Progress in developing the CO_2 Sounder Lidar as a candidate for the ASCENDS Mission

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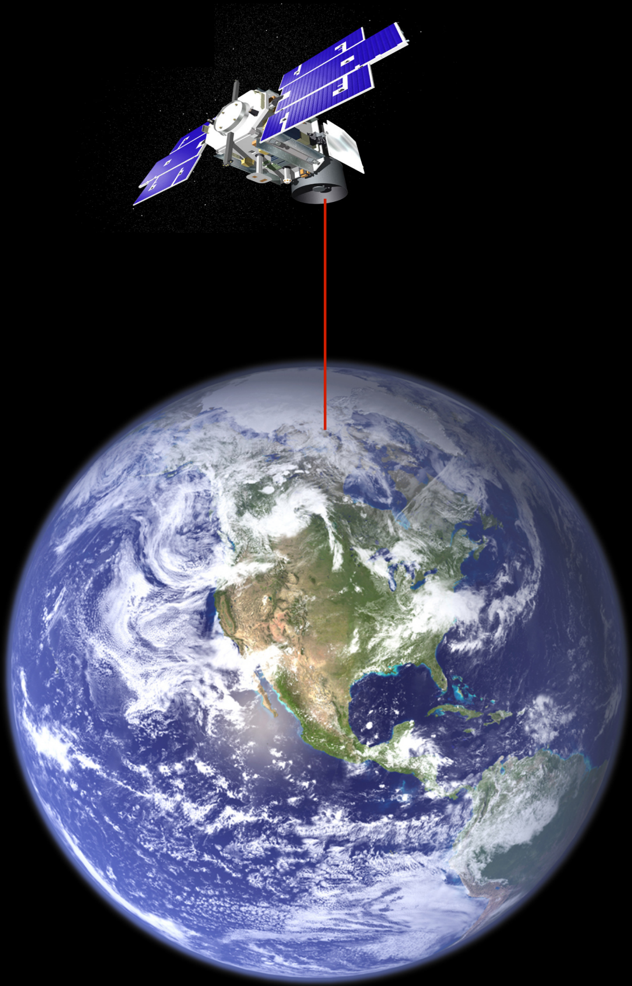

Presentation to:

2014 NASA ESTF Conference

October 30, 2014

**- Support from:*
NASA ESTO IIP-10 & QRS programs
ASCENDS Pre-formulation Activity, Goddard IRAD program

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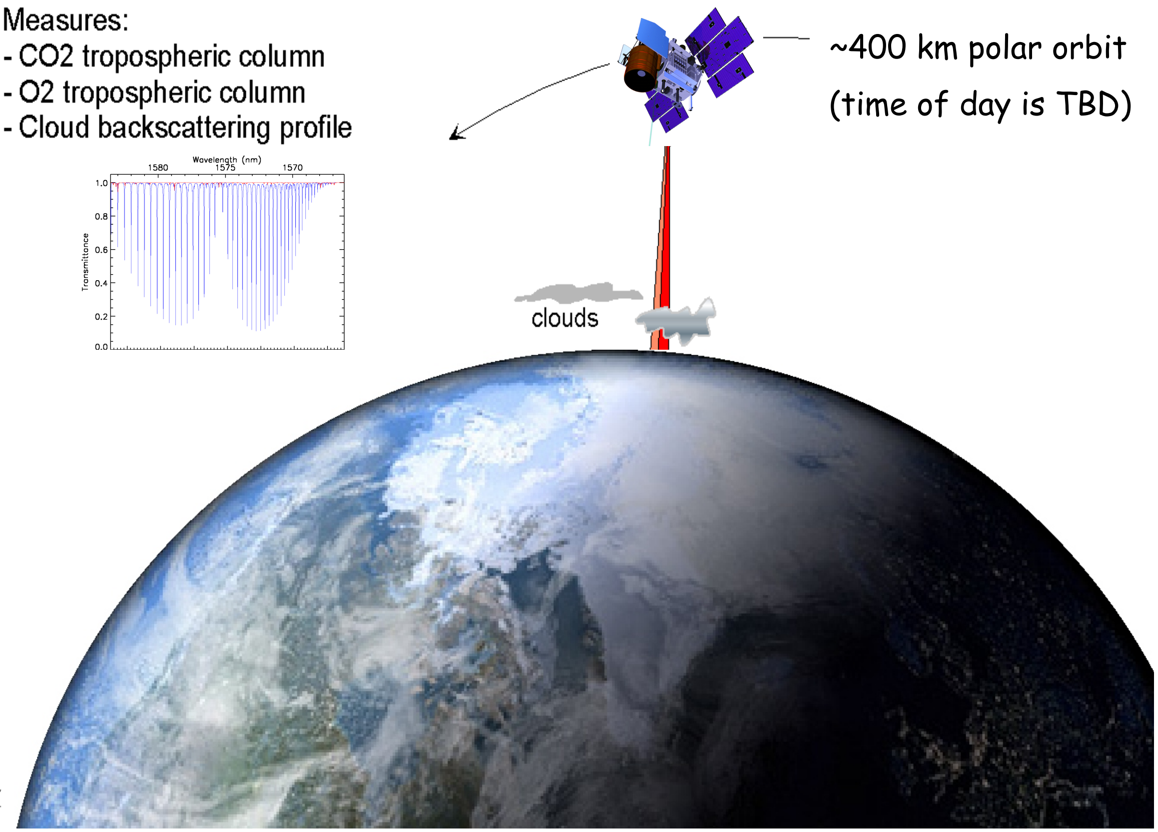
ASCENDS Mission Overview



Continuous laser measurements:

Pointed toward or near nadir

- CO_2 lower tropospheric column
- Range to scattering surface at CO_2 wavelength
- O_2 total column
- Range to scattering surface at O_2 wavelength

with

- >50 Hz measurement rates
- ~50 m laser footprints
- Accommodate rapid changes in scattering surface height and in echo signal strengths

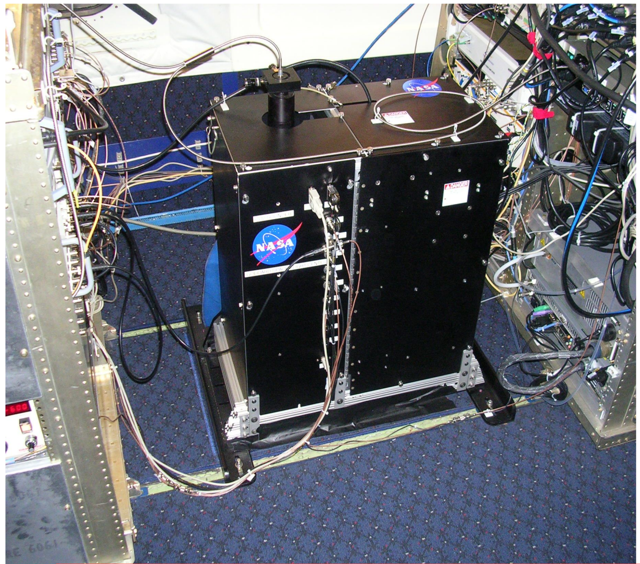
Summary of ASCENDS requirements will presented at 2014 Fall AGU meeting (GHG session, Thursday)

Requirements for XCO_2:

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



CO2 Sounder Characteristics:

Optimized as space instr. Simulator

CO2: 25 uJ/pulse at 10 KHz (250 mW)

30 λ's/line, 300 Hz sweep rate

NIR PMT detector (~4% QE)

O2: ~2 uJ/pulse at 10 KHz (~20 mW)

40 λ's line, 250 Hz sweep rate

Geiger Si APD detector

Common 20 cm dia. receiver telescope

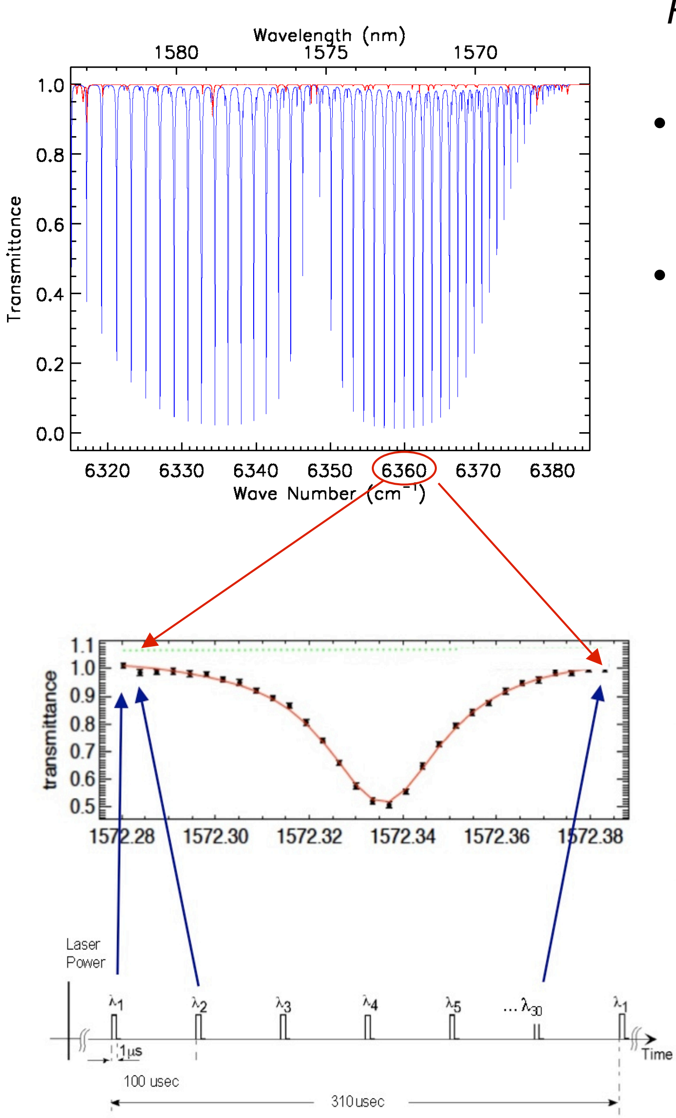
MCS (R-resolved histogram) recorders

2011 ASCENDS Flights

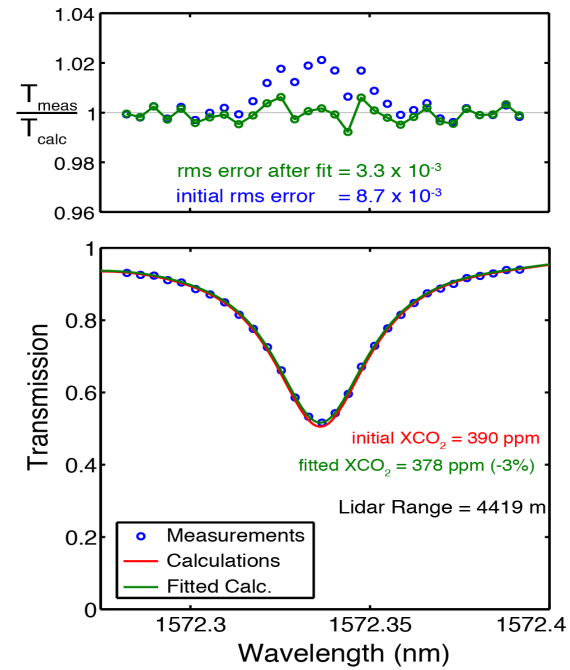
Objectives: Measure CO2 columns over a variety of topographic targets & under varying atmospheric conditions with developmental lidar candidates & in-situ sensors for the ASCENDS mission

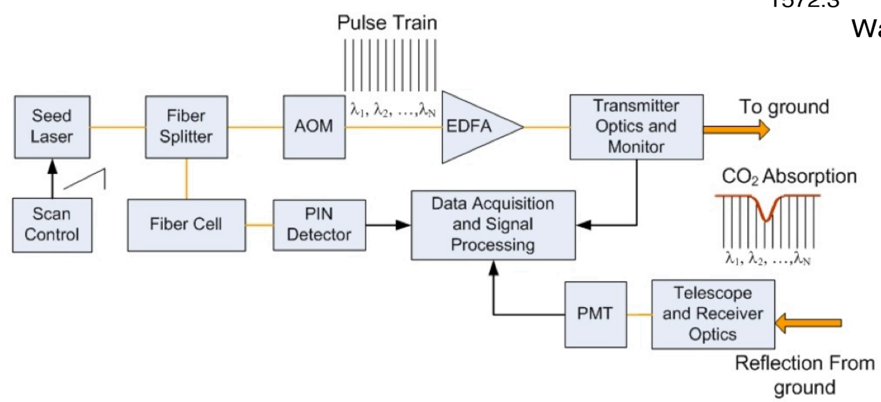
CO_2 Sounder Approach: Airborne CO_2 Line Sampling & Absorption line analysis

From Abshire et al., 2013 (slide 24)



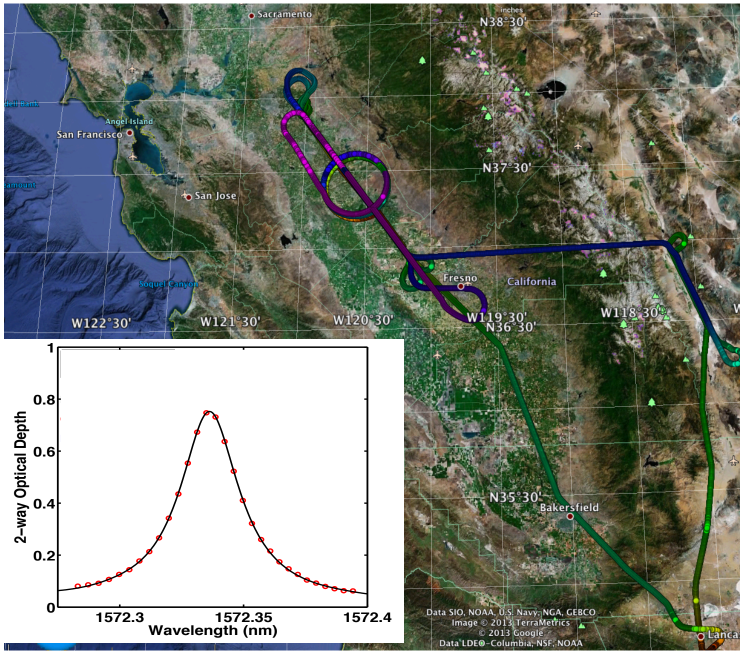
- *Lidar* measures "dots" (wavelength samples)
- *Post flight: Retrievals* (based on model atmosphere) calculates range, normalized line shapes & solves for best fit concentration

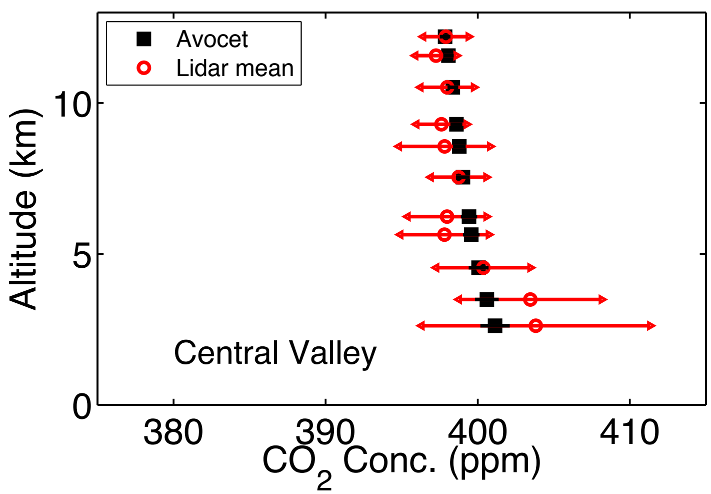


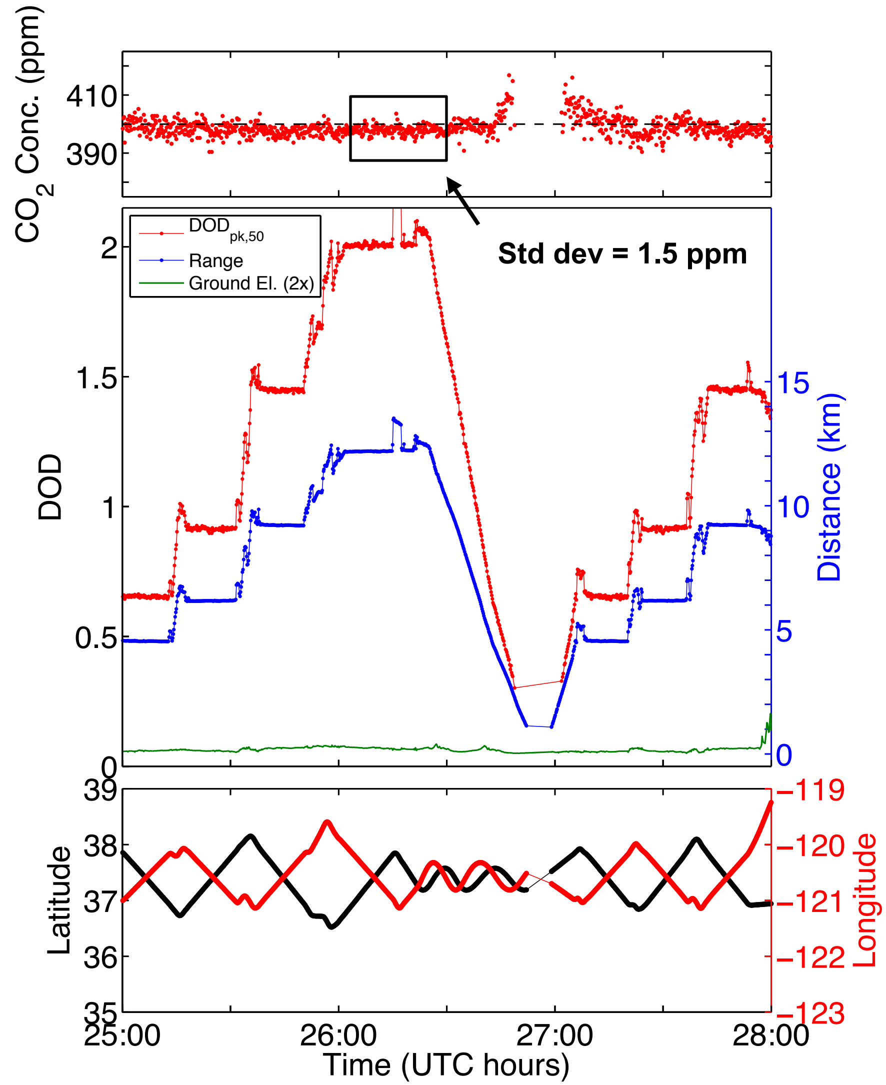


Laser: Master Oscillator, Power amplifier(s) (MOPA)

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



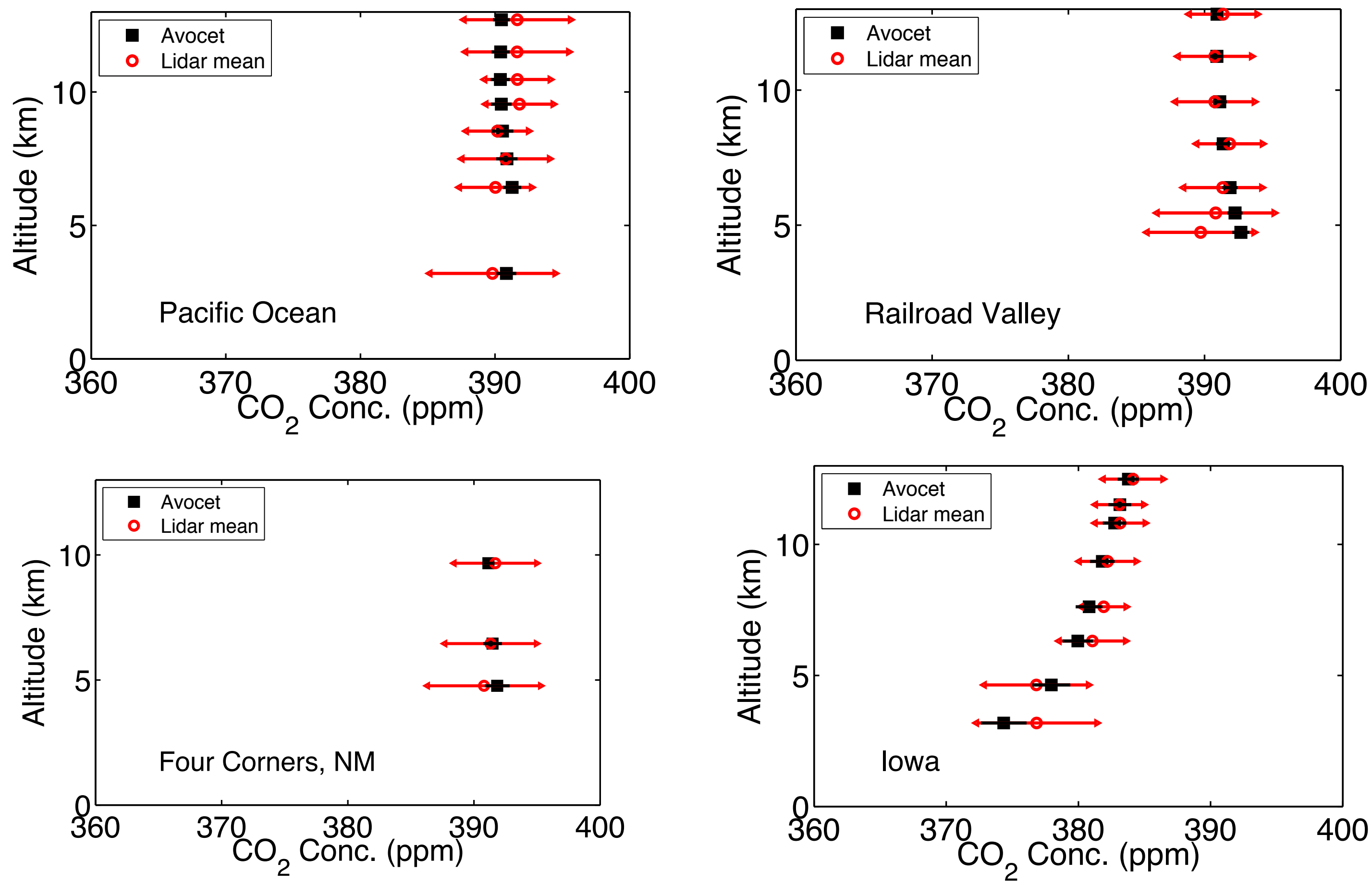




CO_2 Sounder example
Lidar-based retrievals vs in-situ for 2011 flights

• - Lidar retrievals using model atmosphere based on DC-8 measurements in spiral

• - AVOCET in-situ measurements

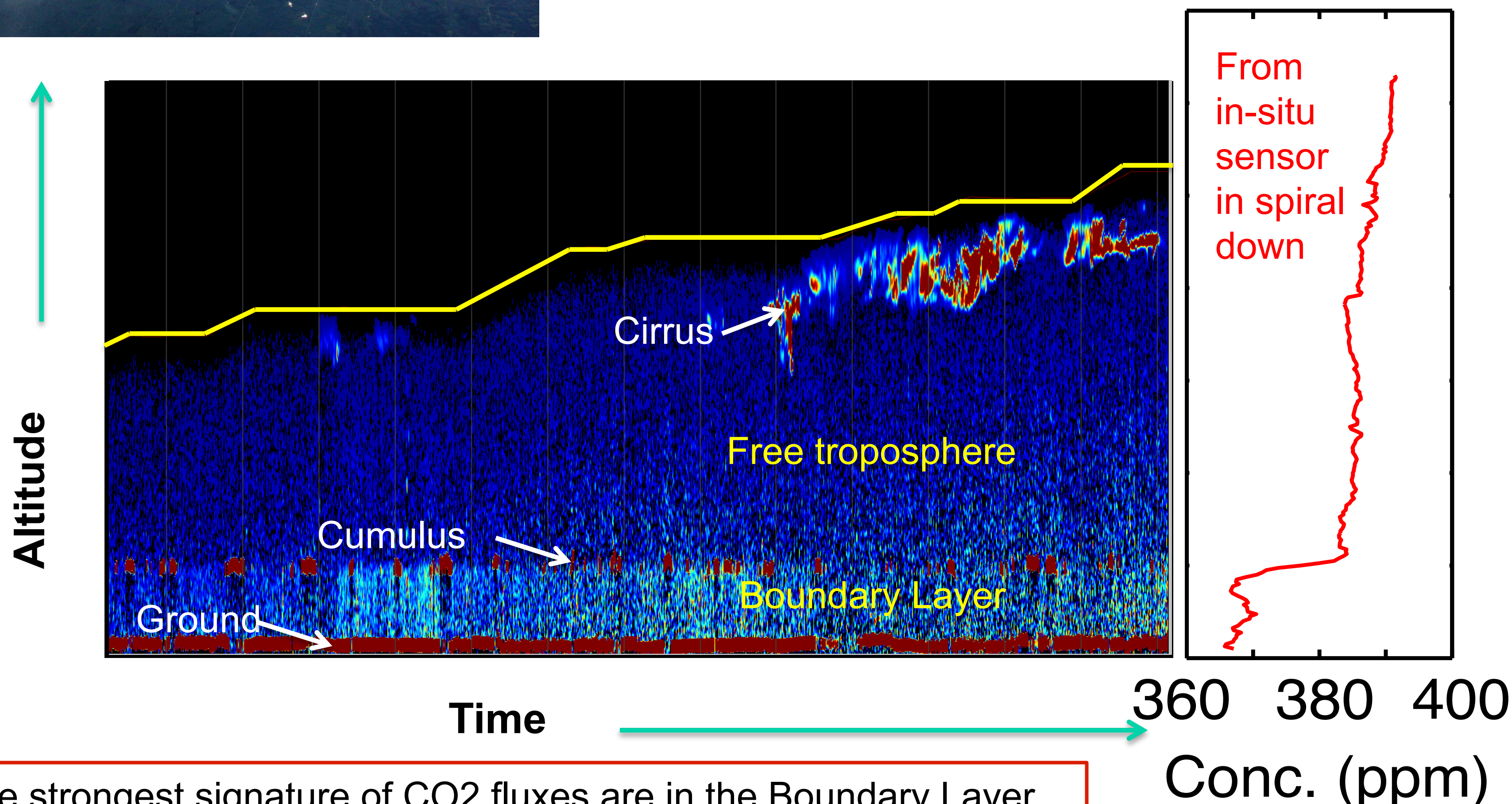


From Abshire et al., 2014 (slide 24)

- Comparison of column average retrievals from 2011 airborne lidar measurements vs altitude
- Lidar measurement error bars are +/- 1 std dev for a 10 second average

Backscatter Profile History
(Measured made over Iowa 2011)

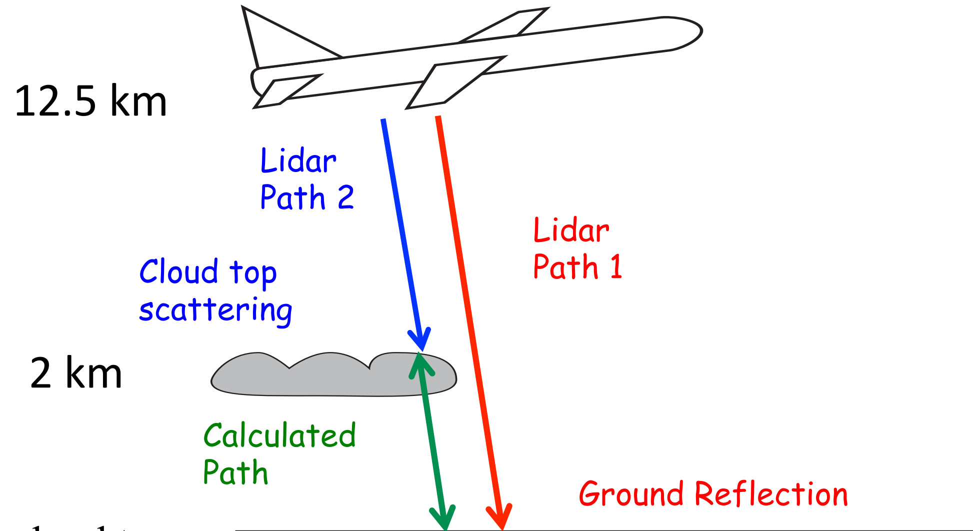
Backscatter profiles reveal elevated scattering layers



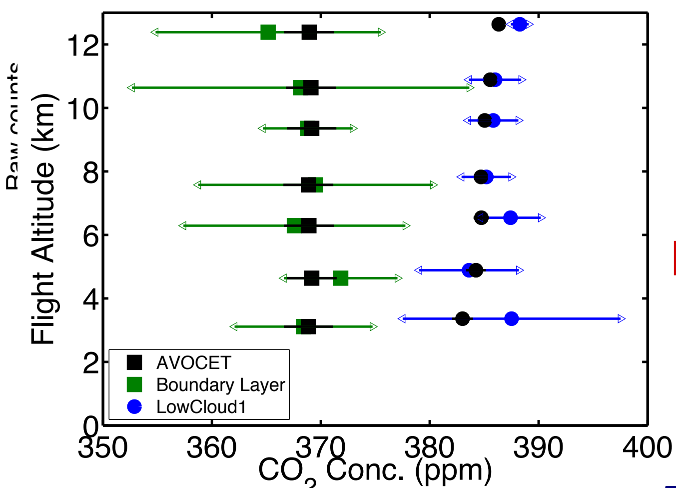
The strongest signature of CO2 fluxes are in the Boundary Layer concentrations

Resolving two vertical CO_2 layers via IPDA lidar measurements & "Cloud Slicing"

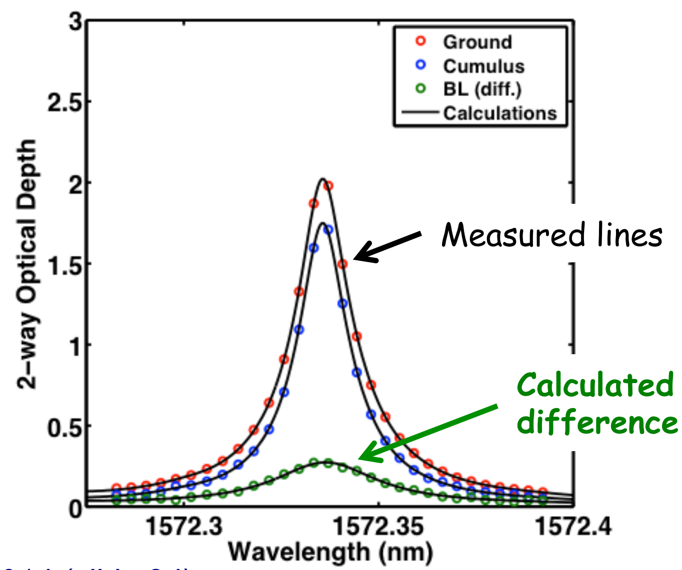
GSFC



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



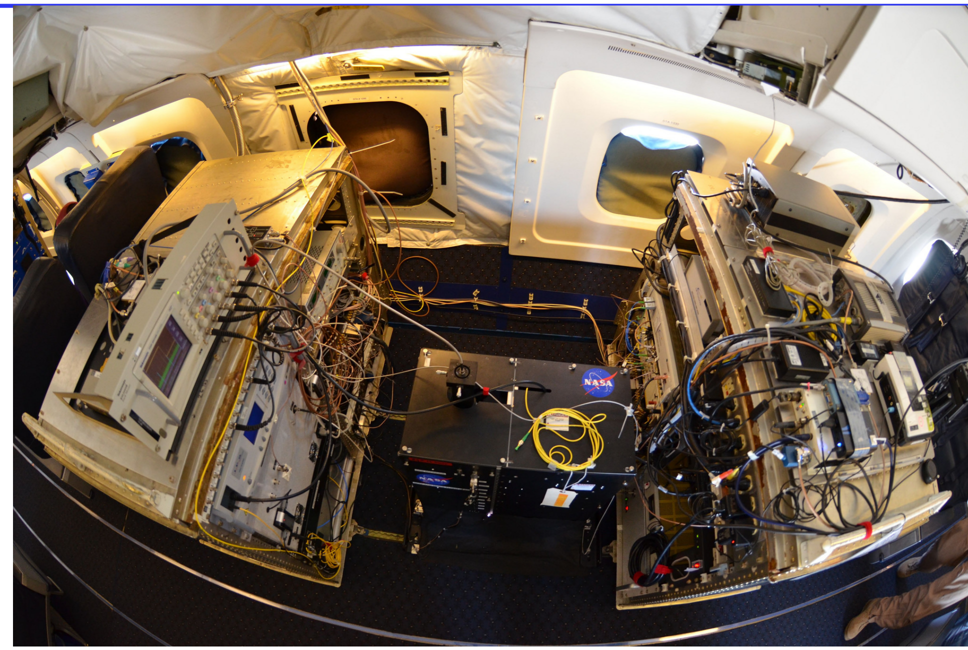
Results



From Ramanathan et al., 2014 (slide 24)

2014 CO2 Sounder Lidar

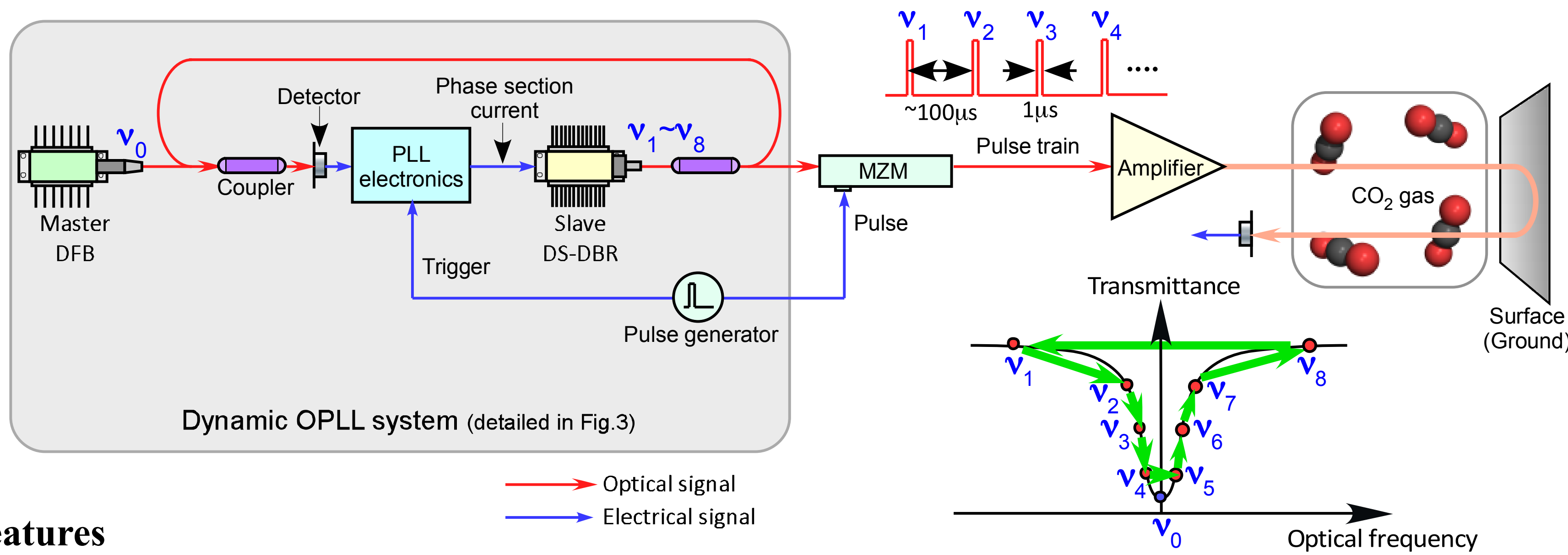
(Graham Allan, Anand Ramanthan, Kenji Numata)



Improvements demonstrated in 2014:

1. Step-locked CO2 seed source
2. Wider wavelength sampling across CO2 line
3. Optimized wavelength spacing across line
4. HgCdTe APD detector in receiver
5. Analog digitizer data recording
6. 10 Hz recording & retrieval resolution

Precision Step-Locked CO2 seed laser
(Jeff Chen and Kenji Numata)



Features

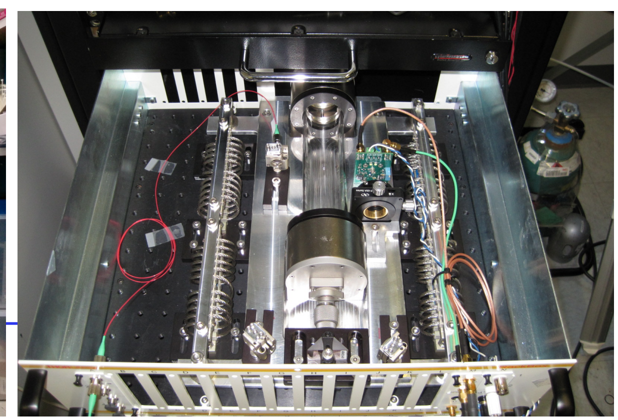
- DS-DBR laser is dynamically offset-locked to master DFB laser using optical phase-locked loop
- Frequency-stepped pulse train carved by MZM and subsequently amplified.
- Effective optical frequency noise of laser was < 0.2 MHz

Status

- Published design
- US patent submitted & pending
- **Used successfully with 30 λ's in CO2 Sounder in FY14 airborne campaign.**

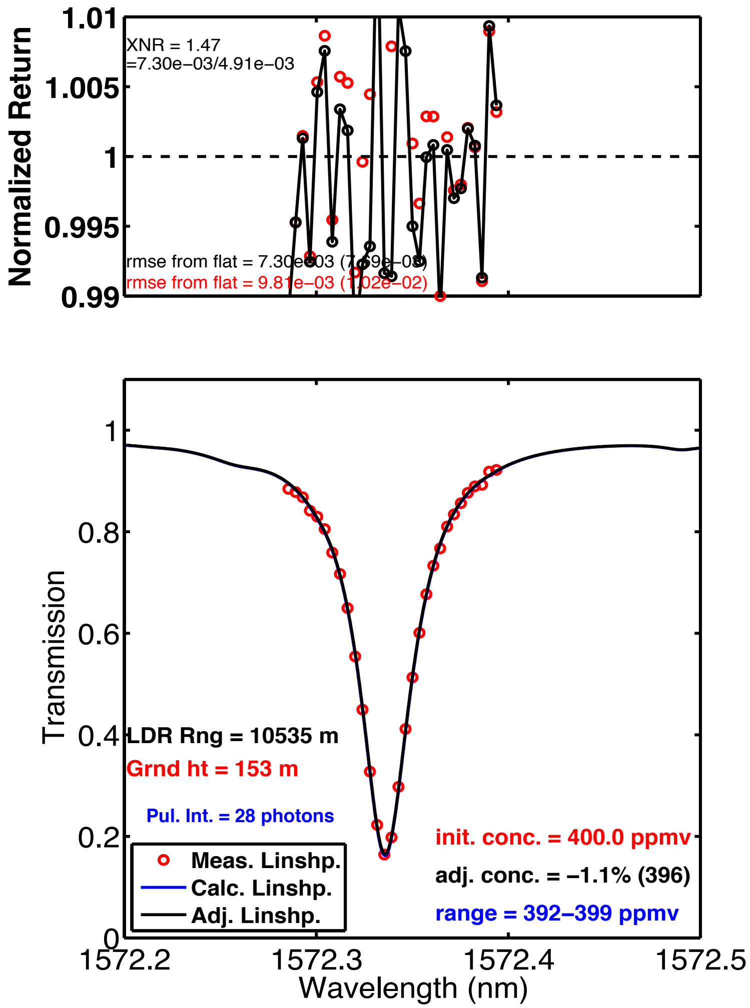
Step locked laser in DC-8 rack

CO2 cell for master laser locking



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

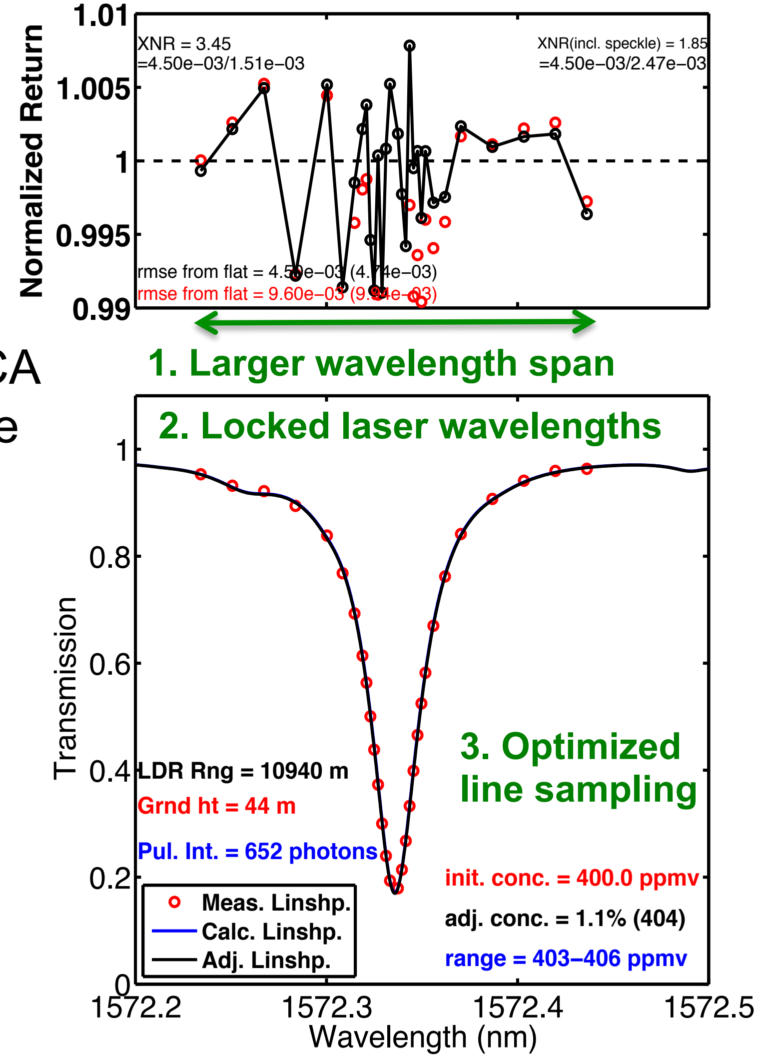
2013



Conditions:

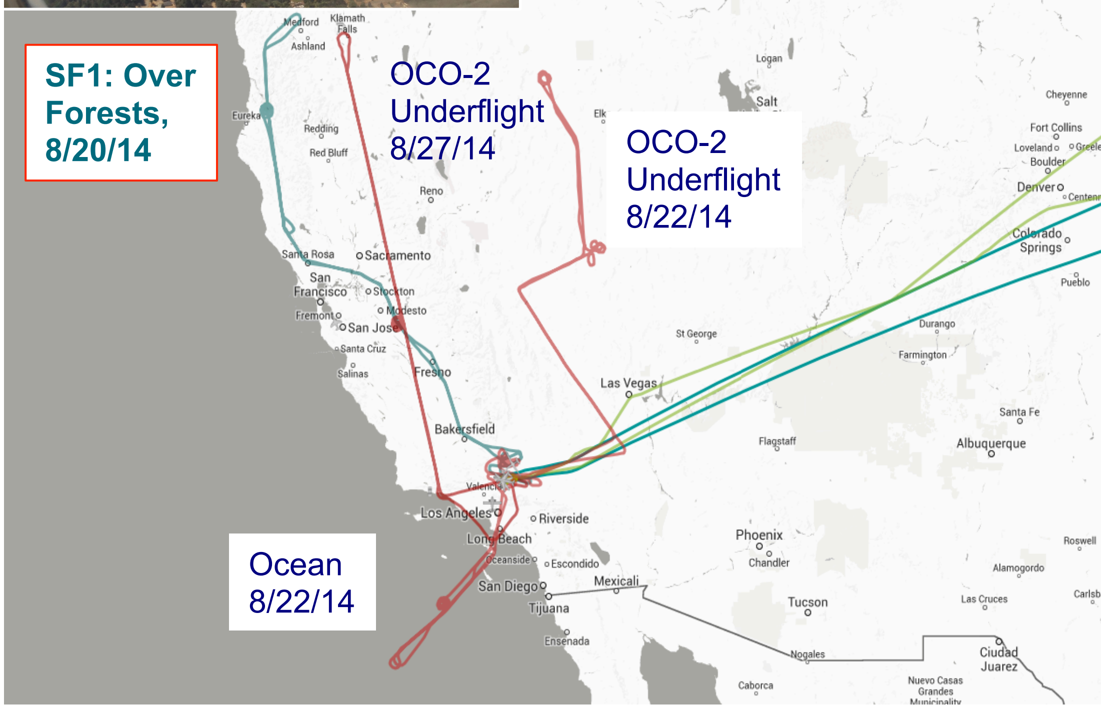
- Central Valley CA
- ~ 10 km altitude
- 10 sec ave

2014



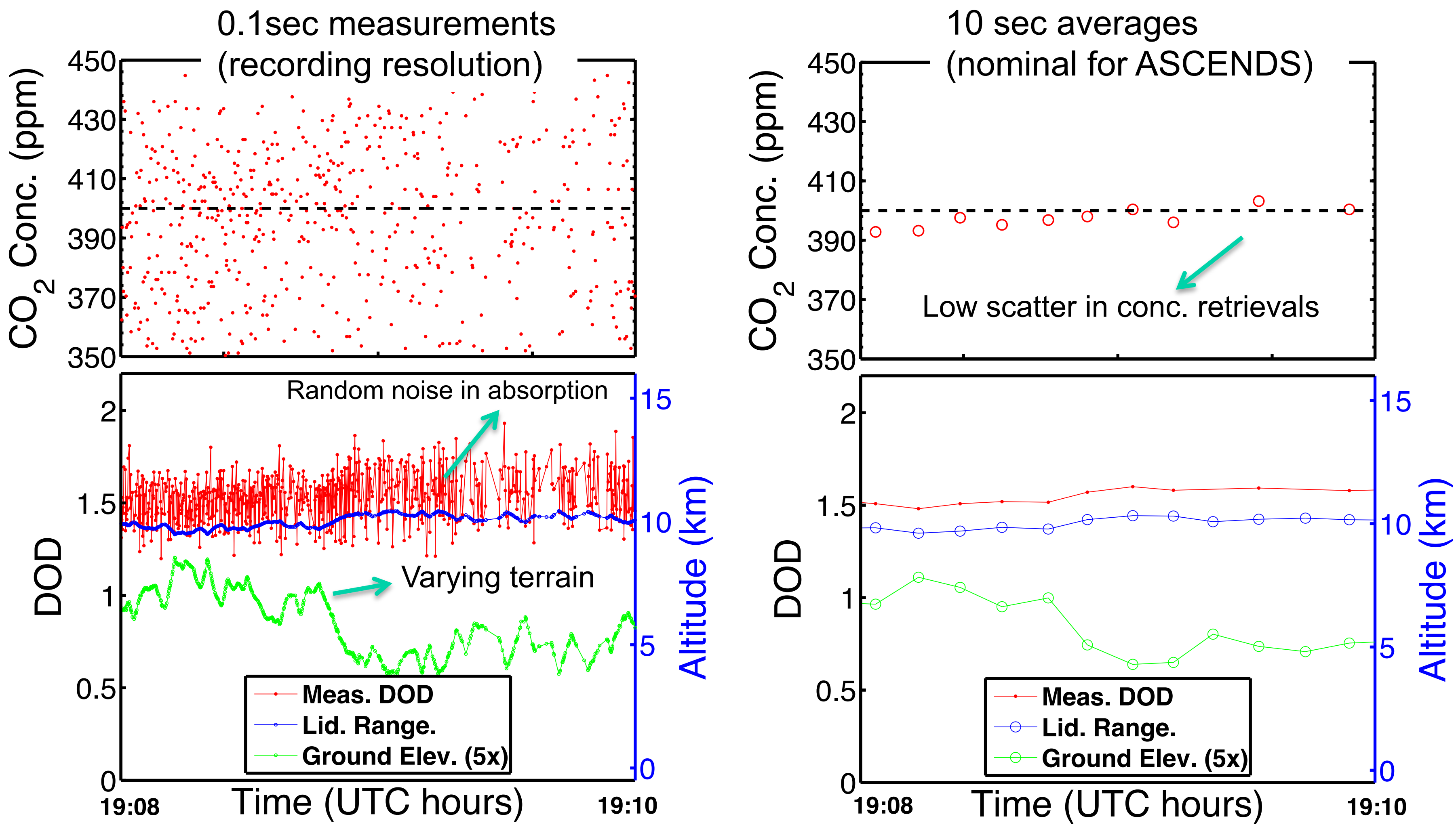
2014 ASCENDS Airborne Campaign

- Flights successfully measured column CO_2 & range:
  - Targets: forests in CA, growing agriculture both at dusk and dawn over Iowa, and an urban area
- IPDA lidar approach allows measurements under these conditions that are difficult for passive sensors.
- Two flights under flew the OCO-2 satellite.
- Instrument Teams: AVOCET (LaRC), MFFL lidar (LaRC, ITT), CO2 LAS (JPL)
- CO2 Sounder team (GSFC)



Co2 Sounder for NASA's ASCENDS Mission

2014 SF1: Measured range, terrain elevation and CO2 Absorption



120 sec of data shown. ~1000 raw 0.1 sec measurements

2014 SF1:surface reflectivity
Retrieved CO_2 concentrations vs DC-8 altitude

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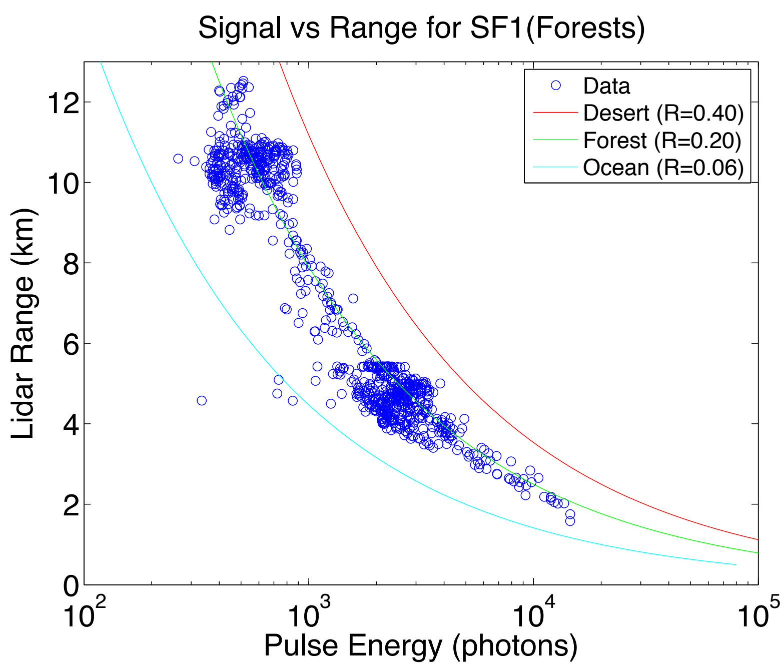
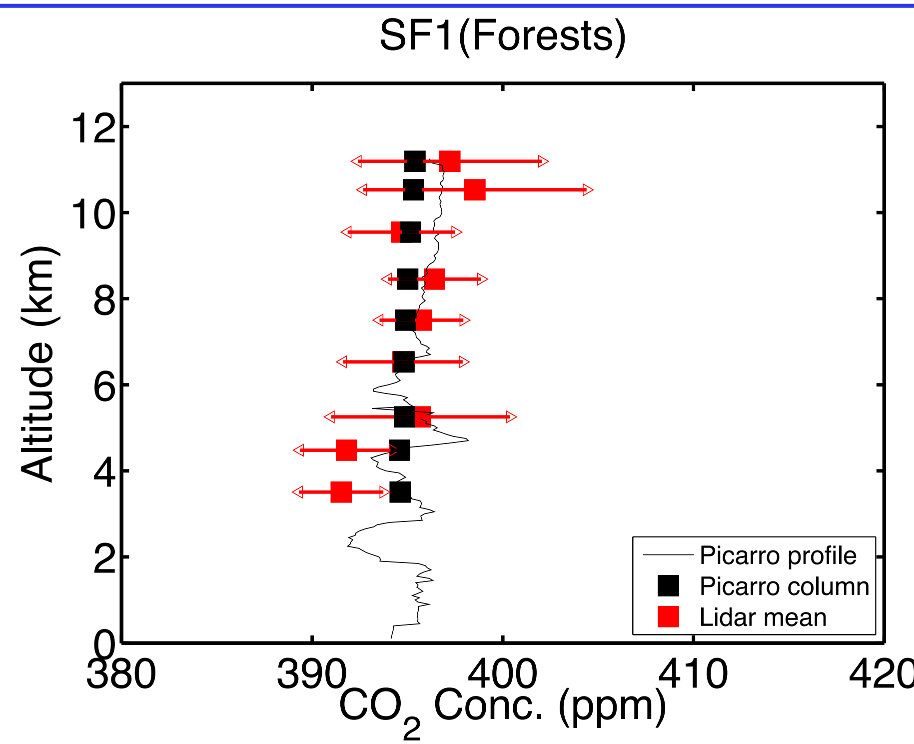


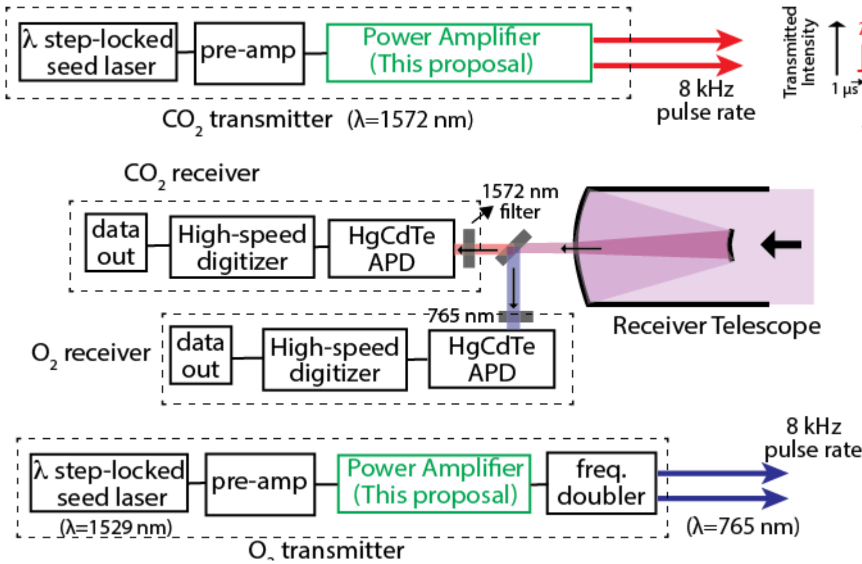


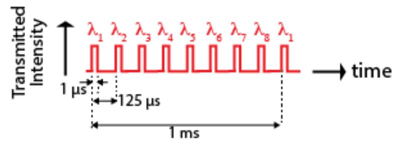
- Signal energies/pulse follow R-2 as expected
- Surface reflectivity ~ ½ desert, as expected

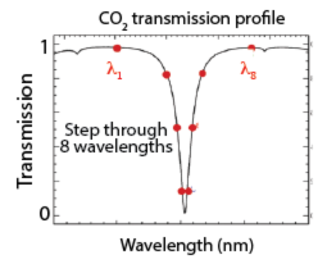
- Preliminary data - Calibrations currently are being refined
- Model atmosphere using radiosonde data
- No bias correction applied

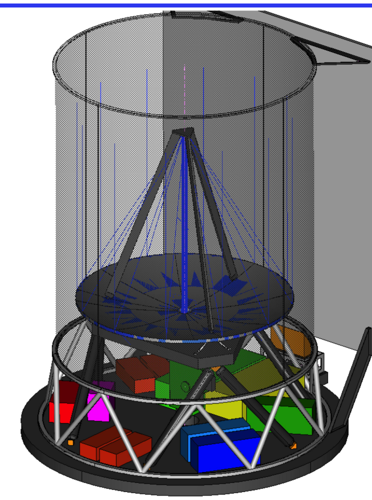
Very good agreement !

Scaling CO_2 Sounder lidar to Space



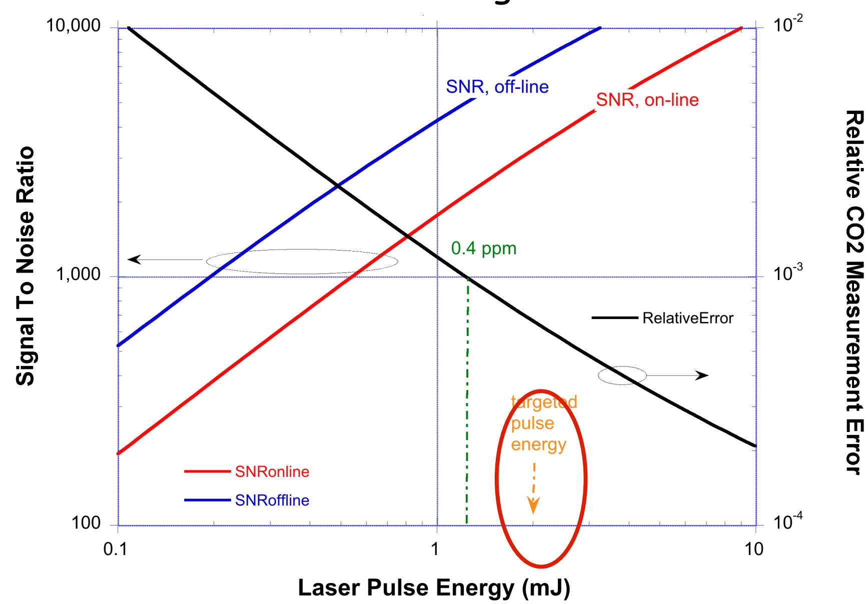






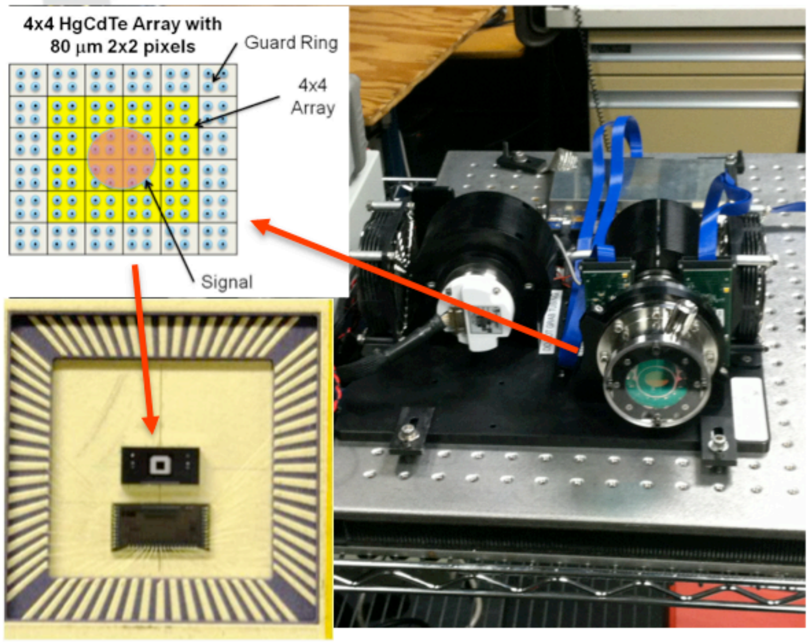
Parameters	Value
Orbit Altitude	400 km
Equator crossing time	dawn/dusk
Integration Time	10 sec (70 km)
Telescope diameter	1.5 m
Time between laser pulses	125 usec
Laser Pulse widths	1 usec
Online wavelength	1572.33 nm
Beam divergence	125 urad
Wavelength sequence rate	1.25 KHz
# of wavelengths in scan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

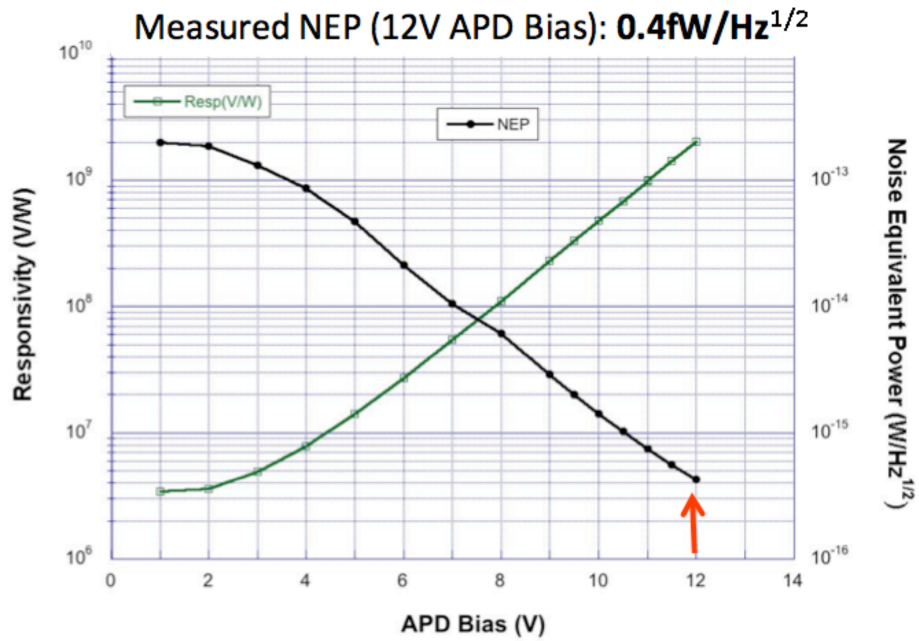
Random error over desert surface with 10 sec integration time



20W ave power

New HgCdTe APD Detector*
(for 2014 airborne campaign & space)



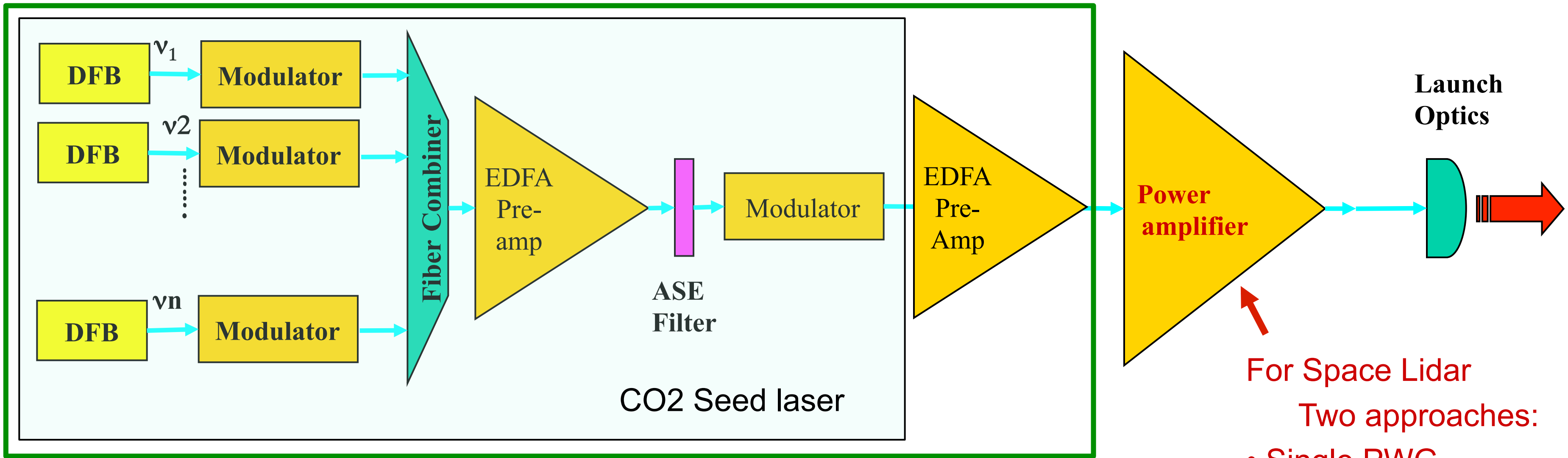


- Highly sensitive 4x4 element HgCdTe APD array developed by DRS that was delivered in April 2013
- Operates inside a mini-dewar/crycooler assembly.
- Pixels are square 80 um on a side
- Electrical bandwidth is ~ 7 MHz.

- 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

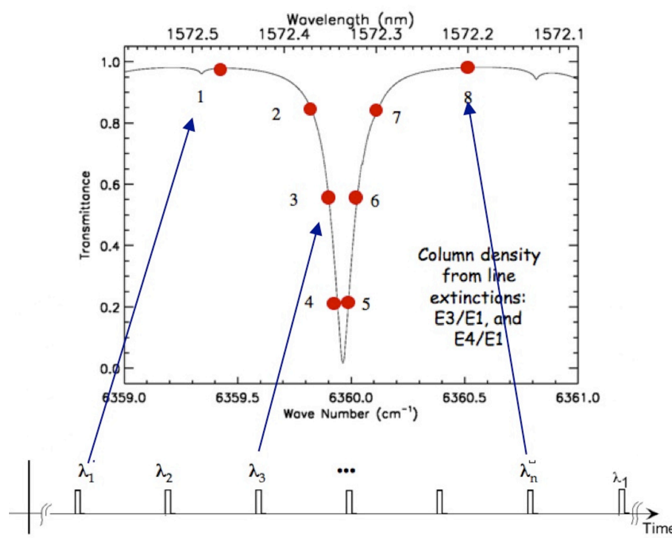
* From - Beck et al. 2014 (see slide 24)

Space Transmitter: 3 stage MOPA Design



For Space Lidar
Two approaches:
- Single PWG
- Parallel EDFAs

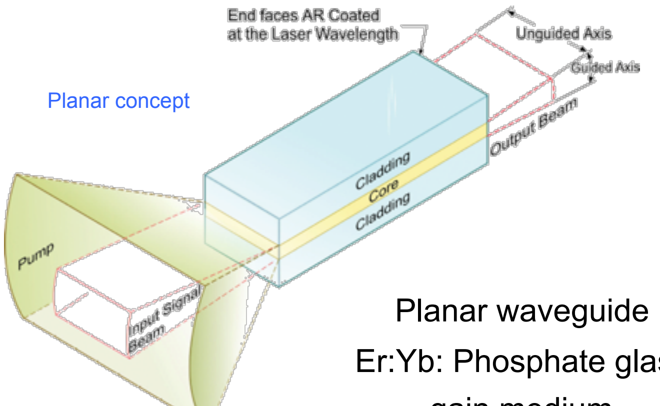
Demonstrated in airborne campaigns



Space lidar: 8 wavelength samples across line

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

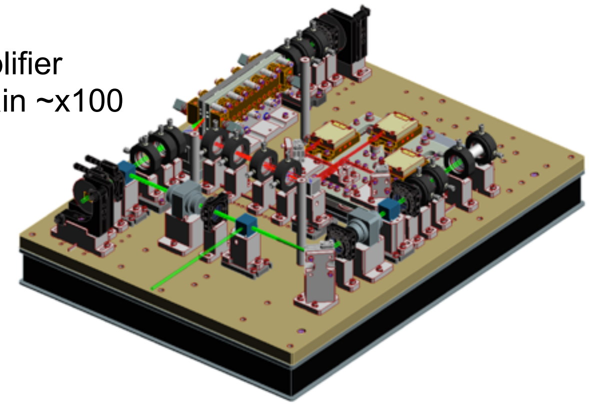
Planar concept

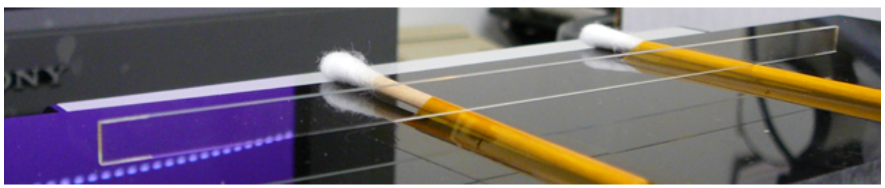


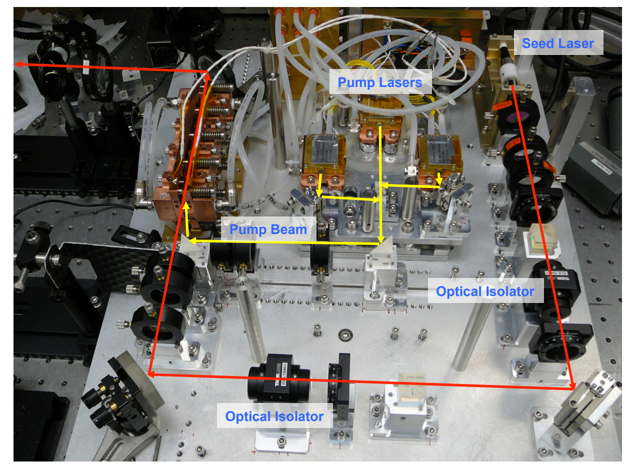
Planar waveguide

Planar waveguide
Er:Yb: Phosphate glass gain medium

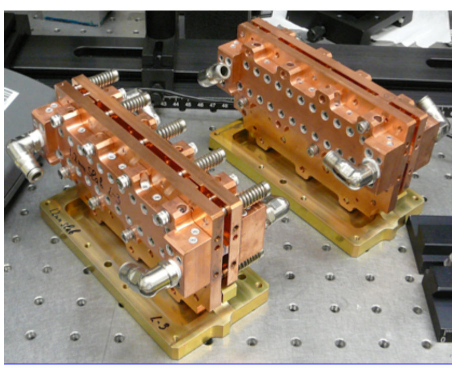
Design:
- 4-pass PWG amplifier
- Optical energy gain ~x100







PWG amplifier module



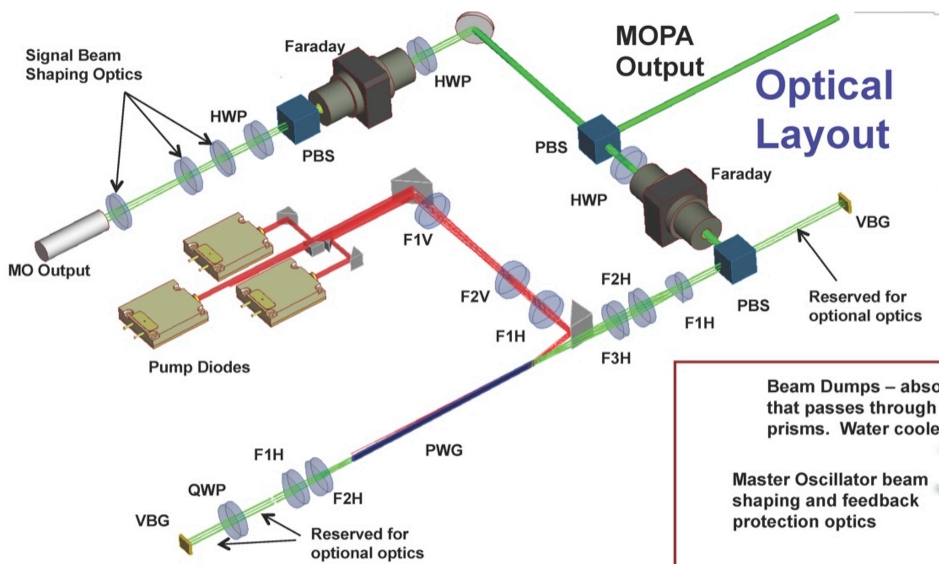
Alexander Betin/Raytheon

Anthony Yu/554

Seed Laser & Preamplifier → ~25 µJ → Power Amp Stage (Full Power Scaling) → 2.7 mJ

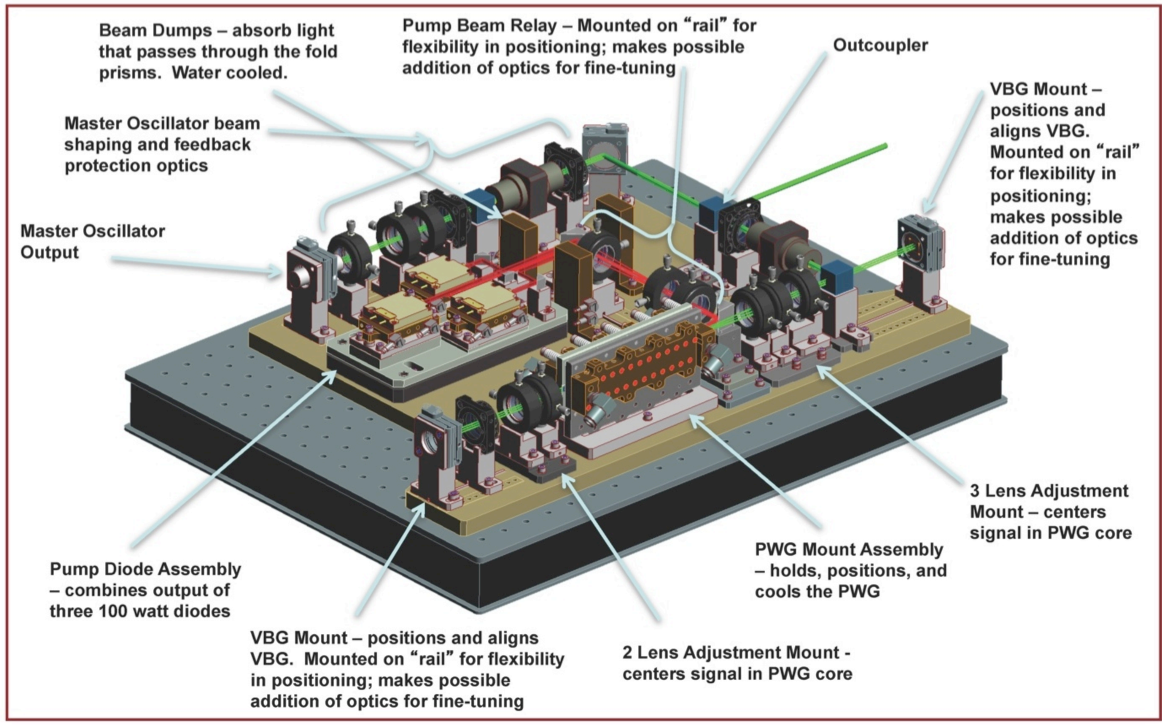
Breadboard Planar Waveguide (PWG) Amplifier

GSFC



- Leveraged earlier Yb:YAG PWG amplifier design (ESTO IIP) for 1030 nm laser
- Laser diode pumped at 974 nm
- Designed for x100 gain: 1572 and 1529 nm

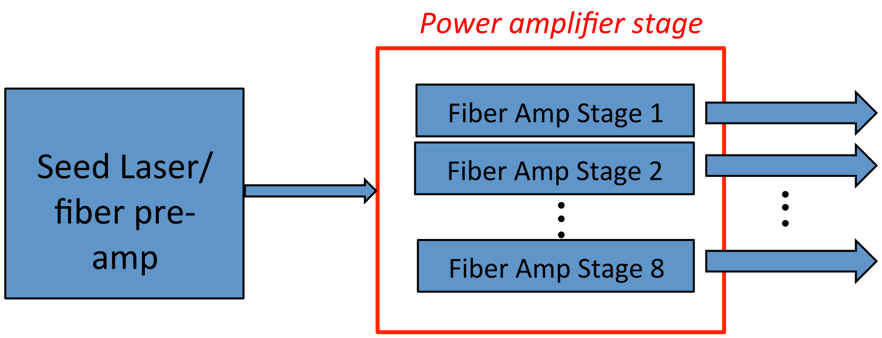
- Breadboard uses COTS optical breadboard and components
- Size: 24" x 18" x 6.4"
- Delivery February 2015



Approach for all-Fiber-Amplifier-based Space Laser Transmitter

GSFC

- ***A parallel amplifier approach, using Er:Yb LMA fibers:***
- ***Several Er:Yb LMA gain fiber types are candidates***
- ***Modular, flexible, compact & rugged***

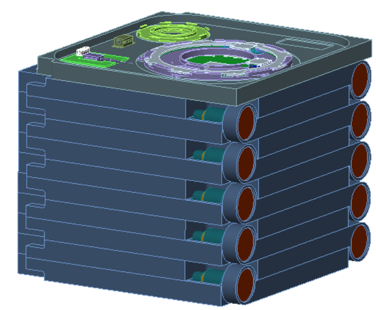


Beams overlap in far field:
Targets for ASCENDS:

- Total power ~ 20W
- Total energy ~2.7 mJ
- Pulse Energy/ Amplifier Stage = ~330 uJ

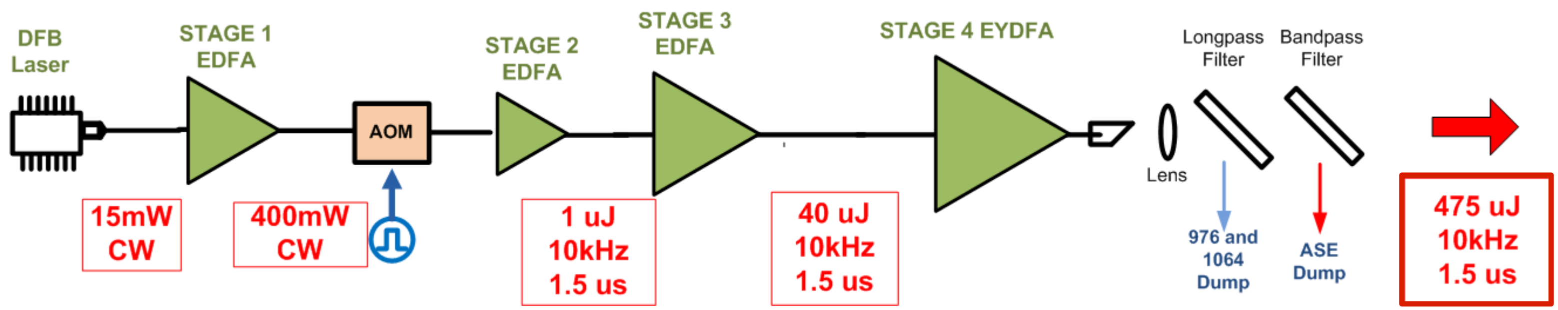
7.5 KHz laser Pulse rate

One amplifier packaging Concept

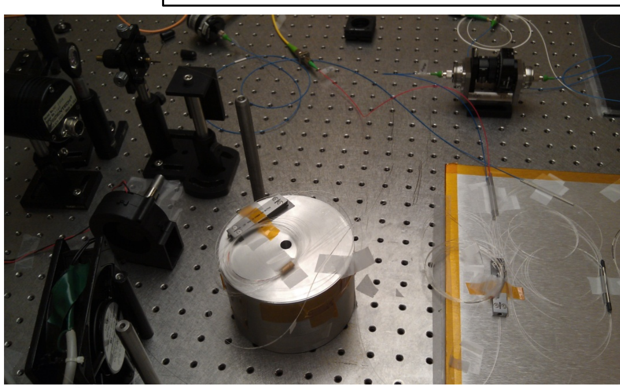


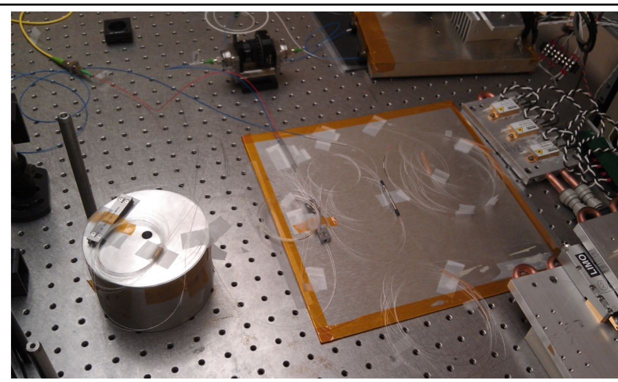
Fibertek
vision – innovation – leadership

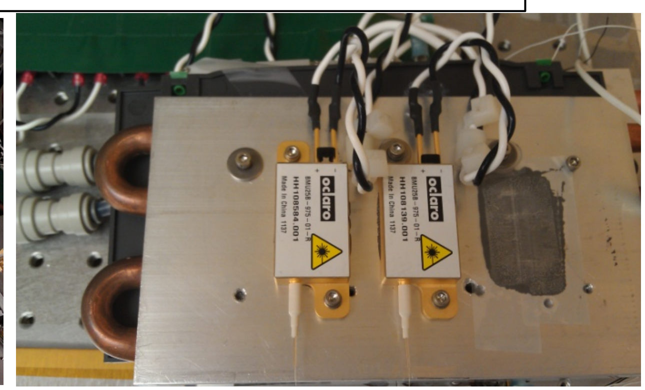
EDFA Power Scaling for Space for CO_2 Sounder (IIP-10 funded experiments at 1572 nm)



- 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 (see slide 26)





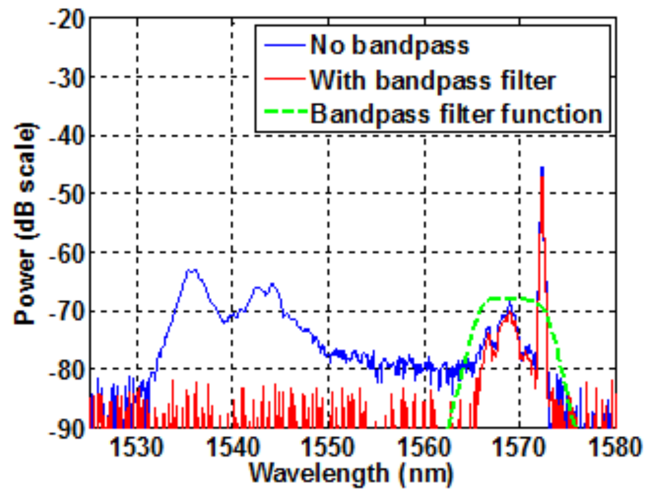


1572.33 nm Pulsed Fiber Amplifier Breadboard Demonstrated Performance

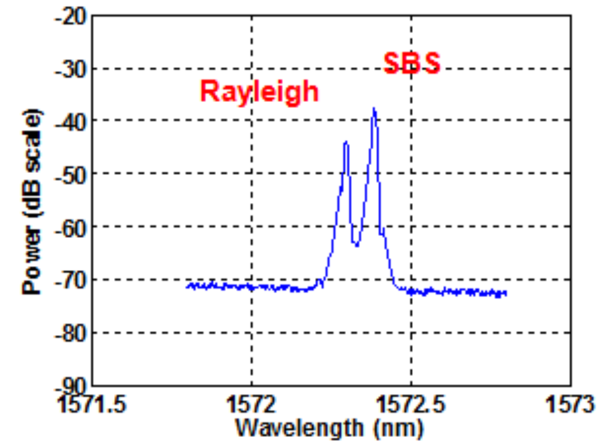
Fibertek
vision – innovation – leadership

- 160 µJ transform limited, ~ 1 MHz
- 300 µJ @ 50 MHz Linewidth
- 475 µJ @ 100 MHz Linewidth
- 3% ASE
- SBS threshold defined as 0.01% backward energy.
- 1.5 µs pulse width, 10 kHz rep. rate
- 16.7% Opt-Opt efficiency @ 475 µJ
- 15 % Opt-Opt transform limited
- Beam Quality Estimate < 1.2 using 25 µm core.
- PER = 17.3 dB at 375 µJ

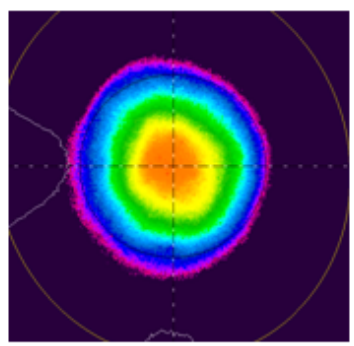
Forward Optical Spectrum Transform Limited



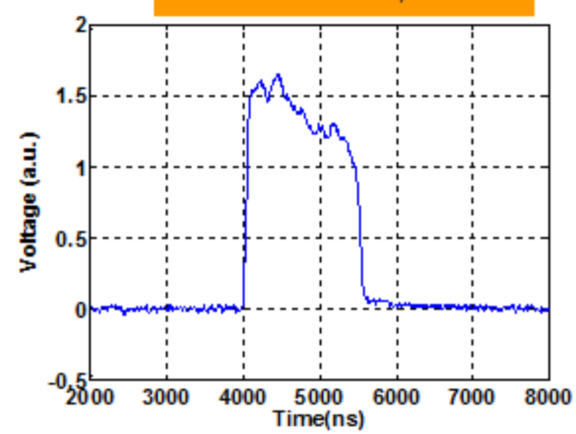
Backward Optical Spectrum



TEM oo



Time-Domain, 1.5 us



Summary

Have advanced the readiness of the CO_2 Sounder for the ASCENDS Mission:

Benefits of this Lidar Approach:

1. Uses mature pulsed lidar approach with direct detection receiver. Provides accurate estimates of range to scattering surfaces. Clearly separates atmospheric scattering layers.

2. Are several candidate CO2 lines that are temperature insensitive with minimal water vapor interference

3. ASCENDS measurements require very low (~0.1%) bias. This approach samples CO2 line shape with 8 or more wavelengths. This is a robust approach to solve for (and greatly reduce) biases.

4. Demonstrated measurements of CO2 column concentrations at two vertical layers using measurements to cloud tops.

5. Measures of the atmospheric backscatter profile, which indicates atmospheric boundary height, which aids calculation of CO2 fluxes.

6. Have demonstrated accurate retrievals of CO2 mixing ratio from aircraft

7. The pulsed lidar approach is power efficient. Laser power demands for space are < 1/4th those of modulated CW approaches.

Benefits of 1.57 um laser technology:

1. Laser operates at in the fiber-optic telecom band. There is a very strong global technology base from industrial investments in the global fiber internet.

2. The lasers have 7-10% wall-plug efficiency and have extremely long lifetimes.

3. The MOPA laser design is modular & is very flexible.

4. Are several approaches for the laser power amplifier for space

5. The lasers are fiber coupled without free space optics. This makes the laser very rugged.

6. NASA, and DoD have invested in fiber-optic based lasers for free space communications. Many needed components have already been radiation tested and space qualified.

7. Developed a very sensitive HgCdTe APD detector and demonstrated it in an airborne campaign.

Thank you to the ESTO IIP& QRS programs for the support !

Reporting –Papers & Presentations since 2011
Avail on: http://ssed.gsfc.nasa.gov/co2sounder/

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Papers by Year (links go to PDF)

2014

- Randy Kawa et al., "Observing System Simulations in Support of ASCENDS Requirements Definition," 10th International Workshop on Greenhouse Measurements from Space (IWGGMS-10), Noordwijk, The Netherlands, May 2014.
- James B. Abshire et al., "Atmospheric CO2 Column Concentrations Measured by Pulsed Lidar with High Accuracy in the ASCENDS 2011 and 2013 Airborne Campaigns,"10th International Workshop on Greenhouse Measurements from Space (IWGGMS-10), Noordwijk, The Netherlands, May 2014.
- Anand Ramanathan et al., "Multi-layer retrievals of atmospheric CO2 mixing ratio using multi-wavelength pulsed lidar measurements from aircraft," 10th International Workshop on Greenhouse Measurements from Space (IWGGMS-10), Noordwijk, The Netherlands, May 2014.
- Haris Riris et al., "A Methane IPDA Lidar using Optical Parametric Laser Technology," 10th International Workshop on Greenhouse Measurements from Space (IWGGMS-10), Noordwijk, The Netherlands, May 2014.
- Jeff Beck, Terry Welch, Pradip Mitra, Kirk Reiff, Xiaoli Sun, and James Abshire, "A Highly Sensitive Multi-element HgCdTe e-APD Detector for IPDA Lidar Applications," Journal of Electronic Materials, 2014.
- Abshire, J.B.; Ramanathan, A.; Riris, H.; Mao, J.; Allan, G.R.; Hasselbrack, W.E.; Weaver, C.J.; Browell, E.V. "Airborne Measurements of CO2 Column Concentration and Range Using a Pulsed Direct-Detection IPDA Lidar," *Remote Sensing* 2014, **6**, 443-469.

2013

- H. Riris, M. Rodriguez, G.R. Allan, W. Hasselbrack, J. Mao, M. Stephen, J. Abshire, "Pulsed airborne lidar measurements of atmospheric optical depth using the Oxygen A-band at 765 nm," *Applied Optics, 52*(25), 6369-6382 (2013).
- Anand Ramanathan, Jianping Mao, Graham R. Allan, Haris Riris, Clark J. Weaver, William E. Hasselbrack, Edward V. Browell, James B. Abshire, "Spectroscopic measurements of a CO2 absorption line in an open vertical path using an airborne lidar,"*Applied Physics Letters*, 103, 214102 (2013), DOI:http://dx.doi.org/10.1063/1.4832616
- J. Abshire, H. Riris, C. Weaver, J. Mao, G. Allan, W. Hasselbrack, and E. Browell, "Airborne measurements of CO2 column absorption and range using a pulsed direct-detection integrated path differential absorption lidar," Appl. Opt. 52, 4446-4461 (2013).
- X. Sun, X.; J.B. Abshire, J.F. McGarry, G.A. Neumann, J.C. Smith, J.F. Cavanaugh, H.J. Zwally, D.E. Smith, M.T. Zuber. "Space Lidar Developed at the NASA Goddard Space Flight Center - The First 20 Years," IEEE Journ. Selected Topics in Applied Earth Observations, Vol.6, 1660-1675 (2013).doi: 10.1109/JSTARS.2013.2259578
- J. Beck; J. McCurdy, M. Skokan, C. Kamilar, R. Scritchfield , T. Welch, P. Mitra, X. Sun, J. Abshire, K. Reiff; "A highly sensitive multi-element HgCdTe e-APD detector for IPDA lidar applications", Proc. SPIE 8739, Sensors and Systems for Space Applications VI, 87390V (2013); doi:10.1117/12.2018083.
- A. Amediek, Xiaoli Sun, J.B. Abshire, "Analysis of Range Measurements From a Pulsed Airborne CO2 Integrated Path Differential Absorption Lidar," IEEE Trans Geosci. Rem. Sensing, vol. PP, no.99, pp.1-7, 2012, doi: 10.1109/TGRS.2012.2216884.

2012

- X. Sun and J. Abshire, "Comparison of IPDA lidar receiver sensitivity for coherent detection and for direct detection using sine-wave and pulsed modulation," Opt. Express, Vol. 20, 21291-21304 (2012), http://dx.doi.org/10.1364/OE.20.021291.
- K. Numata, J. R. Chen, and S. T. Wu, "Precision and fast wavelength tuning of a dynamically phase-locked widely-tunable laser", Optics Express, Vol. 20, Issue 13, pp. 14234-14243 (2012)
- H. Riris, K. Numata, S. Li, S. Wu, A. Ramanathan, M. Dawsey, J. Mao, R. Kawa, and J. Abshire, "Airborne measurements of atmospheric methane column abundance using a pulsed integrated-path differential absorption lidar," Appl. Opt. 51, 8296-8305 (2012).

BACKUP

Pulsed fiber EDFA: 330 uJ/pulse at 1563 nm, single Frequency (Fibertek and Nufern, 2007)

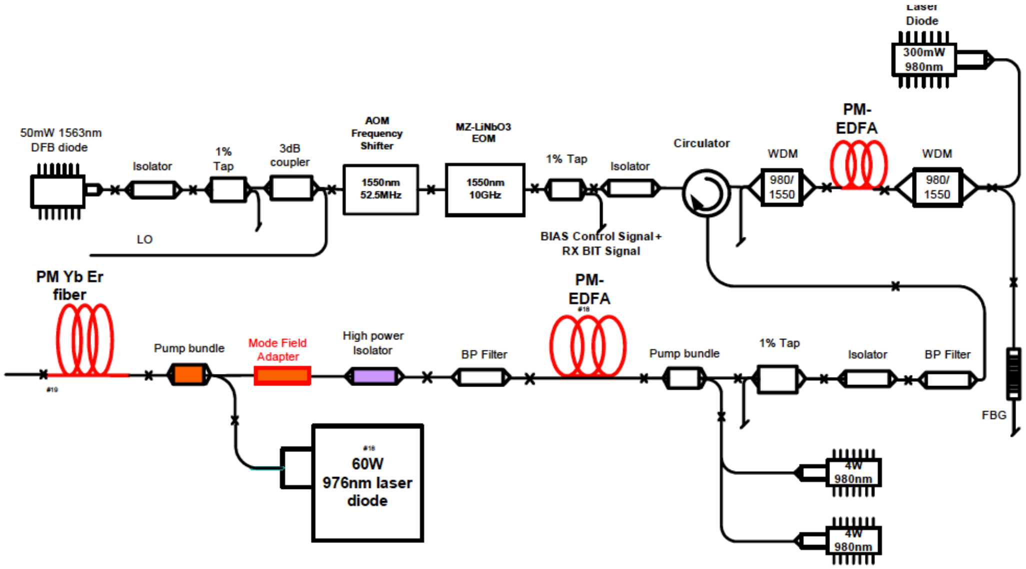

Figure 1: All fiber circuit allowing up to 500W/pulse 660ns long or10W average power. The last amplifier is pumped by a single fiber coupled diode laser bar operating at 976nm and 45°C to improve the overall system efficiency.

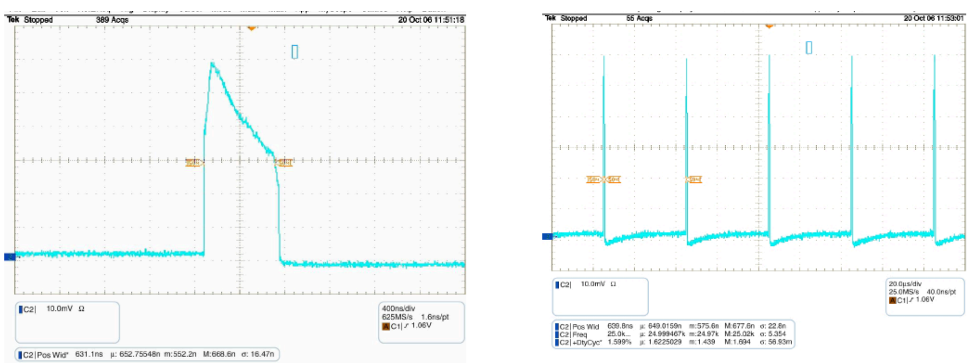

Figure 2: Output 660ns pulses at 20Kpps generated by our all fiber Transmitter

High peak power Eye-Safe Coherent EYDFA Laser Source

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1 Abstract

Coherent Laser Radar is a powerful remote sensing tool, which can be applied to range-finding, target discrimination, vibrometric monitoring, air pollution monitoring, aircraft wake-vortex and clear-air turbulence analysis. A high power, highly efficient, near diffraction limited and highly reliable pulsed coherent laser source is a key sub-system required in a coherent Lidar sensor. When humans are involved, eye safe laser emission is also typically required. Therefore a highly efficient fiber laser system based on a coherent Master-Oscillator followed by a chain of Erbium (EDFA) and Erbium co-doped with Ytterbium fiber amplifiers (EYDFA) is ideally suited for this application suite.

In this paper, we are presenting an all polarization-maintaining fiber architecture and experimental results on such a high peak power fiber laser system allowing for versatile modulation strategies at a wavelength of 1563nm commensurate with a clear atmospheric transmission window and eye-safe operation. The system is constituted by three amplification stages, all based on Polarization-Maintaining fiber. With 660ns and 20Kpps, over 500W peak power pulses have been experimentally demonstrated with near diffraction limited performance with this all PM fiber system.

4 High Peak Power Eye Safe Fiber Amplifiers

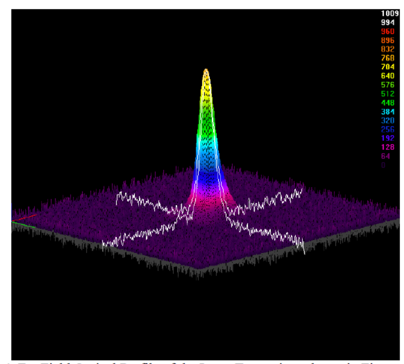

Figure 4: Far Field Optical Profile of the Laser Transmitter shown in Figure 1

Laser Source Technology for Defense and Security III, edited by Gary L. Wood, Mark A. Dubinskii, Proc. of SPIE Vol. 6552, 65520T, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.721458

Proc. of SPIE Vol. 6552 65520T-1