Airborne Double Pulsed 2-micron IPDA Lidar for Atmospheric CO₂ Measurement

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Outline

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Introduction

- The study of global warming needs precisely and accurately measuring greenhouse gases concentrations in the atmosphere. CO$_2$ and H$_2$O are important greenhouse gases that significantly contribute to the carbon cycle and global radiation budget on Earth.
- NRC Decadal Survey recommends a mission for Active Sensing of Carbon Dioxide (CO$_2$) over Nights, Days and Seasons (ASCENDS).
- 2 micron laser is a viable IPDA transmitter to measure CO$_2$ and H$_2$O column density from space.
- The objective is to demonstrate a first airborne direct detection 2 micron IPDA lidar for CO$_2$ measurements.
2µm Pulsed Lidar Approach

- Unambiguously defines the optical path of the detected signal; eliminate contamination from aerosols and clouds to yield high accuracy measurements

- Auxiliary altimetry lidar may not needed

- The weighting function in the 2-µm region is most favorable for making CO\textsubscript{2} measurements near the surface and PBL, where the sources and sinks of CO\textsubscript{2} are located

- Straightforward data analysis

- The pulse approach can potentially determine CO\textsubscript{2} concentrations as a function of distance, a valuable data product that is not easily available
Time between successive measurements: 0.1S

Transmit and receive near nadir-pointing laser beams with on and off-line wavelength channels
- Ground surface reflection (land and sea)
- Measure difference in integrated path absorption at these two wavelengths
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

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

- Other IPDA products include ranging and surface reflectivity.
Provided availability of meteorological data, differential optical depth can be converted into dry mixing ration (XCO2)

\[ XCO2 = \frac{DAOD_{cd}}{\int_0^R 2 \cdot \Delta \sigma_{cd} \cdot N_{dry} \cdot dr} = \frac{N_{cd}}{N_{dry}} \]

\[ N_{dry} = N_{air} - N_{wv} \]
\[ N_{wv} = f_n(RH) \]
\[ N_{air} = \frac{P}{k \cdot T} \]
Modeling: Spectroscopy

\[ \Delta \sigma_{cd} = f_n(\lambda, P, T) \]

- Calculated using HITRAN 2012 database targeting CO\textsubscript{2} R30 line
- Voigt line profile was assumed
- Calculation includes 5550 CO\textsubscript{2} neighboring lines from 2044.22 nm to 2059.57 nm
- Calculation includes 1816 H\textsubscript{2}O neighboring lines from 2022.21 nm to 2080.36 nm
- US Standard Atmospheric model was assumed
Absorption profiles are used for evaluating the CO2 weighting-functions, applied to convert the IPDA optical depth measurement into weighted average column dry-air volume-mixing ratio for comparison to in-situ sensors.
Calculated for nadir operation from ocean surface at different operating conditions. Calculation based on the hard target lidar equation:

\[
P = \eta_r \cdot \varphi_r \cdot \frac{A}{\left(R_A - R_G\right)^2} \cdot \frac{E}{t} \cdot \frac{\rho}{\pi} \cdot T
\]

For fixed on-line, transmission is based on the molecular and aerosol optical depths:

\[
T = \exp\left(-OD_{cd} - OD_{wv} - OD_A\right)
\]
**Modeling: Double-Path Differential Optical Depth**

$\text{CO}_2$ double-path optical depth is modeled according to

$$\text{OD}_{cd} = 2 \int_{R_G}^{R_A} \sigma_{cd} \cdot N_{cd} \cdot dr$$

$\text{CO}_2$ differential optical depth, at different operating conditions

$$d\text{OD}_{cd} = \text{OD}_{cd}(\lambda_{on}) - \text{OD}_{cd}(\lambda_{off})$$
SNR calculated as the ratio of the return power to the total noise power. Total noise power obtained by combining instrument fixed noise and signal dependent shot noise. Fixed noises include electronic noises and background radiation. Dominant electronic noises sources, such as detector dark current and TIA feedback Johnson noise, input current and voltage noises and coupling noise, were considered.
# IPDA Lidar Specification

## Transmitter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (On / Off Line)</td>
<td>2051.023 / 2051.250 nm</td>
</tr>
<tr>
<td>Pulse Energy (On / Off Line)</td>
<td>100 / 45 mJ</td>
</tr>
<tr>
<td>Pulse Width (On / Off Line)</td>
<td>200 / 350 nsec</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>10 Hz (Double Pulse)</td>
</tr>
<tr>
<td>Laser Divergence Angle</td>
<td>160 µrad</td>
</tr>
<tr>
<td>CO2 Cell</td>
<td>8 m path length, 5 Torr</td>
</tr>
<tr>
<td>Lidar Configuration</td>
<td>Co-axial</td>
</tr>
</tbody>
</table>

## Receiver

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian Telescope Diameter</td>
<td>0.40 m f/2.3</td>
</tr>
<tr>
<td>Receiver Field-of-View</td>
<td>570 µrad</td>
</tr>
<tr>
<td>Detector</td>
<td>PIN: Hamamatsu G12183-203K</td>
</tr>
<tr>
<td>Detector Responsivity</td>
<td>1.15 A/W</td>
</tr>
<tr>
<td>TIA Gain</td>
<td>$10^3$ V/A – $10^6$ V/A</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>High / Low Gain Channel</td>
<td>90 / 10 %</td>
</tr>
<tr>
<td>Digitizer Rate</td>
<td>200MS / s</td>
</tr>
</tbody>
</table>
System Schematic
Laser Transmitter

- Double Pulsed
- Injection Seeded
- High Beam Quality $M^2 = 1.05$
- Narrow Line Width 2.2 / 1.3 MHz
- Beam Expanded 0.16mrad
- Stable Operation ~200µs between On/Off

Transmitter Performance

$y = -0.28286 + 0.12813x \quad R= 0.99937$

$y = -0.25858 + 0.10774x \quad R= 0.99966$
Aft Optics and Detector

- Two channel receiver design
- Pulse energy monitor
- Aft-optics
- Detector and preamplifier PIN InGaAs, FEMTO DHPCA-100
- Narrow band filter not applied
Ground Testing

- Mobile lidar, configured and installed safety
- Calibrated target reflectivity at 2 micron wavelength
- Transmitter alignment to the telescope Field of View (FOV)
- Aligned the receiver Aft optics
- Characterize and Calibrate the narrow band width filters
- Establish pointing knowledge and stability
- Operated both during day and night, and several long duration data collected
10 Flights in March & April 2014

<table>
<thead>
<tr>
<th>Date</th>
<th>Purpose</th>
<th>Duration</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 20</td>
<td>Instrument Check Flight</td>
<td>2.1 hr</td>
<td>VA</td>
</tr>
<tr>
<td>March 21</td>
<td>Engineering</td>
<td>2.7 hr</td>
<td>VA</td>
</tr>
<tr>
<td>March 24</td>
<td>Engineering</td>
<td>3.0 hr</td>
<td>VA</td>
</tr>
<tr>
<td>March 27</td>
<td>Early morning</td>
<td>3.0 hr</td>
<td>VA</td>
</tr>
<tr>
<td>March 27</td>
<td>Mid-afternoon</td>
<td>2.5 hr</td>
<td>VA</td>
</tr>
<tr>
<td>March 31</td>
<td>Inland-Sea</td>
<td>2.5 hr</td>
<td>VA, NC</td>
</tr>
<tr>
<td>April 02</td>
<td>Power Station</td>
<td>2.4 hr</td>
<td>NC</td>
</tr>
<tr>
<td>April 05</td>
<td>With NOAA</td>
<td>3.7 hr</td>
<td>NJ</td>
</tr>
<tr>
<td>April 06</td>
<td>Power Station</td>
<td>3.0 hr</td>
<td>NC</td>
</tr>
<tr>
<td>April 10</td>
<td>Late afternoon</td>
<td>2.3 hr</td>
<td>VA</td>
</tr>
</tbody>
</table>

- Aircraft had temperature, pressure, humidity sensors, LiCor and GPS
- Some of the flights were supported by balloon launches
IPDA Lidar Capability

- Ranging
- Cloud Slicing
- Signals at various ground condition
- DAOD
- Power Station
- Flight data comparison with NOAA flights which collects a flask at multiple altitudes to obtain vertical profile
Ranging Capability

![Graph showing ranging capability with time and range data]
Cloud Slicing

<table>
<thead>
<tr>
<th></th>
<th>Alt. m</th>
<th>DAOD Lidar</th>
<th>DAOD Model</th>
<th>dDAO D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>6805</td>
<td>1.072</td>
<td>1.094</td>
<td></td>
</tr>
<tr>
<td>Cloud</td>
<td>5631</td>
<td>0.757</td>
<td>0.782</td>
<td></td>
</tr>
<tr>
<td>Lidar</td>
<td></td>
<td></td>
<td></td>
<td>0.315</td>
</tr>
<tr>
<td>Model</td>
<td></td>
<td></td>
<td></td>
<td>0.312</td>
</tr>
</tbody>
</table>
IPDA Airborne Lidar: Sample Return Signals

Lidar Signal (v) vs. Time (μs) for different scenarios:

- Veg/Soil: Lidar Signal = 1.89, SNR (peak) = 398, SNR (power) = 485, DAOD Model = 1.0551, DAOD w/mon. = 1.0550
- Sea: Lidar Signal = 0.552, SNR (peak) = 111, SNR (power) = 139, DAOD Model = 1.0551, DAOD w/mon. = 1.0883
- Cloud: Lidar Signal = 1.78, SNR (peak) = 328, SNR (power) = 452, DAOD Model = 0.7805, DAOD w/mon. = 0.757
Power Station Roxboro

36° 28'52.79"N 79° 04'08.97"W

DAOD

Time (S)
IPDA Airborne Testing: Sample Return Signals

- 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.

### Comparison with the airborne air-sampling measurements

<table>
<thead>
<tr>
<th>RA [m]</th>
<th>(x_{cd}) [ppm]</th>
<th>(X_{cd,c}) [ppm]</th>
<th>(X_{cd,m}) [ppm]</th>
<th>(\delta X_{cd,m}) [ppm]</th>
<th>(\Delta X_{cd}) [ppm]</th>
<th>(\varepsilon_{cd,m}) [%]</th>
<th>(\beta_{cd,m}) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6125.6</td>
<td>400.75</td>
<td>404.08</td>
<td>405.22</td>
<td>4.15</td>
<td>1.14</td>
<td>1.02</td>
<td>0.28</td>
</tr>
<tr>
<td>5242.6</td>
<td>400.96</td>
<td>404.34</td>
<td>405.84</td>
<td>4.74</td>
<td>1.50</td>
<td>1.17</td>
<td>0.37</td>
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<tr>
<td>3976.7</td>
<td>401.61</td>
<td>404.89</td>
<td>406.60</td>
<td>8.69</td>
<td>1.71</td>
<td>2.14</td>
<td>0.42</td>
</tr>
<tr>
<td>3051.9</td>
<td>401.55</td>
<td>405.54</td>
<td>407.10</td>
<td>12.83</td>
<td>1.56</td>
<td>3.15</td>
<td>0.38</td>
</tr>
</tbody>
</table>

\(x_{cd}\) - airborne air-sampling measurements

\(X_{cd}\) - weighted average column dry-air volume-mixing ratio of CO\(_2\) for 4 GHz on-line wavelength setting

\(X_{cd,c}\) - Obtained from modeling through NOAA data

\(X_{cd,m}\) - Obtained from IPDA lidar DAOD measurements

\(\delta X_{cd,m}\) - IPDA \(X_{cd}\) measurement standard deviation

\(\Delta X_{cd}\) - Offset, \((\Delta X_{cd} = X_{cd,m} - X_{cd,c})\)

\(\varepsilon_{cd,m}\) - Measurement error, \((\varepsilon_{cd,m} = \delta X_{cd,m}/X_{cd,m})\)

\(\beta_{cd,m}\) - Measure bias \((\Delta X_{cd}/X_{cd,m})\)
Summary

• Developed a 2-μm double-pulsed laser transmitter and IPDA lidar system for CO₂ measurement
• Modeling and simulation of the 2-μm IPDA lidar instrument projected performance and science data retrieval algorithms
• Successful airborne IPDA lidar operation demonstrating robust integration and reliability
• Demonstrated airborne IPDA return signals obtained through different weighting functions and ground conditions, including soil, vegetation, ocean, sand and snow, beside cloud slicing capability all with high single-shot signal-to-noise ratio exceeding 100
• Bias and sensitivity verified through DAOD measurement
• Analysis of water vapor interference on CO₂ measurement indicated minimal error contribution due to precise selection, tuning and locking of the selected operational wavelengths.