Measurements of Atmospheric CO$_2$ Column in Cloudy Weather Conditions using An IM-CW Lidar at 1.57 Micron

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Outline

❖ Introduction
  - Carbon sciences and challenges
  - Lidar CO$_2$ measurement approach
  - Instrumentation and flight campaigns

❖ Lidar Measurements
  - In-situ observations for validation
  - Accuracy of CO$_2$ measurements
  - Precision of CO$_2$ measurements
  - Ranging measurements
  - CO$_2$ measurements through thin clouds
  - CO$_2$ column measurements to cloud tops

❖ Summary
Land plants and ocean uptake removes some of atmospheric CO₂
Atmosphere CO₂ budgets: large variations
Prediction of this trend and variability, especially in changing climate (?)
Simultaneously transmits $\lambda_{on}$ and $\lambda_{off}$ reducing noise from the atmosphere and eliminating surface reflectance variations.

Approach is independent of the system wavelength and allows simultaneous CO$_2$ & O$_2$ (1.26 $\mu$m) number density measurements, combining them to derive XCO$_2$. 

**Weighting Functions**

Offsets from Line Center (pm)

- Line-Center (+3 pm)
- Off-Line-1 (+50 pm)
- Off-Line-2 (-50 pm)

Altitude, km

- 0 km
- 10 km
- 20 km
- 40 km

Pressure, mb

Peak Normalized $\Delta_{\text{atm}} dP$, mb$^{-1}$

+0

+2

+3

+4.6

+10
IM-CW Laser Absorption Lidar
1.57-μm CO₂ Measurement Technique

Multiple channel Intensity Modulations: orthogonal waveforms

Simultaneously transmitted Intensity modulated range encoded waveforms

Simultaneously received Online and Offline IPDA returns

Measurement: Output of correlation between transmitted and received waveforms

Range encoded approach for detection and ranging is analogous to mature CW Radar and GPS measurement techniques

\[ DAOD = \frac{1}{2} \ln \left( \frac{P_{off} \cdot E_{on}}{P_{on} \cdot E_{off}} \right) \]
Airborne System Demonstration

ASCENDS CarbonHawk Experiment Simulator (ACES developed at LaRC with support from Harris)

Multifunctional Fiber Laser Lidar (MFLL) (developed by Harris in 2004 Harris and Langley since 2005)

Instrument-aircraft integration

advancing key technologies for spaceborne measurements of CO₂ column mixing ratio
Development & Demonstration

21-25 May 2005, Ponca City, OK (DOE ARM)
  5 Lear Flts: Land, Day & Night (D&N)
20-26 June 2006, Alpena, MI
  6 Lear Flts: Land & Water (L&W), D&N
20-24 October 2006, Portsmouth, NH
  4 Lear Flts: L&W, D&N
20-24 May 2007, Newport News, VA
  8 Lear Flts: L&W, D&N
17-22 October 2007, Newport News, VA
  9 Lear Flts: L&W, D&N, Clear & Cloudy
  10 UC-12 Flts: L&W, D&N, Rural & Urban
10-16 July 2009, Newport News, VA
  5 UC-12 Flts: L&W
31 July – 7 Aug. 2009, Ponca City, OK
  5 UC-12 Flts: L&W, D&N
10-20 May 2010, Hampton, VA
  6 UC-12 Flts: L&W, D&N
5-11 May 2011, Hampton, VA
  5 UC-12 Flts: L&W, D&N, Clear and Cloudy
6-18 July 2010, Palmdale CA
  6 DC-8 Flts: L&W, D
28 July – 11 Aug. 2011, Palmdale CA
  8 DC-8 Flts: L&W, D
February 19 – March 9, 2013, Palmdale CA
  7 DC-8 Flts: L&W, D&N
August 13 – September 3, 2014, Palmdale CA
  5 DC-8 Flts: L&W, D

ranging capability enabled

MFL on Lear-25
MFL on UC-12
MFL on DC-8

total 14 MFLL flight campaigns since 2005, plus 1 ACES in Hampton, 2014
In Situ and Lidar Comparision
(MFLL OCO-2 Under Flight: 20140827)

In-situ derived (or modeled) Value
- In-situ from Spiral: $XCO_2$, T/p/q profiles
- Radiative transfer model
- Ranging correction with lidar range data
- In-situ derived (or modeled) DAOD
- In-situ derived (or modeled) $XCO_2$

difference (ppm): 0.18
2013 ASCENDS Campaign:
Measurements over varying terrain

Arizona Desert
precision $\sim 0.21\%$ ($\sim 0.80$ ppmv)

Colorado Aged Snow
difference $\sim 0.26\%$ ($\sim 0.99$ ppmv); Precision $\sim 0.42\%$ ($\sim 1.6$ ppmv)
Comparison of Range Determination from PN Altimeter and Off-line CO₂ Signal

Range estimates obtained from the off-line CO₂ return and time coincident returns from the onboard PN altimeter over the region of Four Corners, NM from the DC-8 flight on 7 August 2011.

RMS errors < 3 m
CO₂ Column Measurements Through Thin Cirrus (22 Feb 2013)

CO₂ concentration (22-Feb-2013)

CO₂ mixing ratio (ppm) vs. Altitude (m)

Amplitude vs. Time and range (km)

Cloud optical depth vs. Time (UT, hr)

10 Hz data
Column CO$_2$ DAOD and Equivalent XCO$_2$ Measurements

consistent CO$_2$ column observations obtained for clear and cloudy conditions

cloudy XCO2– clear XCO2 = $-0.7$ ppm

10 Hz data
CO₂ Column Measurements over Thick Low Level Clouds
(10 Aug 2011)

• Sufficient CO₂ absorption for DAOD measurements
• Strong enough signals to low level thick clouds
• Legs: 4, 5, 7
Range and Column CO₂ to Surface and Thick Cloud Tops

10 Hz data
## Column CO₂ Measurements to Surface and Thick Cloud Tops

<table>
<thead>
<tr>
<th></th>
<th>Leg 4</th>
<th>Leg 5</th>
<th>Leg 7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>lidar DAOD&lt;sub&gt;surface&lt;/sub&gt;</strong></td>
<td>0.4271 ± 0.0056</td>
<td>0.5196 ± 0.0093</td>
<td>0.6902 ± 0.0155</td>
</tr>
<tr>
<td><strong>lidar DAOD&lt;sub&gt;cloud&lt;/sub&gt;</strong></td>
<td>0.3480 ± 0.0143</td>
<td>0.4368 ± 0.0243</td>
<td>0.6007 ± 0.0339</td>
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<td><strong>lidar DAOD&lt;sub&gt;bndrylyr&lt;/sub&gt;</strong></td>
<td>0.0791 ± 0.0154</td>
<td>0.0828 ± 0.0260</td>
<td>0.0895 ± 0.0373</td>
</tr>
<tr>
<td><strong>In-situ DAOD&lt;sub&gt;surface&lt;/sub&gt;</strong></td>
<td>0.4243</td>
<td>0.5160</td>
<td>0.6939</td>
</tr>
<tr>
<td><strong>In-situ DAOD&lt;sub&gt;cloud&lt;/sub&gt;</strong></td>
<td>0.3417</td>
<td>0.4334</td>
<td>0.6075</td>
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<tr>
<td><strong>In-situ DAOD&lt;sub&gt;bndrylyr&lt;/sub&gt;</strong></td>
<td>0.0826</td>
<td>0.0826</td>
<td>0.0826</td>
</tr>
<tr>
<td><strong>lidar XCO₂&lt;sub&gt;surface&lt;/sub&gt;</strong></td>
<td>383.2 ± 5.02</td>
<td>384.3 ± 6.88</td>
<td>381.6 ± 8.57</td>
</tr>
<tr>
<td><strong>lidar XCO₂&lt;sub&gt;cloud&lt;/sub&gt;</strong></td>
<td>391.5 ± 16.09</td>
<td>387.7 ± 21.31</td>
<td>382.0 ± 21.56</td>
</tr>
<tr>
<td><strong>In-situ XCO₂&lt;sub&gt;surface&lt;/sub&gt;</strong></td>
<td>380.8</td>
<td>381.7</td>
<td>383.8</td>
</tr>
<tr>
<td><strong>In-situ XCO₂&lt;sub&gt;cloud&lt;/sub&gt;</strong></td>
<td>384.6</td>
<td>384.9</td>
<td>386.4</td>
</tr>
</tbody>
</table>

*10 Hz data*
Global/regional atmospheric CO$_2$ observations require high accuracy and precision measurements owing to very small variations in atmospheric CO$_2$ mixing ratio.

Laser absorption lidar at 1.57$\mu$m with ranging-encoded IM provides advanced capability in cloud/aerosol discriminations.

IM-CW lidar has demonstrated the capabilities of precise CO$_2$ measurements through many airborne flight campaigns under variety of environment conditions, including CO$_2$ column measurements through thin cirrus clouds and to thick clouds. For low level clouds, boundary layer CO$_2$ measurements consistent with in-situ observations can be obtained.

Analysis shows that current IM-CW lidar approach will meet space CO$_2$ observation requirements and provide precise CO$_2$ measurements for carbon transport, sink and source studies.