Double-pulsed 2-\(\mu\)m lidar validation for atmospheric CO\(_2\) measurements

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SPIE Remote Sensing
New Developments in Lidar Technology I

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Objectives

Demonstrate ground-based and airborne CO₂ measurement capability using 2-μm double-pulse IPDA lidar.
CO₂ 2-μm Double-Pulse IPDA Lidar

- Methodology
- Spectroscopy
- Instrument and Integration
- IPDA Ground Testing
- IPDA Airborne Testing
- Summary and Conclusion
Objective

- Develop, integrate and demonstrate a 2-micron pulsed Integrated Path Differential Absorption Lidar (IPDA) instrument CO₂ Column Measurement from Airborne platform
- Conduct ground validation test to demonstrate CO₂ retrieval
- Conduct engineering test flights to demonstrate CO₂ retrieval from UC-12 aircraft
- Conduct post flight data analysis for the purpose of evaluation of CO₂ measurement capability

Approach:

- Repurpose existing hardware including previously developed transmitter, receiver and data acquisition system
- Complete fabrication of transmitter, wavelength control and receiver units assembly
- Integrate existing and to be developed subsystems into a complete breadboard lidar system
- Fabricate a mechanical structure and integrate completed subsystem

Key Milestones

- Design of laser transmitter assembly: 10/12
- Design, manufacture and assembly of receiver: 04/13
- Integrate subsystems into breadboard lidar system: 06/13
- Conduct ground test of the integrated lidar assembly: 07/13
- Integrate lidar system on UC-12 aircraft: 11/13
- Conduct post flight data analysis: 09/14

TRL\textsubscript{in} = 3 \hspace{1cm} TRL\textsubscript{out} = 5 (AIRCRAFT)

Co-Is/Partners: Jirong Yu, Mulugeta Petros, Syed Ismail, NASA LaRC
Methodology

- IPDA lidar relies on the Hard Target Lidar Equation

\[ E_T = \eta_r \cdot \varphi_r \cdot \frac{A_t}{\Delta R^2} \cdot E_M \cdot \frac{\rho}{\pi} \cdot \exp[-OD(\lambda, R_G)] \]

- Double-pulse tuning defines CO₂ differential optical depth, the main IPDA product

\[ dOD_{cd} = \int_0^R 2 \cdot \Delta \sigma_{cd} \cdot N_{cd} \cdot dr \approx \ln \left( \frac{E_{T,off} \cdot E_{M,on}}{E_{M,off} \cdot E_{T,on}} \right) \]

- Other IPDA products include ranging and surface reflectivity
• Standard models are used for estimating optical depth, return pulse strength, SNR and errors for any operating condition.
• Modeling and meteorological data are used for XCO2 derivation.
Instrument and Integration

2-μ double-pulse IPDA lidar
IPDA Ground Testing

Differential optical depth– model and measurement

Dry mixing ratio
IPDA vs (in-situ) measurement
Aircraft had temperature, pressure, humidity sensors, LiCor and GPS
Some of the flights were supported by balloon launches
• Aerial picture of Roxboro steam plant, Semora, North Carolina
• 2 GW capacity (one of the largest power plants in the USA)
• Plant rely on coal-firing resulting in significant CO₂ plumes
• CO₂ optical depth measurement from the 2-μm double-pulse IPDA lidar
• Instrument flying, against wind, above plant incinerator
• Ninth flight; 1 km altitude and 4 GHz on-line operation
• Model derived from onboard LiCor in-situ sensor
• Data collected at different altitudes
• Tenth flight; IPDA operating at 3 GHz on-line offset
IPDA Airborne Testing

- NOAA air sampling and IPDA lidar optical depth comparison
- Return signal samples from different altitudes up to 6km
- IPDA range measurements compared to on-board GPS
- Eighth flight; IPDA operating at 3 and 4 GHz on-line offsets
Comparison of the airborne air-sampling measurements, $x_{\text{cd}}$, and weighted average column dry-air volume-mixing ratio of CO$_2$, $X_{\text{cd}}$, for 4 GHz on-line wavelength setting at different altitude. $X_{\text{cd}}$ are obtained from modeling through NOAA data, $X_{\text{cd},c}$, and the IPDA lidar differential optical depth measurements, $X_{\text{cd},m}$. IPDA $X_{\text{cd}}$ measurement standard deviation, $\delta X_{\text{cd},m}$, offset, $\Delta X_{\text{cd}}$ ($\Delta X_{\text{cd}} = X_{\text{cd},m} - X_{\text{cd},c}$), and measurement error, $\varepsilon_{\text{cd},m}$ ($\varepsilon_{\text{cd},m} = \delta X_{\text{cd},m}/X_{\text{cd},m}$), are also listed. As well as the measurement bias ($\beta_{\text{cd},m} = \Delta X_{\text{cd}}/X_{\text{cd},m}$)

<table>
<thead>
<tr>
<th>R$_A$</th>
<th>$x_{\text{cd}}$</th>
<th>$X_{\text{cd},c}$</th>
<th>$X_{\text{cd},m}$</th>
<th>$\delta X_{\text{cd},m}$</th>
<th>$\Delta X_{\text{cd}}$</th>
<th>$\varepsilon_{\text{cd},m}$</th>
<th>$\beta_{\text{cd},m}$</th>
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<tbody>
<tr>
<td>m</td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
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<td>6125.6</td>
<td>400.75</td>
<td>404.08</td>
<td>405.22</td>
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<td>1.14</td>
<td>1.02</td>
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<td>5242.6</td>
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<td>404.34</td>
<td>405.84</td>
<td>4.74</td>
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<td>3976.7</td>
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<td>404.89</td>
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<td>3051.9</td>
<td>401.55</td>
<td>405.54</td>
<td>407.10</td>
<td>12.83</td>
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<td>3.15</td>
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</table>
Schematic of cloud slicing concept for CO$_2$ measurement within the atmospheric boundary layer.

- Difference in CO$_2$ measured differential optical depth from clear and thick cumulus clouds conditions, representing total column range and free troposphere, respectively, estimates the boundary layer CO$_2$ content.
- IPDA ranging capability aids in distinguishing and selecting the data for clear and thick cloud conditions.
### Specifications

<table>
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<th></th>
<th>Current Technology</th>
<th>Projected Technology</th>
<th>Current Space Requirement†</th>
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<tr>
<td>Transmitter Technique</td>
<td>Single-Laser</td>
<td>Single-Laser</td>
<td>Two Lasers</td>
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<tr>
<td>Cooling</td>
<td>Liquid</td>
<td>Conductive</td>
<td>Single-Pulse</td>
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<tr>
<td>Wavelength (μm)</td>
<td>2.051</td>
<td>2.051</td>
<td>2.051</td>
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<tr>
<td>Pulse Energy (mJ)</td>
<td>100 / 50</td>
<td>50 / 15 / 5</td>
<td>40 &amp; 5</td>
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<tr>
<td>Repetition Rate (Hz)</td>
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<tr>
<td>Power (W)</td>
<td>1.3</td>
<td>3.5</td>
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<td>Pulse Width (ns)</td>
<td>200 / 350</td>
<td>30 / 100 / 150</td>
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<td>Optical-Optical Efficiency (%)</td>
<td>4.0</td>
<td>5.0</td>
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<td>Wall-Plug Efficiency (%)</td>
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<td>2.1</td>
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<td>Multi-Pulse Delay (μs)</td>
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<td>200</td>
<td>250 ± 25</td>
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<td>Transverse Mode</td>
<td>TEM₀₀</td>
<td>TEM₀₀</td>
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<td>Longitudinal Modes</td>
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<td>Pulse Spectral Width (MHz)</td>
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<td>Beam Quality (m²)</td>
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<td>Freq. Control Accuracy (MHz)</td>
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<td>Spectral Purity (%)</td>
<td>99.9</td>
<td>99.9</td>
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</tr>
</tbody>
</table>

*ESA Report of Assessment, SP-1313/1 (2008).*

### Future Work

**Path To Space**

Comparing 2-μm Double-Pulse IPDA and Triple-Pulse IPDA to ESA Requirements for CO₂ Space Mission
Conclusions

- CO₂ 2-µm double-pulse IPDA lidar development and validation at NASA LaRC
- Double-pulse IPDA ground testing demonstrated successful CO₂ measurement as compared to in-situ sensors
- Double-pulse IPDA CO₂ airborne measurements agrees with different validation models through different sources:
  - CO₂ plume detection
  - Onboard CO₂ sensor
  - NOAA air sampling
- Cloud slicing technique separates boundary layer and free troposphere CO₂ measurements, for better source and sink and transport studies.
- IPDA lidar extended capabilities through triple-pulse operation, for simultaneous and independent CO₂ and H₂O measurement.
- 2-µm IPDA lidar meets or exceeds current space requirement set by ESA, projected in A-SCOPE
Questions?