

National Aeronautics and Space Administration



AAS 25-519

NDL

NAVIGATION DOPPLER LIDAR

**Navigation Doppler Lidar Performance Assessment and Trajectory
Reconstruction of the Intuitive Machines IM-1 Lunar Landing**

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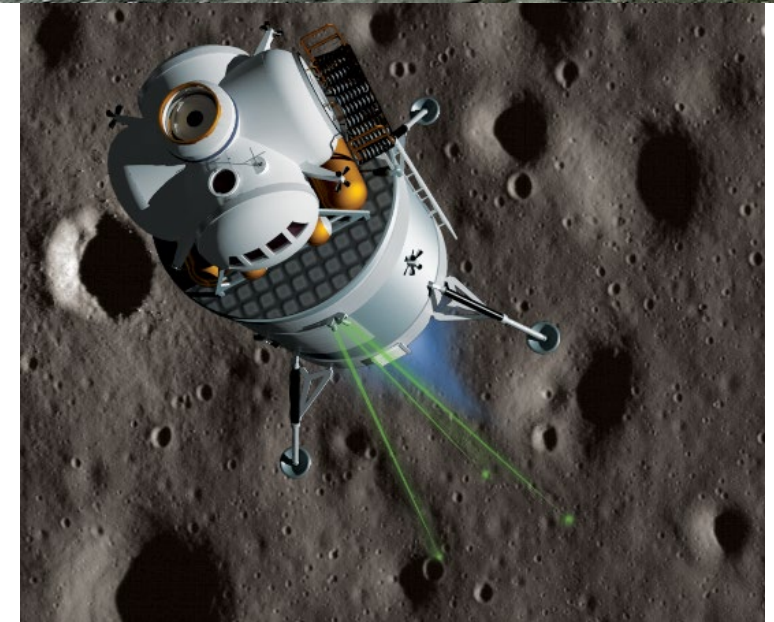
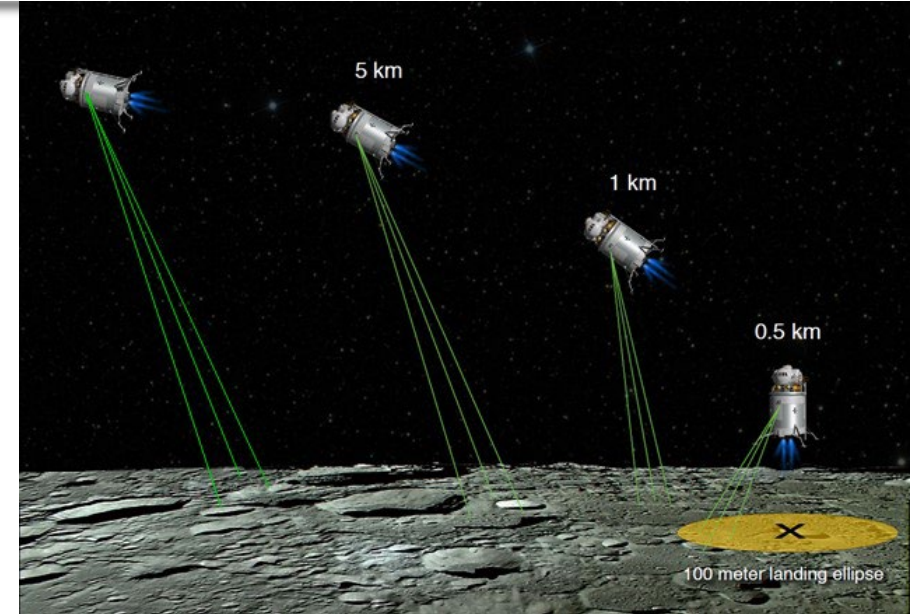
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Navigation Doppler Lidar (NDL)

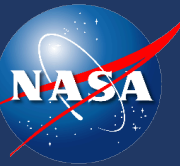


- **Safe and precise landing of robotic and crewed space landing systems requires advanced sensing systems for closed-loop GN&C**
- **NDL provides range and velocity data that are measured simultaneously**
 - Range is measured based on laser beam time of arrival thus it is affected by terrain features
 - Velocity is measured based on the Doppler effect thus it is *not* affected by terrain features
- **Simultaneous line-of-sight measurements along 3 beams can estimate:**
 - Velocity vector relative to ground
 - Altitude relative to ground
 - Pitch attitude relative to ground





NDL from Concept to Lunar Landing Demonstration



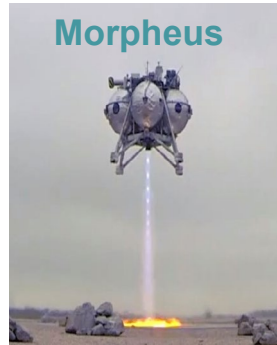
2008



2010



2012



Morpheus

2014



Masten

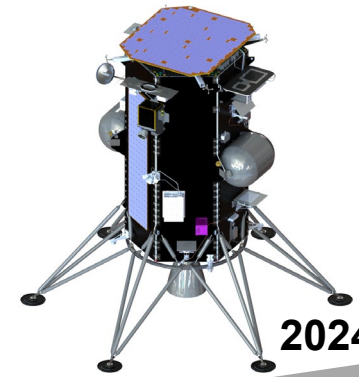
2017

New Shepard



2021

Intuitive Machines
Nova-C Vehicle



2024

Breadboard without real-time processing

Fully-Autonomous Prototype

Spaceflight ETU

Proof-of-Concept



GEN 1



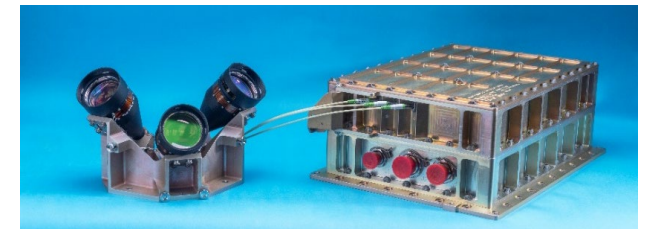
GEN 2



GEN 3

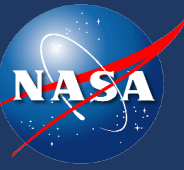


GEN 4

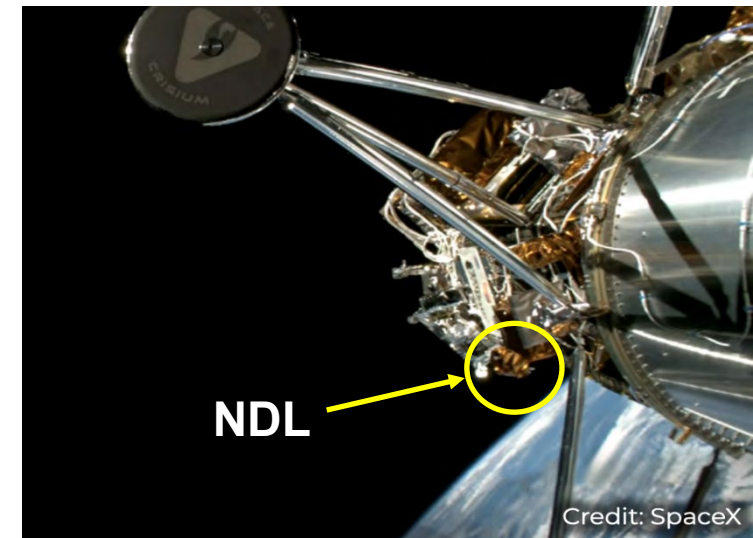
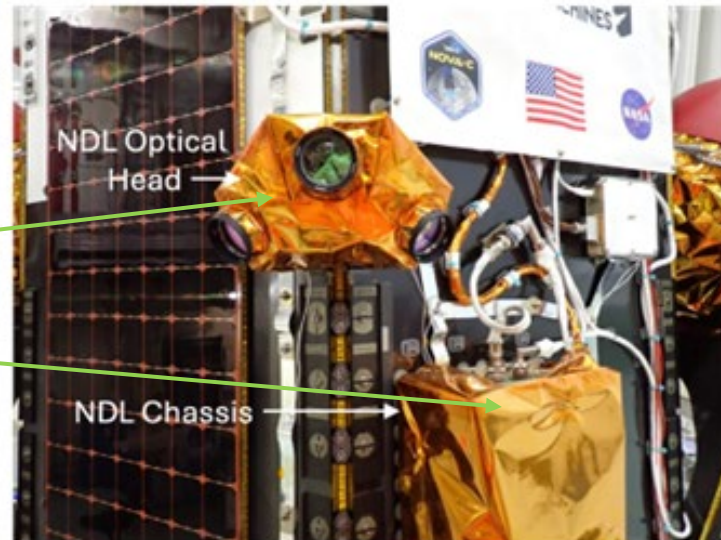
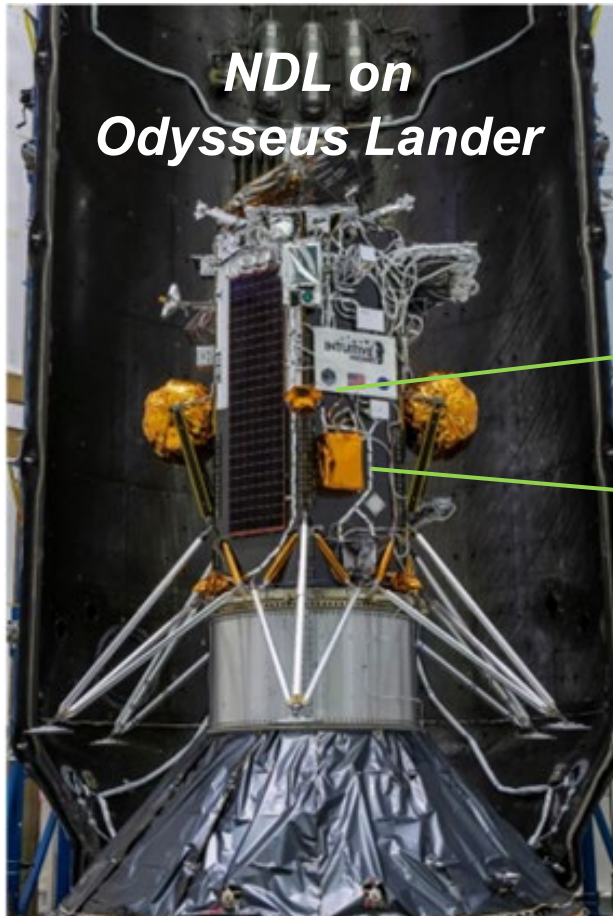




Intuitive Machines 1 (IM-1) Mission

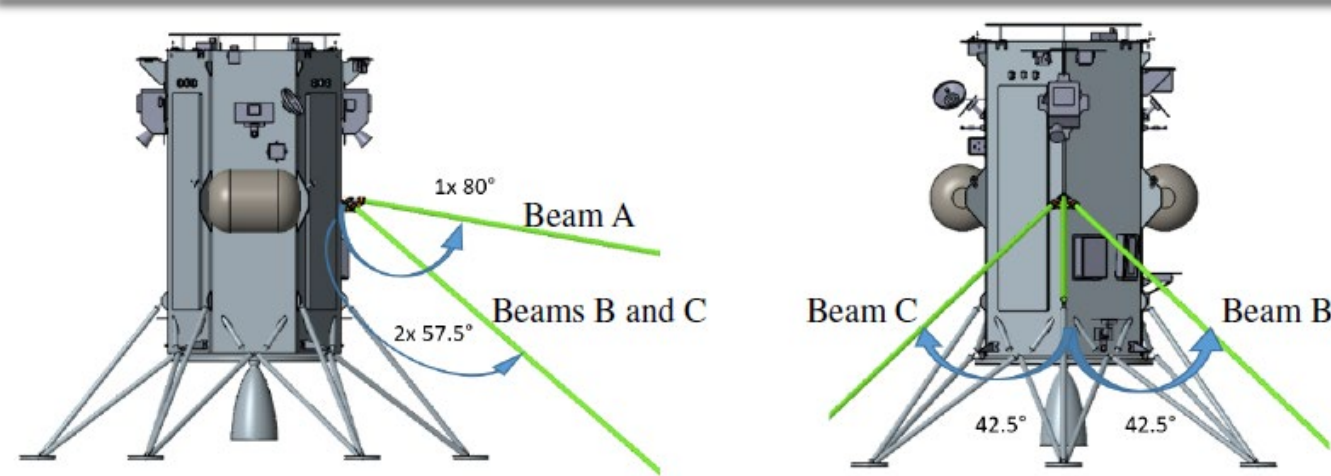
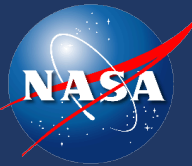


- Commercial Lunar Payload Services (CLPS) program
- Launched on Falcon 9 rocket on February 15, 2024
- Landed on the Moon on February 22, 2024

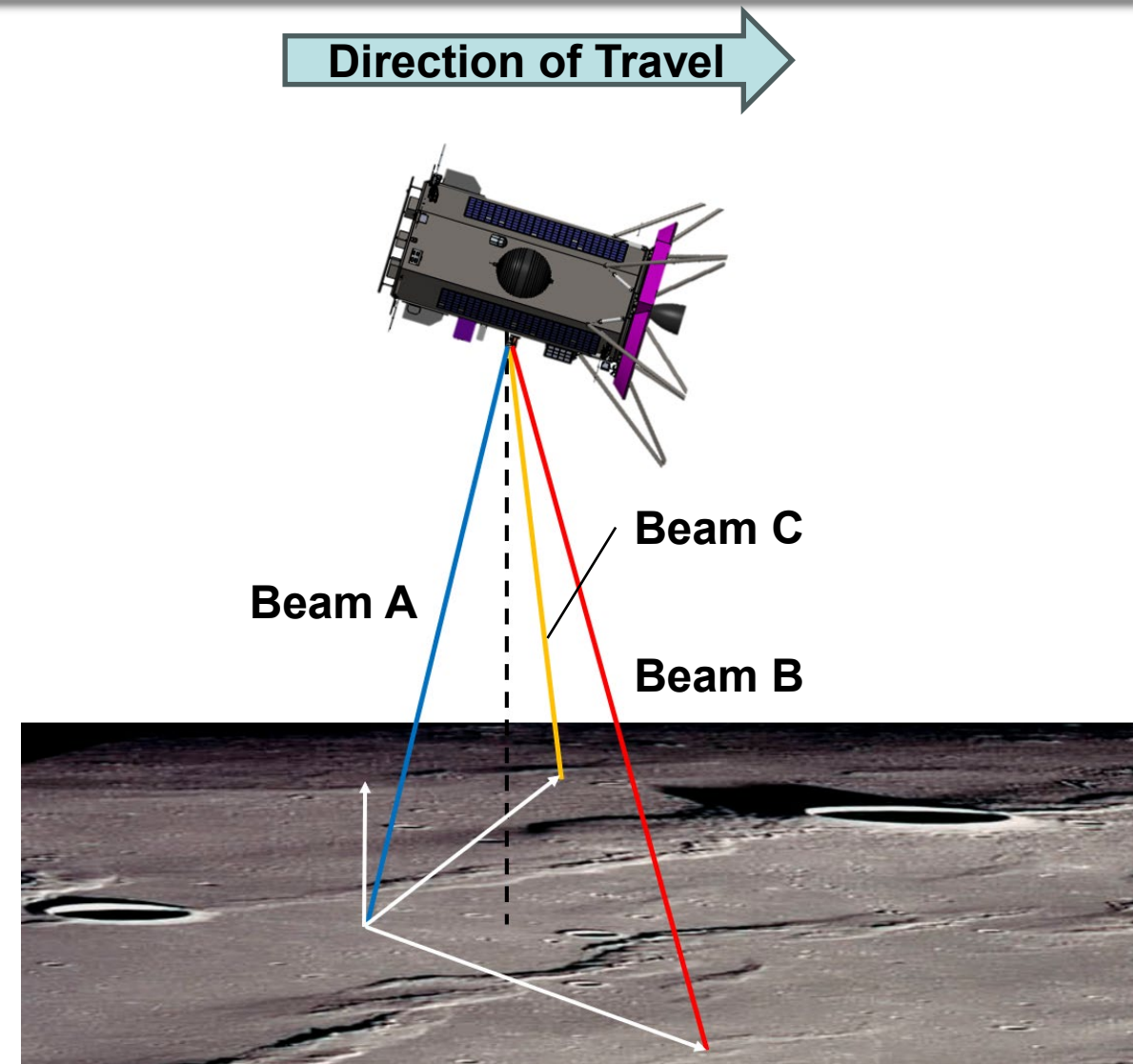


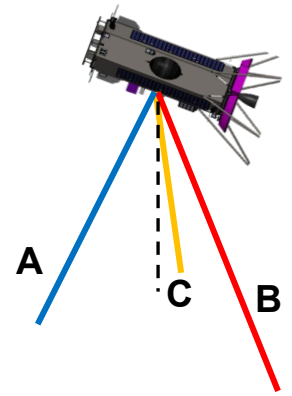
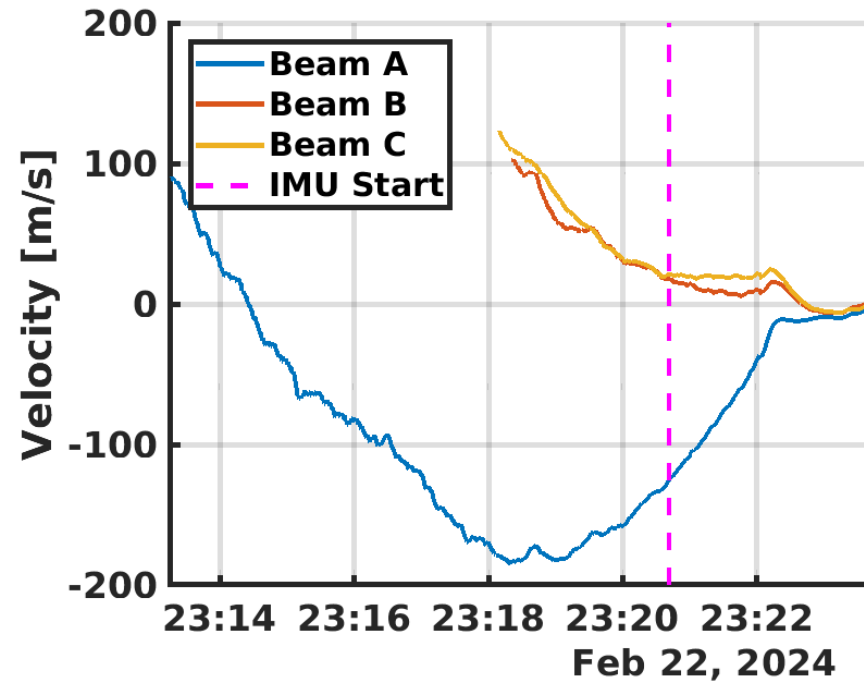
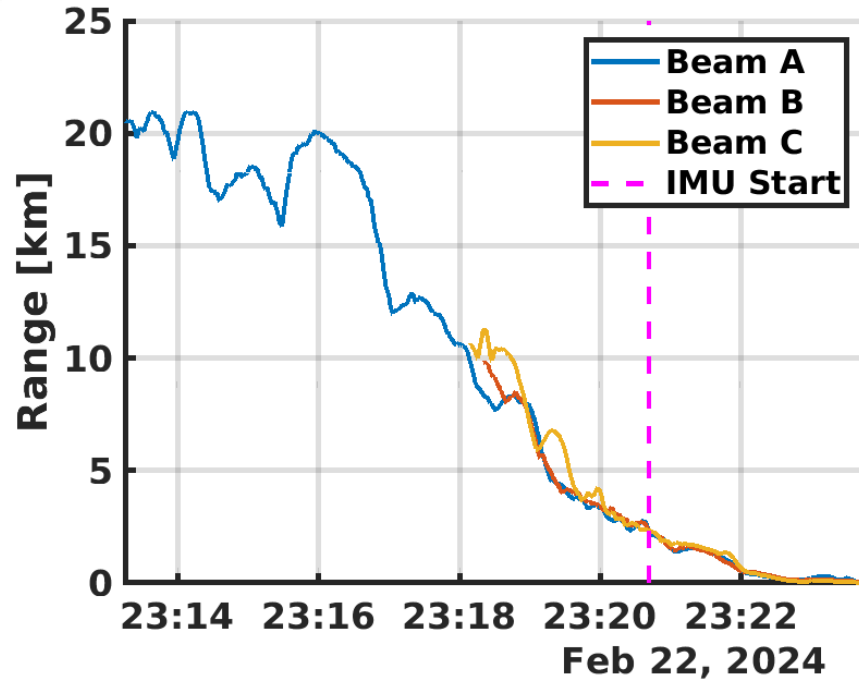


Navigation Doppler Lidar on IM-1



- **NDL measures simultaneous range and velocity along 3 beams (A, B, and C)**
- **Frequency modulated continuous wave measurement technique**
- **Designed to measure velocities up to 218 m/s at ranges from 5000 to 2 m**
- **Sample rate of 20 Hz**





- **NDL data exceeded expectations**

- NDL was designed to deliver range and velocities from ranges of 5 km and below
- NDL Beam A recorded range data greater than 20 km, Beams B and C ~10 km and below
- 629 s of data from Beam A, 324 s from Beam B, and 336 s from Beam C
- 324 s of data where all three beams intersect with the lunar surface without any dropouts

- **Evidence of craters in beam range data**



Other Data Sources



- **Inertial Measurement Unit (IMU)**
 - 2 IMUs on board: Honeywell HG1700 and Emcore SDI-505
 - Data from each unit agreed, higher sample rate unit chosen for the reconstruction (Emcore SDI)
 - IMU data was limited to last 184 s of trajectory (or roughly 2 km altitude and below) due to limitations on what could be sent back to Earth after landing
 - 6-DOF trajectory reconstruction limited to last 184 s of trajectory where IMU data are available
 - Some trajectory information can be reconstructed from NDL alone prior to start of IMU data
- **Lunar Terrain Engine**
 - Digital Elevation Model (DEM) based on data from the Lunar Orbiter Laser Altimeter (LOLA)
 - Ray tracing algorithm used to compute terrain intercept points, previous flight validation on Mars Science Laboratory and Mars 2020
- **Gravity Model**
 - Gravity Recovery and Interior Laboratory (GRAIL) gravity model GRGM660PRIM

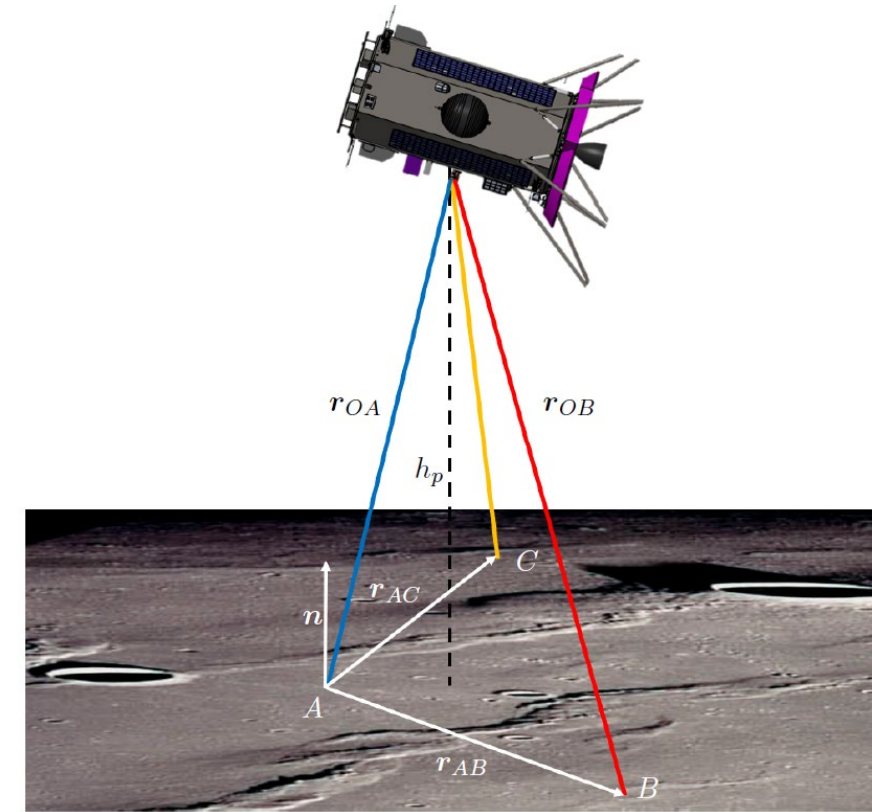
- **6-DOF trajectory reconstruction is limited to last 184 s where IMU data are available**
 - Some trajectory data can be reconstructed from the 3 NDL beam data alone prior to start of IMU data
 - 324 s of data where all 3 beams intersect with the surface

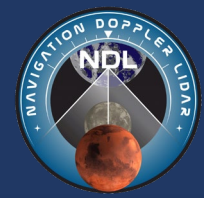
- **Surface normal:**
$$\mathbf{n} = \frac{\mathbf{r}_{AB} \times \mathbf{r}_{AC}}{\|\mathbf{r}_{AB} \times \mathbf{r}_{AC}\|}$$

- **Altitude relative to surface:**
$$h_p = -\mathbf{r}_{OA} \cdot \mathbf{n}$$

- **Pitch angle relative to surface:**
$$\zeta = \pi/2 - \cos^{-1}(\mathbf{x}_b \cdot \mathbf{n})$$

- **Body-axis velocity relative to surface:**
$$\mathbf{V} = \begin{Bmatrix} V_x \\ V_y \\ V_z \end{Bmatrix} = \mathbf{S}^{-1} \begin{Bmatrix} \nu_A \\ \nu_B \\ \nu_C \end{Bmatrix}$$





Kalman Filter Trajectory Reconstruction



- **New Statistical Trajectory Estimation Program (NewSTEP)**

- Iterative Extended Kalman Filter-Smoother formulated for trajectory reconstruction problems
- Initially developed for X-43A (2001-2004), subsequently applied to many flight projects (Ares I-X, Mars Science Laboratory, etc)

- **Trajectory reconstruction blends the IMU and NDL data over the last 184 s**

- **Filter States:**

- Position, Velocity, Attitude

- **Measurements:**

- IMU data used to integrate equations of motion
- NDL data used to provide state updates from range and velocity measurements.

$$x = [r \quad \phi \quad \theta \quad u \quad v \quad w \quad e_0 \quad e_1 \quad e_2 \quad e_3]^T$$

$$\dot{r} = -w$$

$$\dot{\phi} = \frac{u}{r}$$

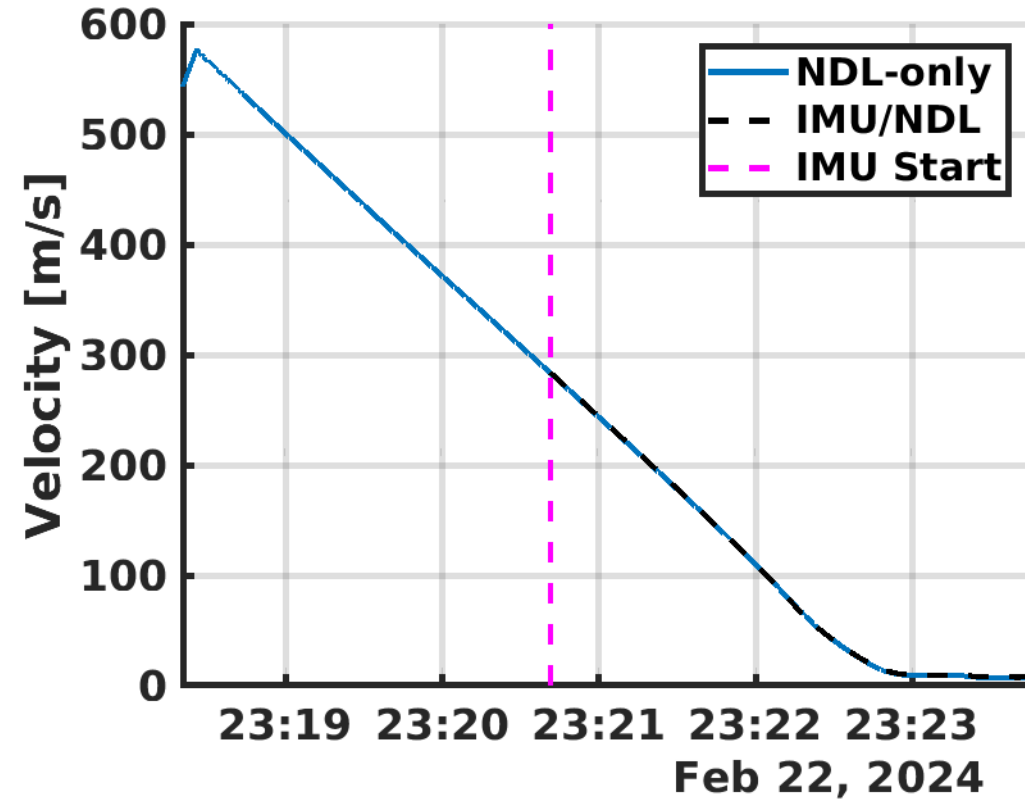
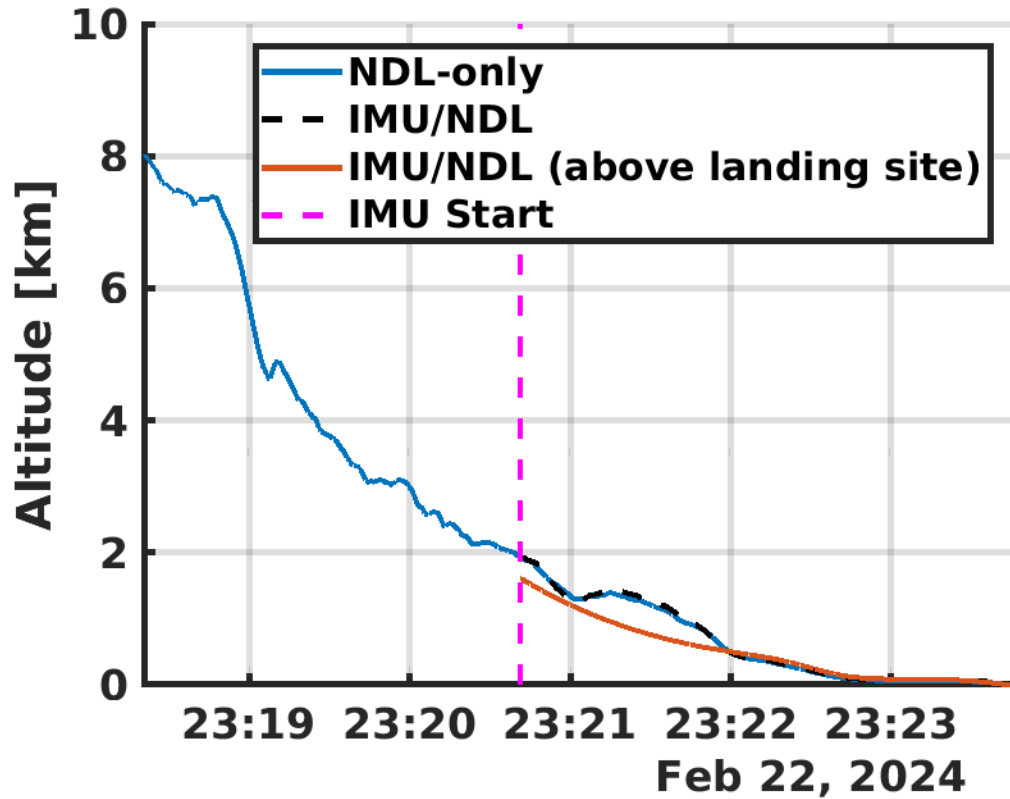
$$\dot{\theta} = \frac{v}{r \cos \phi} - \Omega$$

$$\begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{Bmatrix} = R_{CN}^T \begin{Bmatrix} a_x \\ a_y \\ a_z \end{Bmatrix} + \begin{Bmatrix} (uw - v^2 \tan \phi) / r + g_u \\ (uv \tan \phi + vw) / r + g_v \\ -(u^2 + v^2) / r + g_w \end{Bmatrix}$$

$$\begin{Bmatrix} \dot{e}_0 \\ \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{Bmatrix} = \frac{1}{2} \begin{bmatrix} -e_1 & -e_2 & -e_3 \\ e_0 & -e_3 & e_2 \\ e_3 & e_0 & -e_1 \\ -e_2 & e_1 & e_0 \end{bmatrix} \left(\begin{Bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{Bmatrix} - \frac{1}{r} R_{CN} \begin{Bmatrix} v \\ -u \\ -v \tan \phi \end{Bmatrix} \right)$$

$$y = [\rho_A \quad \rho_B \quad \rho_C \quad \nu_A \quad \nu_B \quad \nu_C]^T$$

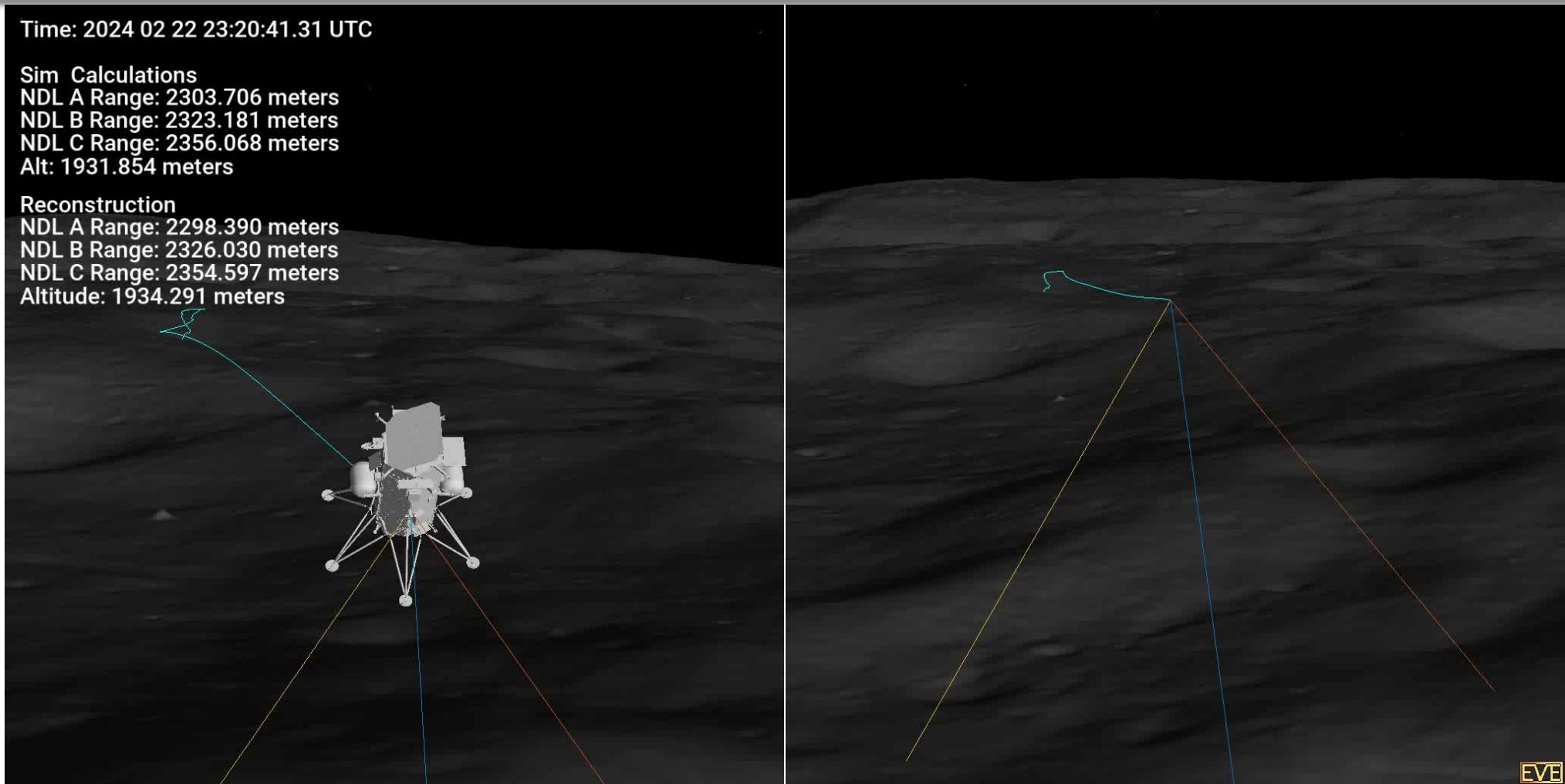
IMU systematic error and NDL beam alignment uncertainties are modeled as “consider” parameters



- **NDL-only altitude is the altitude above the triangle formed by the 3 range vector measurements**
- **IMU/NDL altitude is computed relative to the DEM**
- **Lunar terrain/craters are evident in the data**

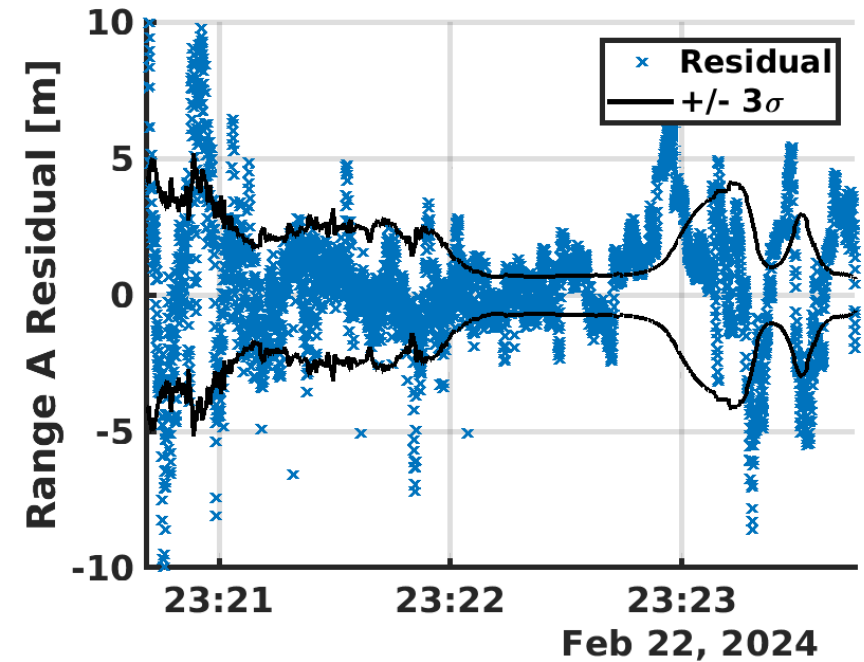


Animation – Exploration Visualization Environment



EVE provides an independent check of the range calculations

- **NDL flew as on the IM-1 mission to the Moon**
- **The NDL data exceeded expectations**
 - Range measurements more than 20 km (Beam A), 10 km (Beams B and C) compared to 5 km as designed
 - Beam velocities up to 218 m/s
- **Reconstruction results show agreement between measured data and lidar beam models. Lunar terrain features can be seen in the data and reconstruction**
- **Reconstruction process provides validation of terrain modeling engine**





BACKUP



Other Data Sources



- **Inertial Measurement Unit (IMU)**

- 2 IMUs on board: Honeywell HG1700 and Emcore SDI-505
- Data from each unit agreed, higher sample rate unit chosen for the reconstruction (Emcore SDI-505, 200 Hz data rate)
- IMU data was limited to last 184 s of trajectory (or roughly 2 km altitude and below) due to limitations on what could be sent back to Earth after landing (compared to 324 s / 8 km altitude of NDL data where all 3 beams provide data)
- 6-DOF trajectory reconstruction limited to last 184 s of trajectory where IMU data are available
- Some trajectory information can be reconstructed from NDL alone prior to start of IMU data

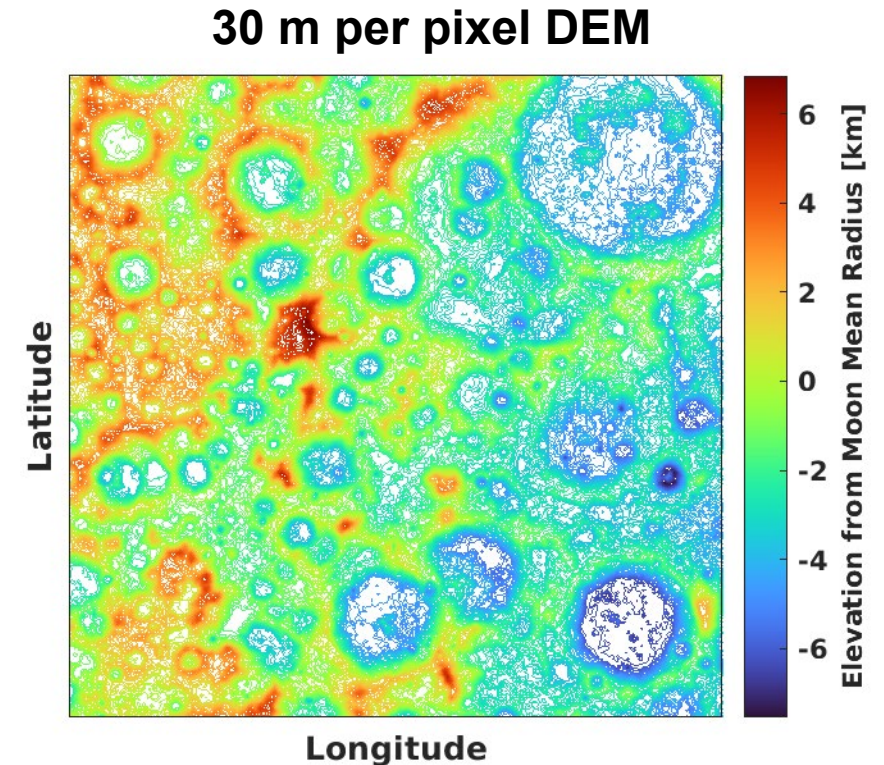
- **Gravity Model**

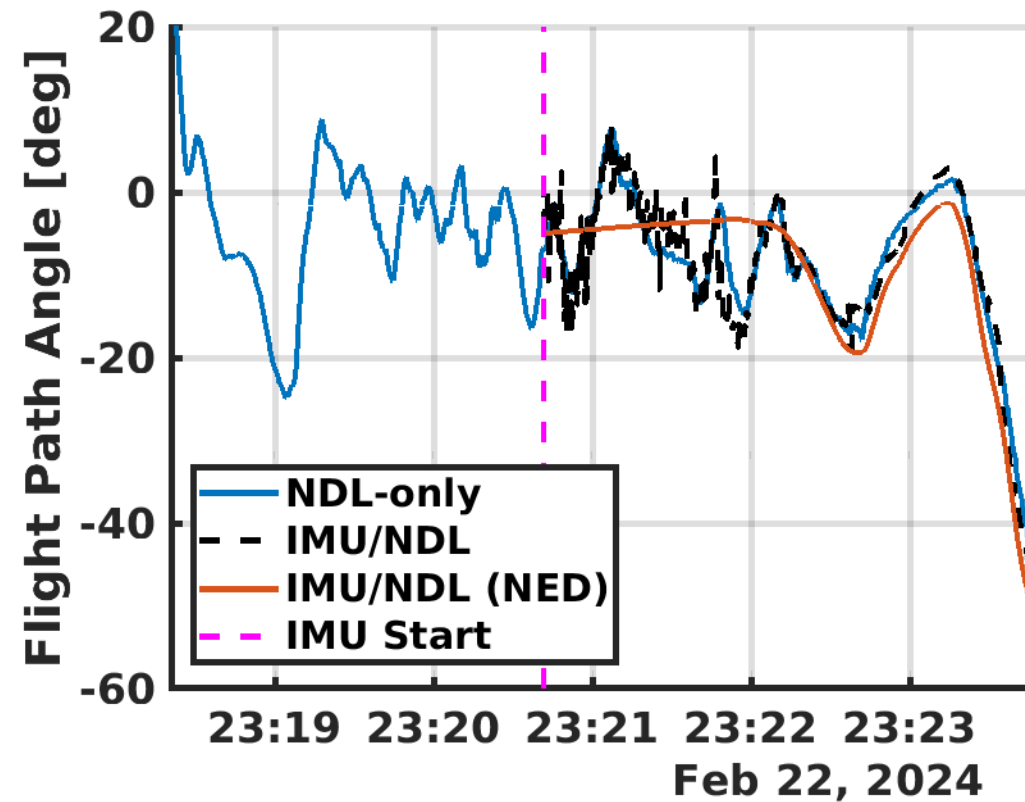
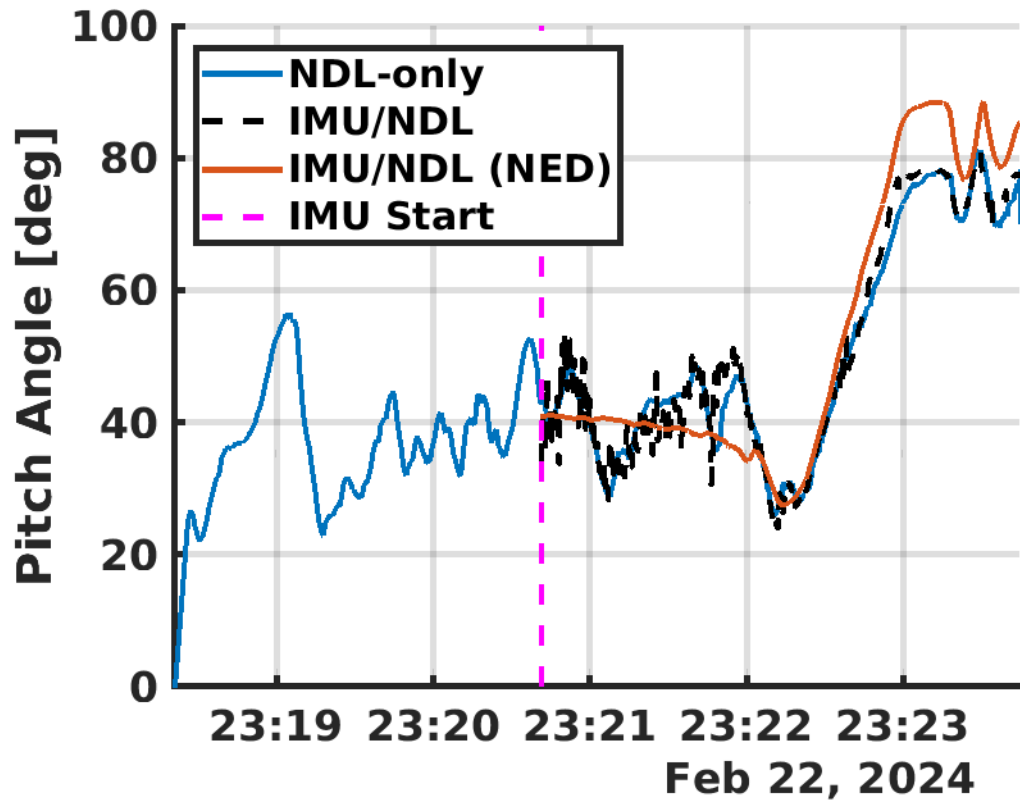
- Gravity Recovery and Interior Laboratory (GRAIL) gravity model GRGM660PRIM

- **Post-Mission Trajectory**

- Copernicus simulation tuned to match navigation states and other observables
- Used only to provide initial conditions for the Kalman filter reconstruction in this work

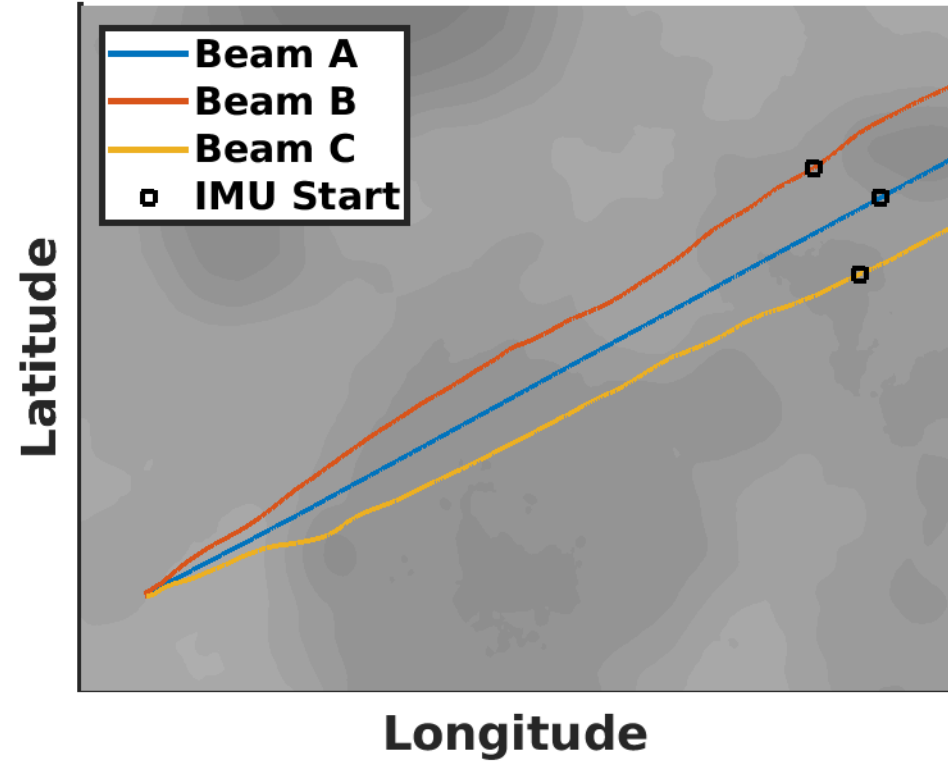
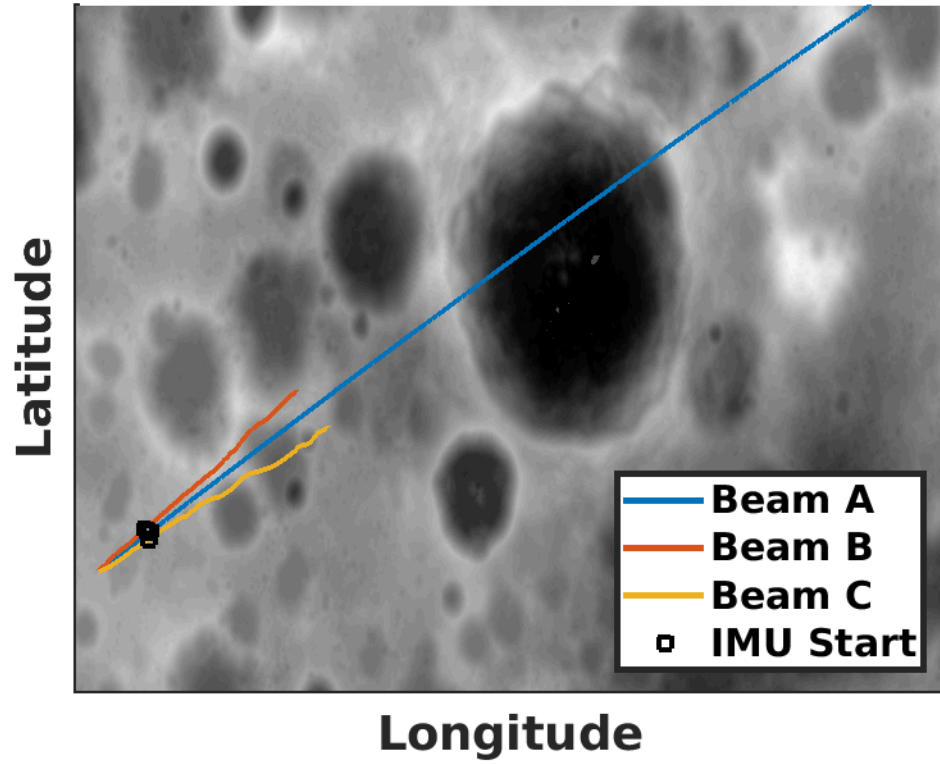
- **Digital Elevation Model (DEM) based on data from the Lunar Orbiter Laser Altimeter (LOLA)**
 - 30 m per pixel resolution from -75 latitude to pole
 - 20 m per pixel resolution from -80 latitude to pole
 - IM-1 landing site: -80.1276 deg latitude
- **A ray tracing algorithm to determine intercept points on the DEM is used in the NDL range measurement equation**
 - Ray tracing method originally developed, and flight validated for the Mars Science Laboratory (MSL) Terminal Descent Sensor (TDS). Also used for the Mars 2020 TDS flight reconstruction.



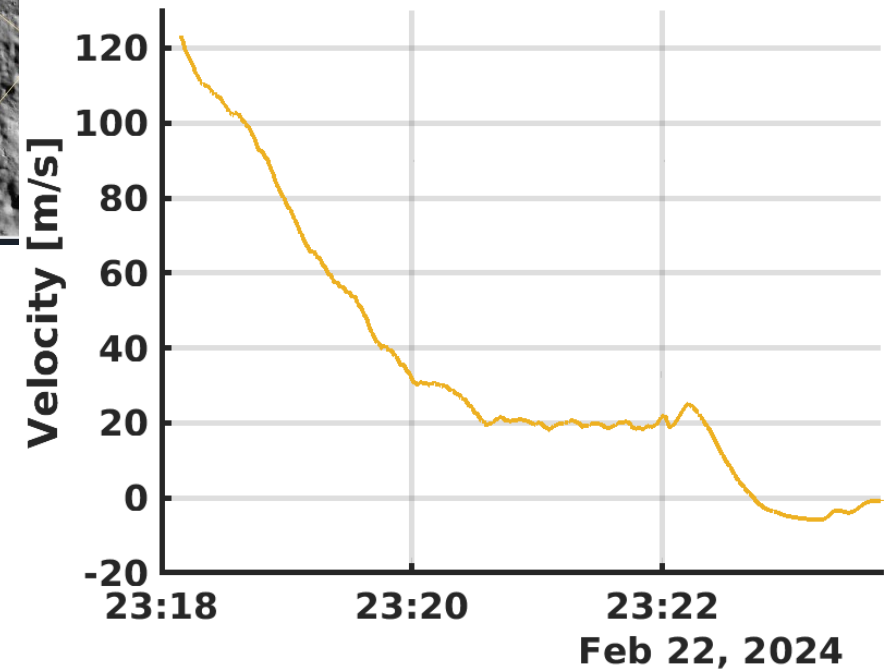
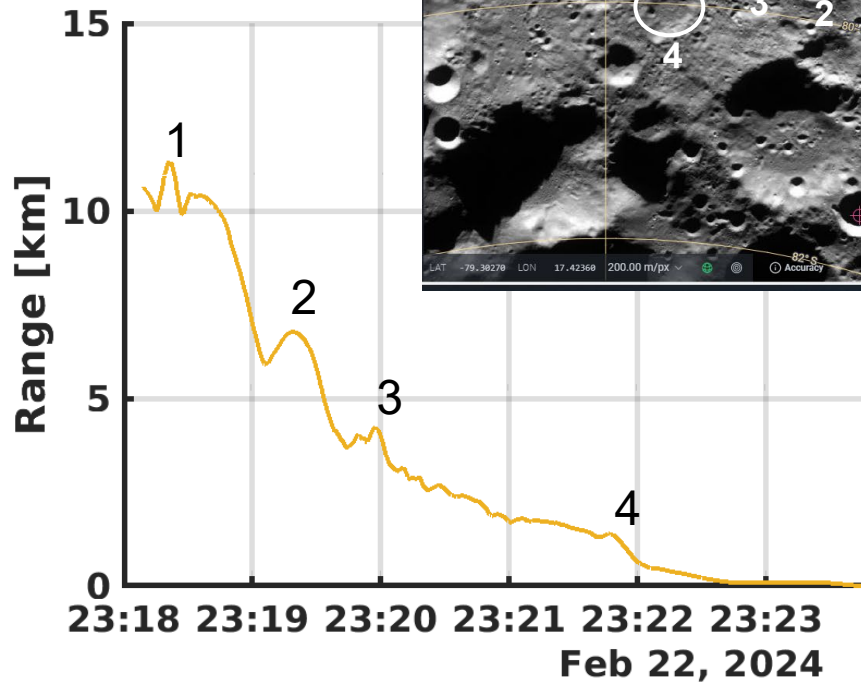
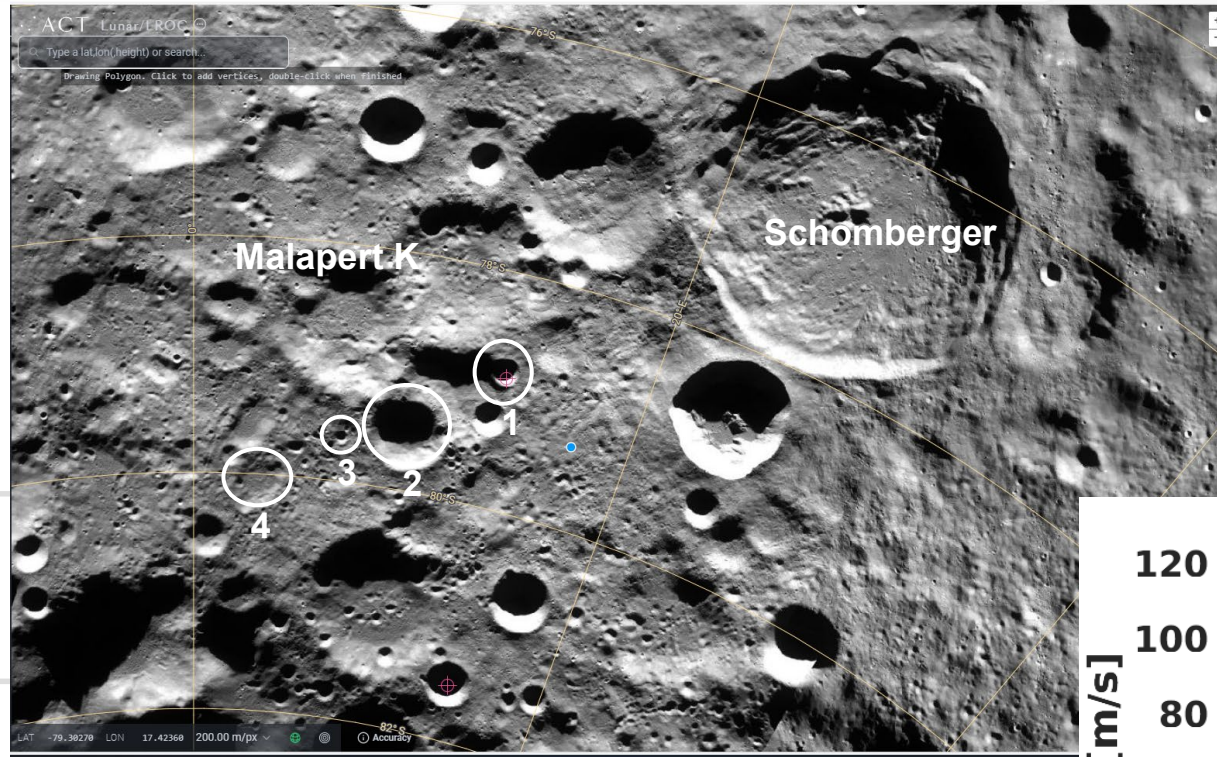


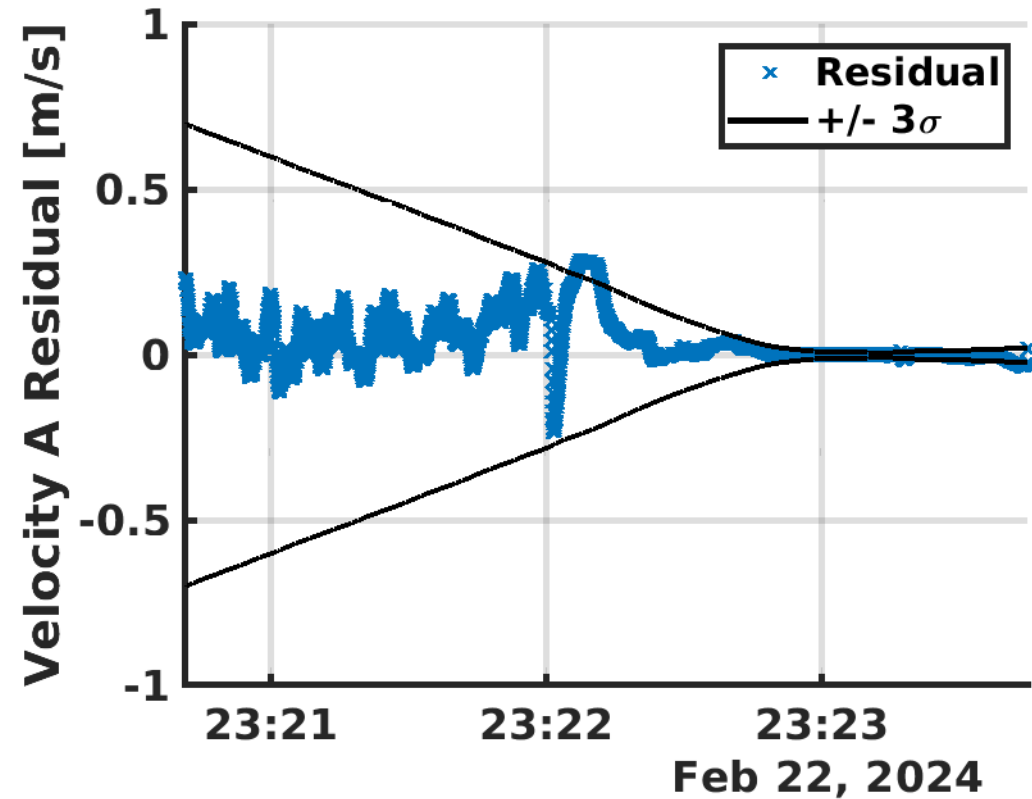
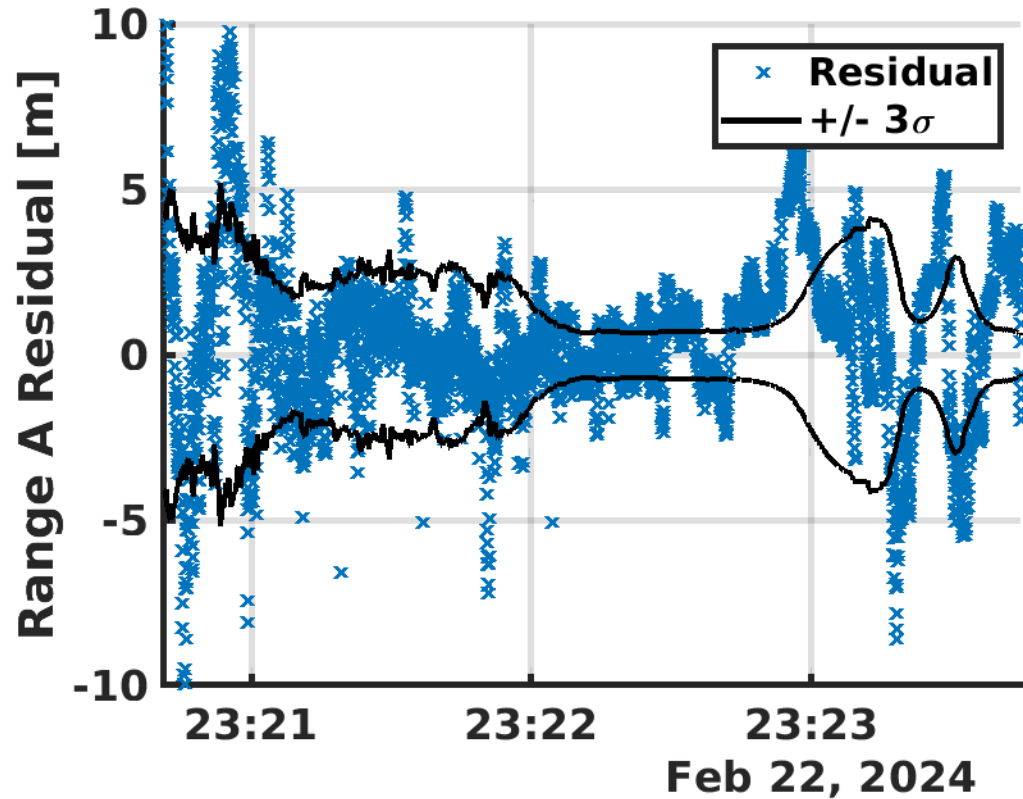
- **NDL-only pitch and flight path angle are computed relative to the triangle formed by the 3 range vector measurements**
- **IMU/NDL angles computed relative to the DEM**
- **Lunar terrain/craters are evident in the data**

Beam/Surface Intersection Ground Tracks



Beam C Traces Several Deep Craters





- Beams B and C show similar results