Regional and Global Atmospheric CO$_2$ Measurements Using 1.57 Micron IM-CW Lidar

Bing Lin$^1$, Michael Obland$^1$, Amin Nehrir$^1$, Edward Browell$^2$, F. Wallace Harrison$^1$, Jeremy Dobler$^3$, Joel Campbell$^1$, Susan Kooi$^4$, Byron Meadows$^1$, Tai-Fang Fan$^4$, Zhaoyan Liu$^4$, and LaRC ASCENDS team

$^1$NASA Langley Research Center, Hampton, VA, USA
$^2$NASA Langley/STARSS II Affiliate, Hampton, VA, USA
$^3$Exelis Inc. (now part of Harris Corp.), Ft. Wayne, IN, USA
$^4$Science System and Application, Inc, Hampton, VA, USA

18th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases, and Related Measurement Techniques 13-17 September, 2015, La Jolla, California, USA
Outline

- **Introduction**
  - Lidar approach for CO$_2$ measurement
  - CO$_2$ lidar instrumentation

- **Lidar Measurements**
  - CO$_2$ column measurements
  - Ranging capability
  - Accuracy and precision
  - CO$_2$ column measurements with clouds
  - Space application

- **Summary**
CO₂ Measurement Architecture
IM-CW Laser Absorption Lidar

- Precise CO₂ measurements using the Integrated Path Differential Absorption (IPDA) technique with a range-encoded intensity-modulated continuous-wave lidar.
- Simultaneously transmits l_on and l_off reducing noise from the atmosphere and eliminating surface reflectance variations.

\[
\tau_{DAOD} = \frac{1}{2} \ln \left( \frac{S_{on} R_{off}}{S_{off} R_{on}} \right)
\]

Dobler et al., and Lin et al. Applied Optics, 2013
Instrument Development
(joint effort of LaRC and Exelis)

ASCENDS CarbonHawk Experiment Simulator
(ACES developed at Langley with support from Exelis)

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

3×10W amplifier 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

Total of 14 MFLL flight campaigns since 2005
Total of 2 ACES test flight campaigns in Hampton, 2014-2015
Comparison of Range Determination from PN Altimeter and Off-line CO$_2$ Signal

Dobler et al., *Applied Optics*, 2013

Simultaneously transmitted Intensity modulated range encoded waveforms

RMS errors < 3 m

Range estimates obtained from the off-line CO$_2$ 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.
In Situ and Lidar Comparison
(MFLL OCO-2 Under Flight: 20140827)

In-situ derived (or modeled) Value
- In-situ from Spiral: CO$_2$, 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

2014 AVOCET In Situ CO2
08/27/14
21:14:09 to 21:44:50 UT

Estimated XCO2 (ppm)

Spiral point

Black curves: lidar measured XCO2
Blue curves: in-situ derived XCO2
2013 ASCENDS Campaign: Measurements over varying terrain

Arizona Desert

precision ~ 0.21% (~0.80 ppmv)

Colorado Aged Snow

difference ~ 0.26% (~0.99 ppmv); Precision ~ 0.42% (~1.6 ppmv)
Natural Variability
(lidar and in-situ measurements)
(Mid-West Flight: Iowa Box; 02 Sept 2014)

Significant spatiotemporal variations (a few ppm) found from lidar observations and when comparing spiral with non-spiral in-situ observational data.
CO$_2$ Column Measurements Through Thin Cirrus (22 Feb 2013)

Lin et al., *Optics Express*, 2015

Blythe, CA

10 Hz data
Derived XCO$_2$ Column Measurements to the Surface Under Clear and Cloudy Conditions

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

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

cloudy XCO$_2$ – clear XCO$_2$ = $-0.7$ ppm

Lin et al., *Optics Express*, 2015

10 Hz data
Range and Column CO$_2$ to Surface and Thick Cloud Tops
(West Bank, Iowa; 10 Aug 2011)

Lin et al., *Optics Express*, 2015

10 Hz data
The ACT-America suborbital mission addresses the three primary sources of uncertainty in atmospheric carbon inversions: transport error, prior flux uncertainty and limited data density.
ASCENDS Mission Development

Today: MFLL and ACES instruments in DC-8 racks
- Size = 100” x 43” x 24”
- Mass = 787.2 lb.
- Size = 44” x 34” x 24”
- Mass = 317.1 lb

Global Hawk
- Size = 100” x 43” x 24”
- Mass = 787.2 lb.

TBD: ASCENDS mission

TBD: ISS Tech Demo?
Space CO₂ Lidar Modeling and Measurement

Same instrument architecture: increased power and telescope


- Cloud height: 9 km
- 0.1-s integration time
- High SNR & small bias (< 0.1%)
- Cloud OD < ~0.4
- Dawn/dusk orbit, 42W power
- Other LEO orbits are also applicable
Summary

- IM-CW lidar at 1.57 μm with ranging-encoded IM has demonstrated the capability of precise CO₂ measurements through many airborne flight campaigns under variety of environment conditions, including CO₂ column measurements through thin cirrus clouds and to thick clouds.

- Over land, clear-sky lidar CO₂ measurements with 1-s integration reach a precision as high as within 1 ppm; these measurements are also consistent with coincident in situ measurements with mean bias much smaller.

- Ranging uncertainties are shown to be at sub-meter level.

- Analysis shows that current IM-CW lidar approach will meet space CO₂ observation requirements and provide precise CO₂ measurements for carbon transport, sink and source studies.
# 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>
</tr>
<tr>
<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>
</tr>
<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>
</tbody>
</table>

Lin et al., *Optics Express*, 2015

10 Hz data