Monitoring Atmospheric CO₂ from Space: Challenge & approach

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Outline

❖ Introduction
  o Carbon sciences and challenges
  o Lidar CO₂ measurement approach
  o Instrumentation

❖ Lidar Measurements
  o CO₂ column measurements
  o Accuracy and precision
  o CO₂ 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 CO$_2$ 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

\[ DAOD = \frac{1}{2} \ln \left( \frac{P_{\text{off}} \cdot E_{\text{on}}}{P_{\text{on}} \cdot E_{\text{off}}} \right) \]
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 AVO CET In Sit u CO2

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

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

Comparison of CO\textsubscript{2} 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

- **Flight 1**: Central Valley (20 kft Leg)
  - **DAOD**: 0.55 to 0.53
  - **ΔDAOD**: -0.28% (ΔCO₂ = 1.1 ppm)

- **Flight 3**: Railroad Valley Mountain Track
  - **DAOD**: 0.54 to 0.50
  - **ΔDAOD**: -0.44% (ΔCO₂ = 1.7 ppm)

SNR Comparisons

<table>
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<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 !, ppmv</th>
<th>10-s SNR</th>
<th>10-s !, ppmv</th>
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<td>20.08</td>
<td>198.0</td>
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<td>396</td>
<td>0.96</td>
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</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 CO₂ Column Measurements Through Thin Cirrus (22 Feb 2013)

CO₂ concentration (22-Feb-2013)

- **On**
  - Amplitude
  - Time (UT, hr)
  - Range (km)

- **Off**
  - Amplitude
  - Time (UT, hr)
  - Range (km)

**Figure (a)**
- DAOD
- Lidar measured:
  - Clear: 0.6571 ± 0.0047
  - Cloudy: 0.6558 ± 0.0067
- In-situ derived: 0.6610

**Figure (b)**
- XCO₂ (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 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
Ranging over Hampton Roads (ACES in June 2014)

Chesapeake Bay Bridge

Elevation (m)
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

TBD: ISS Tech Demo?

TBD: ASCENDS mission
Space CO$_2$ 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.