Development of an Airborne Triple-pulse 2-micron Integrated Path Differential Absorption Lidar (IPDA) for Simultaneous Airborne Column Measurements of Carbon Dioxide and Water Vapor in the Atmosphere

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Outline

• Objective
• Introduction
• Methodology
• Instrument specifications
  o Transmitter
  o Receiver
  o Data Acquisition & Control
• Summary
Objective

To demonstrate and validate simultaneous and independent measurements of the weighted-average, column dry-air mixing ratios of carbon dioxide ($\text{XCO}_2$) and water vapor ($\text{XH}_2\text{O}$) using a single instrument from an airborne platform.
Introduction

Active remote sensing of CO₂ have been recommended by the National Research Council (NRC) to increase our understanding of the gas worldwide sources, sinks, and fluxes to enhance carbon-cycle and climate studies\[1\]

Based on the above recommendation and the success of ESTO funded Double-Pulse Integrated Path Differential Absorption (IPDA) Lidar, this effort funded by ESTO Instrument Incubator Program -2013, we present the current status of developing a next generation of the lidar: An Airborne triple-pulse 2-µm IPDA Lidar for CO₂ and H₂O Column Measurement

- Why Pulsed?
  Pulsed operation allows range determination

- Why Triple-Pulse?
  Triple-pulse operation enables measurement of two species with a single instrument

- Why 2-µm wavelength?
  This wavelength provides the required measurement sensitivity with mature and reliable technology

Methodology

- $\lambda_1$ and $\lambda_2$ for H$_2$O sensing, with the same amount of CO$_2$ absorption.
- $\lambda_2$ and $\lambda_3$ for CO$_2$ sensing, with the same amount of H$_2$O absorption.
- Simultaneous measurement of the CO$_2$ and H$_2$O while avoiding interference.

\[
dOD_{1,2} = \int_0^R 2 \cdot (\Delta \sigma_{\text{wv}}^{1,2} \cdot N_{\text{wv}} + \Delta \sigma_{\text{cd}}^{1,2} \cdot N_{\text{cd}}) \cdot dr = \ln \left( \frac{E_{T,2} \cdot E_{M,1}}{E_{M,2} \cdot E_{T,1}} \right)
\]

\[
dOD_{2,3} = \int_0^R 2 \cdot (\Delta \sigma_{\text{wv}}^{2,3} \cdot N_{\text{wv}} + \Delta \sigma_{\text{cd}}^{2,3} \cdot N_{\text{cd}}) \cdot dr = \ln \left( \frac{E_{T,3} \cdot E_{M,2}}{E_{M,3} \cdot E_{T,2}} \right)
\]
Methodology

Targets

- Design and fabricate a conductively-cooled, triple-pulsed, 2-µm laser transmitter
- Design and develop wavelength control system for rapid and fine tuning of the three sensing lines of the CO₂ and H₂O IPDA lidar
- Integrate receiver optics and direct detection electronics
- Integrate laser transmitter with receiver to develop the 2-µm triple-pulsed IPDA lidar instrument
- Conduct ground-based and airborne CO₂ and H₂O measurements and validate with *in-situ* sensors
Instrument Specifications

Instrument Block Diagram

- **Electronics unit**
  - Laser drivers
  - Q-S driver and monitors
  - Laser timing control
  - Interlocks
  - Center line locking
  - Triggers

- **Cooling unit**
  - Flow 1-2 liter/min
  - 5-15 deg. C
  - Rod/Bench cooler

- **Laser unit**
  - 2.05096 µm

- **Wavelength control**

- **Data Acquisition And processing**

- **Telescope Lidar detector**
### Instrument Specifications

#### Laser Transmitter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ($\lambda_1 / \lambda_2 / \lambda_3$)</td>
<td>2050.5094 / 2051.0590 / 2051.1915</td>
<td>(nm)</td>
</tr>
<tr>
<td>Output Energy</td>
<td>50 / 15 / 5</td>
<td>(mJ)</td>
</tr>
<tr>
<td>Pulse length</td>
<td>30 / 60 / 100</td>
<td>(ns)</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>50</td>
<td>(Hz)</td>
</tr>
<tr>
<td>Pulse separation</td>
<td>200</td>
<td>(µs)</td>
</tr>
<tr>
<td>Beam Divergence</td>
<td>150</td>
<td>(µrad)</td>
</tr>
<tr>
<td>Beam Quality</td>
<td>&lt; 2</td>
<td>($M^2$)</td>
</tr>
<tr>
<td>Laser Line Width</td>
<td>Transform limit</td>
<td></td>
</tr>
<tr>
<td>Frequency Control Accuracy</td>
<td>1</td>
<td>(MHz)</td>
</tr>
<tr>
<td>Wall-plug Efficiency</td>
<td>2</td>
<td>(%)</td>
</tr>
</tbody>
</table>
## Instrument Specifications

### Receiver

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope Dia.</td>
<td>40</td>
<td>(cm)</td>
</tr>
<tr>
<td>Telescope Field of View</td>
<td>300</td>
<td>(μrad)</td>
</tr>
<tr>
<td>Telescope F#</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Optical Efficiency</td>
<td>65</td>
<td>(%)</td>
</tr>
</tbody>
</table>

### Detector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Efficiency</td>
<td>67.75</td>
<td>(%)</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>300</td>
<td>(mV)</td>
</tr>
<tr>
<td>Dark current</td>
<td>3.7</td>
<td>(nA)</td>
</tr>
<tr>
<td>Capacitance</td>
<td>29.3</td>
<td>(pF)</td>
</tr>
</tbody>
</table>
Instrument Specifications

Instrument Integration Task Flow

- Design and Fabrication (20 Month)
  - Triple-Pulse Laser Transmitter
  - Receiver System Optics
  - Detection System
  - Software and Data Acquisition
  - Electronics and Interfacing
  - Thermal Loads Management

- Integration and Testing (8 Month)
  - Mechanical Design/FAB
  - Structural Analysis
  - Trailer Integration
  - Ground Testing and Validation

- Campaign and Result (8 Month)
  - Aircraft Integration
  - Flight Campaign
  - Data Analysis
  - Results Interpretation
## Transmitter Design Parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser crystal</td>
<td>Ho:Tm:YLF</td>
<td>Triple pulse, R30, long lifetime</td>
</tr>
<tr>
<td>Tm concentration</td>
<td>2%, 3%, 4%</td>
<td>Heat load reduction</td>
</tr>
<tr>
<td>Ho concentration</td>
<td>&gt;.8%</td>
<td>Better Q-S performance</td>
</tr>
<tr>
<td>Laser crystal size</td>
<td>2x2x15</td>
<td>Heat extraction</td>
</tr>
<tr>
<td>Operation temperature</td>
<td>5-15°C</td>
<td>Ground state depletion (GSD)</td>
</tr>
<tr>
<td>Crystal configuration</td>
<td>Diffusion bonded</td>
<td>pump face cooling</td>
</tr>
<tr>
<td>Cooling method</td>
<td>conductive</td>
<td></td>
</tr>
<tr>
<td>Pump power</td>
<td>200W max 2.5ms</td>
<td>25 watt heat</td>
</tr>
<tr>
<td>Pump wavelength</td>
<td>792nm</td>
<td></td>
</tr>
<tr>
<td>Pump beam radius</td>
<td>500µm</td>
<td></td>
</tr>
<tr>
<td>Resonator configuration</td>
<td>Ring &lt;1m</td>
<td></td>
</tr>
</tbody>
</table>
## Transmitter Design Parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Enclosure</td>
<td>6”x26”x11”</td>
<td>compatibility</td>
</tr>
<tr>
<td>Laser Configuration</td>
<td>Oscillator</td>
<td></td>
</tr>
<tr>
<td>Output Reflectivity</td>
<td>75%</td>
<td></td>
</tr>
<tr>
<td>Pump configuration</td>
<td>End pump</td>
<td>Higher efficiency</td>
</tr>
</tbody>
</table>

![Diagram of Laser Head and QS](image-url)
Transmitter

Crystal Concentration Study

- Thulium (Tm) and Holmium (Ho) concentrations are modified in the crystal
- Reduced Tm concentration from 6% to 2-4% to accommodate thermal loading
- Raised Ho concentration to enhance the Q-S performance
Transmitter

Experimental Setup for a Prototype Ring Laser
Initial 2 µm Long Pulse Performance at 15 Hz

- The initial laser output indicates sufficient energy storage in the crystal
- 81% reflective mirror produces higher energy but the potential for damage is high in QS operation mode
- The energy dropped when the repetition rate was raised to 25 Hz

Initial Laser Demonstration at 15 Hz & 15°C
Laser Technical Challenges

- Thermal loading on the crystal at 50 Hz operation reduced output energy
- Thermal fracture resulted from single-end pumping of the crystal
- The crystal non-uniform thermal expansion induced excessive mechanical stress
- Single-end pumping created uneven absorption along the length of the crystal and resulted in reabsorption loss

Transmitter

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Max. temp.</th>
</tr>
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<tbody>
<tr>
<td>3%Tm</td>
<td>377K</td>
</tr>
<tr>
<td>3%Tm</td>
<td>320K</td>
</tr>
<tr>
<td>3%Tm</td>
<td>303K</td>
</tr>
<tr>
<td>2%Tm</td>
<td>299K</td>
</tr>
</tbody>
</table>
Transmitter

Solutions Sought

- Optimized pump length from 5 ms down to 3 ms
- Crystal double-end pumping
- Custom-designed, spring loaded crystal mount to accommodate non-uniform thermal expansion
- Crystal length optimization with respect to Tm concentration to homogenize pump absorption distribution
- Diffusion bonding of pump-ends of the crystal with undoped YLF to cool the pump spot and provide six surface cooling
Transmitter

Performance Characterization

Triple Pulse Laser Performance

\[ y = -0.040433 + 0.20695x \quad R = 0.99941 \]

\[ y = -0.019166 + 0.11824x \quad R = 0.9958 \]
GOAL: Generate three distinct wavelengths, with respect to a CO$_2$ absorption locked center-line wavelength.
Wavelength Control Electronics

- Center line locking successfully completed
- A second center line locking hardware built. It will be used to further characterize the spectral line width and the jitter of the locked line system
The receiver system consists of two Aft-optics configurations:

- A room temperature pin InGaAS detector (double pulsed system) and a high sensitivity cryogenic cooled MCT e-APD detector
- LaRC modifies the double pulsed system aft-optics to accommodate a fiber port to Godard’s detector
- Work with Godard provides MCT e-APD detection system complete with the aft-optics and control electronics
Receiver
Receiver

MCT e-APD Hardware

- System packaging is in progress
- Performance testing of the detector using blackbody radiation and 2-µm fast LED.

Detection system enclosure 19” rack, 7U
It includes electronics access to each of the pixel in the array
Data Acquisition

Waveform Digitizers

IPDA State-of-the-art Digitizers
Manufactured by Agilent

<table>
<thead>
<tr>
<th><strong>Part Number</strong></th>
<th><strong>Number of Bits</strong></th>
<th><strong>Maximum Sampling Rate</strong></th>
<th><strong>Number of Channels</strong></th>
<th><strong>Bandwidth</strong></th>
<th><strong>Input Impedance</strong></th>
<th><strong>Coupling</strong></th>
<th><strong>Support</strong></th>
<th><strong>Energy Monitor</strong></th>
<th><strong>Hard Target Return</strong></th>
<th><strong>Both</strong></th>
<th><strong>Number of Bits</strong></th>
<th><strong>Maximum Sampling Rate</strong></th>
<th><strong>Number of Channels</strong></th>
<th><strong>Bandwidth</strong></th>
<th><strong>Input Impedance</strong></th>
<th><strong>Coupling</strong></th>
<th><strong>Support</strong></th>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>U1065A</td>
<td>U1066A</td>
<td>U5303A</td>
<td>12 Bits</td>
<td>1.0 GS/s</td>
<td>2-Channels</td>
<td>50 Ω</td>
<td>DC Coupling</td>
<td>Supported</td>
<td>Obsolete</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>10 Bits</td>
<td>12 Bits</td>
<td></td>
<td></td>
<td></td>
<td>DC Coupling</td>
<td>Supported</td>
<td>Obsolete</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 GS/s</td>
<td>420 MS/s</td>
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<td>DC Coupling</td>
<td>Supported</td>
<td>Obsolete</td>
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<td></td>
<td>2-Channels</td>
<td>2-Channels</td>
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<td></td>
<td></td>
<td>DC Coupling</td>
<td>Supported</td>
<td>Obsolete</td>
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<td></td>
<td></td>
<td></td>
<td>DC up to 3 GHz</td>
<td>DC up to 300 MHz</td>
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<td></td>
<td>DC Coupling</td>
<td>Supported</td>
<td>Obsolete</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>50 Ω</td>
<td>50 Ω</td>
<td></td>
<td></td>
<td></td>
<td>DC Coupling</td>
<td>Supported</td>
<td>Obsolete</td>
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Double-Pulse IPDA

Triple-Pulse IPDA

New Product
Data Acquisition & Control

Control Electronics

- **Laser Transmitter Control (LTC) Electronics**
  - Controls the laser pump of the transmitter
  - Injection locking and Q-switching functions
  - Sends synchronizing signal to data acquisition and wavelength control

- **Wavelength Control Electronics**
  - Seed laser driver
  - Provides CO₂ Online Locking
  - Generates three frequencies offset from the center line
Summary

- Triple-pulse 2-μm IPDA lidar instrument is under development for measuring atmospheric CO₂ and H₂O simultaneously
- IPDA transmitter is under development
- IPDA receiver and data acquisition systems have progressed well
- Instrument compact design fits NASA B-200 payload requirement
- Projected full system integration and ground testing by the end of this year
- Airborne testing is planned for next year