctrl

1064 nm (pump)
OPA Open-path measurement setup
CH$_4$ Laser Transmitter: OPO-OPA

- **Laser Transmitter:** OPO-OPA
- **Signal Line:** ~1650 nm
- **Seed(s)**: ~1650 nm
- **Pump**: Yb fiber, Nd:YAG or hybrid (1030-1064 nm)
- **OPO (cavity)**: DFB: $l_1(t)$, DBR: $l_1(i)$
- **Burst Pulse**: ~100 µs separation
- **Idler (IR)** & Residual Pump
- **Signal $l_1$ Methane Line ~1650 nm**

Diagram showing the laser transmitter setup with single and burst pulse outputs.