DIFFERENTIAL ABSORPTION LIDAR FOR GREENHOUSE GAS MEASUREMENTS

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• Program & Project Objectives
• What is measured
• Background about LIDAR and Differential Absorption LIDAR
• Our Approaches
• Results and Current Status
CHALLENGES FOR GHG EMISSION MEASUREMENTS

**Bottom-Up**
- **Electricity Generation**
- **Industrial Energy Generation**
  - Stationary Sources: 0.005–0.05 km
- **Agriculture**
- **Landfills**
- **Coal Mines**
  - Distributed/Area Sources: 0.5–5 km

**Top-Down**
- **Forests & Woodlands**
- **Estuaries & Coastal Ocean**
  - Regional Sinks/Sources: 10–100 km
- **Satellite Observations**
- **Atmospheric Observations**
  - International: 100–1,000 km

**Measurement Tools, Methodologies, Application Areas, and Spatial Scales**
- **CEM Technology**
  - Gas Concentration Standards
  - Stack Gas Velocity
- **Fuel Calculation-Based Approaches**
  - Fuel Quantification
  - Fuel Property Analysis
- **Open Path Measurements**
  - Optical Reference Data
  - Advanced LIDAR Methods
- **Atmospheric Monitoring**
  - Optical Spectral Reference Data
  - Advanced Measurement Tools
- **Surface-Based Networks**
  - Gas Concentration Standards
  - Wind Velocity Standards
- **Atmospheric Monitoring**
  - Satellite Observations
  - Radiometry
  - Optical Spectral Reference Data
  - Microwave Standards
  - Atmospheric Transport Methods
NIST PROGRAM OBJECTIVES

• Develop and validate advanced measurement tools that improve the quantitative determination of GHG sources and sinks and the accuracy of climate science measurements.

• Deliverable: Transfer new, validated diagnostic and measurement technologies to the private sector and embody their methods in documentary standards.

Project Objectives – Diff. Absorption LIDAR

• Develop methods for accurately quantifying greenhouse gas emissions from natural and anthropogenic distributed sources and sinks.

• Develop an indoor testing facility to rigorously test hardware components and software algorithms in well quantified conditions.
OVERALL GOAL:
SUPPORT MEASUREMENT BASED GHG INVENTORIES

GHG Flowrate (Flux)

\[ m_{ghg} = \sum m_t x_{gi} \]

Where: \( m_t \) is total mass flow rate
\( x_{gi} \) is relative abundance of \( i^{th} \) gas

Inventory: Sum of continuous flux over a year
(either emissions to or capture from the atmosphere)

For a flux measurement, both the density of GHG and its velocity are required, along with error contributions from both quantities.
OBJECTIVES

- Construct prototype DIAL systems for the detection of GHGs from distributed area sources
  - 3 - 5 km range
  - ~10 meter spatial resolution

- Integrate DIAL concentration measurements with measurements of wind speed (Doppler LIDAR)

- Develop and assess GHG flux retrieval algorithms and understand measurement uncertainties
WHAT IS LIDAR?

LIGHT DETECTION AND RANGING

1) Pulses of laser light scatter in the atmosphere
2) A telescope receives a small portion of backscattered light
3) A detector converts received light to electronic signals
4) A data system digitizes and stores the signals
5) Range is found from pulse time-of-flight (150 m/µs)
WHAT IS DIAL?

DIFFERENTIAL ABSORPTION LIDAR

1) Use two or more wavelengths of light
2) Exploit the fact that the REFLECTANCE of atmospheric aerosols and Rayleigh backscattering are WEAKLY dependent on wavelength
3) Exploit the fact that the ABSORPTION of trace gases (CO$_2$, CH$_4$, H$_2$O, etc) STRONGLY depends on wavelength

• **Ratio** of captured reflected light at two different wavelengths as a function of time reveals the **density** of the measured gas **as a function of distance**
• **Ratio** removes common effects – geometry, collection efficiencies, etc.
Absorption features relevant for GHG DIAL

- CH₄
- CO₂ (x1000)
- N₂O
- H₂O

On Resonance
Off Resonance

Absorbance

Frequency (cm⁻¹)

1.57 µm

1.57 µm

8 x 10⁻⁵

6 x 10⁻⁵

4 x 10⁻⁵

2 x 10⁻⁵

1 x 10⁻⁵

0

0

1.65 µm

1.57 µm
DIFFERENTIAL ABSORPTION LIDAR (DIAL) CARTOON

- Telescope
- Detector
- Backscattered light
- More absorption in denser plume

**Raw signal**
- Photon collection
- Off-resonant light (not absorbed by CO₂)
- Resonant light (absorbed by CO₂)

**Processed signal**
- Concentration of CO₂
- Range (m)

\[ \alpha \frac{d}{dR} \ln \left( \frac{N_{\lambda on}}{N_{\lambda off}} \right) \]
ADVANTAGES OF OPERATION IN THE NEAR IR

- Eye safety
- Wide availability of laser sources
- High sensitivity detectors (PMT)
- COTS technology from telecom industry
- Relatively weak absorption strength means DIAL can probe longer distances
- Minimal water absorption

![Laser Eye Safety](image)

The ANSI standard is in terms of fluence (J/cm²).
GOAL

Simultaneous concentration & wind speed

DIAL System Designs

Direct Detection (PMT)

Light source (OPO | Fiber Amp)

Sequential multi-λ rapid λ switching

Etalon based wind measurement

Heterodyne Detection (InGaAs APD)

Light Source (OPO | Fiber Amp)

Simultaneous multi-λ

Wind speed from Doppler shifted aerosol return
RISTRA Optical Parametric Oscillator Features

- New technology
  A tunable high energy laser source with good beam quality needed for long range remote sensing

- Wavelength ranges
  - Signal 1595 nm – 1650 nm
  - Idler 2995 nm – 3082 nm

Demonstrated: 50 mJ/pulse at 1.6 mm  
200 MHz spectral linewidth
Repetition rate: 500 kHz (designed for short range)
Mean power : 3W
Peak power : 25-30W
Energy/pulse : 6μJ

Provides a tunable high energy laser source with good beam quality needed for long range remote sensing AND ultra-portable, no alignment needed
SMALL-SCALE HARD-TARGET SYSTEM
Laser transmitter

Newtonian telescope

Current Controller

DFB laser

1610 nm

Wavelength Meter

EOM Switch

Fiber Amp

ref detector

Laser transmitter

Newtonian telescope

signal detector

4” dia. PVC flow pipe

3 meters

CO₂

10%
90%

EOM Switch

Fiber Amp

ref detector

Laser transmitter

Newtonian telescope

signal detector

4” dia. PVC flow pipe

3 meters

CO₂

Current Controller

Wavelength Meter

1610 nm

EOM Switch

Fiber Amp

ref detector

Laser transmitter

Newtonian telescope

signal detector

4” dia. PVC flow pipe

3 meters

CO₂
• NDIR sensor calibrated with 5500 ppm CO₂ (10% uncertainty) and zeroed with high purity N₂
COMPARISON OF HT DIAL TO NDIR MONITOR
ETALON-BASED HIGH-SPEED WAVELENGTH SWITCHING

Diode Laser \(\rightarrow\) CS 10%

90%

CS \(\rightarrow\) EOM 24 GS/s AWG

EOM \(\rightarrow\) PZT, Heater

Fiber Coupled Reference Cavity

Fiber Coupled Reference Cavity

Wavemeter

Provides any pulse or pulse sequence

Operates as a narrowband filter

\(\lambda/4\)

\(\lambda/2\)

PBS

\(900\) um MM Fiber

Ref. Det.

APD/PMT

\(\rightarrow\) DIAL Output Beam

DIAL Output Beam

Frequency (MHz)

Cavity transmission

\(\rightarrow\) PZT, Heater

Heater

PZT

Operates as a narrowband filter

Provides any pulse or pulse sequence

24 GS/s AWG

EOM

EOM

PZT, Heater

Fiber Coupled Reference Cavity

Wavemeter
• Produce multiple wavelengths simultaneously across the absorption line of

• Heterodyne detection puts each frequency point (black dot) on the absorption curve into a separate detection channel.
THE 2ND PARAMETER – WIND SPEED MEASUREMENT

- A 2 mph (1 m/s) wind velocity yields a 1 MHz Doppler shift at 1.6 mm
- Doppler shift can be measured using heterodyne techniques or by exploiting filter properties of Fabry-Perot cavities.

Several approaches are being pursued:

1. OPO laser system ➔ We estimate 5 – 10 mph resolution limit
2. Fiber amplifier system ➔ 2 mph resolution limit
3. Commercially available systems ➔ 2 mph resolution
**Flux Parameters**

velocity and GHG concentration traceable to NIST standards

30 meter test section allows test gas confinement for independent conc. & velocity determination

100 meters
RESULTS AND SUMMARY

- Designed and constructed two prototype DIAL systems for the detection of GHGs from distributed area sources
  - OPO operating at 100 Hz
  - Fiber based amplifier operating at 500 kHz

- Developed new methods to perform rapid sequential scans for direct detection and single pulse multi-l scans for heterodyne detection.

- Developing an indoor test facility for characterization of the DIAL system in a controlled environment.

- Goal is to move system outside to characterization of GHG densities and fluxes at the few km scale