Pulsed Lidar Measurements of the Atmospheric CO2 Column Concentration in the ASCENDS 2013 and 2014 Airborne Campaigns

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Presentation to:
IWGGMS-11 Conference
June 18, 2015
Pasadena, CA

Support from:
NASA ESTO IIP-10 & QRS programs
ASCENDS Pre-formulation Activity, Goddard IRAD program
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NASA’s Planned ASCENDS Mission

**Why lasers?**

- Measures at night & all times of day
- Constant nadir/zenith path
  - Illumination = observation path
  - One mode with continuous “glint” measurements over oceans
- Measure range to scattering surface
- Small measurement footprint
- Measure through cirrus clouds & haze
- Measure through broken clouds
- Measure to cloud tops

-> High accuracies with much improved coverage under challenging conditions

-> Some vertical resolution
CO₂ Sounder Lidar
A pulsed IPDA lidar for CO₂ on NASA DC-8

CO₂ Sounder Characteristics:
- Optimized as space instr. Simulator
- 25 uJ/pulse at 10 KHz (250 mW)
- 30 λ/s/line, 300 Hz sweep rate
- 20 cm dia. receiver telescope
- Detector, backscatter profile recorder:
  - <2014: NIR PMT (∼4-8% QE)
  - Photon counting MCS
  - ≥ 2014: HgCdTe APD (QE ∼70%)
  - Analog digitizer (10 Hz)

2011, 2013, 2014 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

Update on CO₂ Sounder for IWGGMS-11
CO₂ Sounder Approach:
Airborne CO₂ Line Sampling & Absorption line analysis

- **Lidar** measures “dots” (wavelength samples) to all scattering surfaces

- **Post flight: Retrievals** (based on model atmosphere) calculates range, normalized line shapes & solves for best fit concentration

Update on CO₂ Sounder for IWGGMS-11
2014 CO$_2$ Sounder Lidar
(Graham Allan, Anand Ramanthan, Kenji Numata)

Improvements for 2014 ASCENDS flights:
1. Step-locked CO2 seed source
2. Wider wavelength sampling across CO2 line
3. Optimized wavelength spacing
4. HgCdTe APD detector in receiver
5. Analog digitizer data recording
6. 10 Hz recording & retrieval resolution
CO2 Line Sampling and fits: ASCENDS Flights in ≤ 2013 & 2014

≤ 2013

Conditions:
- Central Valley CA
- ~ 10 km altitude
- 10 sec ave

2014

1. Larger wavelength span
2. Locked laser wavelengths
3. Optimized line sampling

init. conc. = 400.0 ppmv
adj. conc. = 1.1% (404)
rang = 403–406 ppmv
CO₂ Sounder
Full Retrieval Algorithm
(Ramanathan & Mao)

1. No a priori CO₂ information is required

2. Sampling many wavelengths across the line:
   - allows solving for potential biases
   - allows assessing line fits
   - allows a robust measurement

3. More information:
   Poster by A. Ramanathan
2014 ASCENDS Airborne Campaign

- Targets: forests in CA, growing agriculture at dusk and dawn over Iowa, & urban area
- IPDA lidar allows measurements under conditions that are difficult for passive sensors.
- Two flights under flew the OCO-2 satellite track

Instrument Teams for 2014 Flights:
- AVOCET in-situ (LaRC)
- MFLL lidar (LaRC, ITT)
- CO2 LAS lidar (JPL)
- CO2 Sounder lidar (GSFC)
2014 In-situ measured CO₂ vertical profiles from AVOCET (NASA LaRC)

SF-1, SF-3, SF-4, SF-5

SF-2 (1st OCO-2 under-flight)

1st - NV
2nd - Edwards
3rd - Ocean
Observing CO₂ drawdown over Cropland Measurements at Dawn over Iowa 2014-9-03

Flight Pattern:
- Square pattern over Iowa at 3 altitudes
- Spiral down over Iowa West Branch tower

The lidar measurements show the CO₂ drawdown (decrease with altitude) also seen by AVOCET & Picarro
Ongoing work suggests offset may caused by bias in WV column estimate in GEOS-5
Update on CO2 Sounder Measurements to IWGGMS-11

Abshire et al. - GSFC

SF4 – OCO-2 Under flight – retrievals through haze
Atmospheric Backscatter Profiles & retrievals

North Bound Flight Track East of Mount Shasta
Northern California (30mins)

Spiral Descent and Climb Out from Castle (30mins)

Aerosols

SF4(Central Valley)

CO2 Conc. (ppm)

in situ profile
in situ column
Lidar mean
Lidar "profile"

South Bound Flight Track
(50 mins)

Aerosols

2014-08-27

2014-08-27
Column Retrieval - through aerosol layers

- Range-resolved measurements allow timing gating to minimize impact from atmospheric scattering
- Allow robust retrievals with low bias
- Minimizes retrieval errors over rough surfaces (terrain, and tree cover)
Update on CO2 Sounder Measurements to IWGGMS-11

Abshire et al.

• Results show a N-S gradient over Nevada from 3 independent flight altitudes
• Gradient is ~1 ppm/deg. lat. ($R^2 > 0.4$)
• Gradient matches that seen in a PCTM*

(*-Parameterized Chemistry Transport Model)

2014 flight over NV: Horizontal Gradient in XCO₂ (~12 km ground track avg.)

- Alt = 6.1 km (Conc. = 394.6 +1.1 $\delta$ lon -0.5 $\delta$ lat, Corr=0.424)
- Alt = 10.7 km (Conc. = 392.7 +0.6 $\delta$ lon -0.7 $\delta$ lat, Corr=0.595)
- Alt = 11.2 km (Conc. = 394.3 +0.0 $\delta$ lon -1.5 $\delta$ lat, Corr=0.847)

See poster by A. Ramanathan
CO\(_2\) Sounder - Backscatter Profiles enable measurements to cloud tops as well as ground.

- Flight to Iowa, 8/10/2011;
- Height-resolved lidar clearly separates line shapes for returns from elevated surfaces – ground, cumulus and cirrus cloud tops.
Resolving two vertical CO₂ layers via IPDA lidar measurements & “Cloud Slicing”

- Measure column absorption & range to ground & cloud tops
- **Difference** measurements to get bottom layer CO₂

**Results**

![Graph showing CO₂ concentration and flight altitude with measured and calculated data.]

**Key Points:**
1. Cloud slicing with lidar can sense CO₂ in the planetary boundary layer.

**Graph Details:**
- **X-axis:** CO₂ Concentration (ppm)
- **Y-axis:** Flight Altitude (km)
- **Data Points:** AVOCET, Boundary Layer, LowCloud1

**Ground Reflection:**
- **Lidar Path 1:** Direct path
- **Lidar Path 2:** Path through cloud scattering
- **12.5 km:** Path length
- **2 km:** Cloud top scattering path

**Measurements:**
- **Calculated difference**
- **Measured lines**

**AVOCE:**
- **Wavelength (nm):** 1572.3, 1572.35, 1572.4
- **2-Way Optical Depth:** 0, 0.5, 1.0, 1.5, 2.0, 2.5
Summary

- Our airborne CO2 Sounder lidar has been very valuable - we continue to improve it
- Bias was < 1.2 ppm, for 7 of 9 flight segments in 2014, at altitudes > 7.5 km
- Despite modest (0.25W) laser power, have achieved 0.9 ppm precision over desert

**Recent measurement summary:**

<table>
<thead>
<tr>
<th>Flight</th>
<th>Surface</th>
<th>Shot Noise limit</th>
<th>Measured precision</th>
<th>Bias</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 Railroad Valley</td>
<td>Desert</td>
<td>1.5 ppm</td>
<td>2.7 ppm</td>
<td>0.4 ppm</td>
<td></td>
</tr>
<tr>
<td>2013 Central Valley</td>
<td>Desert/vegetation</td>
<td>0.7 ppm</td>
<td>1.5 ppm</td>
<td>0.1 ppm</td>
<td>Best with PMT. Limited by detector dynamic range.</td>
</tr>
<tr>
<td>2014 Central Valley</td>
<td>Desert/vegetation</td>
<td>0.45 ppm</td>
<td>0.9 ppm</td>
<td>0.3 ppm</td>
<td>Limited by optical losses, electronic &amp; speckle noise</td>
</tr>
<tr>
<td>2014 Forest (P. Northwest)</td>
<td>Forests</td>
<td>0.5 ppm</td>
<td>1.3 ppm</td>
<td>1.0 ppm*</td>
<td>Limited by optical losses, electronic &amp; speckle noise, *-WV est.</td>
</tr>
</tbody>
</table>

**Ongoing work:**

- Making instrument improvements for January 2016 campaign
- Expect to enhance precision ~x2 to ~0.5 ppm
More information

1. Posters

Anand Ramanathan - “High accuracy CO2 measurements with vertical information from a pulsed IPDA lidar using multiple wavelength sampling”

Jianping Mao - “Atmospheric CO2 Concentration Measurements with Clouds from Airborne Lidar Measurements during ASCENDS Science Campaigns”

Anand Ramanathan - “Surface Reflectivity Measurements made by the CO2 Sounder on the ASCENDS 2013 and 2014 Airborne campaigns”

Related:

Haris Riris - “Pulsed airborne lidar measurements of atmospheric optical depth using the Oxygen A band at 765 nm”

Haris Riris - “A Methane Lidar for Greenhouse Gas Measurements”

2. CO2 Sounder Website:

http://ssed.gsfc.nasa.gov/co2sounder/

3. ASCENDS Workshop on Friday
Offline signals allow Surface Reflectivity Measurements (Example - Snow in Colorado Mountain Basins & Iowa)

- Pulse Energy (photons)
  - $10^1$
  - $10^2$
  - $10^3$
  - $10^4$

- Lidar Range (km)
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10
  - 12

- Data (Iris)
- Data (Iris)

- Surface Reflectivity
  - Desert (R=0.40)
  - Vegetation (R=0.20)
  - Cloud (R=0.10)
  - Snow (R=0.05)

- Frequency (arb units)
  - 0
  - 200
  - 400
  - 600
  - 800
  - 1000
  - 1200
  - 1400

- Mean = 0.10
- Std. Dev. = 0.062
- Median = 0.09

Reflectivity for SF4 (Mountain Snow)

- Mean = 0.06
- Median = 0.05
- Std. Dev. = 0.032

Reflectivity for SF5 (MidWest Snow)

See poster by A. Ramanathan for complete set
More wavelengths give more information & allow more accurate measurements

<table>
<thead>
<tr>
<th>No. of Wavelengths</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10+</th>
<th>30</th>
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</thead>
<tbody>
<tr>
<td>Reflectivity</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CO₂ column mean</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Linear baseline</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Doppler shift</td>
<td>×</td>
<td>×</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CO₂ vertical gradient</td>
<td>×</td>
<td>×</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Nonlinear baseline</td>
<td>×</td>
<td>×</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Water vapor content</td>
<td>×</td>
<td>×</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CO₂ mid-troposphere</td>
<td>×</td>
<td>×</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Fit quality</td>
<td>×</td>
<td>×</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
• Before 2014, we used a wavemeter as reference for our scanning laser wavelength
• In the 2013 flights, the wavemeter failed - impacted most CO2 retrievals for 2013
• However lidar worked well
• 2013 & 2014 measurements allowed a survey of surface reflectance at 1572 nm
Lidar data-in situ data comparisons are in column from flight altitude to ground.
ASCENDS Mission Overview

Continuous laser measurements:

- Pointed toward or near nadir
- CO2 lower tropospheric column
- Range to scattering surface at CO2 wavelength
- O2 total column
- Range to scattering surface at O2 wavelength
  
  with

- >50 Hz measurement rates
- ~50 m laser footprints
- Accommodate rapid changes in scattering surface height and in echo signal strengths

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

~400 km polar orbit
(time of day is TBD)

Requirements for XCO2:

Random error: ~ 1ppm in ~100 km along track sample  
or ~ 0.5 ppm in ~10 sec over deserts

Bias: < 0.5 ppm
CO₂ Sounder example
Lidar measurements vs in-situ for 2011 flights

- Lidar measurements
- AVOCET in-situ measurements for comparison

Comparison of lidar measurements for 4 different flights
Except desert, it is challenging for GOSAT/OCO-2 to make measurements for the conditions shown
Lidar measurement error bars are +/- 1 std dev for 10 sec ave
Excellent accuracy (very low bias)