Advances in the CO_2 Sounder Lidar for measurements from Aircraft and in Scaling for Space

James B. Abshire[1], Xiaoli Sun[1],
Anand Ramanathan[1,2], Haris Riris[1],
Graham R. Allan[1,3], William E. Hasselbrack[1,3],
Jianping Mao[1,2], Mark Stephen[4]

[1]NASA Goddard, Sciences and Exploration Directorate,
[2]ESSIC, University of Maryland
[3]Sigma Space Inc.
[4]NASA Goddard, Lasers and Electro-Optics Branch

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James.B.Abshire@nasa.gov

Atmospheric CO2 & Earth’s Carbon Cycle

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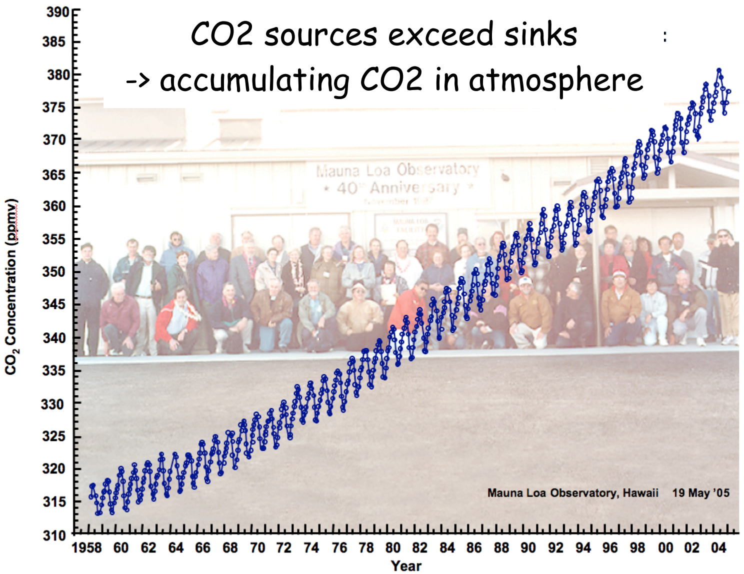


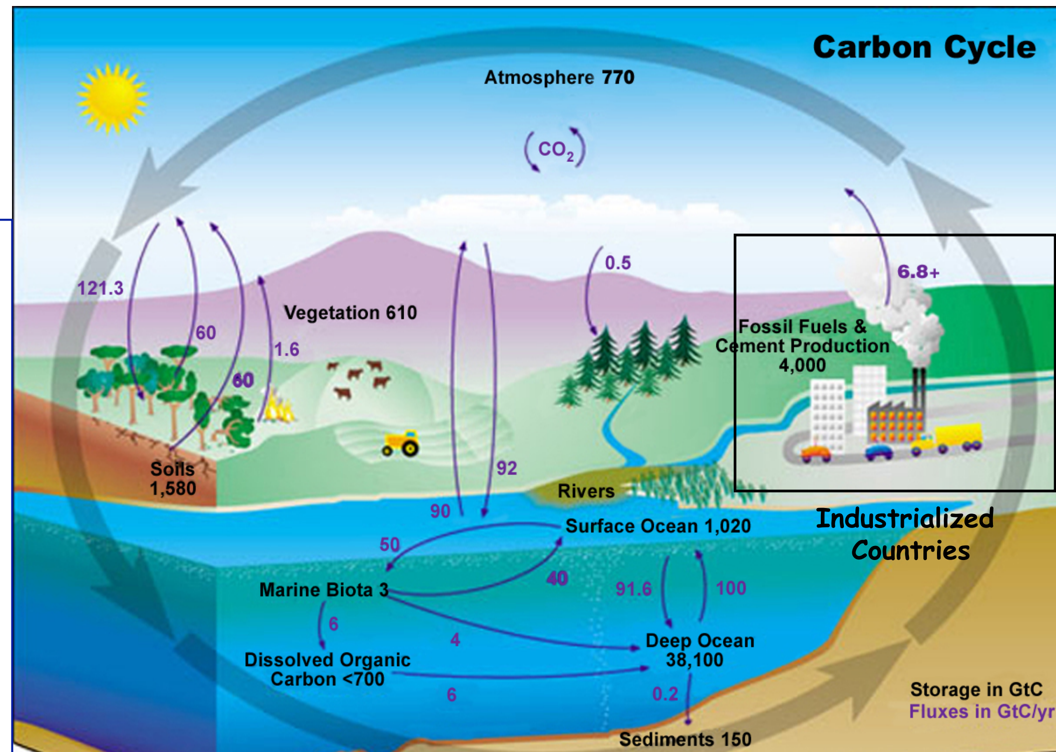
Major Questions about CO2 Sinks:

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

Recommended by 2007 Earth Science Decadal Survey

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Science Measurements:

Laser absorption by atmospheric column CO_2

- Polar orbit
- Nadir pointing
- Accurately measures absorption of a single CO_2 absorption line
- Continuous measurements of CO2 column absorption and range to surface

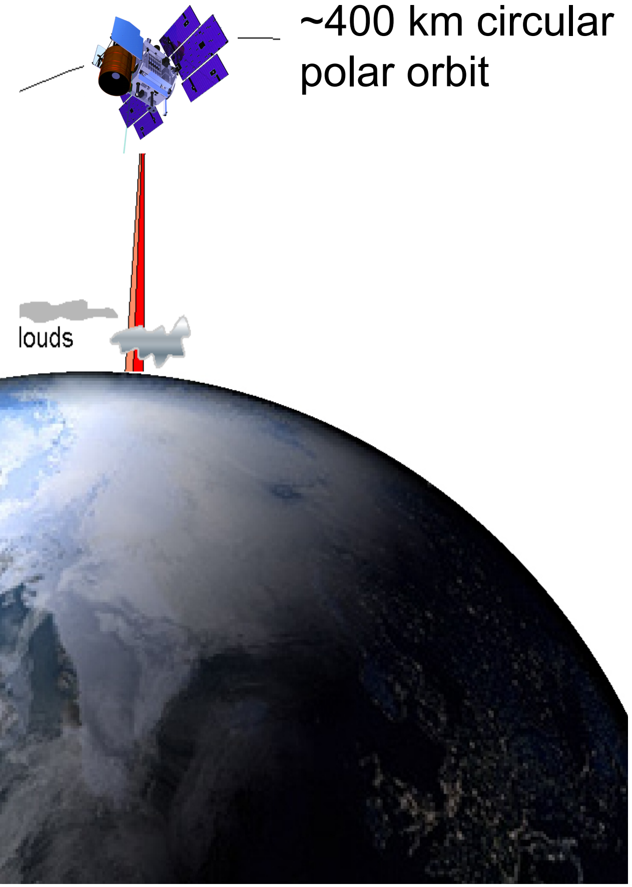
Minimum Requirements:

- Random measurement error:
  < 0.5 ppm with 10 sec integration
  over deserts
- **Bias: <<0.5 ppm**
  Primary causes

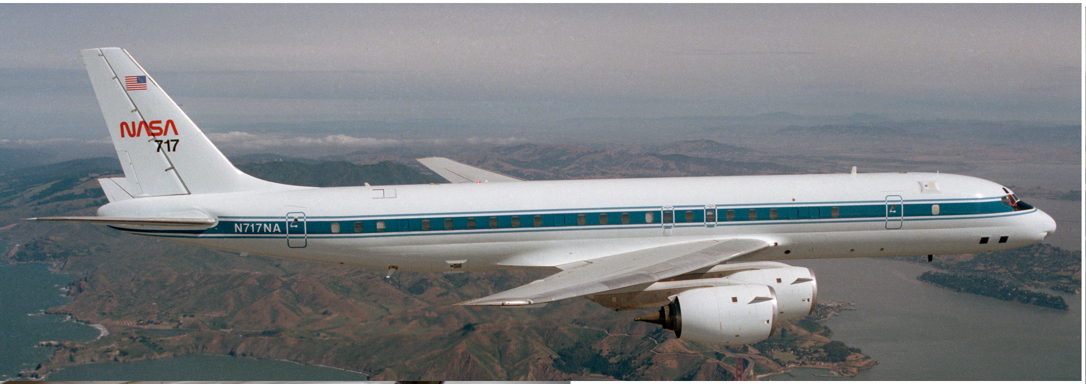
  - Measurement environment
  - Instrument artifacts

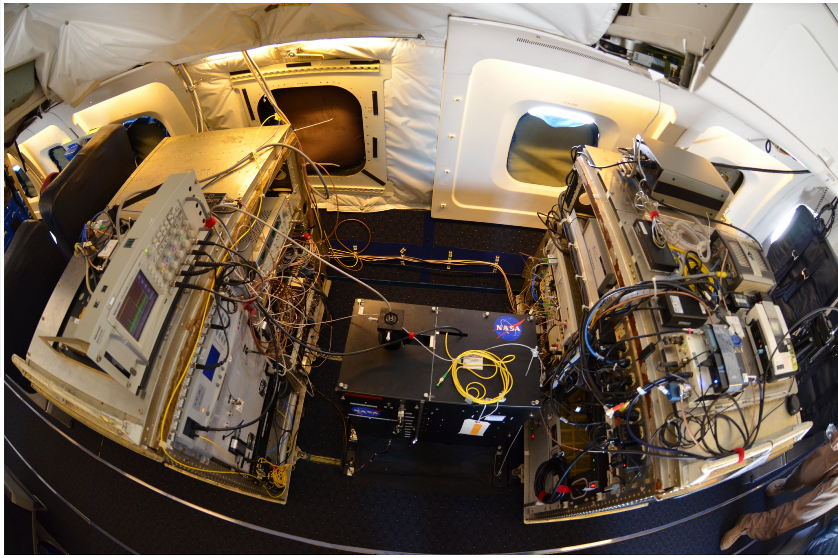
Measures CO_2 column absorption & range to scattering surfaces:
- Ground
- Ocean surface
- Cloud tops

~400 km circular polar orbit



CO_2 Sounder Airborne Lidar in 2014 & 2016



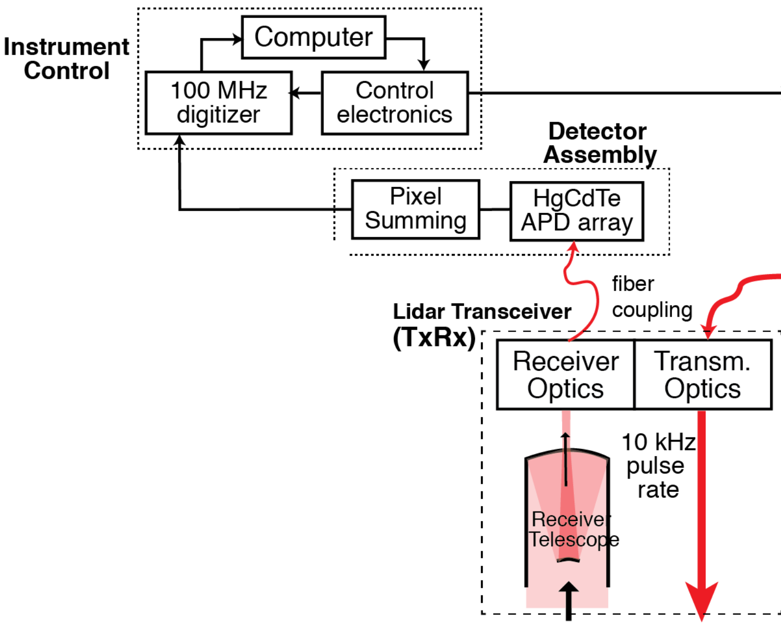


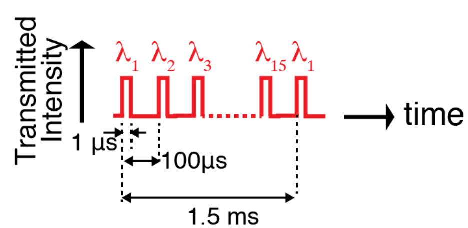
Improvements for 2014 & 2016 ASCENDS flights:

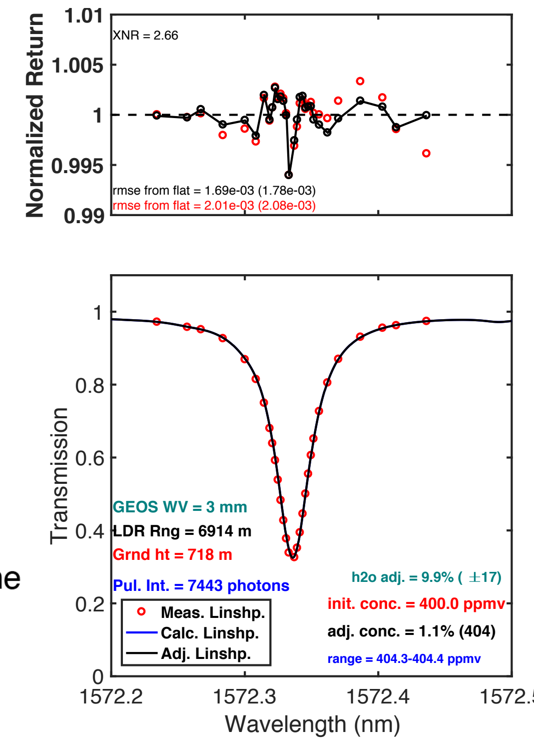
1. Optimized wavelength sampling across CO2 absorption line from 15 to 30 laser wavelengths
2. Step-locked seed laser
3. HgCdTe APD detector in receiver
4. Analog waveform data recording
5. 10 Hz recording & retrieval resolution
6. Larger laser footprint (2016)

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

- Multiple wavelength samples across the CO_2 absorption line to reduce measurement bias
- Pulsed laser to give range resolved measurements
- Laser wavelengths locked to the CO_2 line center with given offsets
- Post flight XCO_2 retrievals based on atmosphere model, meteorological data, and least squares fit.







CO_2 Sounder uses a Pulsed Multi-wavelength Lidar Approach

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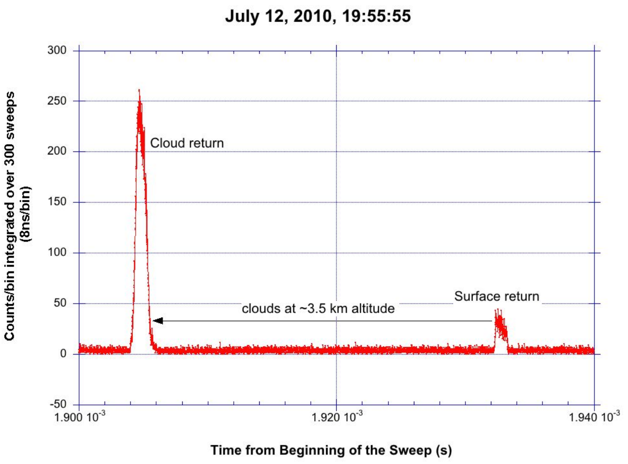
Time-resolved backscatter measurements allow:

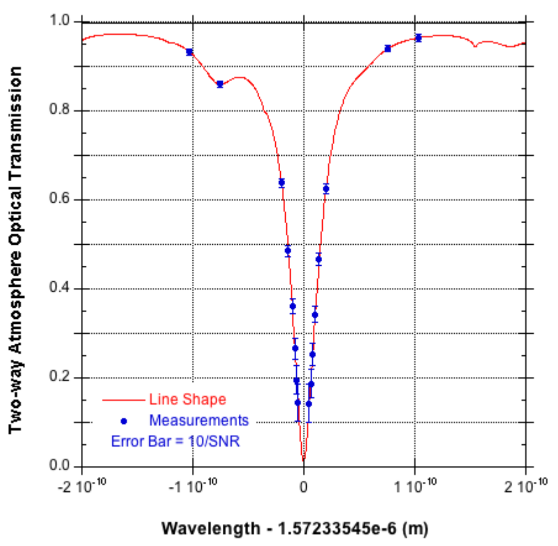
- Direct measurement of the path-length
- Detecting cloud & aerosol scattering
- Time gating around surface:
  - Eliminates atmospheric scattering
  - Reduced solar background noise



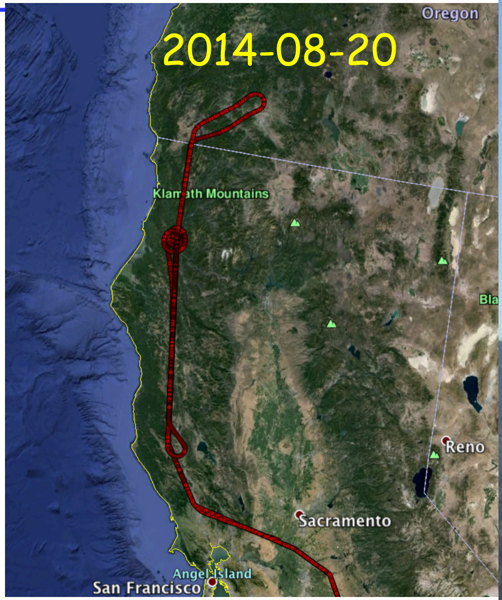
Multi-wavelength sampling of CO_2 absorption line:

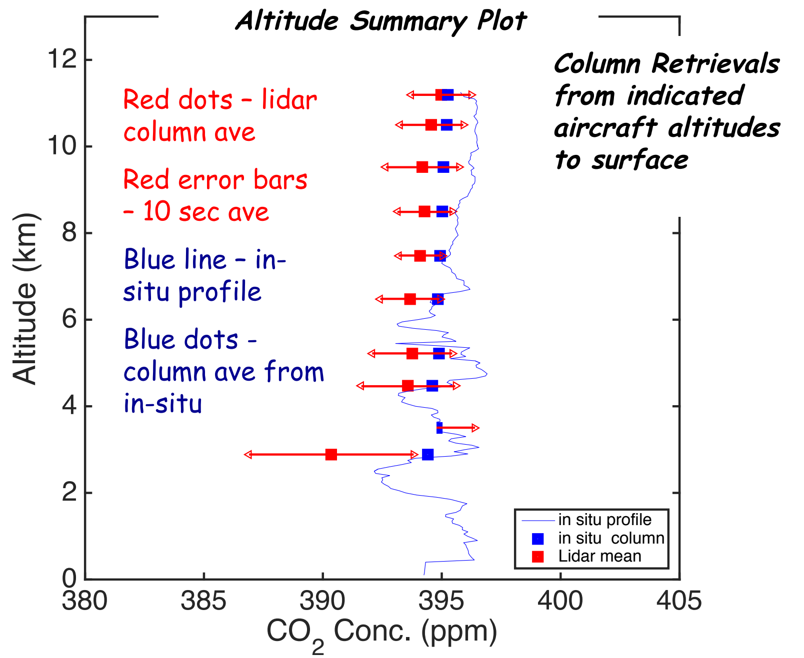
- Allows correcting for uneven instrument spectral response
- Allows solving for Doppler shift and eliminates its effect in XCO_2 retrieval
- Allows correction for influences of water vapor on CO_2 line shape & in retrievals

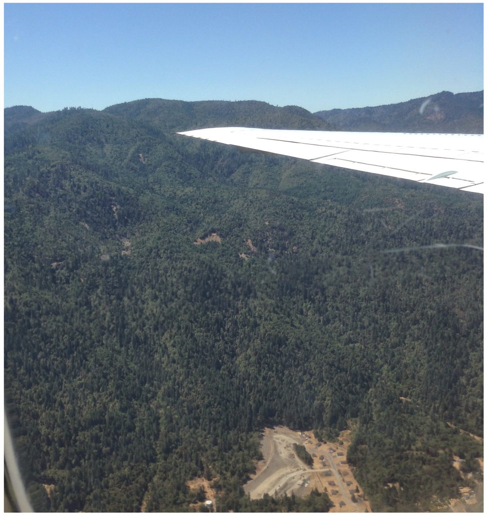
Retrieval solves for XCO2 via a least square fit of the predicted CO2 line shape to the lidar measurements



Lidar Measurements over Tall forests in Coastal California (Redwood forests on several km high mountains)



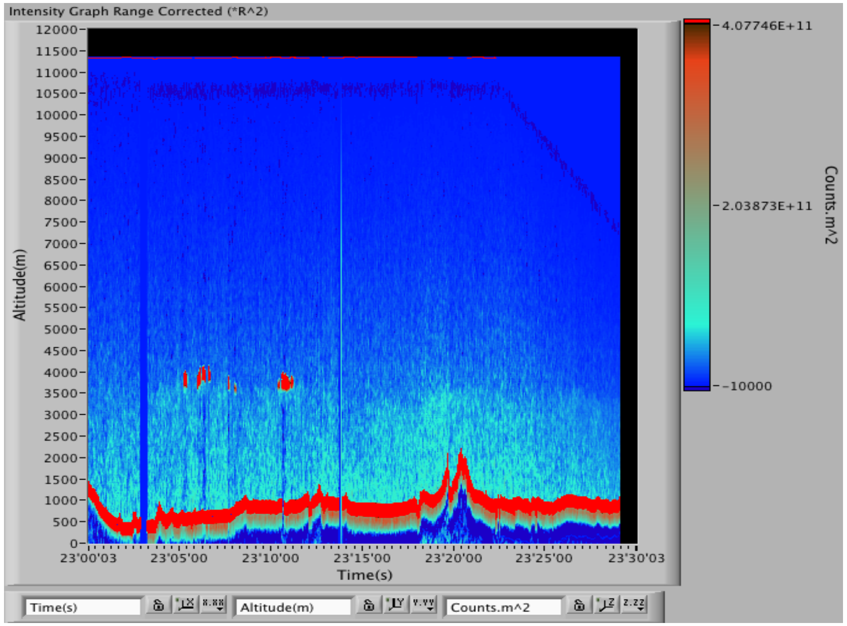




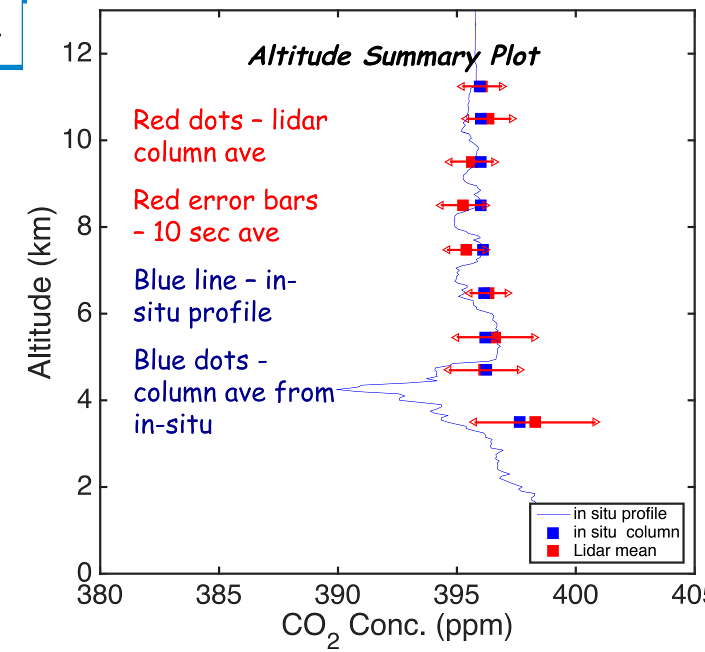
- **Why ?: Accurate CO_2 measurements over Amazon, Congo & Boreal forests are important for ASCENDS**
- **Varying tree canopy & terrain -> rapid change in column length**
- **Results show accurate (very low bias) measurements in challenging conditions**

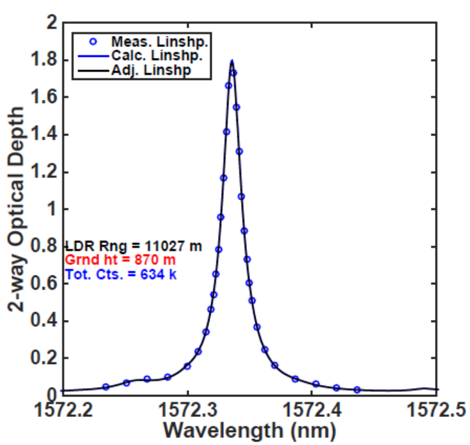
Accurate Lidar Measurements though aerosols over desert: (2014 SF-2 over Edwards AFB)

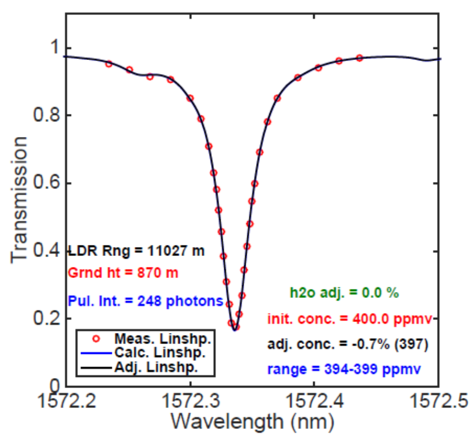
ASCENDS



8/22/2014

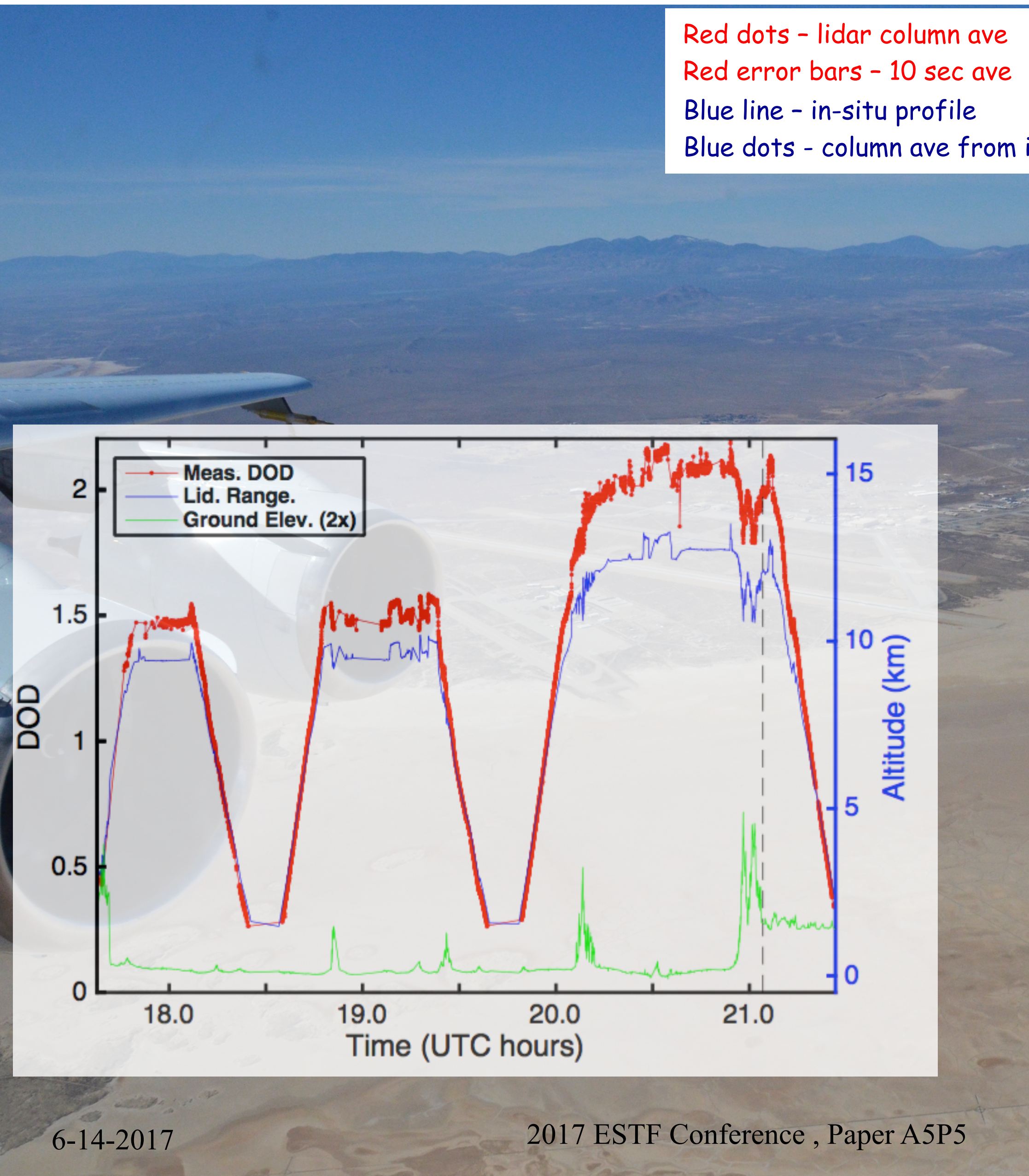




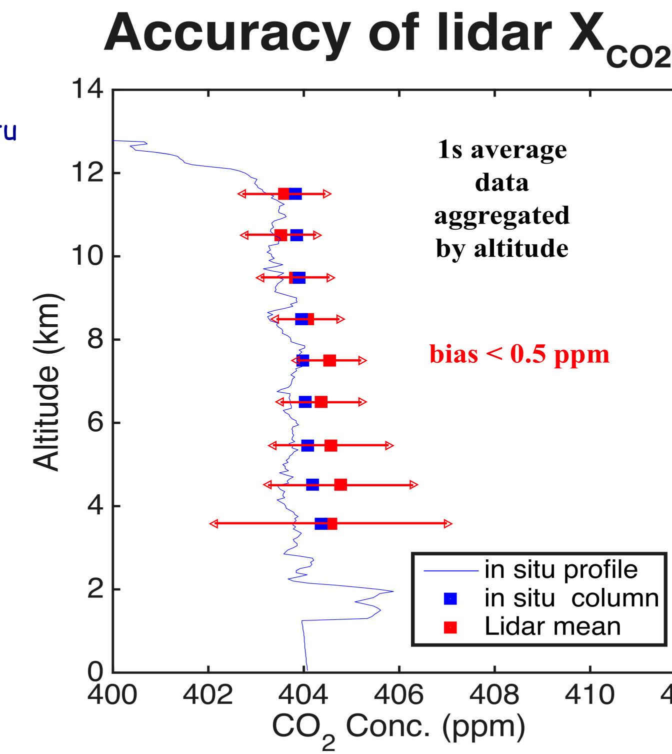


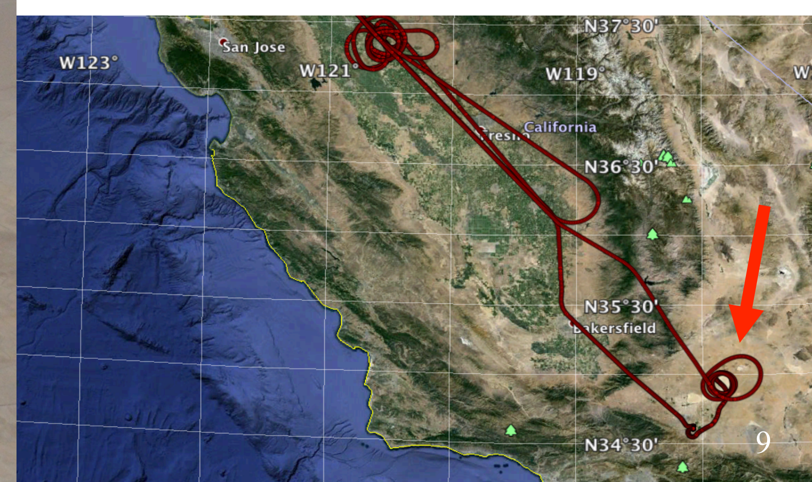
- Range-resolved measurements allow timing gating to minimize impact from atmospheric scattering
- Allow robust retrievals with low bias
- Minimizes retrieval errors over rough surfaces (terrain, and tree cover)

Lidar Measurements over desert on February 10, 2016
Spiral over Edwards AFB CA

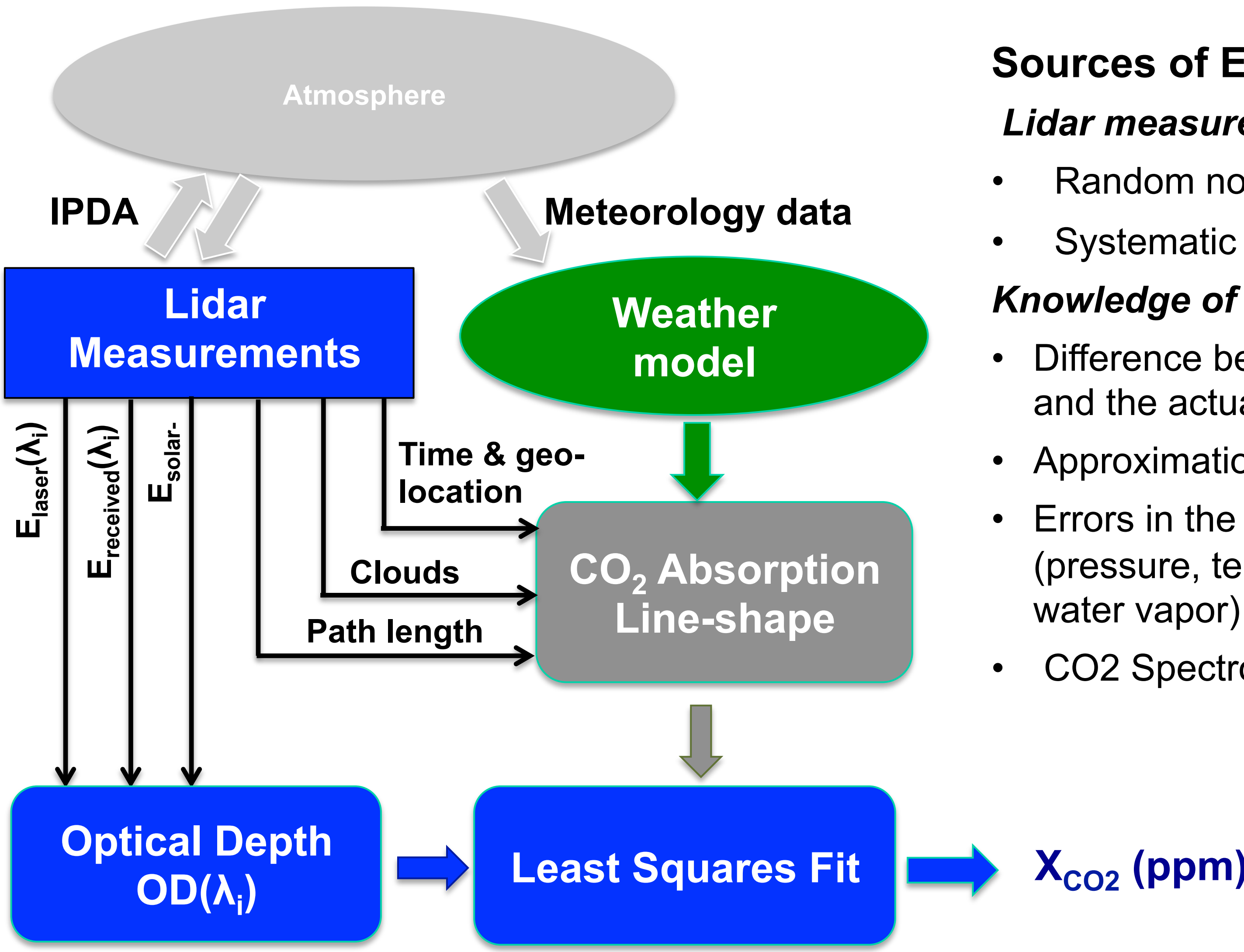


Red dots – lidar column ave
Red error bars – 10 sec ave
Blue line – in-situ profile
Blue dots - column ave from in-situ





XCO_2 Retrieval for the CO2 Sounder Measurements



Sources of Errors:

Lidar measurements:

- Random noise
- Systematic errors and biases

Knowledge of atmosphere:

- Difference between the model and the actual atmosphere
- Approximations in modeling
- Errors in the meteorology data (pressure, temperature, and water vapor)
- CO2 Spectroscopy

CO2 Sounder Lidar Measurement Model & Airborne Measurements over Desert (Feb. 2016)

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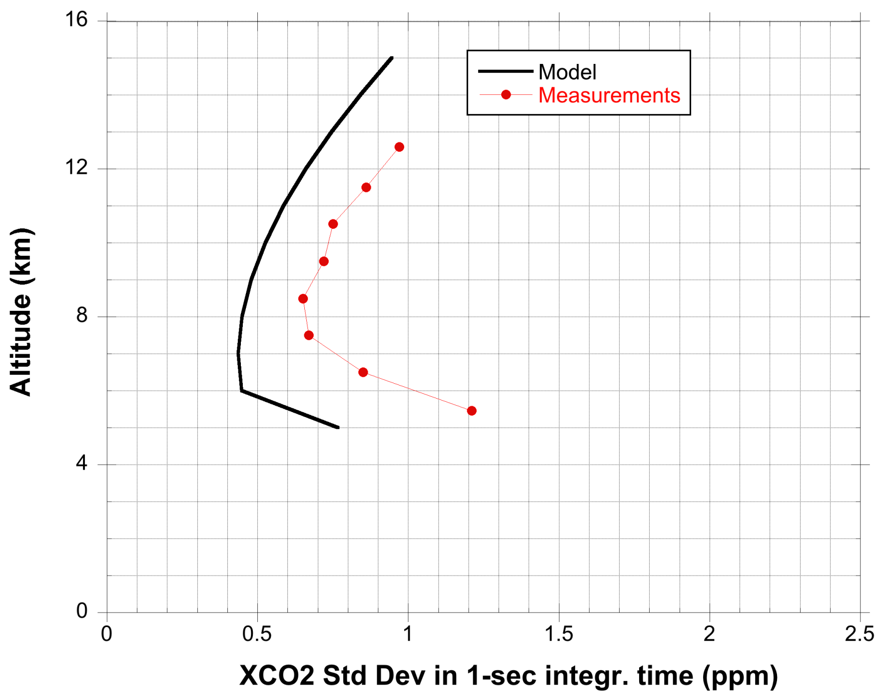
- **Measurements & airborne lidar model agree well from 7 to 13 km altitude**
- Error offset is likely due to slighter higher noise in detector amplifier
- For < 8 km altitudes, the errors increase, caused by:
  - Lower CO_2 absorption in shorter column
  - Smaller Laser footprint => more impact from surface reflectivity changes.

Airborne-borne CO_2 Sounder Lidar Parameters	
Nominal laser pulse energy	25 µJ
Laser pulse width and rate	1.0 µs at 9 kHz
Orbit altitude	2-12 km
Telescope diameter	20 cm
Receiver optics transmission	73%
Receiver FOV	500 µrad
Receiver optical bandwidth	1.4 nm FWHM
Off-line atmosphere transmission	80%
Surface reflectance (off-line)	44% (desert)
Receiver integration time	1 sec.
Detector quantum efficiency including fill factor effect	η_{APD} =70%
Detector gain and excess noise	G_{APD}=600, F_{excess}=1.05
Detector dark current	5 fA
Receiver NEP	0.56 fW/Hz$^{1/2}$



Scaling Lidar to Space: Approach & Model-Predicted Performance

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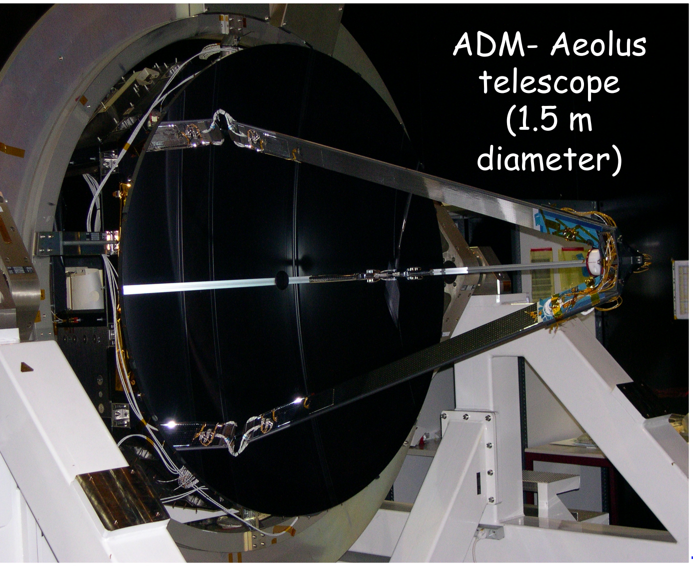
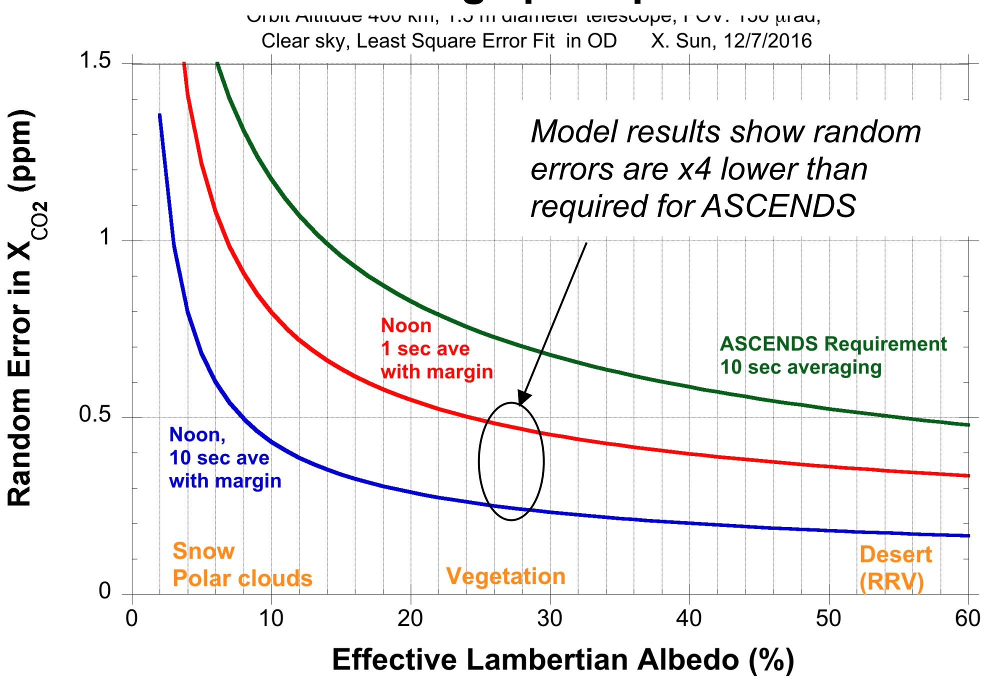


Same CO2 Sounder measurement model, but using space parameters



- Laser transmitter emits 20W (2.7 mJ at 7.5 KHz)
  - Laser development on its way to TRL-6
- 1.5 diameter telescope, similar to ADM
- HgCdTe APD Detector, near TRL 6 now
- Space lidar size similar to ADM, but simpler & less. power (~600 W)

Laser Pathway to Space*

(Ongoing ESTO QRS Development– TRL 6 by Dec 2017)

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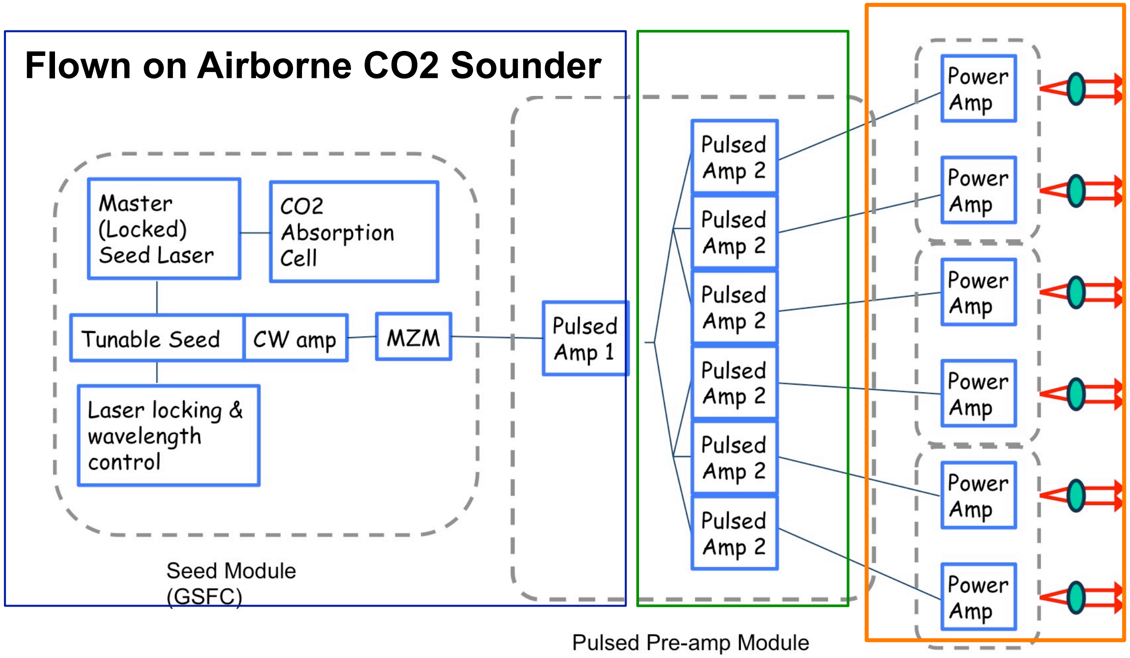
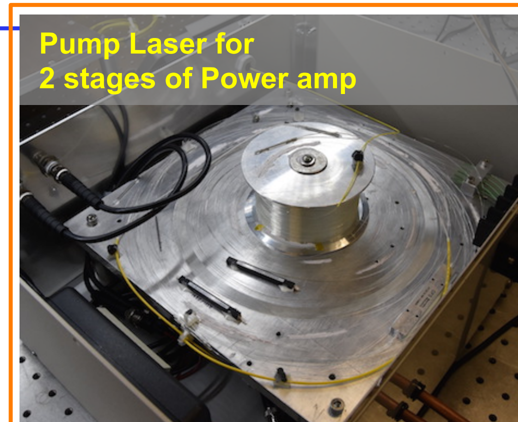
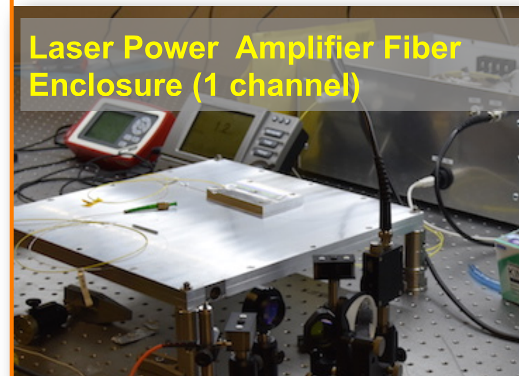


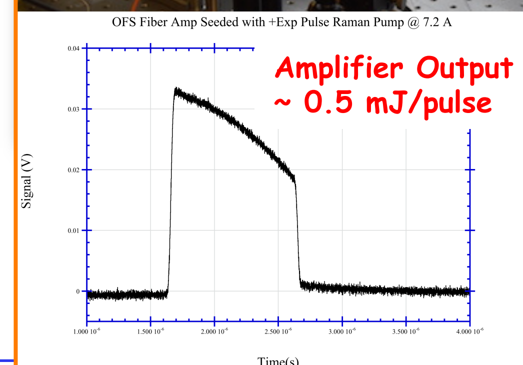
Pulsed Pre-amp Module
Nuphoton, Inc.

0.45 mJ/pulse per amp

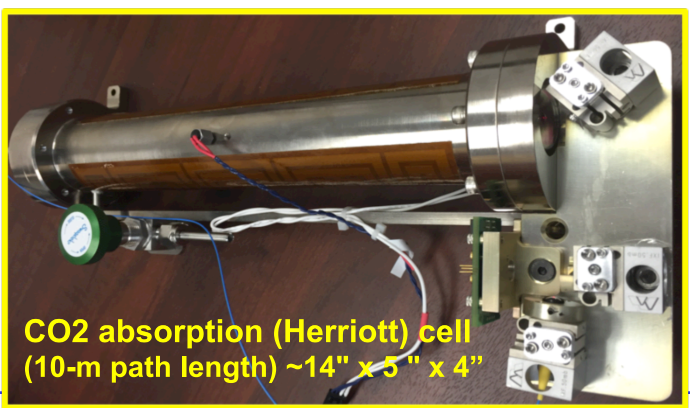
Total energy per pulse (6 amplifiers) 2.7 mJ

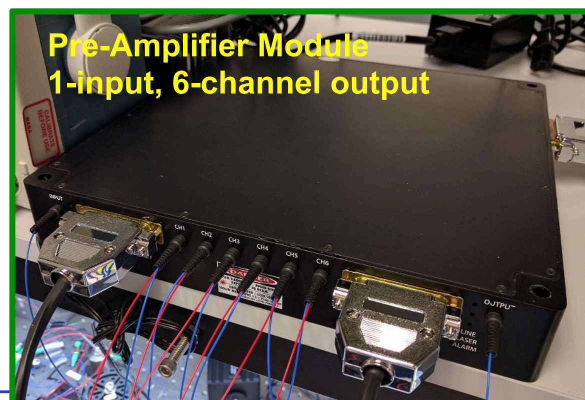






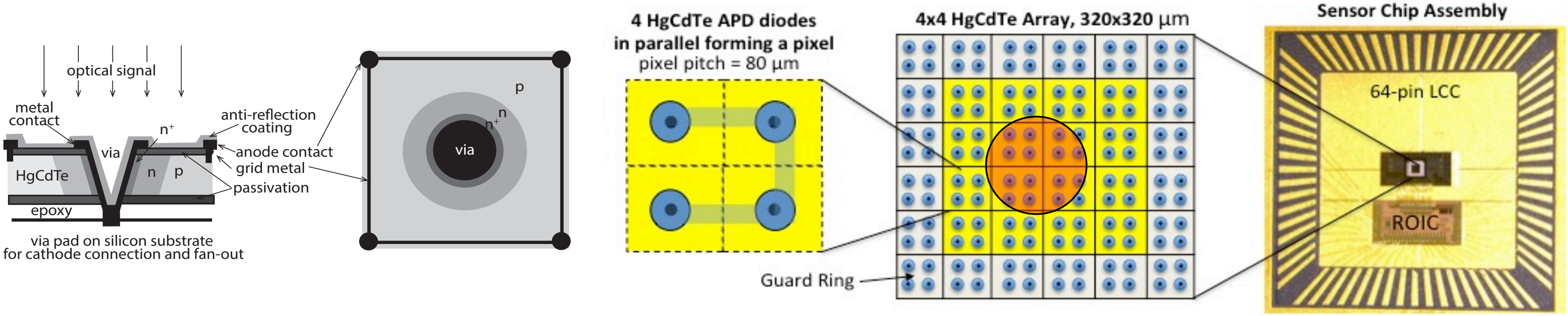
New Technology Developments





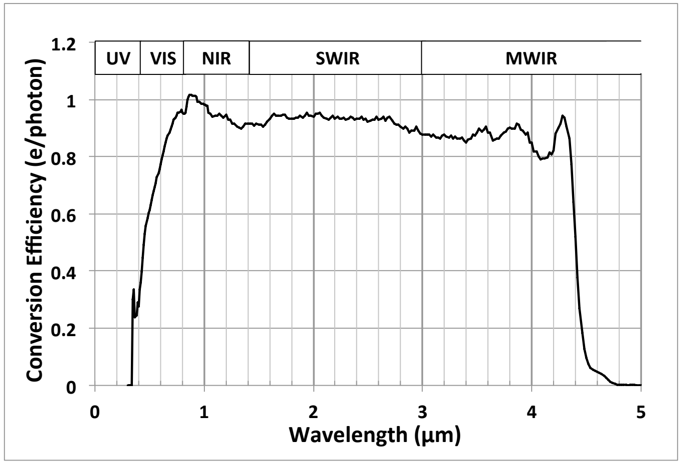
*ESTF 2017, Paper A5P2

A key to CO2 Sounder Lidar performance: 4x4 HgCdTe APD Array Detector*

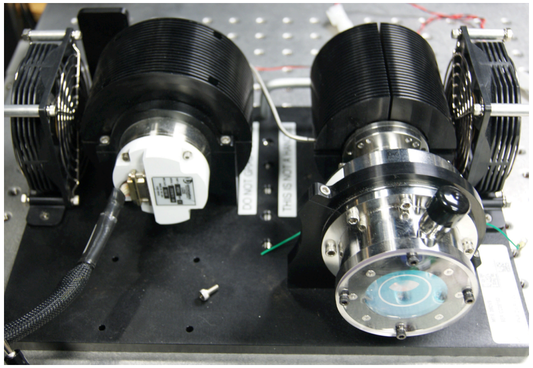


*- Developed under ESTO- IIP10

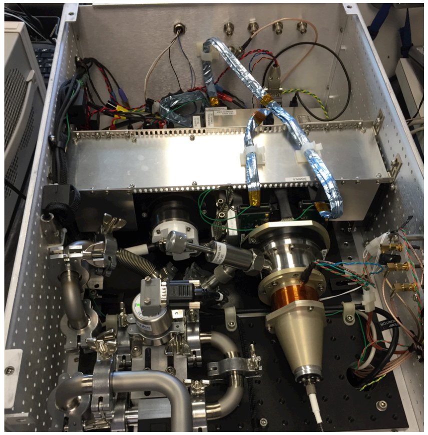
~90% Quantum efficiency from 0.7 to 4.3 µm



Closed-cycle cryocooler used for lab tests and aircraft

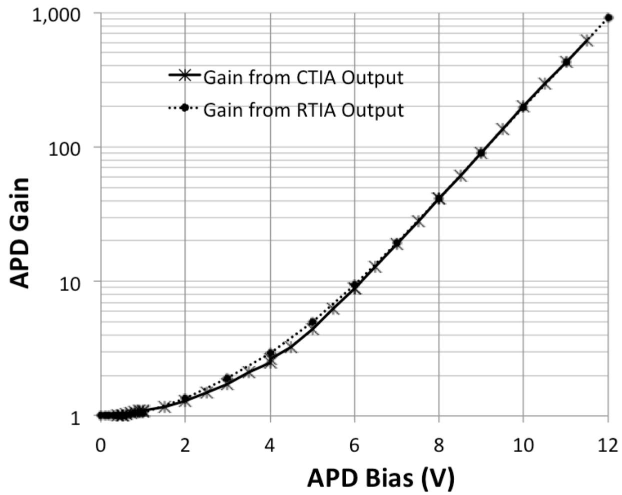


Packaged detector system for airborne lidar

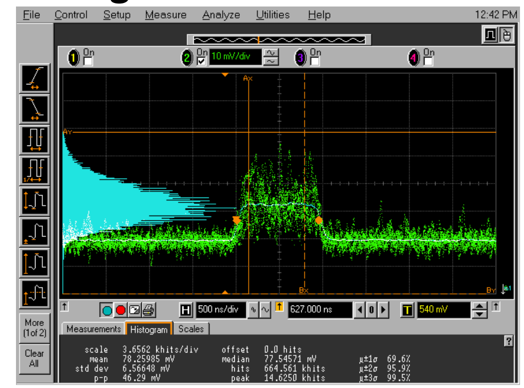


Lab Tests show the 4x4 HgCdTe APD Detector is nearly ideal for IPDA lidar

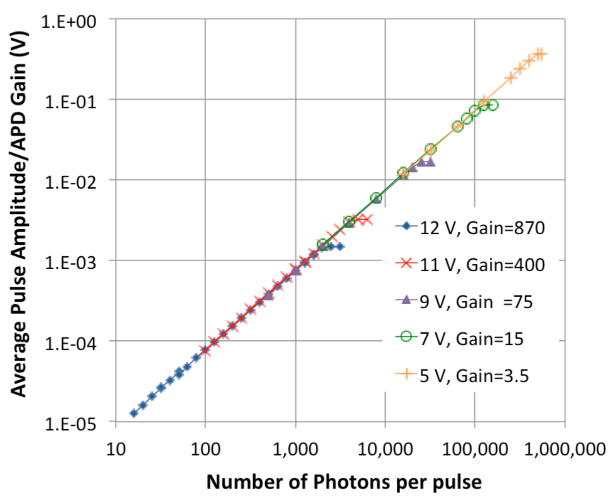
High and noiseless APD gain to override circuit noise



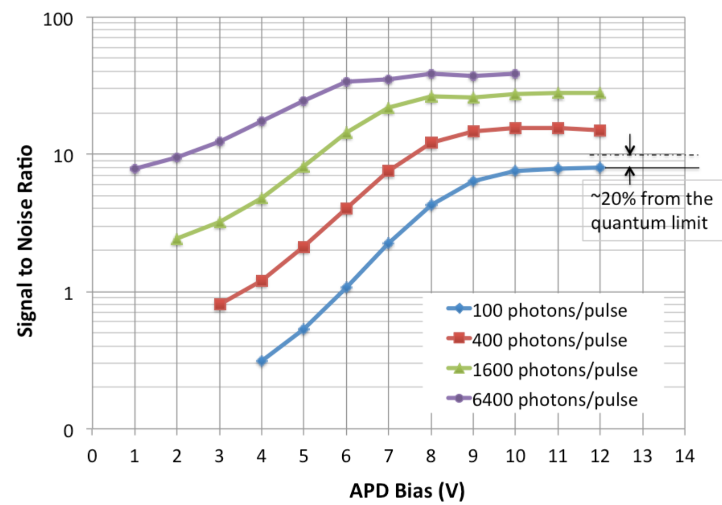
Analog Detection Performance



Wide linear dynamic range to accommodate signals from various ground surface and airplane altitude

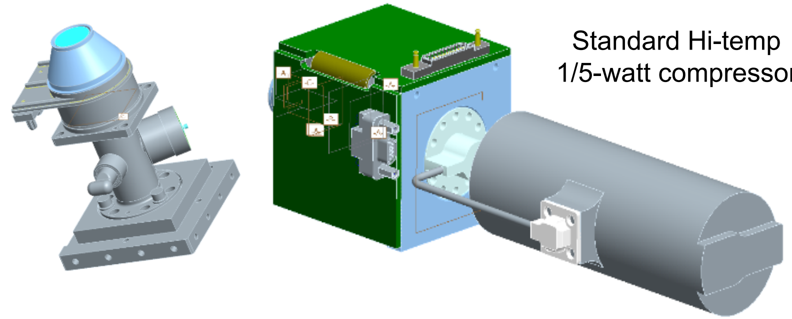


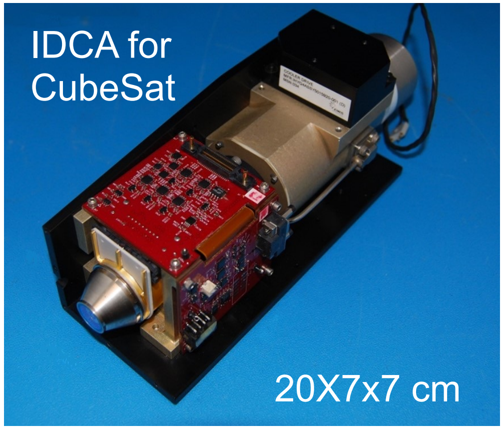
Quantum limited receiver SNR

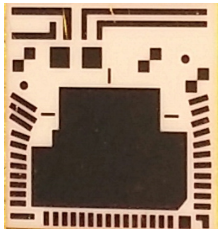


HgCdTe APD Detector in Mini Cryo-Cooler Developed for Space

- Funded by ESTO InVEST and QRS program for a similar (2x8) HgCdTe detector
- Miniature Stirling cryo-cooler from DRS with multi-year life time (Rawlings, SPIE 9070, 2014)
- Detector operating temperature 80 K or 110 K
- Mass: ~1 kg,
- Electrical power: 6-8 W with heat sink at 30°C
- Vibration & thermal cycle tests per NASA GEVS specification
- Thermal vacuum and proton radiation tests in Summer 2017.





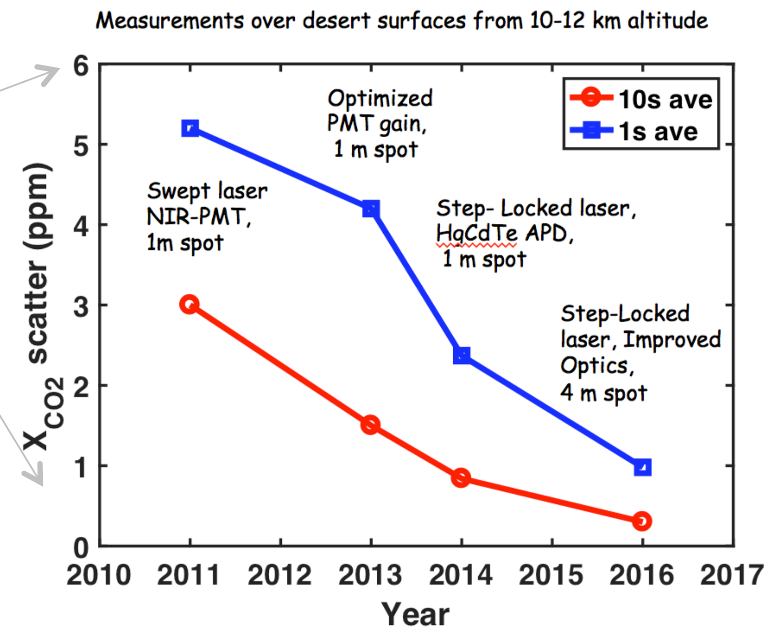


Chip carrier for the 4x4 HgCdTe APD in same cooler (ESTO-QRS 2015)

Summary

GSFC

- Pulsed multi-wavelength CO_2 Sounder lidar provides a robust measurement of XCO_2
- Steadily improved airborne performance since 2011
- Technologies developed for major components, now at or near TRL-6
- Developed an instrument model and XCO_2 retrieval algorithm and verified them with airborne data
- Model scaled to space shows lidar has ¼ random error required by ASCENDS
  - Allow 10x higher spatial resolution or a smaller instrument size.



We acknowledge the outstanding work of our team and appreciate the support from ESTO