Developing the CO_2 Sounder Lidar as a candidate for ASCENDS under the IIP-10 Program

James B. Abshire

Haris Riris, Graham Allan, Jeffrey Chen, Tony Yu, Bill Hasselbrack, Anand Ramanathan, Jianping Mao, Michael Rodriguez

NASA - Goddard Space Flight Center

Greenbelt MD 20771

Presentation to:

2015 NASA ESTF Conference

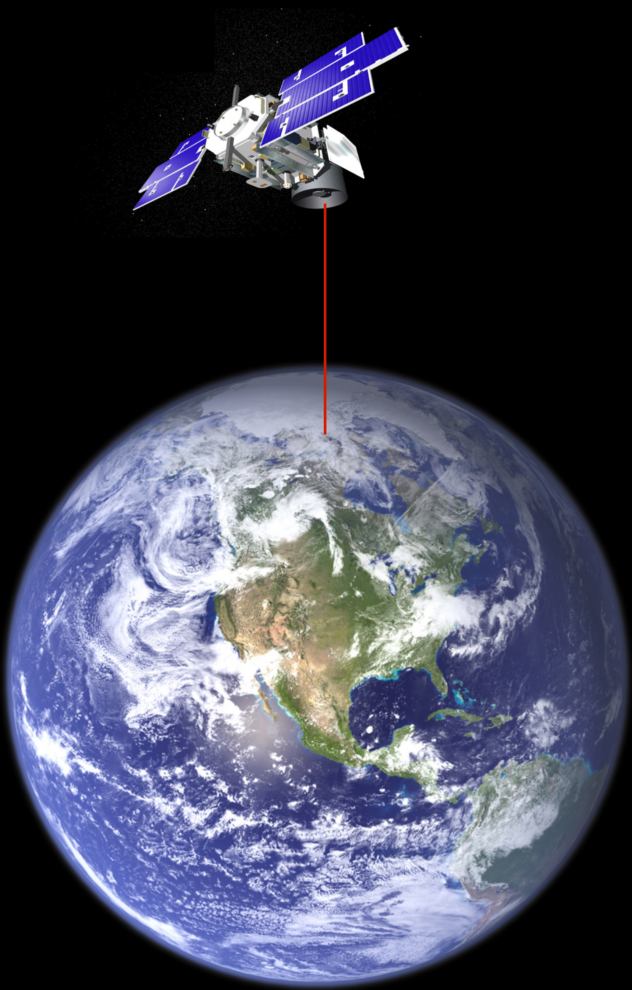
June 24, 2015

**- Support from:*

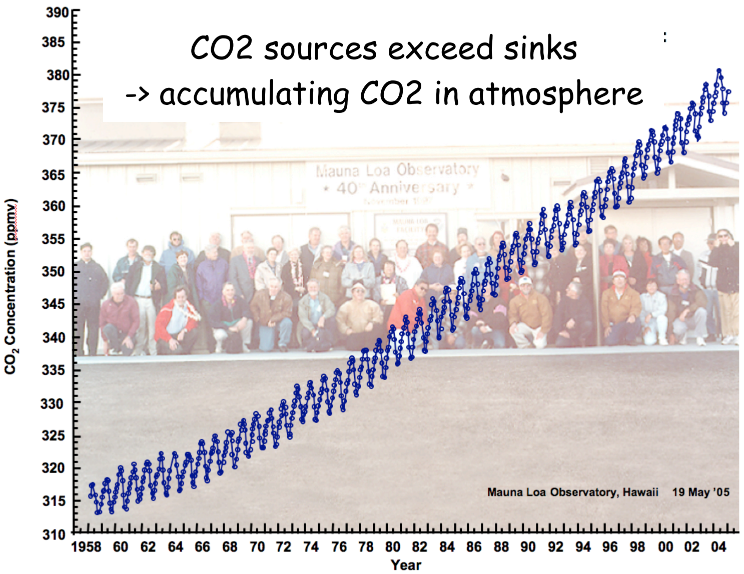
NASA ESTO IIP-10 & QRS programs

ASCENDS Pre-formulation Activity, Goddard IRAD program

James.B.Abshire@nasa.gov



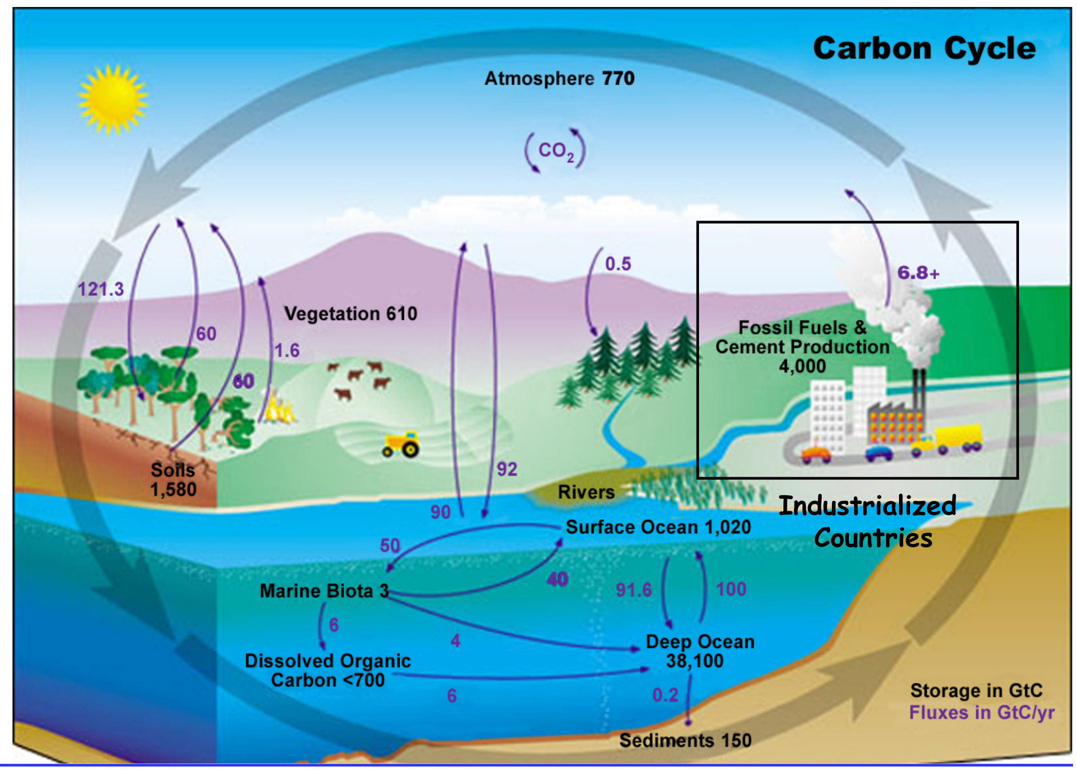
Atmospheric CO2 & Earth's Carbon Cycle



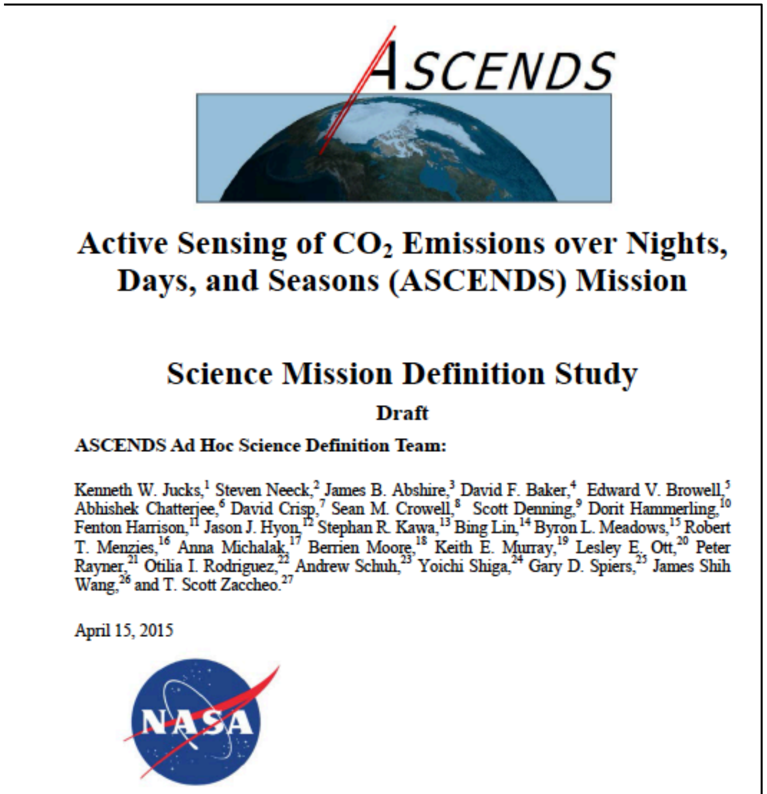
Major Questions about CO2 Sinks:
Is considerable uncertainty in locations, strengths, dynamics & evolution with time
=> Space Observations (OCO, ASCENDS)

Challenges:

- Fluxes of great interest produce only very small signatures in atmospheric CO_2 (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 Overview



ASCENDS

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

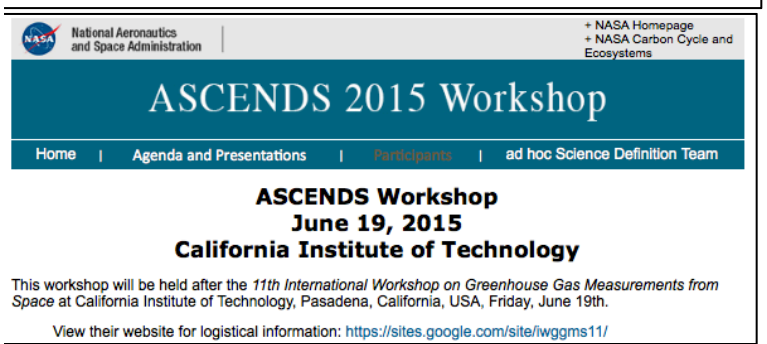
Science Mission Definition Study

Draft

ASCENDS Ad Hoc Science Definition Team:

Kenneth W. Jucks,[1] Steven Neeck,[2] James B. Abshire,[3] David F. Baker,[4] Edward V. Browell,[5] Abhishek Chatterjee,[6] David Crisp,[7] Sean M. Crowell,[8] Scott Denning,[9] Dorit Hammerling,[10] Fenton Harrison,[11] Jason J. Hyon,[12] Stephan R. Kawa,[13] Bing Lin,[14] Byron L. Meadows,[15] Robert T. Menzies,[16] Anna Michalak,[17] Berrien Moore,[18] Keith E. Murray,[19] Lesley E. Ott,[20] Peter Rayner,[21] Otilia I. Rodriguez,[22] Andrew Schuh,[23] Yoichi Shiga,[24] Gary D. Spiers,[25] James Shih Wang,[26] and T. Scott Zaccheo.[27]

April 15, 2015



National Aeronautics and Space Administration

+ NASA Homepage
+ NASA Carbon Cycle and Ecosystems

ASCENDS 2015 Workshop

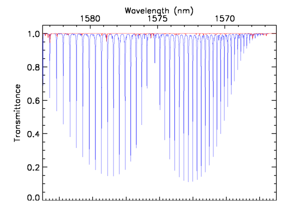
Home | Agenda and Presentations | Participants | ad hoc Science Definition Team

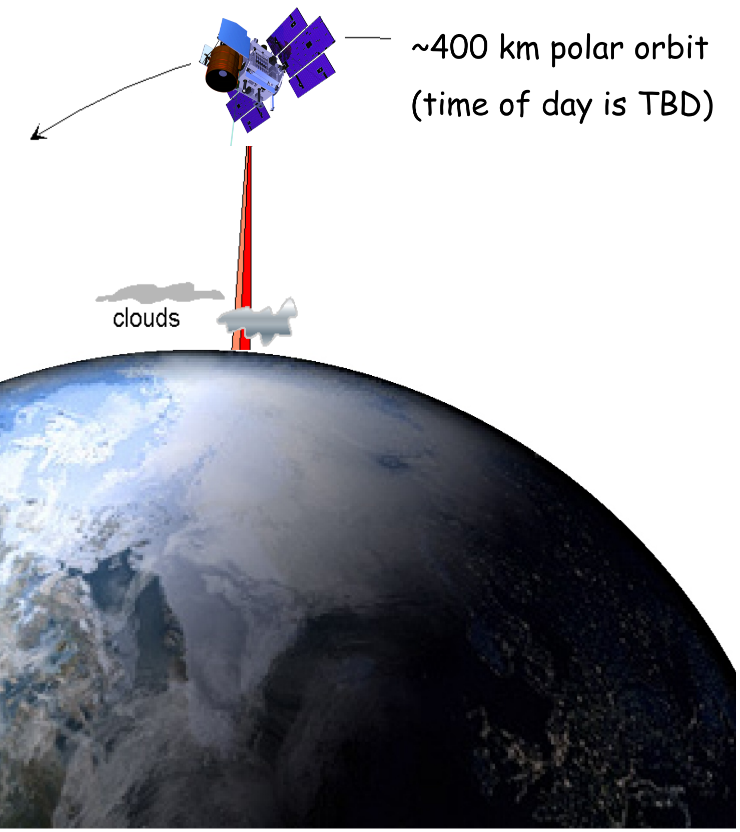
ASCENDS Workshop
June 19, 2015
California Institute of Technology

This workshop will be held after the *11th International Workshop on Greenhouse Gas Measurements from Space* at California Institute of Technology, Pasadena, California, USA, Friday, June 19th.

View their website for logistical information: https://sites.google.com/site/iwggms11/

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





Requirements for XCO2:

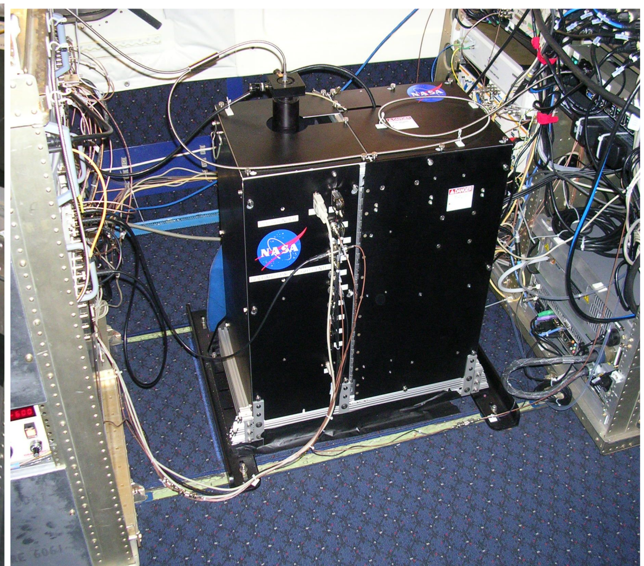
***Random error*: ~ 1ppm in ~100 km along track,**
or ~ 0.5 ppm in ~10 sec over deserts

***Bias:* < 0.5 ppm (< 1 part in 800)**

Lower errors provide more benefit for flux est's.

CO_2 Sounder Lidar
A pulsed IPDA lidar for CO_2 on NASA DC-8

GSFC

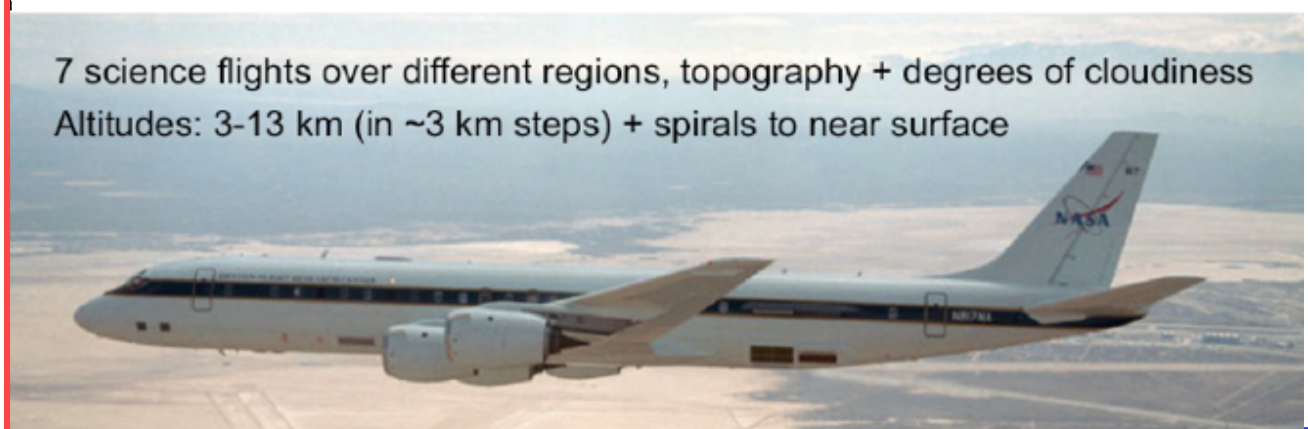

CO2 Sounder Characteristics:

Optimized as space instr. Simulator

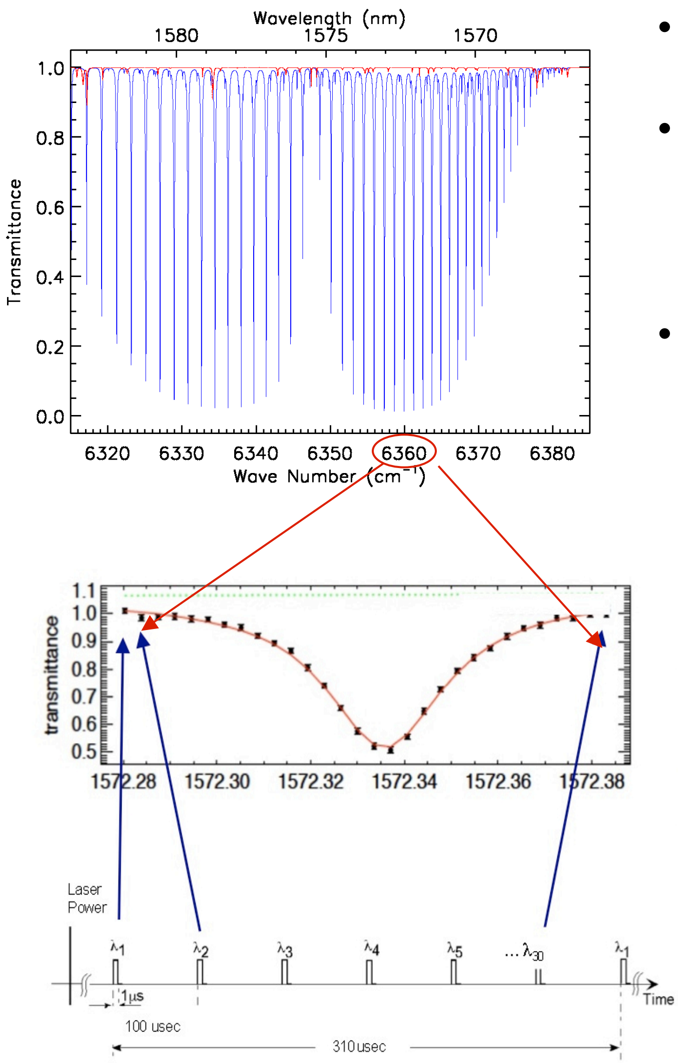
- 25 uJ/pulse at 10 KHz (250 mW)
- 30 λ's/line, 300 Hz sweep rate
- 20 cm dia. receiver telescope
- Detector, backscatter profile recorder:
  - <2014: NIR PMT (~4-8% QE)
    - Photon counting MCS
  - ≥ 2014: HgCdTe APD (QE ~70%)
    - Analog digitizer (10 Hz)

2011, 2013, 2014 ASCENDS Flights

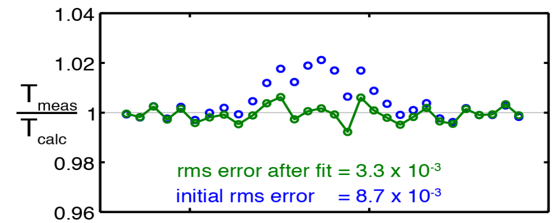
Objectives: Measure CO2 columns over a variety of topographic targets & under varying atmospheric conditions with lidar candidates & in-situ sensors

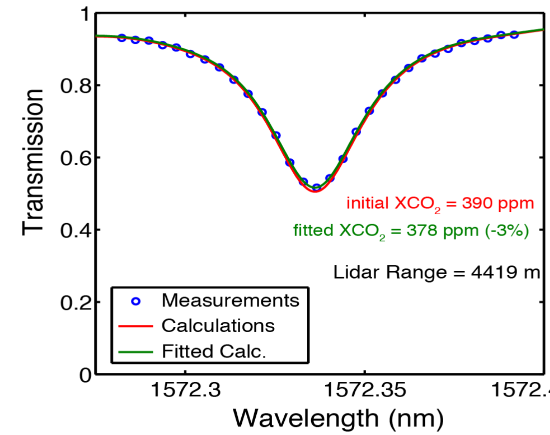


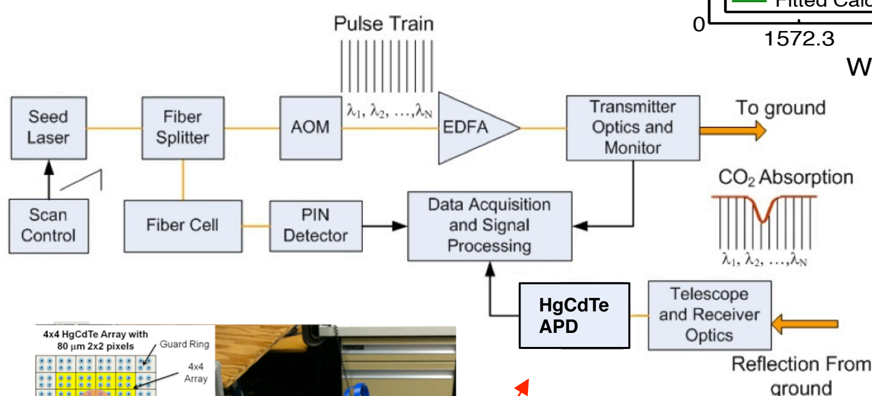
CO_2 Sounder Approach: Airborne CO_2 Line Sampling & Absorption line analysis

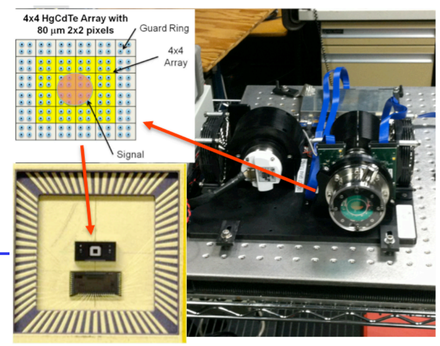


- *Line at 1572.33 nm*
- *Lidar* measures "dots" (wavelength samples) to all scattering surfaces
- *Post flight: Retrievals* (based on model atmosphere) calculates range, normalized line shapes & solves for best fit concentration









HgCdTe APD Detector in 2014 flights

Measurement Approach & CO_2 Sounder Retrieval Algorithm (Ramanathan & Mao)

- *Are many critical elements for a lidar for ASCENDS*

- *The lidar method & retrieval algorithm are key*

- *They drive the laser & receiver design, & their parameters*

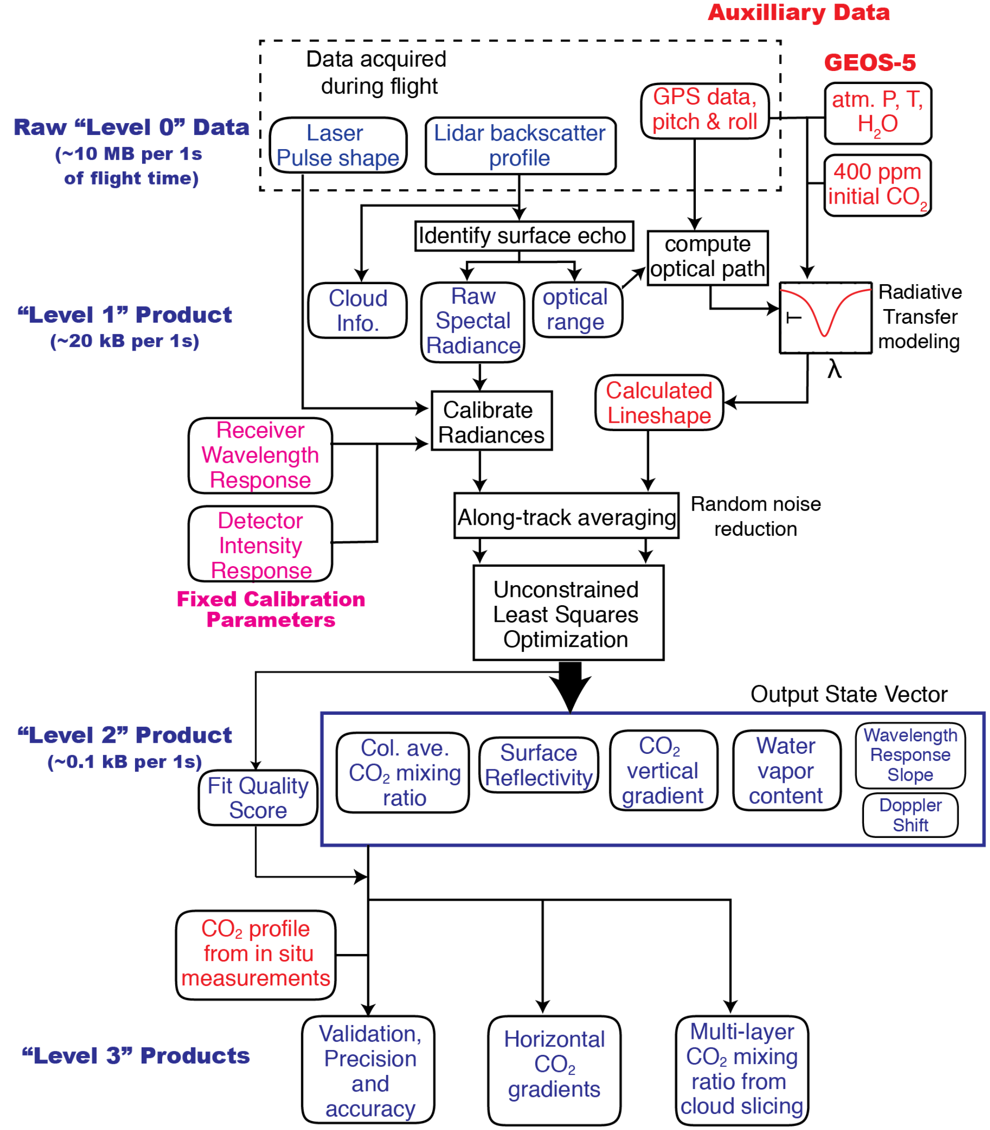
- *Have addressed all these during this IIP*

- *We found that sampling the CO2 line rapidly at multiple wavelengths is important:*

  - Provides information to solve for and eliminate biases

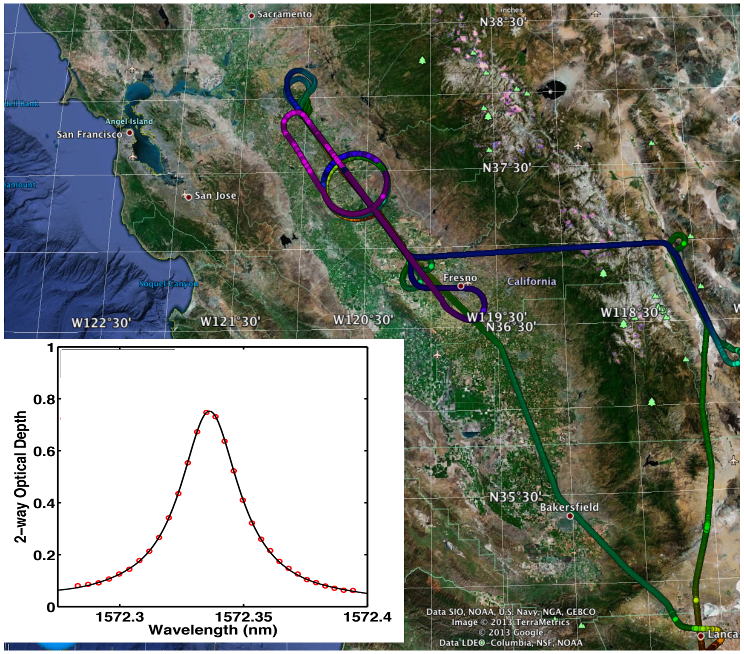
  - Allows assessing line fits

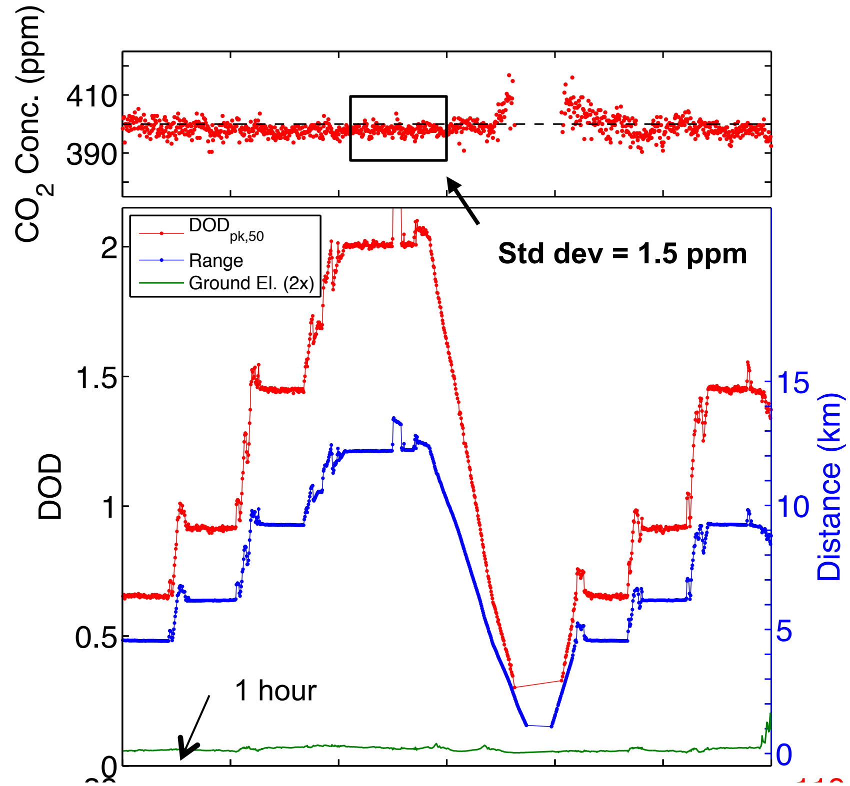
  - Allows a robust measurement

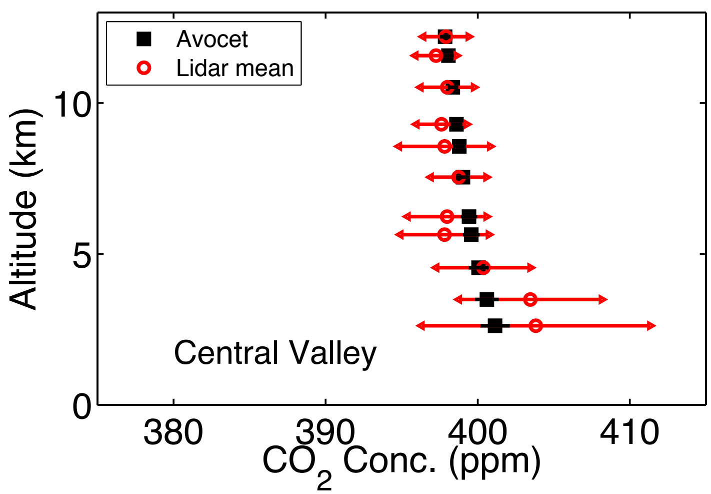


CO_2 Sounder - detecting boundary layer enhancement 2013 Flight over California Central Valley

GSFC







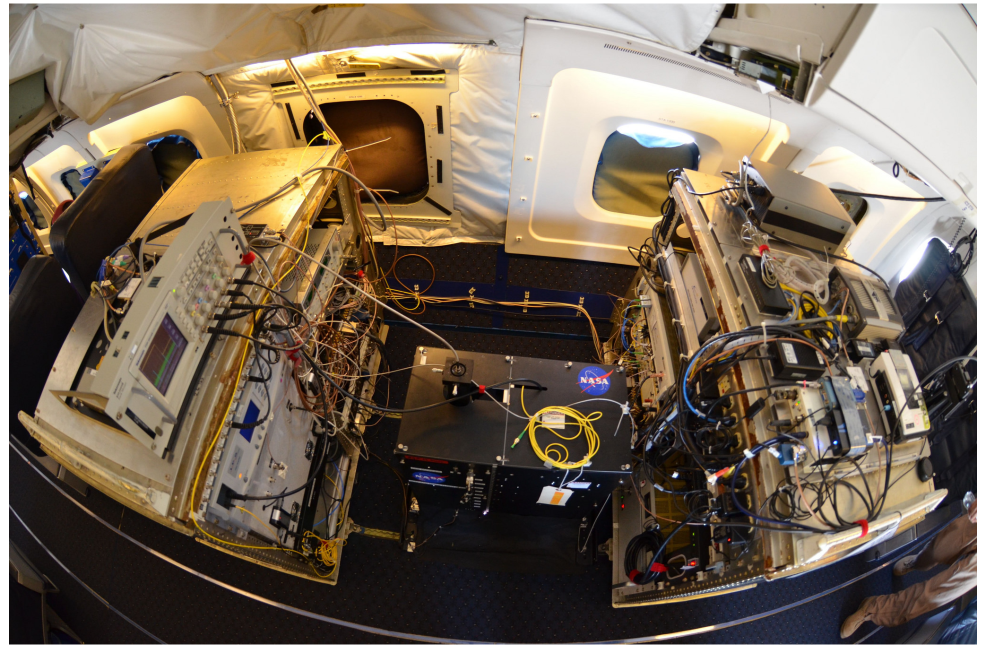
2013 Airborne Co2 Sounder:

- Used PMT detector & photon histogramming
- 1 second along track resolution, 10 sec ave time

Legend for plot:

- Black dots – column average to surface from in-situ (truth)
- Red dots – CO2 Sounder mean
- Red lines – CO2 sounder standard deviation

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



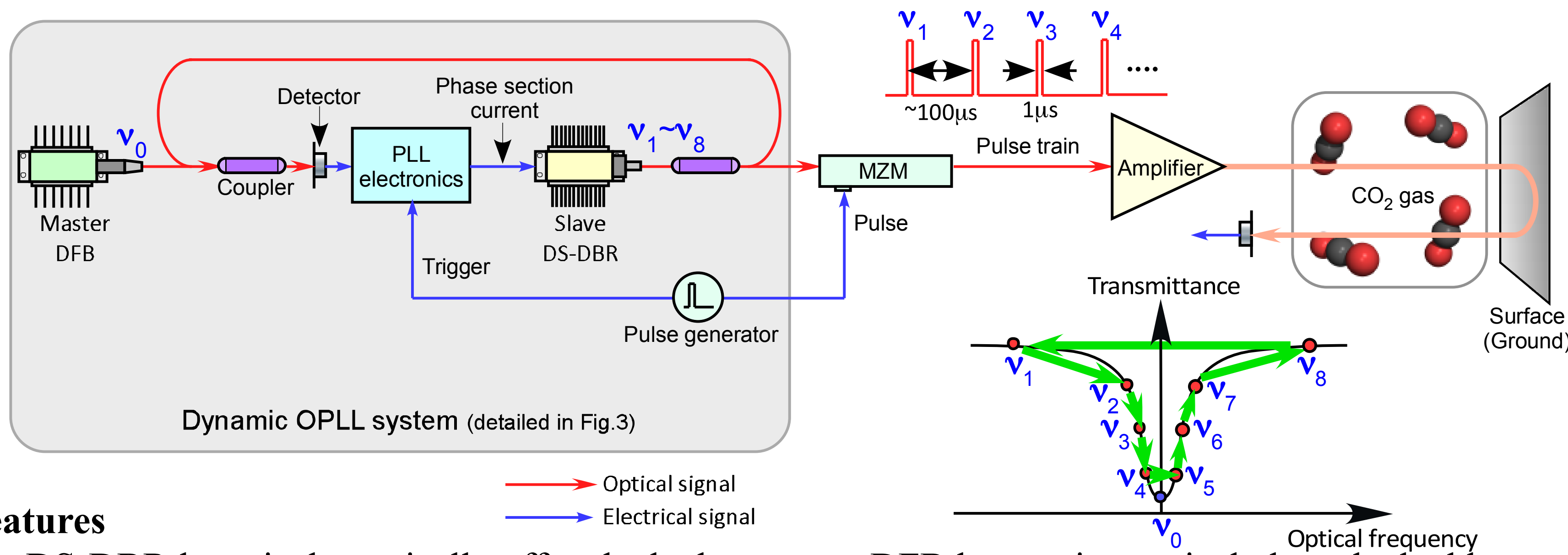
Improvements for 2014 ASCENDS flights:

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 Sounder for NASA's ASCENDS Mission

Precision Step-Locked CO2 seed laser

(Jeff Chen and Kenji Numata)



Features

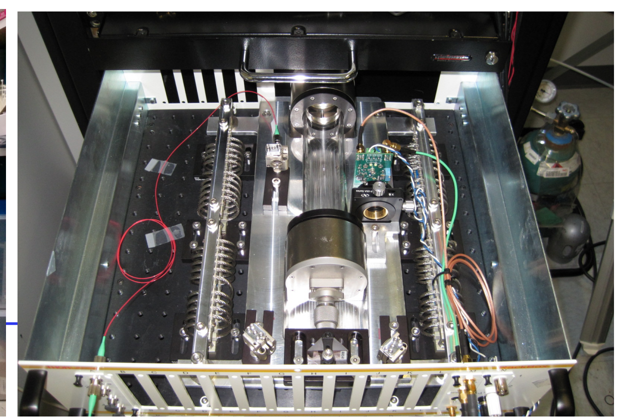
- DS-DBR laser is dynamically offset-locked to master DFB laser using optical phase-locked loop
- Frequency-stepped pulse train carved by MZM and subsequently amplified.
- Effective optical frequency noise of laser was < 0.2 MHz

Status

- Published design & US patent pending
- **Used successfully with 30 λ's in CO2 Sounder in FY14 airborne campaign**
- **Very flexible in # of wavelengths & wavelength set points**

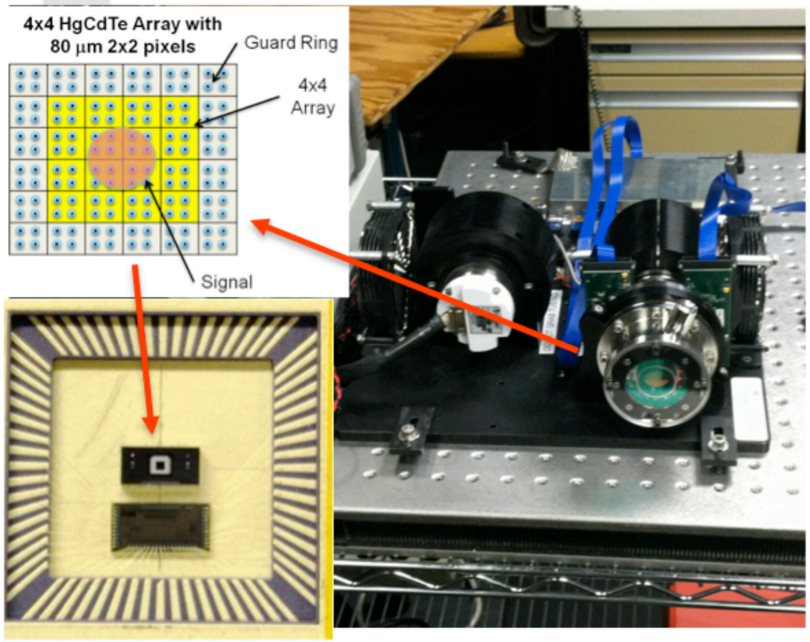
Step locked laser in DC-8 rack

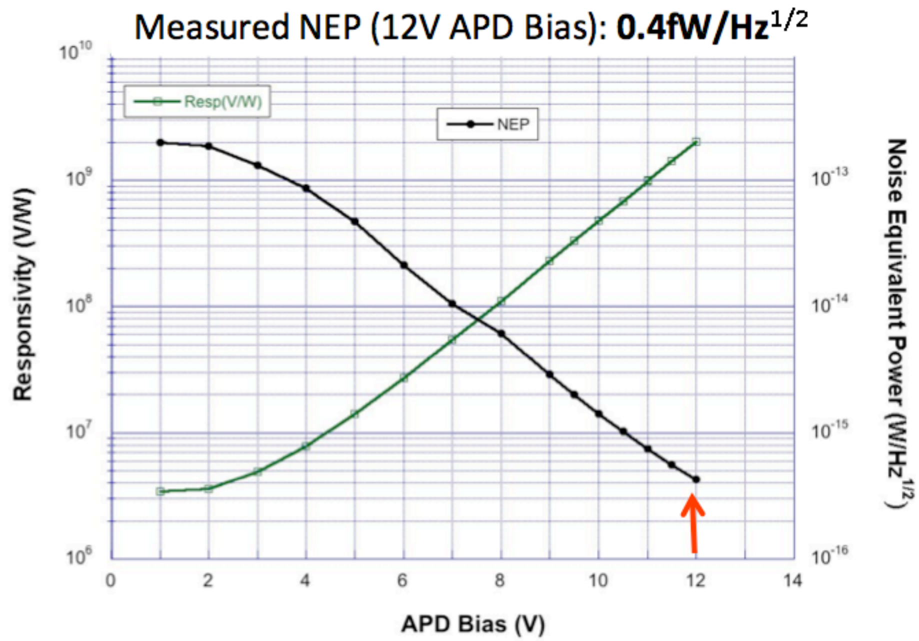
CO2 cell for master laser locking



New HgCdTe APD Detector

Used in 2014 campaign – Xiaoli Sun & Jeff Beck/DRS





- Highly sensitive 4x4 element HgCdTe APD array developed by DRS
- Pixels are square, 80 um on a side
- 400-4000 nm spectral response
- Operates inside a mini-dewar/crycooler assembly.
- ~ 7 MHz Electrical bandwidth
- Delivered to GSFC in April 2013

- Results from evaluation of detector sensitivity
- The pixels have QE > 70%
- Noise equivalent power is ~0.4 fW/root (HZ).
- > 16 times more sensitive than PMT used previously
- Analog response, > 1000:1 linear dynamic range

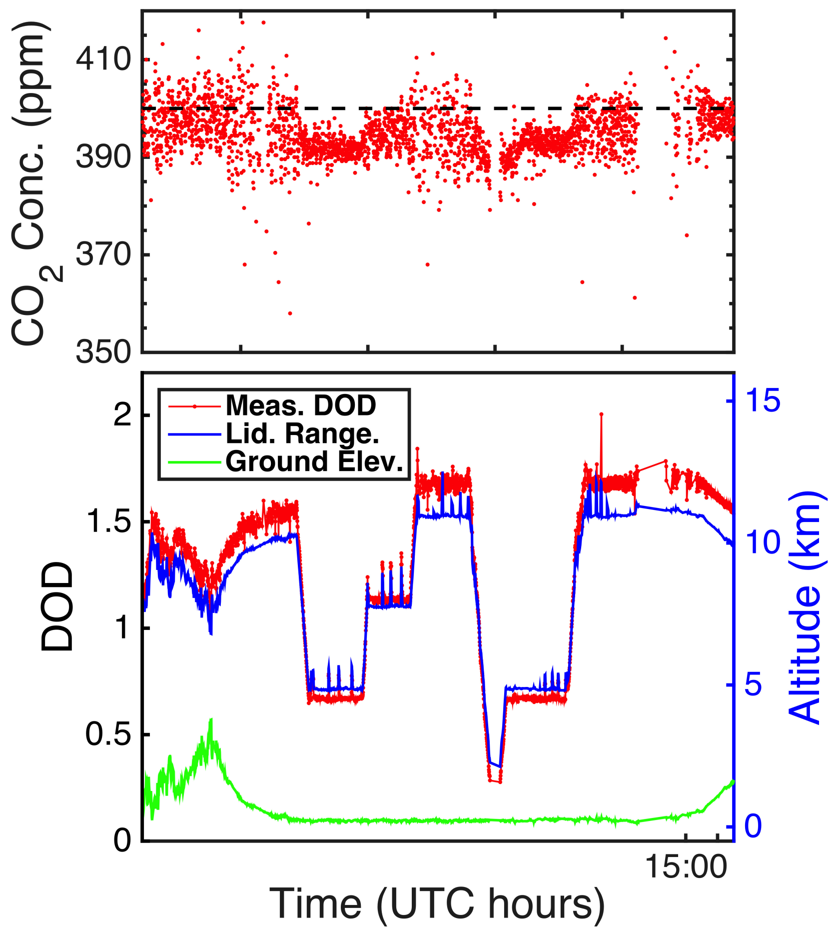
Follow on work:

Copies for GSFC CH4 Lidar, LaRC 2 um lidar

Spare detector chips being made for future use

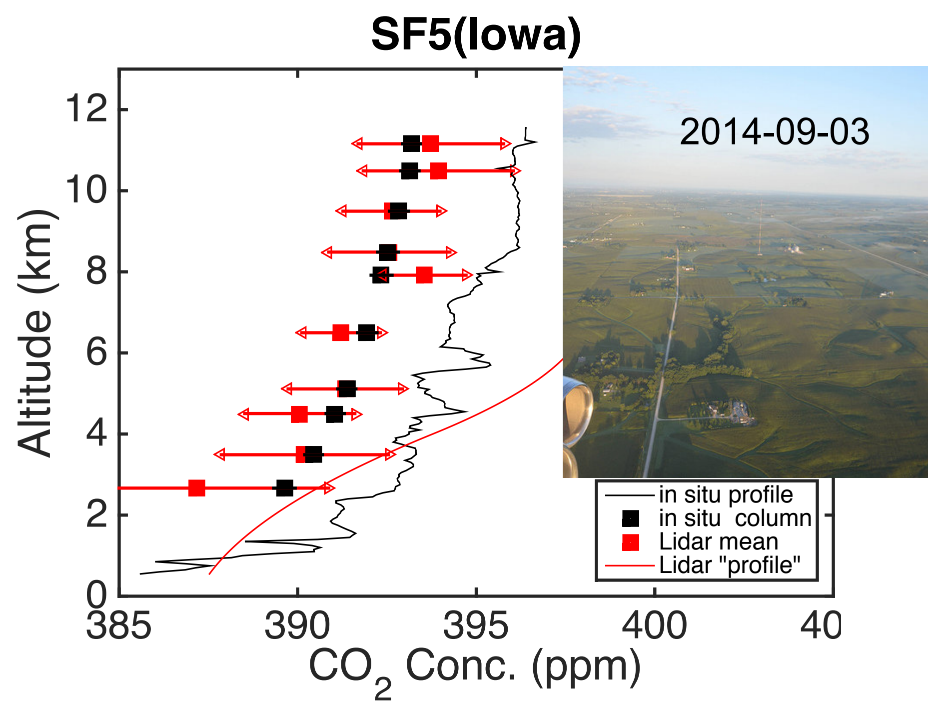
Observing CO_2 drawdown over Cropland

Measurements at Dawn over Iowa 2014-9-03



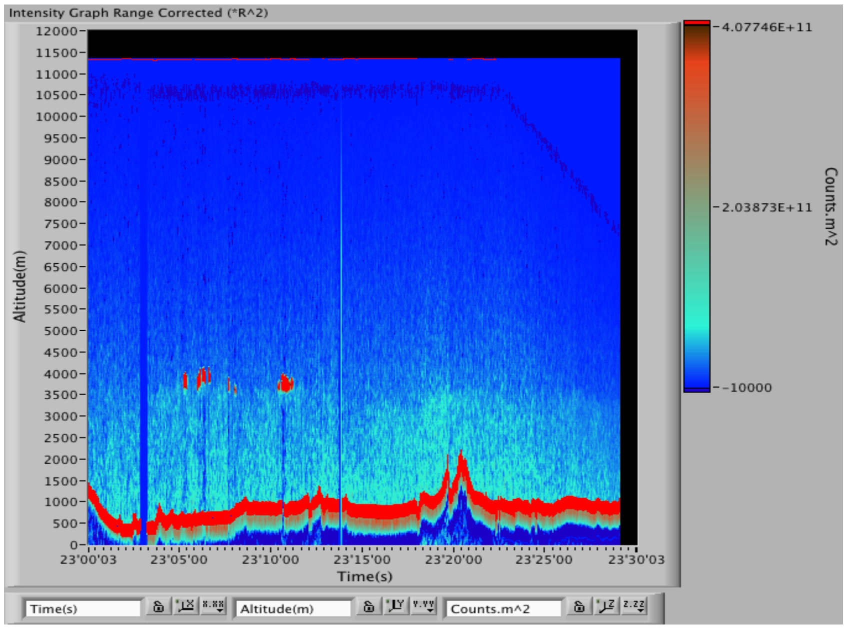
Flight Pattern:

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

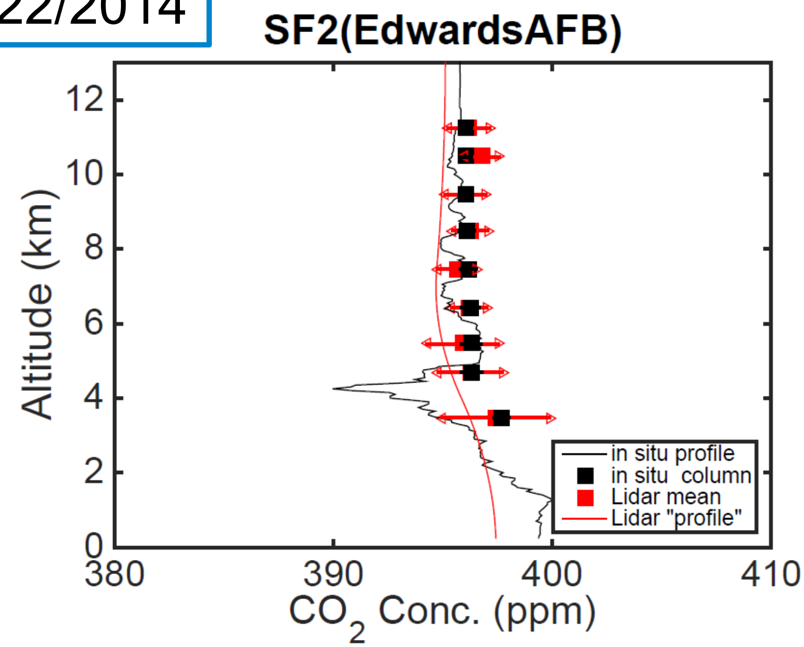


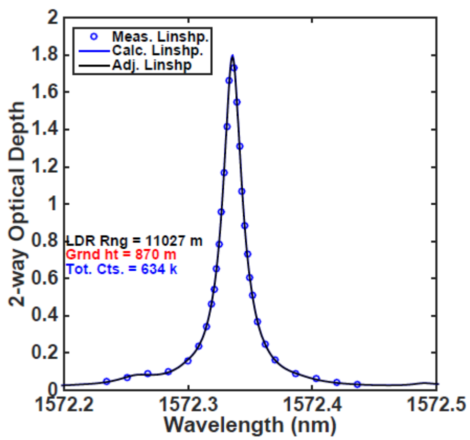
- Very good agreement between lidar average & in-situ above 8 km
- Lidar measurements show CO2 drawdown (decrease with altitude) seen by AVOCET

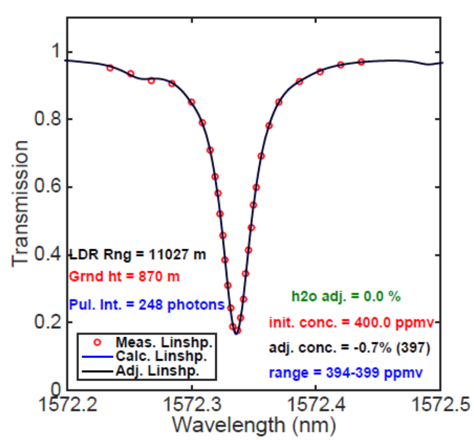
Very Accurate Column Retrievals over desert - through aerosol layers



8/22/2014







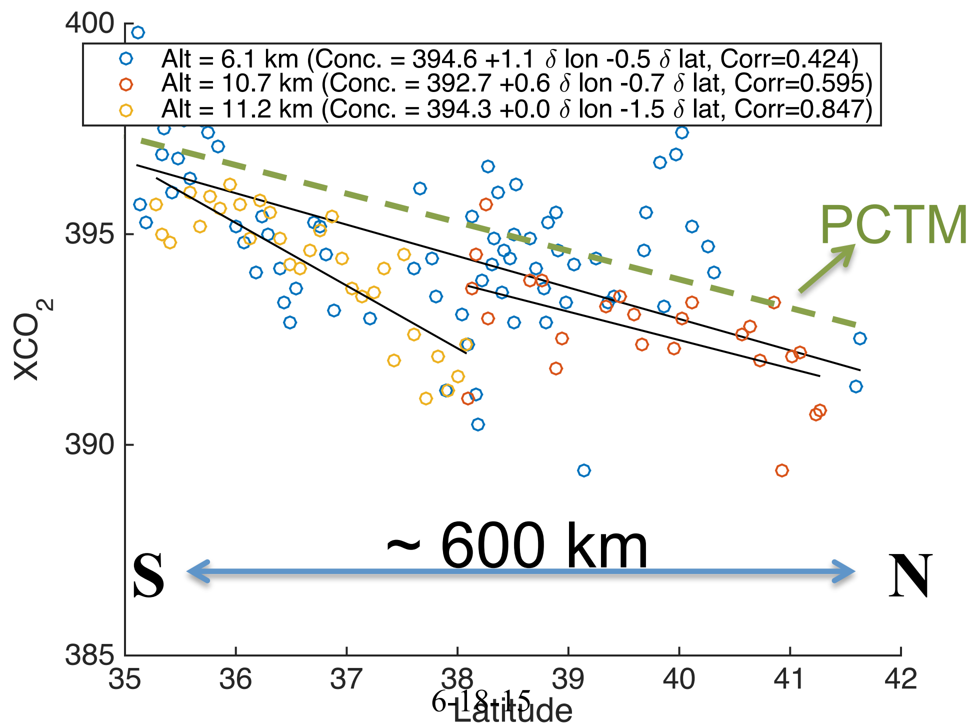
- Range-resolved measurements allow timing gating to minimize impact from atmospheric scattering
- Allow robust retrievals with low bias
- Minimizes retrieval errors over rough surfaces (terrain, and tree cover)

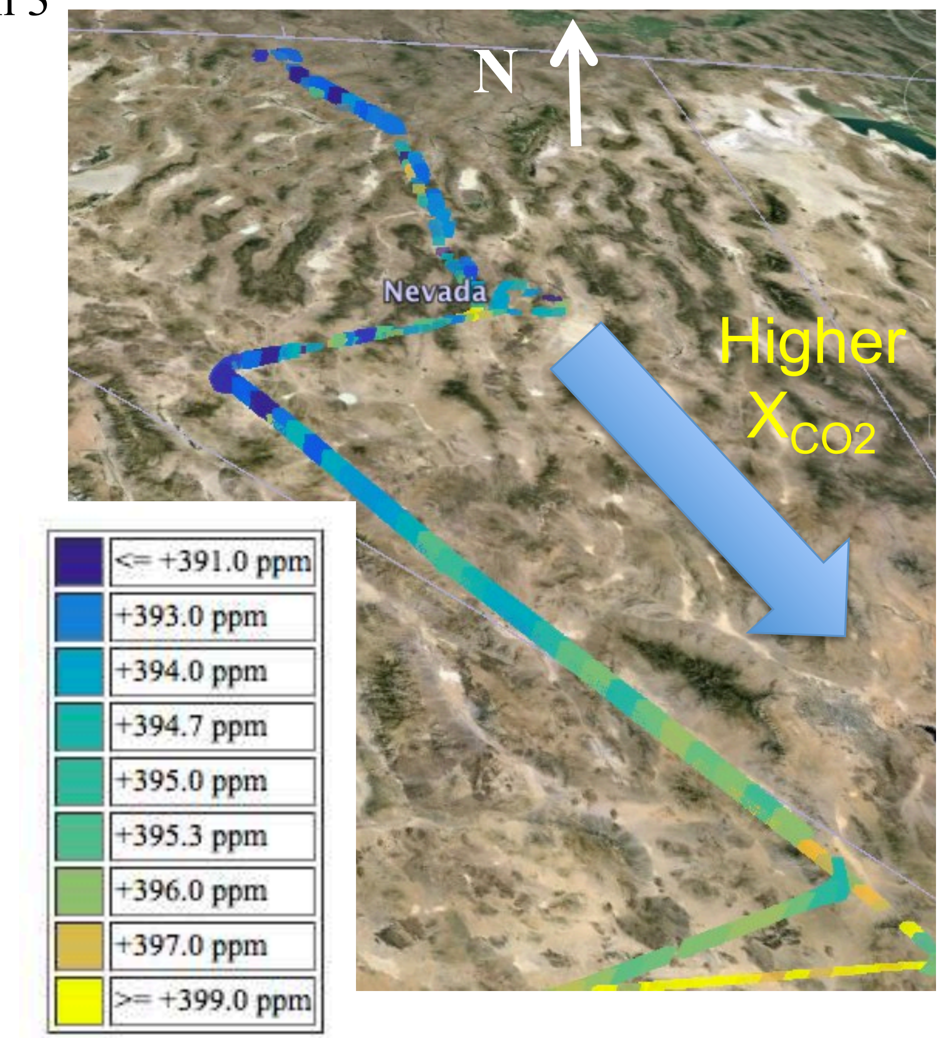
Measured Horizontal Gradient in XCO_2

(SF2 over Northern NV with ~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

1st demonstration - Resolving two vertical CO_2 layers via IPDA lidar measurements & "Cloud Slicing"

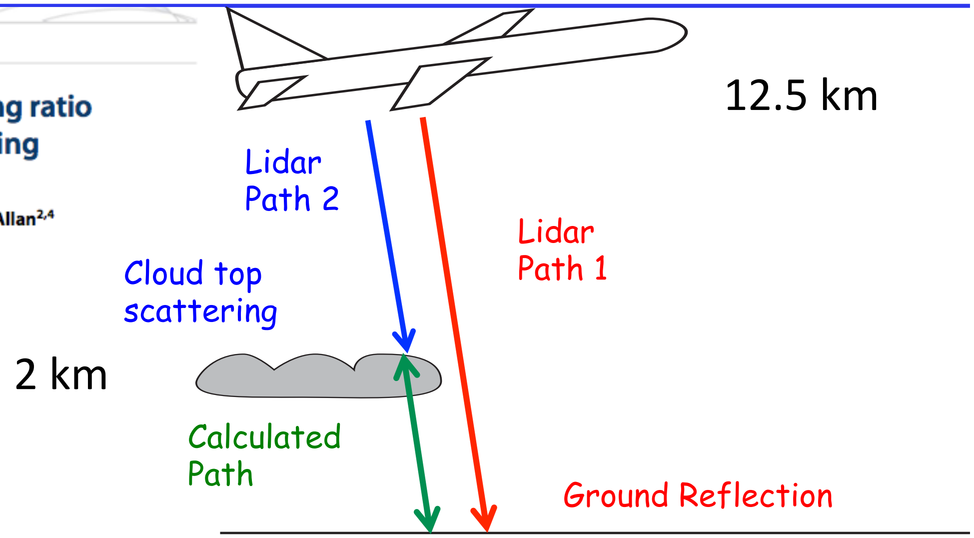
Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL062749

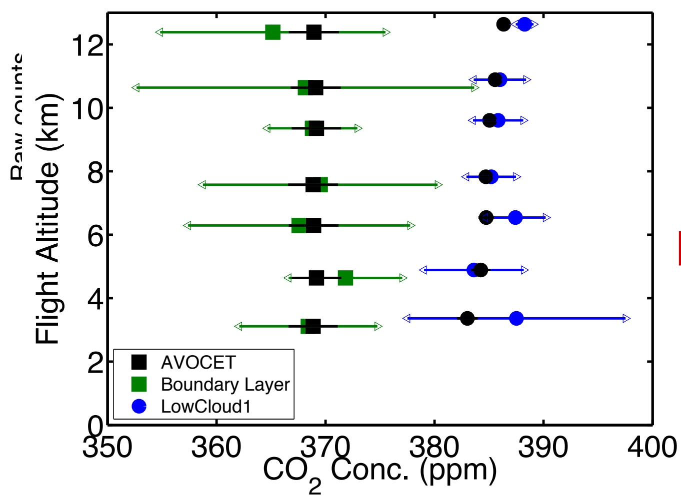
Key Points:
- Cloud slicing with lidar can sense CO_2 in the planetary boundary layer

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

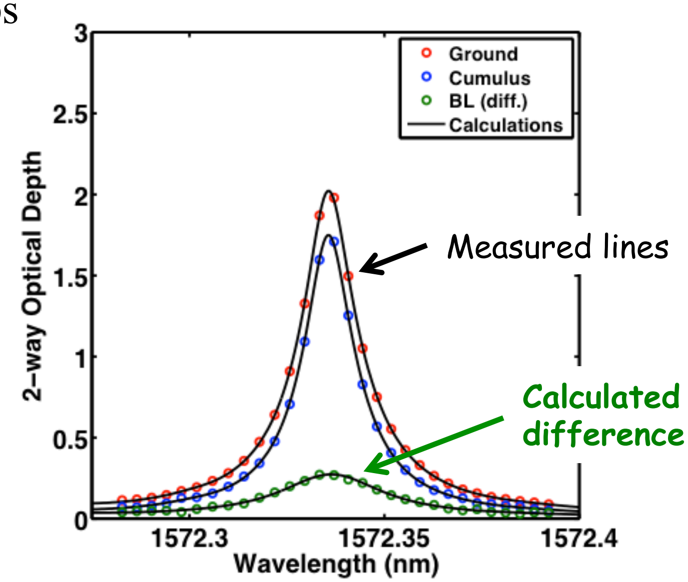
Anand K. Ramanathan[1,2], Jianping Mao[1,3], James B. Abshire[2], and Graham R. Allan[2,4]



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



Results



ASCENDS Flight Summary – to date

- **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, we have achieved 0.9 ppm precision over desert

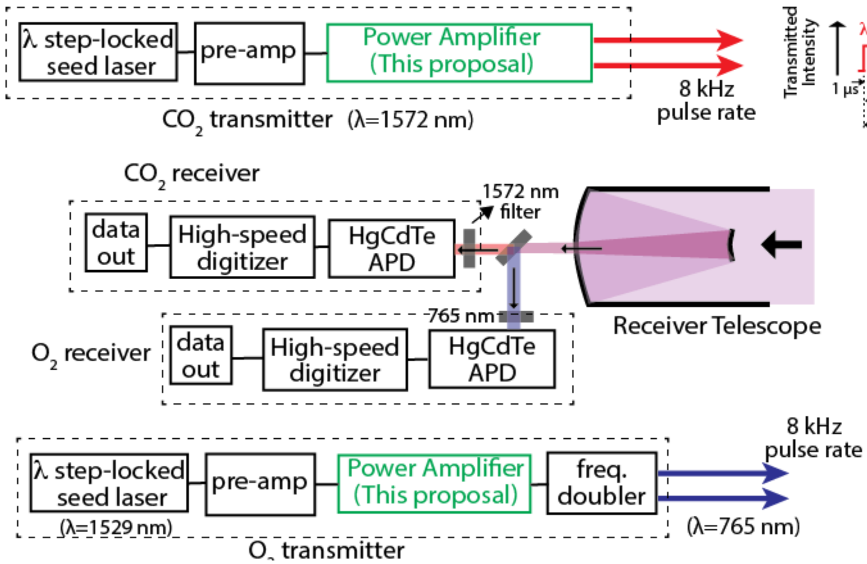
Recent measurement summary:

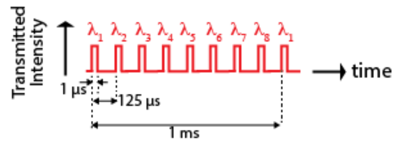
Flight	Surface	Shot Noise limit	Measured precision	Bias	Comments
2011 Railroad Valley	Desert	1.5 ppm	2.7 ppm	0.4 ppm	
2013 Central Valley	Desert/ vegetation	0.7 ppm	1.5 ppm	0.1 ppm	Best with PMT. Limited by detector dynamic range.
2014 Central Valley	Desert/ vegetation	0.45 ppm	0.9 ppm	0.3 ppm	Limited 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.

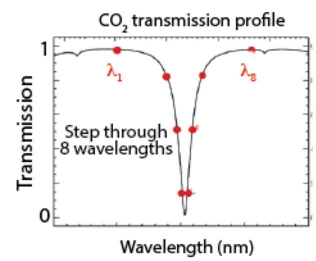
Ongoing work:

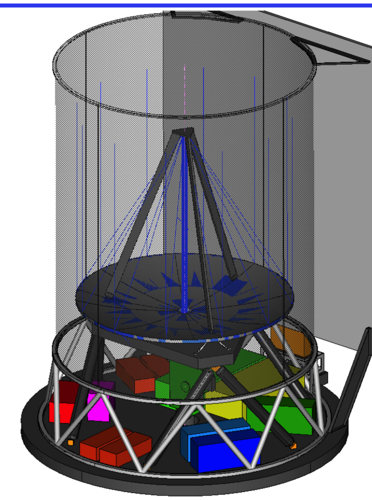
- Making lidar receiver improvements for January 2016 campaign
- Expect to enhance precision ~x2 to ~0.5 ppm

Scaling CO_2 Sounder lidar to Space



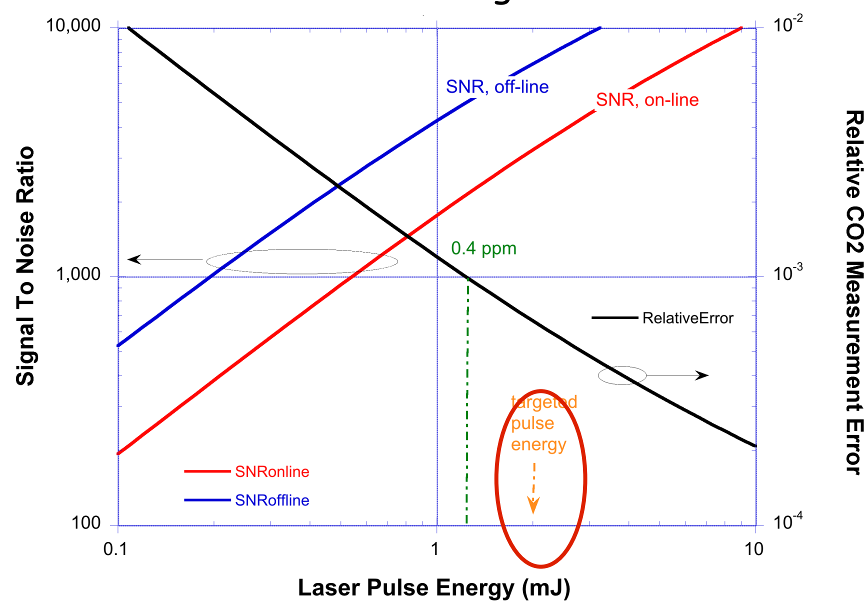






Parameters	Value
Orbit Altitude	400 km
Equator crossing time	dawn/dusk
Integration Time	10 sec (70 km)
Telescope diameter	1.5 m
Time between laser pulses	125 usec
Laser Pulse widths	1 usec
Online wavelength	1572.33 nm
Beam divergence	125 urad
Wavelength sequence rate	1.25 KHz
# of wavelengths in scan	8
On line (side of line) absorption	40%
Detector type & QE	HgCdTe APD, 75%

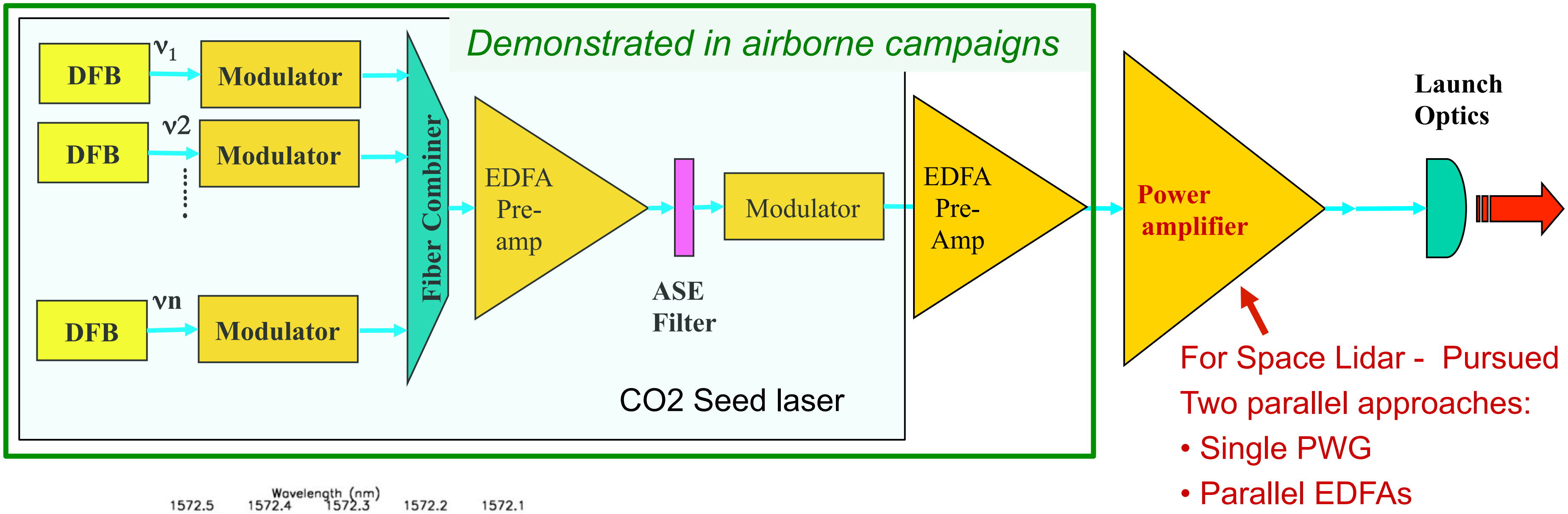
Random error over desert surface with 10 sec integration time

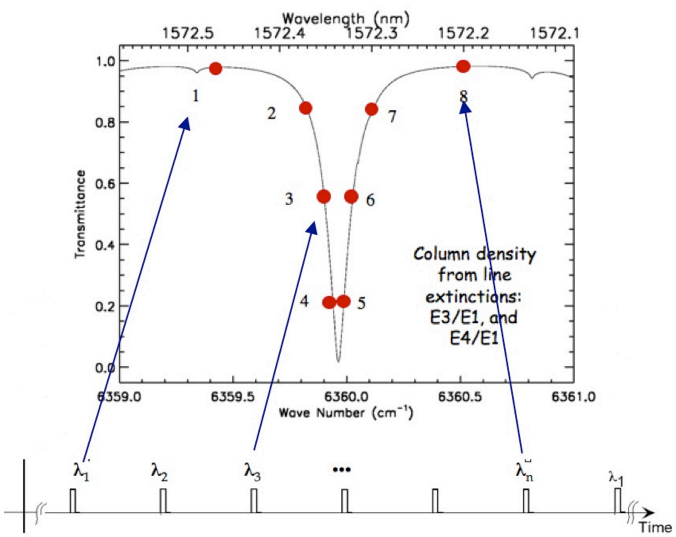


20W ave power

Laser for CO_2 Measurements from Space
3 stage MOPA Design (Tony Yu & Jeff Chen)

GSFC





Space lidar: 8 wavelength samples across line

Laser Amplifier Development for IPDA Lidar measurements of CO_2 from Space

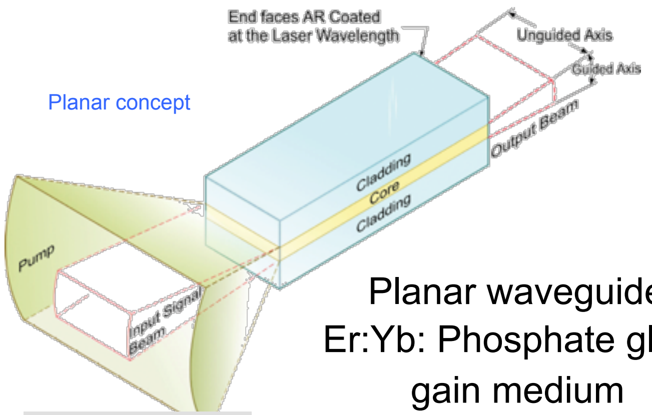
Anthony W. Yu *[a], James B. Abshire [a], Mark Storm [b], Alexander Betin [c]
[a] NASA Goddard Space Flight Center, Greenbelt MD USA 20771;
[b] Fibertek, Herndon VA 20171;
[c] Raytheon Space and Airborne Systems, El Segundo, CA, USA 90245

Solid State Lasers XXIV: Technology and Devices, edited by W. Andrew Clarkson, Ramesh K. Shori,
Proc. of SPIE Vol. 9342, 93420M · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2080792

Proc. of SPIE Vol. 9342 93420M-1

Space Laser Power Amplifier: Single Planar Waveguide Approach (Raytheon)

Planar concept

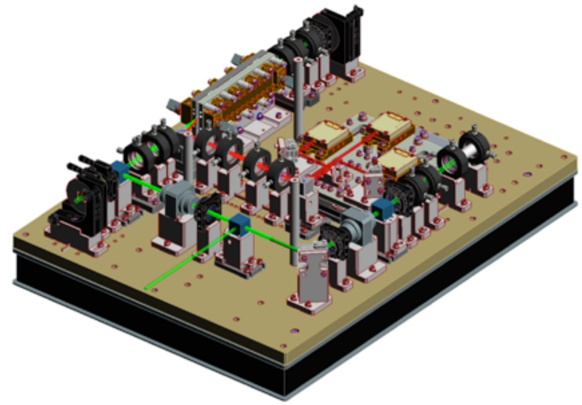


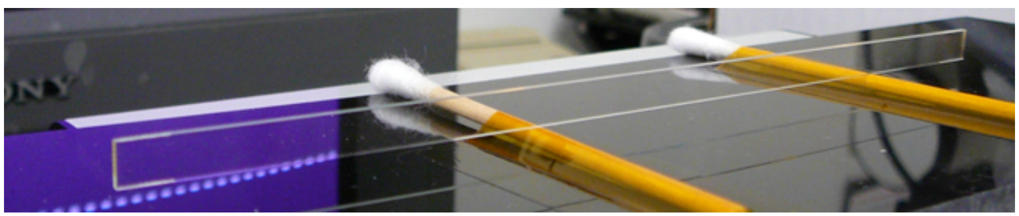
Planar waveguide

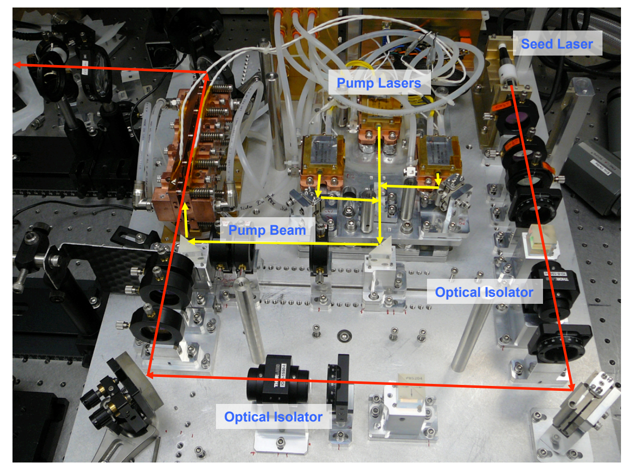
Planar waveguide
Er:Yb: Phosphate glass
gain medium

Design:

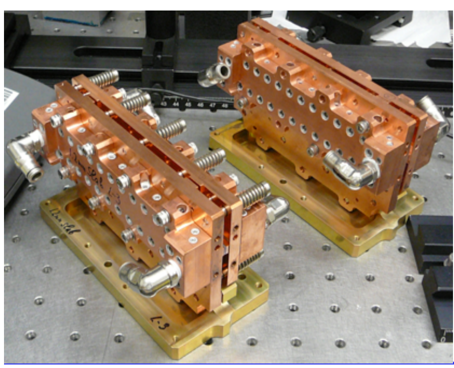
- 4-pass optical amplifier
- Free space coupled
- Optical energy gain ~x100
- LD pumped at 974 nm
- Designed for x100 gain:
  - both 1572 and 1529 nm
- Size: 24” x 18” x 6.4”





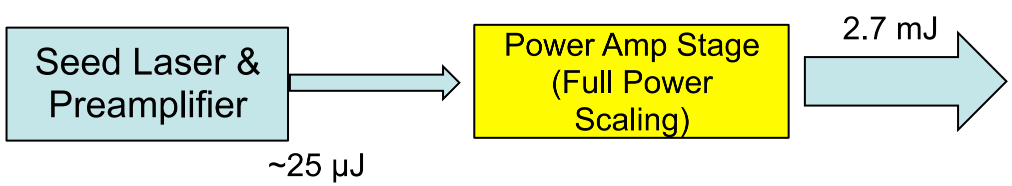


PWG amplifier module

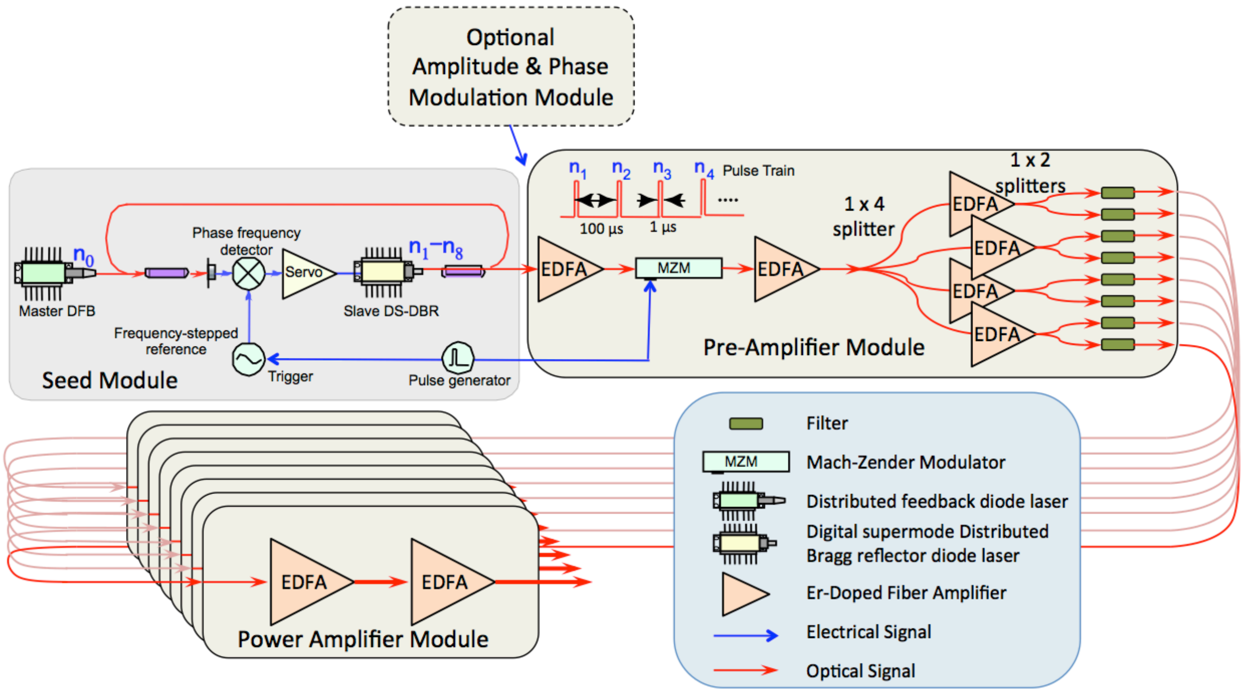


Alexander Betin/Raytheon

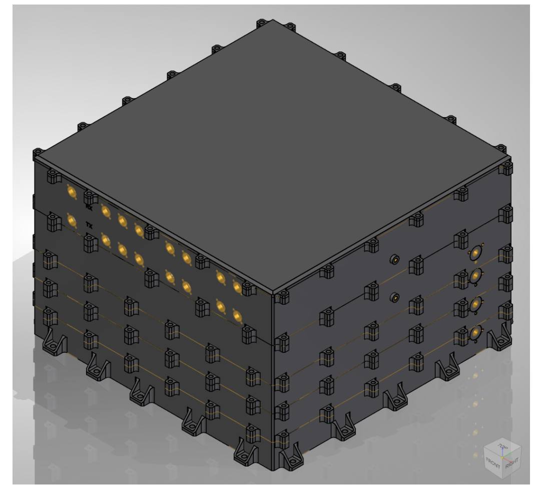
Anthony Yu/554

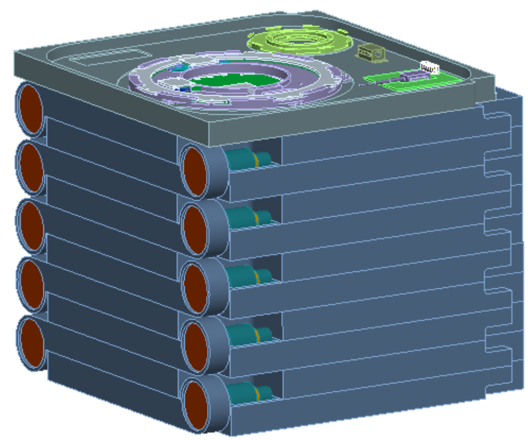


Space Laser Transmitter using Fiber laser amplifiers



Seed and preamp stages



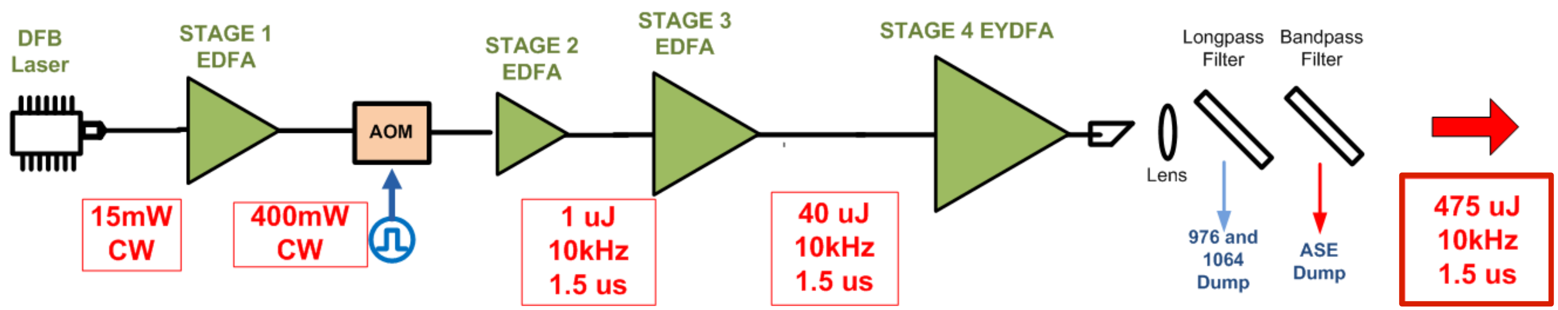


Power Amplifier stages

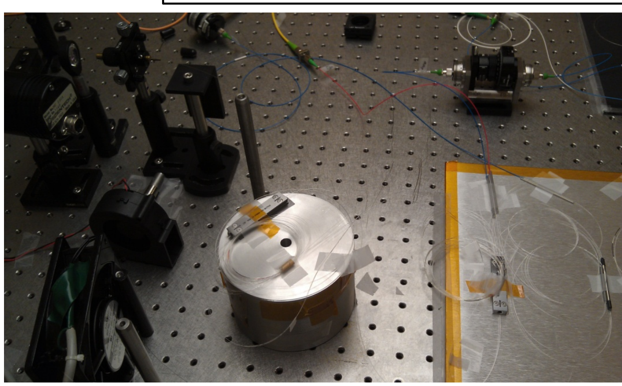
Status:

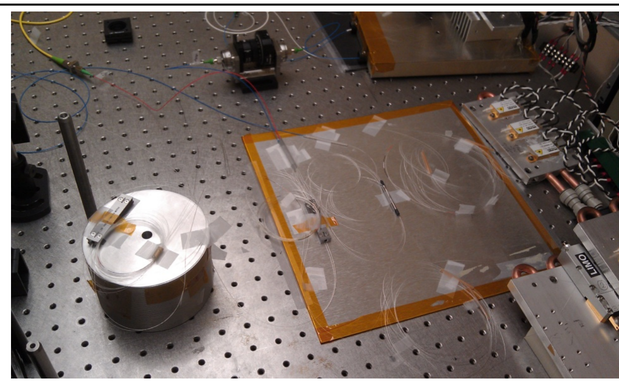
- Approach under development now, 30 month effort
- Objective: Develop fiber laser with space power to TRL 6
- Mark Stephen/GSFC, PI , partnered with Fibertek
- Jointly supported via ESTO ATI-QRS award & Goddard IRAD
- Joe Famiglietti - ESTO task manager

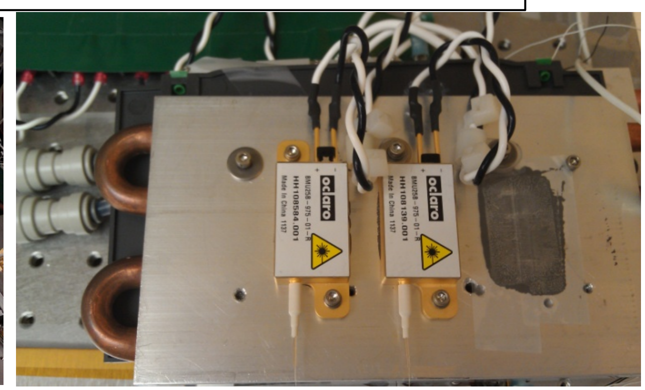
EDFA Power Scaling for Space for CO_2 Sounder (IIP-10 funded experiments at 1572 nm)



- All-PM, All-fiber MOPA, All Commercial Components
- External PM Phase Modulator for line broadening
- PM AOM for high extinction ratio pulse carving (~50dB)
- 4-stage amplification for low noise and high-gain
  - Commercial PM LMA fiber in last amplifier stage
  - ~976nm diode CW pumping
- Similar to EDFA developed by Fibertek at 1563 nm & reported in SPIE





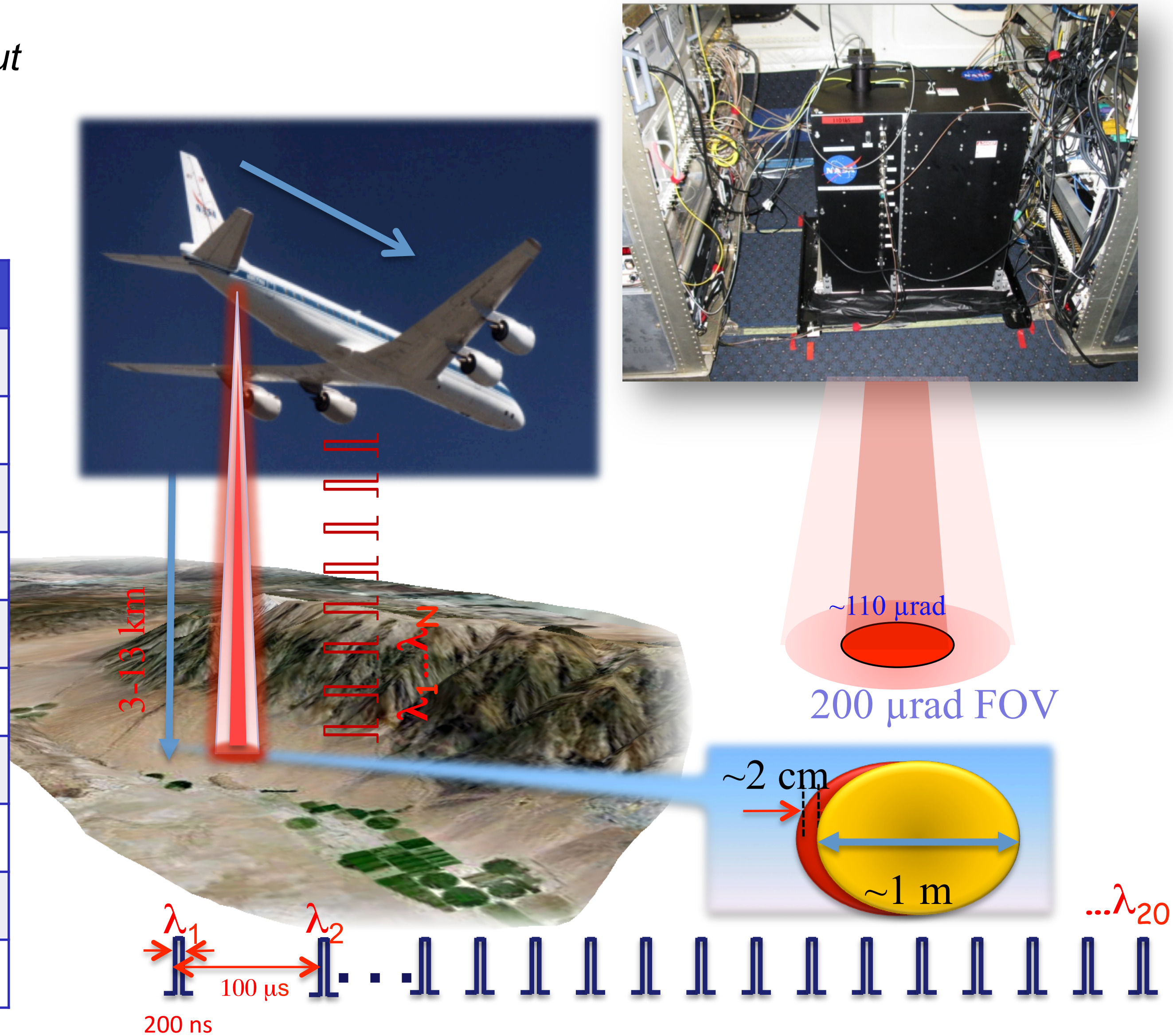


Airborne O_2 Sounder Lidar

(Haris Riris & Mike Rodriguez)

Similar approach as CO_2, but measuring O_2 line pair near 765 nm.

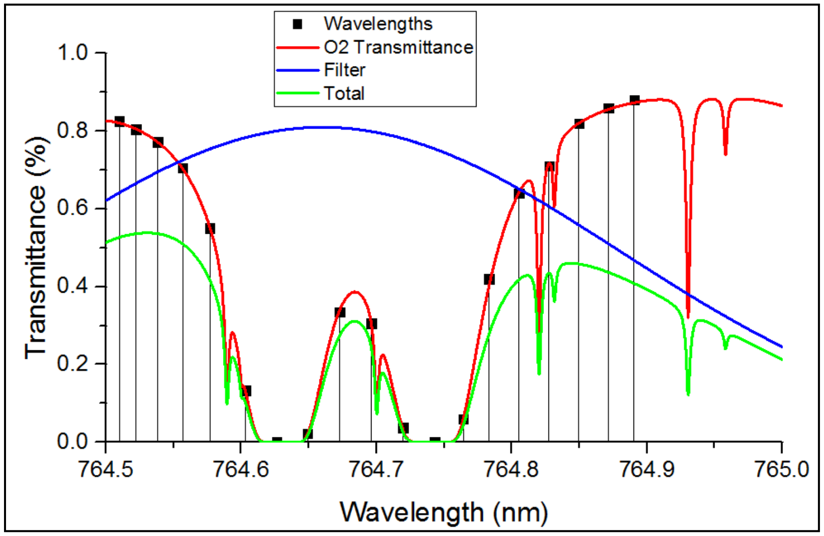
Parameter	Value
Center λ	764.685 nm
PRF	10 KHz
Pulsewidth	~200 ns
Energy	~ 1.5-2.0 µJ
Bin Width	10 ns
Divergence	~110 µrad
FOV	200 µrad
Bandpass	0.8 nm
Averaging T	125 ms
Det. QE	~ 50%

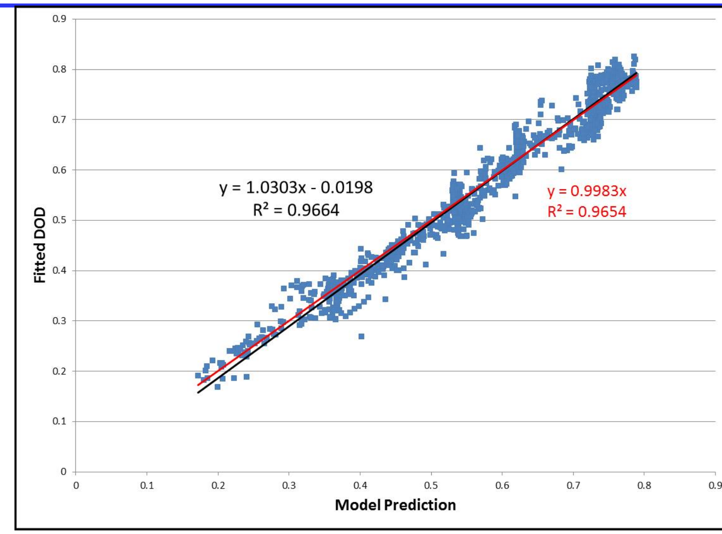


O2 Sounder - 2013 Central Valley Flight

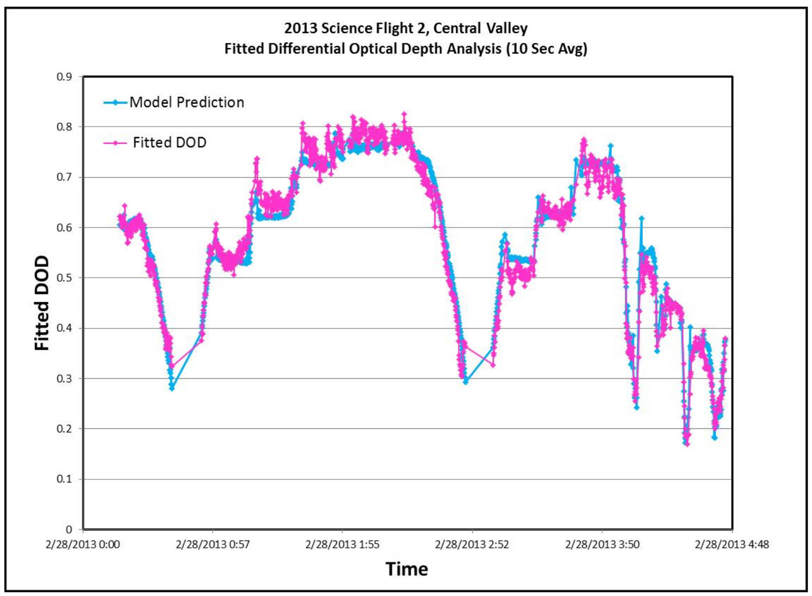
(Haris Riris & Mike Rodriguez)

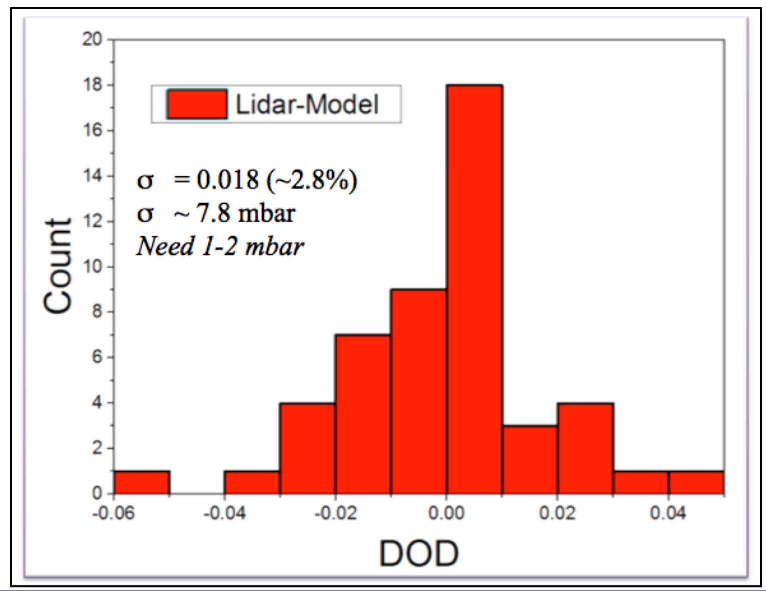
GSFC





- 2013 measurements made with 2 uJ pulse energy at 765 nm
- New O2 power amplifier increased 765 nm energy to ~12 uJ
- Should reduce random error x2.5 to ~3 mbar





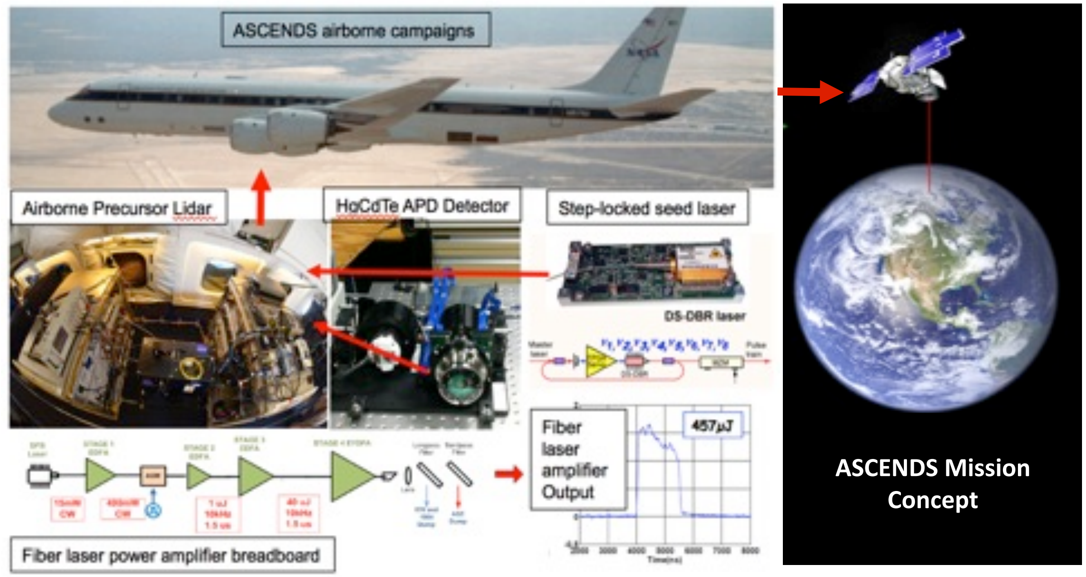
Summary

- ***Advanced measurement approach & demonstrated accurate CO_2 retrievals***
- ***Developed technologies needed for scaling airborne CO_2 Sounder lidar to space:***

  - Rapidly tuned λ-locked laser seed source

  - Fiber laser amplifier stage with space-needed power

  - HgCdTe APD detector: >70% QE, photon counting sensitivity



- ***Demonstrated improved airborne CO2 measurements from 3-12 km:***
  - Participated in 2011, 2013, 2014 ASCENDS airborne campaigns
  - Showed accurate CO2 measurements over all ASCENDS-relevant surfaces
  - Demonstrated 1st "CO2 cloud slicing": measurements to cloud tops to estimate surface fluxes
- **Demonstrated airborne O2 lidar column measurements, precision < 8 mbar**

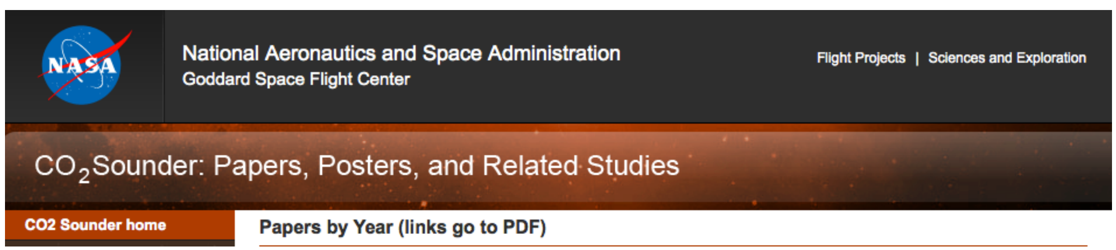
Ongoing work:

- ASCENDS ad-hoc SDT
- ASCENDS airborne campaigns
- Space Laser development via ESTO ATI-QRS & GSFC

More information:

Papers & presentations on the CO_2 Sounder Website:

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



Thank you to the ESTO IIP Program for the support !

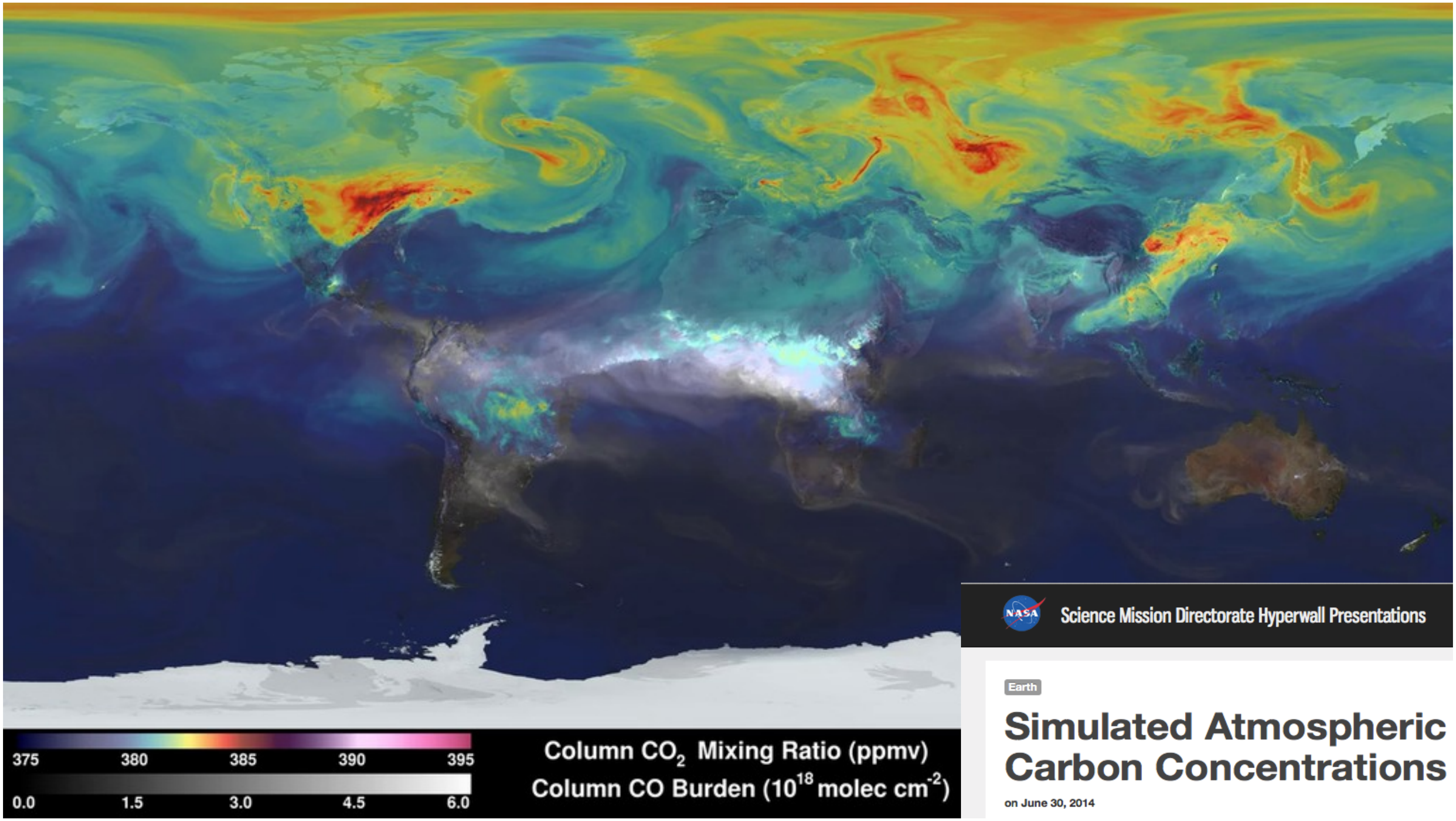
GSFC

BACKUP

Targeted CO_2 Fluxes produce only very small signatures (typ. < 1 of 400 ppm) in Atmospheric CO_2

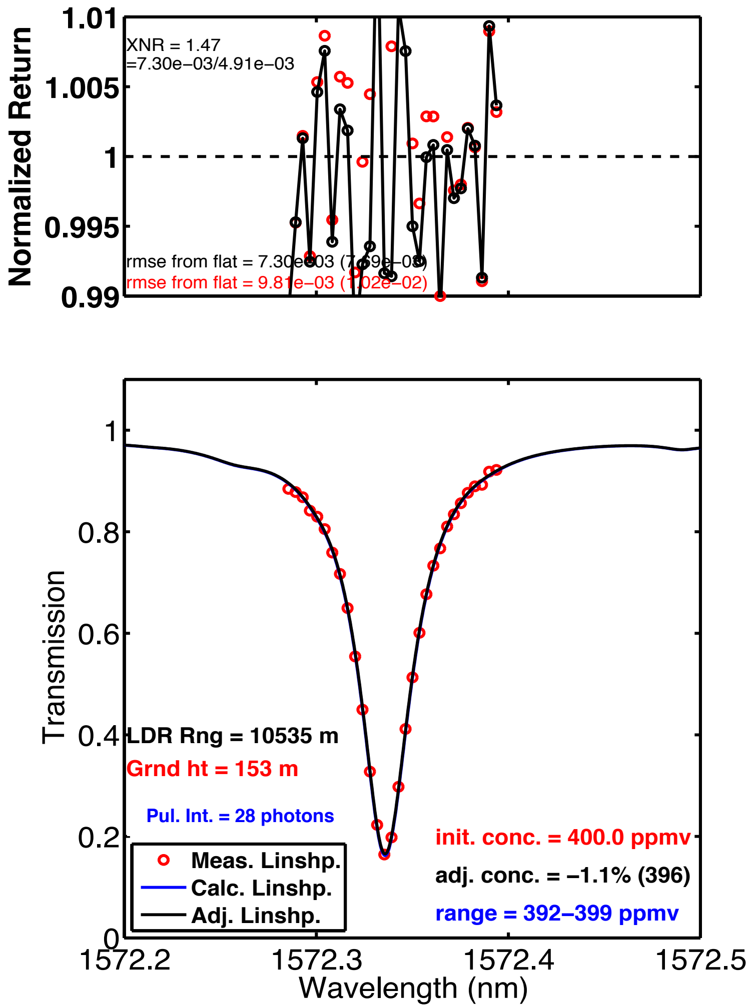
GSFC

http://svs.gsfc.nasa.gov/vis/a030000/a030500/a030515/



CO2 Line Sampling and fits: ASCENDS Flights in ≤ 2013 & 2014

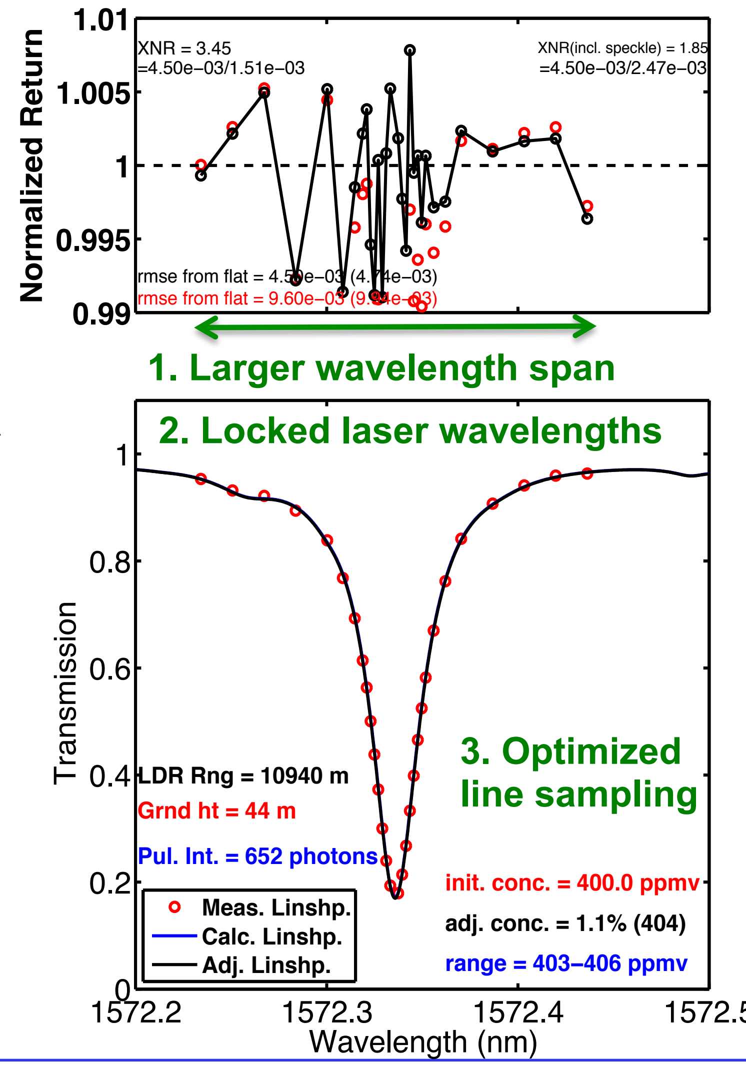
≤ 2013



Conditions:

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

2014

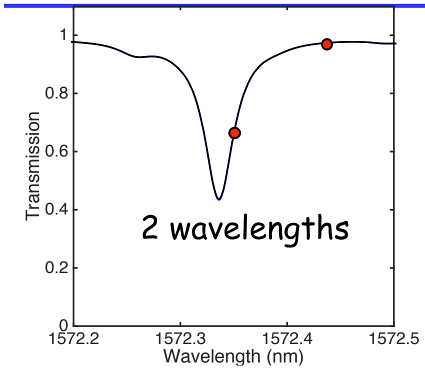


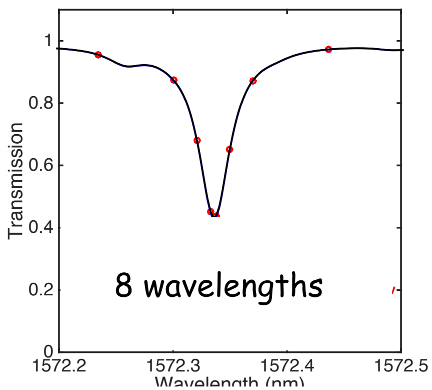
CO2 Sounder for NASA's ASCENDS Mission

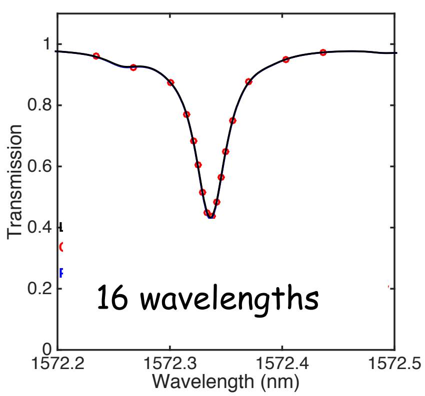
More wavelengths give more information & allow more accurate measurements

Present airborne

Planning for Space



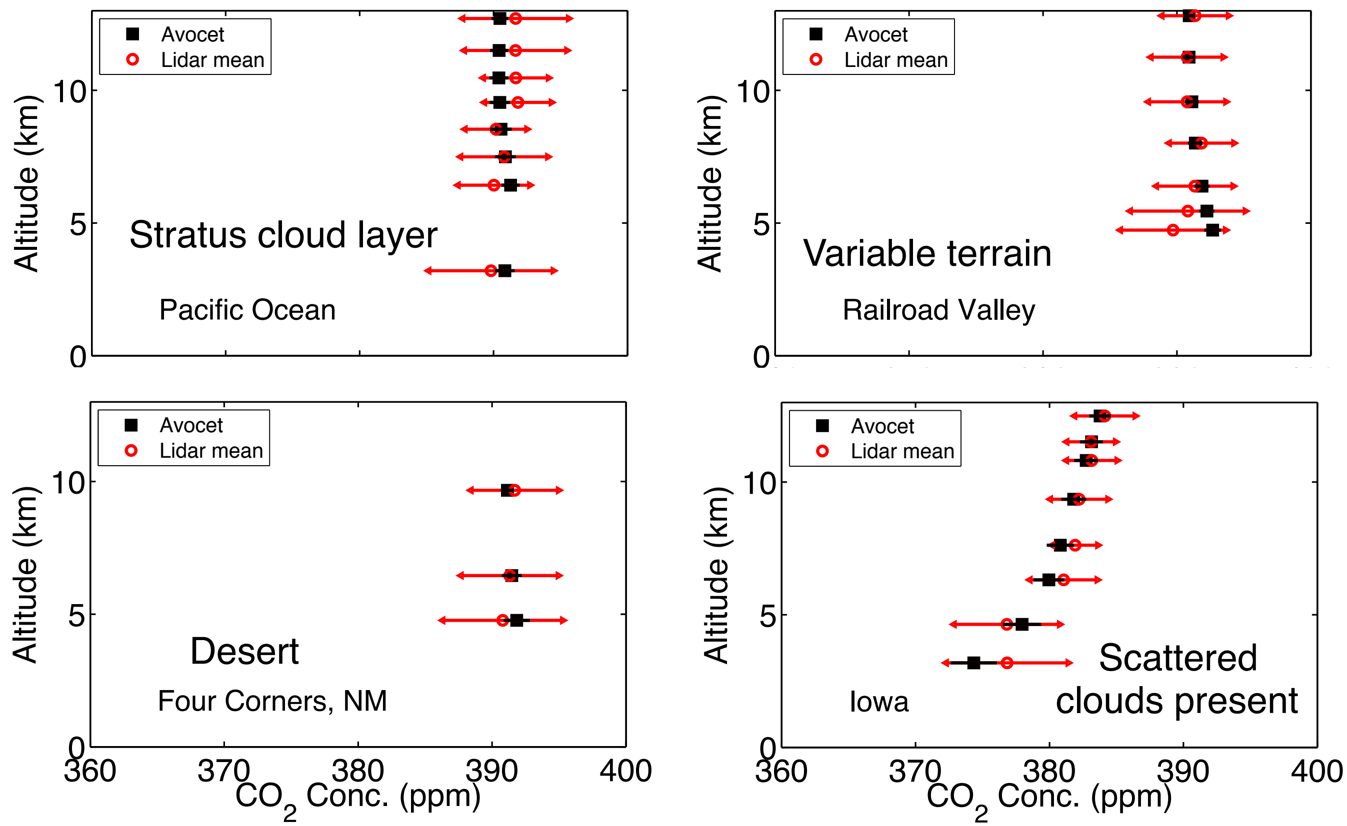




No. of Wavelengths	1	2	3	4	6	8	10+	30
Reflectivity	✓	✓	✓	✓	✓	✓	✓	✓
CO_2 column mean	✗	✓	✓	✓	✓	✓	✓	✓
Linear baseline	✗	✗	✓	✓	✓	✓	✓	✓
Doppler shift	✗	✗	✗	✓	✓	✓	✓	✓
CO_2 vertical gradient	✗	✗	✗	✗	✓	✓	✓	✓
Nonlinear baseline	✗	✗	✗	✗	✗	✓	✓	✓
Water vapor content	✗	✗	✗	✗	✗	✗	✓	✓
CO_2 mid-troposphere	✗	✗	✗	✗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

CO_2 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
- Challenging for GOSAT/OCO-2 to make measurements for these conditions
- Lidar measurement error bars are +/- 1 std dev for 10 sec ave
- **Excellent accuracy (very low bias)**

remote sensing
ISSN 2072-4292
www.mdpi.com/journal/remotesensing

Article

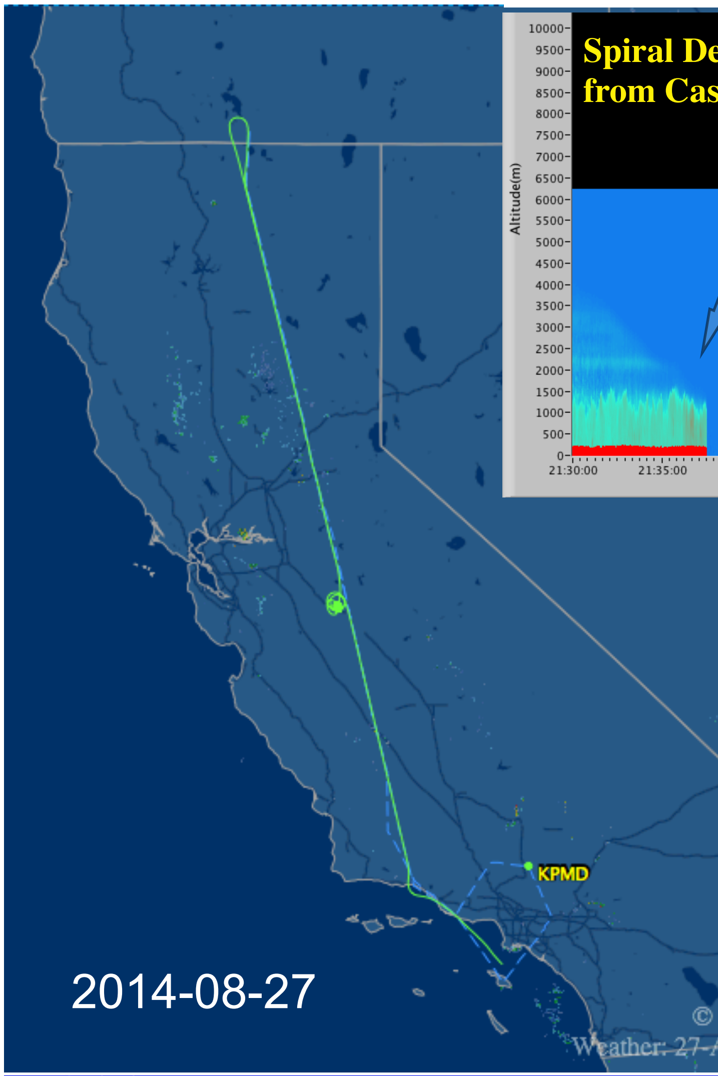
Airborne Measurements of CO_2 Column Concentration and Range Using a Pulsed Direct-Detection IPDA Lidar

James B. Abshire [1,*], Anand Ramanathan [2], Haris Riris [1], Jianping Mao [2], Graham R. Allan [3], William E. Hasselbrack [3], Clark J. Weaver [2] and Edward V. Browell [4]

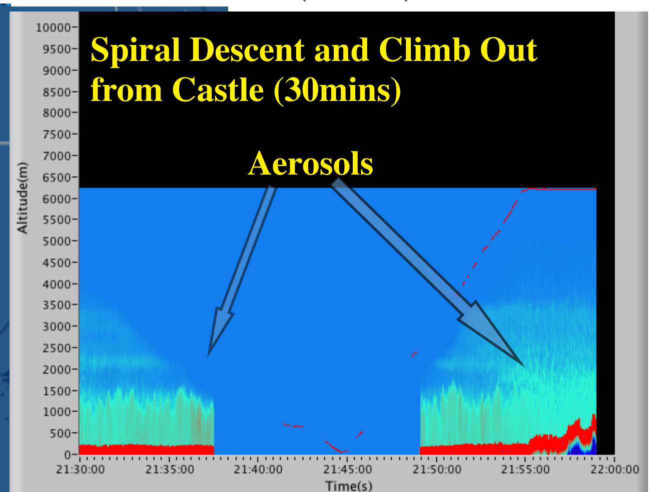
Earth Science Technology Office

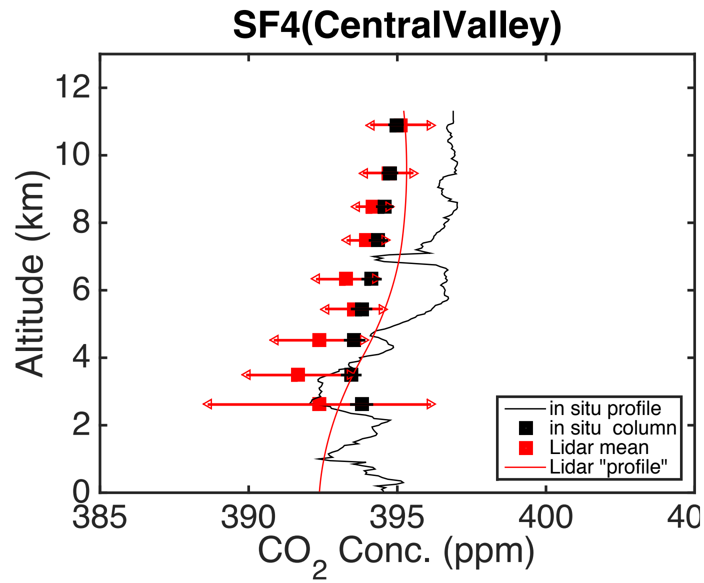
SF4 – OCO-2 Under flight – retrievals through haze

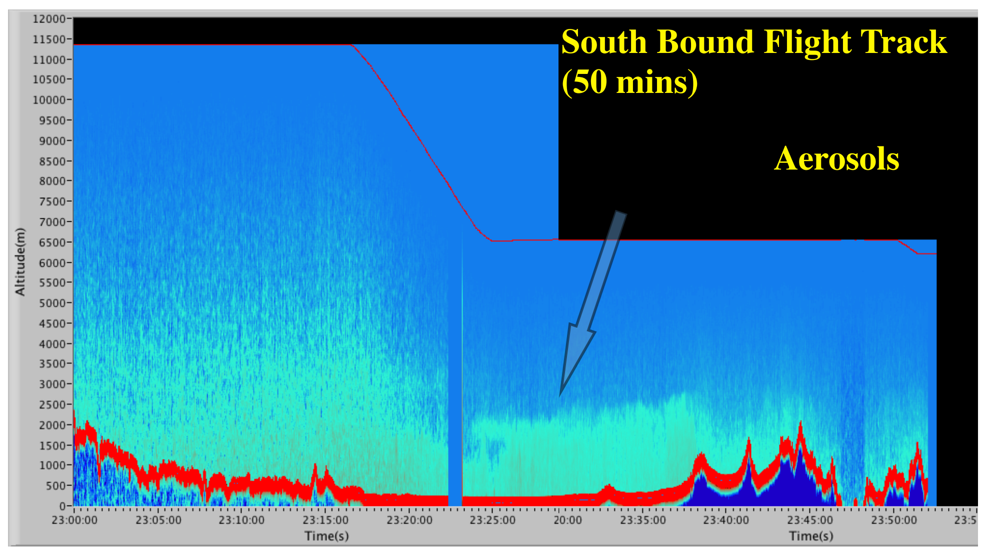
Atmospheric Backscatter Profiles & retrievals



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







Evolution

CO_2 Laser Sounder for the ASCENDS Mission

Progress:

✔ Initial concept (2001) & lab measurements

✔ White paper to RFI - helped lead to ASCENDS

✔Field measurements at CO2 tower (2007)

✔ 1st Space Instrument Study (2008)

✔ CO2 Airborne demonstrations (2008)

✔ASCENDS joint flight experiments (2009)

✔2nd Space Instrument Study (2009)

✔ ASCENDS flight exp'ts on DC-8 (2010)

✔ Airborne measurements of O2 absorption (2010)

✔ 2011 ASCENDS campaign & improved analysis

✔ Fiber amplifier BB shows space-needed power (2012)

✔ Airborne measurements over snow & trees (2013)

✔ HgCdTe detector shows record sensitivity (2014)

✔ASCENDS flights: locked seed & HgCdTe APD (2014)