

National Aeronautics and
Space Administration



Volatiles Investigating Polar Exploration Rover

Terry Fong

Chief Roboticist

VIPER Rover Deputy Manager

NASA Ames Research Center

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Just Two Decades Ago...

The Moon was a very different place from how we understand it today

Studied from the Earth, in-situ and with samples returned to Earth

The “general” thinking was:

- The surface was relatively constant
- A thin exosphere of Argon, Sodium, Potassium
- **Bone dry (~100 ppm of water in soils)**



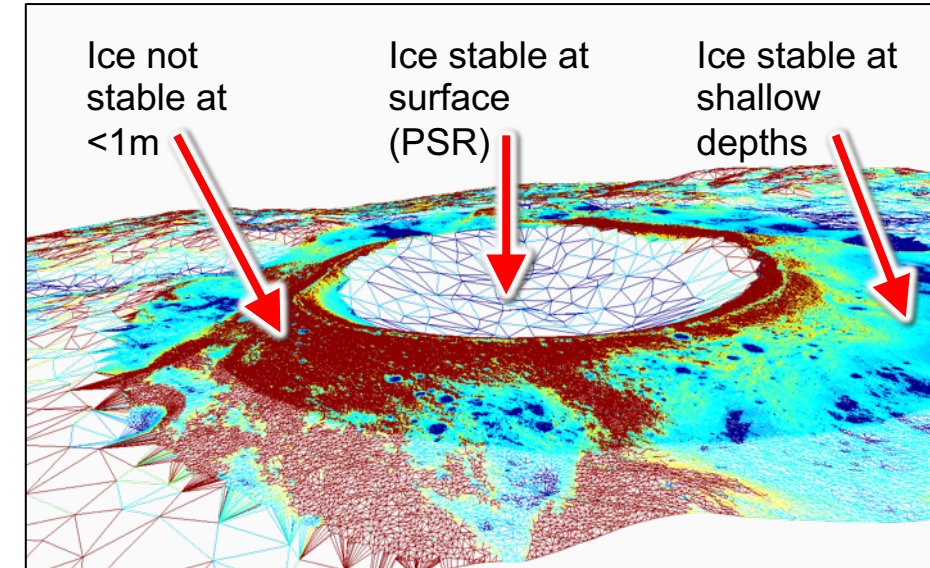
Where is water (ice) at the lunar poles?

Environmental factors

- Temperatures (surface or subsurface) must be low enough to retain water ice
- Geophysical properties (topography, materials, depth, etc.)

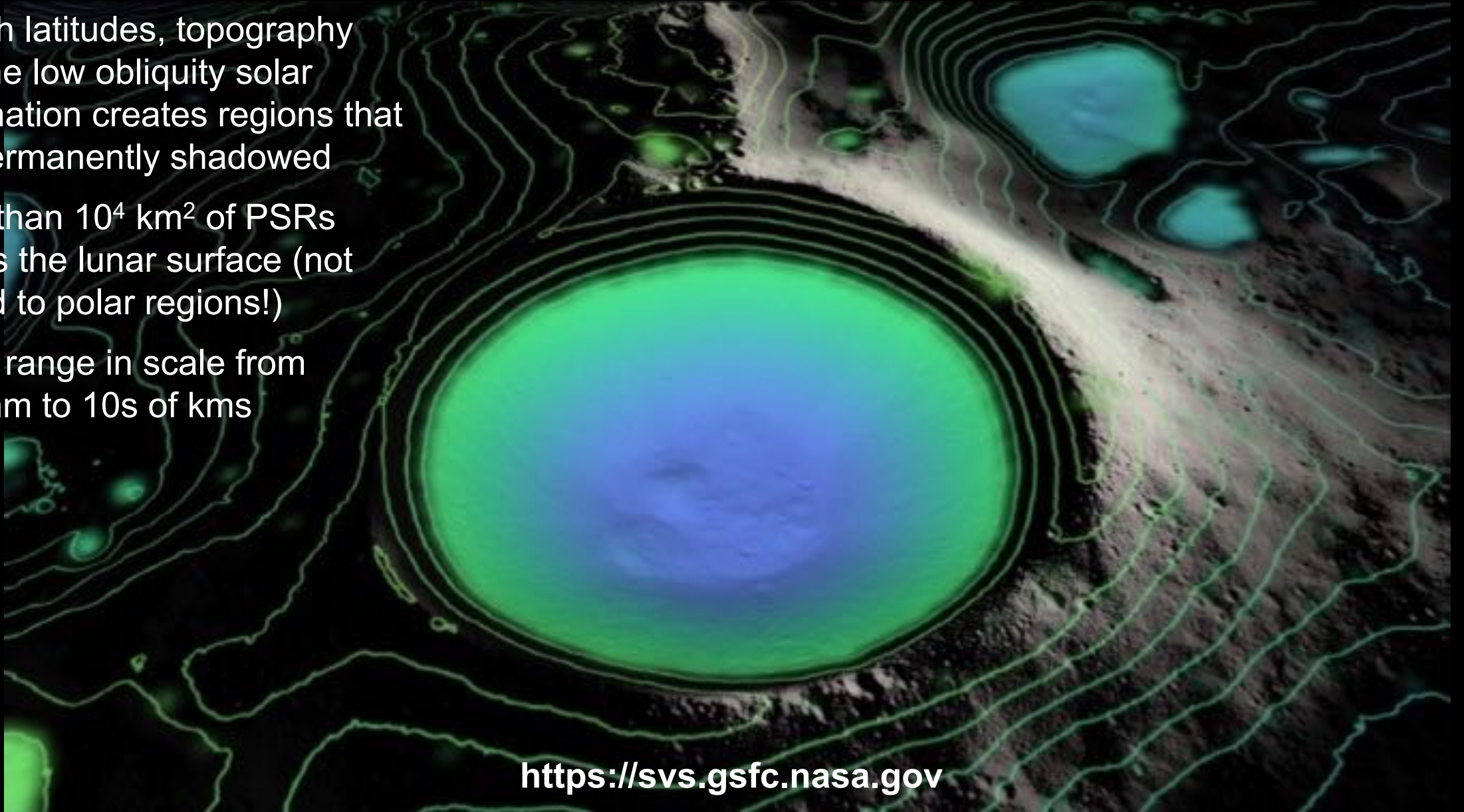
Ice Stability Regions

- **Dry:** Temperatures in the top meter expected to be too warm for ice stability
- **Deep:** Ice expected to be stable between 50-100 cm of the surface
- **Shallow:** Ice expected to be stable within 50cm of surface
- **Surface:** Ice expected to be stable at the surface (**Permanently Shadowed Region**)



Permanently Shadowed Regions (PSR)

- At high latitudes, topography and the low obliquity solar illumination creates regions that are permanently shadowed
- More than 10^4 km² of PSRs across the lunar surface (not limited to polar regions!)
- PSRs range in scale from sub-mm to 10s of kms



<https://svs.gsfc.nasa.gov>



VIPER Mission

Science objectives

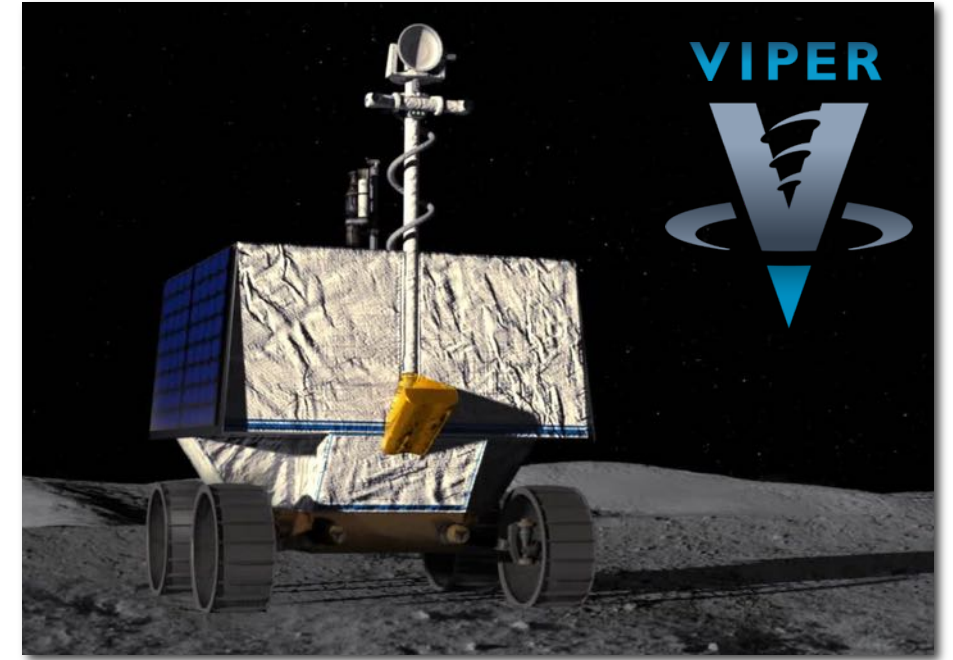
- Characterize distribution and physical state of volatiles (water ice, etc)
- Evaluate the potential for lunar ISRU

Unique challenges (among many...)

- Dynamic environment: light + shadows
- Real-time mission ops and science
- Prospecting & “speed made good”

History

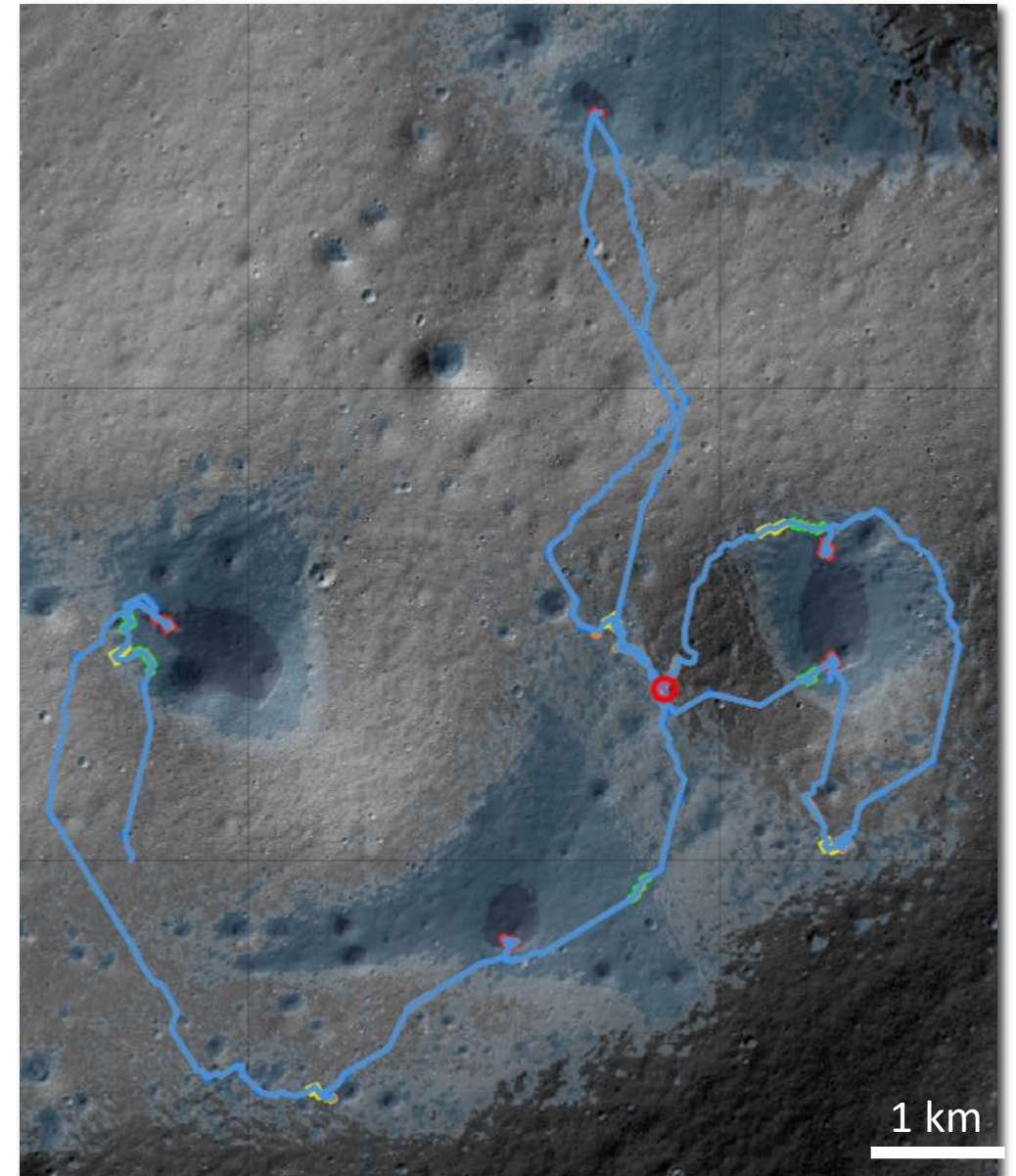
- **2014 to 2018** **Resource Prospector development (Phase A-B)**
 - 2018-04-24 Resource Prospector canceled
- **2019 to 2024** **VIPER development (Phase A-D)**
 - 2024-07-17 VIPER mission canceled
- **2025-09-19** **New VIPER flight (CS-7) announced!**



Mission Specs

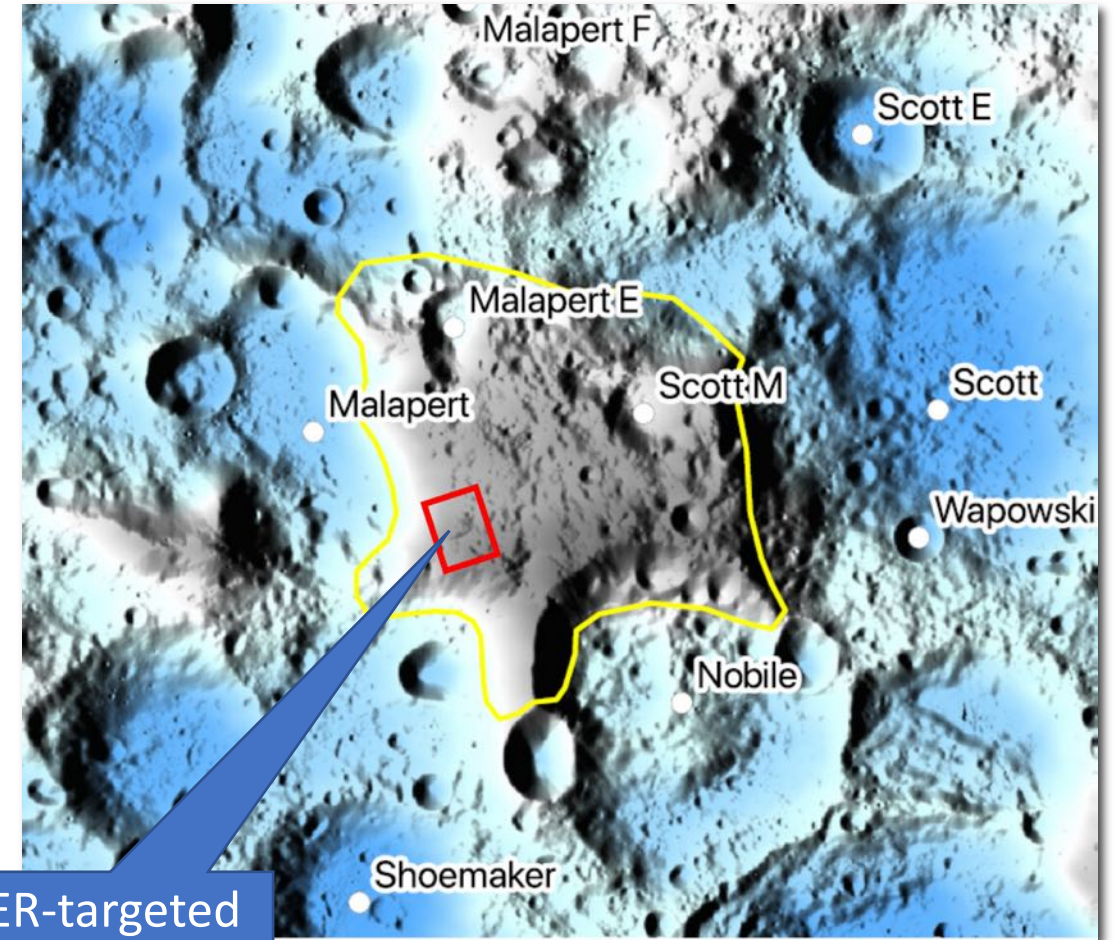
Lunar south pole

- 5-6 lunar days of operations
- 20 km of traverse distance (with potential for 30+ km)
- Exploring temperature regimes ranging from 40 K to 300 K
- 50x 1m drilling activities
- 1,700 m of driving in PSRs (multiple entries)
- 5x 1m drilling activities in PSR
- 20 cm/s max driving speed (approx. 5x Perseverance)
- 0.8 cm/s “Speed Made Good” (approx. 25x Perseverance)



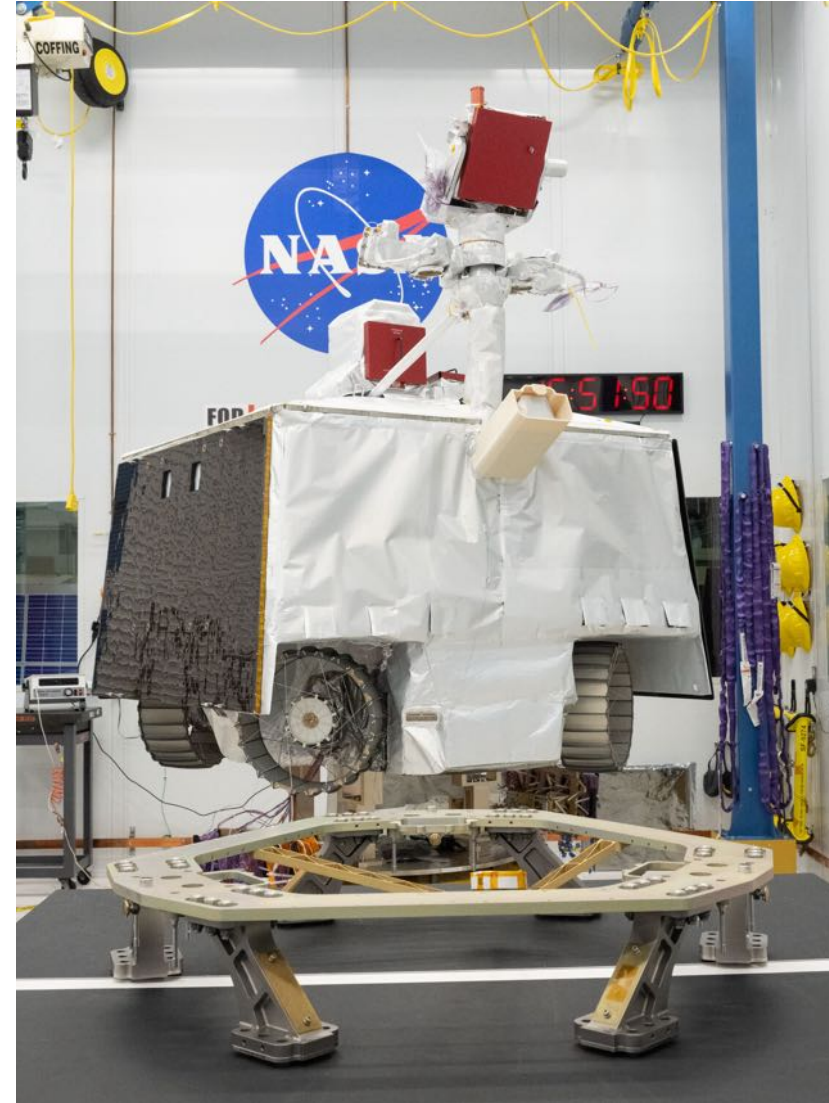
Mission Area

- VIPER will operate on the west side of Nobile crater (approx. 84.6°S, 31.0°W)
- VIPER team secured IAU naming of the mountains surrounding the VIPER mission area (see yellow tracing)
- “Mons Mouton”, honors Melba Mouton, a NASA mathematician and computer programmer who worked at the Goddard Space Flight Center



VIPER-targeted
region

Flight Rover

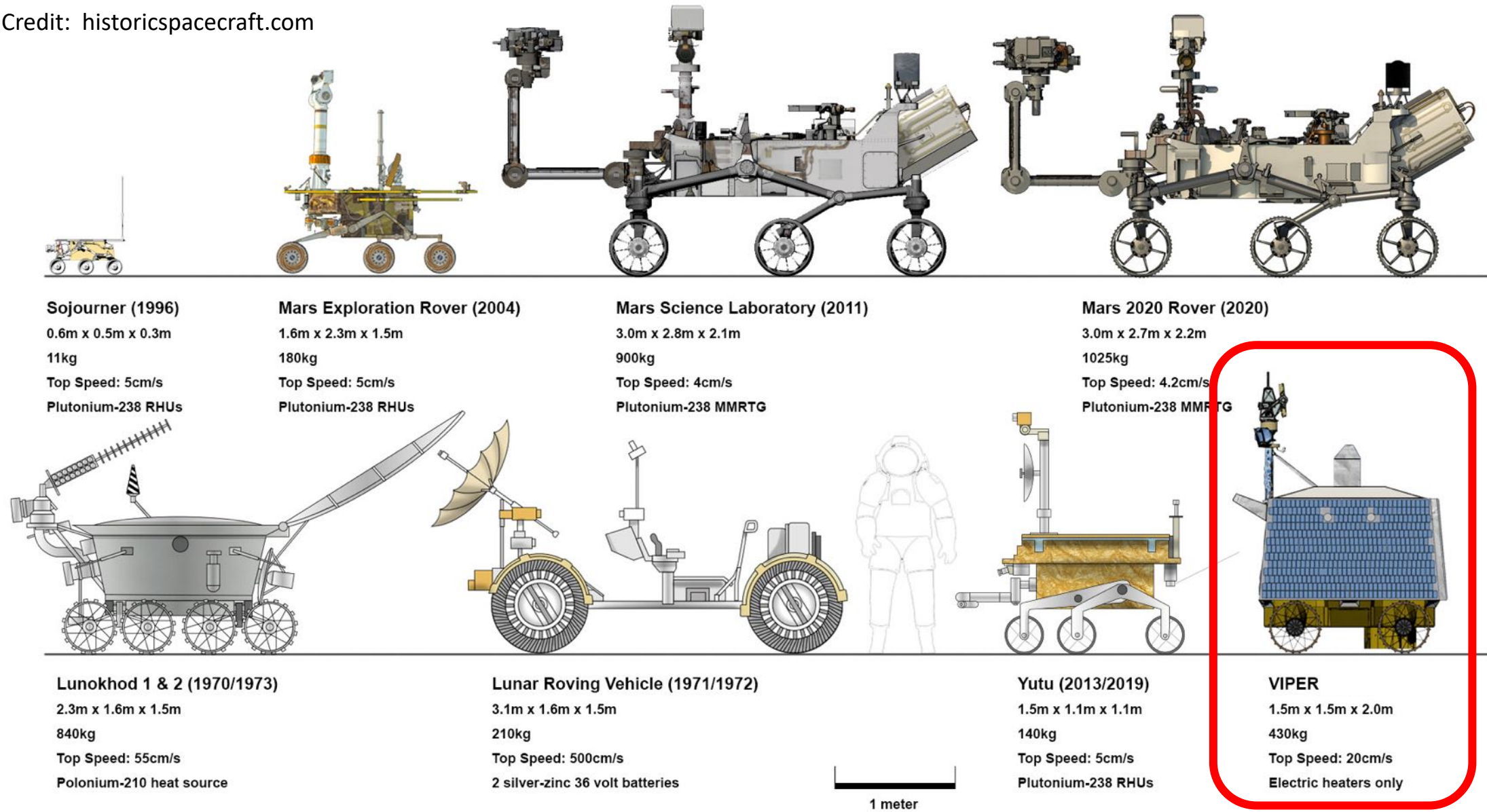


Assembly
complete
4 June 2024



Rover Comparison

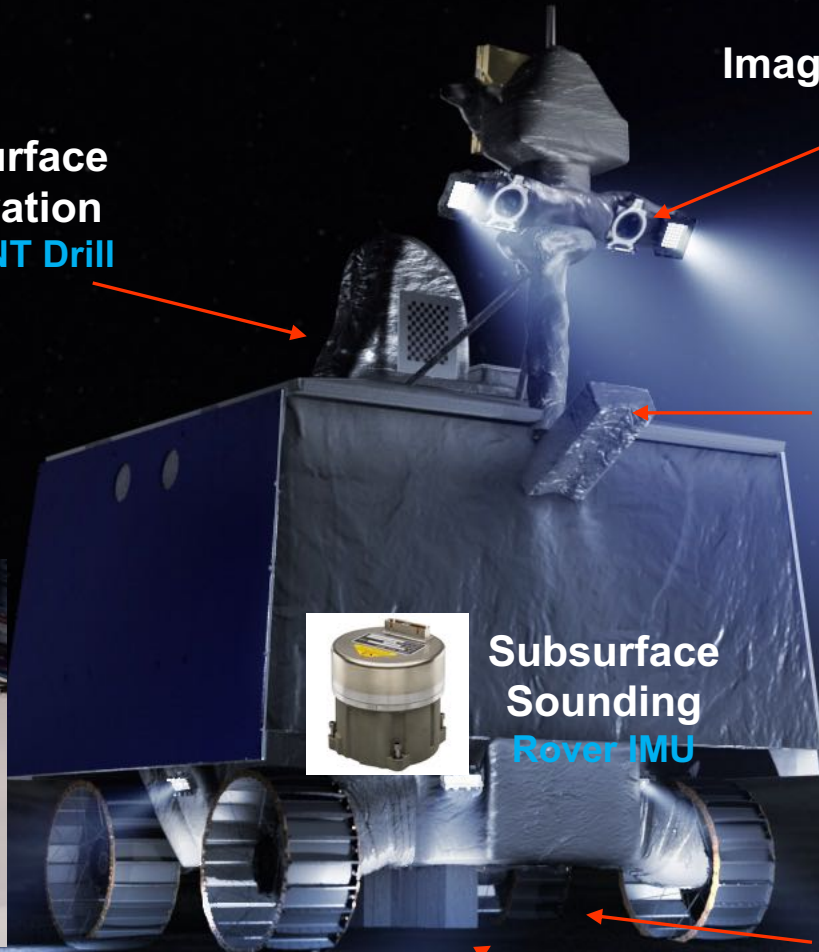
Credit: [historicspacecraft.com](https://www.historicspacecraft.com)



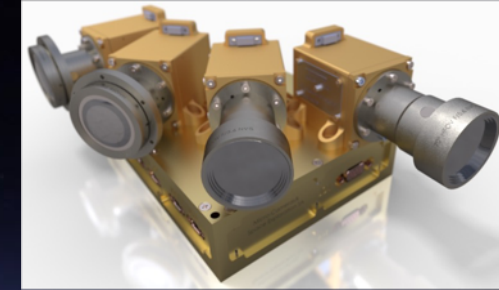
Instruments



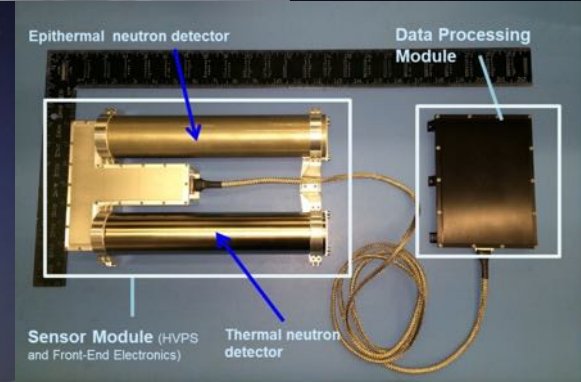
Subsurface excavation
TRIDENT Drill



Imaging Science
VIS



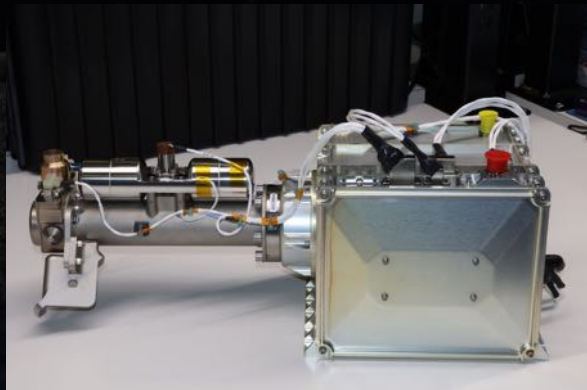
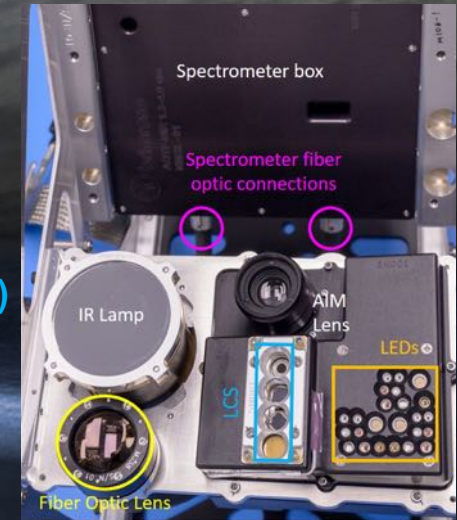
Prospecting
Neutron Spectrometer System (NSS) Instrument



Subsurface Sounding
Rover IMU



Prospecting & Evaluation
Near Infrared Volatiles Spectrometer System (NIRVSS) Instrument



Prospecting & Evaluation
Mass Spectrometer Observing Lunar Operations (MSolo) Instrument



VIPER Innovations

Hardware

- First rover designed to **operate for multiple lunar day/night cycles** without use of any radioisotopes (RHU or RTG)
- First NASA rover with **hybrid locomotion gaits** (combined active control of propulsion, steering, and suspension)
- First rover with **artificial lighting** system for ops & perception
- First rover with **star tracker for absolute orientation** measurements
- First lunar rover with **loop heat pipe thermal management** system

Software

- First hybrid flight software for lunar rovers using **cFS (on-board)** and **ROS2 (off-board)**
- High-fidelity **lunar rover simulator** for dev, V&V, and ops training
- High-resolution (**1 m/pixel**) “shape from shading” **DEM production**
- High-quality (**4 cm/pixel**) **synthetic terrain modeling**
- Terrain-relative localization: **relative (3m)** and **absolute (20m)**
- Real-time directional **comm antenna Earth pointing while driving**
- Autonomous **comm link recovery**



VIPER Innovations

Mission Ops

- [AI-based strategic traverse planning](#) (incorporates multiple solvers and planning under uncertainty)
- [Tactical planning](#) technology for dynamic operational environment
- [OpenMCT open-source mission operator interfaces](#) (including "Do It Yourself" public mission control)
- Real-time [interactive rover operations](#) (hybrid of ISS real-time and Mars rover command-cycle)
- Real-time [science operations and decision making](#) (similar to ROV deep-sea exploration)

Commercial Partnerships

- [Real-time slip estimation](#) software (ProtoInnovations, SBIR/STTR)
- [Hybrid mobility gait control](#) software (ProtoInnovations, SBIR/STTR)
- TRIDENT [rotary-percussive drill](#) (Honeybee, SBIR)
- Modified [spectrometer](#) for NIRVSS (Brimrose, SBIR)
- Modified [COTS mass spectrometer](#) for MSOLO (Infinicon, SBIR)
- PRIDE [ops procedure system](#) (TRAC Labs, SBIR)

Mobility Architecture

Independent Wheel Modules (4x)

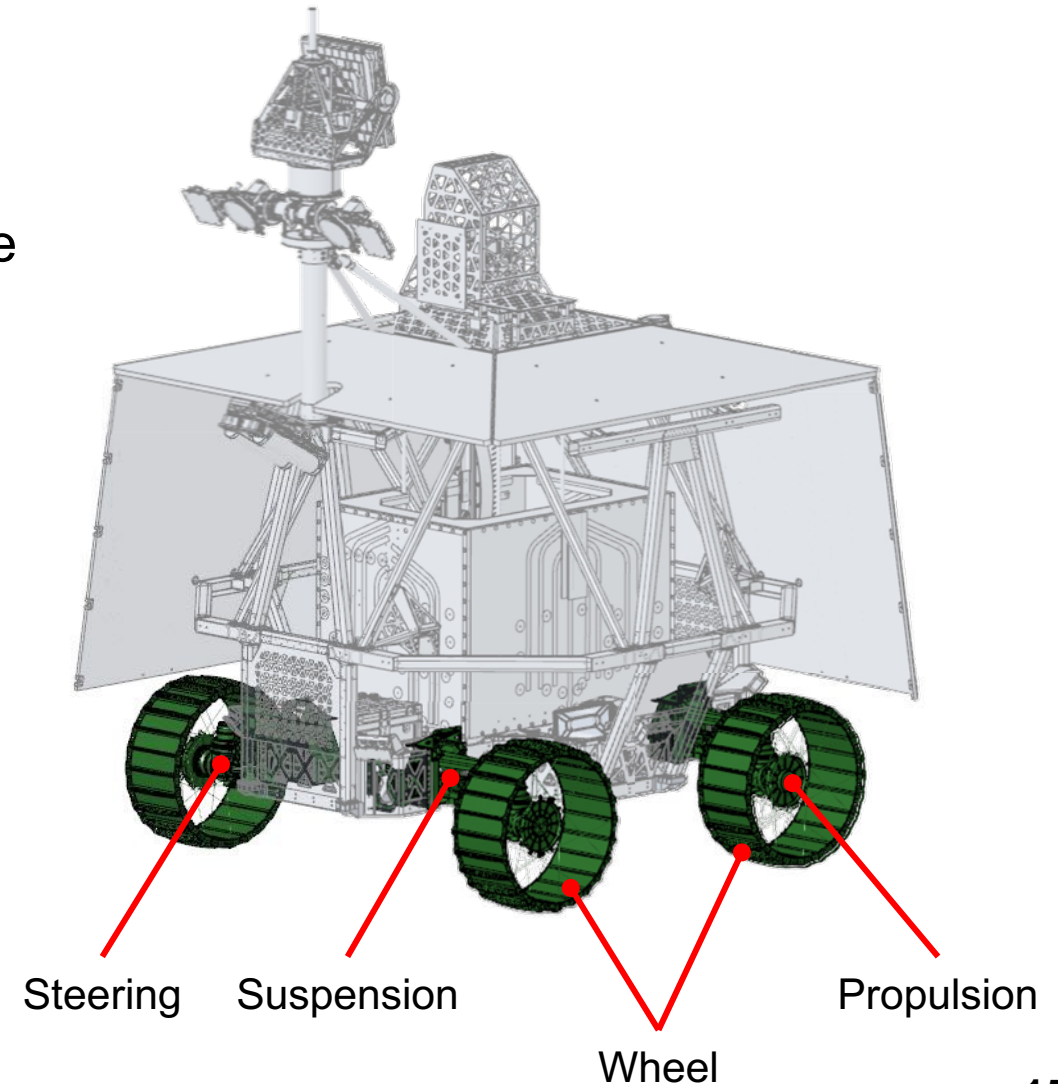
- Suspension: $\pm 40^\circ$, 200 N·m torque
- Steering: $\pm 50^\circ$, 130 N·m torque
- Propulsion: 20 cm/s, 200 N·m torque

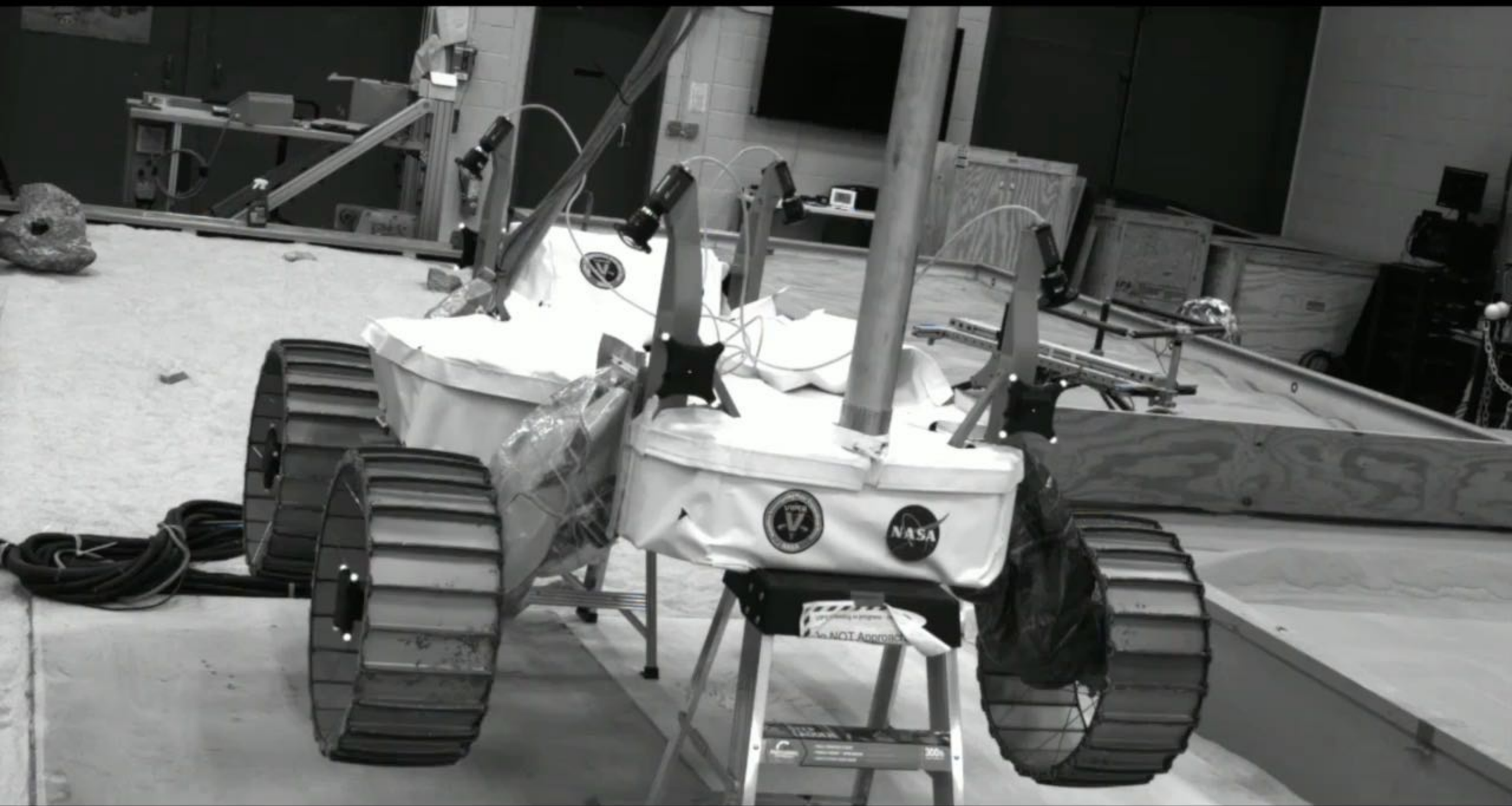
Wheels (4x)

- 50 cm diameter, 20 cm wide
- Rigid sheet metal with spokes
- Rim grousers

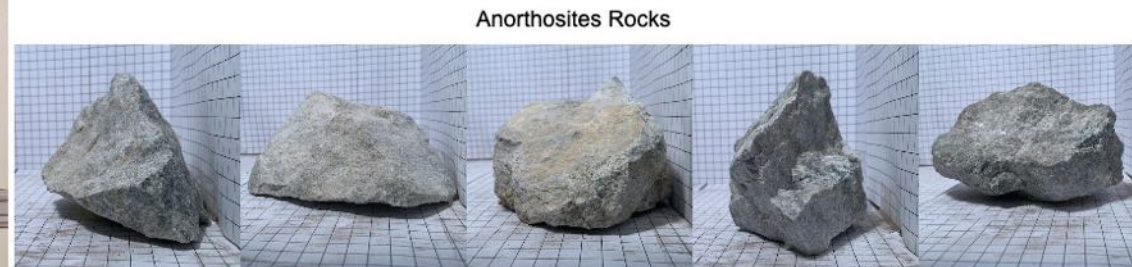
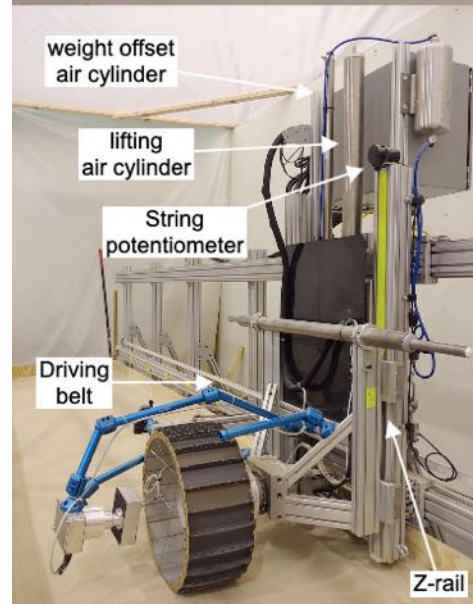
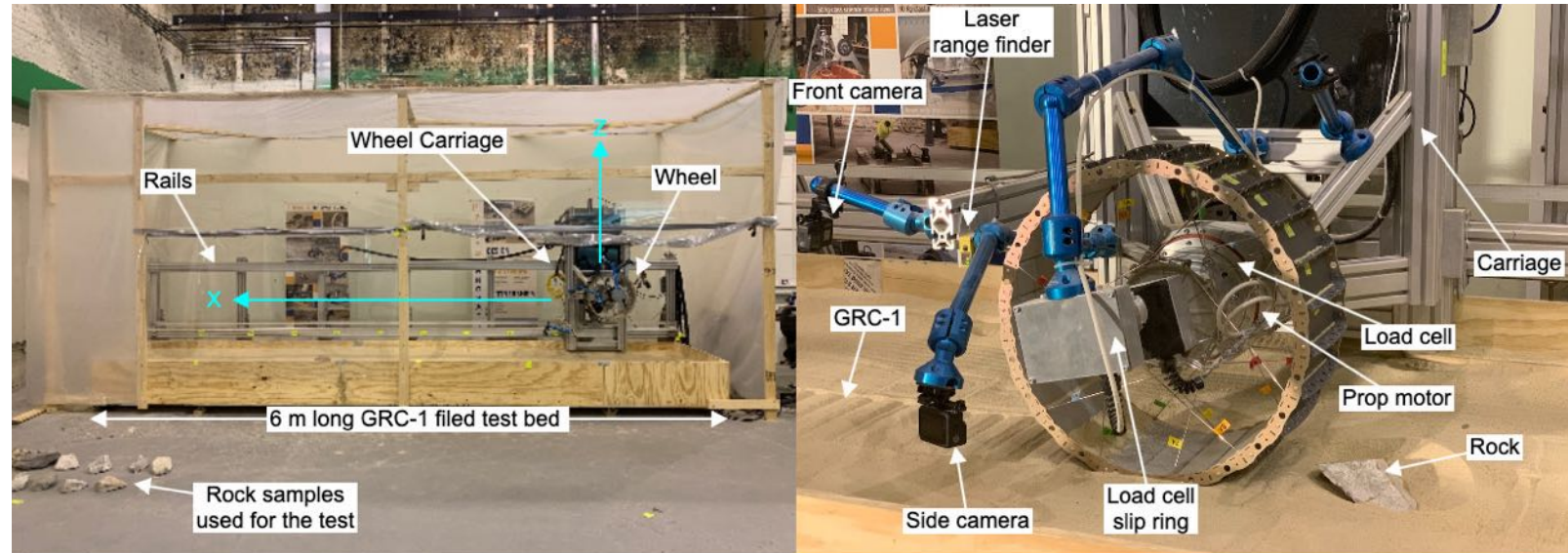
Capabilities

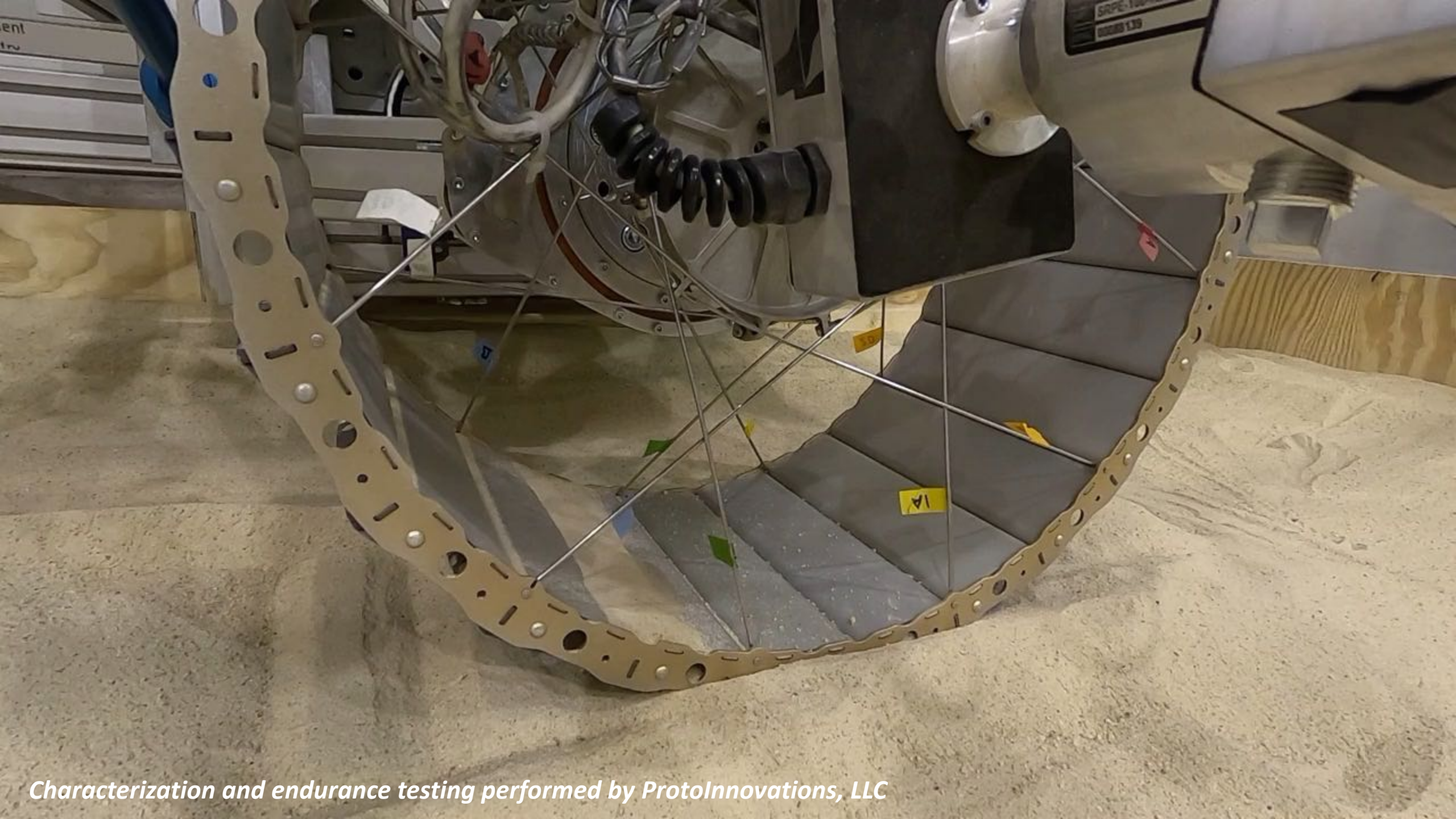
- Actuated suspension enables body attitude and clearance control
- Explicit steering and skid steering
- Alternate mobility





Wheel Lifecycle Testing (40 km)





Characterization and endurance testing performed by ProtoInnovations, LLC

SLOPE Lab (NASA Glenn)



Rock Traversal Testing



Rock with attached load cell

Crater Traversal Testing





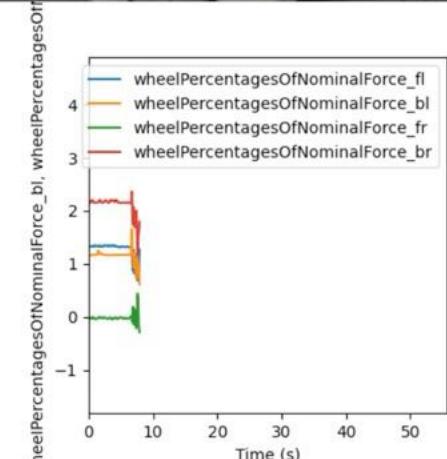
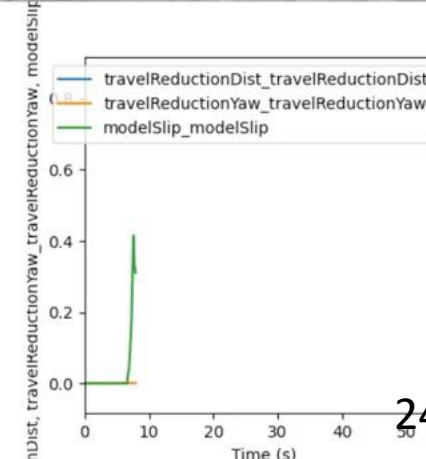
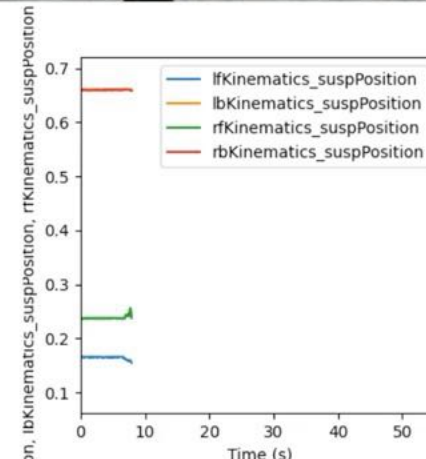
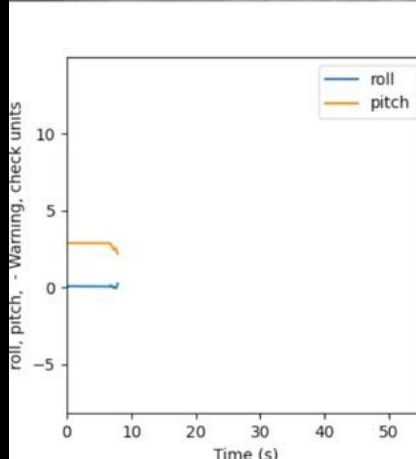
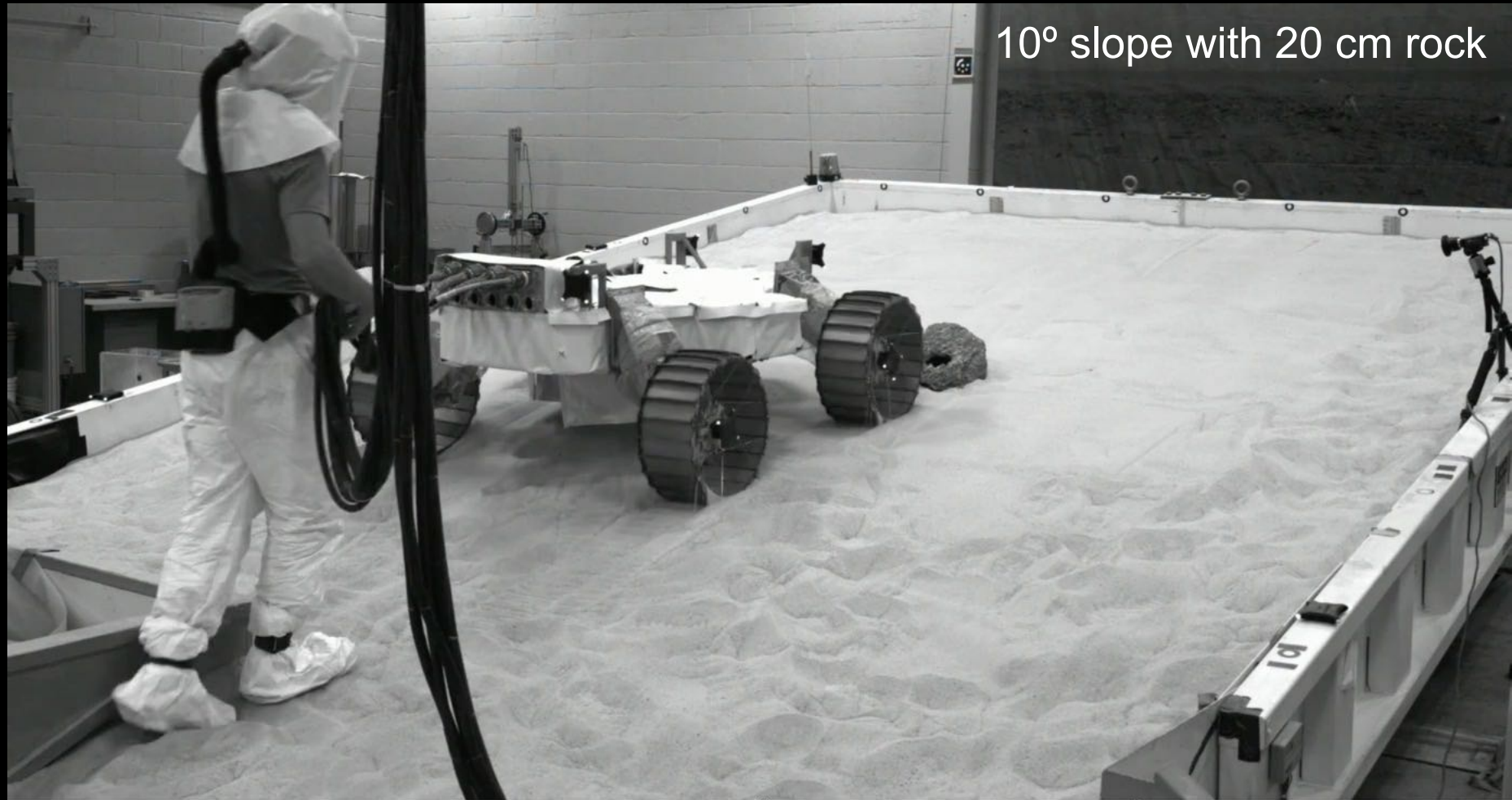
4x speed

Slip Testing (30° Slope)



Slip Detection

- On-board, real-time slip detection performed using proprioceptive model
 - IMU (LN-200S)
 - Motor current
 - Wheel encoders
- Automatic stop to risk of embedding / entrapment:
 - Rover longitudinal slip > a threshold (generally 80%)
 - Rover orientation changes abruptly
- R&D performed with ProtoInnovations, LLC



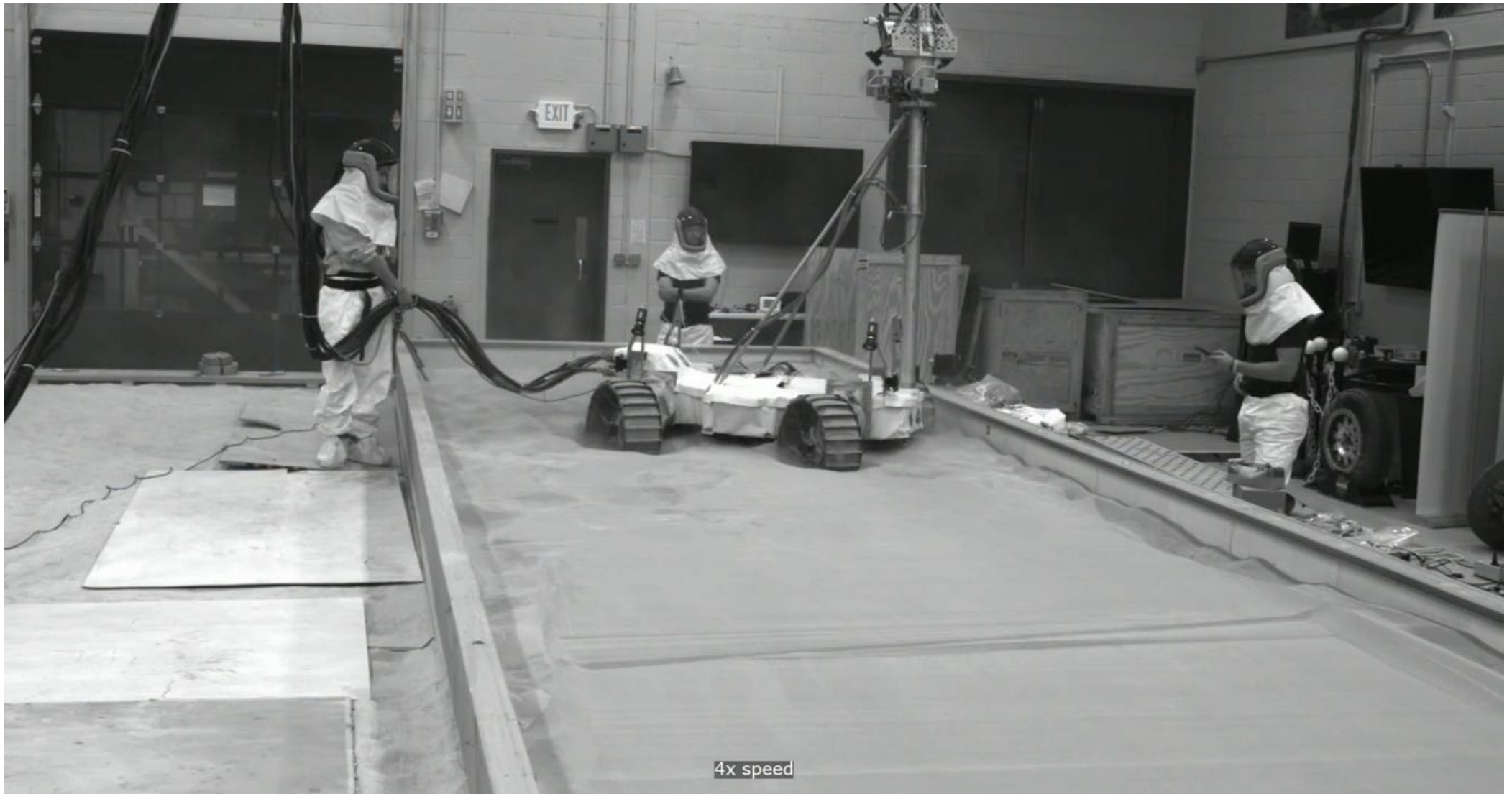
Entrapment Testing



Entrapment Testing

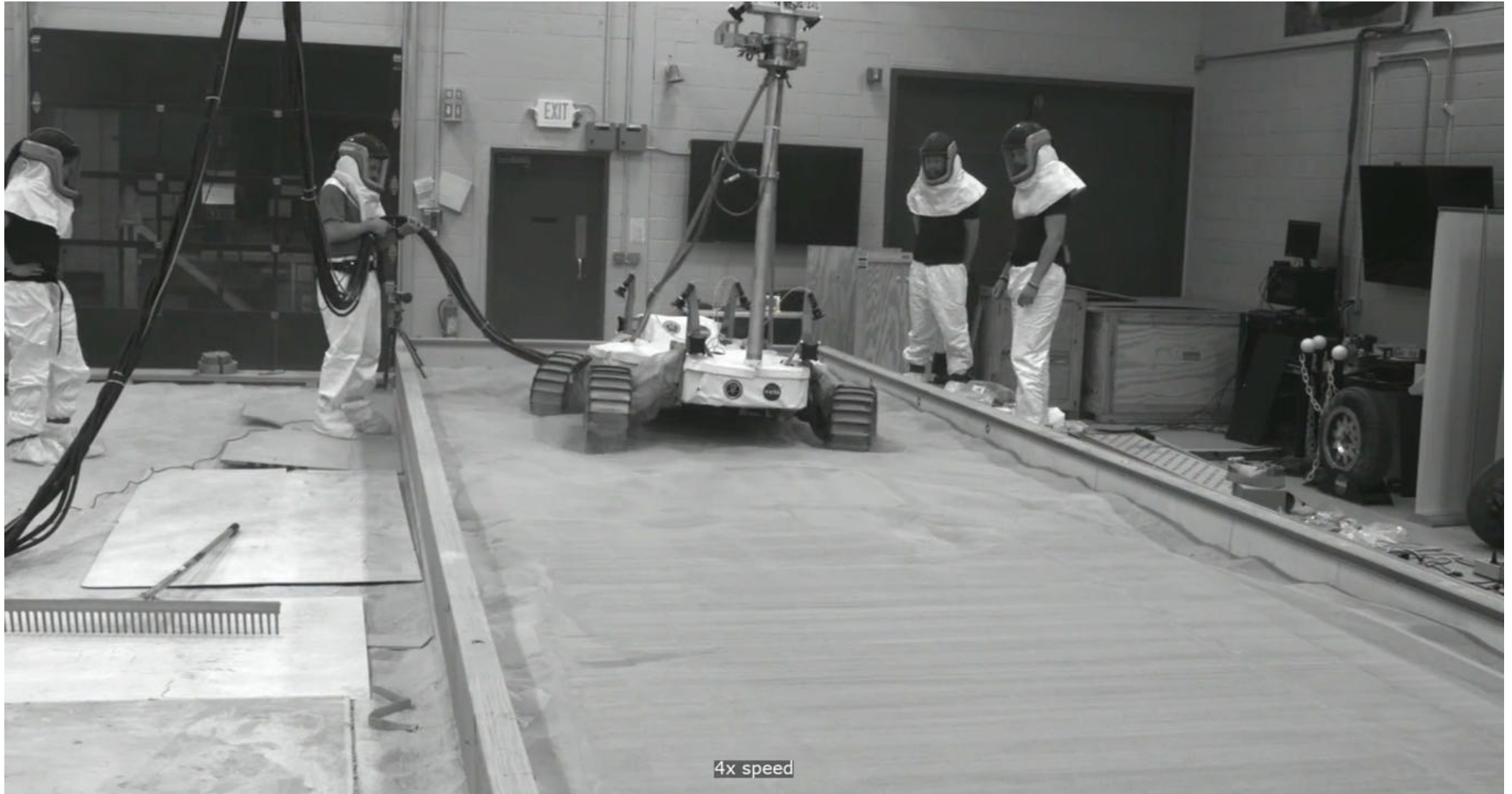


Alternate Mobility Modes



“Inchworm”

Alternate Mobility Modes

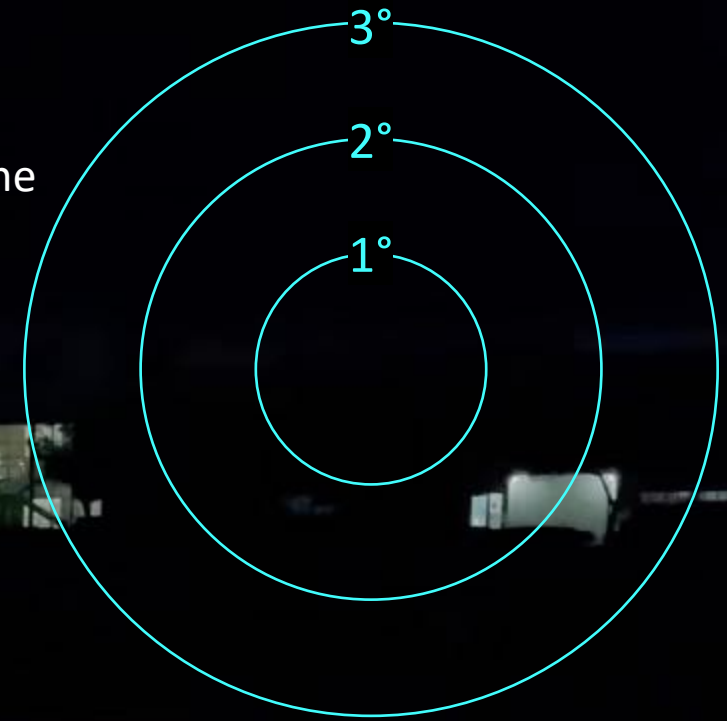


“Wheel Walking”

Antenna Pointing Test



view of the
Moon from the
HGA gimbal



Camera & Light Testing

NASA Ames “Lunar Lab”

- High-fidelity surface appearance testbed
- Highlands: 12 tons of LHS-1 simulant in a 4x20 meter sandbox
- Mare: 8 tons of JSC-1A simulant in a 4x4 meter sandbox
- Terrain can be shaped and dusted to mimic micro-meteorite surface texture

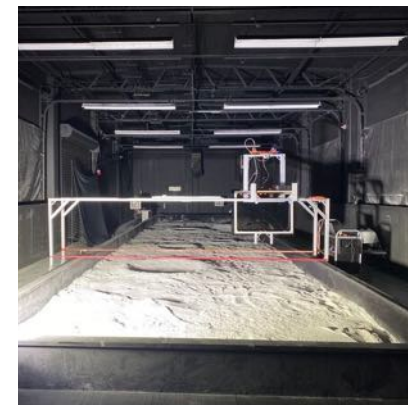
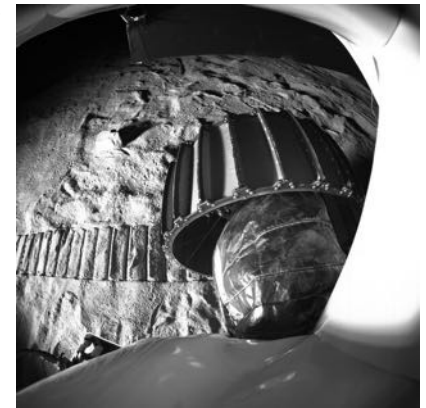
Experimental setup

- Sun simulators for lunar polar lighting
- Sliding gantry provides non-contact data collection for optical sensors
- High accuracy (survey grade) lidar and positioning system for ground truthing



Simulated polar lighting on LHS-1 terrain

*Appearance of
VIPER rover wheel
and tracks*



*Sliding gantry over
LHS-1 terrain*

NASA Ames “Lunar Lab”



NASA Ames Research Center

4m x 19m sandbox with 12+ tons of LHS-1 lunar regolith simulant



VIPER Mission Planning

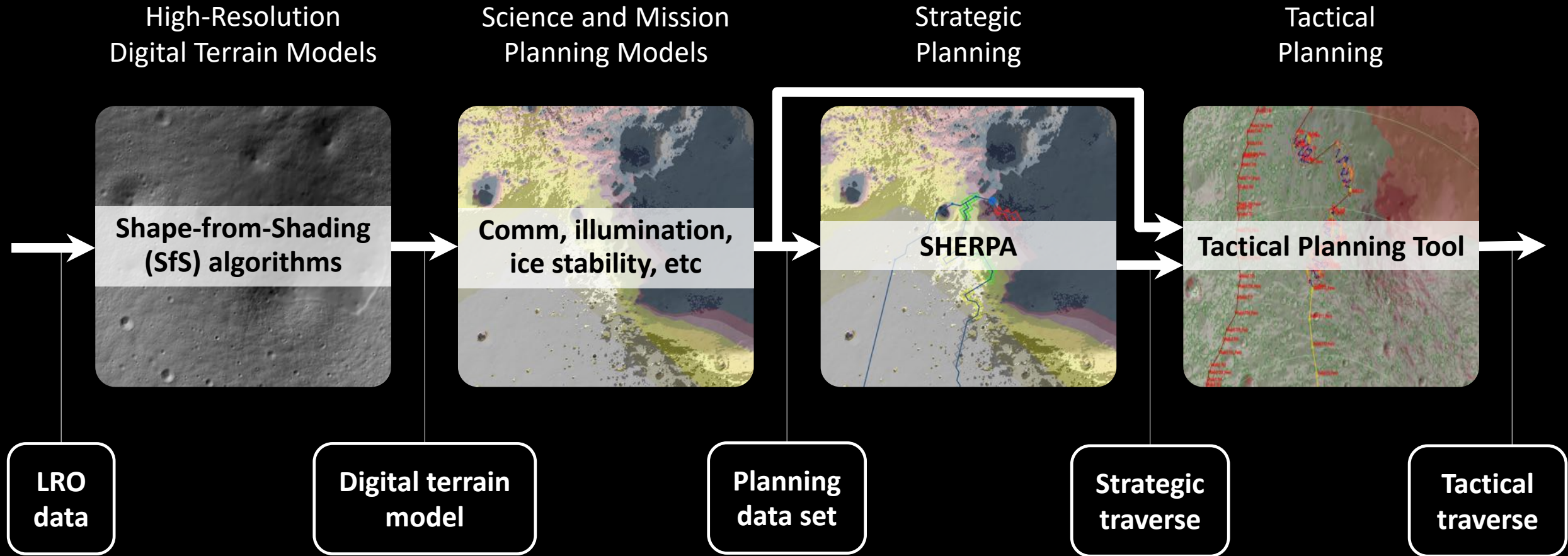
Objectives

- Develop activity, resource, and traverse plans
- Strategic and tactical plans
- Robustly achieve full science success under uncertainty

(A few) constraints

- Measure distribution and state of lunar polar volatiles
- Solar-powered rover with limited battery (shadow endurance)
- Lunar summer “season” (~100 Earth days max)
- Line-of-sight data communications to Earth
- 20 km max drive distance (design limit)
- 15 deg slopes + 20 cm step obstacles (design limit)
- 10 cm/s drive speed while prospecting (instrument limit)
- Moving shadows cast by rover and terrain (0.1 to 1.8 cm/s)

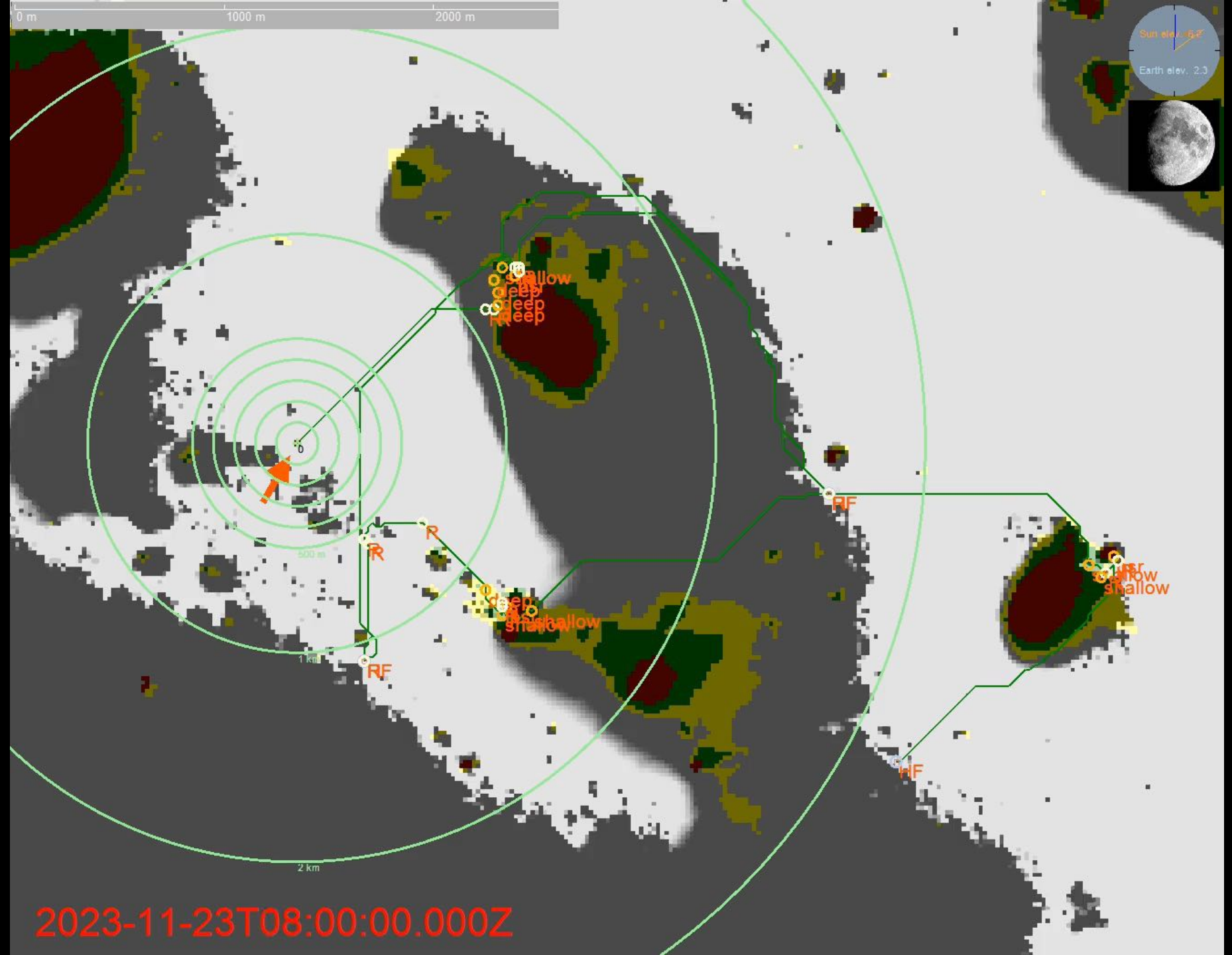
Planning Process



Example Traverse Plan

2023-11-23
to
2024-03-07

106 days



VIPER Rover SIM

High-quality lunar lighting

- Direct/indirect sun, “Earth-shine”, rover lights
- Coherent backscatter (“opposition effect”)

High-fidelity camera models

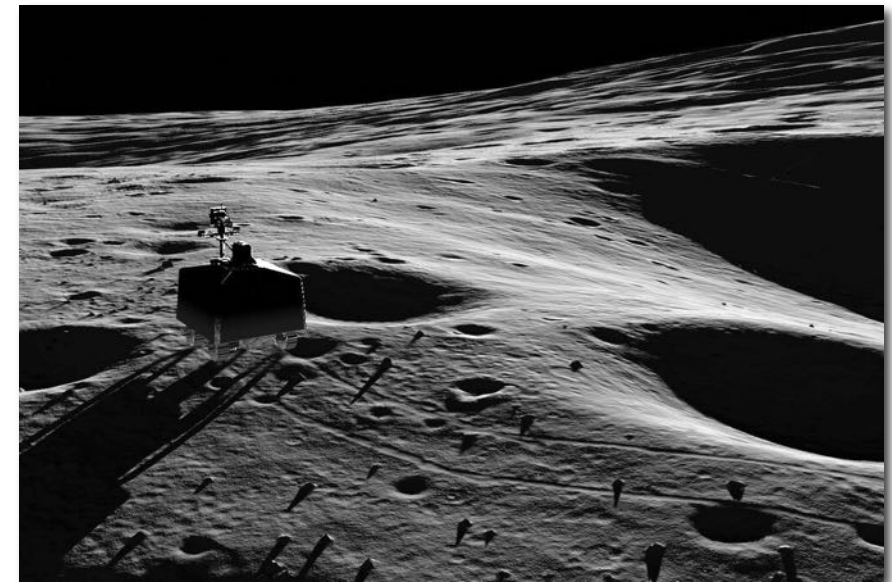
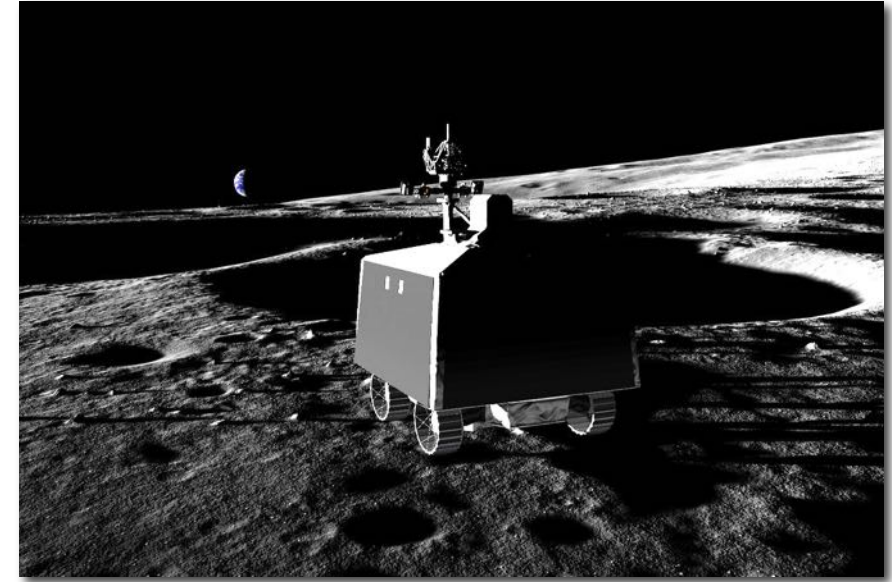
- Exposure, distortion, flare, fixed pattern noise, pixel defects, bit depth, read noise, etc.
- Tuned using NASA Ames “Lunar Lab” tests with camera/light EDUs

Real-time slip modeling

- Driving on unconsolidated soil
- Tuned using NASA Glenn “SLOPE” tests with mobility EDU

High-resolution lunar terrain models

- 1 m/pix DEM (photoclinometry, many images)
- 4 cm/pix synthetic DEM (science-based)



High-fidelity Camera Models

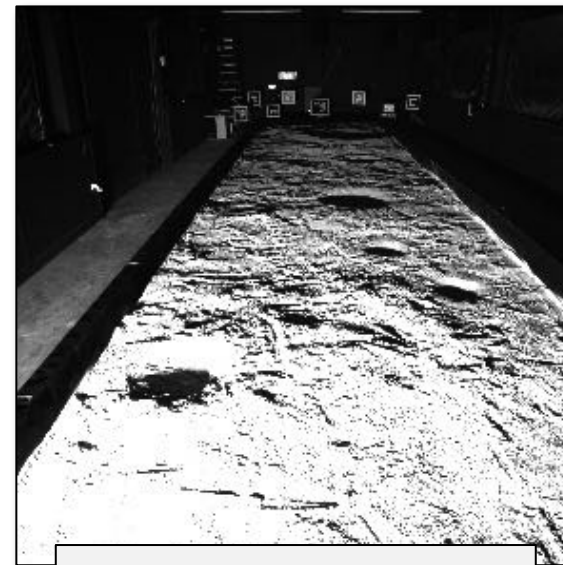
Lunar Lab



Under Exposure



Optimal Exposure



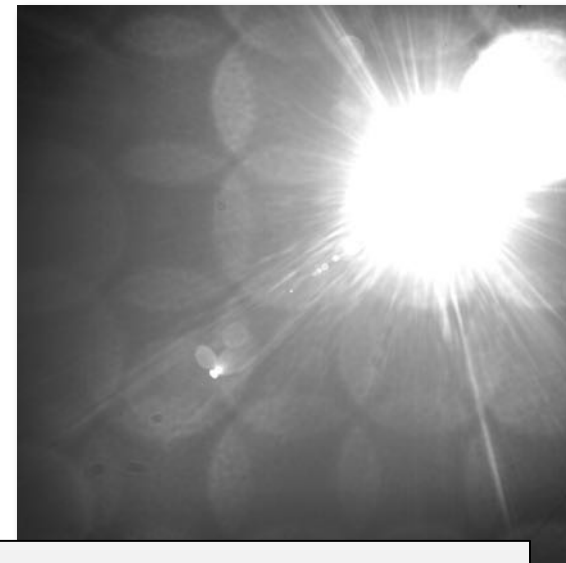
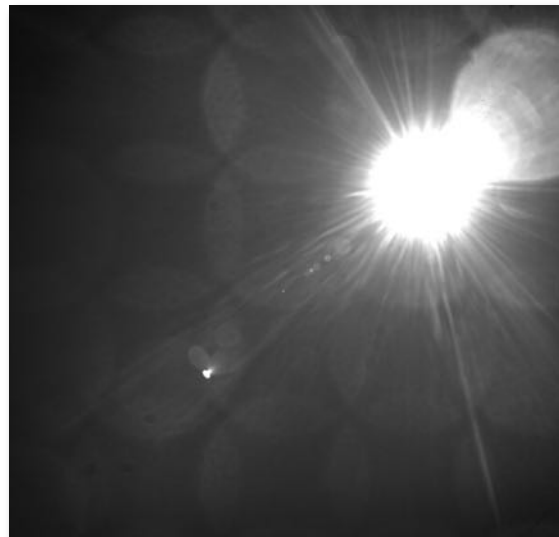
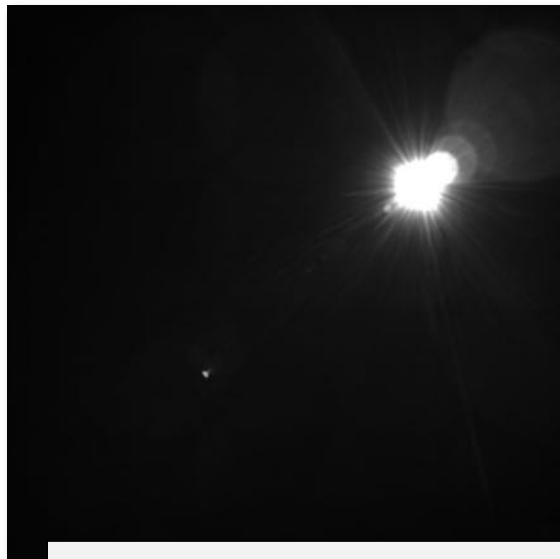
Over Exposure

RSIM



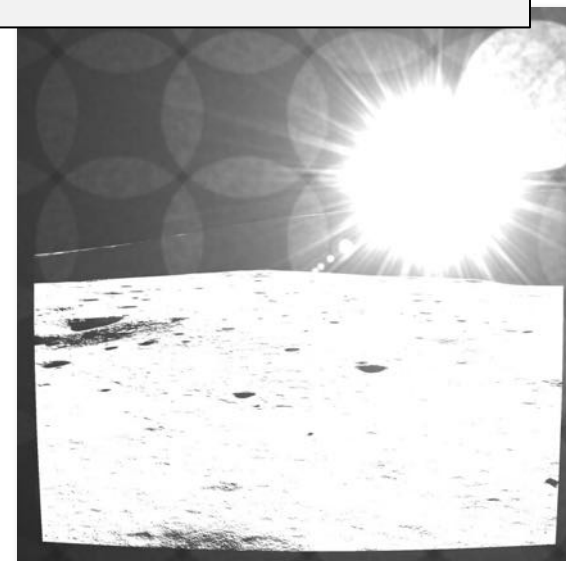
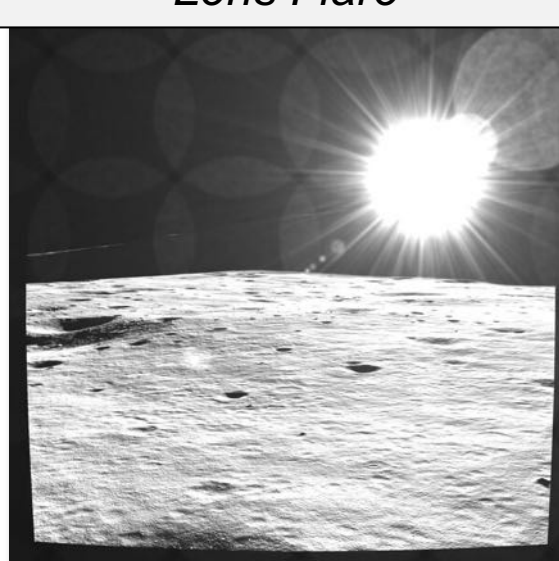
High-fidelity Camera Models

Lunar Lab



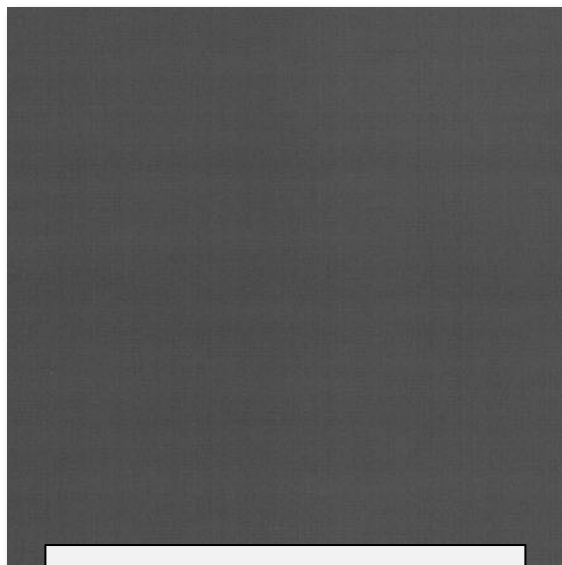
Lens Flare

RSIM

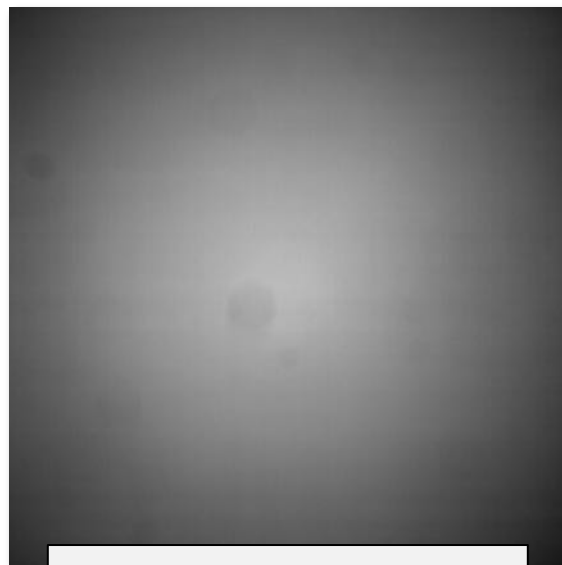


High-fidelity Camera Models

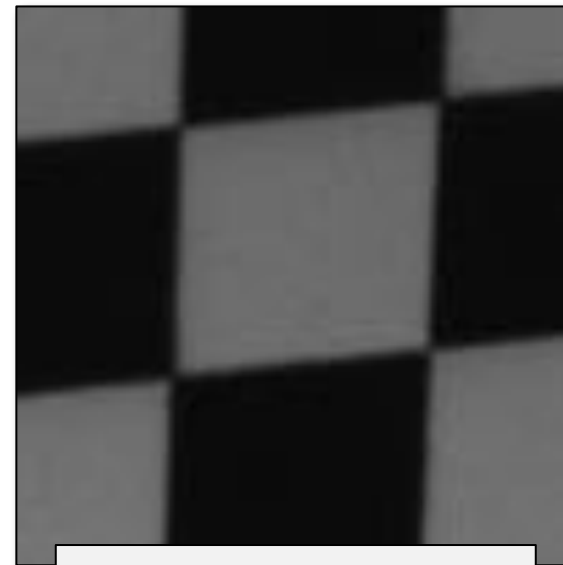
Lunar Lab



Fixed Pattern Noise

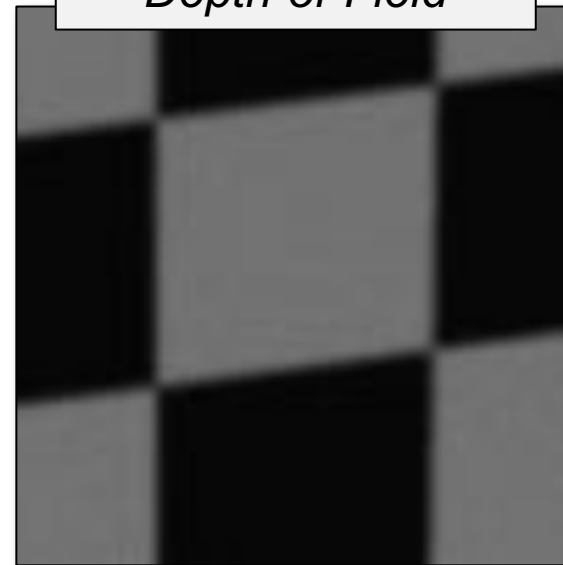
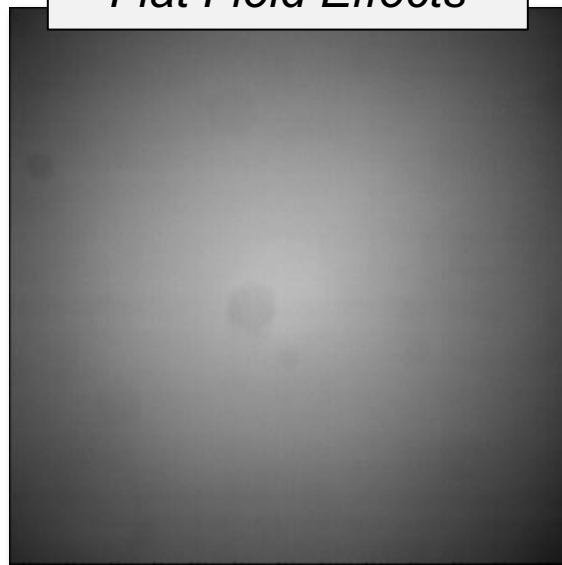
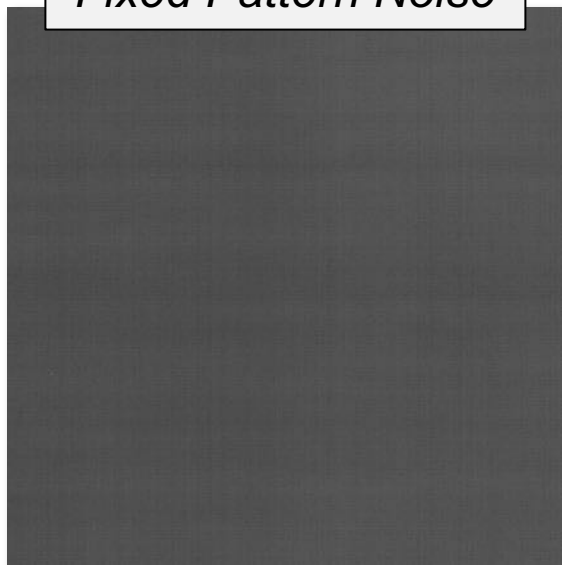


Flat Field Effects



Depth-of-Field

RSIM



Lunar Digital Elevation Models (DEM)

Ames Stereo Pipeline

- Open-source photogrammetry
- C++ code on GitHub (Apache 2 license)
- Linux and macOS
stereopipeline.readthedocs.io

Lunar Maps

- LRO laser altimeter (LOLA) yields DEMs at **5 m/pixel** (mostly interpolated)
- Combine with stereo images (LROC-NA) yields DEMs at **3 m/pixel**



DEM based on LRO LOLA at 5 m/pixel

Lunar Digital Elevation Models (DEM)

Ames Stereo Pipeline

- **Photoclinometry**
("shape from shading")
- Estimate slope of each pixel from its shading in multiple images
- Combine many images (generally dozens) to model lunar surface at **1 m/pixel**



"Shape from Shading" (SfS) DEM at 1 m/pixel

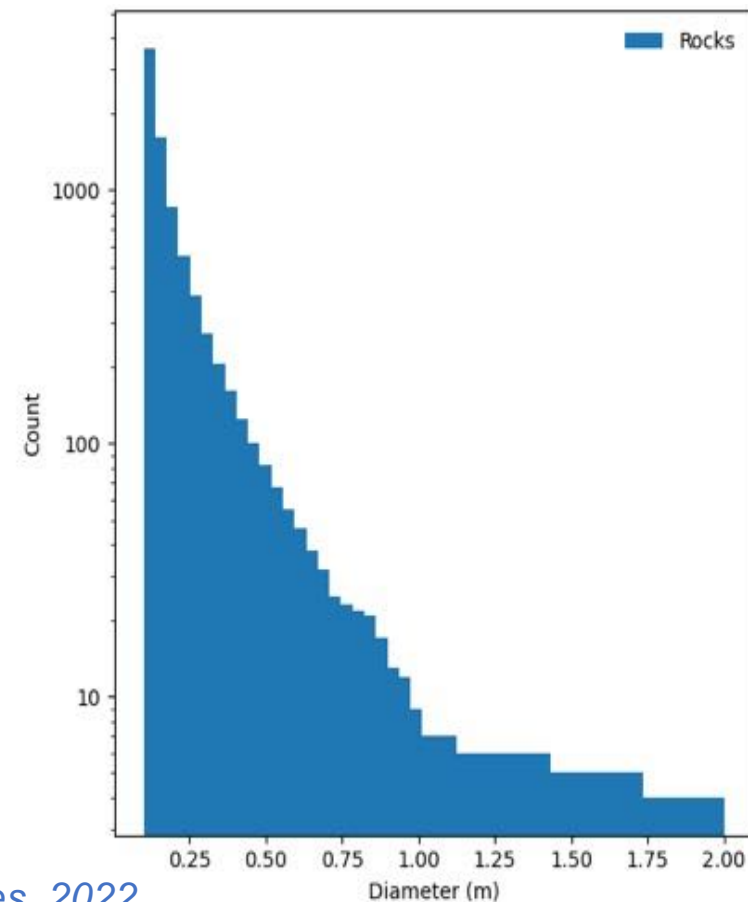
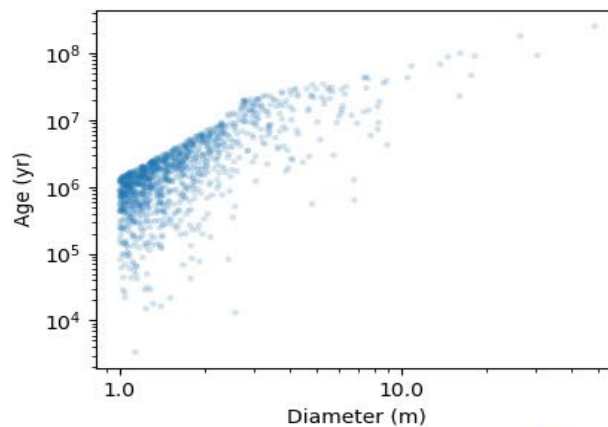
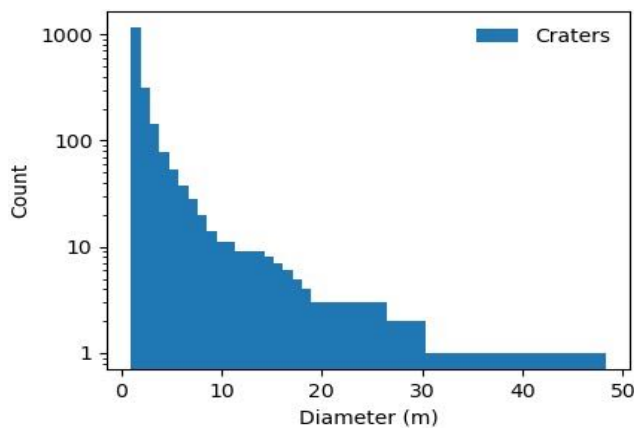
VIPER Synthetic Terrain Tools

Objective

- Produce **scientifically plausible**, very high-resolution (**cm/pixel**) DEMs

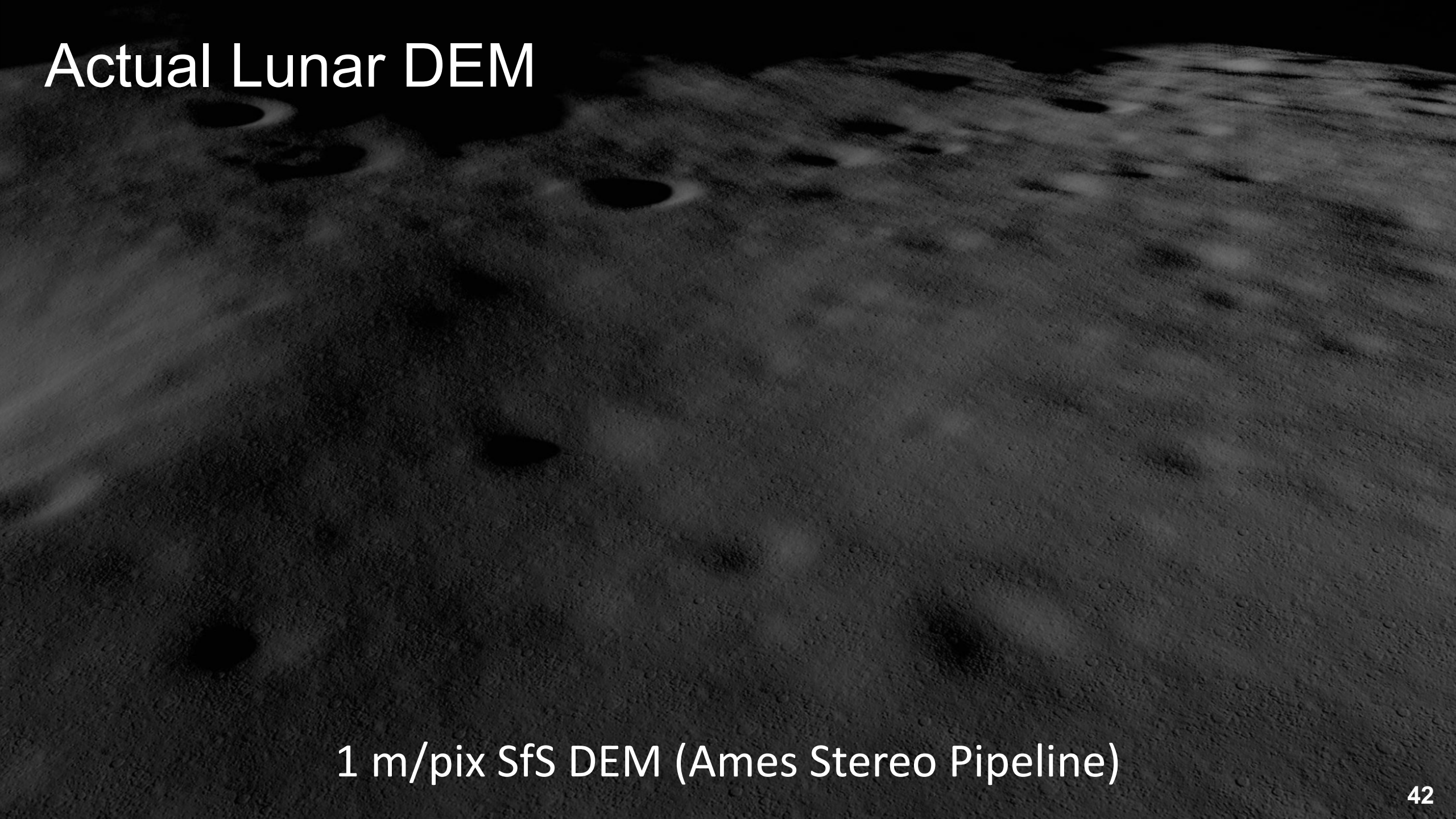
Approach

- Begin with lunar SfS DEM (1 m/pixel)
- Upscale DEM via fractal synthesis (4 cm/pixel)
- Add synthetic craters and rocks based on size-frequency distribution studies*
- Apply age effects (e.g., crater shape)



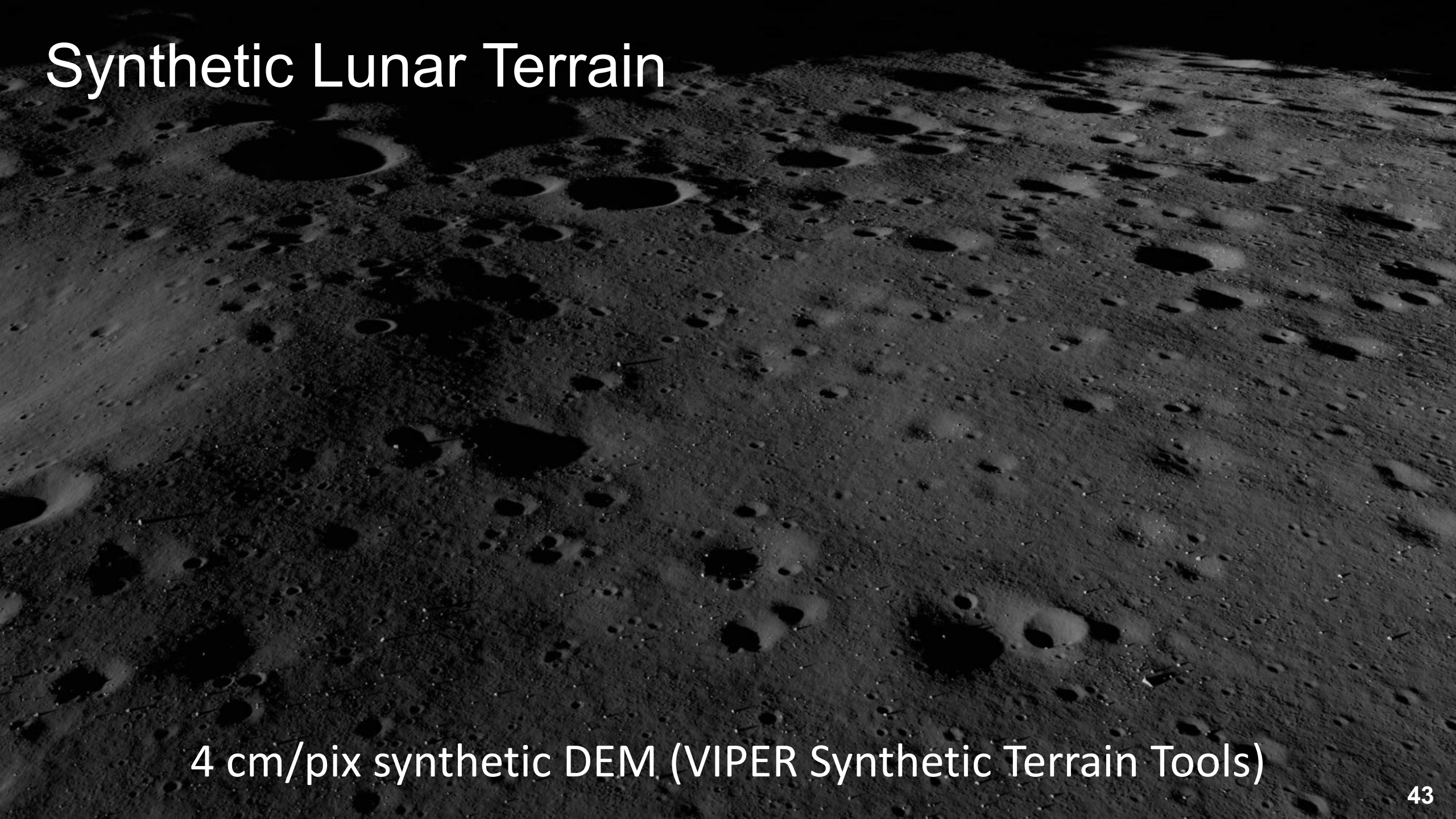
*VIPER Environmental Specification, VIPER-MSE-SPEC-001, NASA Ames, 2022.

Actual Lunar DEM



1 m/pix SfS DEM (Ames Stereo Pipeline)

Synthetic Lunar Terrain

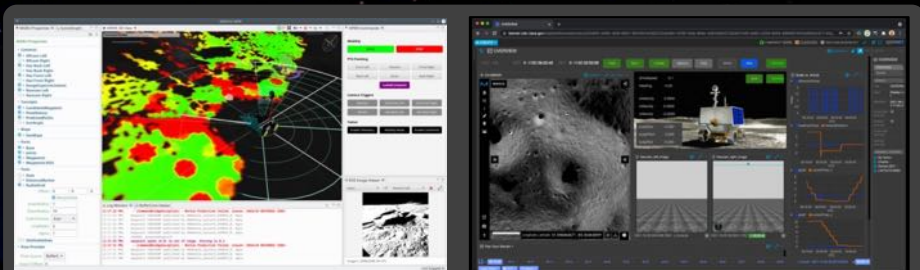
A grayscale synthetic Digital Elevation Model (DEM) of the lunar surface. The terrain is covered with numerous craters of various sizes, from small pits to large, deep basins. The lighting creates strong shadows, highlighting the rugged topography and the depth of the craters. The overall appearance is a detailed, high-resolution representation of the Moon's surface.

4 cm/pix synthetic DEM (VIPER Synthetic Terrain Tools)



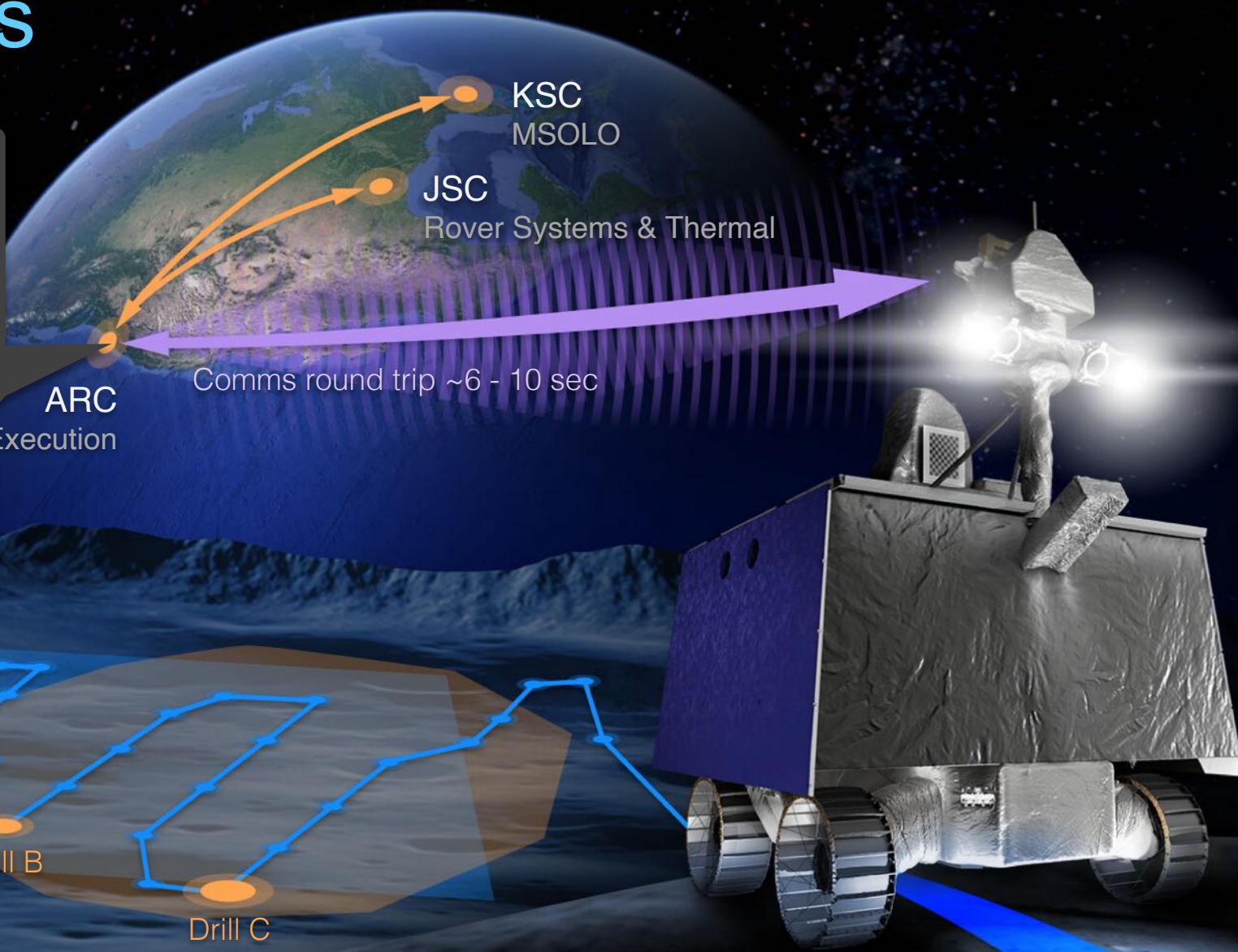
Real-time lunar surface simulation (VIPER RSIM)

Mission Operations



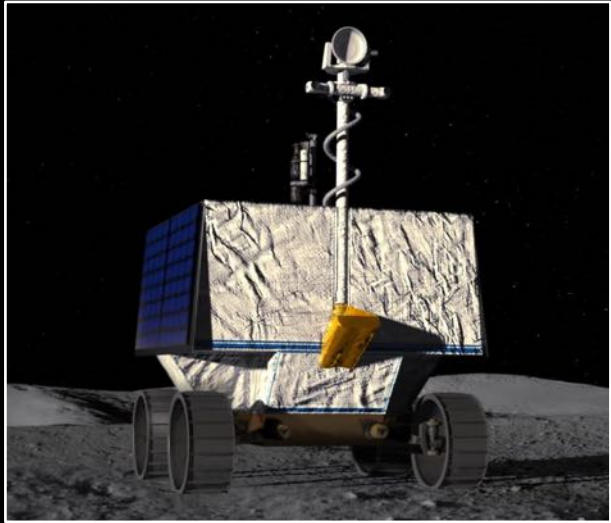
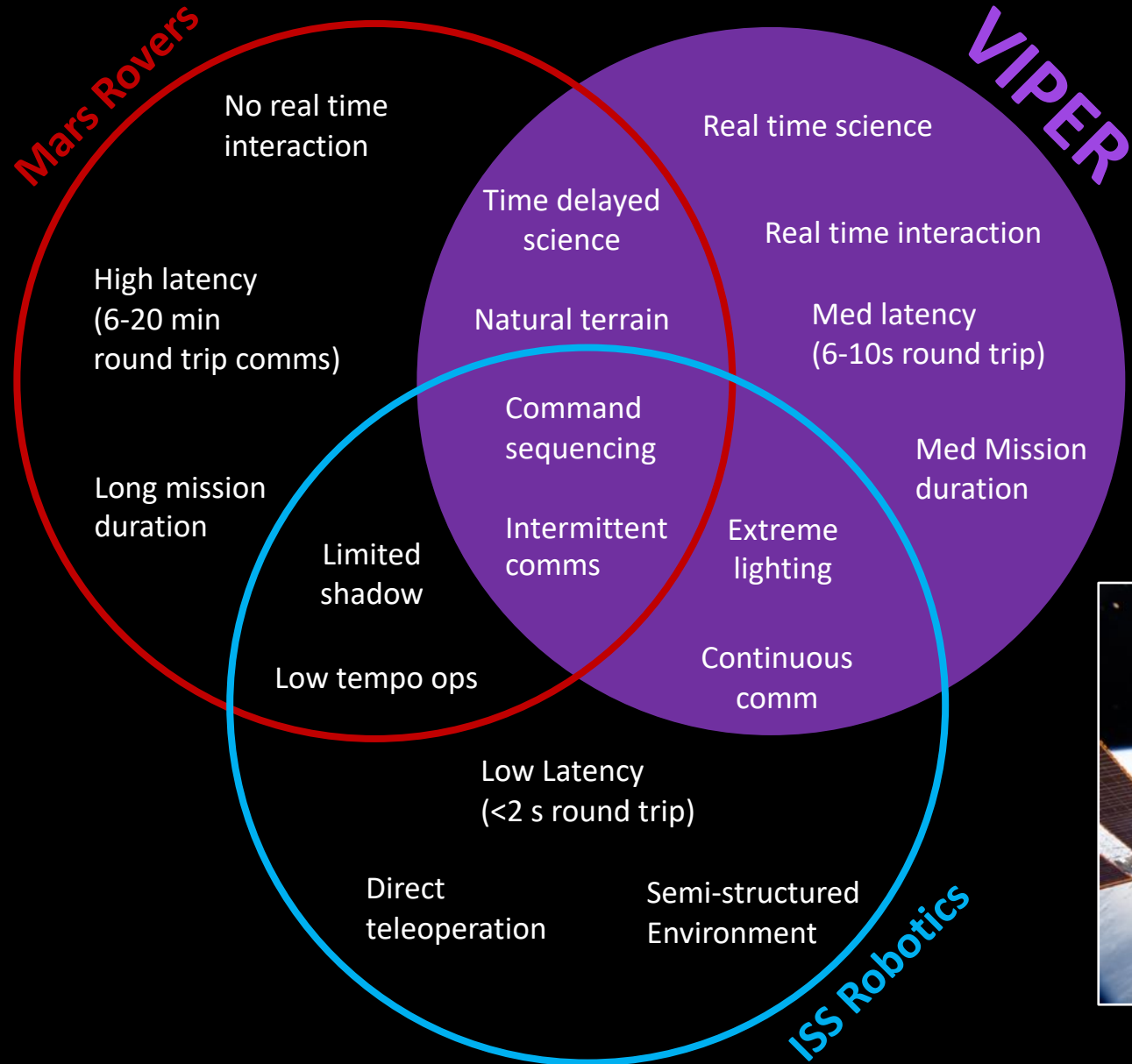
Rover Driving

Mission Monitoring



Mons Mouton (84.6°S, 31.0°W)
near Nobile Crater

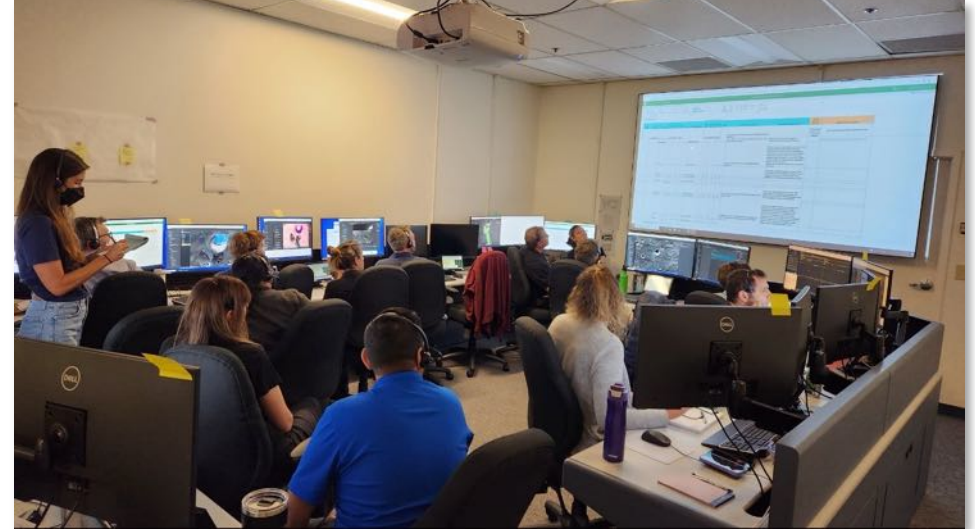
VIPER vs ISS vs Mars Rovers



Real-Time Science Operations

Interactive decision making

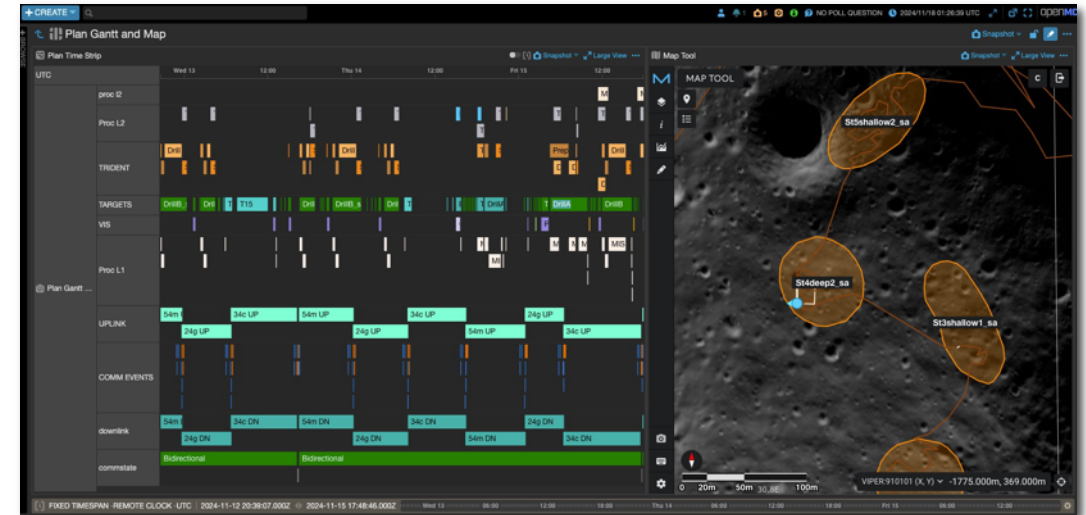
- Tight integration between science and spacecraft ops
- Fluid, interactive presentation, exploration of data **as it is collected**
- Rapid, on-site data analysis using pre-defined packages with multiple tools ARCGIS, Excel, MATLAB, etc.
- Planning and replanning of rover traverse and activities **based on real-time science measurements**



OpenMCT

Ground data system framework

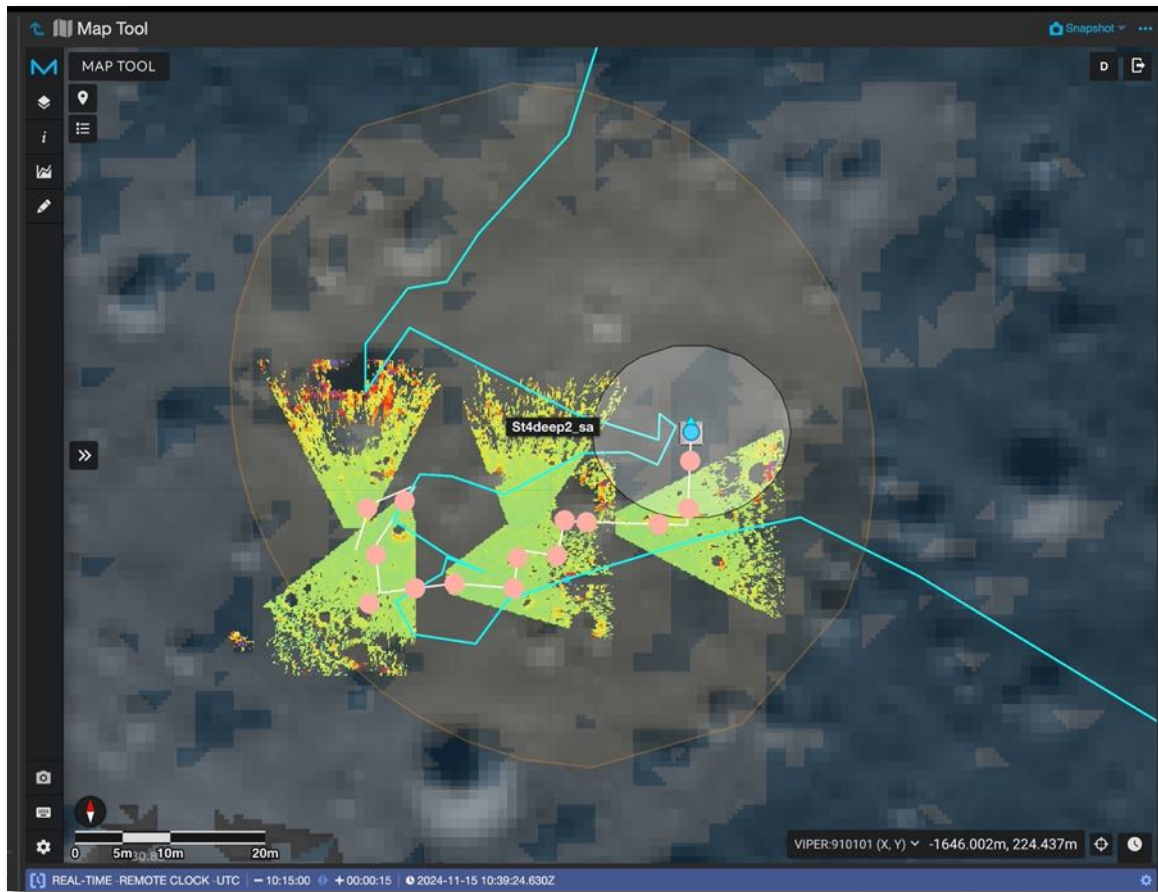
- Web-based front-end
- Data management (annotate, export, filter, search, etc).
- Real-time status displays
- Time series data displays (raw and computed)
- Integrated tools (e.g., MMGIS)
- NASA open-source <https://nasa.github.io/openmct>



MMGIS

Map-based Geographic Information System tool

- Real-time geospatial data from rover and instrument measurements
- Multiple map layers (including sets, overlays, annotation, search)



Rover Operations



VIPER Mission Operations Center (NASA Ames)

“Drive Team”

Real-Time Science

Driver

Co-Driver

Navigator





VIPER Interactive Rover Driving

“Drive Team” Ops Structure

- **Driver** – command rover mobility and imaging
- **Co-Driver** – supports decision making, mobility monitoring, voice loops
- **Navigator** – monitors pose (absolute/relative) and nav sensor health
- **Real-time Science** – supports real-time science ops, liaison to science team

Command Cycle (5 min duration)

- Terrain hazard assessment, tactical motion planning, image capture planning, interactive science, and waypoint driving
- Highly **interdependent teamwork** using decision support tools

Primary Motion Control = Waypoint Driving

- Interactively command rover to drive to a waypoint 4-8m away
- Rover on-board control achieves the waypoint
- Employ a variety of tactical driving techniques to handle different surface conditions and environments (slopes, craters, shadows, etc)

Drive Team Command Cycle Tasks

Task	Driver	Co-Driver	Navigator	Real-Time Sci
Assess rover state	Review mobility state Review mobility health Review current pose	<i>Shadow driver</i>	Review nav sensor state Review nav sensor health Review localization quality	
Assess terrain hazards	Assess geometric hazards Assess non-geometric hazards (near/mid-field)	<i>(when possible)</i>	Review hazard product (hazmap, point clouds) quality	Assess non-geometric hazards (mid/far field)
Plan tactical path	Define tactical path based on traverse plan, terrain hazards, ops constraints (power, science, thermal, etc.), & drive techniques	Sanity check (concur)	Provide nav constraints	Provide science constraints (spatial & temporal tolerances)
Plan rover motion	Define next rover move (posture or pose change mode, etc)			
Plan navigation imaging	Define next imaging based on consideration of traverse plan, imaging constraints (incl science), and localization needs	Sanity check (concur)	Sanity check (concur)	Sanity check (concur)
Command rover motion	Confirm driving is authorized Countdown to command Execute command	<i>Call halt if needed</i>	<i>Call halt if needed</i>	<i>Call halt if needed</i>
Command navigation imaging	Confirm imaging is authorized Countdown to command Execute command	<i>Call halt if needed</i>	<i>Call halt if needed</i>	<i>Call halt if needed</i>

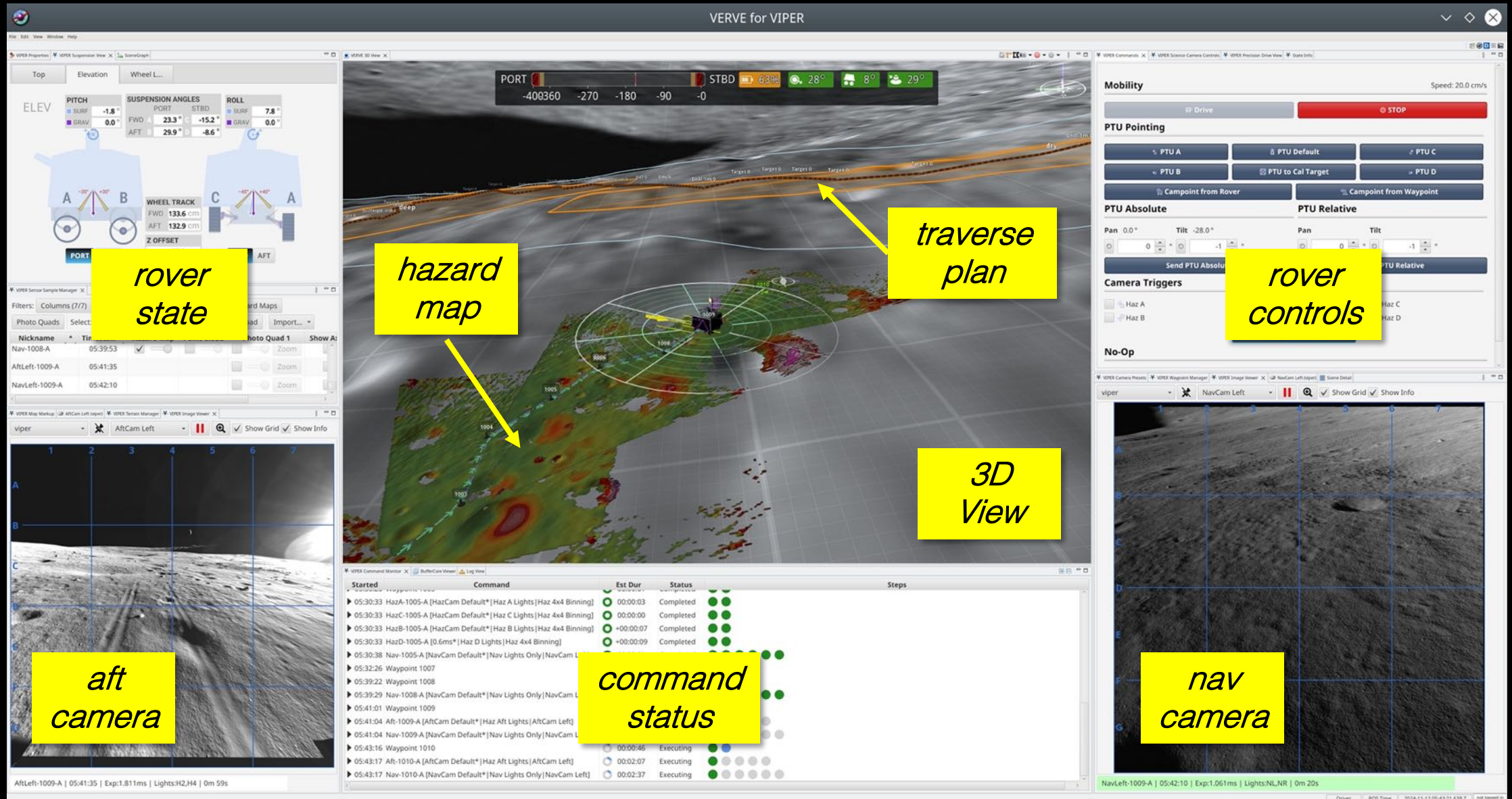
SENSE

PLAN

ACT

5 min duration

Rover Driving Interface (VERVE)



Assess terrain + place waypoint

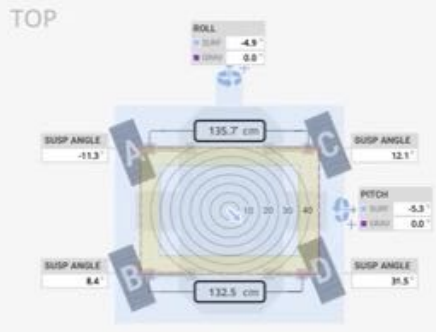
VERVE 3D View



VERVE Command Monitor

Started	Command	Est Dur	Status
01:50:33	Waypoint 1010	00:00:02	Completed
01:50:49	Set Pan/Tilt (-11.2°/-21.1°)	+00:31:57	Overdue
01:50:56	Nav-1010-A [NavCam Default*] [Nav Lights ...]	+00:02:39	Completed
01:53:23	Waypoint 1011	00:00:08	Completed
01:53:47	Set Pan/Tilt (-22.7°/-13.2°)	+00:28:59	Overdue
01:53:49	Nav-1011-A [NavCam Default*] [Nav Lights ...]	+00:08:11	Completed
02:01:49	Waypoint 1012	00:00:08	Completed
02:01:58	Set Pan/Tilt (2.6°/-17.2°)	00:00:09	Completed
02:02:05	Nav-1012-A [NavCam Default*] [Nav Lights ...]	+00:00:49	Completed
02:03:20	Set Pan/Tilt (-42.3°/-16.4°)	00:00:11	Completed
02:03:27	Nav-1012-B [NavCam Default*] [Nav Lights ...]	+00:13:37	Completed
02:10:28	Waypoint 1013	00:00:06	Completed
02:17:19	Set Pan/Tilt (21.8°/-25.2°)	00:00:08	Completed
02:17:30	Nav-1013-A [NavCam Default*] [Nav Lights ...]	+00:02:48	Overdue
02:19:56	Set Pan/Tilt (-50.7°/-14.6°)	00:00:09	Completed
	Nav-1013-B [NavCam Default*] [Nav Lights ...]	+00:02:35	Overdue
		00:00:19	Executing

VERVE Suspension View



VERVE Science Camera

Mobility

Speed: 20.0 cm/s

Drive

STOP

PTU Pointing

PTU A

PTU Default

PTU C

PTU B

PTU to Cal ...

PTU D

Campoint from Rover

Campoint from Waypoint

PTU Absolute

PTU Relative

Send PTU Absolute

Send PTU Relative

Camera Trigg...

Haz A

NavCam Stereo

Haz C

Haz B

AltCam Stereo

Haz D

Trigger ...

VERVE Precision Drive View

Suspens...

Drive

Advanced

States

DRIVE_CART

SUSP_CART

DRIFT_ON

ATT_ON

ATT_OFF

ATT_ON

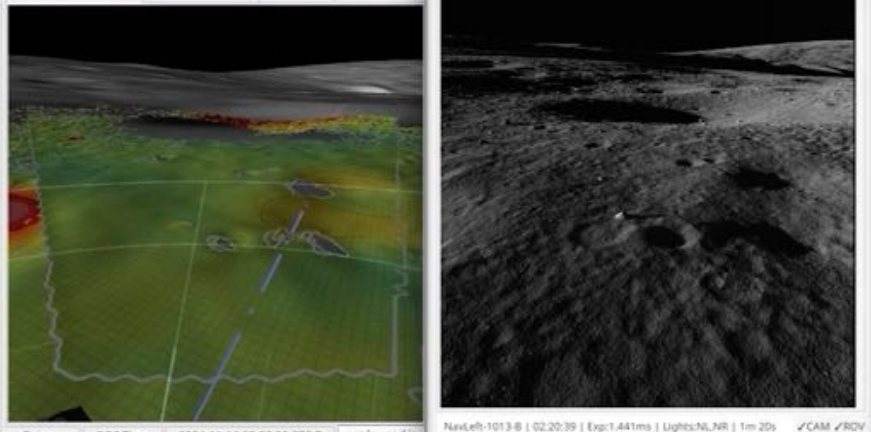
ATT_OFF

VERVE Image Viewer

NavCam Left

VERVE Camera

VERVE Waypoi...



rover simulator

VERVE

55

Refine waypoint + command motion

The screenshot displays the Verve 3D View interface, which is used for controlling a rover. The main window shows a 3D terrain model with a rover positioned on it. The rover is a small, boxy vehicle with a camera and a solar panel. The terrain is a grayscale image of a planetary surface, likely Mars, with various craters and ridges. The rover is positioned on a relatively flat area, and its shadow is cast onto the ground. The interface includes several panels and controls:

- VERVE 3D View X:** The main window showing the 3D terrain model. It includes a toolbar with buttons for 'Recenter PhotoQuad' and 'Zoom Out'. A color scale bar at the top indicates 'PORT' and 'STBD' values from -400 to 0.
- VERVE Commands X:** A panel on the right side of the interface. It contains sections for 'Mobility' (with 'Drive' and 'STOP' buttons), 'PTU Pointing' (with buttons for PTU A, PTU Default, PTU C, PTU B, PTU to Cal, and PTU D), 'PTU Absolute' (with 'Send PTU Absolute' and 'Send PTU Relative' buttons), and 'Camera Trigg...' (with buttons for Haz A, Haz B, Haz C, Haz D, NavCam Stereo, and AltCam Stereo).
- VERVE Precision Drive View X:** A panel at the bottom right of the interface. It contains sections for 'SUSP...' (with 'DRIVE_CART', 'SUSP_CART', 'OFF_ON', and 'ATT_ON' buttons), 'Z Offset' (with a value of 36.5 cm), and 'ATT_ON' and 'ATT_OFF' buttons.
- VERVE Command Monitor X:** A panel at the bottom left of the interface. It displays a list of commands and their status. The table has columns for 'Started', 'Command', 'Est Dur', and 'Status'. The commands include 'Waypoint 1010', 'Set Pan/Tilt (-11.2°/-21.1°)', 'Nav-1010-A [NavCam Default*] [Nav Lights ...]', 'Waypoint 1011', 'Set Pan/Tilt (-22.7°/-13.2°)', 'Nav-1011-A [NavCam Default*] [Nav Lights ...]', 'Waypoint 1012', 'Set Pan/Tilt (2.6°/-17.2°)', 'Nav-1012-A [NavCam Default*] [Nav Lights ...]', 'Set Pan/Tilt (-42.3°/-16.4°)', 'Nav-1012-B [NavCam Default*] [Nav Lights ...]', 'Waypoint 1013', 'Set Pan/Tilt (21.8°/-25.2°)', 'Nav-1013-A [NavCam Default*] [Nav Lights ...]', and 'Set Pan/Tilt (-50.7°/-14.6°)'. The status of each command is indicated by a green circle with a checkmark (Completed) or a yellow circle with an exclamation mark (Overdue).
- VERVE Sensor Sample Manager X:** A panel at the bottom right of the interface. It displays a table of sensor samples. The table has columns for 'Filter: Columns (7/7)', 'Sensors (10/10)', 'Edit: Hazard Maps', 'Photo Quads', 'Select: Sample Types (4/4)', 'Show/Hide', 'Reload', and 'Import...'. The samples include 'estamp: Hazard Map', 'Point Cloud', and 'Photo Quad 1'. The samples are listed with timestamps and status indicators.
- VERVE Image Viewer X:** A panel at the bottom right of the interface. It displays a grayscale image of the rover's camera feed. The image shows the rover's perspective of the terrain, with various craters and ridges visible.

The text **rover simulator** is overlaid in orange on the right side of the image. The text **VERVE** is overlaid in red on the bottom left corner of the interface.

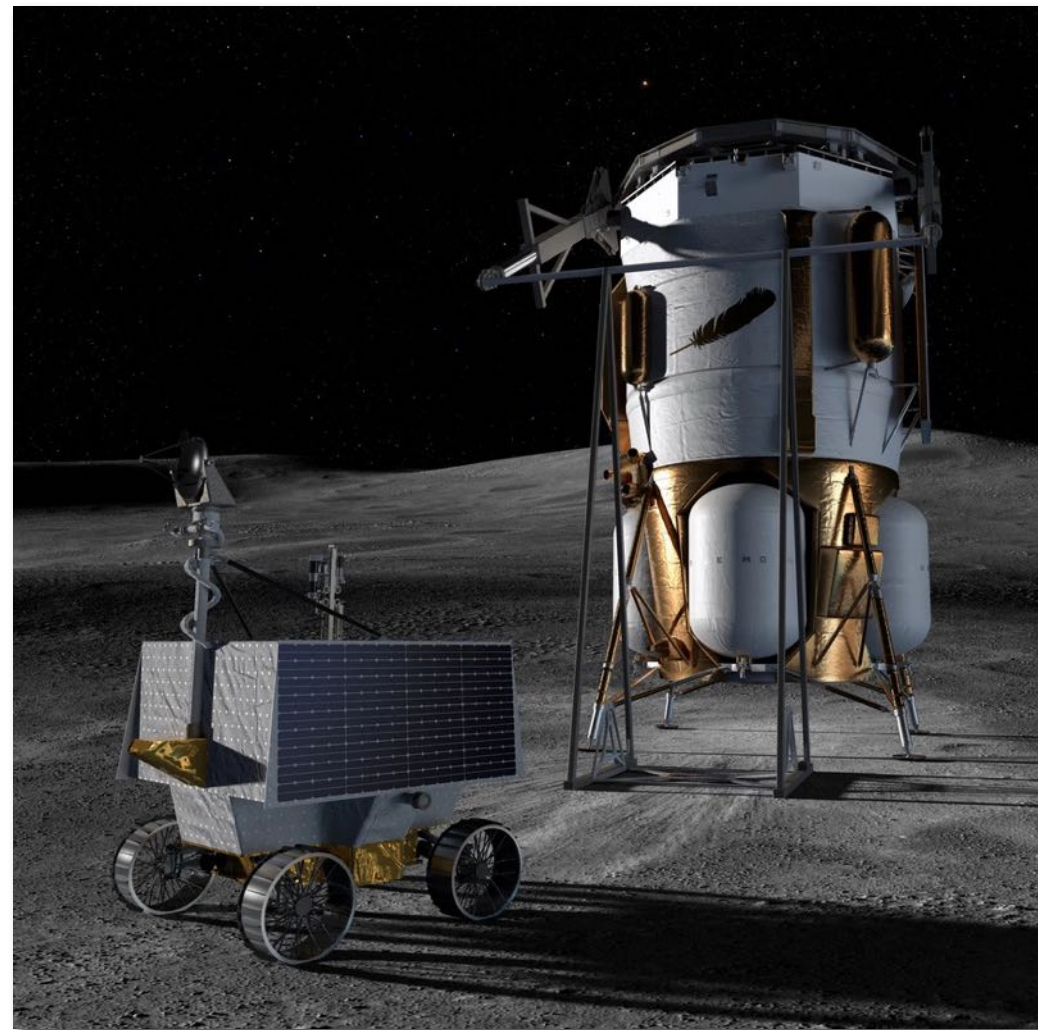
VIPER Flight Mission

To the Moon!

- Sept. 19, 2025 – Blue Origin selected to deliver VIPER to the Moon (CLPS CS-7 mission)

Blue Moon MK1 Lander

- Largest lunar lander built to date
- 8m tall, > 45,000 kg launch mass
- LOX/LH2 BE-7 engine
- Cold gas + Hot gas dual mode integrated RCS system
- Designed for the Blue Origin “New Glenn” launch vehicle (7m fairing)



Credit: Blue Origin

Mission Schedule

Blue Origin contract

- Base period (through June 2026)
 - Design VIPER accommodations
 - Demonstrate off-loading of VIPER from lander deck to ground
 - Maiden flight of MK1 lander (CT-3)
- Option period (July 2026+)
 - Jan 2027 VIPER integration

VIPER

- Aug 2027 Launch (Cape Canaveral)
- Sept 2027 Landing / start operations
- Jan 2028 End operations
- Sept 2028 End of mission

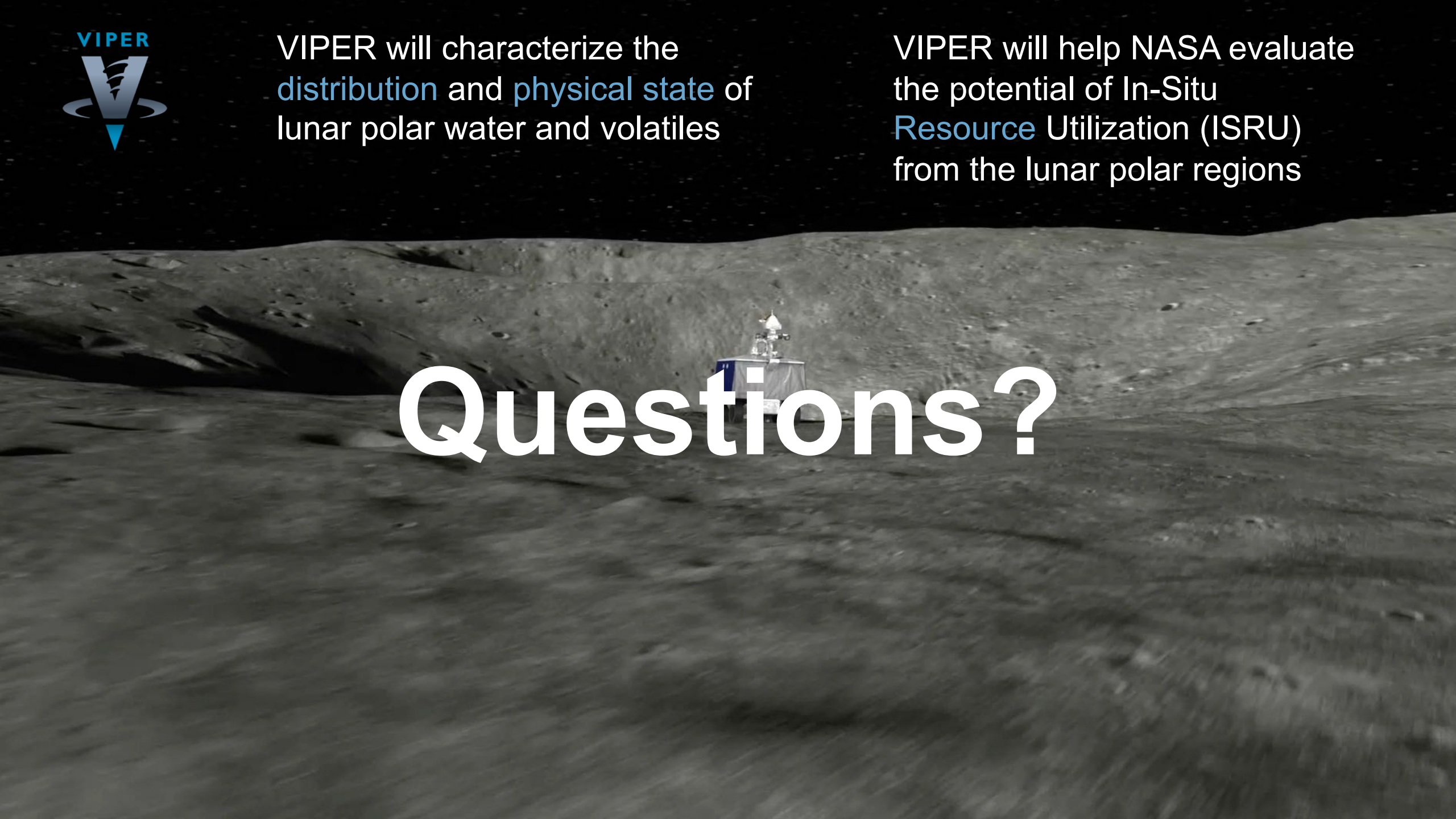


Flight rover operational readiness test
(17 April 2025)



VIPER will characterize the distribution and physical state of lunar polar water and volatiles

VIPER will help NASA evaluate the potential of In-Situ Resource Utilization (ISRU) from the lunar polar regions

A wide-angle, grayscale photograph of the lunar surface. The terrain is covered in craters and ridges. In the center, a small rover is visible, positioned on a relatively flat area. The word "Questions?" is superimposed in large white text over the lower half of the image.

Questions?