Development of a Coherent Doppler Lidar for Precision Landing on Planetary Bodies

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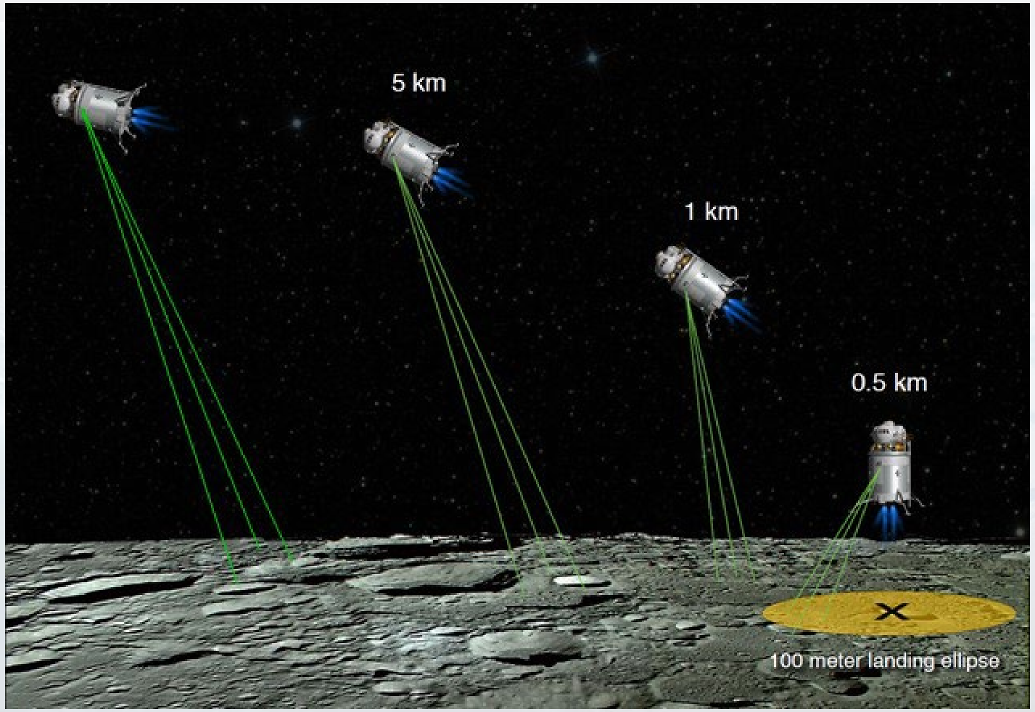
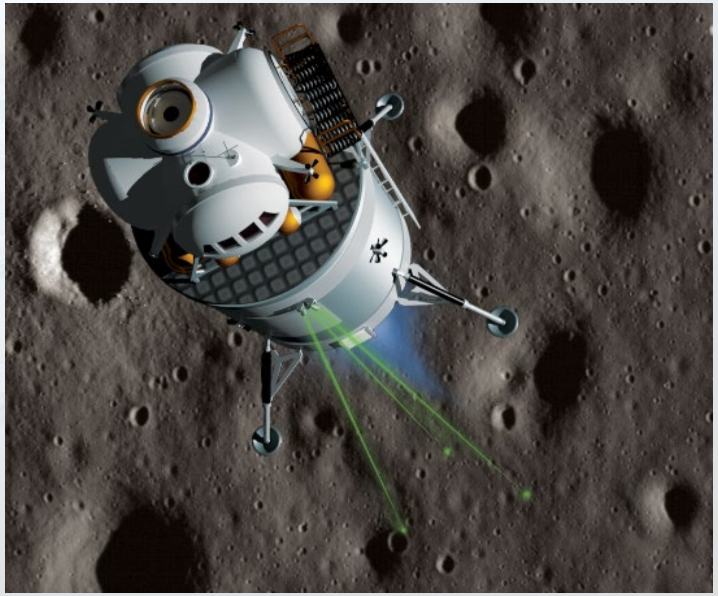
Navigation Doppler Lidar (NDL)

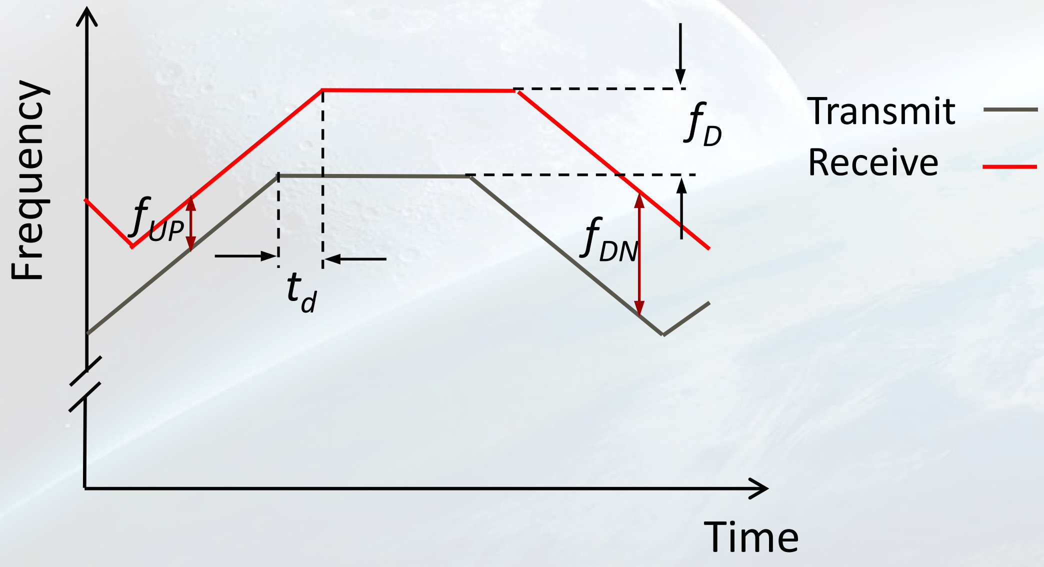
- **NDL is a laser sensor capable of providing precision vector velocity and altitude data**
- **Viable replacement for radars with an order of magnitude higher precision and much better data quality**
  - Enables "***precision navigation***" to the designated landing location
  - Enables "***well-controlled***" descent, landing, and ascent maneuvers to within a few cm/sec

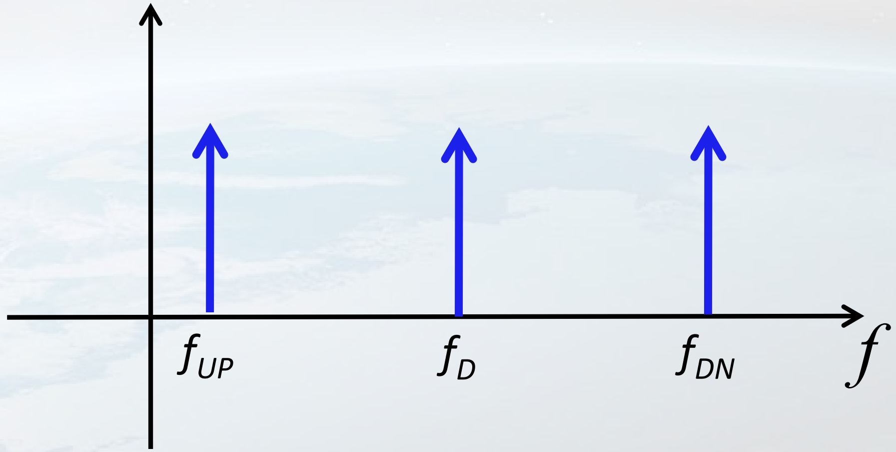




NDL Principal of Operation

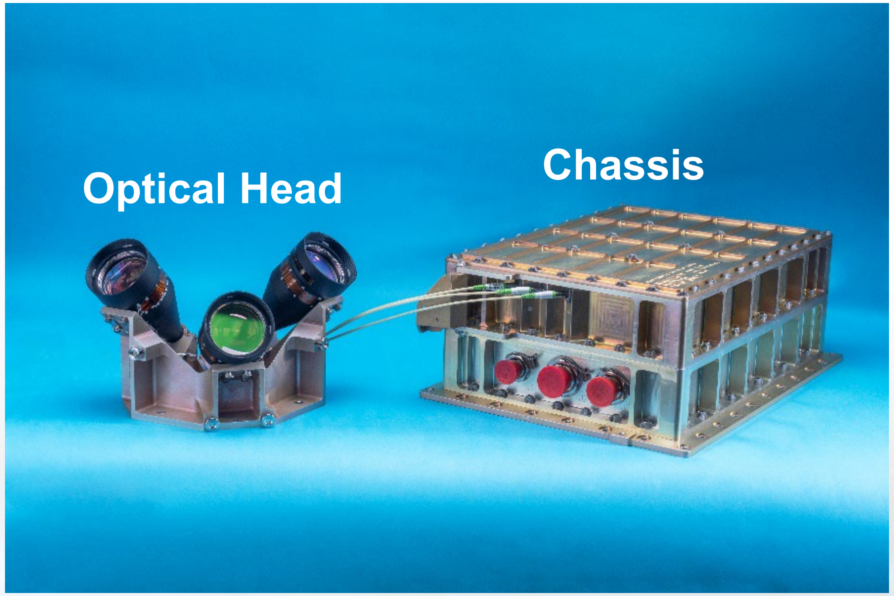
- **NDL utilizes Frequency Modulated, Continuous Wave (FMCW) Technique**
  - 3 segmented frequency waveform
- **Line-of-sight velocity and range are extracted from signal frequencies associated with each segment of the waveform**
- **3 laser beams are transmitted simultaneously to estimate vector velocity and altitude**





$$V = \left(\frac{\lambda}{2}\right) f_D \qquad R = \left(\frac{TC}{2B}\right)\left(\frac{f_{DN} - f_{UP}}{2}\right)$$

Spaceflight Engineering Test Unit (ETU)



- **Built and tested 4 ETUs**
  - **Most parts are Space-Qualified Engineering Models**
  - **Remaining parts are COTS modified to comply with space environments**
  - **Chassis and Optical Head designed for operation on landing vehicles**
    - Operate in radiation and vacuum environments
    - Efficient heat conduction to host vehicle
    - EMI resistance
    - Robust structure
  - **Applied appropriate Quality, Reliability and S&MA processes/standards**
  - **Software is classified as class B with fault tolerance provisions**
  - **Key components were subjected to radiation, vibration and TVAC tests as necessary**
  - **Conducted full system-level environment tests**

NDL Lunar Landing Missions

ETUs

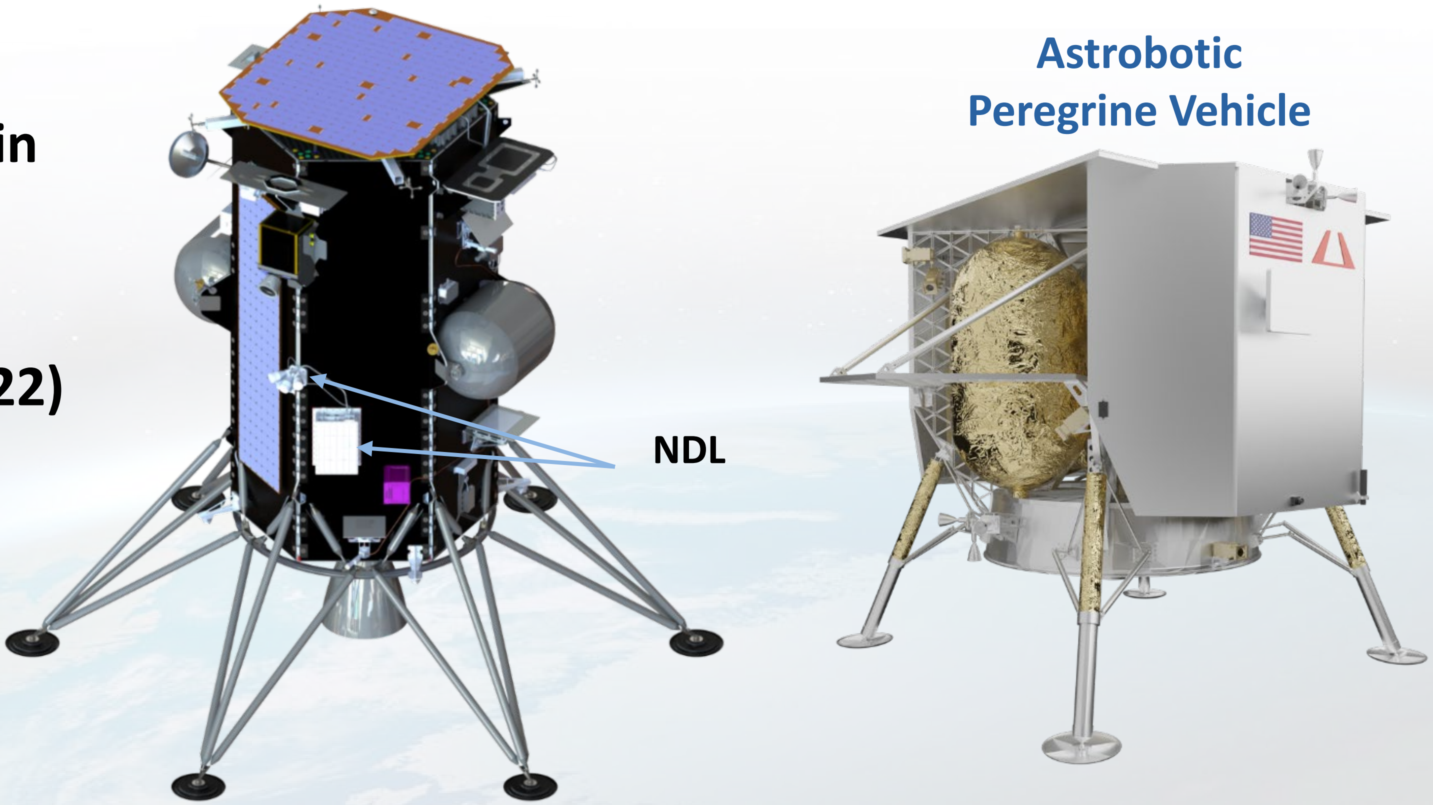
1 – Aircraft flight tests with other avionics

2 – Suborbital flight test on Blue Origin New Shepard vehicle (2021)

3 – Lunar Landing Demonstration onboard Intuitive Machines lander (2022)

4 – Lunar Landing Demonstration onboard Astrobotic lander (2022)

ETU missions will pave the path for future human and robotic landing missions to the Moon, Mars, other destinations.

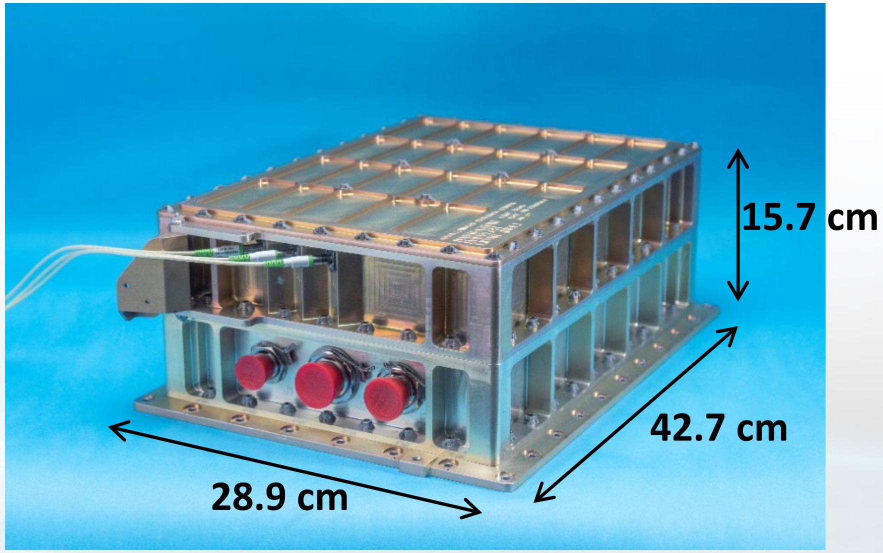


NDL ETU Specifications

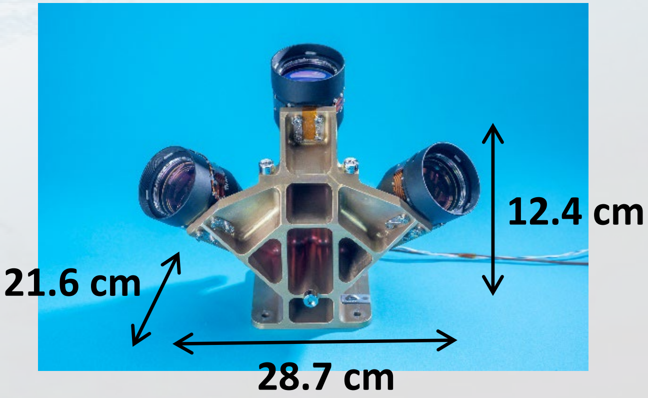
Parameter	Static Platform	Landing Vehicle
Maximum LOS Range on Moon	> 10 km	6.5 km
Maximum LOS Velocity	+/- 218 m/sec	+/- 218 m/sec
Maximum LOS Velocity Error	0.85 cm/sec	20.0 cm/sec
Maximum LOS Range Error	0.98 m	16.1 m
Data Rate	20 Hz	

- **NDL ETU Performance is dominated by the vehicle dynamics**

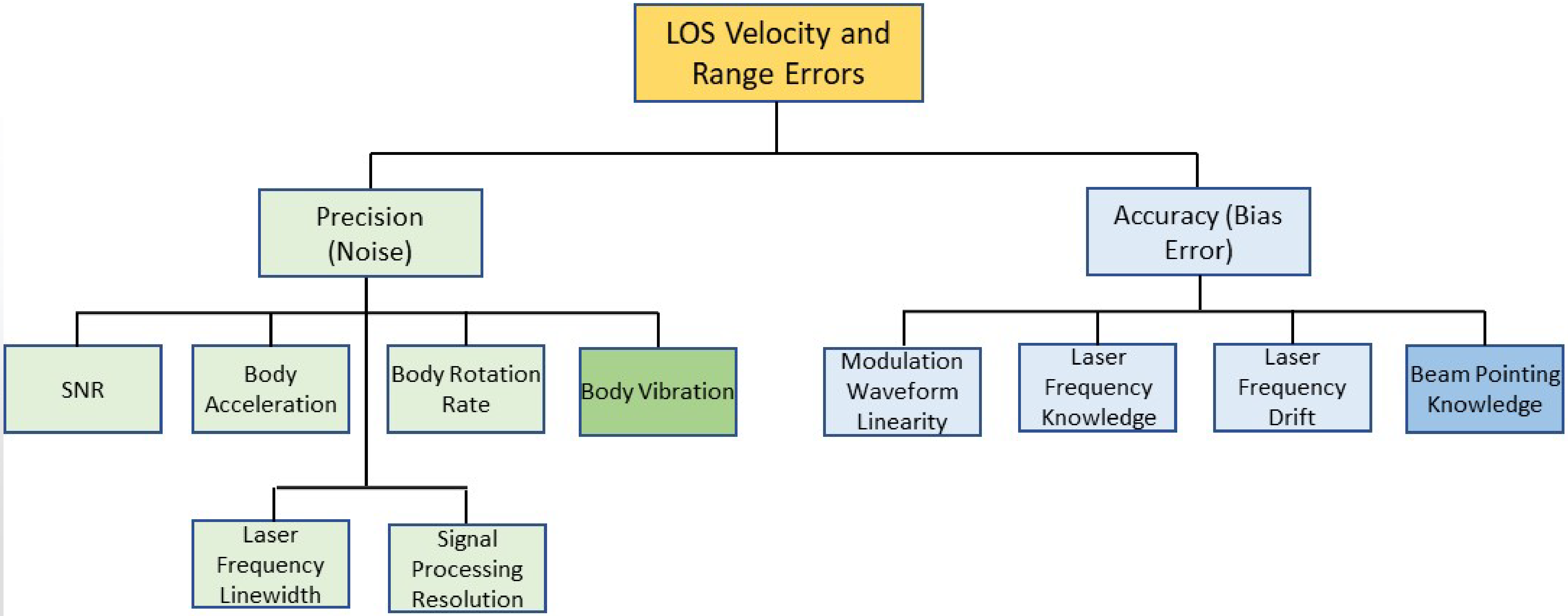
Chassis



Optical Head



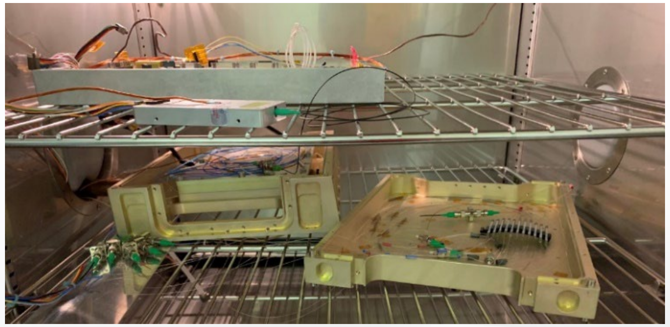
NDL Measurements Error Tree

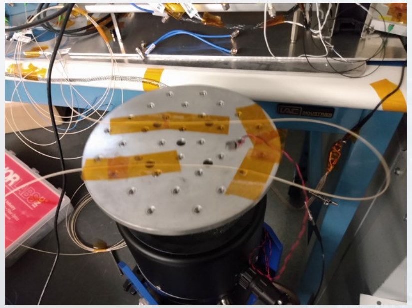


- **Dominant noise source is vibration**
- **Dominant bias error source is beam pointing knowledge**

NDL Functional Tests

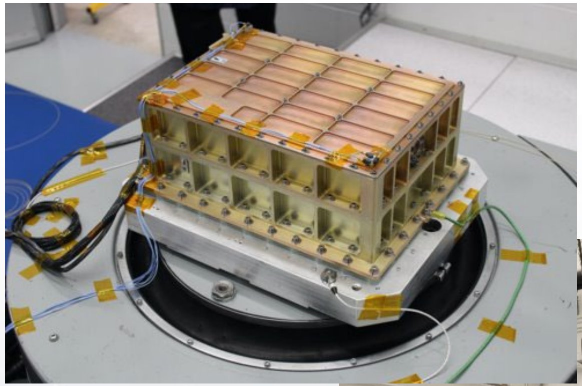
Components Thermal and Vibration tests

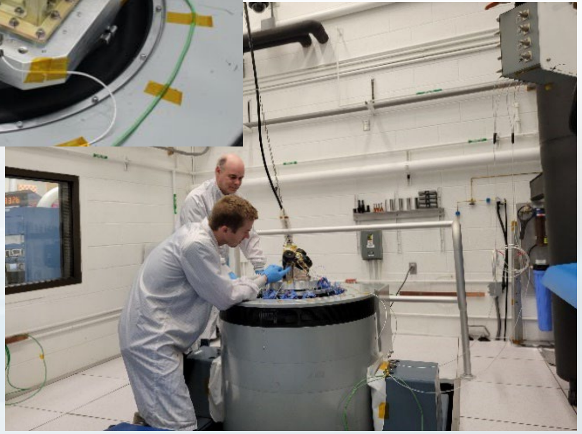




Chassis and Optical Head Thermal/Vacuum Test

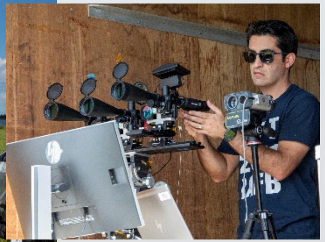
Chassis and Optical Head Vibration Test





Chassis EMI Test

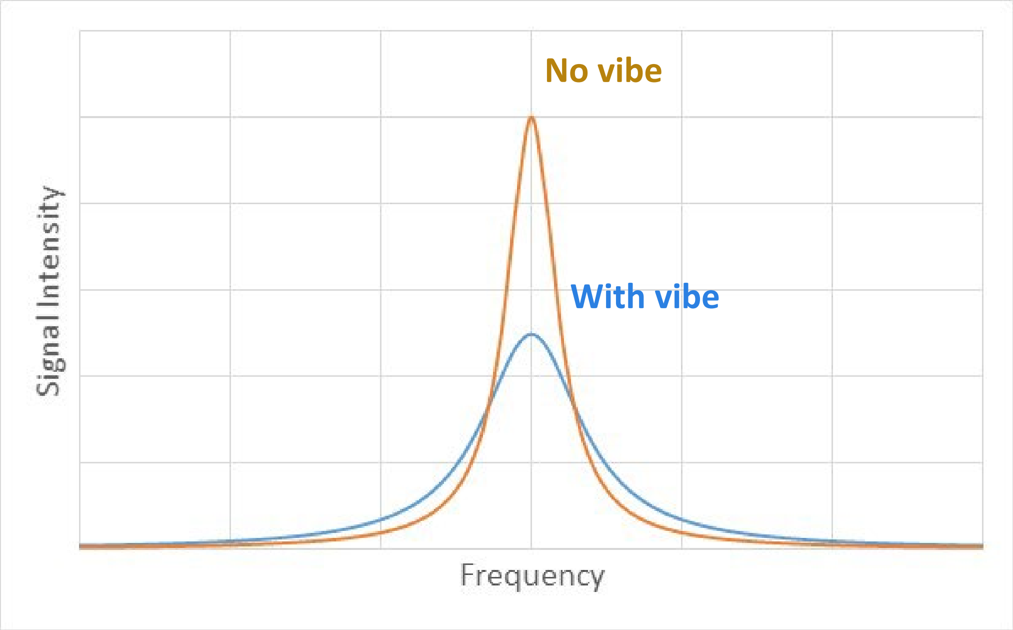
Long Range Functional Test



ETU performance is dominated by vehicle vibration

- **Vibration broadens laser linewidth which in turn broadens the signal frequency spectra and lowers its peak intensity**
  - Reduces maximum operational range
  - Increases measurement noise
- **Signal frequency broadening is proportional to vibration load and increases with range**

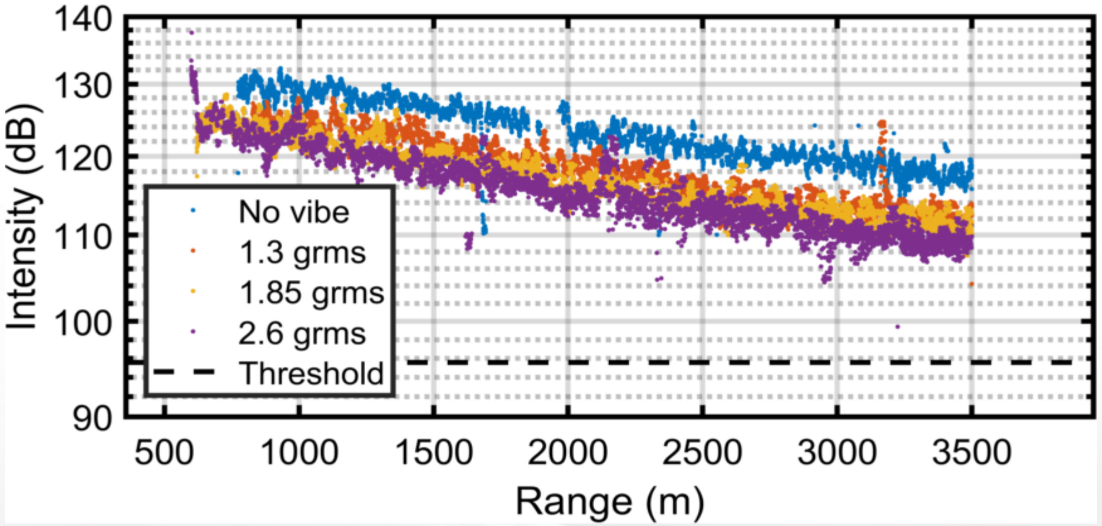
Signal spectra broadening with vibration

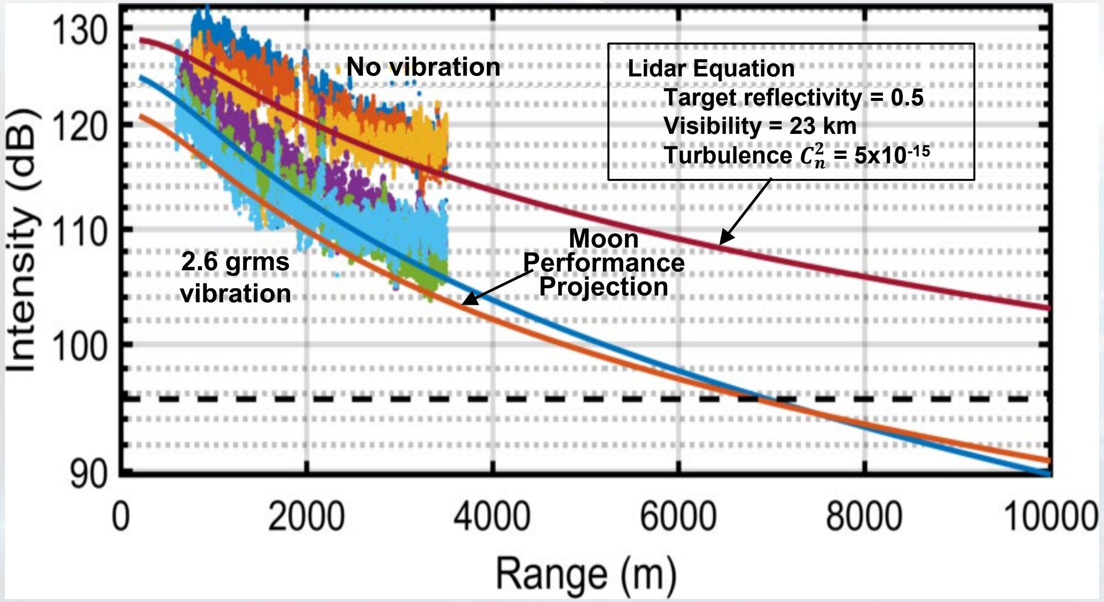


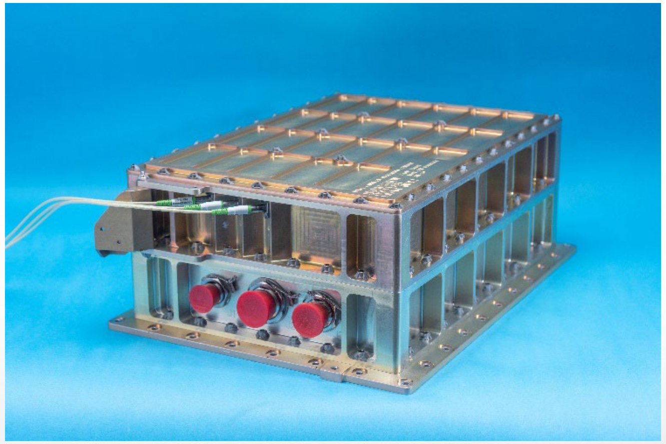
Comprehensive Functional Test

- Signal strength and spectral broadening measurements versus range
  - Chassis at different vibration loads
  - Telescopes in air and vacuum

Maximum Operational Range







- **Maximum operational range in Moon environment is extrapolated from measured data**
  - Remove atmospheric effects
  - Correct for lunar surface albedo

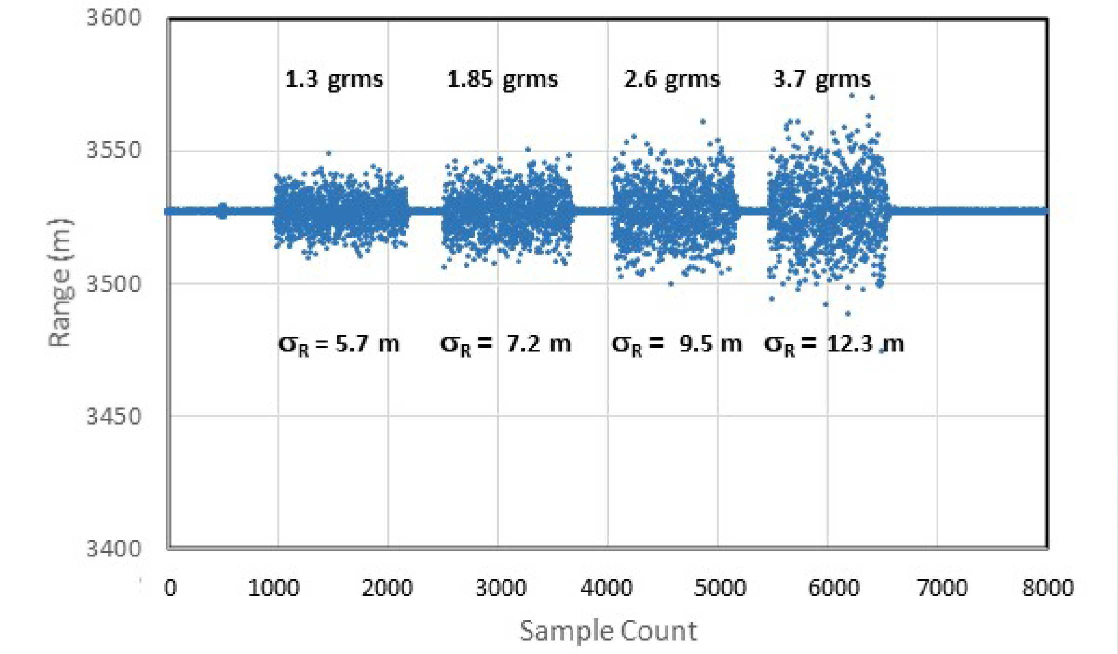
Measurements Precision

- **Estimated ETU range and velocity precision in 2.6 grms vibration environment:**

$$\partial R = 1.59 + 2.21 \times 10^{-3} \times R \quad \text{m}$$

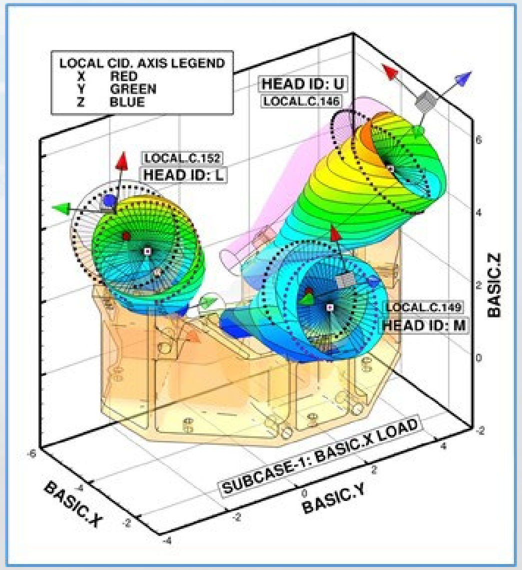
$$\partial v_r = 1.62 \times 10^{-2} + 2.24 \times 10^{-5} \times R \quad \text{m/s}$$

LOS Range	Velocity Noise	Range Noise
1000 m	3.86 cm/s	3.80 m
6500 m	16.2 cm/s	15.96 m



Beam Pointing Knowledge Error

- **Major sources of beam pointing knowledge error:**
  - Beam pointing registration error
  - Thermal expansion of Optical Head
  - Telescope displacement due to launch loads
  - Vehicle flexing and thermal effects
- **Performed full Structural, Thermal, Optical, Performance (STOP) analysis**

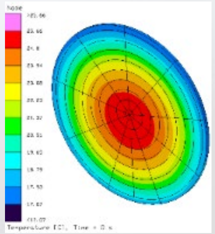


STOP and Structural Analyses

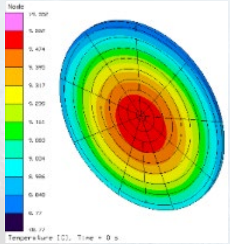
- Develop a full STOP model of the telescopes and validated it by tests
- Investigated the effect of the thermal gradients on optical performance and beam pointing knowledge
- Analyzed the effects of vehicle structural and thermal environments on beam pointing knowledge

Thermal Results

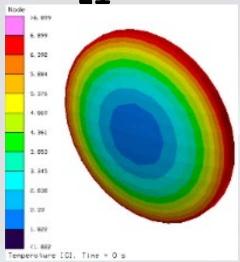
WP1



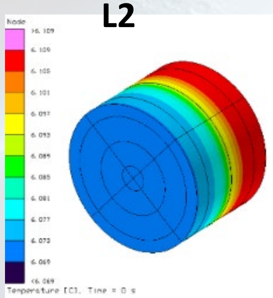
WP2



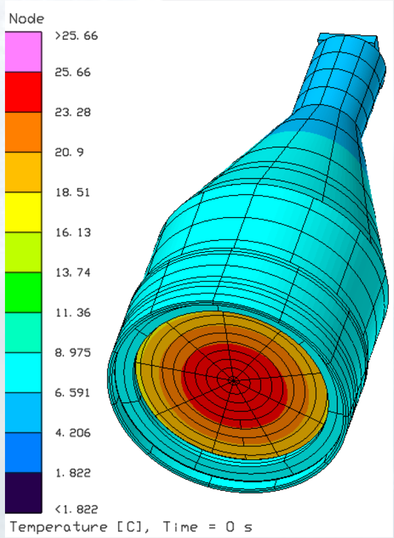
L1



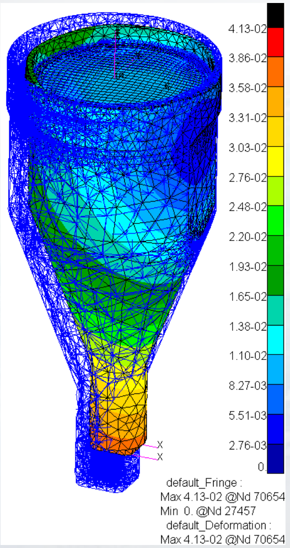
L2

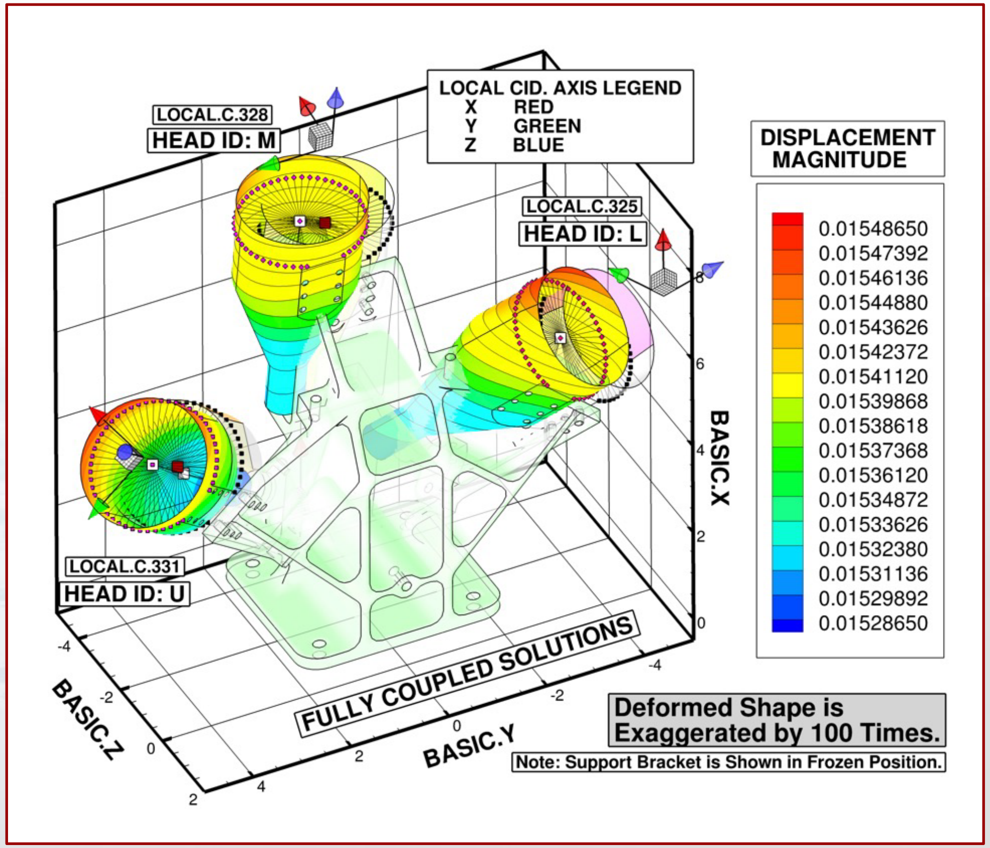


Mapped Temps



Deformations [mm]



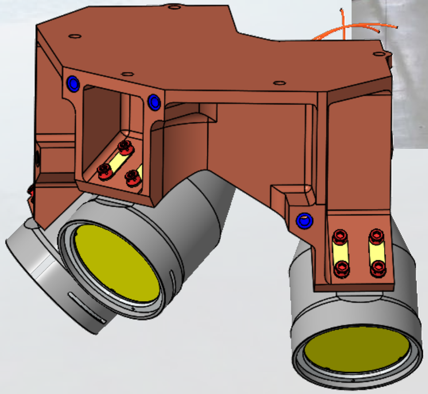


Beam Pointing Knowledge Error

Error Source	Knowledge error actual (mrad, 1-s)	Note
Beam pointing registration error	0.023	Analysis and Measurement
Temperature gradient across telescope	0.022	Analysis and Measurement
Thermal expansion of the optical head	0.093	Analysis
Deflections due to operational vibration loads	0.067	Analysis
Telescope displacement due to launch loads	0.29	CBE based on Measurement
Total RSS mounting error	**0.31 mrad**	

➢ **Vehicle structural changes, such as flexing in space and thermally-induced deflections, are not included**

Optical Head Metrology Measurement



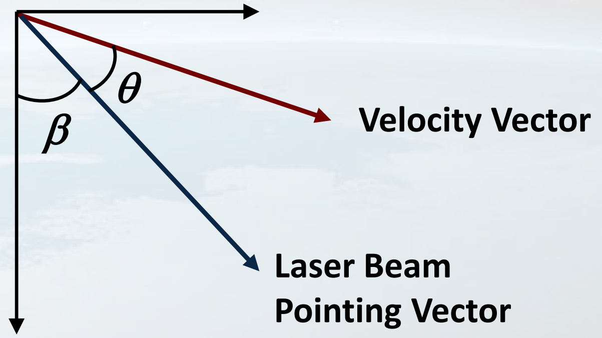
Measurement Errors Due to Beam Pointing Knowledge Error

- $\partial v_r = |v_r|\, tan\, \theta\, \partial\theta$
  - where θ is angle between beam vector and velocity vector

- $\partial R_r = |R_r|\, tan\, \beta\, \partial\beta$
  - where β is the angle between the beam vector and normal to the ground

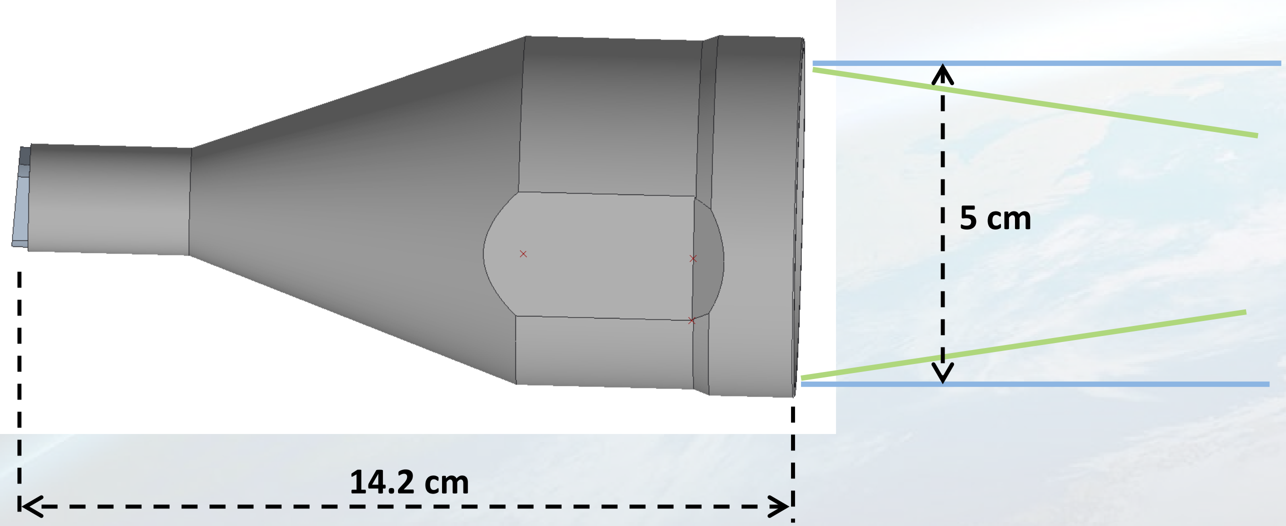
$\partial v_r = |218|\, tan(60^o)\, 0.31 \times 10^{-3}$
$\partial v_r = 11.8$ cm/s

$\partial R_r = |6500|\, tan(45^o)\, 0.31 \times 10^{-3}$
$\partial R_r = 2.03$ m

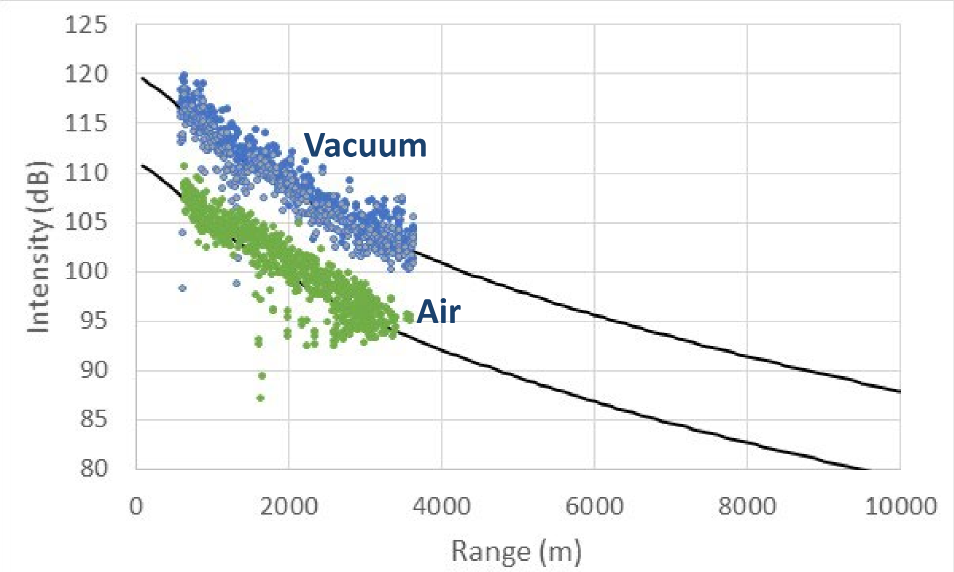


Operation in Vacuum

- Difference in index of refraction between air (n=1.0003) and vacuum (n=1.0000) is sufficient to change the telescope focusing
- Telescopes are aligned for operation in vacuum
- Performance in air is significantly degraded
- Telescopes are placed in vacuum chamber for long range tests



Operation in Vacuum vs. Air



Next Generation NDL

- **Work on next generation NDL leverages the lessons learned for build and test of ETUS is focused on size and mass reduction, reduced vehicle vibration effects, and expanded capabilities**
  - **Reduce size and mass by > 2X: utilize advanced photonic technologies**
  - **Minimize effects of vehicle vibration: upgrade chassis design to minimize the vibration forces applied to the seed laser**
  - **Expand operational capabilities:**
    - **Extend operational range to 10 km on the Moon and Mars**
    - **Increase the number of beams to 4**
    - **Incorporate wind velocity vector (air data) measurement for atmospheric landing**

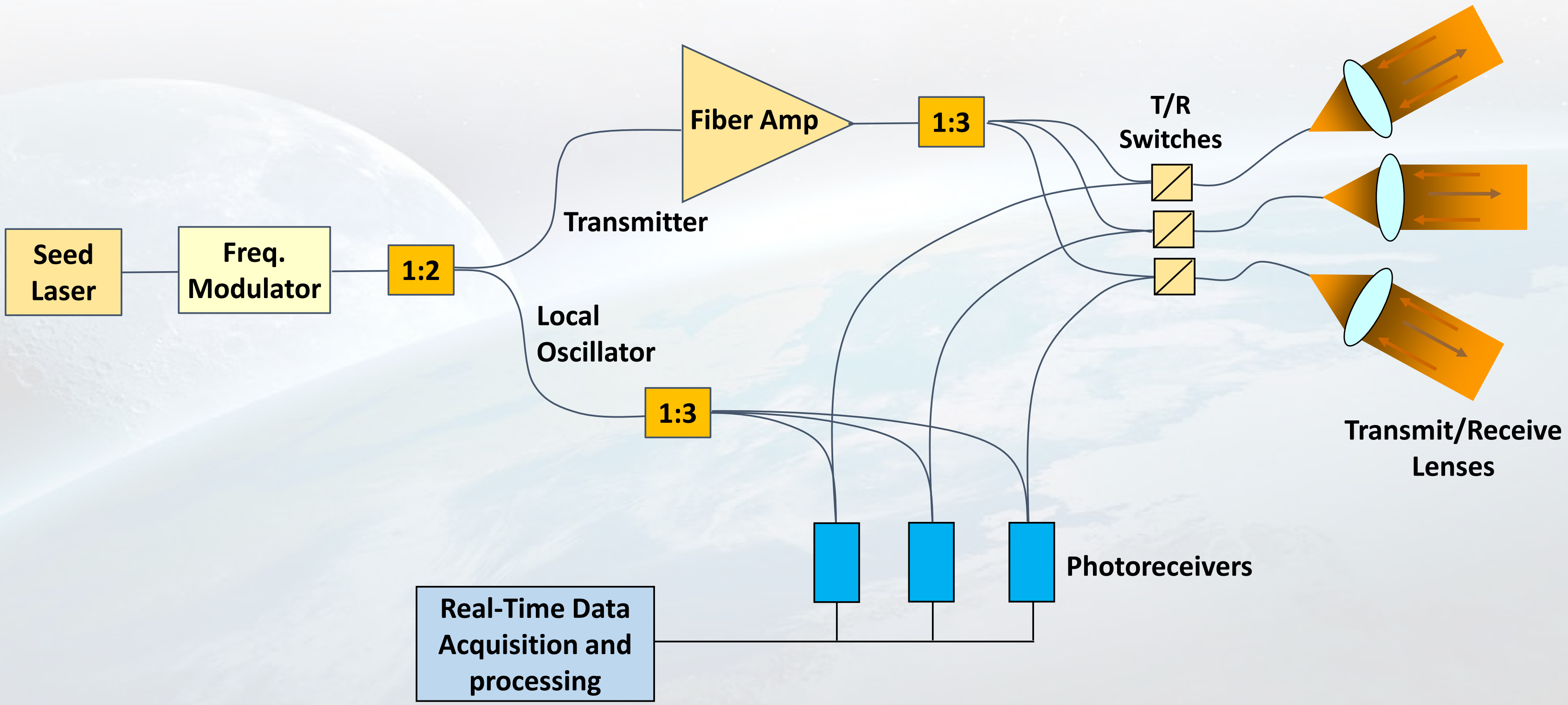
Concluding Remarks

- **NDL provides critical vehicle velocity and altitude data for precision soft landing on the Moon, Mars, and other destinations**
- **Completed 4 ETUs of NDL for lunar landing demonstration and other tests**
- **Conducted a series of tests and analyses to estimate the NDL performance for Moon and Mars landing**
- **Performance of NDL ETU is dominated by the vehicle vibration**
  - Vehicle vibration impacts maximum operational range and measurements precision
  - Velocity and range errors may increase from 1 mm/sec and 10 cm by more than an order of magnitude
- **Work on next generation NDL has already begun**

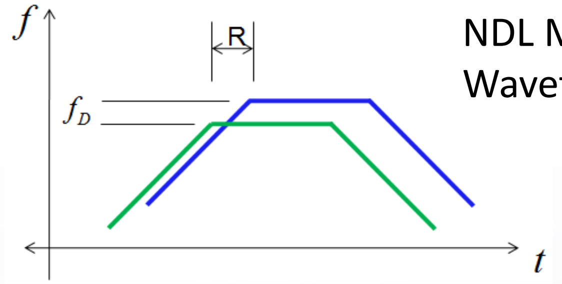
Backup

Navigation Doppler Lidar (NDL)

- Utilizes FMCW technique to measure velocity and range along three laser beams
- Simultaneous line-of-sight measurements are used to estimate:
  - Velocity Vector (V)
  - Altitude relative to local ground (No external data required)



NDL Processor & System Controller



NDL Modulation Waveform