Atmospheric CO₂ Column Concentrations Measured with High Accuracy in the ASCENDS 2011 and 2013 Airborne Campaigns

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Presentation to:
2014 IWGGMS-10, Noordwijk, The Netherlands

May 7, 2014

Support: NASA ASCENDS & ESTO IIP Programs
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**CO₂ Sounder Lidar**

A Pulsed IPDA lidar for CO₂ flown on NASA DC-8 (2011 & 2013)

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### CO₂ Sounder Characteristics:
- Optimized as space instr. simulator
- *Lower SNR than planned for space*
- CO₂: 25 uJ/pulse at 10 KHz (250 mW)
  - 30 λ's/line, 300 Hz sweep rate
  - NIR PMT detector (~4% QE)
- O₂: ~2 uJ/pulse at 10 KHz (~20 mW)
  - 40 λ's line, 250 Hz sweep rate
  - Geiger Si APD detector
- Common 20 cm dia. receiver telescope
- MCS (R-resolved histogram) recorders

### 2011 ASCENDS Flights

*Objectives:* Measure CO₂ columns over a variety of topographic targets & under varying atmospheric conditions with developmental lidar candidates & in-situ sensors for the ASCENDS mission

- 7 science flights over different regions, topography + degrees of cloudiness
- Altitudes: 3-13 km (in ~3 km steps) + spirals to near surface

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Presentation to IWGGMS-10 NASA Goddard
CO₂ Sounder Approach: 
Airborne CO₂ Line Sampling & Absorption line analysis

Once the line is fit, there are many options on reporting values from the fitted line.

So far we report the value (from line fit):

$$\text{DOD}(pk) = \text{OD}(\lambda_{pk}) - [\text{OD}(\lambda_{pk-50}) + \text{OD}(\lambda_{pk+50})]/2$$
Data Analysis
Retrieval approach

Used to:
- Find the range to reflecting surface
- Calculate normalized CO2 line shape
- Fit CO2 line shape
- Do screening
- Determine column average CO2 concentration
- Find other parameters
Improved precision; detecting boundary layer enhancement
(2013 Flight over California Central Valley)

- **CO₂ Conc. (ppm)**
  - Time (UTC hours): 25:00, 26:00, 27:00, 28:00
  - Latitude:
    - -123, -122, -121, -120, -119
  - Longitude:
    - 0, 0.5, 1, 1.5, 2
  - Distance (km):
    - 0, 5, 10, 15

- **CO₂ Conc. (ppm)** vs **Altitude (km)**
  - Central Valley
  - Avocet
  - Lidar mean

- **DOD** vs **Distance (km)**

- **Std dev = 1.5 ppm**

- **Meas. Linshp.** vs **Pred. Linshp.**

- **Residual Plots at Time 24.9912 hrs (245927) Alt 4570m**
  - rmse from flat = 2.75e−03 (2.84e−03)

- **Wavelength (nm)**
  - 2

- **2-way Optical Depth**

- **LDR Rng = 4691 m**
  - Grnd ht = 49 m
  - Pul. Int. = 90 cts/bin/s

- **Presentation to IWGGMS-10 NASA Goddard**
Measurements over Snow:

2013 Flight 5 over Iowa from 12.4 km altitude
CO₂ Measurements over Mountainous Terrain in oval flown near Railroad Valley NV (2011 Flight 3)

- The lidar range (blue, right axis) varied by 8 km as plane flew over mountains & valleys near RRV.
- Fluctuations are reflected in the predicted DOD (black line, left axis).
- Measured DOD of CO₂ line (red circles) follows the predictions closely.
- Retrieved CO₂ concentration (red dots, top plot), is nearly constant.

=> Measurements worked well over mountainous terrain, with large variations in surface elevation & range.
Relatively constant CO2 was concentration measured to the top of Pacific Ocean Marine stratus cloud deck. In this 10sec averaged data, the measured differential optical depth (DOD) tracks the predicted DOD extremely well.
CO$_2$ lidar measurements were made in region of mixed Clouds over Iowa

Atmospheric Conditions for 2011 Flight over Iowa:

*(top): photo

*(middle & bottom): Lidar backscatter profiles* for two 30 minute-long segments in regions of CO2 retrievals

(* - range corrected)
Lidar Measurements of CO$_2$ Column to Ground through cirrus & broken Clouds – 2011 Iowa Flight

**Shows the expected drop in column CO$_2$ when measured from lower aircraft altitudes**

Lower CO$_2$ in boundary layer

![Map and Graph](map-graph.png)
Summary of Lidar-based retrievals for 2011 flights compared with in-situ measurements

- Lidar retrievals using model atmosphere based on DC-8 measurements in spiral

- AVOCET in-situ measurements

- Comparison of column average retrievals from 2011 airborne lidar measurements vs altitude

Lidar measurement error bars are +/- 1 std dev for a 10 second average
Scaling Airborne lidar to Space

Random error over desert surface with 10 sec integration time

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Orbit Altitude</td>
<td>400 km</td>
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<tr>
<td>Equator crossing time</td>
<td>dawn/dusk</td>
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<tr>
<td>Integration Time</td>
<td>10 sec (70 km)</td>
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<td>Telescope diameter</td>
<td>1.5 m</td>
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<td>Time between laser pulses</td>
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<td>Laser Pulse widths</td>
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<tr>
<td>Online wavelength</td>
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<tr>
<td>Beam divergence</td>
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<td># of wavelengths in scan</td>
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<td>On line (side of line) absorption</td>
<td>40%</td>
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<tr>
<td>Detector type &amp; QE</td>
<td>HgCdTe APD, 75%</td>
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</table>
Summary

- Developed pulsed IPDA lidar as low power (0.25 W) airborne demonstrator for space mission
- Flights in 2011 & 2013 demonstrated:
  - Robust measurements of range, CO₂ absorption & retrieved mixing ratio
  - Measurements made from > 12 km above:
    - mountainous regions
    - through cirrus clouds & broken cumulus clouds
    - to tops of a marine stratus cloud deck
    - Over snow
    - Cloud slicing (2-level retrievals) via broken clouds
    - Vertically-resolved backscatter profiles show the boundary layer
- Line sampling approach is robust - allows solving for instrument & environmental offsets
- Performance so far:
  - Agreement with in-situ measurements to < 1.4 ppm for altitudes > 6 km
  - Precision (1.5 ppm) has been limited by dynamic range of IR-PMT detector
- Next steps:
  - Improved precision x4 with HgCdTe APD detector
  - Pursue approach for space: 1.5 m dia. Telescope, 12-16 W ave. laser power
Backup
Abstract:
We report accurate measurements of CO2 column concentration and range from an aircraft over a wide variety of surfaces using a pulsed, wavelength-resolved integrated path differential absorption (IPDA) lidar. The instrument flies on NASA’s DC-8 aircraft and measures the atmospheric backscatter profiles and shape of the 1572.33 nm CO2 absorption line using 30 wavelength samples per scan with 300 scans per second. Our post-flight analysis calculates pulse energies at each wavelength (which gives the absorption lineshape) every second as well as the lidar range to the backscattering surface. Using radiative transfer calculations and HITRAN 2008, we calculate the corresponding model absorption lineshape for the lidar optical path using a fixed CO2 mixing ratio. We then retrieve the lidar column CO2 mixing ratio by solving for the optimum CO2 mixing ratio in the model that best fits the data. For validation we compared the lidar-retrieved CO2 concentrations to those sampled by in-situ sensors on the aircraft.

We participated in the ASCENDS airborne campaigns during August 2011 that included flights over a variety of surface and cloud conditions in and near the US, such as a stratus cloud deck over the Pacific Ocean, a dry lake bed surrounded by mountains, a desert area with a coal-fired power plant, and segments over the Rocky Mountains and Great Plains with both cumulus and cirrus clouds. Analyses show the retrievals of lidar range, CO2 column absorption, and CO2 mixing ratio worked well when measuring over topography with rapidly changing height and reflectivity, through thin clouds, between cumulus clouds, and to stratus cloud tops. The retrievals show the decrease in column CO2 due to growing vegetation when flying over Iowa cropland. For regions where the CO2 concentration was relatively constant, the measured CO2 absorption lineshape (averaged for 50 s) matched the predicted shapes to ~ 0.5%. For 10 s averaging, the scatter in the retrievals was typically 2–3 ppm. This was limited by the received signal photon count from the photomultiplier detector. Retrievals were made using atmospheric parameters from both an atmospheric model and from in situ temperature, water vapor and pressure from the aircraft. The retrievals did not use empirical adjustments, and >70% of the measurements were used in analysis. The differences between the lidar-measured retrievals and in situ measured CO2 column concentrations were <1.4 ppm for flight measurement altitudes >6 km.

Our team also participated in the February/March 2013 ASCENDS campaign, that flew over a variety of locations in the US, including the California Central Valley, a forest with tall (Coastal redwoods) trees near the coast of northern California, desert areas in Arizona, and over cold snow-covered valleys in the Rocky Mountains and snow-covered fields in Iowa and Wisconsin. The retrievals of lidar range, lineshape and CO2 column absorption and concentrations worked well when measuring over topography with rapidly changing height and reflectivity, and through thin clouds. As expected, the relative reflectivity of snow surfaces near 1572 nm was low, about 10% of that of the desert, and good line fits and retrievals were made to these as well. Examples from analyzing these measurements will be presented.