Advancements for Active Remote Sensing of Carbon Dioxide from Space

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4th International Symposium on Atmospheric Light Scattering and Remote Sensing
June 3, 2015
NASA Langley Lidar Sensors

<table>
<thead>
<tr>
<th>Program, Carrier</th>
<th>Circa</th>
<th>Channels</th>
<th>Laser(s) (*tunable)</th>
<th>Measurement or Species</th>
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<tbody>
<tr>
<td>Ground Based 48&quot;</td>
<td>1970</td>
<td>2</td>
<td>ruby @347 &amp; 694 nm</td>
<td>Aerosols/ N₂</td>
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<tr>
<td>Aircraft, Bearda 990</td>
<td>1978</td>
<td>3</td>
<td>Ruby, YAG, YAG/ Dye @1064, 720*, 694, 600*, 532 347, 300* nm</td>
<td>Aerosols H₂O/O₃</td>
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<tr>
<td>LASE ER-2</td>
<td>1994</td>
<td>3</td>
<td>Ti:Al₂O₃ @615 nm</td>
<td>H₂O/Aerosols</td>
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<tr>
<td>LITE Shuttle</td>
<td>1994</td>
<td>3</td>
<td>YAG @1064, 532, 355 nm</td>
<td>Aerosols/ Density</td>
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<tr>
<td>CALIPSO</td>
<td>2006</td>
<td>2</td>
<td>Nd:YAG</td>
<td>Aerosols/ Clouds</td>
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<td>ASCENDS</td>
<td>2022</td>
<td>3</td>
<td>1.57 μm Fiber Laser</td>
<td>CO₂</td>
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</table>
ASCENDS provides an accurate global dataset of atmospheric CO₂ column measurements without seasonal, latitudinal, or diurnal bias.

These measurements will be used in retrieval of CO₂ fluxes to estimate regional carbon sources/sinks and thereby improve understanding of underlying mechanisms to improve climate predictions.
Multifunctional Fiber Laser Lidar (MFLL)
- Developed by ITT/Exelis in 2004, and advanced by Exelis and Langley since 2005
- 14 proof-of-concept field campaigns

ASCENDS CarbonHawk Experiment Simulator (ACES)
- Developed at Langley with technical support from Exelis
- Advancing key technologies for spaceborne measurements of average CO$_2$ column mixing ratio

Instrument Development: Langley and Exelis, Inc.
14 MFLL + 1 ACES flight campaigns

MFLL integrated on DC-8

ACES integrated on HU-25
ACES architecture based on Exelis Multi-functional Fiber Laser Lidar (MFLL):


- Simultaneously transmits multiple $\lambda_{on}$ and $\lambda_{off}$ wavelengths reducing atmospheric noise & eliminating surface reflectance variations.

- Approach is independent of the system wavelength and allows simultaneous $CO_2$ & $O_2$ (1.26 $\mu$m) measurements for deriving mixing ratio ($XCO_2$).
Intensity-Modulated Continuous-Wave (IM-CW) Measurement Technique

Progression of Transmitted and 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 Frequency-Modulated Continuous Wave (FM-CW) Radar and GPS measurement techniques

\[ DAOD = \frac{1}{2} \ln \left( \frac{P_{\text{off}} \cdot E_{\text{on}}}{P_{\text{on}} \cdot E_{\text{off}}} \right) \]
MFLL Optical Depth Comparisons: ASCENDS DC-8 Campaign 28 July – 11 August, 2011

Optical Depth (OD) Comparisons

Flt 1 - Central Valley (20 kft Leg)

1-s Measured OD

Modeled OD

ΔOD = -0.28%  
(ΔCO₂ = 1.1 ppmv)

Flt 3 - Railroad Valley

Mountain Track

1-s Measured OD

Modeled OD

ΔOD = -0.44%  
(ΔCO₂ = 1.7 ppmv)

All OD Comparison Differences (Measured – Modeled)

Average CO₂ Difference: -0.6 ppmv
Standard Deviation: 1.7 ppmv

Flts: 0, 1, 3, 5, 6, 7

Column CO₂ measurements over Midwestern US farm fields showed much larger drawdown signal in 2011 campaign (~8 ppm) compared with measurements in 2014 (~3 ppm)

- Resulting from different corn growth periods and meteorological states

**2011 Midwest Flights**

- Flight 6, 10 August
- Flight 7, 11 August

**25 August 2014 Midwest Flight**

- Preliminary data

- ~3 ppm
IM-CW technique accurately retrieves range over a variety of surfaces and in the presence of optically thin clouds allowing for retrievals of column CO₂ mixing ratios to surface and cloud tops.

Advanced deconvolution techniques resolve cloud and forest features
Our goals address the three primary sources of uncertainty in atmospheric inversions – transport error, prior flux uncertainty and limited data density.

- Five, six-week campaigns over 3 years, covering each season and summer twice
- 2 aircraft: C-130 (MFLL, Cloud Physics Lidar, in situ instruments) & UC-12 (in situ instr.)
- 2 weeks in each region (Wallops/Langley, Sioux City, and Shreveport)
ACT-America preliminary flight plans:
Summary

- NASA Langley Research Center has a long history of successfully designing and implementing airborne and spaceborne lidar systems.
- The Exelis MFLL instrument has collected airborne CO₂ column measurements in 14 campaigns since 2005 and is now preparing for the ACT-America Earth Venture Suborbital campaign.
- The ACES instrument successfully completed its first test flights in 2014, and will continue technology advancement efforts during test flights in August 2015 and January 2016.
  - HgCdTe detector/TIA bandwidth increased to ~4.9 MHz for advanced modulation waveforms
  - Increased transmitter power and receiver aperture yielding high precision measurements over varying surfaces
- Our team is continuing to advance technologies and measurement techniques critical for column CO₂ measurements from space.
Future Directions

• The ACT-America mission has begun, with five airborne campaigns planned for 2016-2018.
• Continue data analysis to fully quantify MFLL and ACES instrument performances
• Continue flight testing of new modulation algorithms and hardware improvements
  – Deconvolution techniques for clouds and forest canopies
  – Operational tests of retrievals with sideline wavelengths
  – Instrument automation for UAV operations
• Continue Technology Readiness Level (TRL) advancement and space qualification of ASCENDS technologies
Thank you to the ISALSaRS organizing committee for inviting this talk.

Thank you to the NASA Science Mission Directorate, the NASA Earth Science Technology Office (ESTO), the NASA Headquarters ASCENDS program, and NASA Langley Research Center for supporting these projects. The authors wish to thank the many contributions to this work from the rest of our teams at Exelis, Welch Mechanical Designs, the University of Melbourne, NP Photonics, NASA Langley, Pennsylvania State University, and the DC-8 and HU-25 aircraft support teams.
Backup Slides
ACT-America data are collected by remote and in situ sensors on two aircraft:

Remote Sensors (C-130):  
- MFLL (Exelis, Inc.):  
  - Column CO₂ number density  
  - Range to ground

Cloud Physics Lidar (NASA Goddard):  
- Atmospheric boundary Layer height  
- Aerosol/Cloud optical depth

In-Situ Sensors (C-130 and UC-12):  
- Picarro and Ozone (NASA Langley):  
  - In situ measurements of CO₂, CH₄, CO, H₂O, and O₃ number density

In-Situ Sensors (Ground Towers):  
- Picarro (Pennsylvania State University):  
  - In situ measurements of CO₂ and CH₄

- Flasks (NOAA):  
  - In situ samples of CO₂, CH₄, CO, ^14CO₂, COS
ACT-America data are collected in three regions across the eastern United States:

- Five, six-week campaigns over 3 years, covering each season and summer twice
- 2 aircraft:
  - C-130 (Wallops)
  - UC-12 (Langley)
- 2 weeks in each region (Wallops/Langley, Sioux City, and Shreveport)
ACES 2014 Test Flights: Preliminary CO$_2$ Retrievals over Ocean and Land:

- CO$_2$ retrieval values (2-s average) are calibrated using primary and secondary offline wavelengths.
- Average of in situ data across entire flight (binned by altitude) used for comparisons.
- Actual CO$_2$ number densities likely different far away from spiral point and airport.
- Further work is needed to compare directly with data from in situ spirals.
Atmospheric Carbon and Transport - America (ACT-America)

April 2015 SD All-Hands Meeting

Ken Davis, Principal Investigator
Thomas Lauvaux, Deputy PI
Chris O’Dell, Deputy PI
Bing Lin, Project Scientist
Mike Obland, Project Manager
Byron Meadows, Aircraft Integration/Logistics Manager
Gao Chen, Data Manager
Amin Nehrir, Instrument Scientist
...and many others
The challenge we are addressing:

- Assertion: Our inability to quantify carbon fluxes with “good” accuracy and precision across regional (larger than a flux tower footprint and smaller than the globe) domains is a primary methodological challenge in carbon cycle science today. It hamstrings our ability to address all other terrestrial carbon cycle science questions.
Pruned ensembles lead to more accurate and precise flux inversions using long-term GHG data (towers, flasks, satellite, NOAA airborne profiling).
The **ASCENDS CarbonHawk Experiment Simulator (ACES)** is an Instrument Incubator Program (IIP) project that seeks to advance technologies critical to measuring atmospheric column carbon dioxide (CO$_2$) mixing ratios from space in support of the ASCENDS (Active Sensing of CO$_2$ Emissions over Nights, Days, and Seasons) Decadal Survey mission:

- Passive satellite measurements cannot make retrievals of CO$_2$ column densities to the surface at night, at high latitudes (i.e. northern Europe during winter and over the poles), and through cirrus clouds, high optical depth aerosols, or in presence of scattered clouds.
- Active measurements using lidars do not have these limitations, and they can therefore fill these data gaps and aid in the refinement and understanding of the global carbon cycle budget.
ACES is advancing 4 key technology areas:

1. Enable development of more advanced modulation waveforms with improved detector subsystem

2. Increase transmit power and efficiency for CO₂ measurements at 1.57 microns using commercial amplifiers with stable, tunable laser-line locking system

3. Demonstrate column CO₂ retrievals with alignment of multiple laser beams transmitting simultaneously in the far-field for scalability to space

4. Continue refining CO₂ column retrieval algorithms in the presence of low optical depth clouds and distributed scattering layers (i.e. aerosol layers)
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
DRS Technologies HgCdTe array
- ~4.9 MHz bandwidth @ gain of $10^6$
- Continuously cooled at 77 K
- NEP: 2.4 fW/Hz$^{1/2}$
- Excess Noise Factor: ~1.1
- Tested with MFLL on DC-8 in 2013

Transmitters:
- Three Erbium-Doped Fiber Amplifiers (each 10 W average, 20 W peak) locked to CO$_2$ absorption line (1.57 microns)
- Wavelength tunable within +/- 50 pm (6 GHz) from line center

Combination of low-noise detector, higher power transmitters, and larger collection apertures improves signal-to-noise ratio; increased bandwidth allows for use of more advanced modulation waveforms.
Flight Summary: 17.4 flight hours

Data recorded at multiple altitudes over land and ocean surfaces with and without intervening clouds.