Pulsed Lidar for Measurement of CO2 Concentrations for the ASCENDS Mission: Progress

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Outline

• ASCENDS Mission
• Lidar measurement environment
• O2 Measurement approach
• CO2 Measurement approach
• Airborne CO2 measurements
• Space Mission simulations
• Scaling to space & technologies
• Summary

Why lidar:
Geoscience Laser Altimeter System – 2003
Aerosol & Cloud Lidar Measurements from Space

J. Spinhirne/ NASA GSFC
**Why lasers?**

- Measures at night & all times of day
- Constant nadir/zenith path
  - Illumination = observation path
  - Continuous “glint” measurements over oceans
- Measurements at high latitudes
- Small measurement footprint
- Measure through broken clouds
- Measure to cloud tops
- Very high spectral resolution and accuracy

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**Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS)**

- **Launch:** 2013-2016
- **Mission Size:** Medium

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**Are several lidar approaches for CO₂ column:**

- Broadband laser - 1570 nm band - λ tuned receiver
- 1 line - 2 um band - pulsed - direct detection
- 1 line - 2 um band - CW heterodyne detection
- 1 line - 1570 nm band - synchronous direct detection
- 1 line - 1570 nm band - pulsed direct detection
Simultaneous laser measurements:

1. CO2 lower tropospheric column
   One line near 1572 nm
2. O2 total column (surface pressure)
   Measure 2 lines near 765 nm
3. Altimetry & atmospheric backscatter profile from CO2 signal:

Measurements use:
- Pulsed lasers
- ~10 KHZ pulse rates
- 8 laser wavelengths for CO2 line
- Time gated Photon counting receiver

CO2 & O2 column measurements:
- Pulsed (time gated) signals:
  - Isolate full column signal from surface
  - Reduces noise from detector & solar background
  - Time of flight provides column length

Target: ~1ppmv in ~100 km along track sample
Need ~0.2% measurements of CO2 & O2 columns in ~10 sec

~450 km polar orbit
CO2: 1572 nm
O2: 765 nm
CO2 Band, Line Sampling & Vertical Weighting Functions

Multi-wavelength Line Sampling allows:

- Detection & correction of Doppler & λ errors
- Modeling & reducing errors from varying λ response
- CO2 retrievals for lower & upper troposphere
- Line shape information

Space lidar plans: 8 wavelength samples across line

Total Column from area of line

Increasing CO2 Column Density

Airborne lidar used 20 wavelength samples across line:
1 usec pulse width, 100 usec pulse period, 450 Hz line scan rate

Primary Online: Midpoint
2ndary Online: Near Peak

1572.34 nm

572.35 nm
Temperature Sensitivity of 1572.33 nm line

- Less sensitivity to atmospheric temperature
- Greater sensitivity to atmospheric CO2 amount
Why use pulsed lasers & ranging gating?

*Atmospheric Scattering*

- Thin cirrus clouds are quite prevalent, $\beta_\pi$ varies with $\lambda$.
- Cloud reflections shorten average optical path -> bias non-gated column estimates.
- Cirrus cloud scattering -> 4-10 ppm errors in non-range gated measurements.
- **Pulsed lasers & range gating eliminate these errors.**

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**Cirrus clouds:**
- Reflect signal in shorter path to cloud.
- Attenuate signal from surface.

**Cloud Optical Depth (km)**

- **Cloud Altitude (km)**

- **p180= 0.04, Sfc albedo= 0.20**
- **CO2 Error (ppmv)**

- **Cirrus clouds**

- Reflect signal in shorter path to cloud.
- Attenuate signal from surface.
• Reflectance over land from MODIS 16-d composite BRDF-adjusted nadir reflectance. Missing data = 0.2.
• Over water, Fresnel reflectance is calculated at nadir using 10-m wind speed from the meteorological analysis.
• Reflectance over ice that is not available from MODIS (e.g., in the polar dark) is assumed to be 0.1.
• Ice cover extent is determined from the GEOS-4 analysis.
Oxygen - Open path measurement of absorption lines near 765 nm

Oxygen A band: Atmospheric transmission for 100 m path at STP

Peak optical power ~ 50 mW
Attenuation for round trip was ~10^6

Tunable 1530 nm diode laser, amplified & doubled to ~765 nm

Scan of Oxygen A-Band Doublet

Measurement
HiTRAN Theory

Transmission

Wavelength (nm)

0.2
0.4
0.6
0.8
1

764.5
764.6
764.7
764.8
764.9

220 m distance
**O2 absorption measurements from laboratory**

**Airborne O2 Lidar Parameters:**
- Diode laser Wavelength: 1529 nm
- Amplifier: NP Photonics EDFA
- Output Wavelength: 764.5 nm
- Output Energy: ~1 uJ/pulse
- Detector: SPCM
- Scan over the absorption with 20-40 Pulses (selectable) at 450 Hz

Distance to target: 1.5 km
Target illuminated by green alignment laser

B33 Room F411
“Truth:” Weather station on top of B33

**Calculated**

- Absorption
- Linear Fit of Absorption
- Polynomial Fit of Absorption
Sample O2 Measurement made over 1.5 km horizontal path using photon counting detector

"Weather station on top of B3"
Pulsed Airborne CO2 Sounder Lidar on the NASA Glenn Lear-25

Experiment Team in Ponca City OK, USA
Nadir port showing transmit and receiver windows

Paper on 2008 flights:
Pulsed Airborne CO2 Lidar

Parameters:

- Laser peak power: 24 watts (24 uJ/pulse)
- Laser: DFB diode laser, AOM, Fiber amplifier
- Wavelength scans: 20 wavelengths, 450 Hz
- Telescope diameter: 20 cm
- Receiver transmission: 65%*
- PMT dark count rate: ~ 550 kHz
- Laser divergence angle: 100 urad
- CO2 line: 1572.33 nm
- Receiver FOV: 200 urad
- Receiver optical bandwidth: 0.8 nm
- Detector quantum efficiency: 1-5%
- Receiver range bin size: 8 nsec*

* Were 470 urad, 16% and 64 nsec, respectively, during 2008 flights
Coordinated Airborne Experiments to Measure CO2 column densities to support ASCENDS Science Mission Definition (August 2009)

0. Checkout on ground
   Ponca City Airport, OK

1. Cessna Takeoff
   (DOE in-situ CO2 sensor)

2. Twin Otter Takeoff
   (JPL 2 um lidar)

3. Lear Takeoff
   (GSFC CO2 Sounder lidar)

4. UC-12 Takeoff
   (LaRC/ITT Lidar, LaRC in-situ)

Ed Browell photos
CO$_2$ Column Height Analysis

Eastern Shore, VA Flight
Aug. 17, 2009
4-5:30 pm local time, Ground speed 150 to 200 m/s

Axel Amediek, DLR
Column Height (Altimetry) Measurements

Approach: Cross correlate the received signal with transmit laser pulse shape
- Use peak of correlation function as laser pulse time of flight.
- Robust & well suited for detecting multiple targets (ground & cloud returns)
- Range was resolved by flight measurements to ~3m accuracy & <1 m from laboratory
Examples of Measurements through 2 Cloud layers
(cloud, cloud, ground echo pulses)

Absorption line shapes:
to clouds - thinner, less deep
to ground - broader & deeper

Example 1: GRC3 July 17th 16:24:35 mixed cloud/ground return

Echo from thin cloud just under aircraft

CO2 line absorption region

mid level cloud echo
ground echo

Example 1: GRC3 July 17th 16:24:35 mixed cloud/ground return

(Raw measurements uncorrected for $\tau_{sys}(\lambda)$)

Nadir Camera Image for Measurement

Expanded view of 1st echo pulse group in sequence

64 pt avg photon counts

bin #

 photon counts

bin #

bin #

bin #

bin #

bin #
Examples of Line shapes vs Altitude
North Carolina Flight - August 17, 2009

- Depth increases with altitude
- Smooth line shapes at all altitudes!
Line Optical Density & # Density vs Altitude
North Carolina Flight - August 17, 2009

- Mean Optical Depths from line fits to CO2 Sounder measurements
- # Densities calculated from LaRC in-situ sensor and radiosonde readings

- 4 papers on 2009 CO2 & O2 measurements at 25th ILRC conference, St. Petersburg, Russia, July 2010.

- Sun synchronous orbit
  - Altitude 500, 450 km
  - Sun-sync inclination, 1:30 pm crossing time
- Mission Risk Class B
  - 5 year mission life
  - 85% mission reliability
  - Mitigate single point failures with redundancy or high reliability parts
- Traditional S/C bus orbit and attitude knowledge sufficient for mission requirements (i.e., no on-instrument attitude processing required)
Space: SNR & Relative Measurement Errors
(10 seconds observing time, 500* km orbit, 1.5m telescope)

CO2 column measurement

O2 column measurement

CO2 Sounder Performance Estimate from Space
1572 nm, 1.2 kHz laser pulse rate, 1 usec laser pulse width
10 second averaging time, JWST HgCdTe Detector

Oxygen Measurement Performance from Space
765 nm, 1.2 kHz laser pulse rate, 1 usec pulse width
10 sec averaging time, Si APD SPCM Detector

Rel Measurement Errors scale as (laser pulse energy)^{-1} \cdot (T)^{-1/2}

~ 3 mJ/pulse energy (HgCdTe detector*)

~ 3 mJ/pulse energy (SPCM detector)

6 mJ energy from 1530 nm amp, 50% doubling

Ave optical power ~25-30 W

Ave optical power ~25-30 W

* - Same performance at 3 mJ/pulse with PMTs at 400 km orbit
Measurement Model & Mission Performance Simulation


- Test sensitivity of inferred CO2 distributions to varying mission & instrument design parameters.
Initial results (CO2 only), 3 mJ/pulse:

- Single-sample (10 sec) errors average ~1.3 ppmv for this instrument configuration.
- Consistent with ASCENDS requirements.
- Work is ongoing
Laser Power Scaling: Amplifier R&D
High SBS-threshold Er/Yb co-doped phosphate glass fiber amplifier

- Develop high SBS-threshold, SM, PM, high power amplifiers for the 100s ns pulses using NP’s proprietary patented large core SINGLE-MODE PM highly Er/Yb codoped phosphate fibers and patented Q-switched single frequency fiber laser seed.

- Develop amplifier prototypes/products: 50μJ, 100s μJ and mJ. Push the SBS threshold to 100s kW.

SBIR (-1 & -2) with NP Photonics (Wei Shi, PI) COTR: Mark Stephen

Amplifier R&D
Planar Waveguide Amplifier

Planar waveguides allow guided mode amplification with larger areas => higher peak powers & energies
Other key elements of space lidar:

**CO2 detectors:**
- **Left:** Hamamatsu H9170-75 PMT: 12% QE used in airborne lidar
- **Right:** ~70% QE HgCdTe detector (under evaluation)

**O2 Lidar detectors:**
- SPCM detectors flown on ICESat/GLAS

**DBR tunable seed lasers:**
- 5MHz linewidth, > 30nm tuning

A 1.5 m Diameter Receiver Telescope (Example from ESA ADM ALADIN)
Summary of 2 Space Lidar Studies

- Conducted studies of this approach for ASCENDS space lidar: 4/08 & 9/09
- Several aspects can be further optimized in design studies
- Straightforward space lidar design:
  - Mass: ~ 400 Kg (can be reduced via more efficient layout)
  - Power: ~ 850W (3dB margin); driven by SNR needs
  - Data rate: ~1.9 Mbit/sec; high latitude comm. ground site
- Low risk: Space qualified telescope, O2 detectors
- Detectors: reliability via multiple detectors & spares.
- Primary power draw: lasers
- Lasers: high efficiency & reliability & spares
- Mission compatible with medium class rocket (Taurus-II or equivalent), with considerable margin

Layout concept from 1st study
Summary

Developing CO2 Sounder approach for ASCENDS:

- CO2 and O2 (pressure) measurements
  - Line shape & Column height measurements
  - 2 altitude weighing functions
  - Robust against atmospheric scattering
  - Ground-based O2 measurements
- Airborne demonstrations:
  - CO2 measurements in 2008 & 2009
  - CO2 & O2 in prep. for 2010
- Studies show lasers & lidar for space are feasible
- 1st mission simulations show can meet science needs, but more are needed.

We appreciate the ESTO support!
Thank you!
Backup
2009 Flight Example: Measuring through Cloud deck over Homer IL

Cirrus at ~32000 ft

Broken Cumulus ~5000’

Example of 1-sec of time resolved laser backscatter (measured over broken Cumulus)

Distance below aircraft (ft)

Cloud echo pulses

Ground Echo pulses

Graham Allan Photo
Measurement approach for Space

CO2

- Total Column Optical transmission
- Gas absorption line
- 8 CW seed lasers individually locked to points shown

O2

- Total Column Optical transmission
- O2 absorption lines

Monopulse Approach

- Transmitted Laser Power
- Time
- λ₁, λ₂, λ₃, λ₄, λ₅, λ₆, λ₇, λ₈
- λ₁, λ₂, λ₃, λ₄, λ₅, λ₆, λ₇, λ₈
- 1μs, 125μs, 1ms