Advances in the CO\textsubscript{2} Sounder Lidar for measurements from Aircraft and in Scaling for Space

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Atmospheric CO2 & Earth’s Carbon Cycle

Major Questions about CO2 Sinks:
Is considerable uncertainty in locations, strengths, dynamics & evolution with time
=> Space Observations (OCO, ASCENDS)

CO2 sources exceed sinks
- accumuating CO2 in atmosphere

Challenges:
- Fluxes of great interest produce only very small signatures in atmospheric CO2 (typ. < 1 of 400 ppm, or < 0.25%)
- Areas of interest are distributed globally (including high latitudes, often with haze or clouds)
- Arctic and southern oceans are in darkness almost half of each year
ASCENDS Mission
Recommended by 2007 Earth Science Decadal Survey

Science Measurements:

Laser absorption by atmospheric column CO₂

- Polar orbit
- Nadir pointing
- Accurately measures absorption of a single CO₂ absorption line
- Continuous measurements of CO₂ column absorption and range to surface

Minimum Requirements:

- Random measurement error: < 0.5 ppm with 10 sec integration over deserts
- Bias: << 0.5 ppm

Primary causes
- Measurement environment
- Instrument artifacts

Measures CO₂ column absorption & range to scattering surfaces:
- Ground
- Ocean surface
- Cloud tops

~400 km circular polar orbit
Improvements for 2014 & 2016 ASCENDS flights:
1. Optimized wavelength sampling across CO2 absorption line from 15 to 30 laser wavelengths
2. Step-locked seed laser
3. HgCdTe APD detector in receiver
4. Analog waveform data recording
5. 10 Hz recording & retrieval resolution
CO$_2$ Sounder Approach: Airborne CO$_2$ Line Sampling & Absorption line analysis

- Multiple wavelength samples across the CO$_2$ absorption line to reduce measurement bias
- Pulsed laser to give range resolved measurements
- Laser wavelengths locked to the CO$_2$ line center with given offsets
- Post flight XCO$_2$ retrievals based on atmosphere model, meteorological data, and least squares fit.

Image descriptions and data points:

- Optical Depth (OD) at certain times and altitudes.
- Residual plots with rmse values.
- Transmissions at different wavelengths.
- Adjusted concentrations and range.

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CO$_2$ Sounder uses a Pulsed Multi-wavelength Lidar Approach

Time-resolved backscatter measurements allow:

• Direct measurement of the path-length
• Detecting cloud & aerosol scattering
• Time gating around surface:
  - Eliminates atmospheric scattering
  - Reduced solar background noise

Multi-wavelength sampling of CO$_2$ absorption line:

• Allows correcting for uneven instrument spectral response
• Allows solving for Doppler shift and eliminates its effect in XCO$_2$ retrieval
• Allows correction for influences of water vapor on CO$_2$ line shape & in retrievals

Retrieval solves for XCO$_2$ via a least square fit of the predicted CO$_2$ line shape to the lidar measurements
Lidar Measurements over Tall forests in Coastal California (Redwood forests on several km high mountains)

Why ?: Accurate CO$_2$ measurements over Amazon, Congo & Boreal forests are important for ASCENDS

Varying tree canopy & terrain -> rapid change in column length

Results show accurate (very low bias) measurements in challenging conditions
Accurate Lidar Measurements though aerosols over desert: (2014 SF-2 over Edwards AFB)

- 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)
Lidar Measurements over desert on February 10, 2016
Spiral over Edwards AFB CA

Red dots - lidar column ave
Red error bars - 10 sec ave
Blue line - in-situ profile
Blue dots - column ave from in-situ

Accuracy of lidar $X_{CO_2}$

1s average data aggregated by altitude
bias < 0.5 ppm

in situ profile
- in situ column
- Lidar mean

DOD

Altitude (km)

$CO_2$ Conc. (ppm)

Time (UTC hours)

Altitude (km)

6-14-2017
2017 ESTF Conference, Paper A5P5
**XCO₂ Retrieval for the CO₂ Sounder Measurements**

Sources of Errors:

*Lidar measurements:*
- Random noise
- Systematic errors and biases

*Knowledge of atmosphere:*
- Difference between the model and the actual atmosphere
- Approximations in modeling
- Errors in the meteorology data (pressure, temperature, and water vapor)
- CO₂ Spectroscopy

**Diagram:***

- IPDA
- Lidar Measurements
- Meteorology data
- Atmosphere
- Weather model
- CO₂ Absorption Line-shape
- Optical Depth \(OD(\lambda_i)\)
- Least Squares Fit
- \(X_{CO₂} (ppm)\)
• **Measurements & airborne lidar model agree well from 7 to 13 km altitude**

• **Error offset is likely due to slighter higher noise in detector amplifier**

• **For < 8 km altitudes, the errors increase, caused by:**
  
  • Lower CO₂ absorption in shorter column
  
  • Smaller Laser footprint => more impact from surface reflectivity changes.

### Airborne-borne CO₂ Sounder Lidar Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal laser pulse energy</td>
<td>25 µJ</td>
</tr>
<tr>
<td>Laser pulse width and rate</td>
<td>1.0 µs at 9 kHz</td>
</tr>
<tr>
<td>Orbit altitude</td>
<td>2-12 km</td>
</tr>
<tr>
<td>Telescope diameter</td>
<td>20 cm</td>
</tr>
<tr>
<td>Receiver optics transmission</td>
<td>73%</td>
</tr>
<tr>
<td>Receiver FOV</td>
<td>500 µrad</td>
</tr>
<tr>
<td>Receiver optical bandwidth</td>
<td>1.4 nm FWHM</td>
</tr>
<tr>
<td>Off-line atmosphere transmission</td>
<td>80%</td>
</tr>
<tr>
<td>Surface reflectance (off-line)</td>
<td>44% (desert)</td>
</tr>
<tr>
<td>Receiver integration time</td>
<td>1 sec.</td>
</tr>
<tr>
<td>Detector quantum efficiency including fill factor effect</td>
<td>$\eta_{APD} = 70%$</td>
</tr>
<tr>
<td>Detector gain and excess noise</td>
<td>$G_{APD} = 600$, $F_{\text{excess}} = 1.05$</td>
</tr>
<tr>
<td>Detector dark current</td>
<td>5 fA</td>
</tr>
<tr>
<td>Receiver NEP</td>
<td>0.56 fW/Hz¹⁄²</td>
</tr>
</tbody>
</table>
Scaling Lidar to Space: Approach & Model-Predicted Performance

- Laser transmitter emits 20W (2.7 mJ at 7.5 KHz)
  - Laser development on its way to TRL-6
- 1.5 diameter telescope, similar to ADM
- HgCdTe APD Detector, near TRL 6 now
- Space lidar size similar to ADM, but simpler & less power (~600 W)

Same CO2 Sounder measurement model, but using space parameters

- Clear sky, Least Square Error Fit in OD X, Sun, 12/7/2016
- Model results show random errors are x4 lower than required for ASCENDS

Launch 2017

ADM- Aeolus telescope (1.5 m diameter)
Laser Pathway to Space*
(Ongoing ESTO QRS Development– TRL 6 by Dec 2017)

**Flown on Airborne CO2 Sounder**

- Master (Locked) Seed Laser
- CO2 Absorption Cell
- Tunable Seed
- CW amp
- MZM
- Laser locking & wavelength control

**Seed Module** (GSFC)

**Pumped Pre-amp Module**

- Pulsed Amp 1
- Pulsed Amp 2

**Laser Power Amplifier Fiber Enclosure** (1 channel)

- Power Amp
- Total energy per pulse (6 amplifiers): 2.7 mJ

**New Technology Developments**

- CO2 absorption (Herriott) cell (10-m path length) ~14" x 5" x 4"

- Pre-Amplifier Module
  - 1-input, 6-channel output

- Pump Laser for 2 stages of Power amp
  - 0.45 mJ/pulse per amp

- Amplifier Output
  - ~ 0.5 mJ/pulse

*ESTF 2017, Paper A5P2
A key to CO2 Sounder Lidar performance: 4x4 HgCdTe APD Array Detector*

~90% Quantum efficiency from 0.7 to 4.3 µm

Closed-cycle cryocooler used for lab tests and aircraft

Packaged detector system for airborne lidar

* - Developed under ESTO- IIP10

~90% Quantum efficiency from 0.7 to 4.3 µm

Conversion Efficiency (e/photon)

0 0.2 0.4 0.6 0.8 1 1.2

0 1 2 3 4 5

UV VIS NIR SWIR MWIR

Wavelength (µm)

Sensor Chip Assembly

64-pin LCC

Guard Ring

Closed-cycle cryocooler used for lab tests and aircraft

Packaged detector system for airborne lidar

* - Developed under ESTO- IIP10
Lab Tests show the 4x4 HgCdTe APD Detector is nearly ideal for IPDA lidar

High and noiseless APD gain to override circuit noise

Wide linear dynamic range to accommodate signals from various ground surface and airplane altitude
HgCdTe APD Detector in Mini Cryo-Cooler Developed for Space

- Funded by ESTO InVEST and QRS program for a similar (2x8) HgCdTe detector
- Miniature Stirling cryo-cooler from DRS with multi-year life time (Rawlings, SPIE 9070, 2014)
- Detector operating temperature 80 K or 110 K
- Mass: ~1 kg,
- Electrical power: 6-8 W with heat sink at 30°C
- Vibration & thermal cycle tests per NASA GEVS specification
- Thermal vacuum and proton radiation tests in Summer 2017.
Summary

- Pulsed multi-wavelength CO$_2$ Sounder lidar provides a robust measurement of XCO$_2$
- Steadily improved airborne performance since 2011
- Technologies developed for major components, now at or near TRL-6
- Developed an instrument model and XCO$_2$ retrieval algorithm and verified them with airborne data
- Model scaled to space shows lidar has $\frac{1}{4}$ random error required by ASCENDS
  - Allow 10x higher spatial resolution or a smaller instrument size.

We acknowledge the outstanding work of our team and appreciate the support from ESTO