A Multi-wavelength Integrated Path Differential Absorption Lidar to Measure XCO_2 from Space: Status

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ASCENDS Mission Approach

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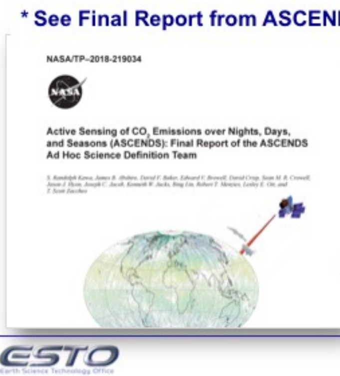
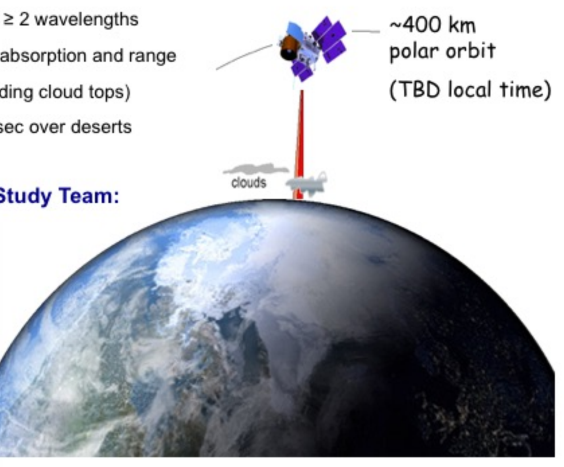
Measures CO_2 (XCO_2) via IPDA lidar* :

- Nadir pointing from LEO orbit
- Measures a single CO_2 absorption line with ≥ 2 wavelengths
- Continuous measurements of CO2 column absorption and range
- Measures range to scattering surface (including cloud tops)
- Random measurement error: < 1 ppm in 1 sec over deserts
- Bias: <0.3 ppm

*** See Final Report from ASCENDS Study Team:**





CO_2 Sounder Lidar Approach

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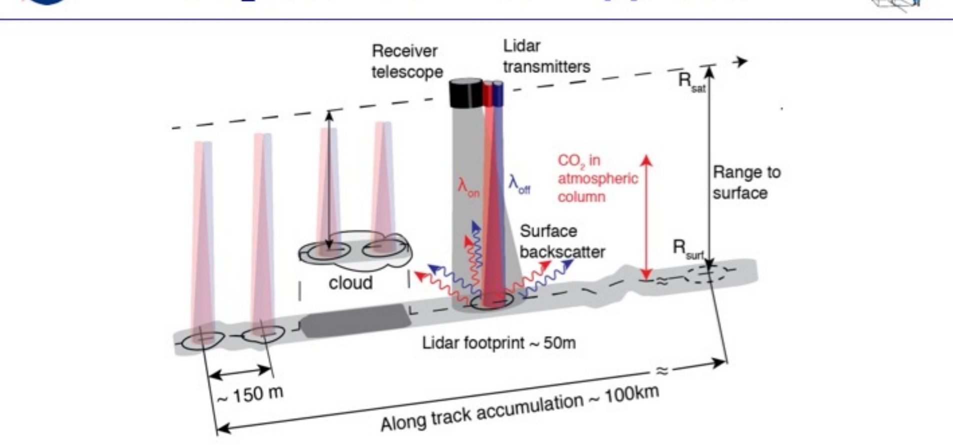

- Multi-wavelength Integrated Path Differential Absorption (IPDA) lidar measurements to scattering surfaces.
- Column average CO_2 mixing ratio (XCO_2) retrieved by fitting lidar measurements to an atmospheric model.

CO_2 Sounder Lidar

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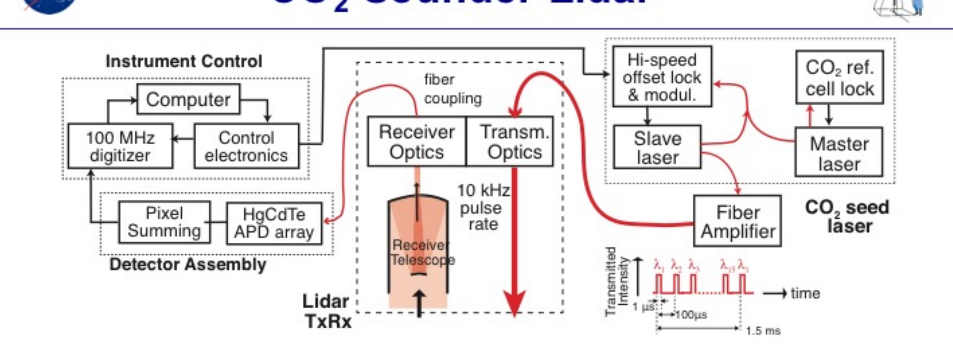
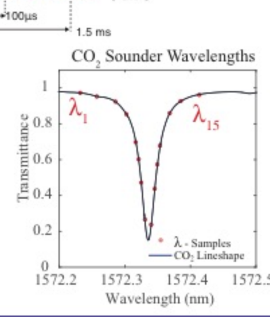


- Direct Detection IPDA lidar
- Lidar samples the CO2 line with 15 to 30 laser wavelengths
- Sampling line shape allows retrieval's line fit to reduce biases:
  - Typical ones are from instrument artifacts, such as laser wavelength drift & receiver's non-uniform spectral response
  - Others can be from Doppler shift, & from WV residual interference
- The number of wavelengths is programmable



Retrieval of XCO_2

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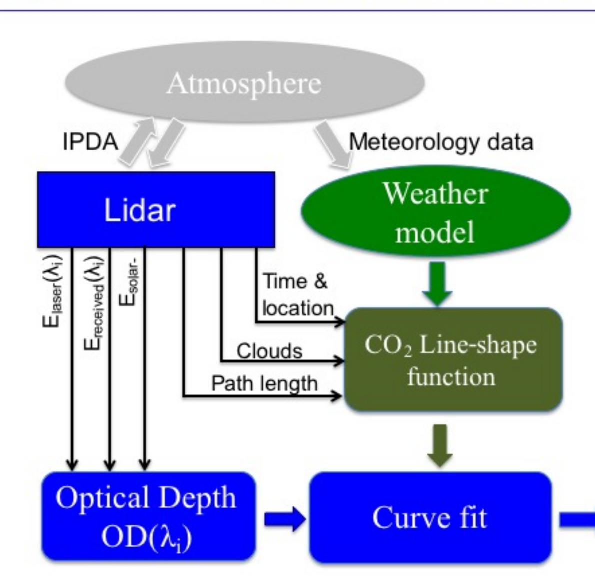

X_{CO2} (ppm)

Sources of Error in XCO_2 retrievals

Lidar measurements

- Random noise
- Biases

Knowledge of atmospheric state:

- Difference between assumptions and actual atmosphere
- Approximations in the model
- Limitations and errors in the meteorology data

CO2 Spectroscopy

Level-0 Data Processing

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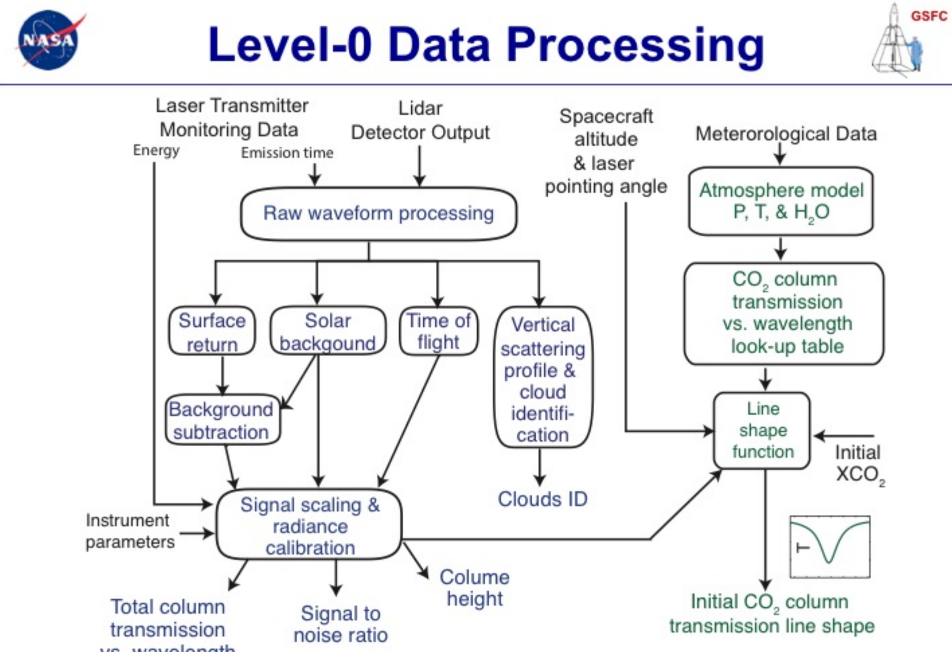

CO_2 Line Fitting Approach

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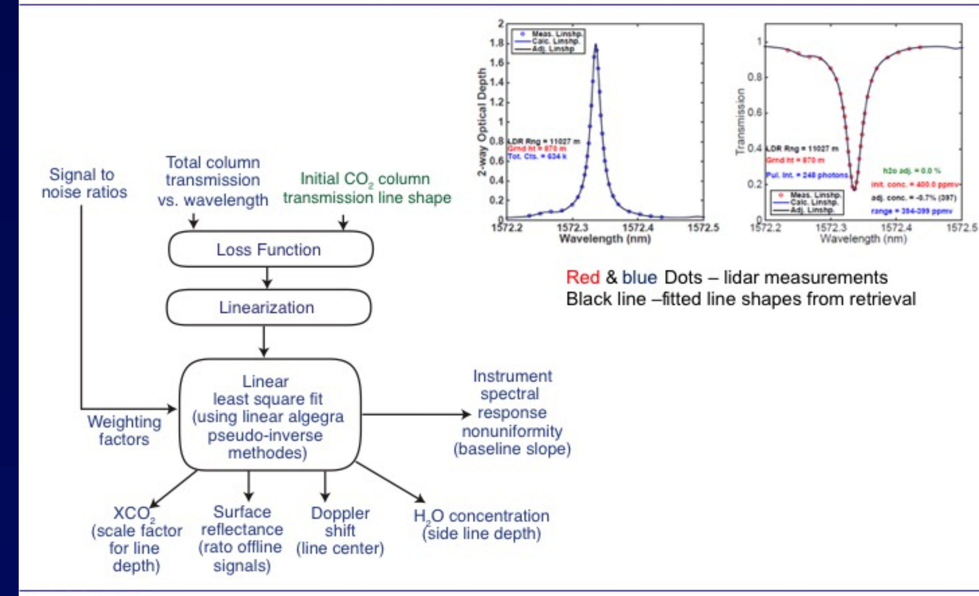

CO_2 Line Fitting Characteristics

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Linearization and least square fit

- Standard methods used in small signal deviation under high signal to noise ratio (SNR)
- Weighting factors vs. wavelength are ~ same as SNR, which can be estimated from signal
- Simultaneous solutions to multiple parameters

Averaging kernel (AK) of XCO_2 from the fit

- The initial line shape assumes an AK at each wavelength across the CO_2 absorption line.
- The XCO_2 from the fit is the scale factor of the line shape function that minimizes residuals at all laser wavelengths.
- The final AK of the XCO_2 is a weighted sum of the pre-assumed AK at different laser wavelengths.
- The final AK may be modified by redistributing the laser wavelengths.

Measurements Demonstrated with Airborne CO_2 Sounder Lidar in ASCENDS Campaigns

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Developed as space lidar 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:
  - HgCdTe APD (QE ~70%)
  - 100 MHz analog digitizer (10 Hz)

2011, 2013, 2014, 2016 ASCENDS Flights

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

Sample Airborne Measurements made in 2017
July 20 Spiral over Edwards CA: CO_2 & XCO_2 Retrievals

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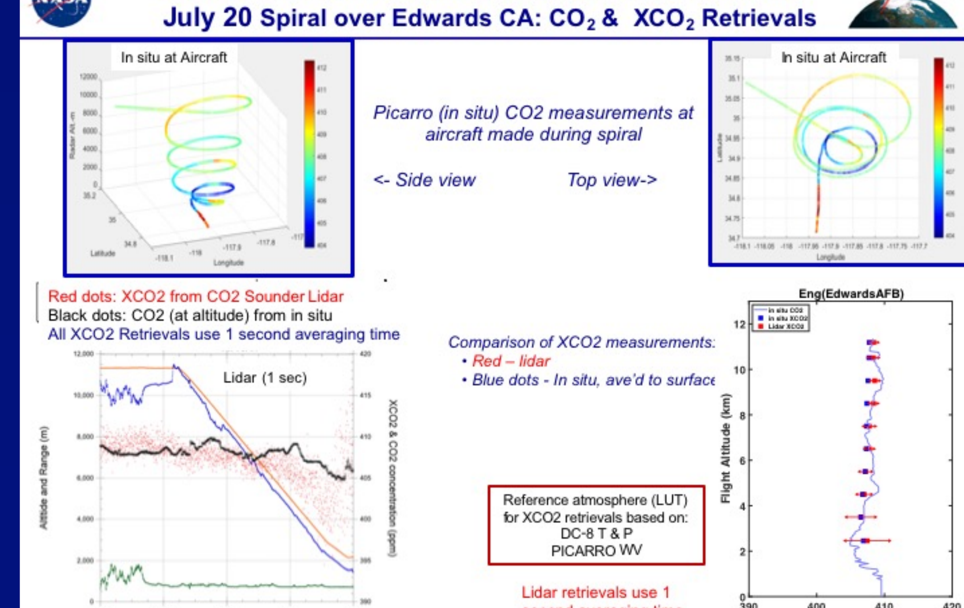

Comparing Error Model with Airborne Data
Scaling the Results for the Space

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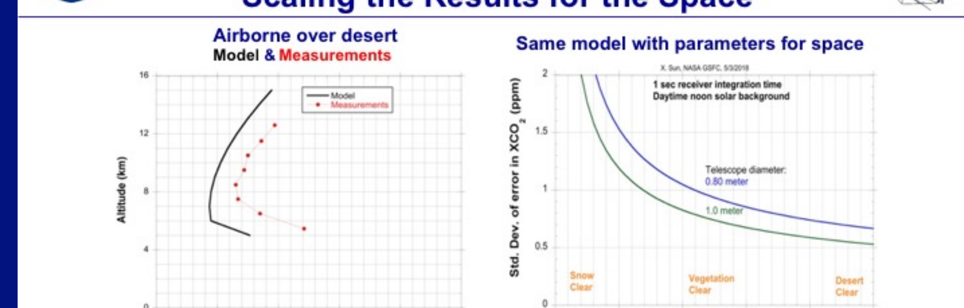

Parameter	Value		Parameter	Value		Parameter	Value
Orbit Altitude	400 km		Laser wavelengths/scan	16		Receiver optical transmission	50%
Laser pulse energy	2.67 mJ		Off-line atmosphere trans.	70%		Detector effective QE	67%
Laser pulse rate	7.5 kHz		Surface reflectivity	varies		Detector APD gain	500
Laser pulse width	1.0 usec		Telescope diameter	0.8 and 1.0 m		Detector dark current	5 fA
Laser divergence	150 urad		Telescope FOV	225 urad		Detector bandwidth	~ 6.5 MHz

(Left top) Comparison of the predicted XCO_2 error and the measurements for the 2016 airborne measurements over Edwards CA that used 1-sec averaging. (Right top) Predicted XCO_2 error of the CO_2 Sounder model versus surface reflectivity for 1-sec averaging and space. The effective diffuse surface reflectivity for RRV is 55%. (Bottom) Some parameters used in the space calculation.

CO_2 Sounder Lidar
- Design for Space, using 1-m telescope

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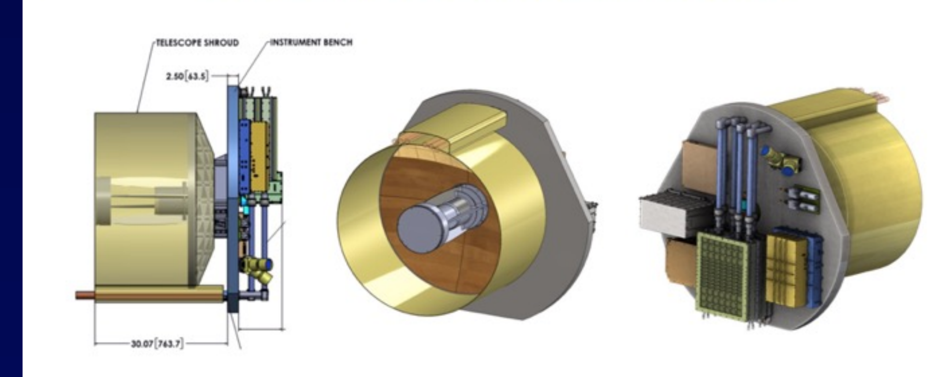

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Laser for Space-based CO_2 lidar

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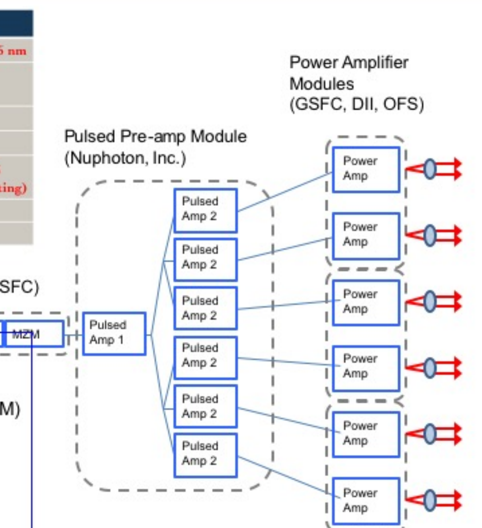
Performance Parameter	Laser Transmitter
Center Wavelength	Nominally centered at 1572.335 nm
Linewidth (each wavelength channel)	≤ 100 MHz
Pulse repetition frequency	7.5 KHz
Pulse Width	1-1.5 µs
Pulse Energy	>3.2 mJ/pulse (goal); >2.6 mJ/pulse (operating, 18% derating)
PER [TBR]	20 dB (TBR)
Wall-plug Efficiency	> 6%



- Seed Module:
  - Dual seed laser and absorption cell
  - CW amp and Mach-Zehnder Modulator (MZM)
- Pulsed Pre-Amp Module:
  - Built by Nuphoton, Inc.
- Power Amplifier
  - Design uses 3 amplifier modules – Packaging approach has 2 amps per module

Laser for Space CO_2 lidar:
Hardware built & in environmental testing

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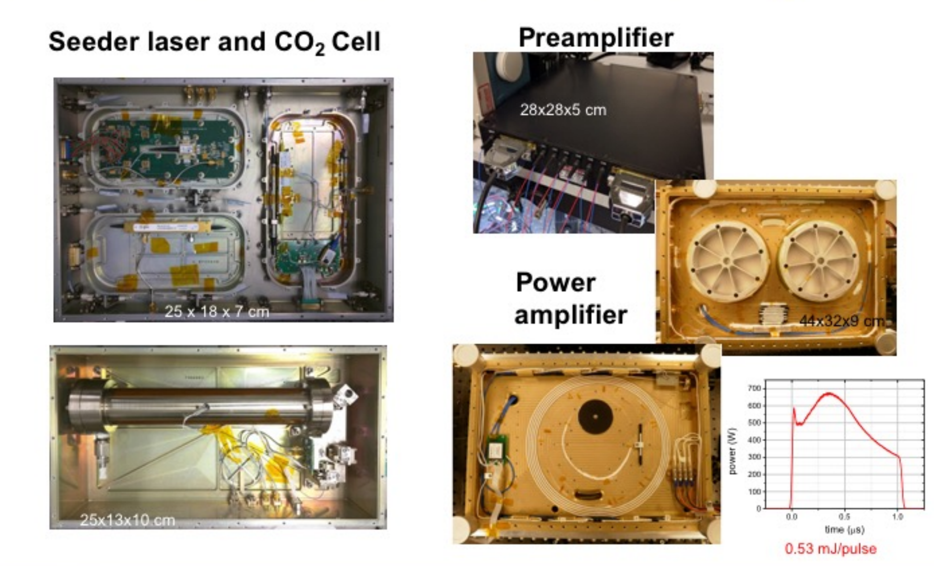

Detector for Space-based CO_2 Lidar
HgCdTe APD in integrated Dewar cooler assembly (at TRL-6)

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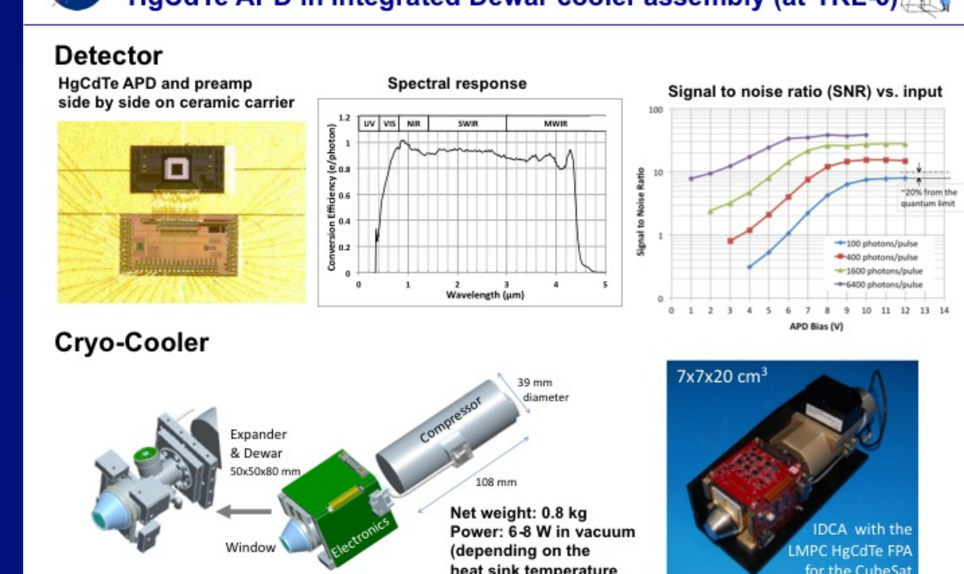

Summary

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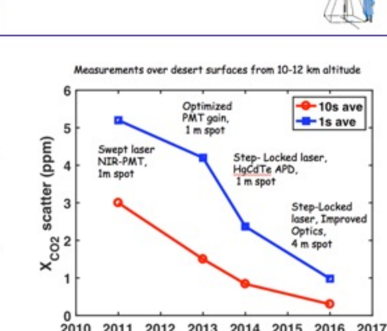
- CO_2 Sounder lidar uses a pulsed multi-wavelength approach
- This provides a robust measurement of XCO_2
- Work steadily improved airborne measurements since 2011
- Developed an instrument model and XCO_2 retrieval algorithm and verified them with airborne data
- Multiple flights show < 1ppm bias errors
- Model, scaled to space, shows lidar has smaller random error than required by ASCENDS
- Technologies developed for major components, & now at or near TRL-6
- **Approach is practical for develop for space now**



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