Monitoring Atmospheric CO₂ from Space: Challenge & approach

Bing Lin¹, F. Wallace Harrison¹, Amin Nehrir¹, Edward Browell², Jeremy Dobler³, Joel Campbell¹, Byron Meadows¹, Michael Obland¹, Susan Kooi⁴, Tai-Fang Fan⁴, Syed Ismail¹, and LaRC ASCENDS team

¹NASA Langley Research Center, Hampton, VA, USA
²NASA Langley/STARSS II Affiliate, Hampton, VA, USA
³Exelis Inc., Ft. Wayne, IN, USA
⁴Science System and Application, Inc, Hampton, VA, USA

The 4th International Symposium on Atmospheric Light Scattering and Remote Sensing
1-5 June 2015, Wuhan, China
Outline

❖ Introduction
  o Carbon sciences and challenges
  o Lidar CO\textsubscript{2} measurement approach
  o Instrumentation

❖ Lidar Measurements
  o CO\textsubscript{2} column measurements
  o Accuracy and precision
  o CO\textsubscript{2} column measurements with clouds
  o Ranging measurements
  o Space application

❖ Summary
Grand Challenge: small changes
(GEOS-5 Simulated XCO$_2$ : Day vs Night)

July 30, 21 Z

July 30, 9 Z

upper: surface XCO$_2$; lower: column averaged XCO$_2$
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 µm) measurements for deriving XCO$_2$ measurement.

Weighting Functions
**IM-CW Laser Absorption Lidar**

**1.57-μm CO₂ Measurement Technique**

Progression of Transmitted/Received Intensity-Modulated 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

\[ DAOD = \frac{1}{2} \ln \left( \frac{P_{off} \times E_{on}}{P_{on} \times E_{off}} \right) \]
Instrument Development
(Langley and Exelis; 14 MFLL + 1 ACES campaigns)

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)

advancing key technologies for spaceborne measurements of CO₂ column mixing ratio
In Situ and Lidar Comparision
(MFLL OCO-2 Under Flight: 20140827)

2014 AVOCET In Situ CO2

08/27/14
21:14:09 to 21:44:50 UT

CO2, ppmv

0 2 4 6 8

Altitude, km

08/27/14
21:14:09 to 21:44:50 UT

In-situ derived (or modeled) Value

- In-situ from Spiral: XCO₂, T/p/q profiles
- Radiative transfer model
- Ranging correction with lidar range data
- In-situ derived (or modeled) DAOD
- In-situ derived (or modeled) XCO₂

difference (ppm): 0.18
Winter 2013 Flight Campaign
(22 Feb. 2013 Flight: Blythe, CA)

Comparison of CO₂ columns from MFLL measurements and in situ derived values

\[
\frac{(\text{DAOD}_{\text{mea}} - \text{DAOD}_{\text{mod}})}{\text{DAOD}_{\text{mod}}} = -0.01\% \quad \text{(or within 0.04 ppm)}
\]
2011 ASCENDS DC-8 Flight Campaign (MFLL during 28 July – 11 August)

Differential Absorption Optical Depth (DAOD) Comparisons

SNR Comparisons

<table>
<thead>
<tr>
<th>Flight #</th>
<th>Start Hour</th>
<th>End Hour</th>
<th>Delta Time, sec</th>
<th>Nadir Range, m</th>
<th>Optical Depth</th>
<th>CO2, ppmv</th>
<th>1-s SNR</th>
<th>1-s SNR, ppmv</th>
<th>10-s SNR</th>
<th>10-s SNR, ppmv</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.07</td>
<td>20.08</td>
<td>198.0</td>
<td>6406</td>
<td>0.708</td>
<td>389.7</td>
<td>433</td>
<td>0.90</td>
<td>1264</td>
<td>0.31</td>
</tr>
<tr>
<td>3</td>
<td>20.03</td>
<td>20.06</td>
<td>211.0</td>
<td>6593</td>
<td>0.755</td>
<td>394.5</td>
<td>517</td>
<td>0.76</td>
<td>1510</td>
<td>0.26</td>
</tr>
<tr>
<td>4</td>
<td>15.63</td>
<td>15.70</td>
<td>396.0</td>
<td>6360</td>
<td>0.704</td>
<td>387.1</td>
<td>460</td>
<td>0.84</td>
<td>1325</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>20.00</td>
<td>20.02</td>
<td>180.0</td>
<td>8063</td>
<td>0.924</td>
<td>391.8</td>
<td>418</td>
<td>0.94</td>
<td>1274</td>
<td>0.31</td>
</tr>
<tr>
<td>7</td>
<td>17.21</td>
<td>17.23</td>
<td>79.2</td>
<td>5805</td>
<td>0.632</td>
<td>379.2</td>
<td>396</td>
<td>0.96</td>
<td>1237</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Avg: 6645 0.745 388.5 445 0.88 1322 0.29

Modeled DAOD: in-situ XCO2 measurements + radiative transfer model to calculate CO2 absorption optical depth.
MFLL CO$_2$ Column Measurements Through Thin Cirrus (22 Feb 2013)

CO$_2$ concentration (22-Feb-2013)

- **CO$_2$ mixing ratio (ppm)**
- **Altitude (m)**

Graph showing the decrease in CO$_2$ concentration with altitude.

The graph includes labels for clear and cloudy conditions, with measurements for lidar and in-situ derived values.

(a) DAOD

- Lidar measured:
  - Clear: 0.6571 ± 0.0047
  - Cloudy: 0.6558 ± 0.0067

(b) XCO$_2$ (ppm)

- Lidar measured:
  - Clear: 395.0 ± 2.83 ppm
  - Cloudy: 394.3 ± 4.08 ppm

- In-situ derived: 397.4 ppm
Comparison of Range Determination from PN Altimeter and Off-line CO$_2$ Signal

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.
Ranging over Hampton Roads
(ACES in June 2014)

Chesapeake Bay Bridge
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

TBD: ISS Tech Demo?

TBD: ASCENDS mission
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
Summary

- Global/regional atmospheric CO₂ observations require high accuracy and precision measurements owing to very small variations in atmospheric CO₂ mixing ratio.
- Laser absorption lidar at 1.57μm with ranging-encoded IM provides advanced capability in cloud/aerosol discriminations.
- IM-CW lidar has demonstrated the capabilities 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 CO₂ measurement precision within 1-s integration is within 1 ppm while mean bias is much smaller.
- Ranging uncertainties are shown to be below 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.
The ACT-America suborbital mission addresses the three primary sources of uncertainty in atmospheric inversions: atmospheric transport, sources and sinks of carbon, and atmospheric concentration measurements.