DOPPLER LIDAR FOR PRECISION LANDING ON PLANETARY BODIES WITH AND WITHOUT ATMOSPHERE

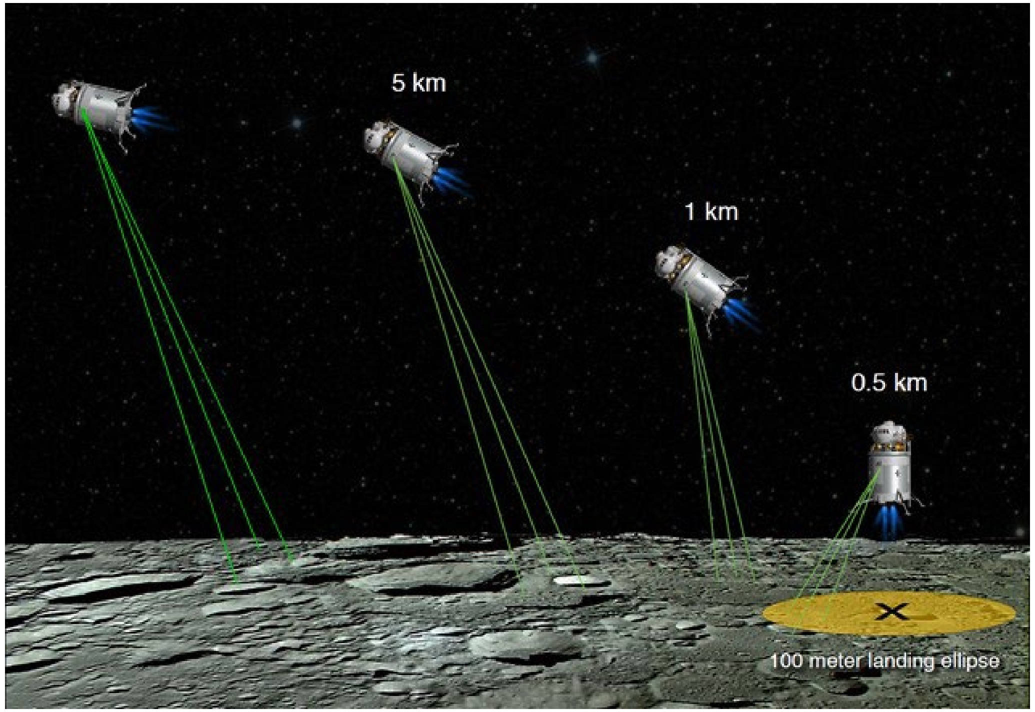
Farzin Amzajerdian, Glenn D. Hines, Aram Gragossian, Nathan A. Dostart, F. Guy Wilson, Jacob M. Heppler, Daniel K. Litton

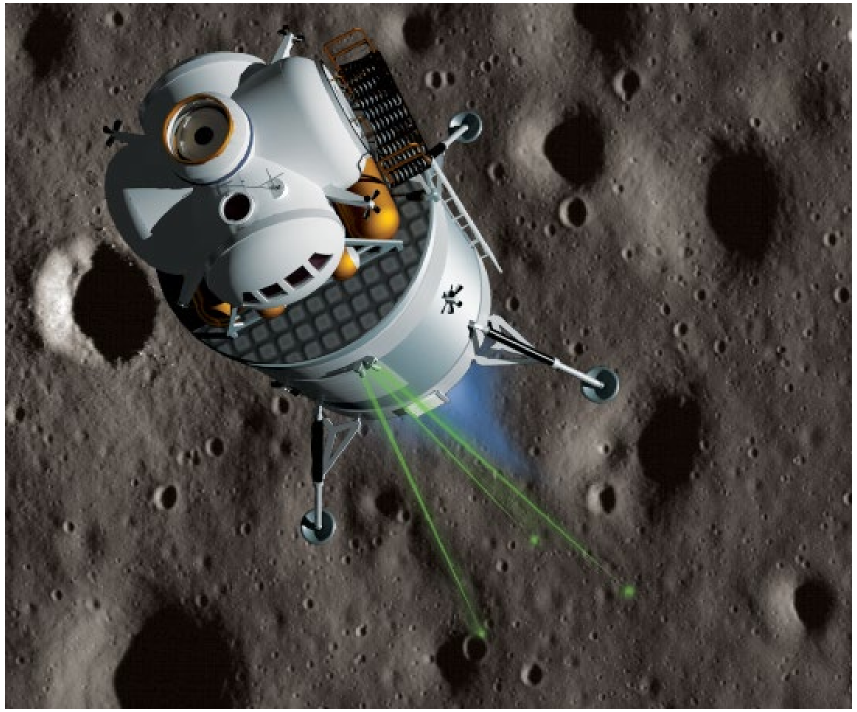
NASA Langley Research Center

19th International Planetary Probe Workshop
(IPPW 2022)

Navigation Doppler Lidar (NDL)

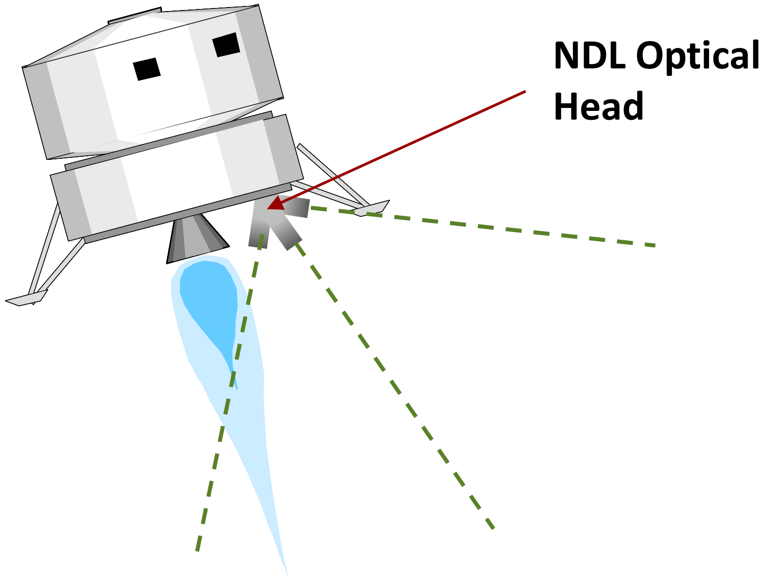
- **NDL provides vehicle precision vector velocity and altitude data**
- **Viable replacement for radars with an order of magnitude higher precision and much better data quality**
  - Enables "***precision navigation***" to the designated landing location
  - Enables "***well-controlled***" descent,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

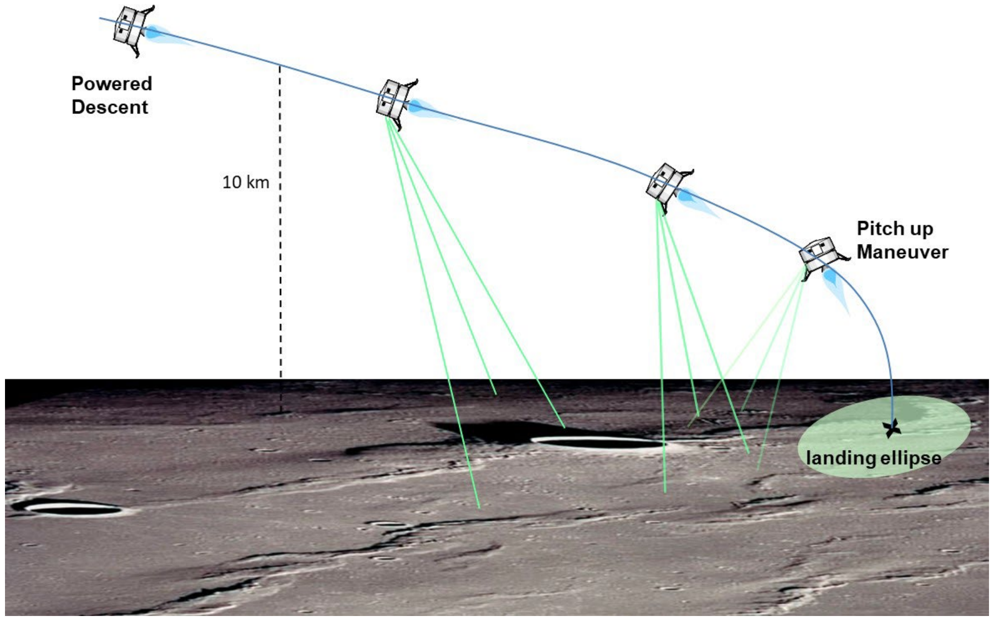




NDL Operation During Descent

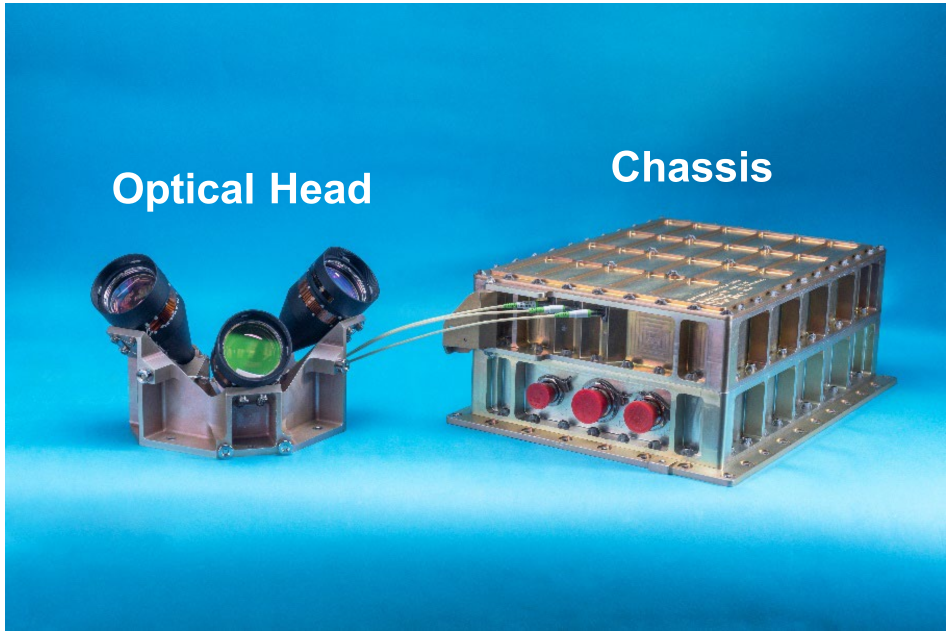
- **NDL transmits 3 laser beams simultaneously**
- **Line-of-sight velocity and range measurements are used to estimate:**
  - Velocity Vector ($\vec{V}$)
  - Altitude relative to local ground (No external data required)
- ***Velocity and range measurements are independent of each other***
  - *Velocity is extracted from Doppler frequency shift*
  - *Range is extracted from laser beam travel time to the ground*





Spaceflight Engineering Test Unit (ETU)

- **Built and tested 4 ETUs**
  - **Chassis and Optical Head designed for operation on landing vehicles**
  - **Many of components are Space-grade EM**
  - **Remaining components are custom built or modified COTS subjected to vibration, TVAC, and radiation tests**
  - **Class B software with fault tolerance provisions**
  - **Applied appropriate Quality, Reliability and S&MA processes/standards**
  - **Conducted full system-level environment tests**



NDL Lunar Landing Missions

ETUs

 # 1 – Aircraft flight tests (2021 -)

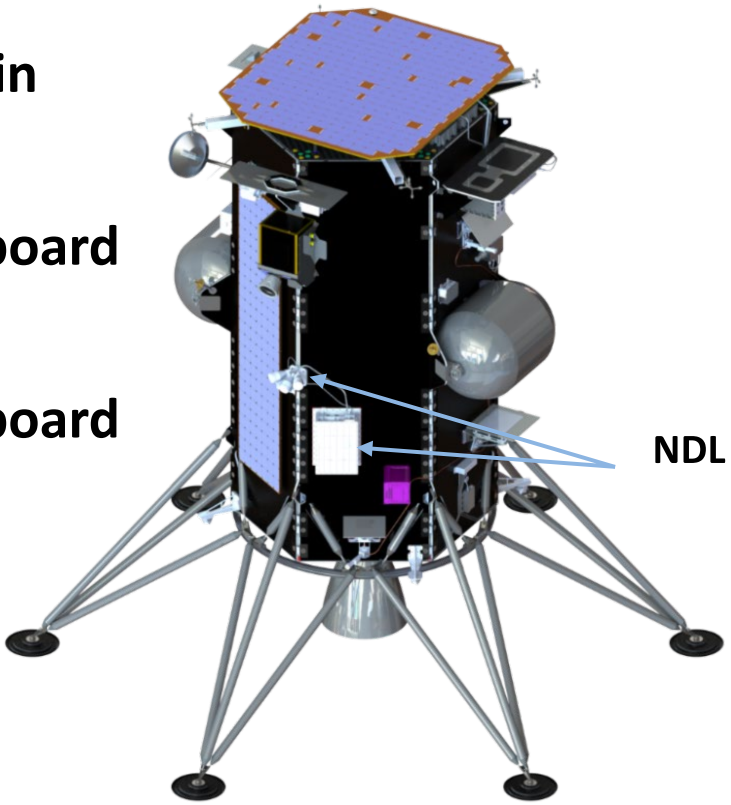
 # 2 – Suborbital flight test on Blue Origin New Shepard vehicle (2021)

 # 3 – Lunar Landing Demonstration onboard Intuitive Machines lander (early 2023)

 # 4 – Lunar Landing Demonstration onboard Astrobotic lander (late 2022)

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

Intuitive Machines
Nova-C Vehicle



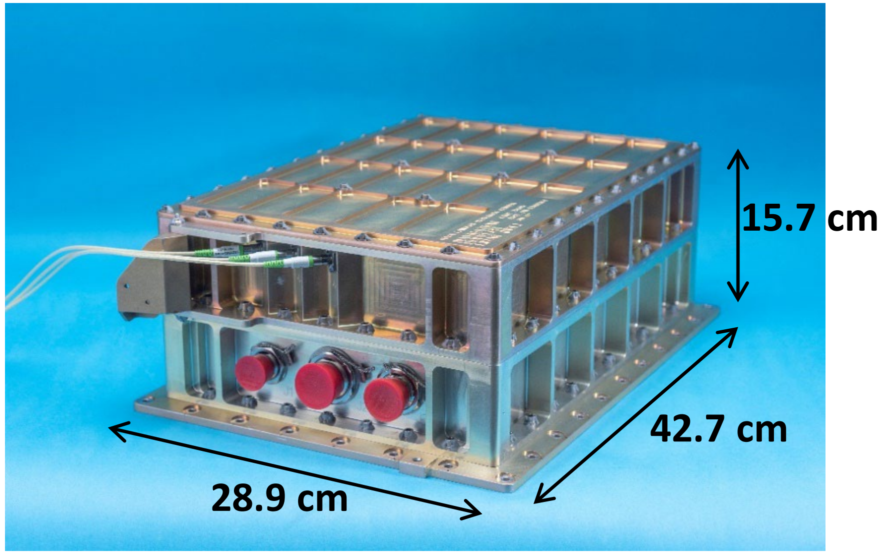
Astrobotic
Peregrine Vehicle

NDL ETU Specifications

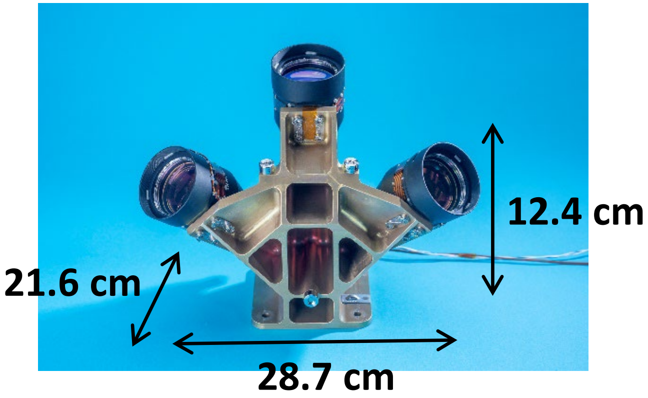
Parameter	Static Platform	Landing Vehicle
Maximum LOS Range	~ 14 km	6.5 km
Maximum LOS Velocity	+/- 218 m/sec	+/- 218 m/sec
LOS Velocity Noise @ 3000 m	0.09 cm/sec	8.3 cm/sec
LOS Range Noise @ 3000 m	0.10 m	8.2 m
Data Rate	20 Hz	

- **NDL ETU Performance is dominated by the vehicle vibration**
- **NDL ETU meets/exceeds landing requirements and outperforms radar sensors by about an order of magnitude in precision**

Chassis



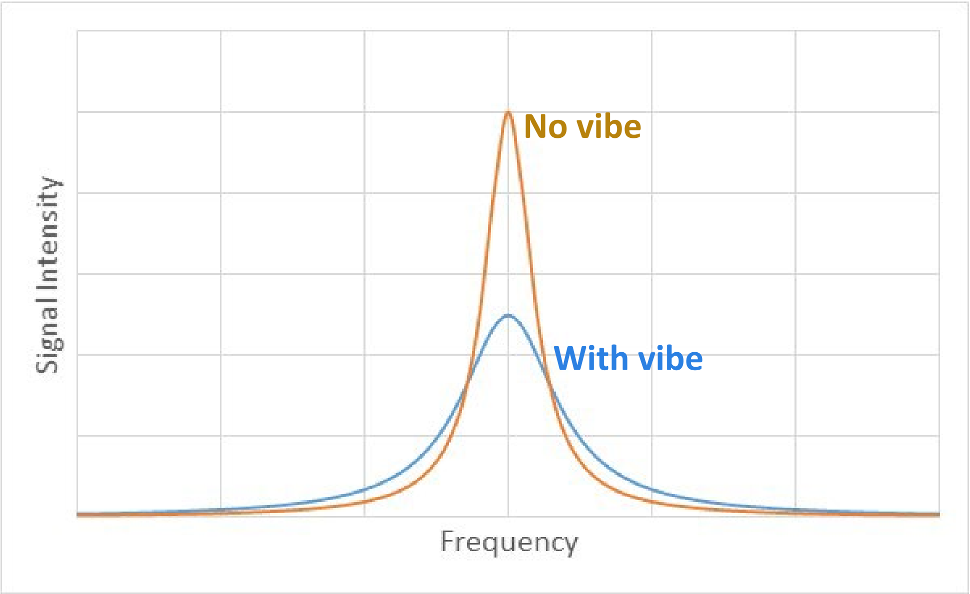
Optical Head



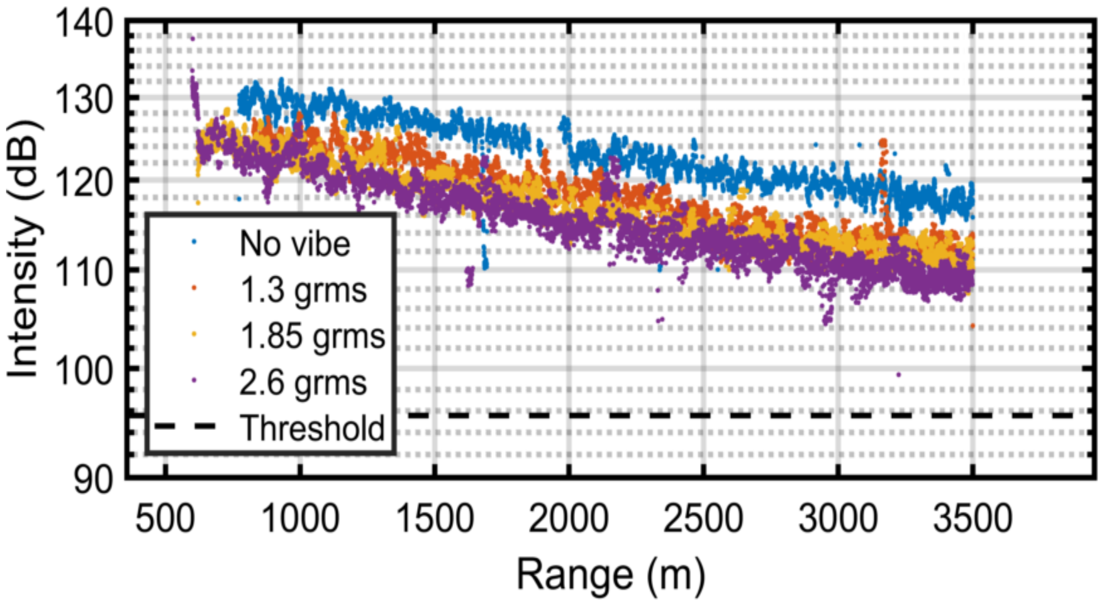
ETU performance is dominated by vehicle vibration

- **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 spectral broadening is proportional to vibration load and increases with range**

Signal spectra broadening with vibration



Signal Intensity vs operational range

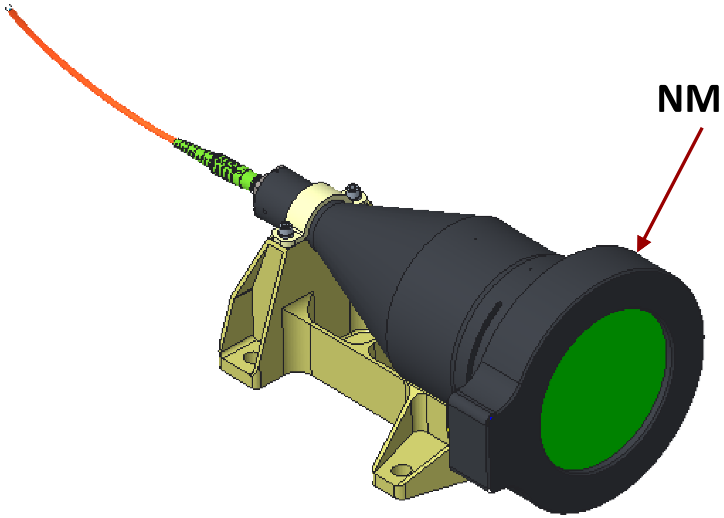


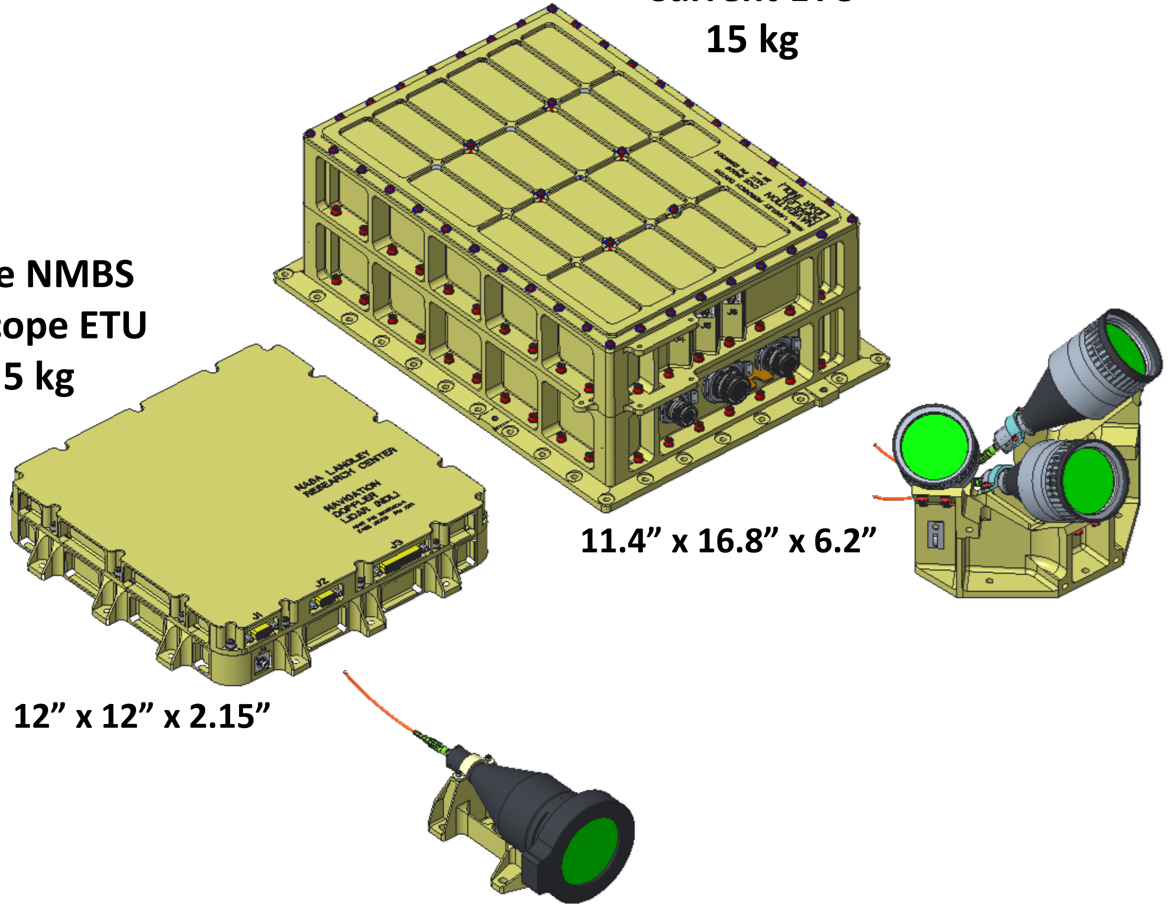
Next Generation NDL

- Work on next generation NDL leverages the lessons learned for build and test of ETUs
  - Reduce size and mass by > 2X: utilize advanced photonic technologies
  - Minimize effects of vehicle vibration: upgrade laser design and mounting to minimize the vibration effect
  - Expand operational capabilities:
    - Increase the number of beams to 4
    - Extend operational range to 10 km on the Moon and Mars
    - Incorporate air data (air speed and angles of attack and sideslip) measurement for atmospheric landing

Next Generation NDL

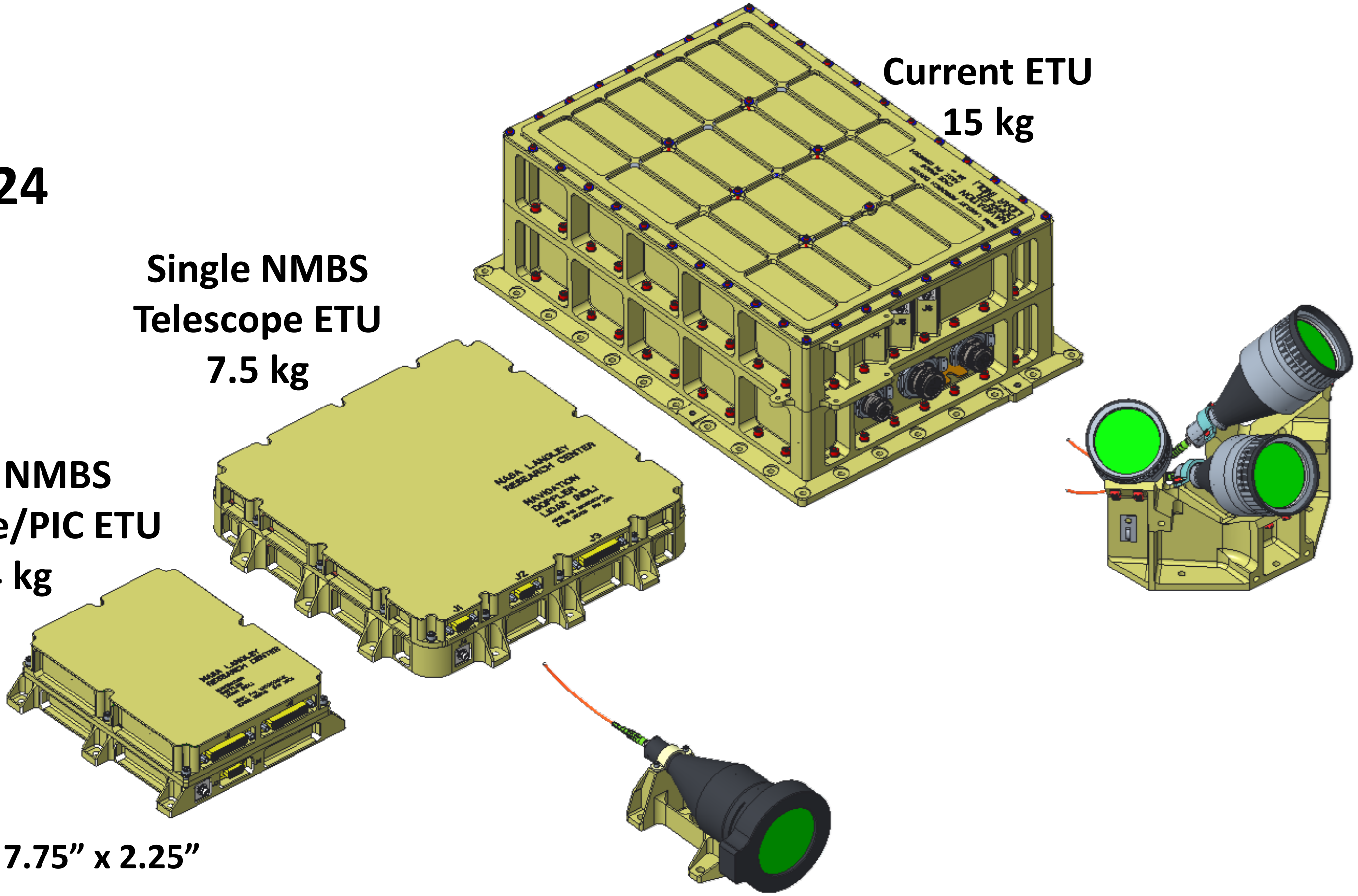
- **Next generation NDL will utilize Non-Mechanical Beam Steering (NMBS) technology to eliminate 2 out of 3 telescopes, receivers, and associated components**
  - Steer the laser beam into 4 directions sequentially
  - Technology demonstration in 2022
  - Reduce size by 4X and mass 2X





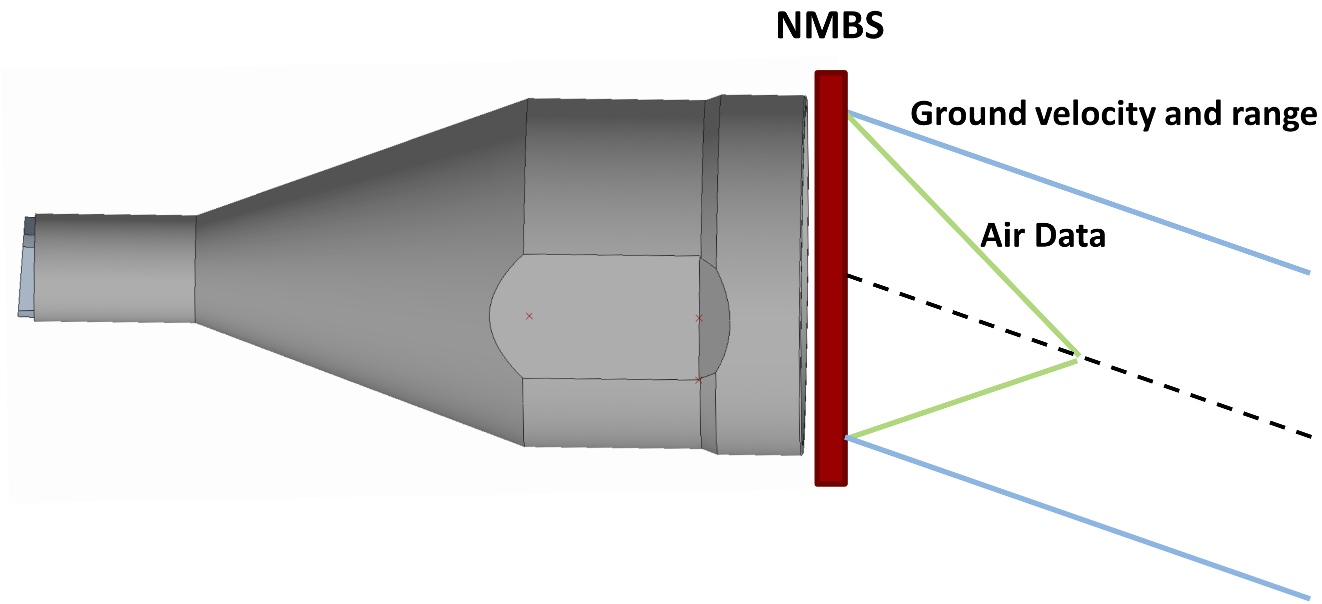
Next Generation NDL

- **Further size and mass reduction and improved robustness utilizing Integrated Photonics Technology**
  - Integrate several electro-optical components into a Photonic Integrated Chip (PIC)
  - Technology demonstration in 2023
  - Reduce size by 9X and mass 3X
- **Demonstrate Air Data capability in 2024**

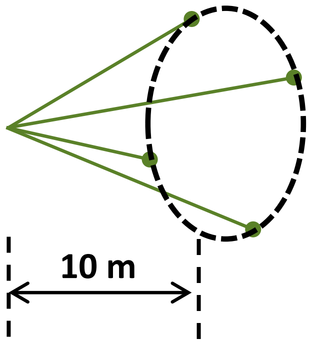


Air Data Measurement

- **Switch between Velocity/Altitude and Air Data modes**
- **Air Data Mode**
  - Focus the beam at about 10 m and use natural aerosols as target
  - Switch to a different laser modulation waveform and signal processing algorithm
- **Provide air speed with approximately 10 cm/sec precision @ 10 Hz**



Air velocity is measured at 4 points on a ~ 60° cone



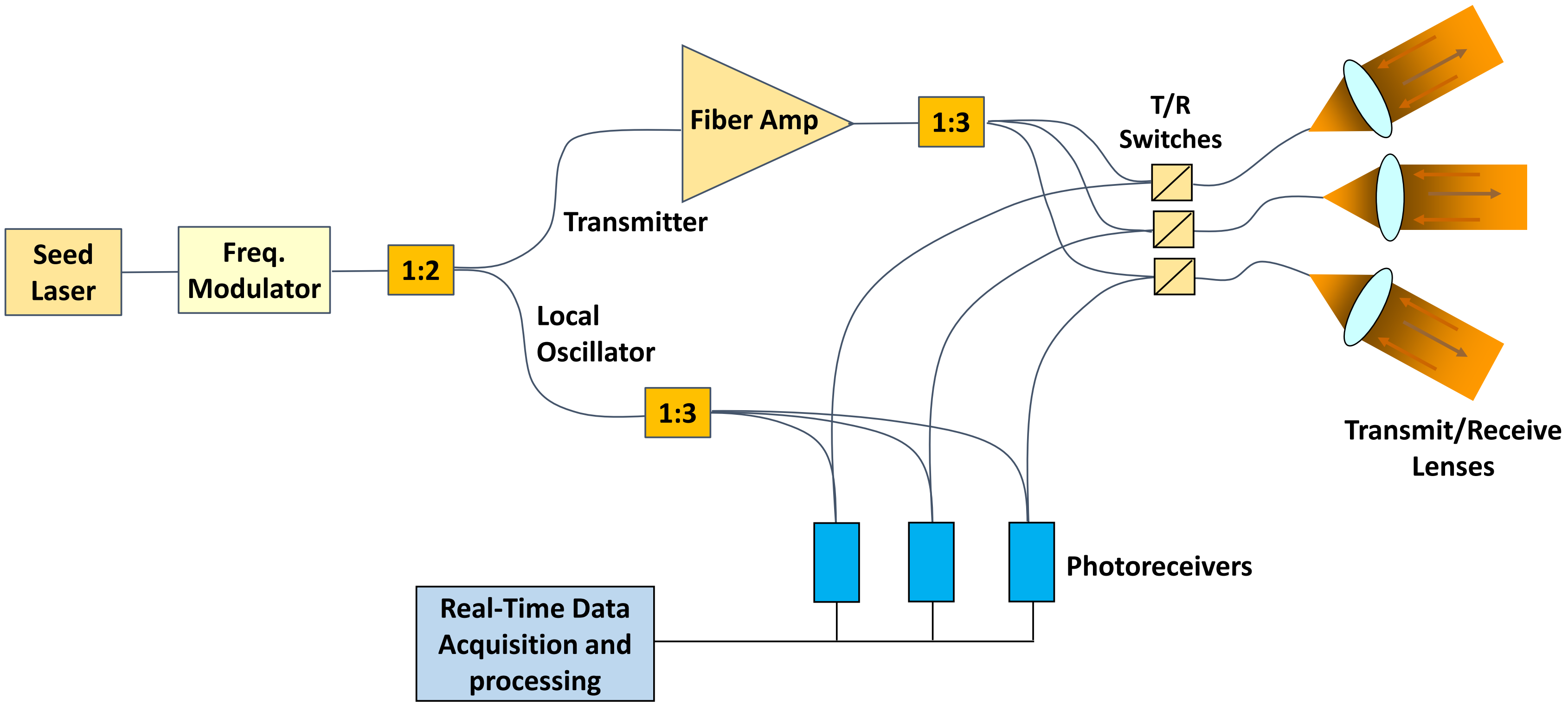
Concluding Remarks

- **NDL provides critical vehicle velocity and altitude data for precision soft landing on planetary bodies**
- **Completed 4 ETUs and conducted performance and environmental tests**
  - Performance of NDL ETU is dominated by the vehicle vibration
- **Upcoming lunar missions will serve as risk reduction demonstration for future human and robotic landing missions to the Moon, Mars, other destinations**
- **Work on next generation NDL has already begun**
  - Much reduced size and mass
  - Longer operational range and higher measurement precision
  - Incorporate Air Data capability for Atmospheric EDL

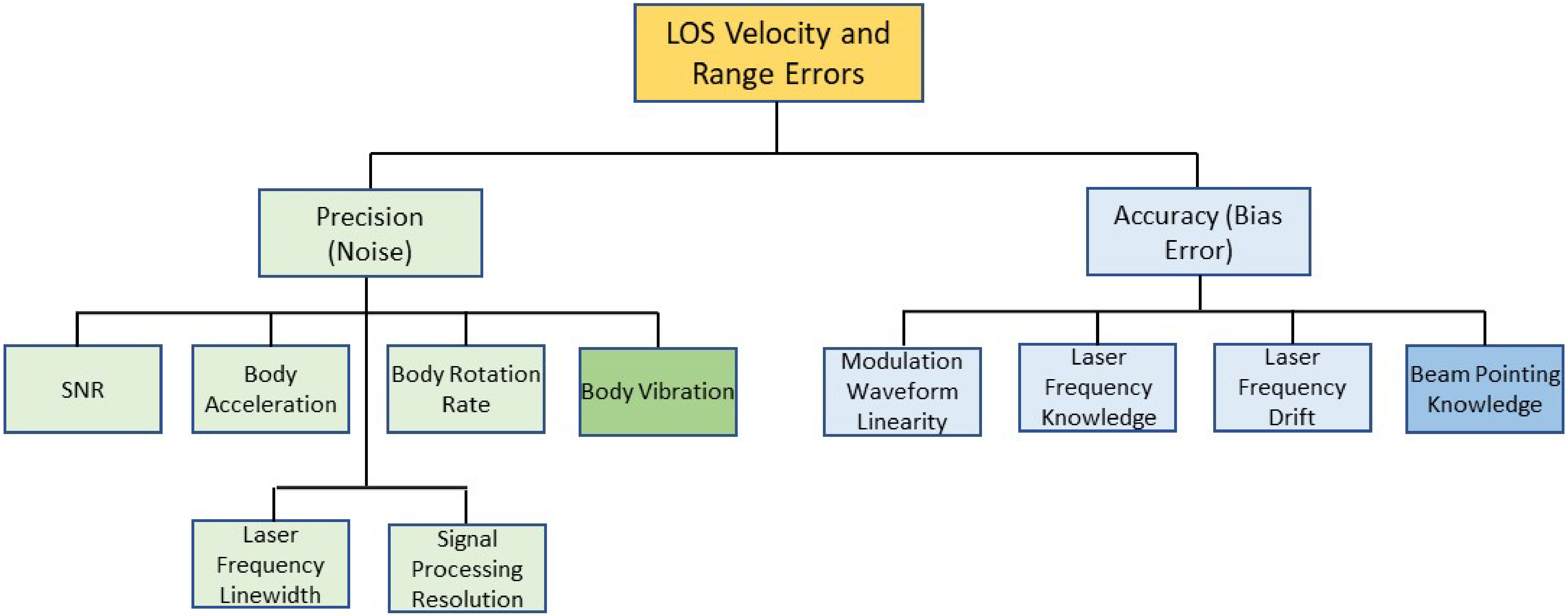
Backup

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 Measurements Error Tree



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

Comprehensive Functional Test

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

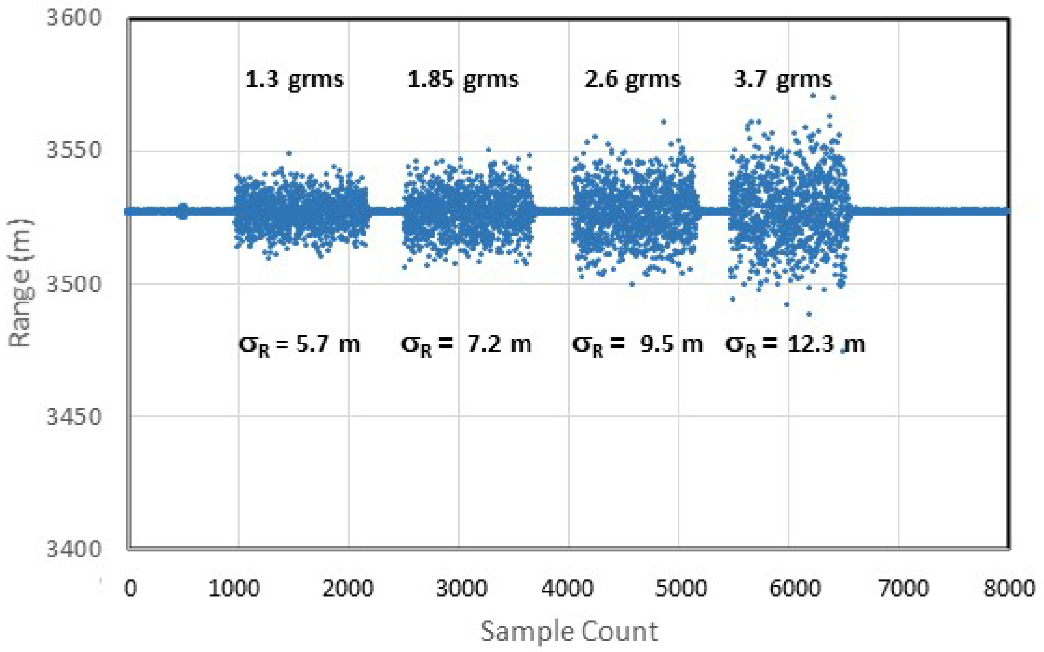
Measurements Precision

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

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

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

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

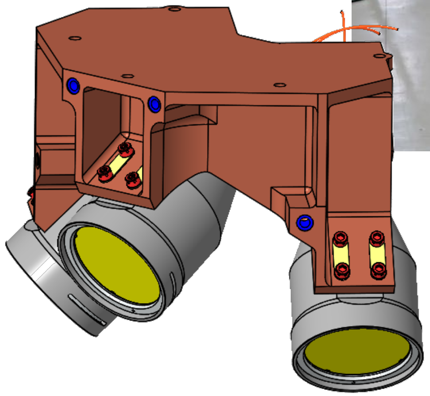


Beam Pointing Knowledge Error

Error Source	Knowledge error actual (mrad, 1-s)	Note
Beam pointing registration error	0.022	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	0.18	CBE based on Measurement
Total RSS mounting error	**0.22 mrad**	

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

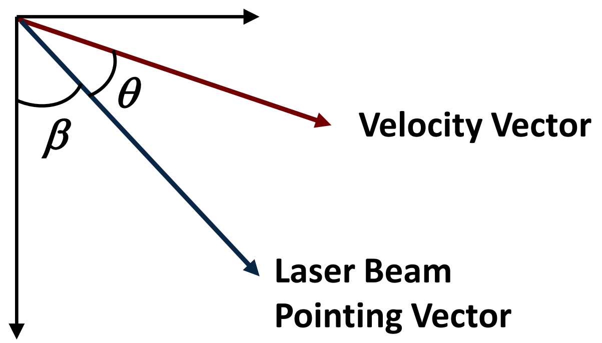
Optical Head Metrology Measurement



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



$$\partial v_r = |218| \, tan(45^o) \, 0.22 \times 10^{-3}$$
$$\partial v_r = 4.80 \text{ cm/s}$$

$$\partial R_r = |6500| \, tan(45^o) \, 0.22 \times 10^{-3}$$
$$\partial R_r = 1.43 \text{ m}$$