Laser Sounder for Measurements of Atmospheric CO2 Concentrations for the ASCENDS Mission

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Outline

• Carbon Cycle and CO$_2$
• CO$_2$ Measurements from space: Passive and Active measurements
• CO$_2$ measurement requirements
• Laser Sounder approach and error sources
• Field measurements with breadboard sounder
• Airborne demonstration
• Oxygen measurements
• Technology development
• ASCENDS precursor and Space instrument
Atmospheric CO₂ & Earth’s Carbon Cycle

Understanding the Carbon Cycle: Observations from Space
Passive: Orbiting Carbon Observatory (OCO-2009)
Active: Active Sensing of CO₂ Emissions over Nights, Days and Season Space Observations (ASCENDS)
CO2 Concentration from Ice Cores

We are entering new territory; old relationships may not apply.

Temperature in Antarctica in °F
Carbon Dioxide Concentration in PPM

300,000 Years Ago
200,000 Years Ago
100,000 Years Ago
Today
**Benefits:**

- Global column measurements
- Much higher coverage than ground networks
- Improve our understanding of carbon cycle
- No active components (lasers)

**Unavoidable Limitations:**

- Susceptible to biases from scattering of sunlight from aerosols & thin clouds
- Sunlit areas only (no day/night observations)
- Optical path can vary during orbit
“The goal of the ASCENDS mission is to enhance understanding of the role of CO$_2$ in the global carbon cycle. The three science objectives are to:

1. quantify global spatial distribution of atmospheric CO$_2$ on scales of weather models in the 2010–2020 era
2. quantify current global spatial distribution of terrestrial and oceanic sources and sinks of CO$_2$ on 1-degree grids at weekly resolution; and
3. provide a scientific basis for future projections of CO$_2$ sources and sinks through data-driven enhancements of Earth-system process modeling.”

(NASA Decadal Survey)
CO2 Measurement Needs

CO2 measurement for ASCENDS requires both **accuracy** and **long term precision** (~ 0.1% to measure 1 ppm).

Sensitivity (i.e. minimum detectable absorption) should not be an issue (absorption from space > 50%).
Laser Spectroscopy Measurements

Lasers Provide:
- Narrow measurement line widths (MHz)
- Tunable wavelengths
- High spectral brightness
- High peak power

Selected CO2 Line

1570 nm CO2 Absorption Band from Space

CO₂ Laser Sounder for ASCENDS Mission
ASCENDS Mission - Laser Sounder Approach

Three simultaneous laser measurements

1. CO2 lower tropospheric column
   One line near 1572 nm
2. O2 total column
   Measured between 2 lines near 765 nm
3. Altimetry & atmospheric backscatter profile:
   Surface height and atmospheric scattering profile

Measurements use:
- Pulsed EDFA lasers
- kHz pulse rates
- 6 or more laser wavelengths
- Time gated Photon counting receiver

Measures:
- CO2 tropospheric column
- O2 tropospheric column
- Cloud backscattering profile

Pulsed (time gated) signals:
- Isolates full column signal from surface
- Reduces noise from detector & solar background

Goal:
- Monthly “grid”, 1 deg spatial resolution, ~1 ppmV

CO₂ Laser Sounder for ASCENDS Mission
Measurement Approach

Laser Sounder Approach

- Use 6 or more pulsed lasers to "trace" CO$_2$ line
- Use time gating to isolate ground returns
- Lock Laser wavelengths (~ 2 – 34 MHz)
- Wavelengths are flexible
- Common nadir-zenith measurement path
- Need < 1 ppm error in CO2 mixing ratio

\[
E_r(\lambda_{on}) / E_r(\lambda_{off}) = E_{tr}(\lambda_{on}) / E_{tr}(\lambda_{off}) \cdot \tau_{sys}(\lambda_{on}) / \tau_{sys}(\lambda_{off}) \cdot \exp(-\sigma N_g z)
\]

\[
N_g = \frac{1}{\sigma z} \ln \left( \frac{E_r(\lambda_{off}) E_{tr}(\lambda_{on}) \tau_{sys}(\lambda_{on})}{E_r(\lambda_{on}) E_{tr}(\lambda_{off}) \tau_{sys}(\lambda_{off})} \right)
\]
Partial Error Source List

- **Atmospheric and Spectroscopy Error Sources:**
  - Temperature dependence (line parameters)
  - Pressure (broadening, shift)
  - H₂O mixing ratio and spectral interference
  - Aerosol/Cloud Scattering

- **Random Instrument Error Sources:**
  - Shot noise
  - Laser noise
  - Johnson Noise
  - Amplifier noise
  - Detector Noise
  - Digitizer Noise

- **Systematic Instrument Error Sources:**
  - Laser wavelength drift
  - Opto-mechanical (alignment) drifts
  - Polarization Drifts
  - Fiber coupling/transmission drifts
  - Detector responsivity drifts
  - Pointing
  - Etalon Fringes
Impact of Atmospheric Scattering

- Cirrus clouds are quite prevalent
- Cloud reflections shorten average optical path -> bias CW (non-gated) column estimates
- Cirrus cloud scattering -> 8-14 ppm errors in non-range gated measurements
- Errors led our team to use a pulsed (& range gated) approach
- Range gating eliminates cloud scattering errors (except for ground fogs)
GSFC CO2 Breadboard Sounder

Far Target ~ 400 m
Near Target 205 m
LICOR input on roof of B33
Breadboard Sounder Measurements

CO$_2$ Laser Sounder for ASCENDS Mission
Breadboard long term precision and accuracy

Stability assessment in Lab
Measurements of Peak Absorption vs Time
in the lab through a 30 cm long Reference Cell
with ~10 mbar Co2

Stability of offset (Zero point)
Measurement in a 30 cm absorption cell
in the lab with no Co2
2/28/07

CO₂ Laser Sounder for ASCENDS Mission
Integration into mobile platform

5/13/08

CO$_2$ Laser Sounder for ASCENDS Mission
CO2 Measurements at NOAA tower, Erie CO

CO2 Tower - Erie Colorado: NOAA BAO Tower

- CO2 sampled with LICORs at 20, 200 and 300 meters.
- ~1.2 km long slant path measurements to near top of tower.
Comparison of measured CO2 line scan with HITRAN Prediction based on the Tower LICOR

Comparison of measured CO2 absorption with LICOR
Retrieval Algorithm

**OBSERVABLE**
- Detector signal, returning
- Monitor signal, outgoing
  (in terms of time index)
- 200 Hz \( \times \) 10 sec

**Fixed quantities**
- Temperature BAO tower \( (T_{10m}, T_{100m}, T_{300m}) \)
- Pressure \( (P_{10m}) \)
- Path length (2.47 Km)
- HITRAN absorption spectra

**Iterative Retrieval Algorithm**

**Analysis (variables)**
- \( \text{CO}_2 \) concentration (column mean)
- Linear coefficients converting time index to wavelength
- Polynomial coefficients for baseline
Laser Sounder and LICOR Comparison

- Stability over 8 hour period
- Low bias with respect to LICOR

### BAO Licor comparison

- Laser
- Licor Column
- Licor 22 m
- Licor 100m
- Licor 300m

### Laser CO2 16 minute average

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Sigma</th>
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<tbody>
<tr>
<td>Laser</td>
<td>355.7</td>
<td>3.67</td>
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<tr>
<td>Licor Column</td>
<td>399.9</td>
<td>1.93</td>
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<tr>
<td>Licor 22 m</td>
<td>406.1</td>
<td>2.67</td>
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<tr>
<td>Licor 100m</td>
<td>406.0</td>
<td>2.71</td>
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<tr>
<td>Licor 300m</td>
<td>387.5</td>
<td>3.54</td>
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</table>
Airborne Demonstration of Laser Sounder:
Aircraft: Lear Jet 25 operated by Glenn Research Center at Lewis Field, Cleveland, OH
Max Altitude: 45,000 ft. (13.7 km)
Range: 1436 Nmi

Overfly WLEF Tower in Park Falls, WI
Airborne Instrument Design

CO₂ Laser Sounder for ASCENDS Mission
Oxygen Measurements

- **Scan of Oxygen A-Band Doublet**
- **Telescope viewing target**
- **Peak optical power ~ 50 mW**
- **Attenuation for round trip was ~10^6**

**Oxygen A band:** Calculated atmospheric transmission for 100 m path at STP

**Measurement**

**5/13/08**

**CO₂ Laser Sounder for ASCENDS Mission**
• Working with several vendors to achieve high peak power and leverage DoD work for space qualification of fiber amplifiers.
• Demonstrated locking of diode lasers to 1 kHz
Technology Development - Detector

- Continue to test several detectors
- Commercial PMTs continue to improve
- Modify JWST HgCdTe detector for lidar application
Moving to Space

Instrument Configuration Concept from 4/08 Study (using 1.5 m ADM ALADIN Telescope)

Delta 2320-10 M Shroud

Carbon Cycle Initiative, CO2/Lidar

Initial Space Mission Study showed space mission concept practical

System Overview

David Everett

To be updated in 2008 with improved estimates for measurement, orbit, and components

5/13/08

CO₂ Laser Sounder for ASCENDS Mission
Summary

• Demonstrated concept of laser sounder in a laboratory setting
• Demonstrated that achieving 1 ppm measurement accuracy and precision is possible with a laser sounder.
• Demonstrated oxygen detection at 765 nm.
• Performed field experiments at GSFC and at Erie, CO.
• Currently addressing technology needs of fiber amplifiers and detectors.
• Plan airborne CO2 measurement demo - fall 2008.
• Develop ASCENDS Precursor (ESTO IIP)
• Moving to Space – ISAL study