

National Aeronautics and Space Administration



LIDAR SENSORS FOR AUTONOMOUS PRECISION SAFE LANDING

Prepared for:

Boeing Virtual Visit

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11/21/2024

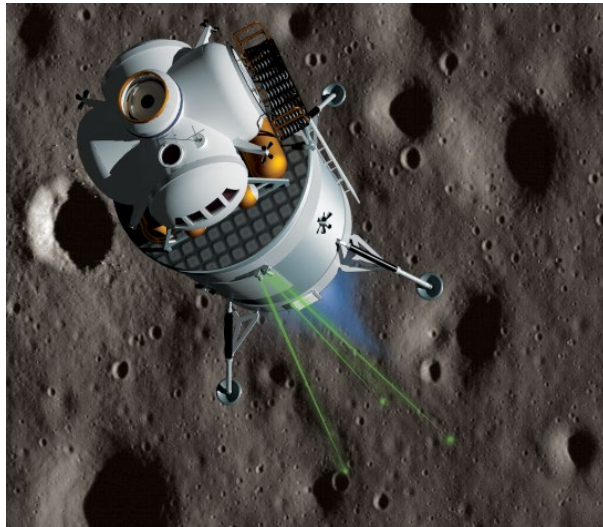


Lidar Sensors for Precision Safe Landing



Navigation Doppler Lidar (NDL) is a multi-beam velocity and altitude sensor

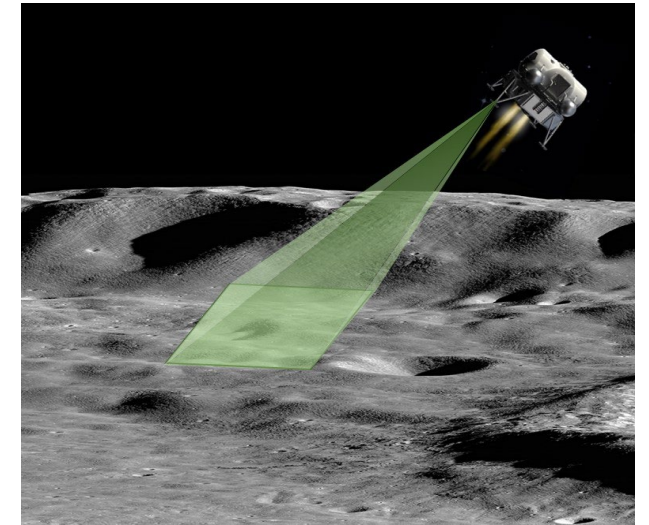
- Enables precision navigation to designated location and executing well-controlled landing



- Replaces radar and/or laser altimeter
 - Higher precision with essentially no false alarms (no ambiguous data)
 - Terrain independent velocity data
 - Saves mass and reduces mission cost and risks

Terrain Sensing Lidar (TSL) is a 3-D imaging lidar

- Enables critical functions for precision safe landing:
 - Terrain Relative Navigation
 - Hazard Detection and Avoidance
- Can be reconfigured for surface mobility and rendezvous and docking



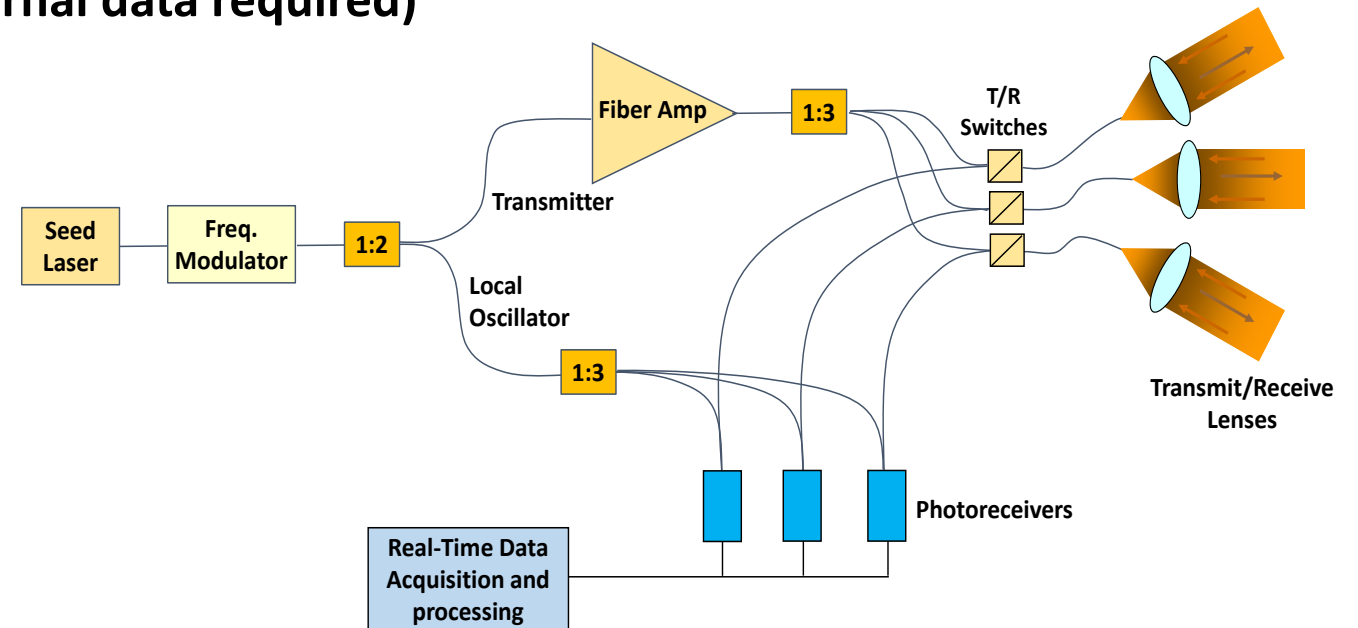
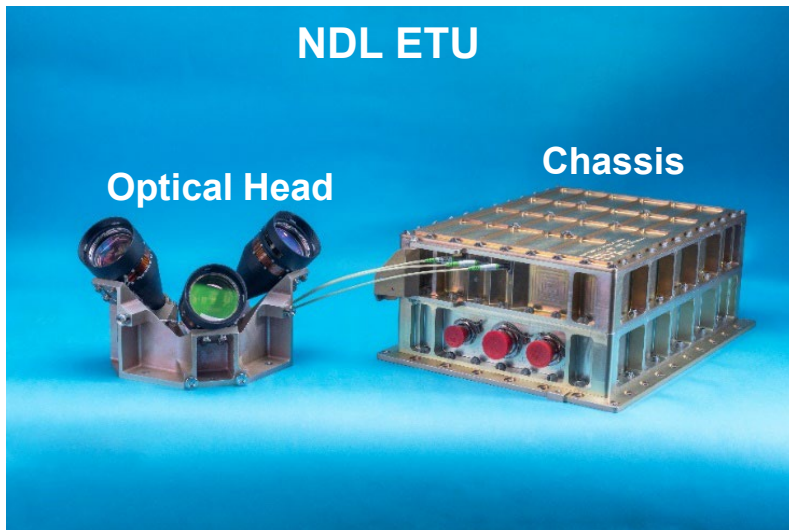
- Replaces optical camera
 - Higher reliability and precision
 - Operate under any lighting conditions (any sun angles or without sun)
 - Much reduced computation resources



Navigation Doppler Lidar (NDL)

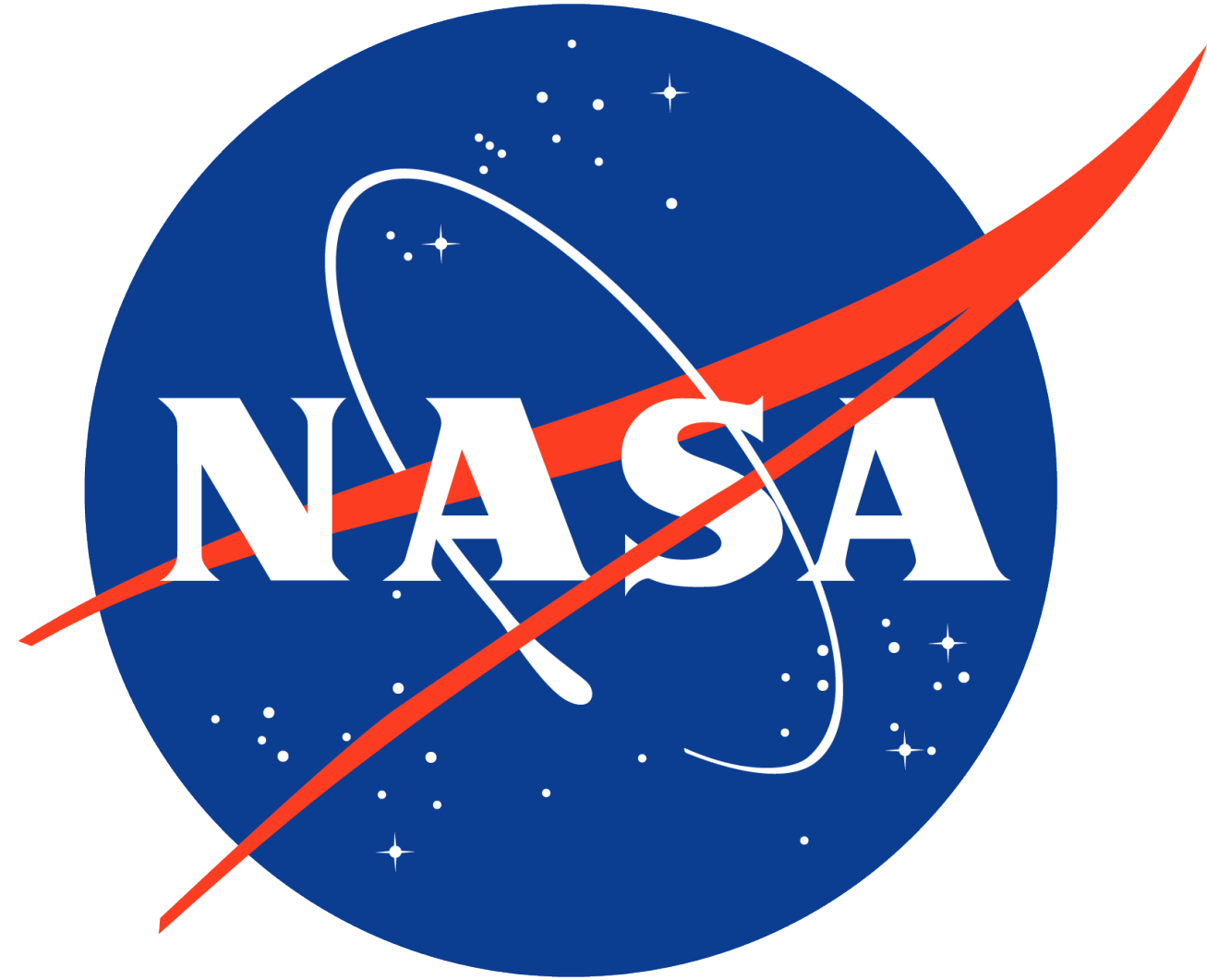


- Utilizes FMCW technique to measure range and velocity along three laser beams
 - Range is measured based laser beam time of arrival thus affected by terrain features
 - Velocity is measured based on Doppler effect not affected by terrain features
- Simultaneous line-of-sight measurements are used to estimate:
 - Vector Velocity (V)
 - Altitude relative to local ground (No external data required)

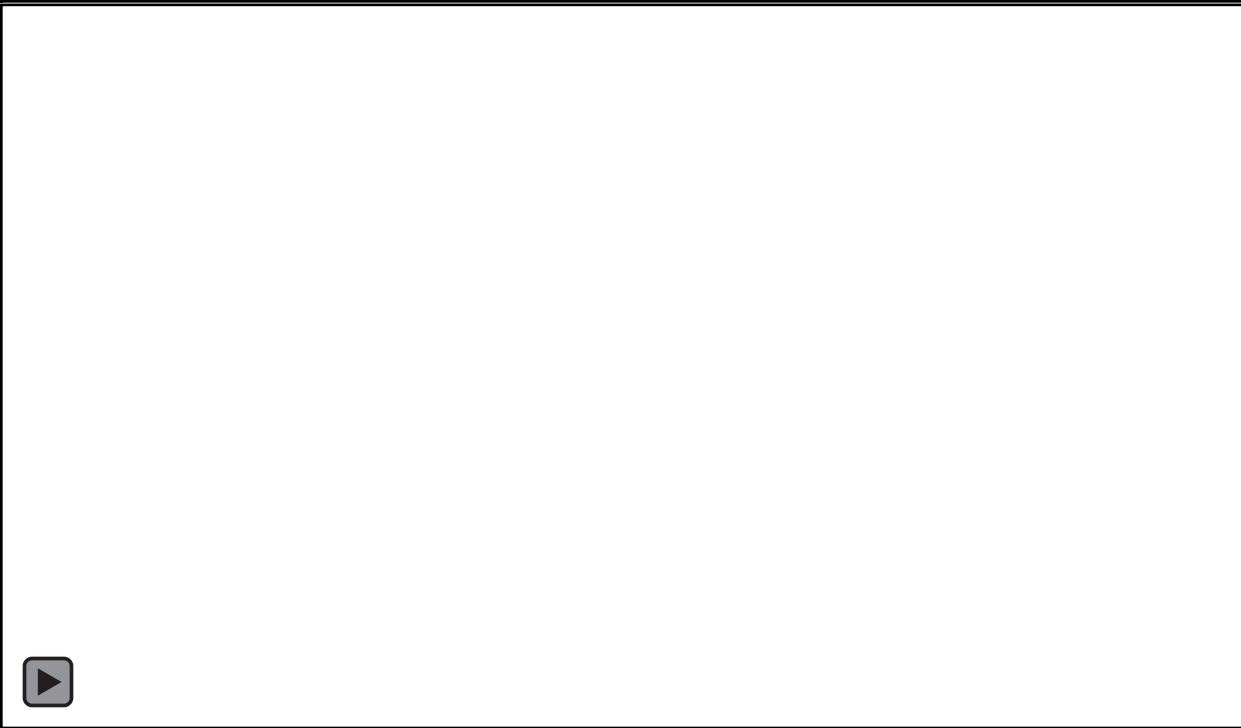




Test Campaign Video

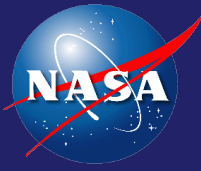






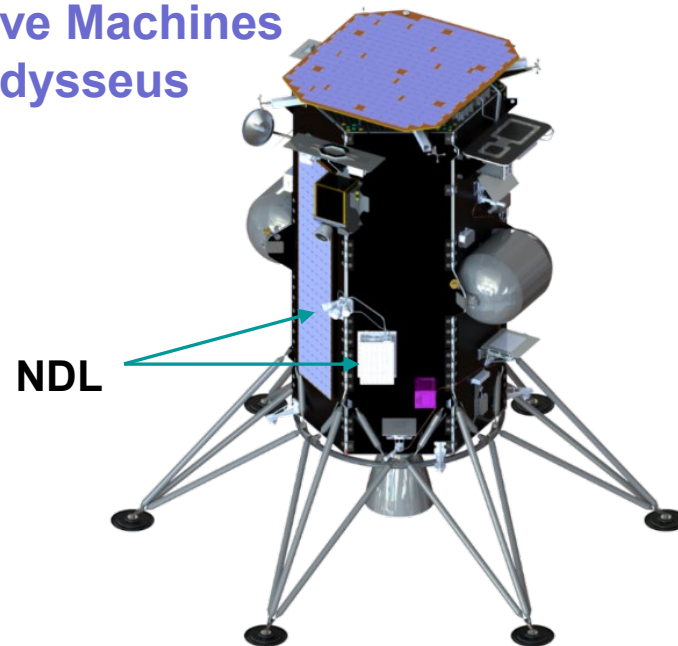


NDL Lunar Landing Missions



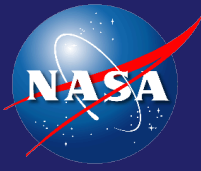
- **NDL was on first two CLPS missions launched in January and February**
- ***Astrobotic*: NDL was the primary navigation sensor**
 - **Not a CLPS payload**
- ***Intuitive Machines*: NDL was planned to be used as a secondary sensor for velocity**
 - **CLPS contract did not allow the use of NDL as a primary/critical sensor**

Intuitive Machines
Odysseus

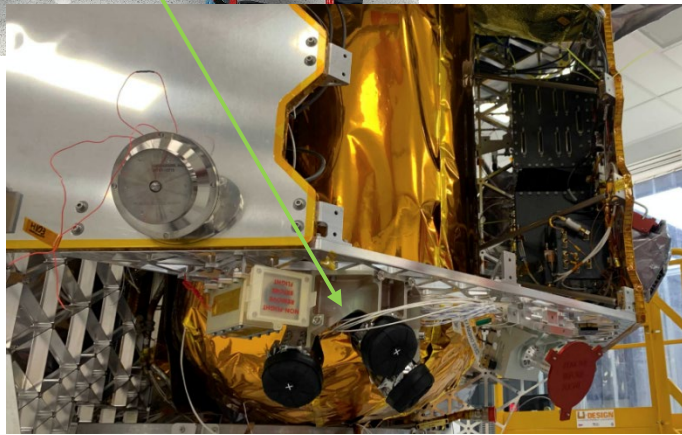


Astrobotic
Peregrine





Astrobotic Mission

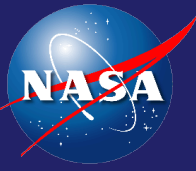


- Launched on Vulcan rocket on January 8, 2024
- Experienced an anomaly with propulsion system about 7 hours after launch and could not complete its mission
- Spacecraft operated 10 days and 13 hours in space before returning to Earth
- NDL operated nominally for 6.5 hours



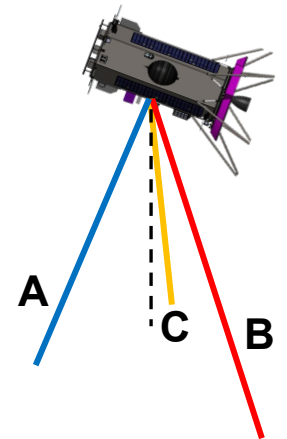
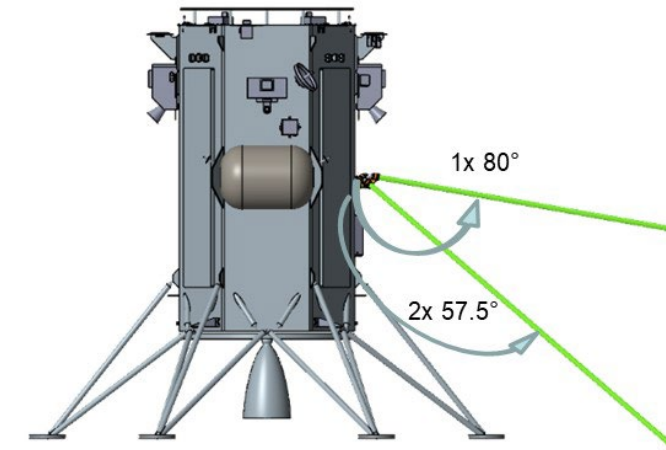
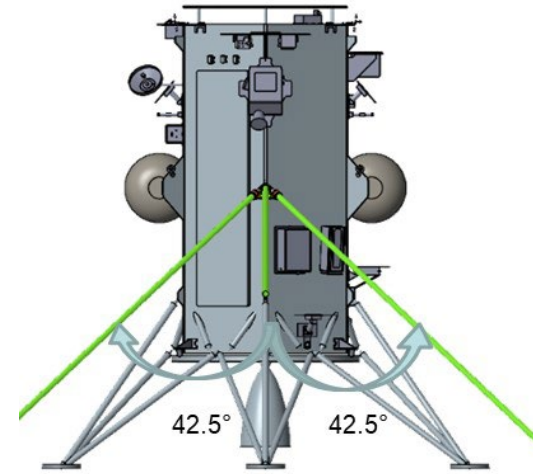
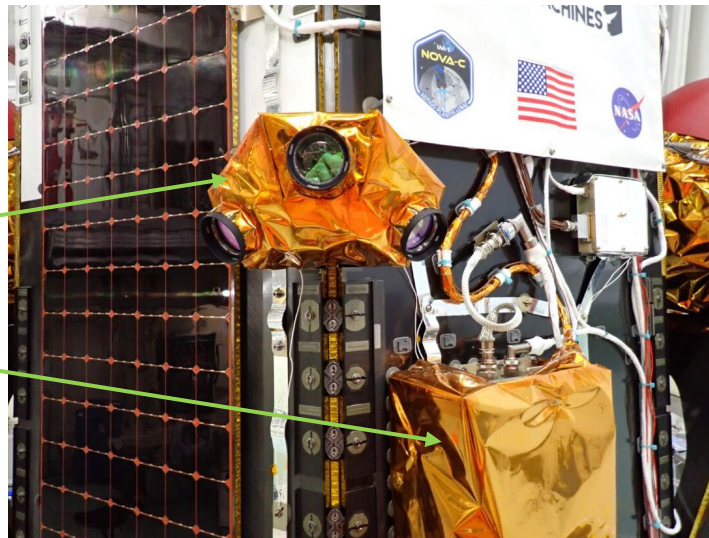


Intuitive Machines Mission



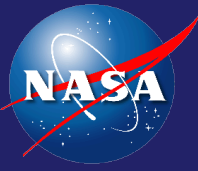
- Launched on Falcon 9 rocket on February 15, 2024
- Landed on the Moon on February 22, 2024

NDL on Odysseus Lander



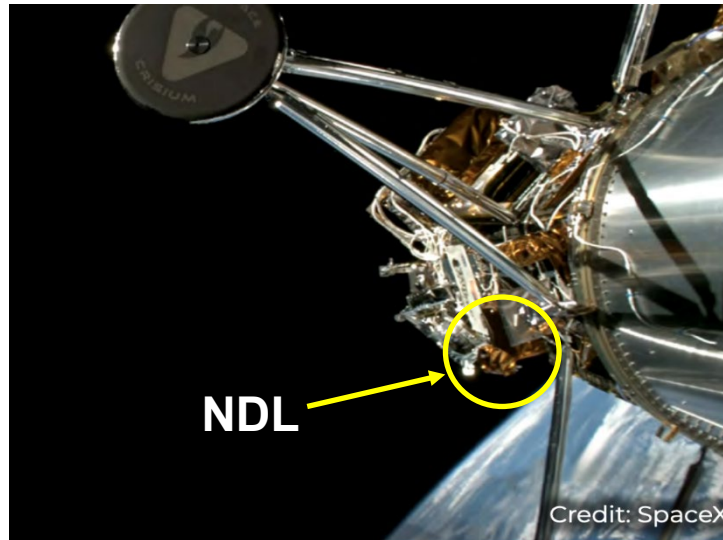


Intuitive Machines (IM) Mission

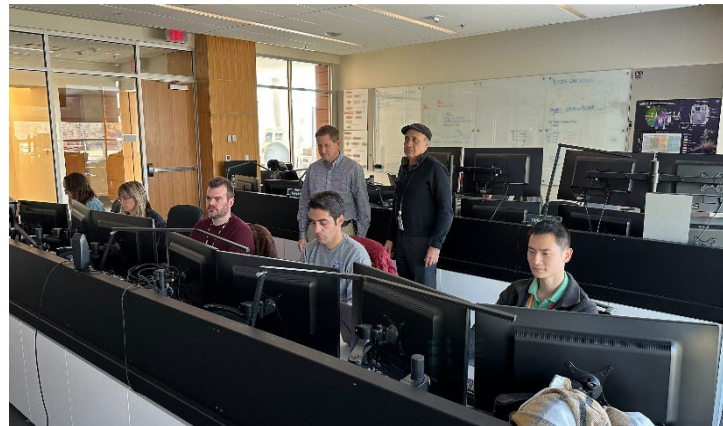
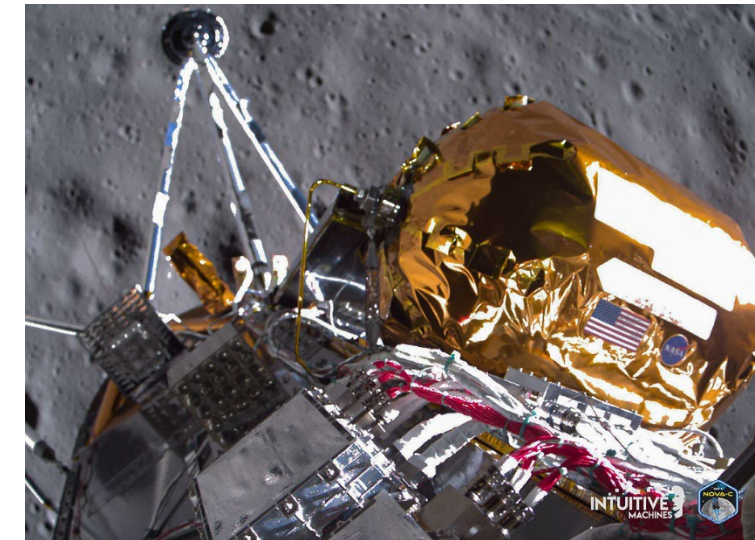


- NDL operated flawlessly for 1.6 hour during checkout and 1.5 hour during deorbit/descent/landing
- Remained in operational mode on the ground for another ~ 4 hours

Transit Checkout on Feb 19



Landing on Feb 22

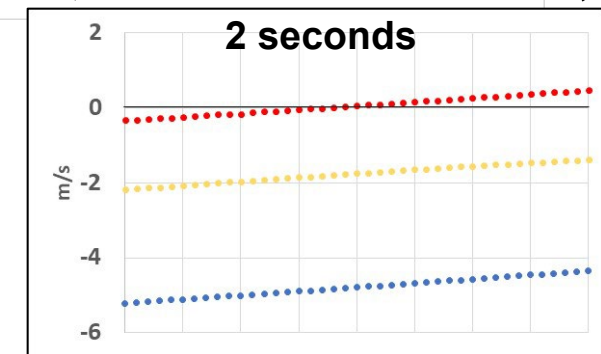
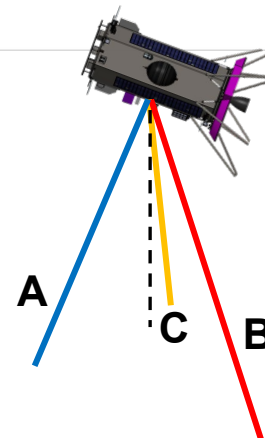
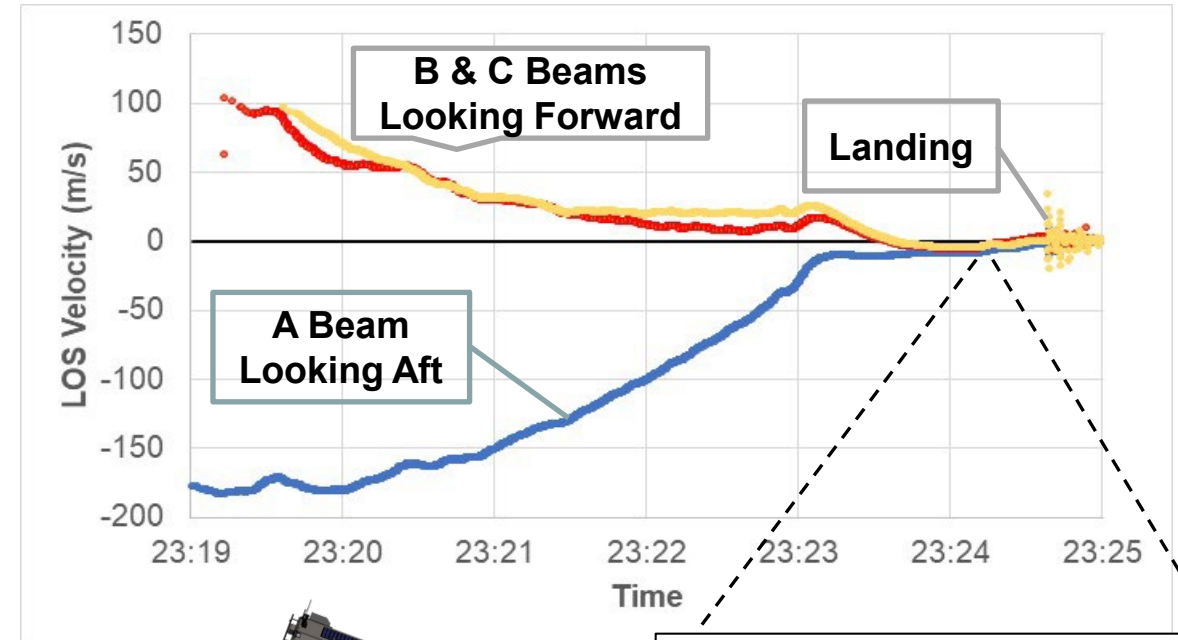
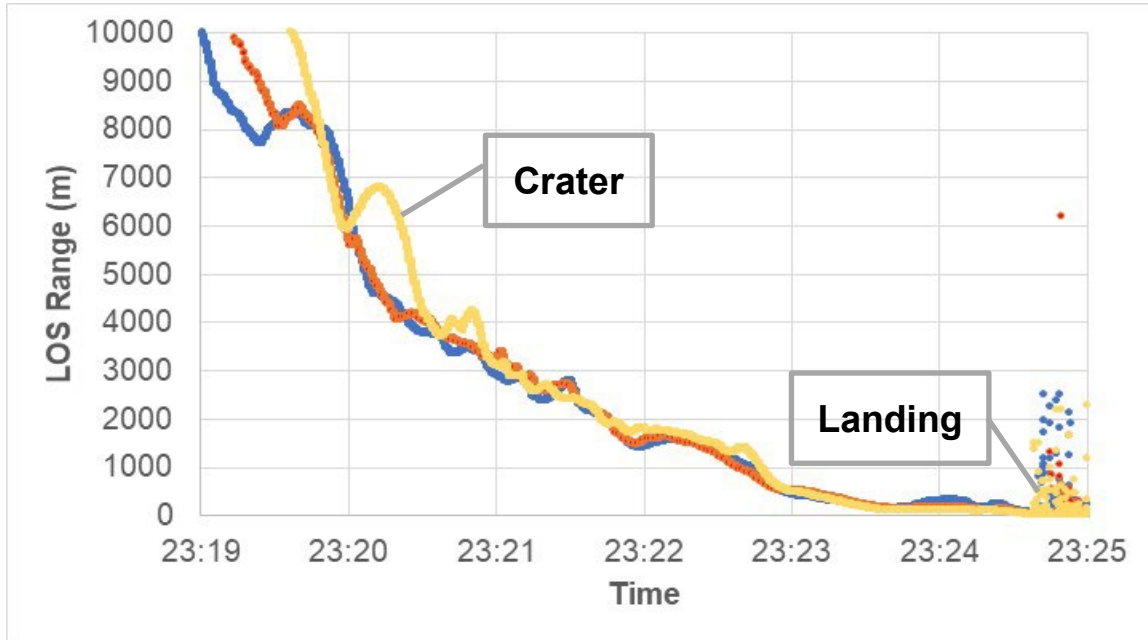




NDL Data from IM Lunar Mission

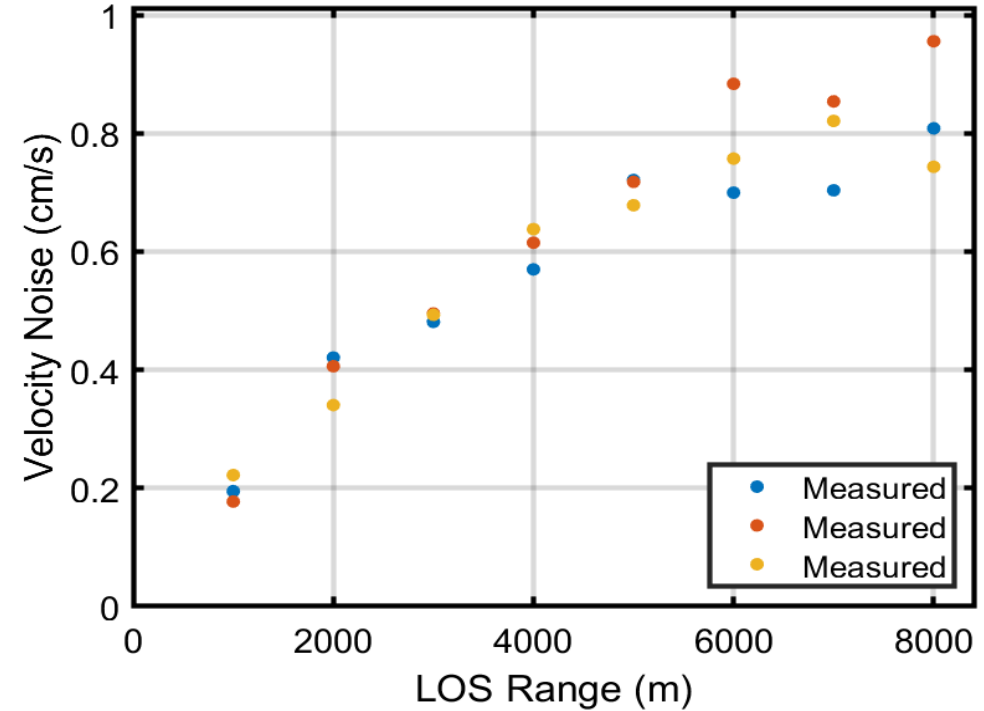
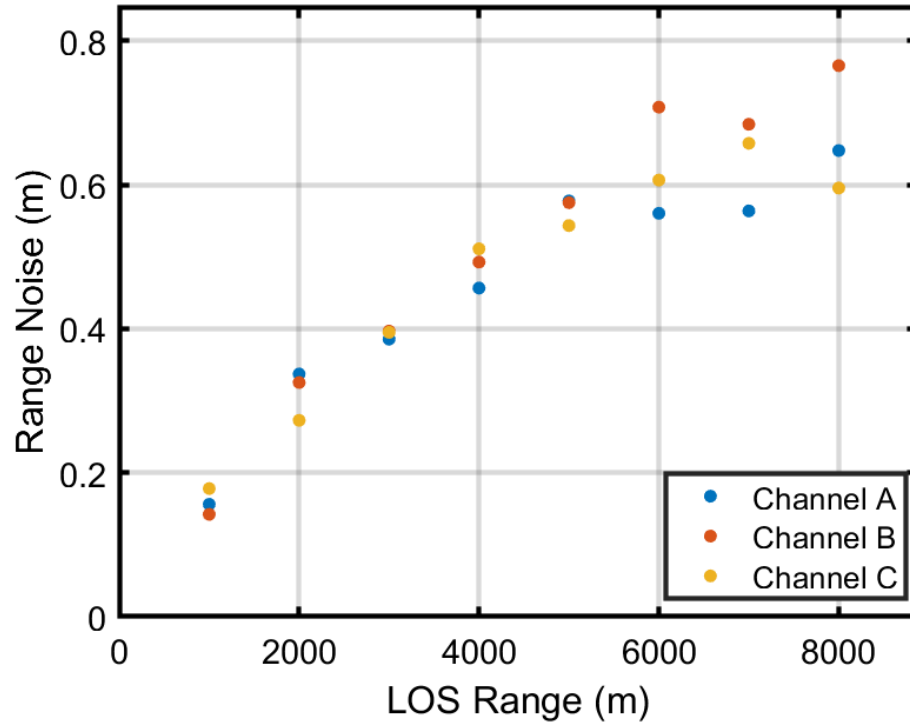


NDL provided 100% valid measurements from 10 km to surface





Range and Velocity Noise

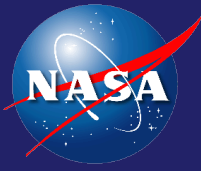


➤ **Measurements precision is over 2 orders of magnitude better than MSL and Mars 2020 Doppler Radar**

- **Range Noise < 0.8 m 1- σ**
- **Velocity Noise < 1 cm/s 1- σ**



Projected Performance vs. Actual



Parameter	Projected Performance	Flight Results
Maximum LOS Range	6.0 km	10.0 km
Maximum LOS Velocity	+/- 218 m/s	+/- 218 m/s
LOS Velocity Noise @ 3 km	8.3 cm/sec	0.4 cm/s
LOS Range Noise @ 3 km	8.2 m	0.4 m
Data Rate	20 Hz	20 Hz

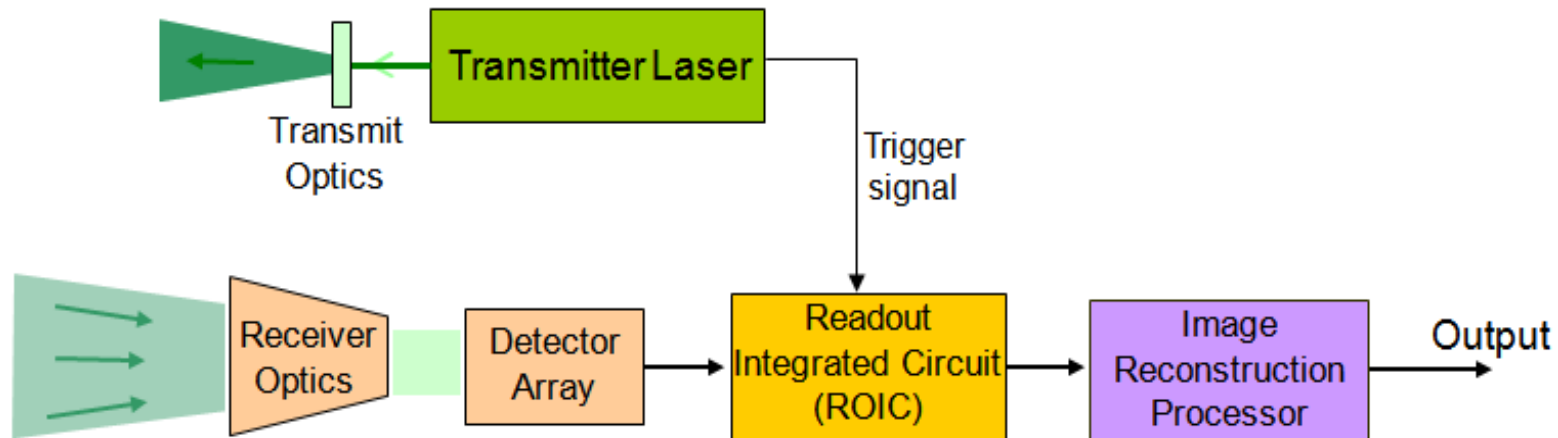
- Performance characterization was challenging due to atmospheric effects
 - Performance estimations were grossly conservative
- Lunar lander provided a perfect test environment
- Odysseus lunar landing was an excellent demonstration of the NDL for future landing missions



Terrain Sensing Lidar (TSL)

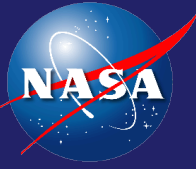


- TSL is based on **flash lidar** technology utilizing real-time image enhancement algorithms
- TSL presents several advantages over scanning lidars
 - Does not require vehicle motion correction
 - Generates organized 3-D pattern (does not need oversampling of the landing site)
 - Fast image acquisition time
 - Able to perform other functions critical for precision navigation





TSL Landing Operation Concept



Altimetry

50 km



20 km

Updating IMU
and reducing
position errors

A-TRN

10 km



Acquire low-resolution
3D terrain images to
identify known features

HDA

1 km

Acquire elevation
maps and select
landing location



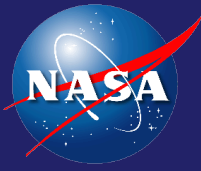
0.5 km

HRN



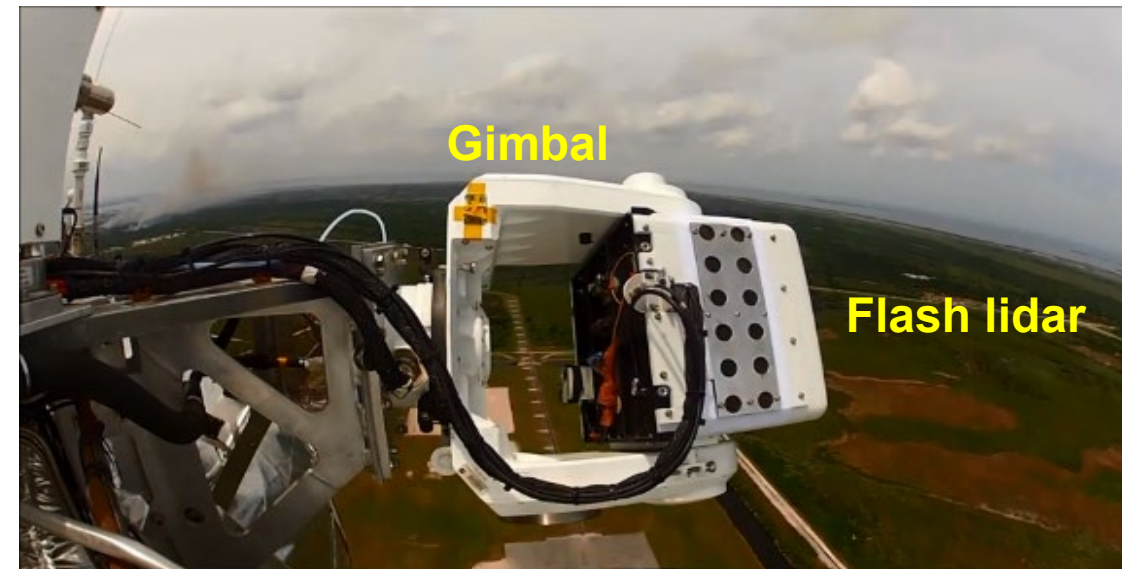


Descent and Landing Requirements



- Commercial linear-mode flash lidar camera has $128 \times 128 = 16.4\text{k}$ pixels
- Mapping $100 \text{ m} \times 100 \text{ m}$ area with 15 cm Ground Sample Distance (GSD) requires $\sim 0.5 \text{ M}$ pixels
- Developed a Super-Resolution algorithm to meet HDA requirements without the need for a mechanical gimbal or scanning mirror

Flash lidar closed-loop demonstration onboard rocket-powered Morpheus vehicle (2014)

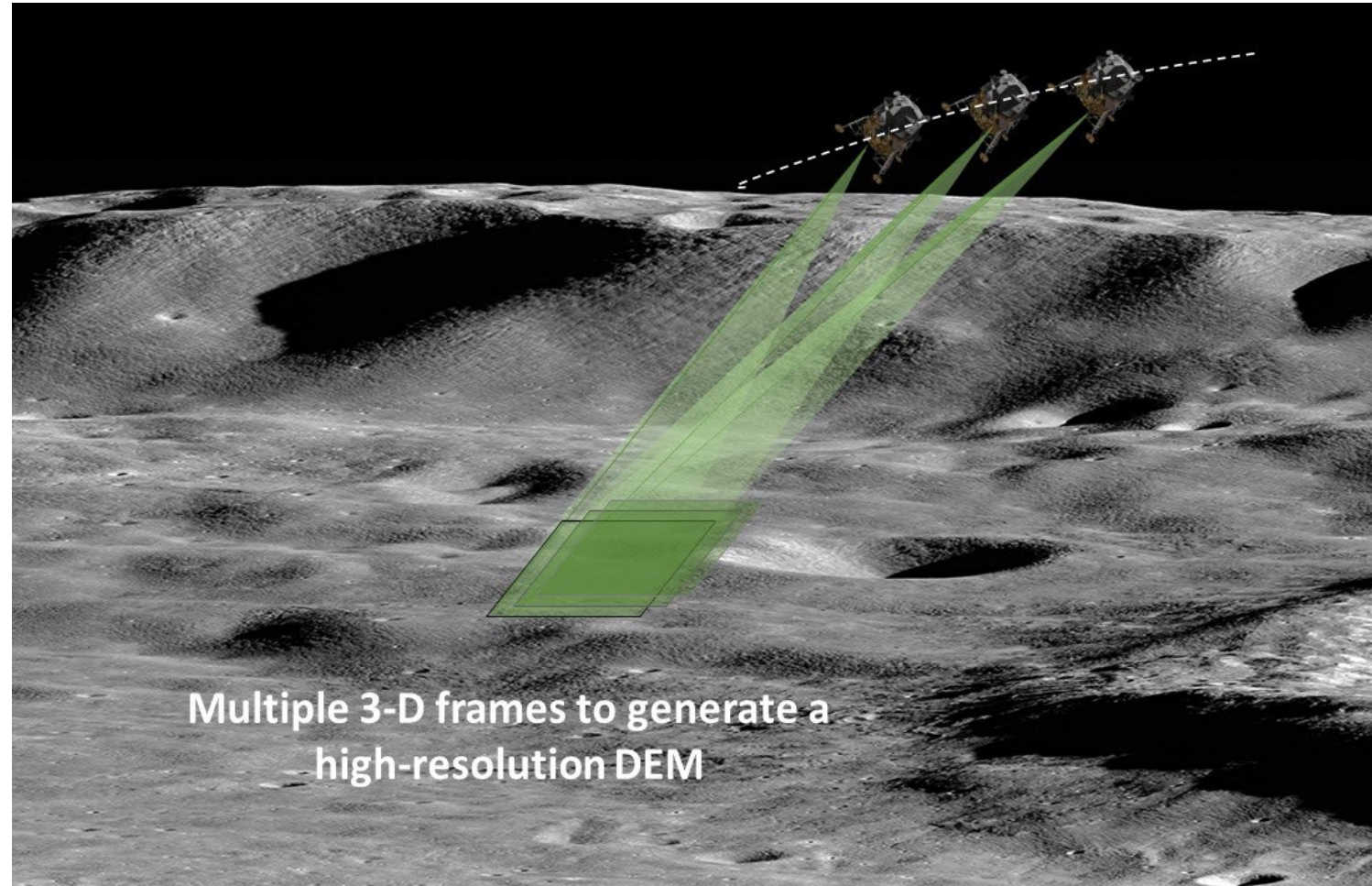




Super-Resolution Algorithm



- Super-Resolution (SR) technique uses a set of consecutive frames, from slightly different positions and angles (resulting from platform motion), to generate a high-resolution DEM
- No external sensor data is required
- Generates high-res DEMs at 1 Hz rate using 20 frames
- Provides 6-DOF relative state vector as byproduct



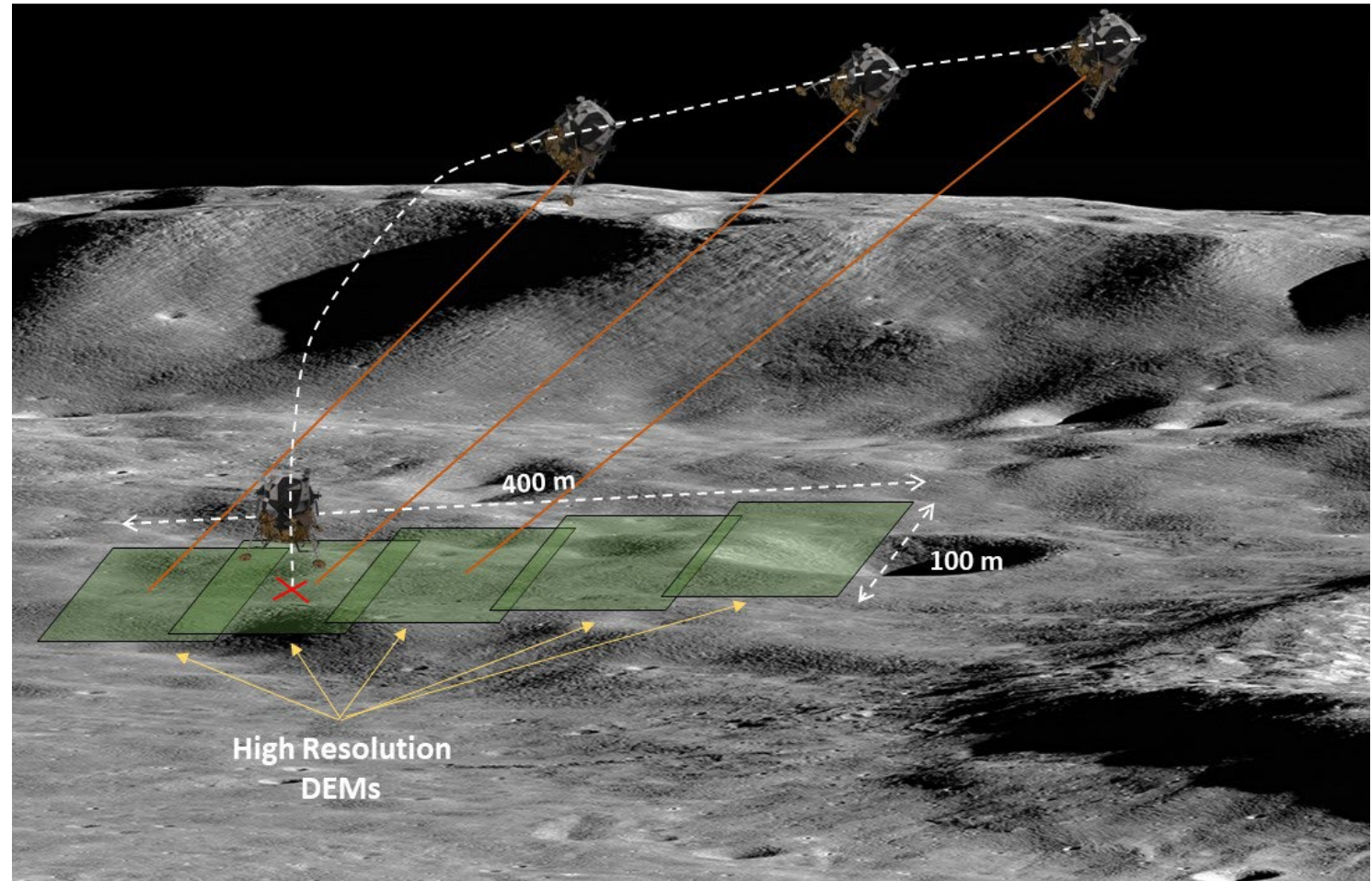


TSL Generates Multiple High-Resolution DEMs



Safe landing locations are provided every 1 second

- DEMs and Hazard Maps are generated every 1 second with 30 msec latency
- 5 seconds CONOPS can support 5 DEMs:
 - Cover up to 100 m x 400 m area
- OR
- Acquire 5 DEMs of 100 m x 100 m area for improved performance and validation of identified safe landing locations



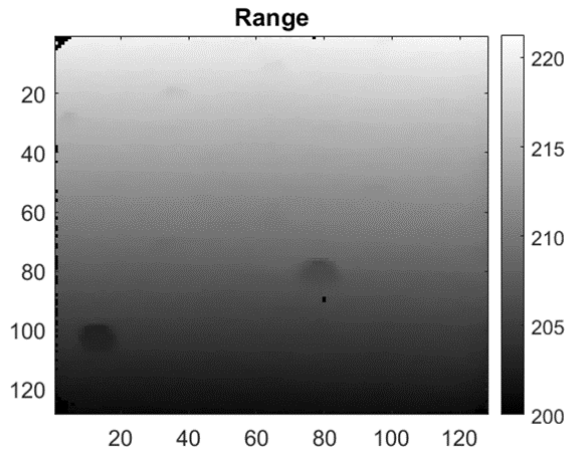


Helicopter Flight Test at Blue Origin West Texas Facility, August 2023

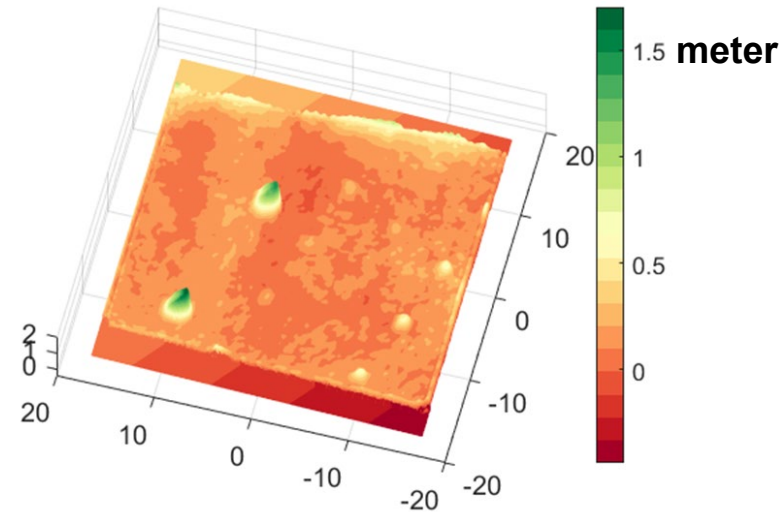


- 100% hazard detection from 250 m @ 45° look angle
 - Smallest hazard: 25 cm dia x 35 cm height

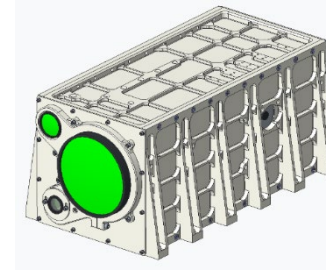
Single Frame



Real-Time Elevation Map



Breadboard Flash Lidar



NASA LaRC Flash Lidar is the only active sensor technology that has successfully demonstrated hazard detection



Terrain Sensing Lidar (TSL) Prototype

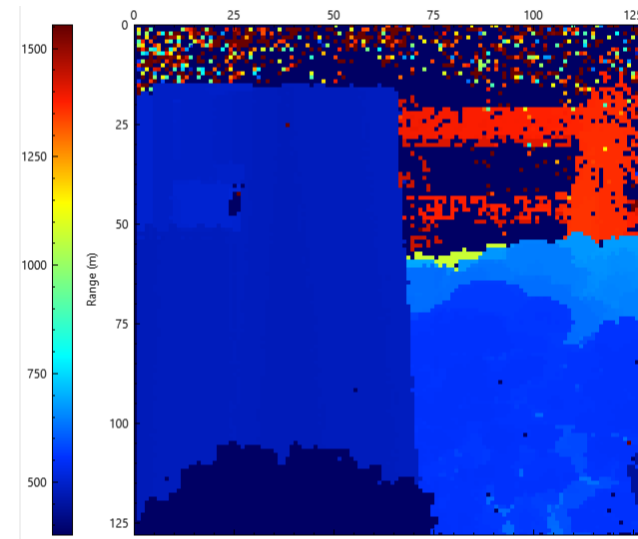
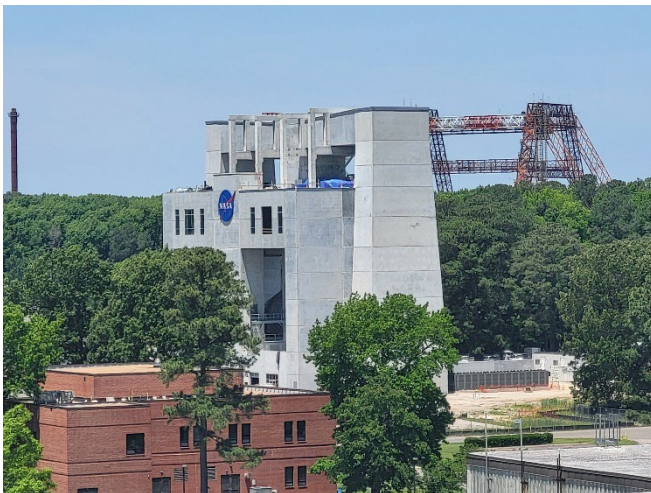


- Performs HDA function from 1.3 km slant range
- Enables long distance *Altimetry* and active *Terrain Relative Navigation*
- Compact design

6.5 kg

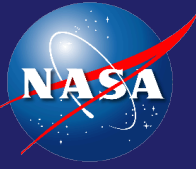


Single Frame Images

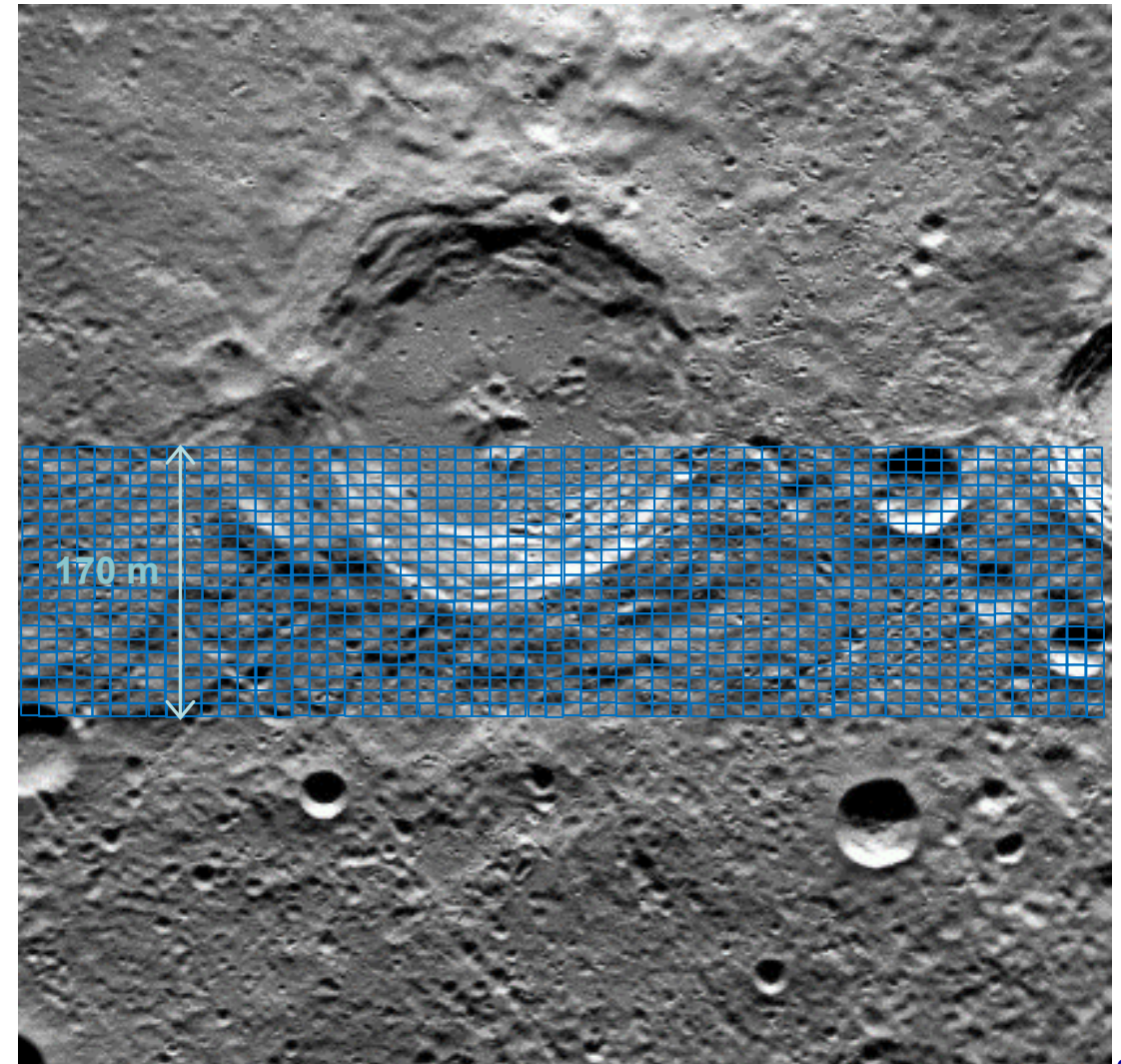
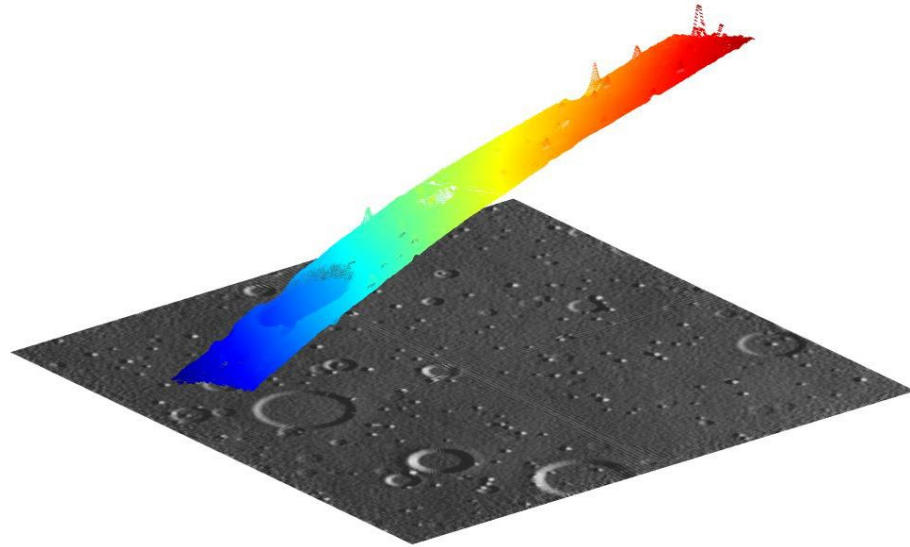




TSL TRN Function

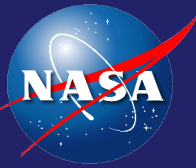


- Generates 170 m wide swath from 10 km
- Sufficient overlap of image frames for applying Super-Resolution algorithm
- 5 m resolution matching LOLA elevation maps pixel size





NDL and TSL together make a powerful sensor suite



Terrain Sensing Lidar

Altitude

TRN

HDA

HRN

50 km

20 km

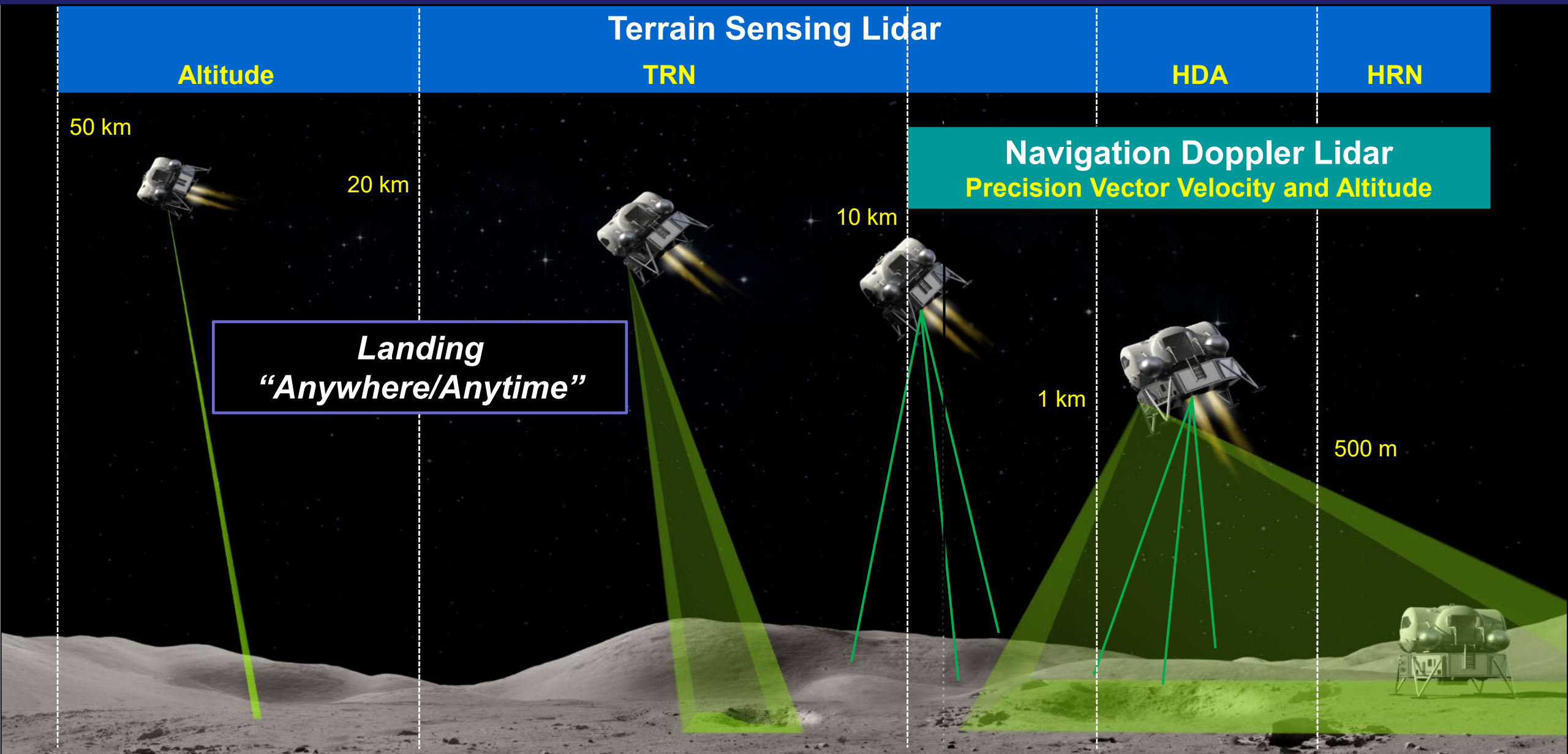
10 km

1 km

500 m

Landing
"Anywhere/Anytime"

Navigation Doppler Lidar
Precision Vector Velocity and Altitude





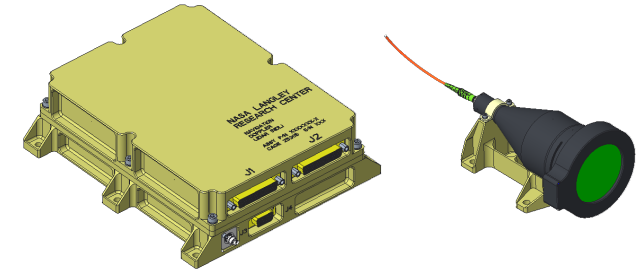
Ongoing Efforts



NDL

- Advanced component technologies for:
 - Reducing size by 9X and mass by 3X
 - Expand operational capabilities of the NDL
 - 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
 - Continue investigations for aerial vehicles

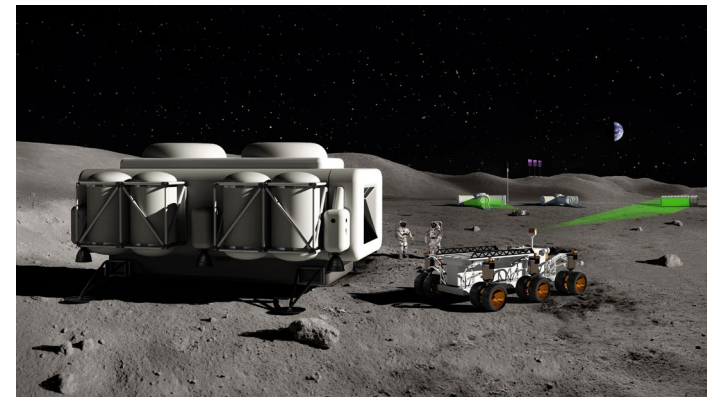
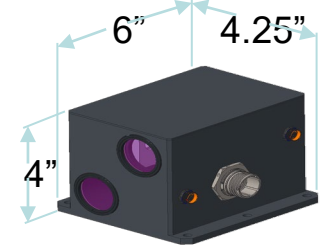
Air Data, Ground Velocity and Range Sensor



TSL

- Drone flight test of prototype TSL
- ETU design
- Design analysis for a short-range TSL for LTV autonomous navigation and mating with habitat

LTV Lidar





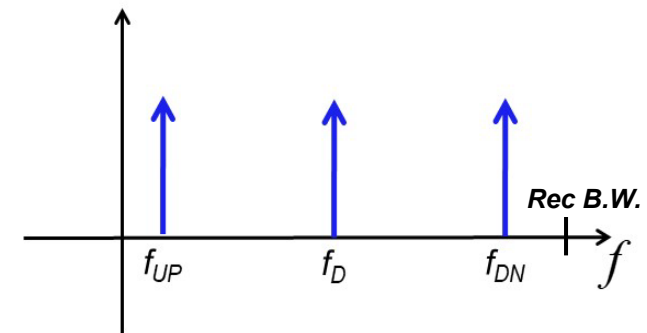
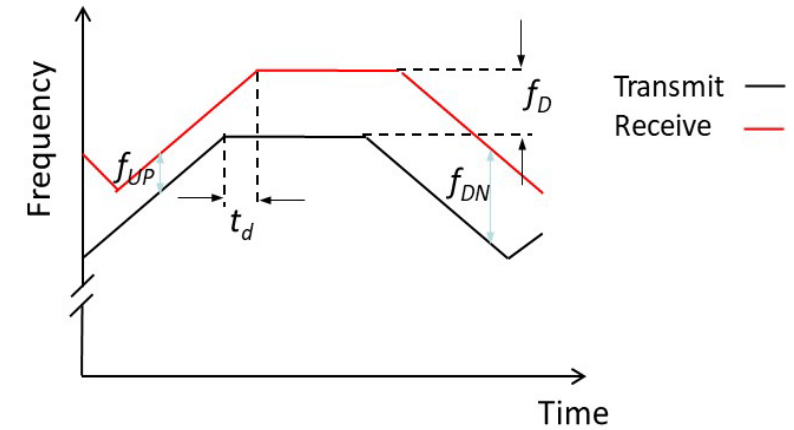
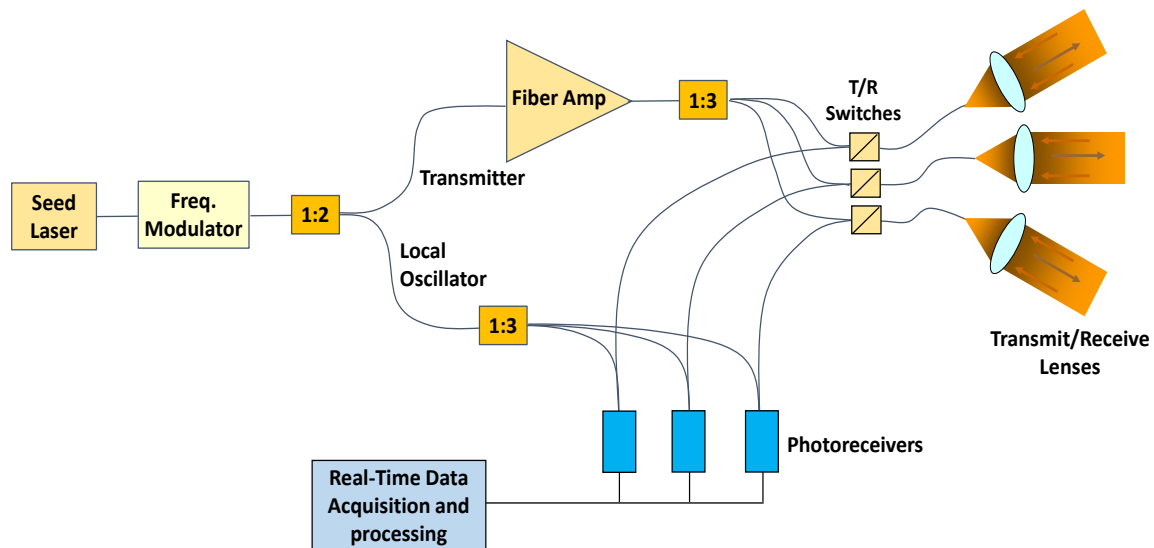
Backup



Navigation Doppler Lidar (NDL)



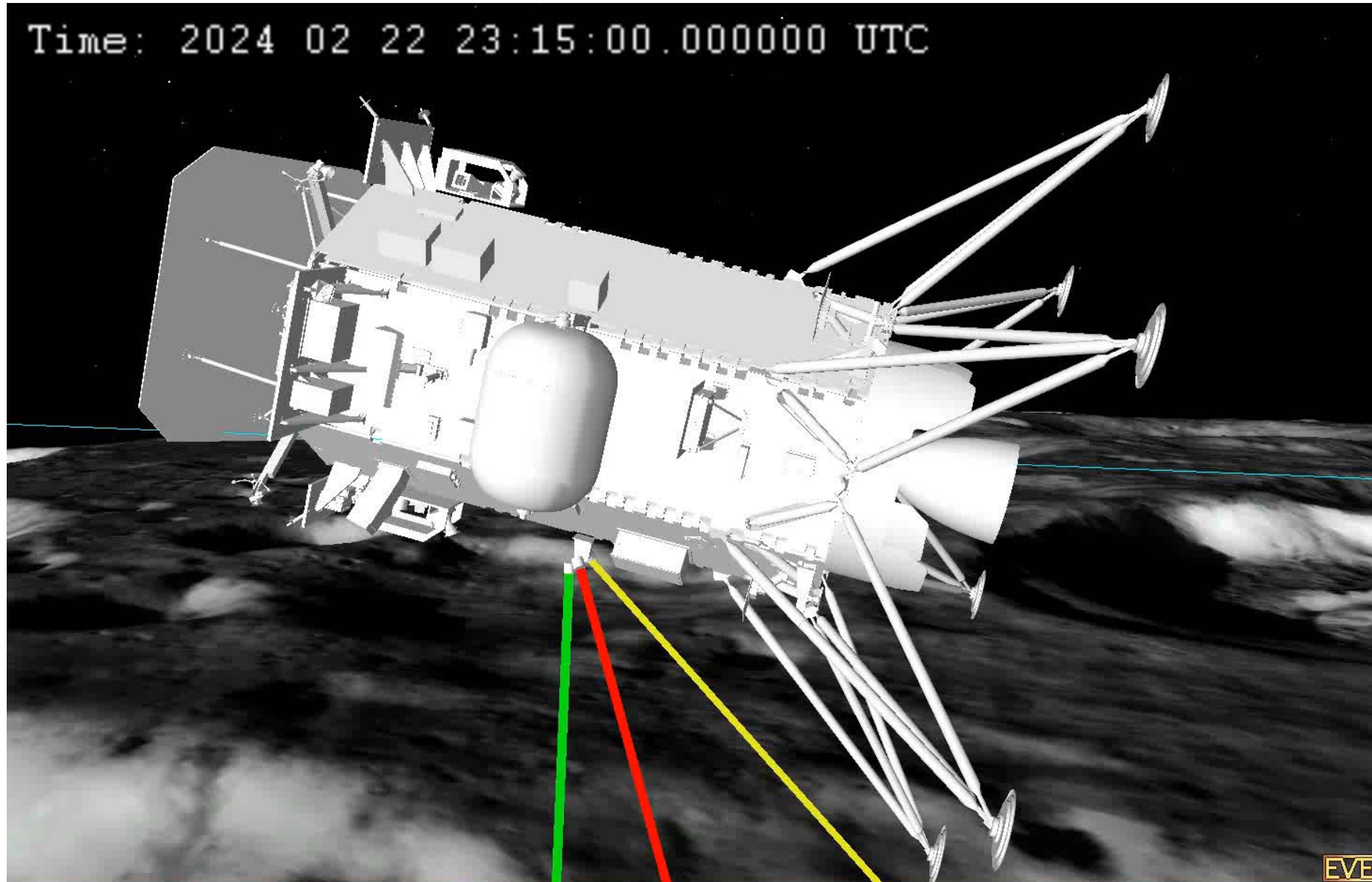
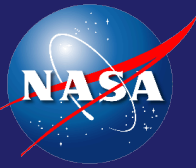
➤ Utilizes FMCW technique to measure velocity and range along three laser beams



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



NDL Operation on Odysseus

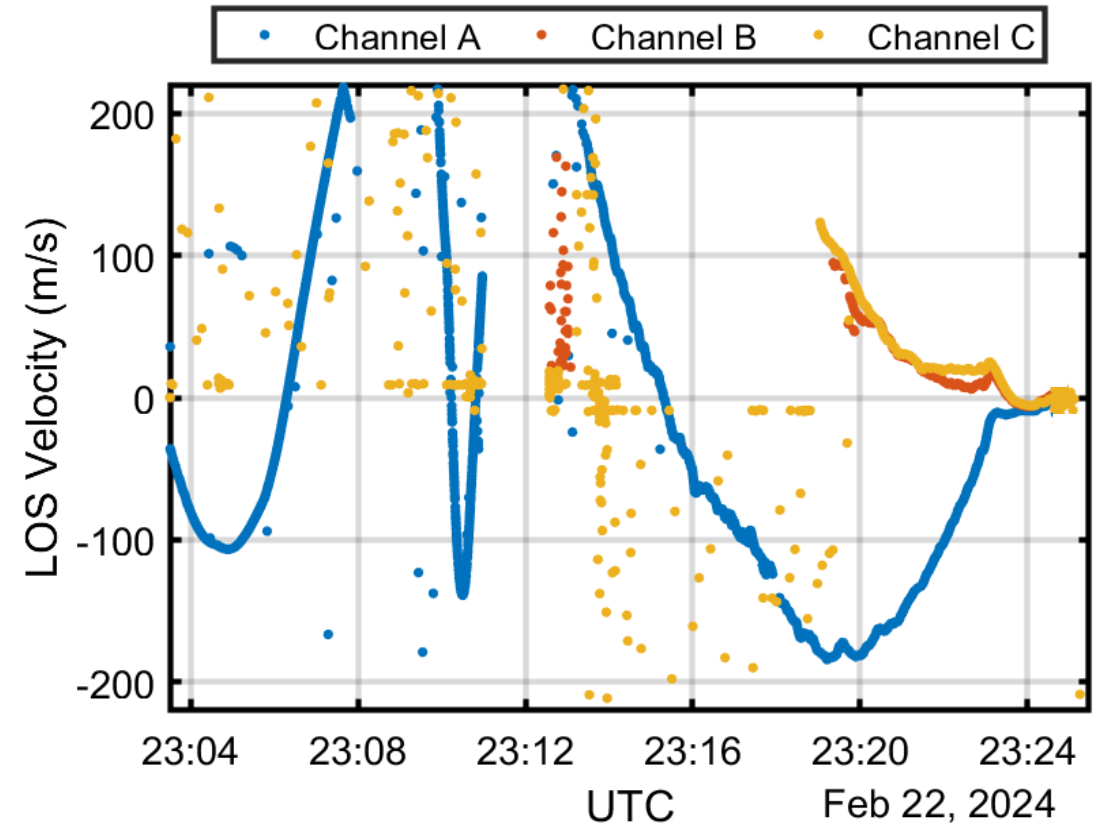
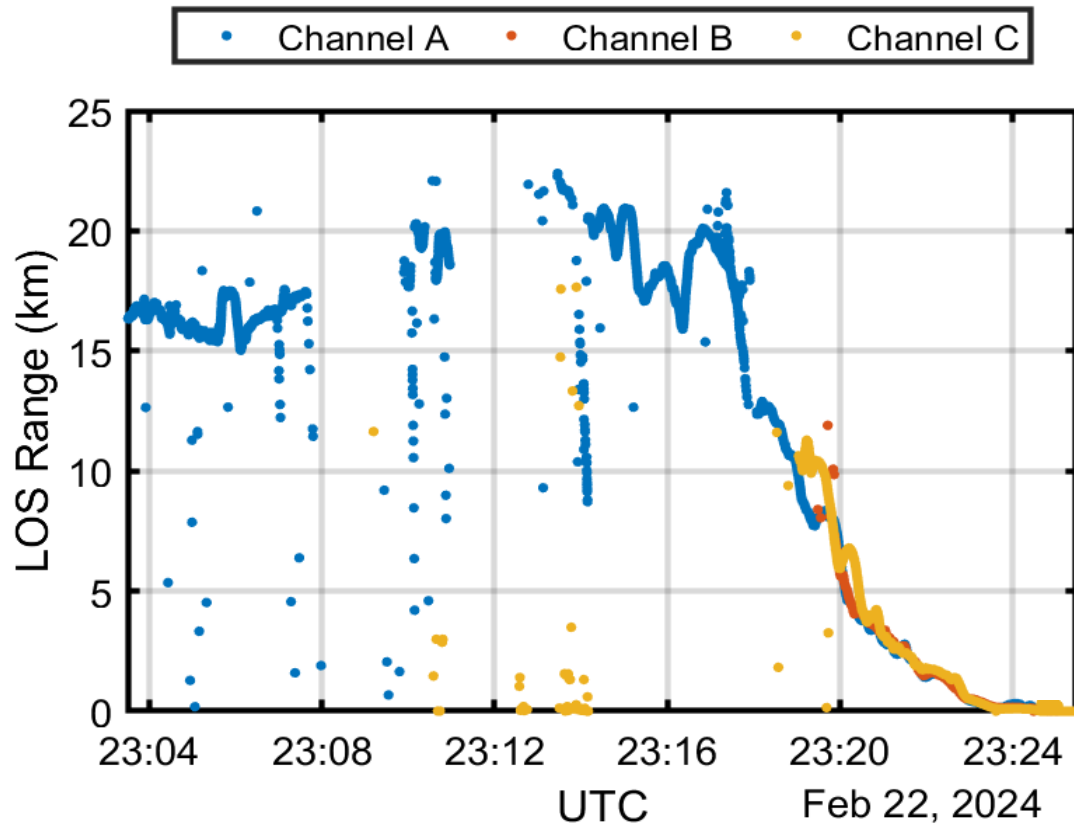




LOS Range and Velocity Measurements



Post-Processed: corrected for aliasing on Ch A



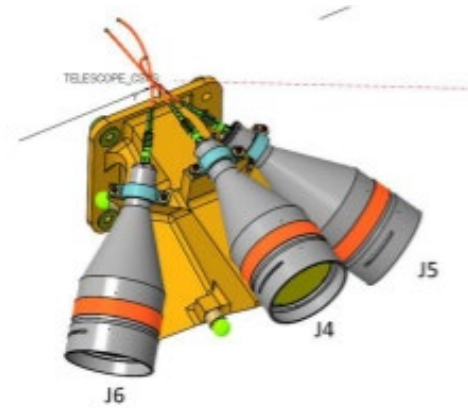
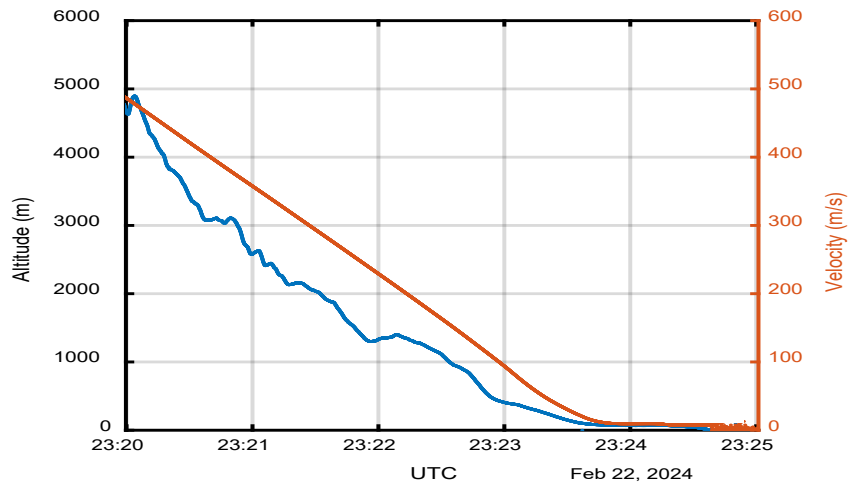
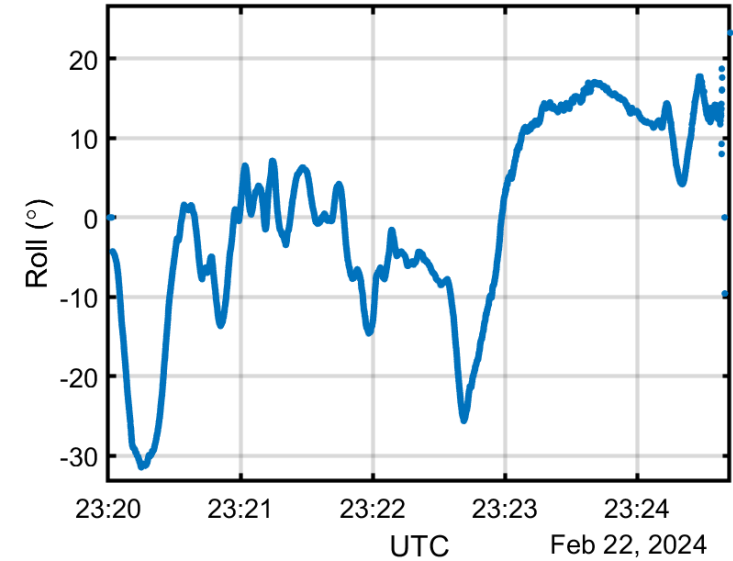
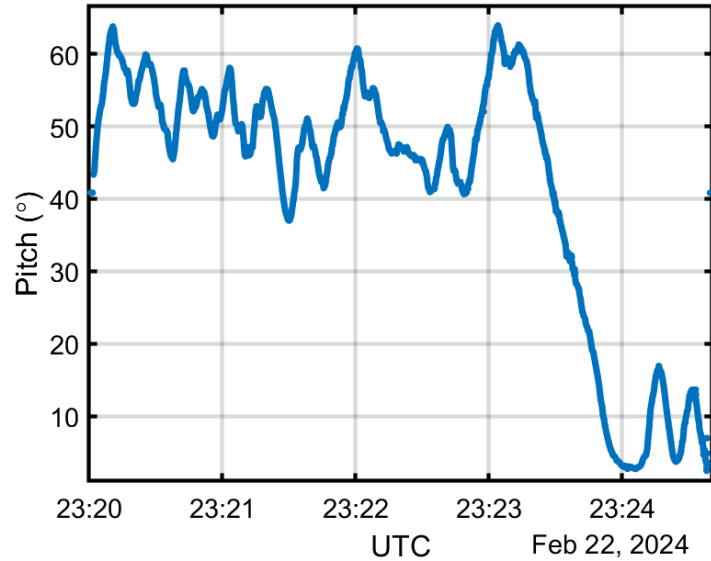
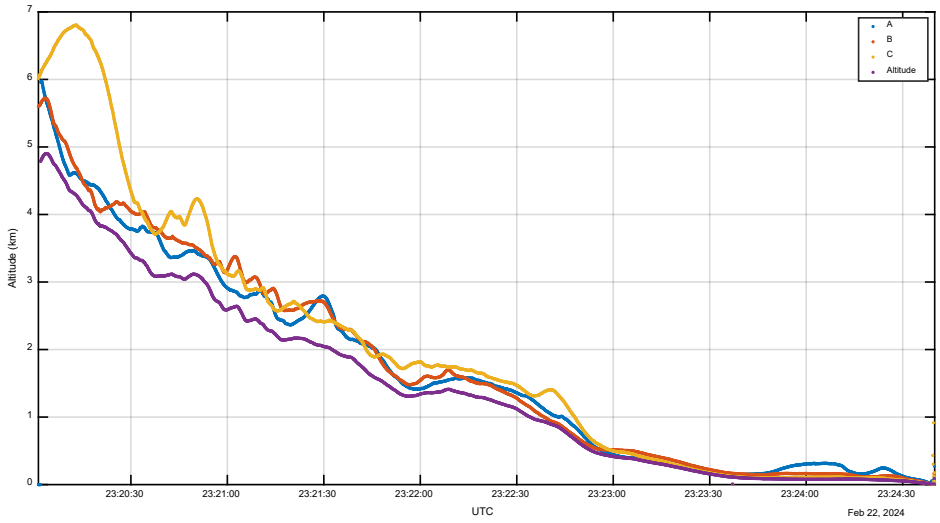
➤ S/C was traveling at very high speed ($\gg 1000$ m/s) above 10 km altitude and Line of Sight (LOS) velocities exceeded the ± 218 m/s limit for most parts



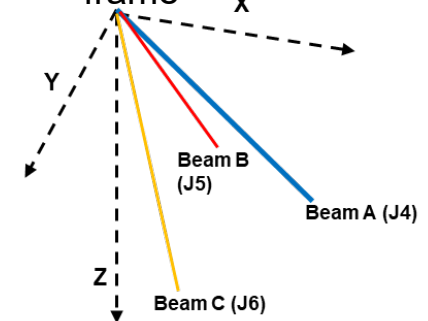
Estimated Altitude, Pitch and Roll



➤ Measurements are in the NDL reference frame



NDL Optical Head reference frame



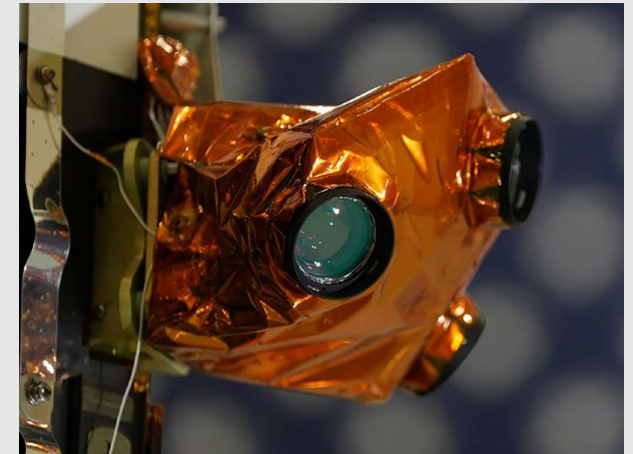


- **NDL was planned as a secondary sensor for velocity data during descent**
- **IM found out hours before landing that their laser range finders couldn't be turned on due to a manual safety switch**
- **IM asked NASA and the project for permission to use NDL as their primary sensor for range data**
- **IM performed an extra orbit to buy 1.5 hours to prepare and upload a software update to ingest NDL range measurements**

9:26 p.m. ET, February 22, 2024

This is the NASA instrument that saved Odysseus' mission

From CNN's Jackie Wattles

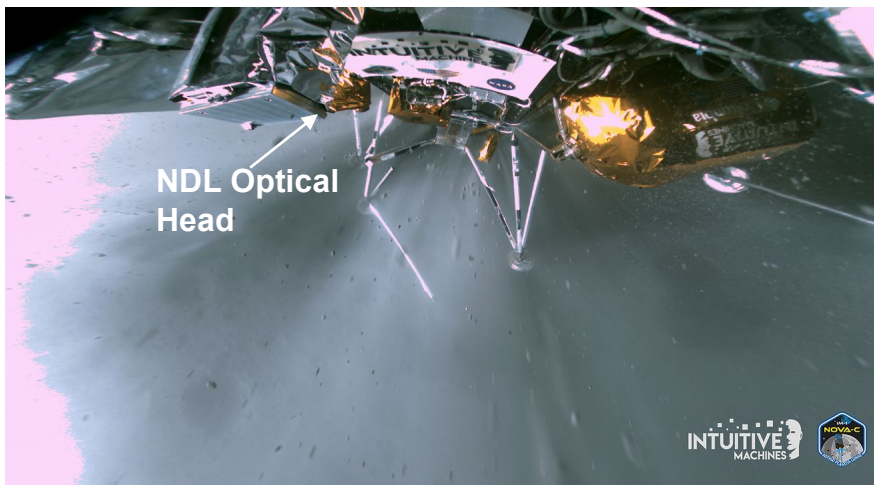


NASA's Navigation Doppler Lidar

IM Attempted Use of NDL During Lunar Descent



- IM realized that the NDL data was not used after analyzing the GNC telemetry data
- There were errors in the last-minute SW update
 - Neither range nor velocity data were used
- Odysseus did not land upright and was short of its original target by ~ 2 km



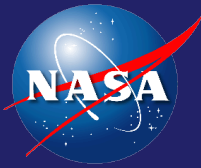
STEVE ALTEMUS, IM CEO, comments on NDL:

As it turns out though, as we worked all day to write that software, to solve the problem with the NASA Doppler LiDAR, as we went into power descent, **we did not receive those NDL measurements.** And so we landed without the laser altimeters in the end. But we had done some work, you know, to get us there. **And we looked at NASA's Doppler LiDAR telemetry, and boy, did it track perfectly so it would have really put us down softly if we could have read those measurements.**

<https://mastersofscale.com/landing-on-the-moon/>



LaRC Lidar Sensors Capabilities



- LaRC has established a unique **“lidar sensors”** capability
- Expertise and facilities developed at LaRC for precision and safe landing over past 20 years are highly valuable to **landing missions, surface mobility** and **in-orbit proximity operation (R&D)**
 - SMEs and recommendations to partners and stakeholders
 - Engagement with technical staff and supporting reviews
 - Analyses and modeling
 - Ground and aircraft tests
 - Specialized lidar environmental tests
 - Lidar sensor technology advancement per evolving requirements
- Successful track record (ALHAT, COBALT, and SPLICE projects, and CLPS missions)