Advances in Pulsed Lidar Measurements of CO₂ Column Concentrations in Airborne Campaigns and for Space

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Outline:
• Why Lidar
• Airborne Lidar Demonstrator
• Airborne Measurement Highlights
• Path to Space
• Predicted Space Performance

Acknowledgements:
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Why lidar for GHG measurements?

Lidar uniquely provides:

- Measurements at night & high latitudes
- High spatial resolution (small footprint)
- Using consistent vertical path
- Accurate knowledge of path length
  - Enables measurements to cloud tops
- Fully-resolve the gas absorption line(s)
- Uses 1 line – much simpler spectroscopy
- Multiple wavelengths on gas line shape:
  - Allows solving for potential biases
Comparison of Coverage from actual OCO-2 with ASCENDS simulator
(* R. Kawa et al.)

ASCENDS shows:
1. More spatially uniform coverage
2. Coverage is uniform throughout year
3. Much better sampling in key areas:
   - Tropics
   - N. Hemisphere
   - Southern Ocean
2014 & 2016 CO2 Sounder Airborne Lidar
(with Graham Allan, Anand Ramanthan, Kenji Numata)

Improvements for 2014 & 2016 ASCENDS flights:
1. Step-locked laser 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
7. Larger laser footprint (2016)
8. Allow 15 or 30 wavelength samples (2016)
CO₂ Sounder Approach:
Airborne CO₂ Line Sampling & Absorption line analysis

- Presently measure line at 1572.33 nm
- 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

* more- see Poster 56, Ramanathan et al.
Example of ASCENDS Airborne Campaign (this one August 2014)

- 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.

**Instruments:**
- CO2 Sounder,
- MFLL (LaRC),
- CO2 LAS (JPL),
- AVOCET (LaRC)

**SF1:** Over Forests, 8/20/14
**SF2:** OCO-2 Underflight 8/22/14
**SF3:** Cropland at Dusk, 8/25/14
**SF4:** Edwards TCCON 8/27/14
**SF5:** Cropland at Dawn, 9/3/14

**SF2:** Ocean 8/22/14
**SF2:** OCO-2 Underflight 8/22/14

AVOCET in-situ CO2 sensor used to measure actual XCO2 profile in spiral locations

Urban Area mid-am 9/3/14

2014 SF-1, SF-3, SF-4, SF-5
2014 SF-1 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 Column Retrievals over desert - through aerosol layers (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)
Observing CO₂ drawdown over Cropland Measurements at Dawn over Iowa (2014 SF-5) 2014-9-03

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

Lidar measurements show the CO₂ drawdown (decrease with altitude) seen by AVOCET
Flight over cold snow – Elko, NV & south at low sun angle: 2016-02-11

*Standard deviations: 3x larger than over Edwards AFB*
  - Expected from ~8x lower reflectivity of snow.
  - Smaller s.d. with 2 laser amplifiers, as expected
Measurements over desert on February 10, 2016
Spiral over Edwards AFB CA

Standard Deviations of XCO2 retrievals over Edwards AFB using 30 wavelength samples. 1 (red) & 10 (blue) second averaging times.

- 10 sec std deviations: 0.21 to 0.24 ppm
- 1 sec std dev's: 0.7 to 0.8 ppm

Differences between in-situ & lidar:
< 0.5 ppm
At all altitudes

Retrievals with Calibrated BPF
Error bars for 1 sec averaging time
April 2016 analysis

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Lidar measurement of *Horizontal Gradient* in XCO$_2$ over Midwest (Colorado – Nebraska - Iowa on 2014 SF-3)

- Clear (-0.3 to -0.7 ppm/deg. Long.) E-W CO$_2$ gradient over Great Plains, US.
- Consistent across both legs & 2-altitudes and in good agreement with PCTM

Also lidar detected gradient in 2014 NV flight
That agreed with PCTM
• ESA’s ADM Aeolus wind lidar: Mass: 470kg, Power 830W
• ASCENDS (CO2 only) expected to be ~ same size, mass & but less (500-600W) power
  • CO2 Sounder approach baseline is to use same 1.5 diameter telescope
  • Detector near TRL 6 now (see above)
  • CO2 Sounder laser: much easier than ADM’s UV laser (see next slide)
• ADM spacecraft power allows flying another laser, for simultaneous measurements of CH4, or O2

Launch 2017
Recent GSFC test shows space-need power

- Demonstration of one laser fiber output (OFS Laboratories)
- Measurements in May 2016
- 6 in parallel will emit > 2.7 mJ
- More energy than is required for space
- Engineering model of full laser now under development
- Will be vibration & vacuum tested by September 2017
For desert model shows $\leq 0.36$ ppm with 1 sec (7 km) averaging
Global average precision $\sim 1$ppm (1 sec)
ASCENDS offers new, important capabilities:
- Much more uniform coverage
- Measurements (year round) in the Arctic, tropics, S. Oceans

- Made more improvements of CO2 Sounder Airborne simulator
- Campaigns show robust measurements of CO$_2$ & retrieved mixing ratio:
  - For mountainous regions with tall trees
  - Through haze, cirrus clouds & broken cumulus clouds
  - Over vegetation with CO2 drawdown & over snow fields
  - Measured horizontal gradients in XCO2 that agree well with PCTM models

- Results:
  - Average retrieved XCO2 values agree from 0.5 to 1ppm with in-situ measurements
  - Random errors ~ 0.7 ppm in 1 sec averaging time over desert

- CO2 Sounder approach: a practical path for ASCENDS
  - Model shows ~1 ppm random errors globally (1 sec ave time)*
  - Laser: Breadboard shows space-needed power

* - Related presentations: Kawa et al (O48), Ramanathan (P56), Mao (P57)
Pathway to Space – Laser
(Mark Stephen – NASA ESTO work ongoing)

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

- Pulsed Pre-amp Module
  - Nuphoton, Inc.
  - 6 Laser Power Amplifier Modules
    - 2 Amps/Module
    - (GSFC, OFS, DII)

- Power Amp
- 0.45 mJ/pulse per amp
- Total energy per pulse (6 amplifiers) 2.7 mJ

- Tunable Seed
- PW Amp 1
- PW Amp 2
- PW Amp 3
- PW Amp 4
- PW Amp 5
- PW Amp 6

- Master (Locked) Seed Laser
- Laser locking & wavelength control

- Advances in CO2 Sounder: IWGGMS-12

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Lidar measurements show a N-S gradient over Nevada

- Seen at 3 independent flight altitudes
- Gradient is ≈1 ppm/deg. lat. (R² > 0.4)
- Gradient matches that seen in NASA PCTM*
- (*-Parameterized Chemistry Transport Model)
Initial Examples of surface reflectivity histograms
Edwards AFB, Castle (Central Valley), Snow

Reflectivity for Engg (EdwardsAFB)

Reflectivity for Engg (Castl15chpol)

Reflectivity for SnowFit (Elko30ch)

Data
Desert (R=0.40)
Vegetation (R=0.20)
Cloud (R=0.10)
Snow (R=0.05)

Data
Desert (R=0.40)
Vegetation (R=0.20)
Cloud (R=0.10)
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