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

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Greenbelt MD 20771

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ASCENDS Pre-formulation Activity, Goddard IRAD program

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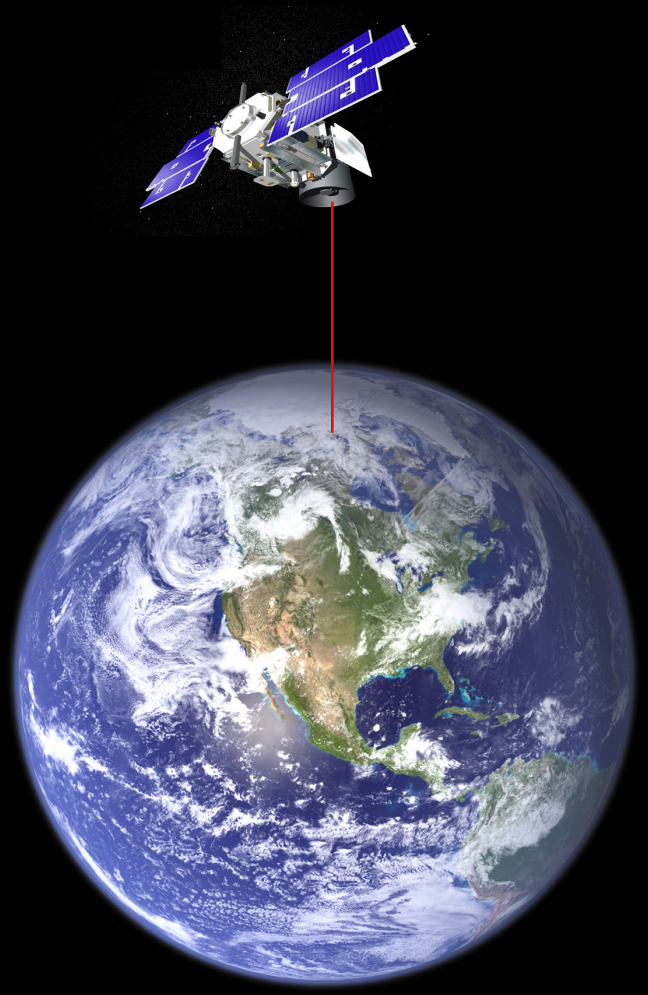


NASA's Planned ASCENDS Mission

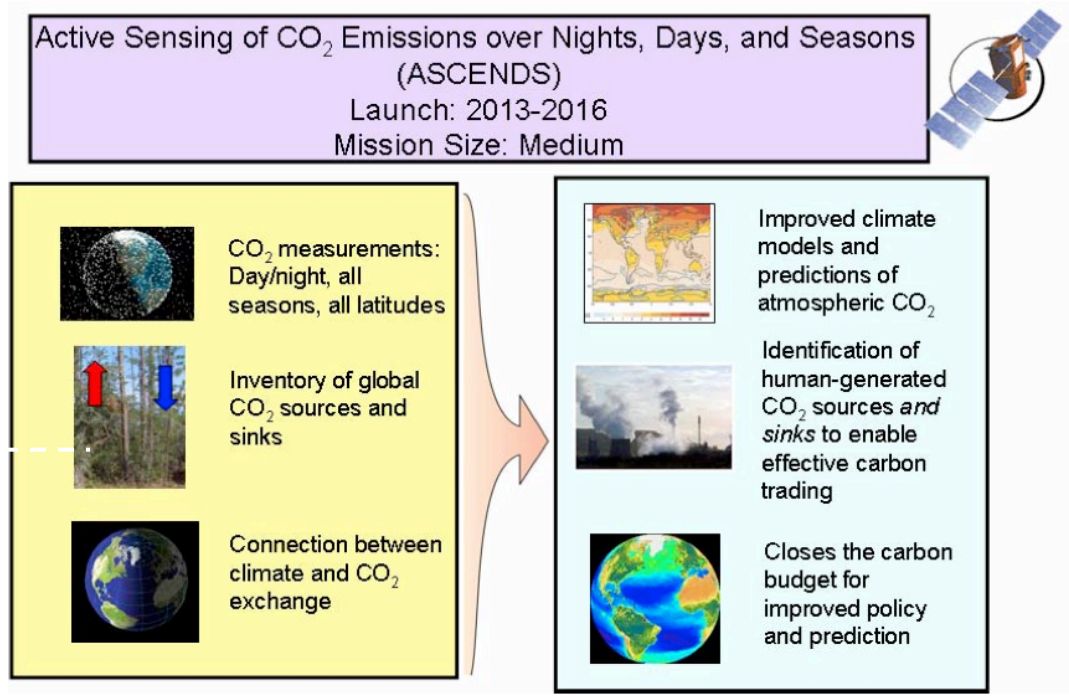
Why lasers ?

- 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

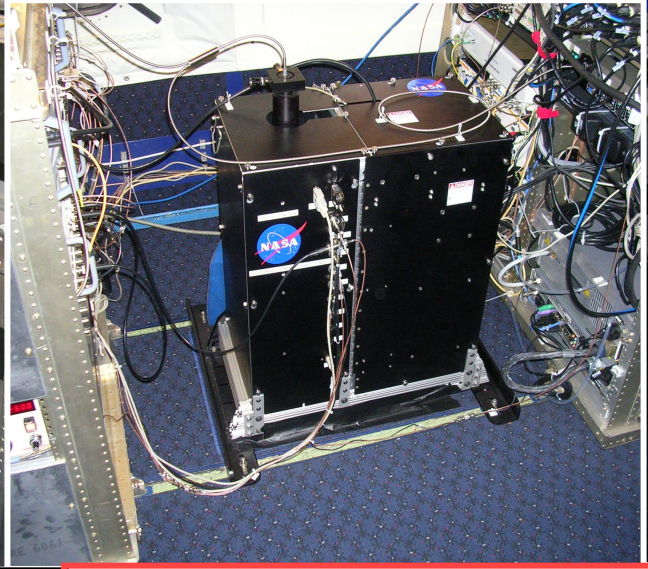
-> High accuracies with much improved coverage under challenging conditions

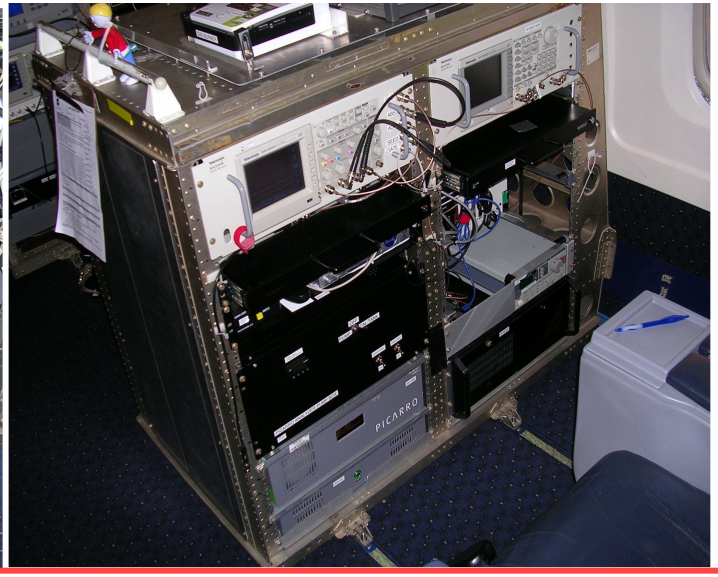
-> Some vertical resolution

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS)



CO_2 Sounder Lidar
A pulsed IPDA lidar for CO_2 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)

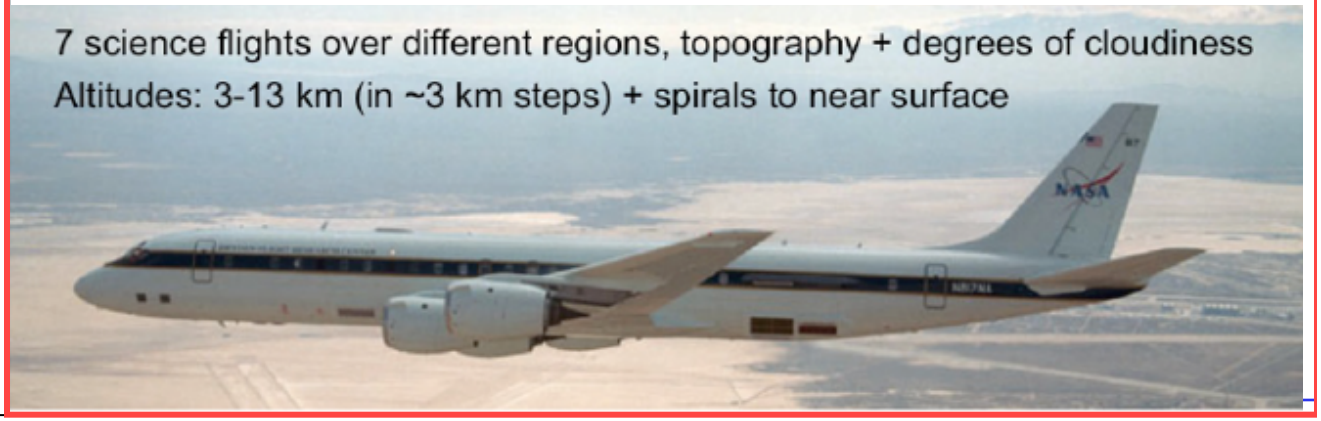
  Photon counting MCS

  ≥ 2014: HgCdTe APD (QE ~70%)

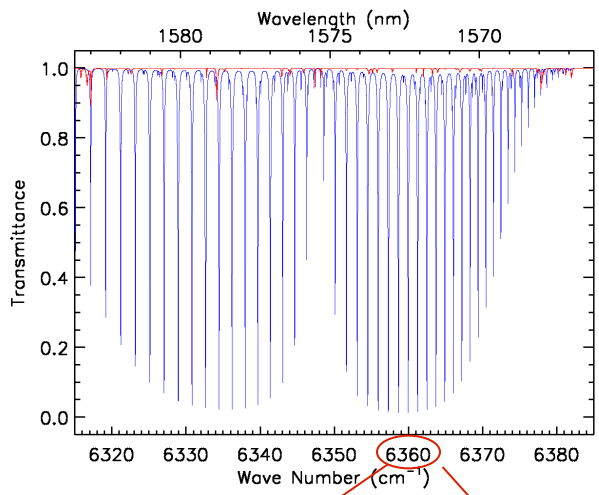
  Analog digitizer (10 Hz)

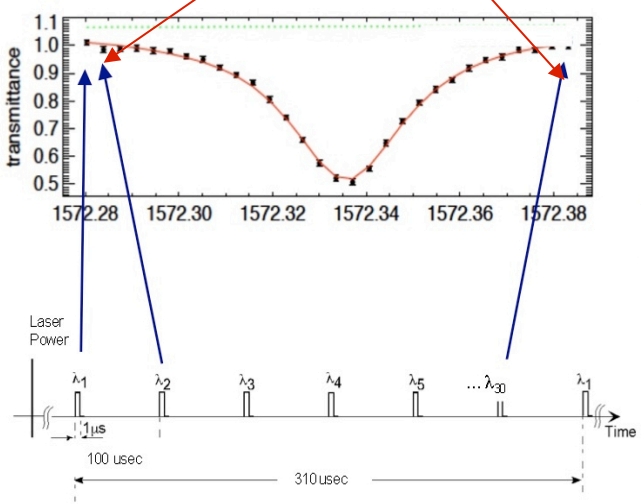
2011, 2013, 2014 ASCENDS Flights

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

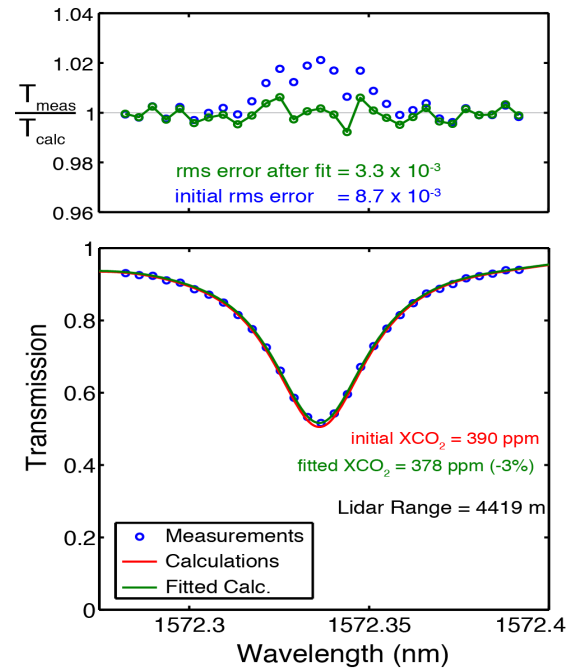


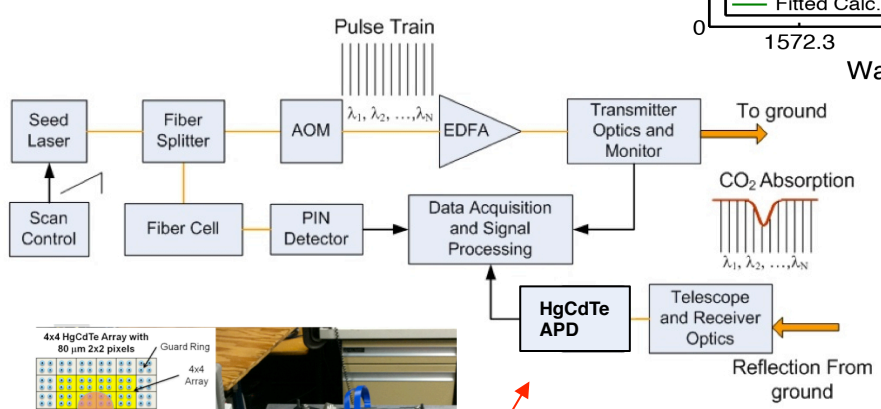
CO_2 Sounder Approach: Airborne CO_2 Line Sampling & Absorption line analysis

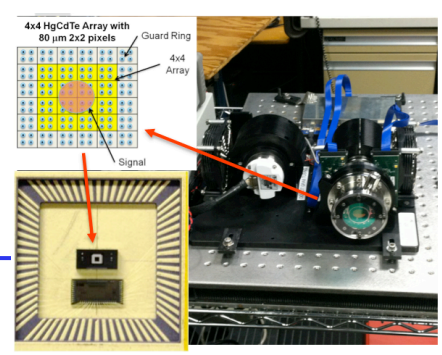




- *Lidar* measures "dots" (wavelength samples) to all scattering surfaces
- *Post flight: Retrievals* (based on model atmosphere) calculates range, normalized line shapes & solves for best fit concentration

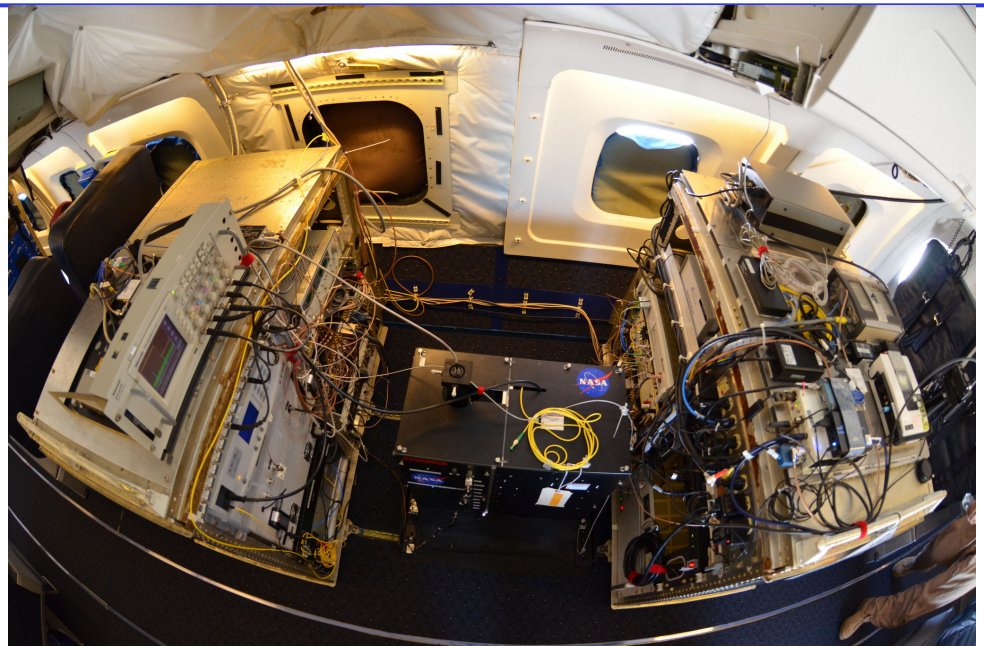






HgCdTe APD Detector in 2014 flights

2014 CO_2 Sounder Lidar
(Graham Allan, Anand Ramanthan, Kenji Numata)

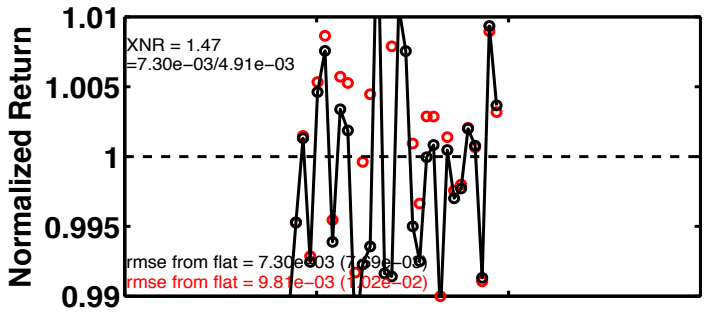


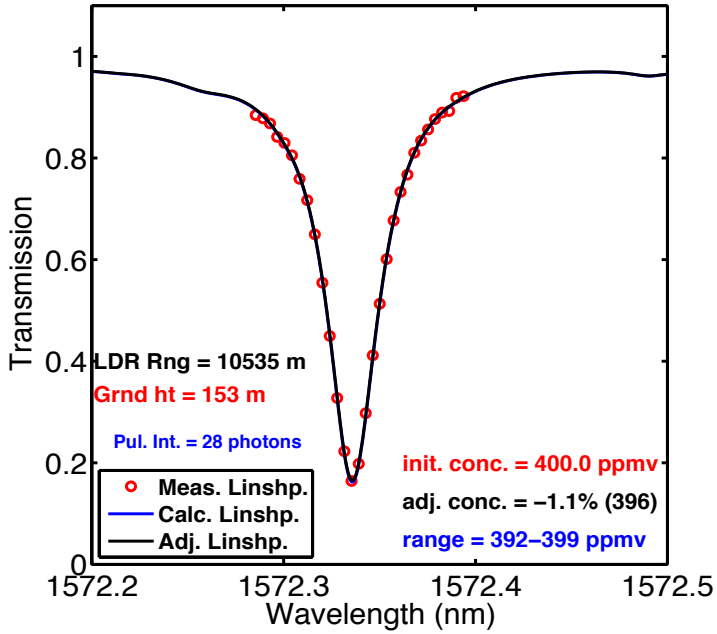
Improvements for 2014 ASCENDS flights:

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

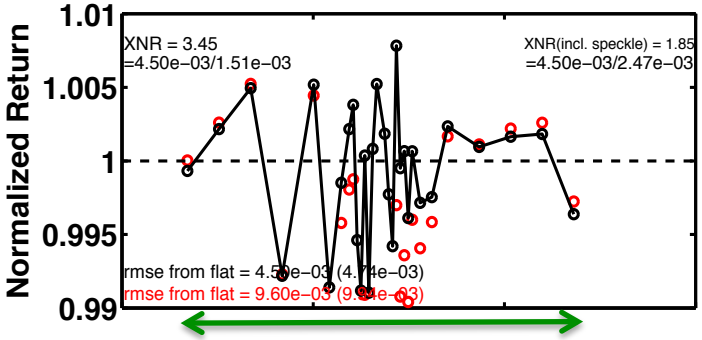




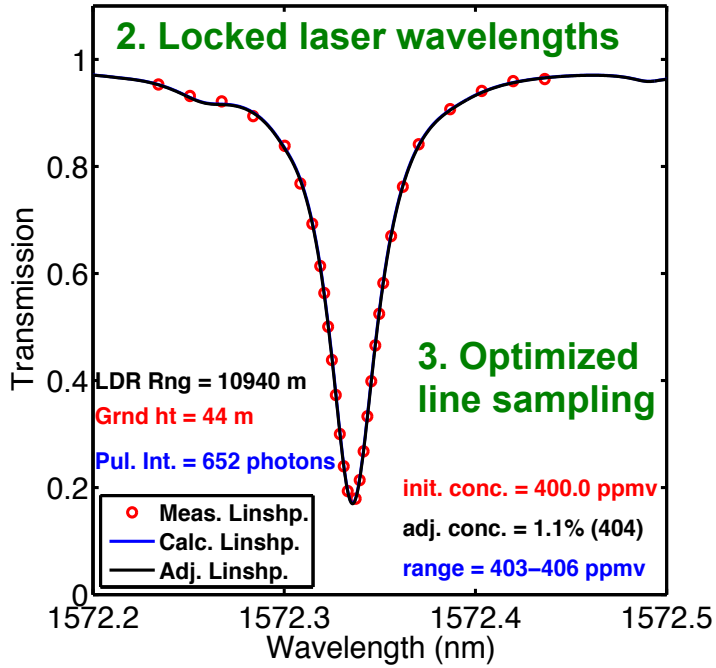
Conditions:

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

2014



1. Larger wavelength span

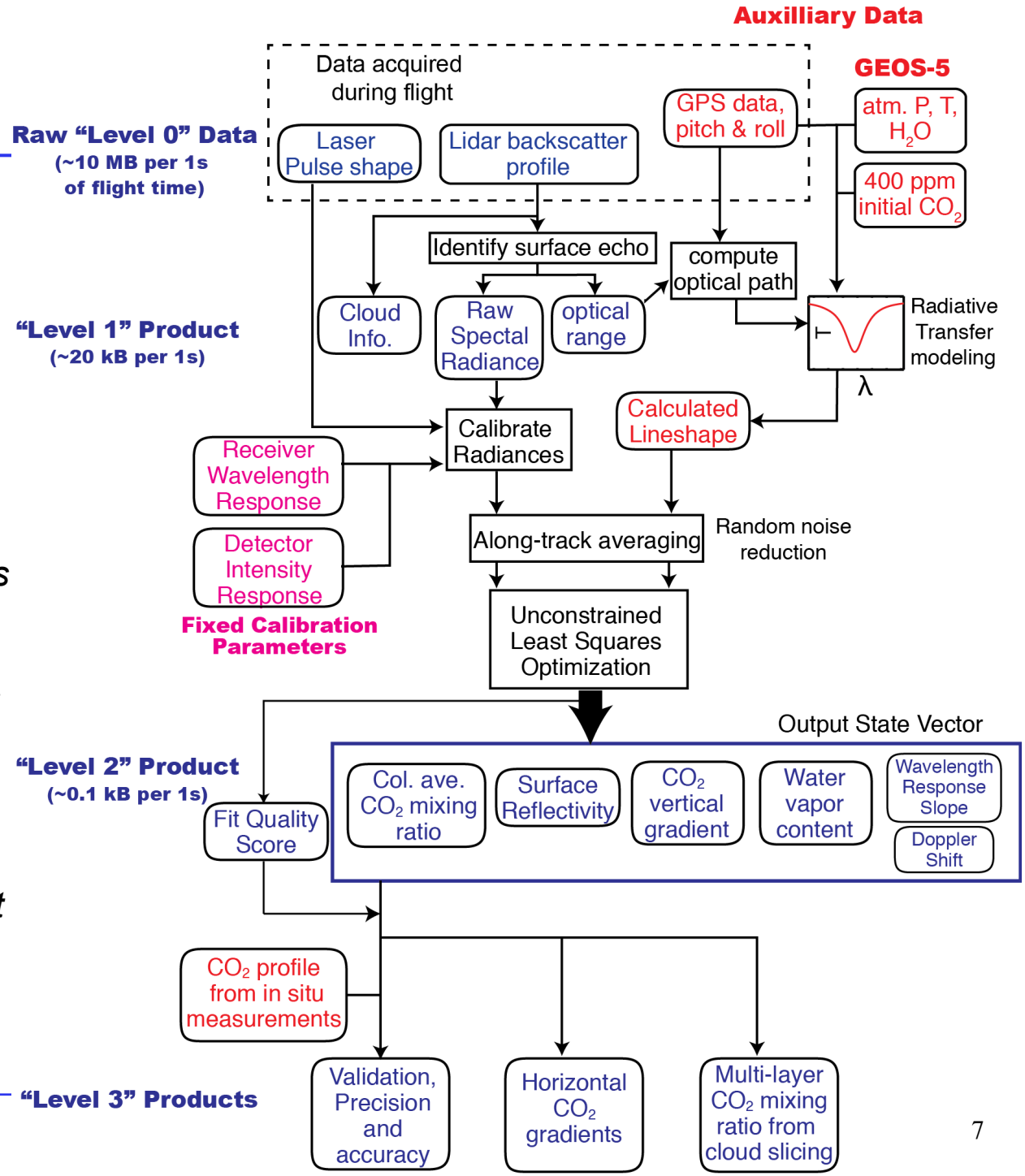


CO_2 Sounder Full Retrieval Algorithm (Ramanathan & Mao)

1. No a priori CO_2 information is required

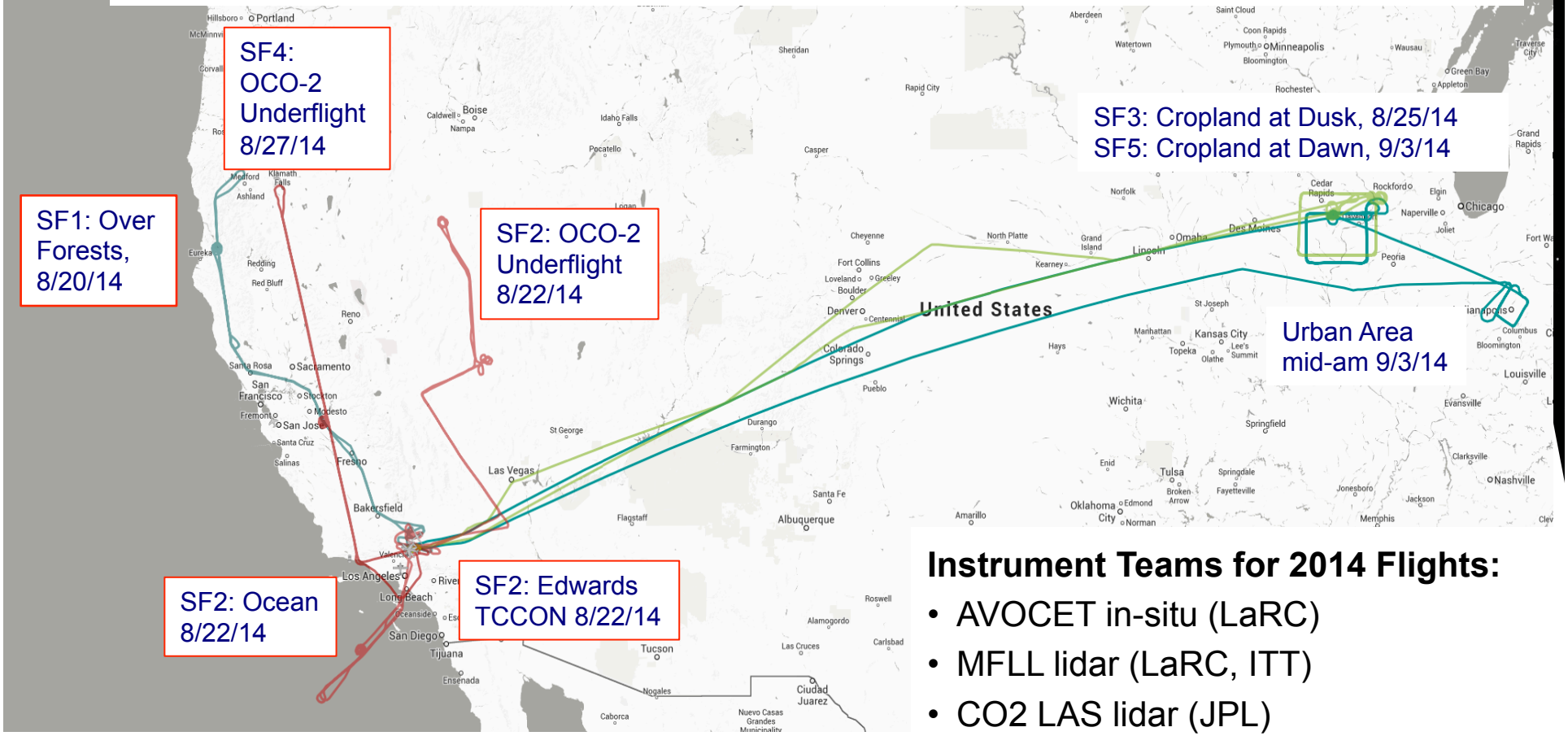
2. Sampling many wavelengths across the line:
- allows solving for potential biases
- allows assessing line fits
- allows a robust measurement

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

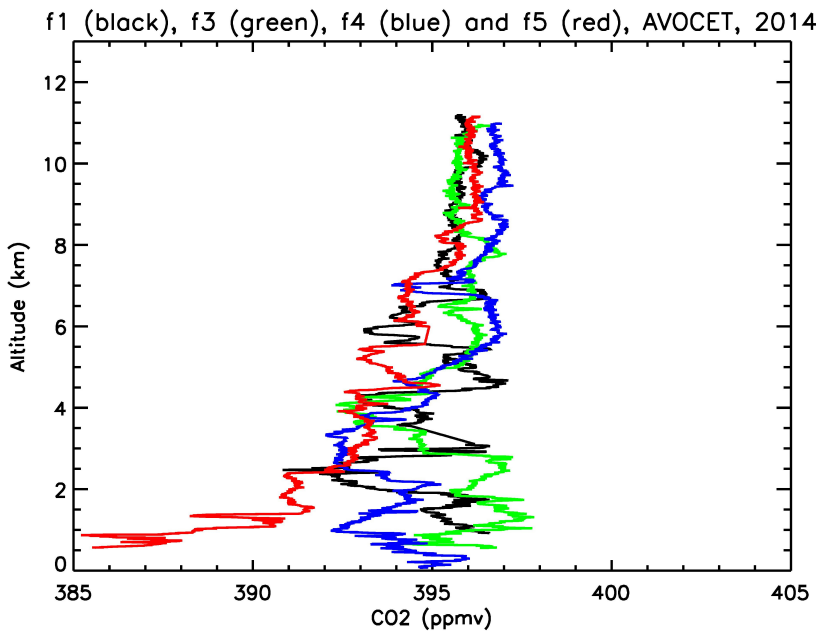


Instrument Teams for 2014 Flights:

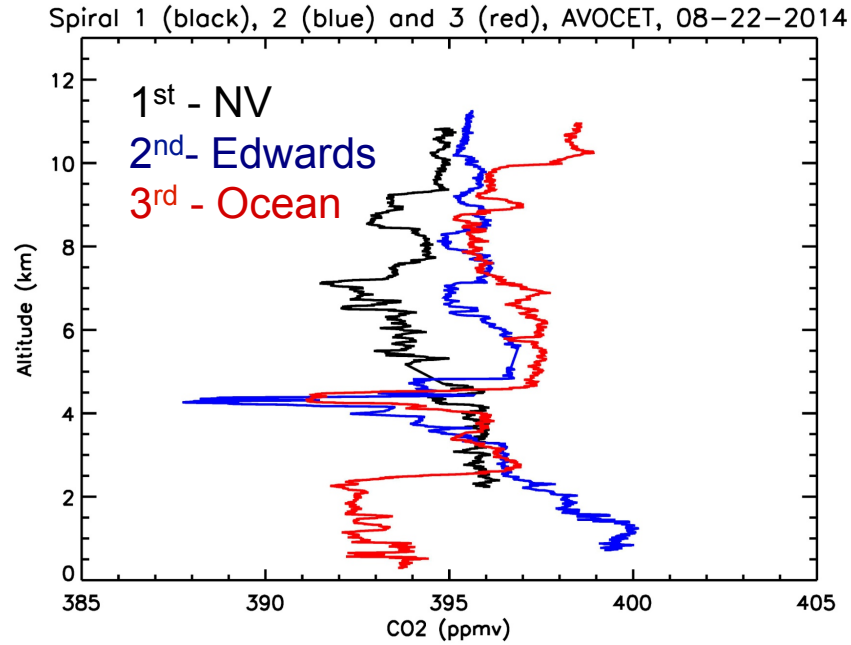
- AVOCET in-situ (LaRC)
- MFLL lidar (LaRC, ITT)
- CO2 LAS lidar (JPL)
- CO2 Sounder lidar (GSFC)

2014 In-situ measured CO_2 vertical profiles from AVOCET (NASA LaRC)

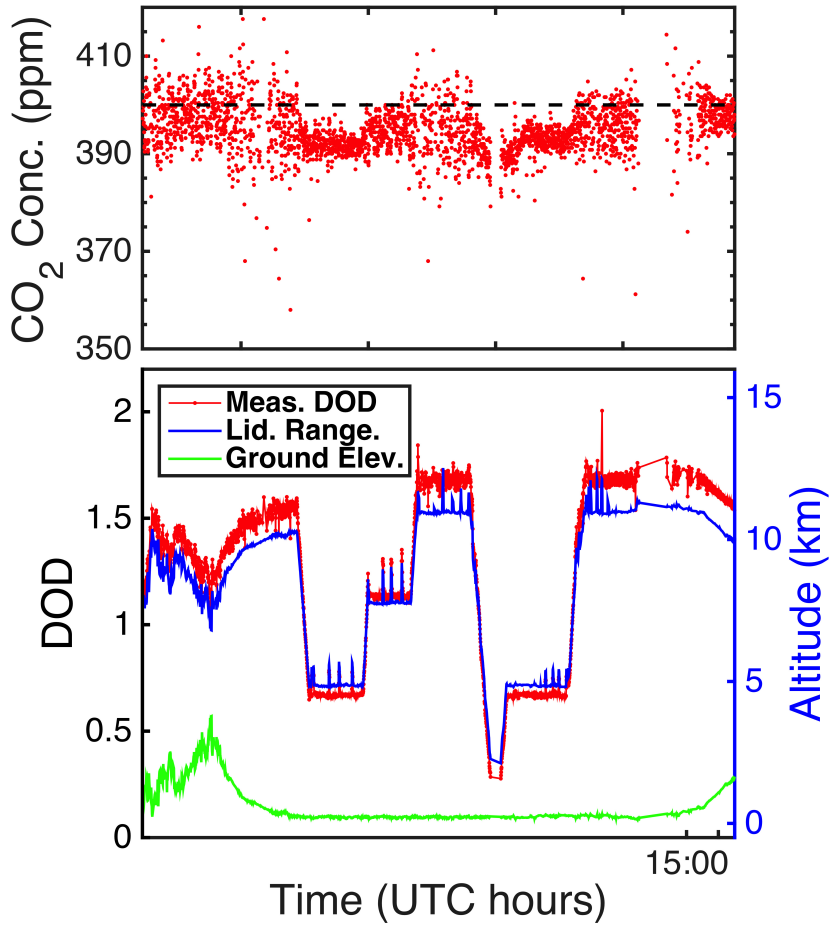
SF-1, SF-3, SF-4, SF-5



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

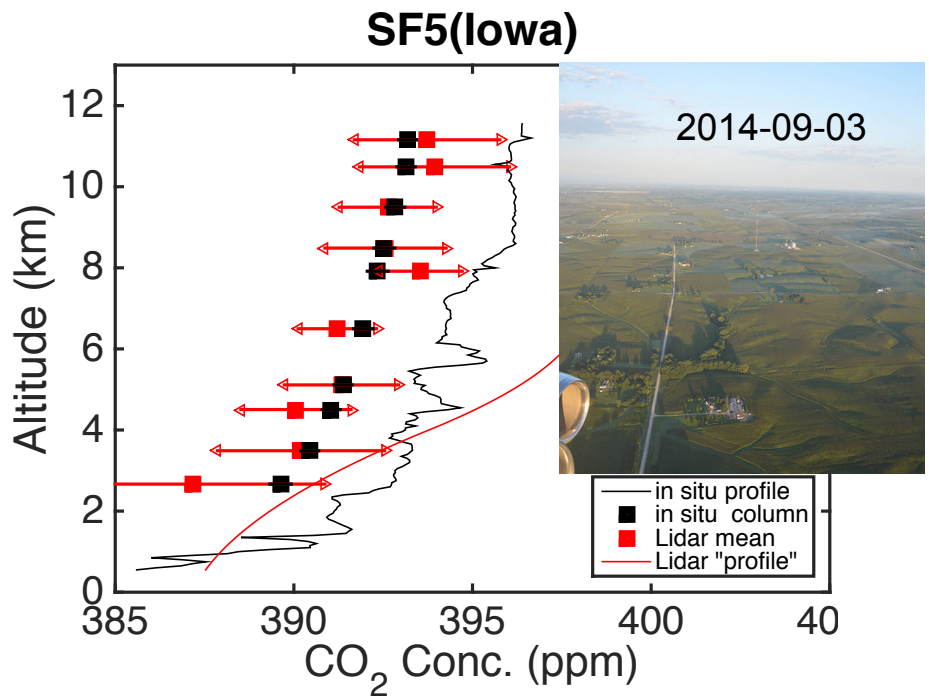


Observing CO_2 drawdown over Cropland
Measurements at Dawn over Iowa 2014-9-03



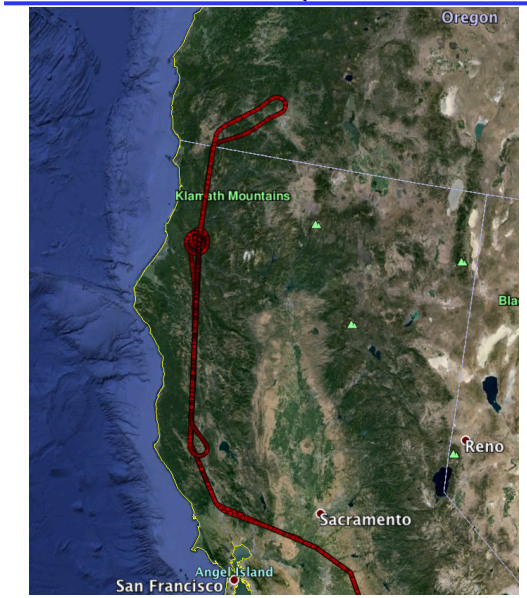
Flight Pattern:

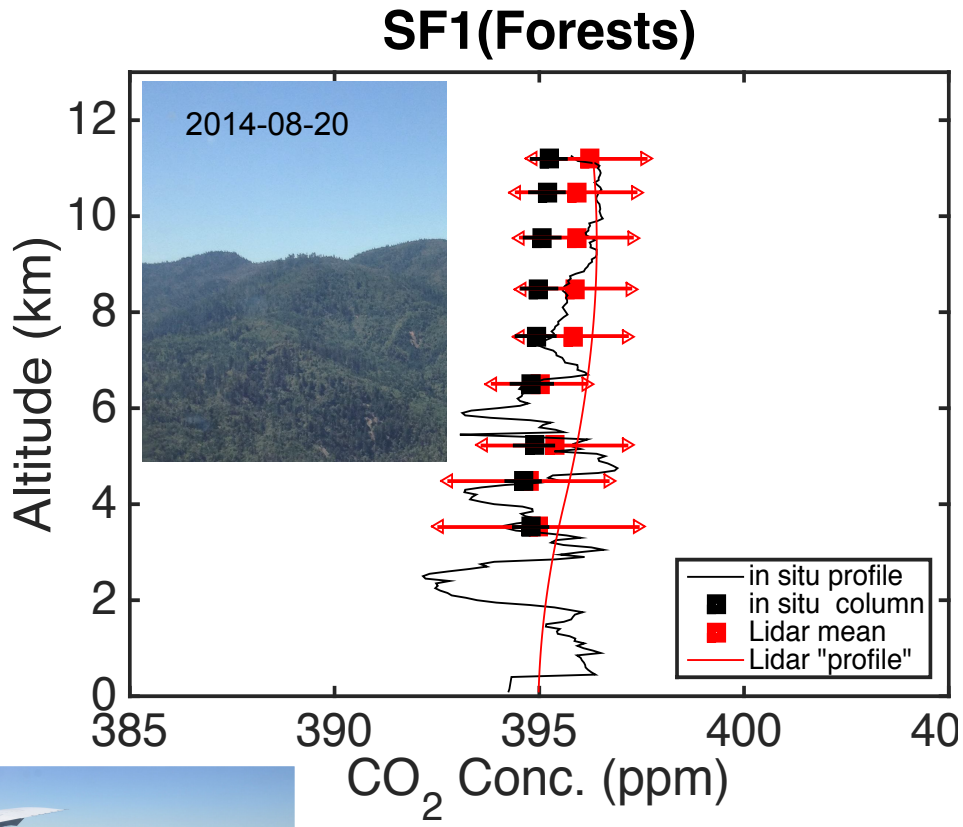
- Square pattern over Iowa at 3 altitudes
- Spiral down over Iowa West Branch tower



The lidar measurements show the CO2 drawdown (decrease with altitude) also seen by AVOCET & Picarro

2014 SF1: Forest Flight Segments (forests on several km high mountains)



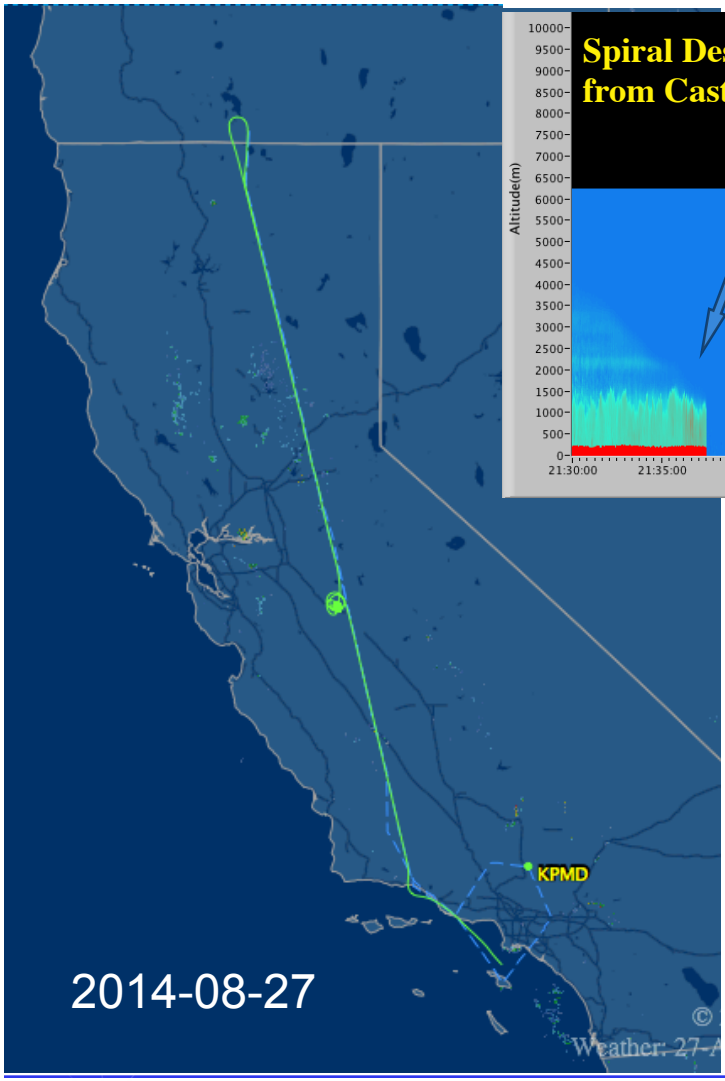


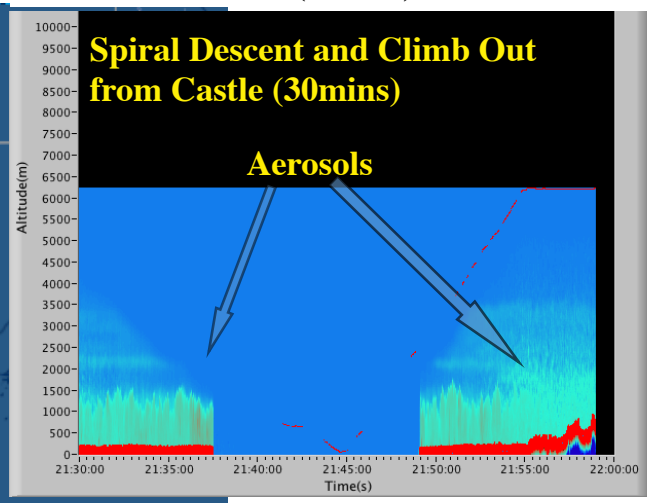
Ongoing work suggests offset may caused by bias in WV column estimate in GEOS-5

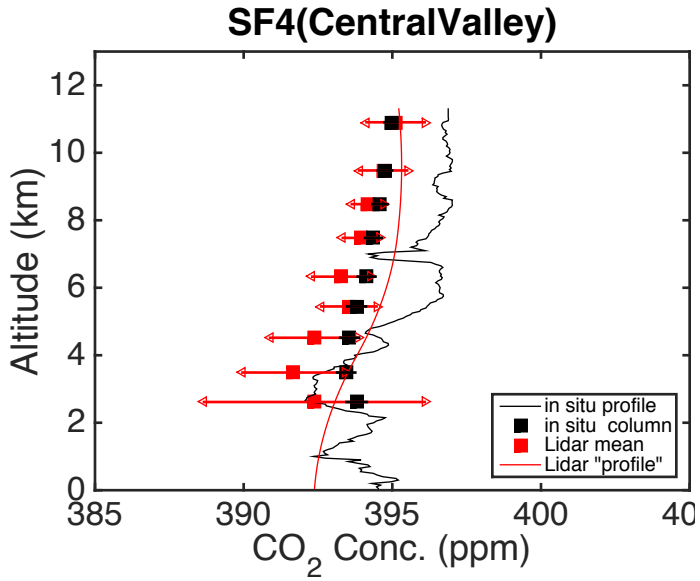
SF4 – OCO-2 Under flight – retrievals through haze

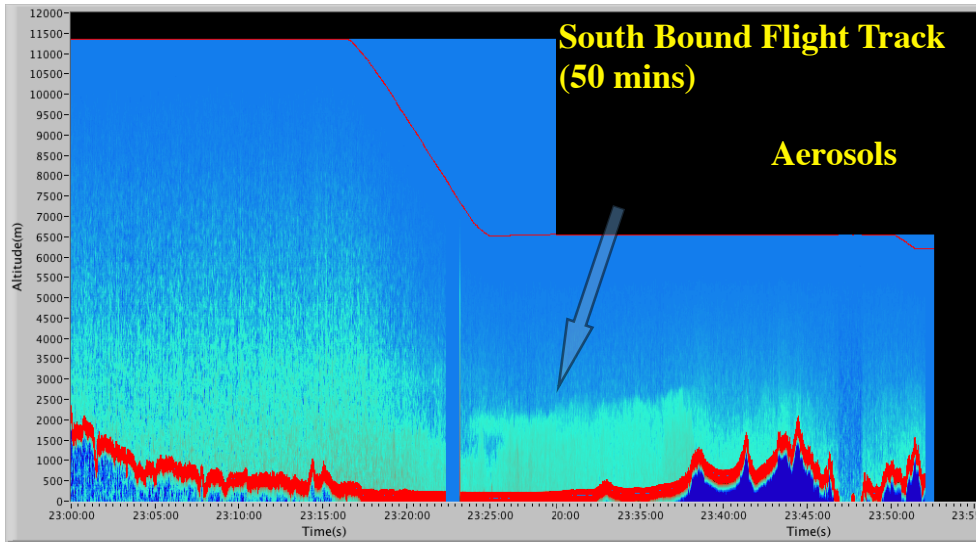
Atmospheric Backscatter Profiles & retrievals

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

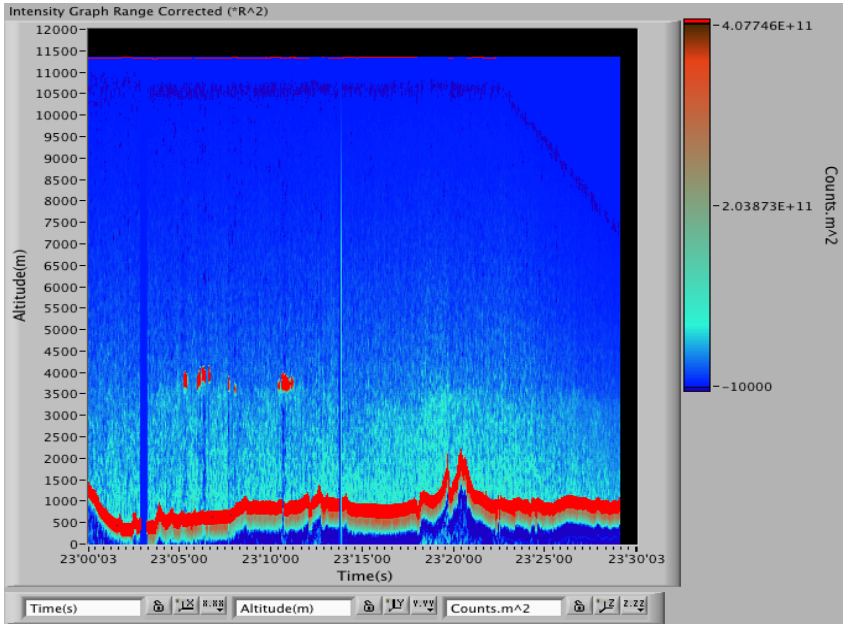




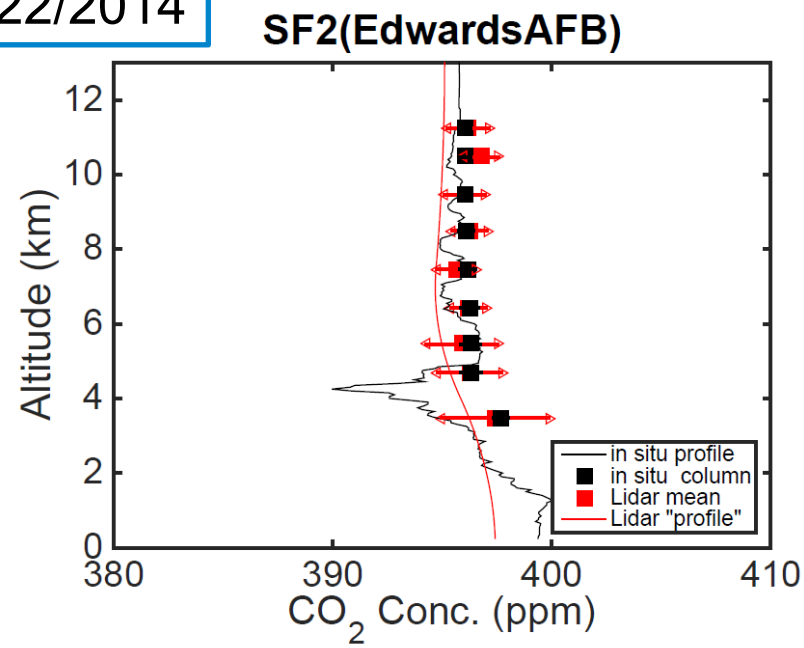


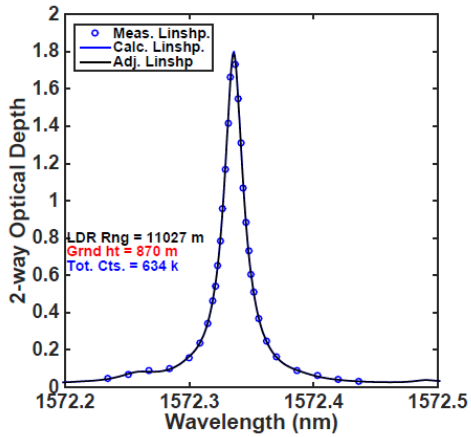


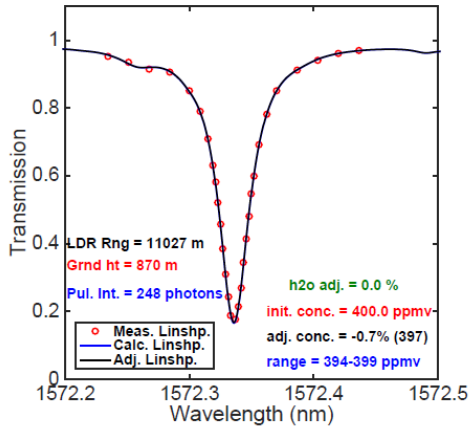
Column Retrieval - through aerosol layers



8/22/2014





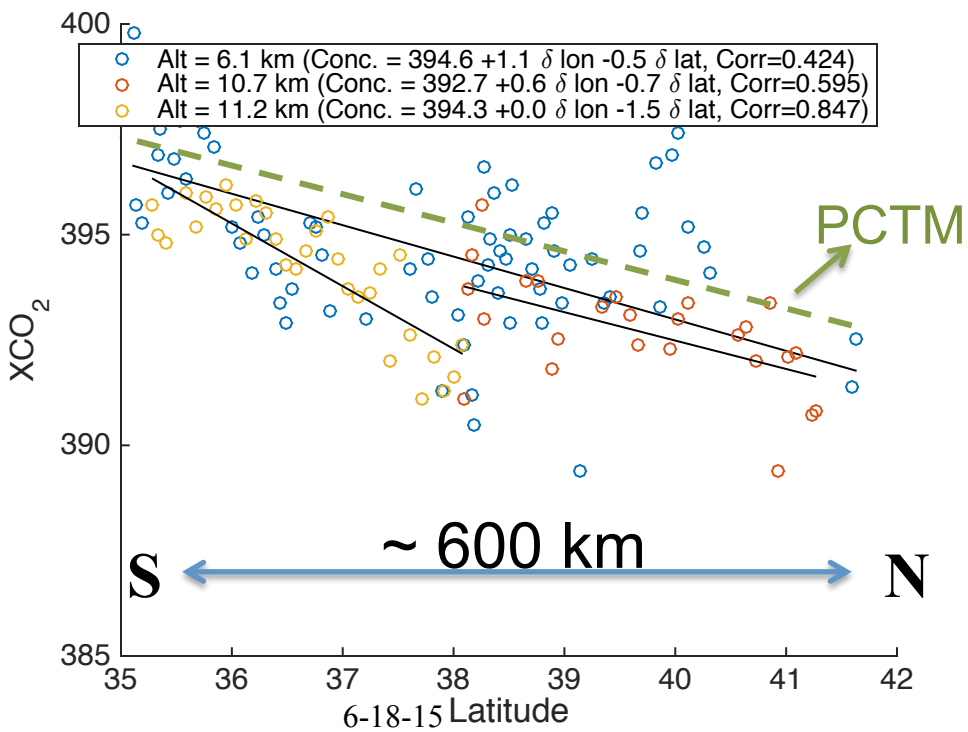


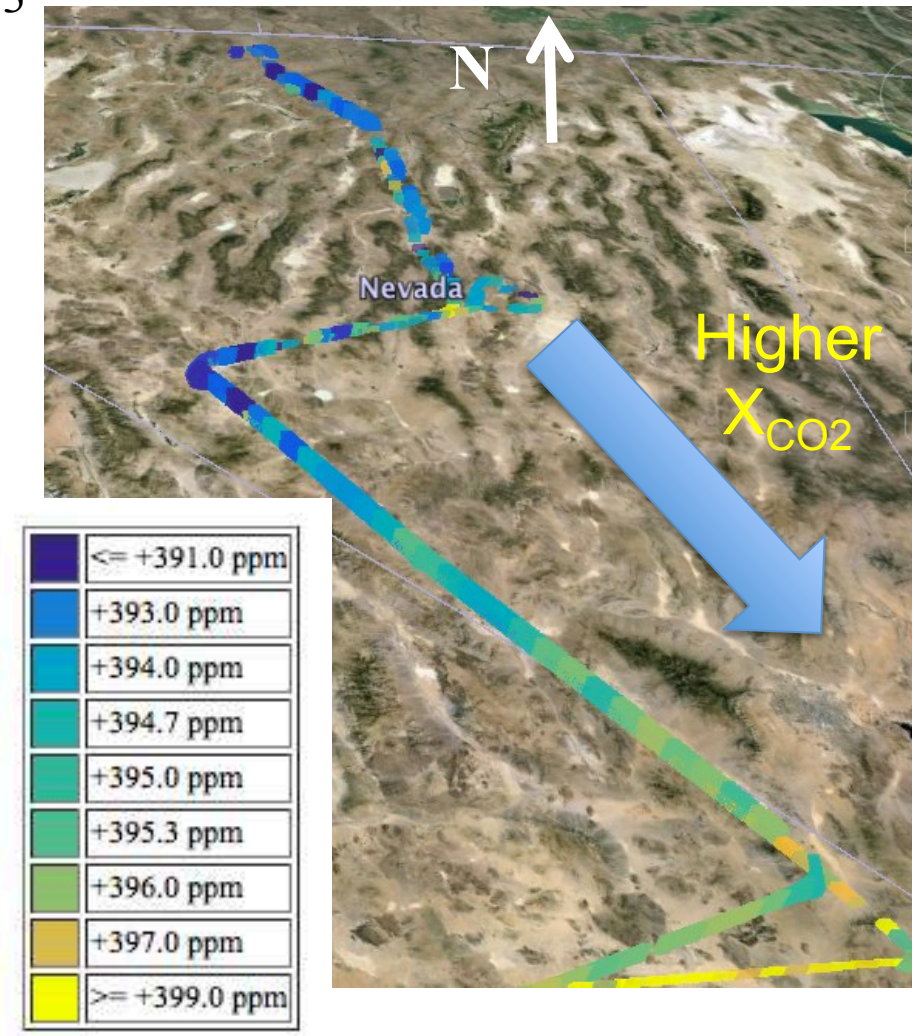
- Range-resolved measurements allow timing gating to minimize impact from atmospheric scattering
- Allow robust retrievals with low bias
- Minimizes retrieval errors over rough surfaces (terrain, and tree cover)

2014 flight over NV: Horizontal Gradient in XCO_2 (~12 km ground track avg.)

- 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*

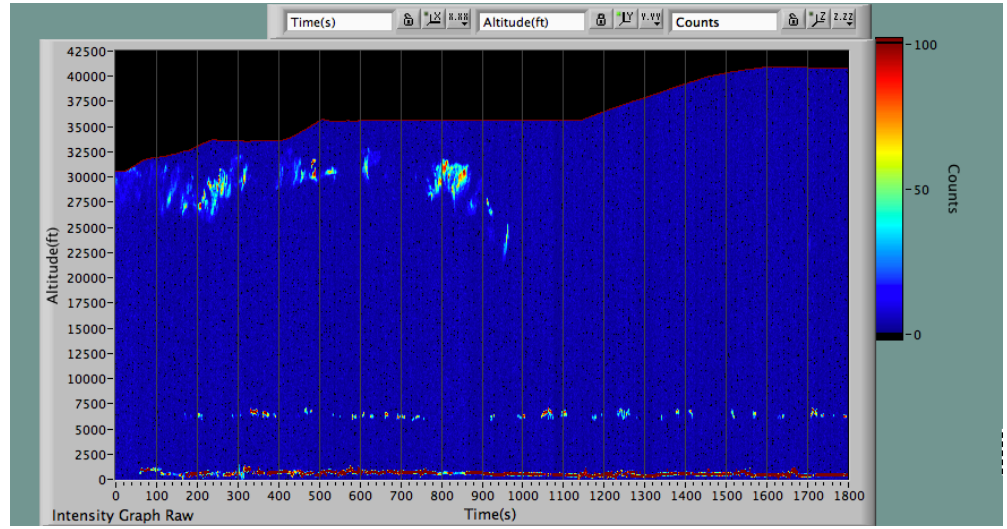
(*-Parameterized Chemistry Transport Model)



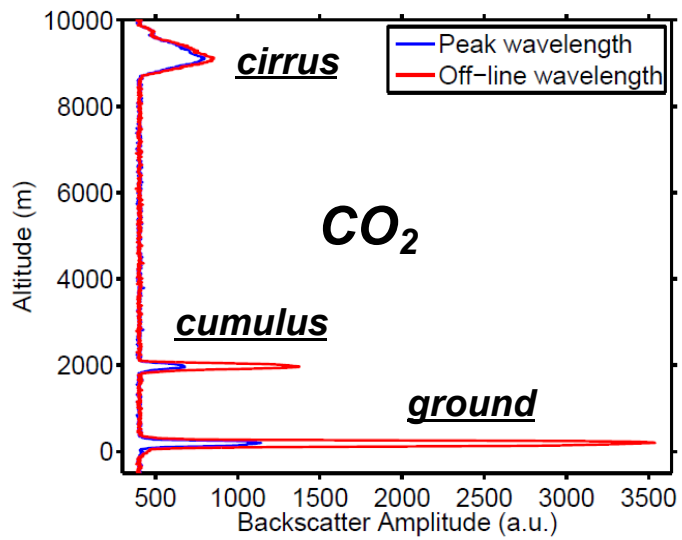


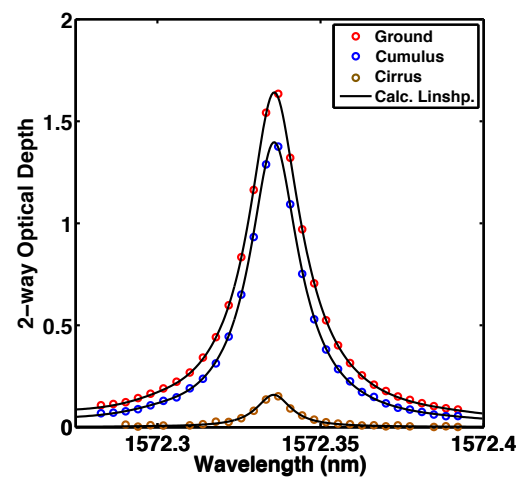
See poster by A. Ramanathan

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 CO_2 layers via IPDA lidar measurements & "Cloud Slicing"

GSFC

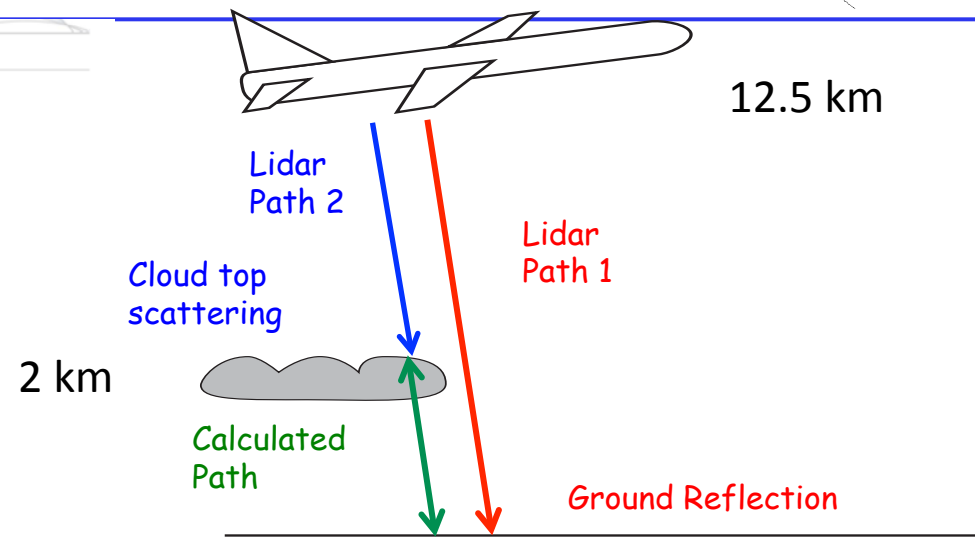

Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL062749

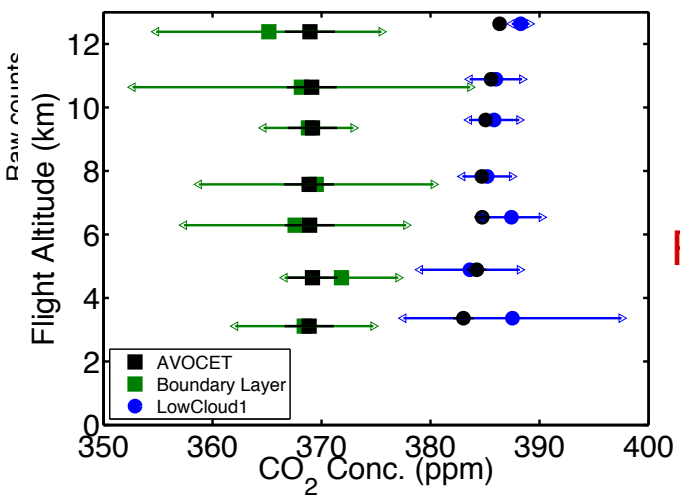
Key Points:
- Cloud slicing with lidar can sense CO_2 in the planetary boundary layer

Remote sensing measurements of the CO_2 mixing ratio in the planetary boundary layer using cloud slicing with airborne lidar

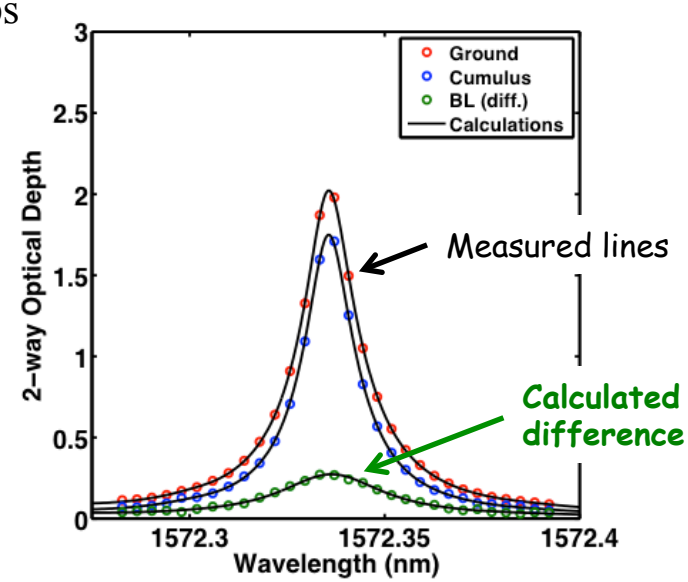
Anand K. Ramanathan[1,2], Jianping Mao[1,3], James B. Abshire[2], and Graham R. Allan[2,4]



- Measure column absorption & range to ground & cloud tops
- ***Difference*** measurements to get **bottom layer CO_2**



Results



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:

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

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"

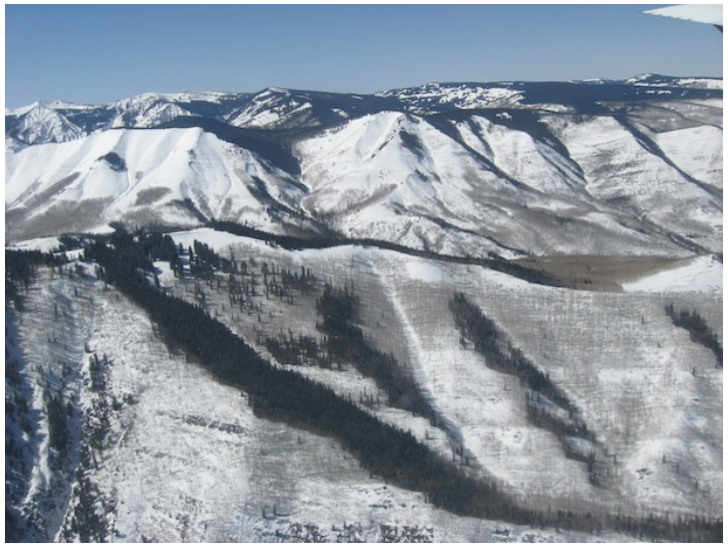
Haris Riris - "A Methane Lidar for Greenhouse Gas Measurements"

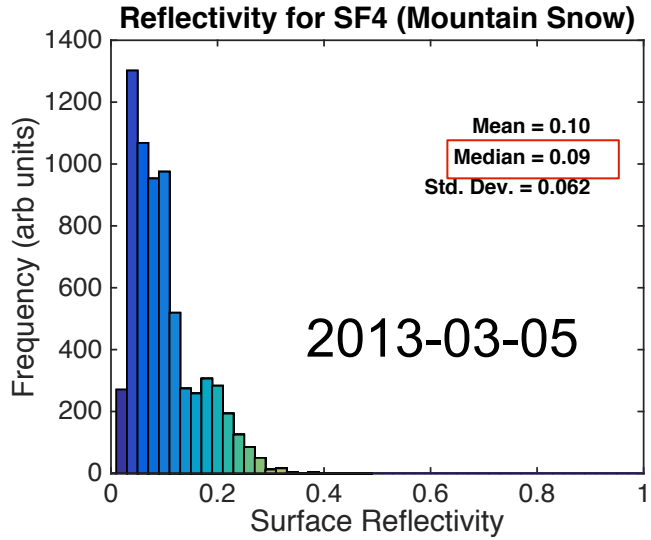
2. CO2 Sounder Website:

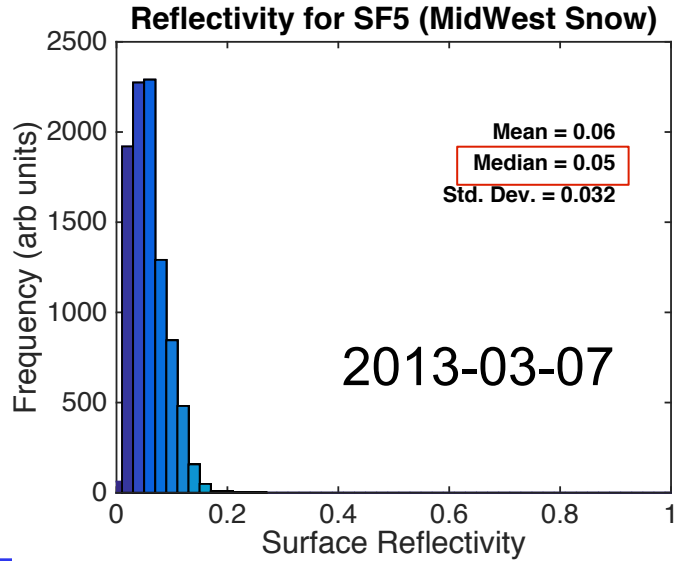
http://ssed.gsfc.nasa.gov/co2sounder/

3. ASCENDS Workshop on Friday

Offline signals allow Surface Reflectivity Measurements
(Example - Snow in Colorado Mountain Basins & Iowa)







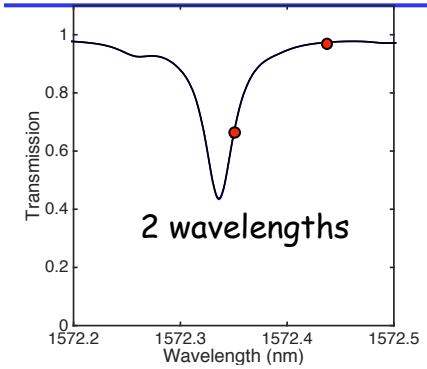
See poster by A. Ramanathan for complete set

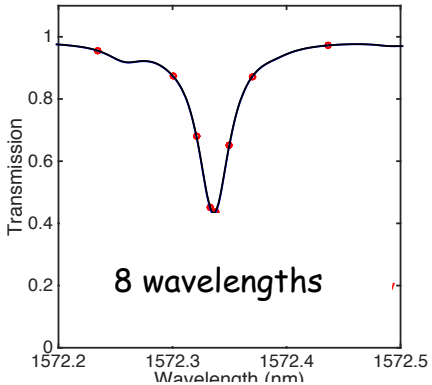
More wavelengths give more information & allow more accurate measurements

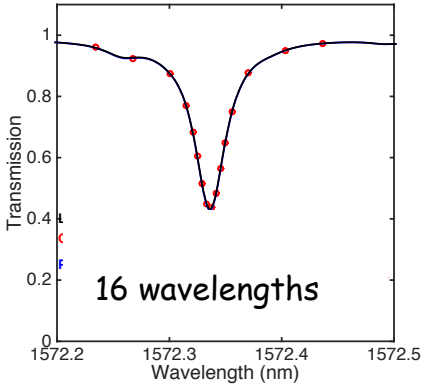
Present airborne

Planning for Space

ASCENDS

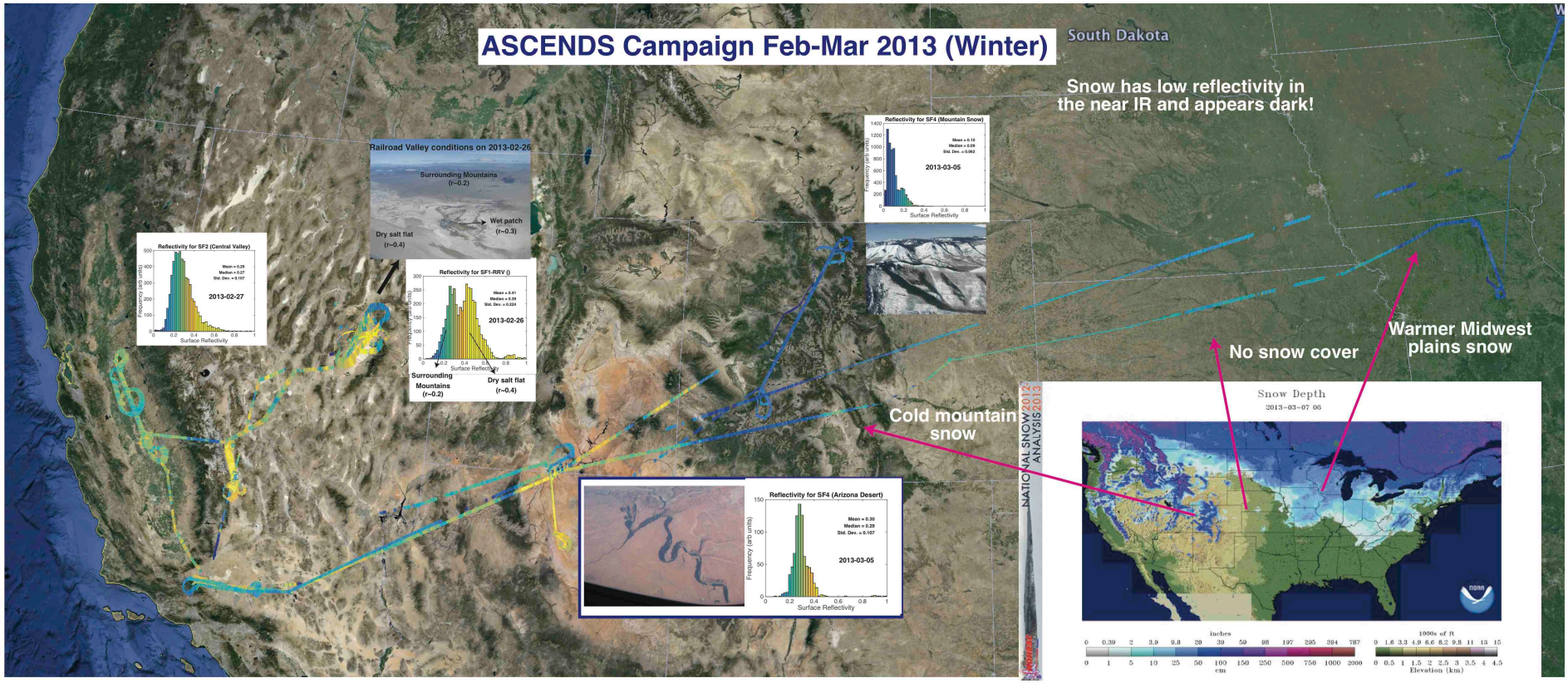






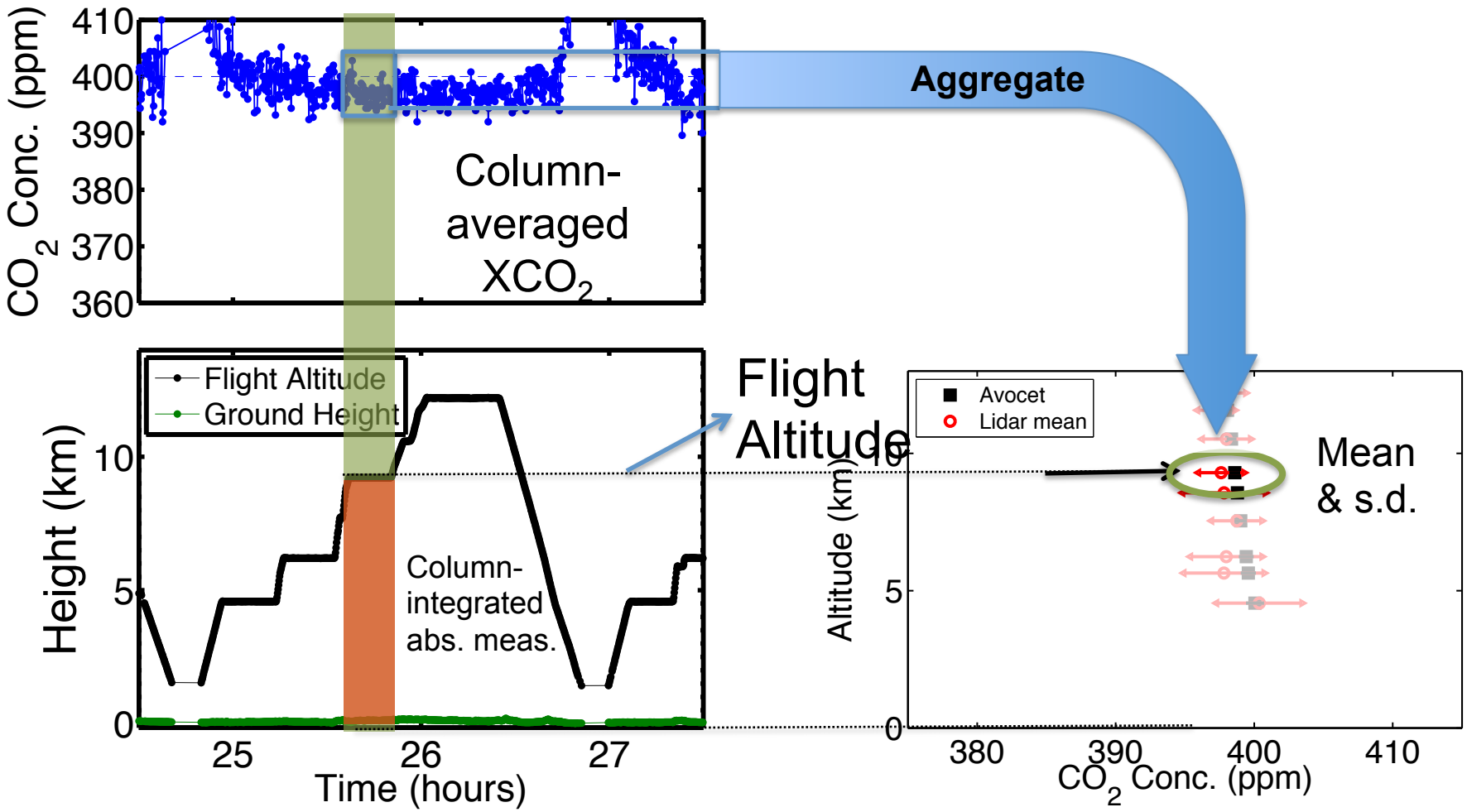
No. of Wavelengths	1	2	3	4	6	8	10+	30
Reflectivity	✓	✓	✓	✓	✓	✓	✓	✓
CO_2 column mean	✗	✓	✓	✓	✓	✓	✓	✓
Linear baseline	✗	✗	✓	✓	✓	✓	✓	✓
Doppler shift	✗	✗	✗	✓	✓	✓	✓	✓
CO_2 vertical gradient	✗	✗	✗	✗	✓	✓	✓	✓
Nonlinear baseline	✗	✗	✗	✗	✗	✓	✓	✓
Water vapor content	✗	✗	✗	✗	✗	✗	✓	✓
CO_2 mid-troposphere	✗	✗	✗	✗	✗	✗	✗	✓
Fit quality	✗	✗	✗	✗	✓	✓✓	✓✓✓	✓✓✓✓✓✓✓✓✓✓✓✓

2013 ASCENDS Campaign - Flight Map



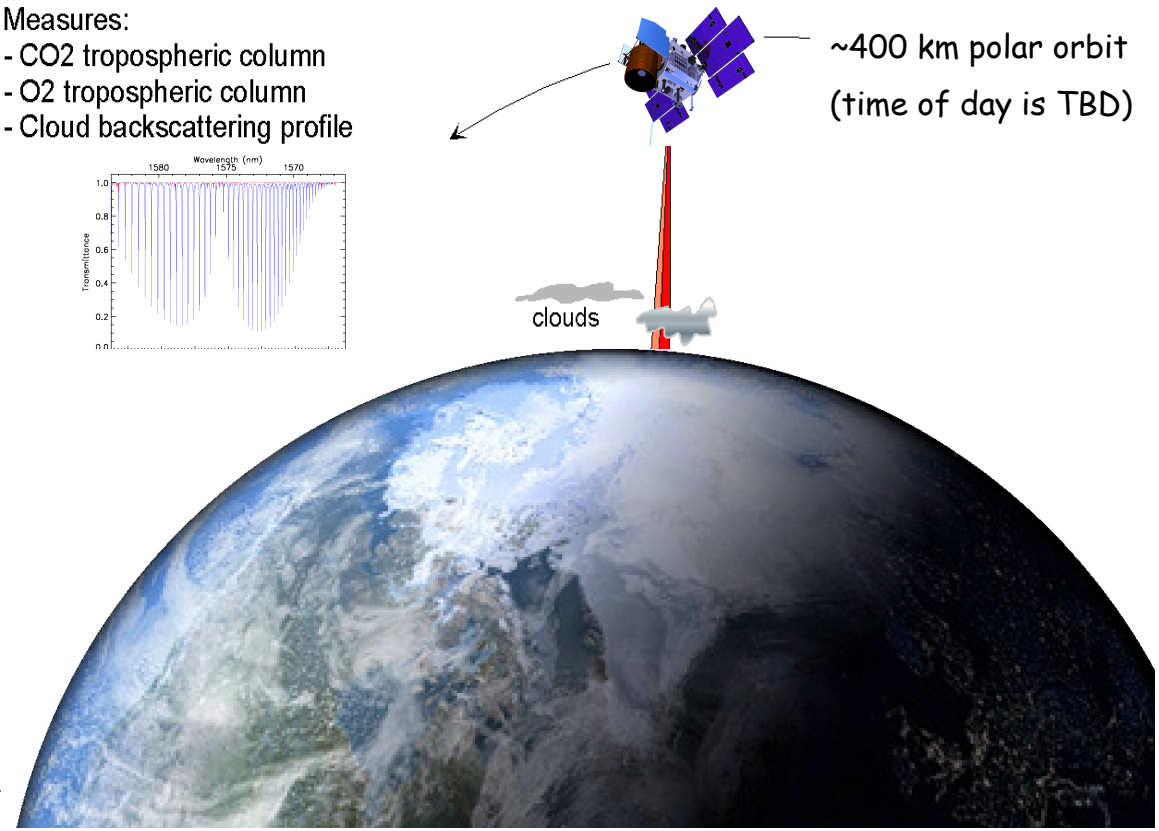
- Before 2014, we used a wavemeter as reference for our scanning laser wavelength
- In the 2013 flights, the wavemeter failed - impacted most CO2 retrievals for 2013
- However lidar worked well
- 2013 & 2014 measurements allowed a survey of surface reflectance at 1572 nm

Lidar data-in situ data comparisons are in column from flight altitude to ground



ASCENDS Mission Overview

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



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

Requirements for XCO2:

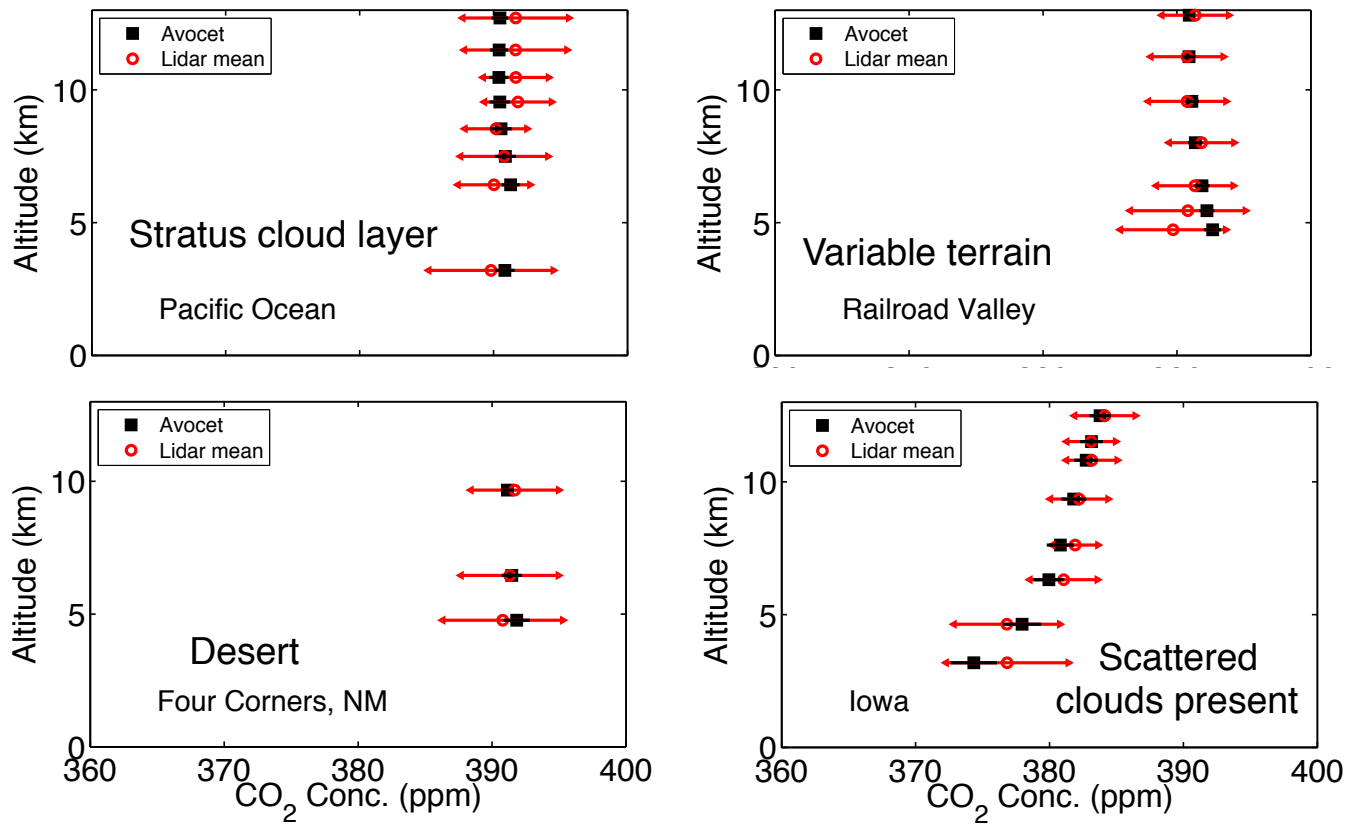
***Random error*: ~ 1ppm in ~100 km along track sample**
or ~ 0.5 ppm in ~10 sec over deserts

***Bias:* < 0.5 ppm**

CO_2 Sounder example
Lidar measurements vs in-situ for 2011 flights

GSFC

- **- 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)**

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Article

Airborne Measurements of CO_2 Column Concentration and Range Using a Pulsed Direct-Detection IPDA Lidar

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