

National Aeronautics and Space Administration

NASA

VIPER

Volatiles Investigating Polar Exploration Rover

Terry Fong
Chief Roboticist
VIPER Rover Deputy Manager
NASA Ames Research Center

10 September 2025

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)**



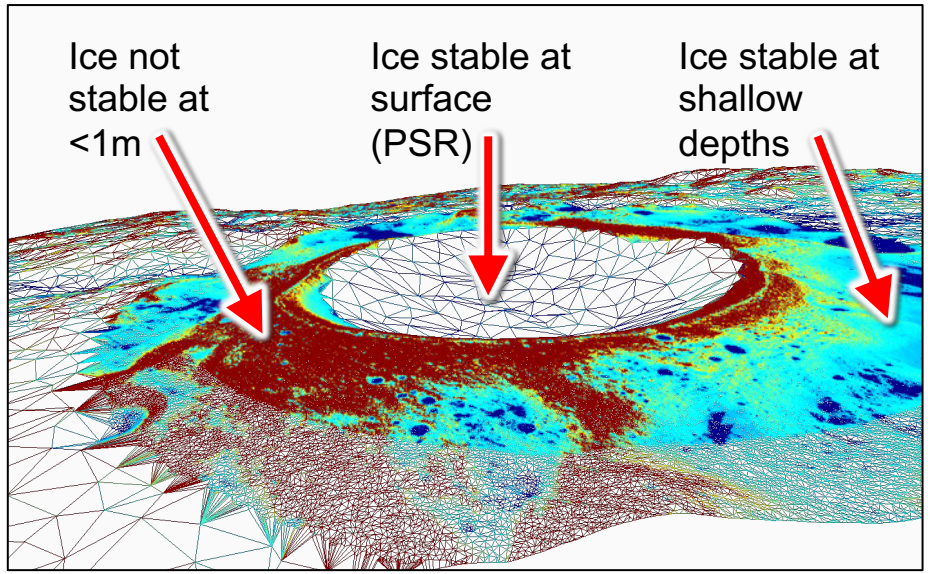
Where is water (ice) at the lunar poles?

Environmental factors

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

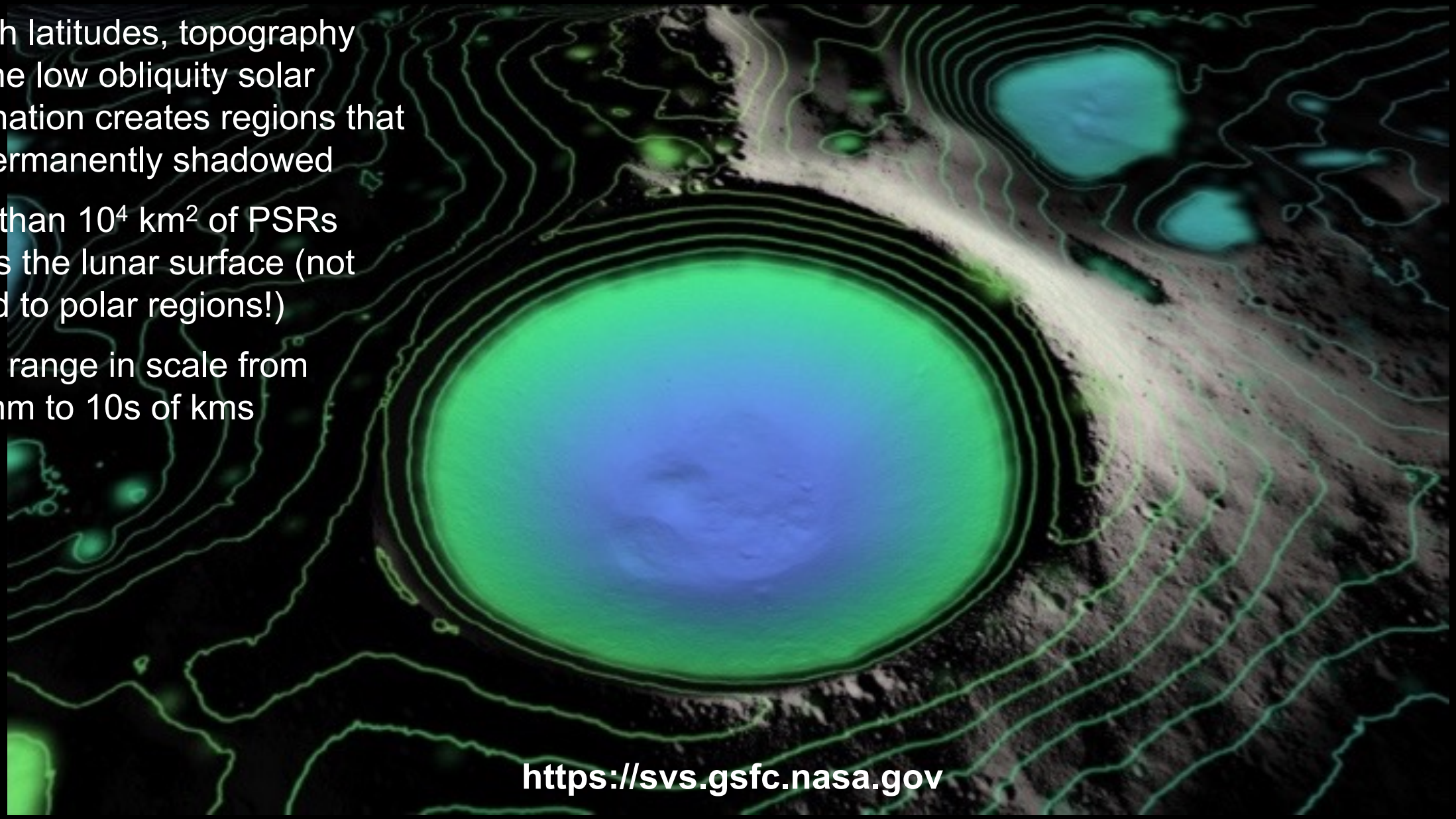
Ice Stability Regions

- **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 km^2 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



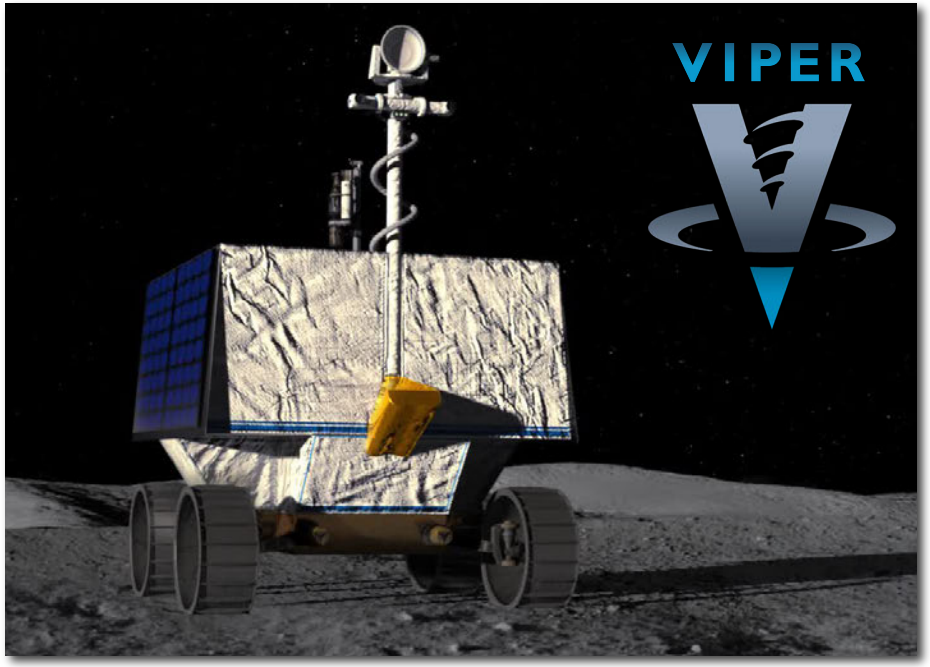
VIPER Mission

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”



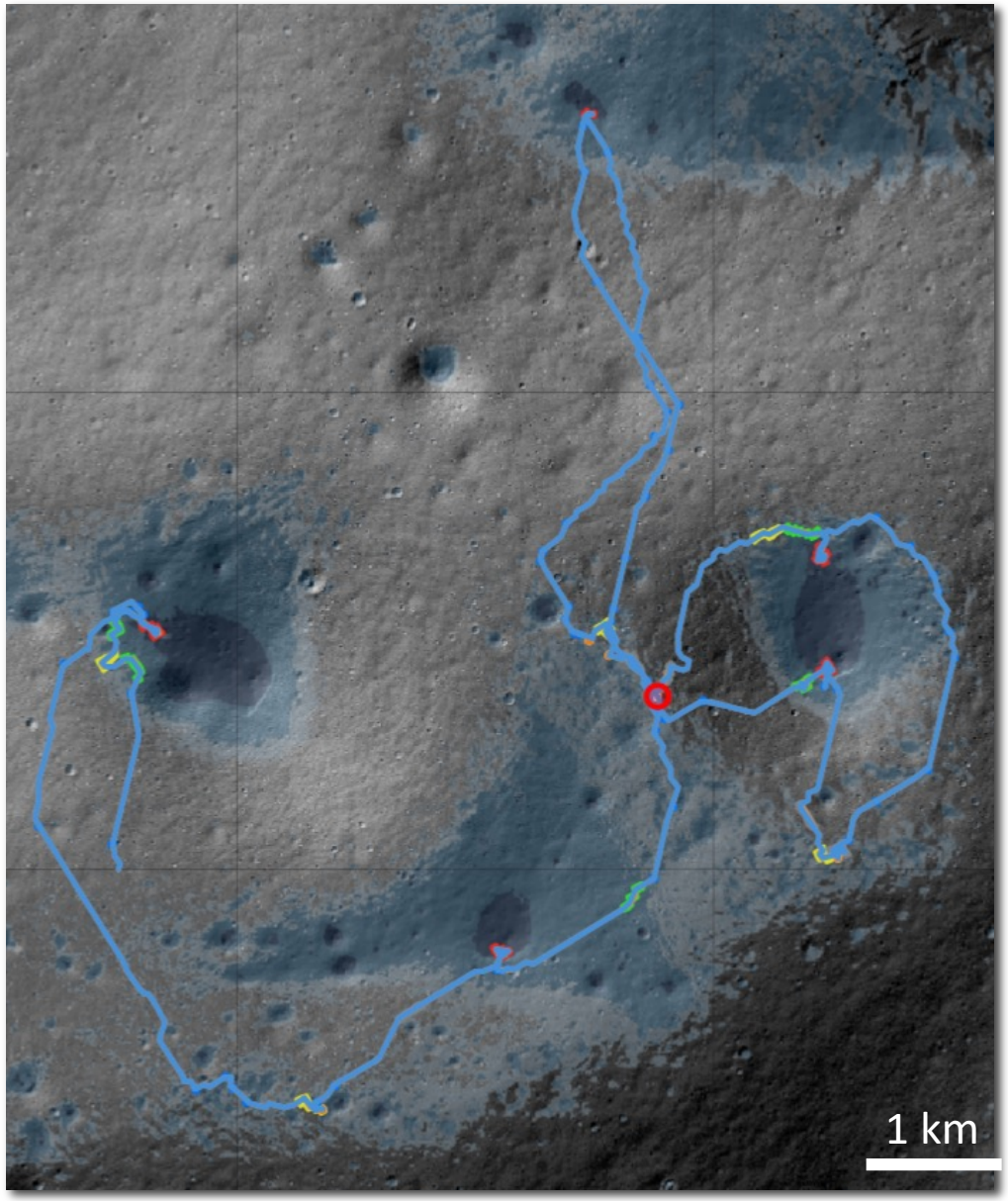
Current status

- Original NASA Science (SMD) mission canceled on July 17, 2024
- Flight hardware, software (flight & ground), and mission ops (products & process) are all complete and ready for flight
- NASA Exploration Science Strategy Integration Office (ESSIO) is now looking at different flight options (including commercial partnership)

VIPER Capabilities

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)



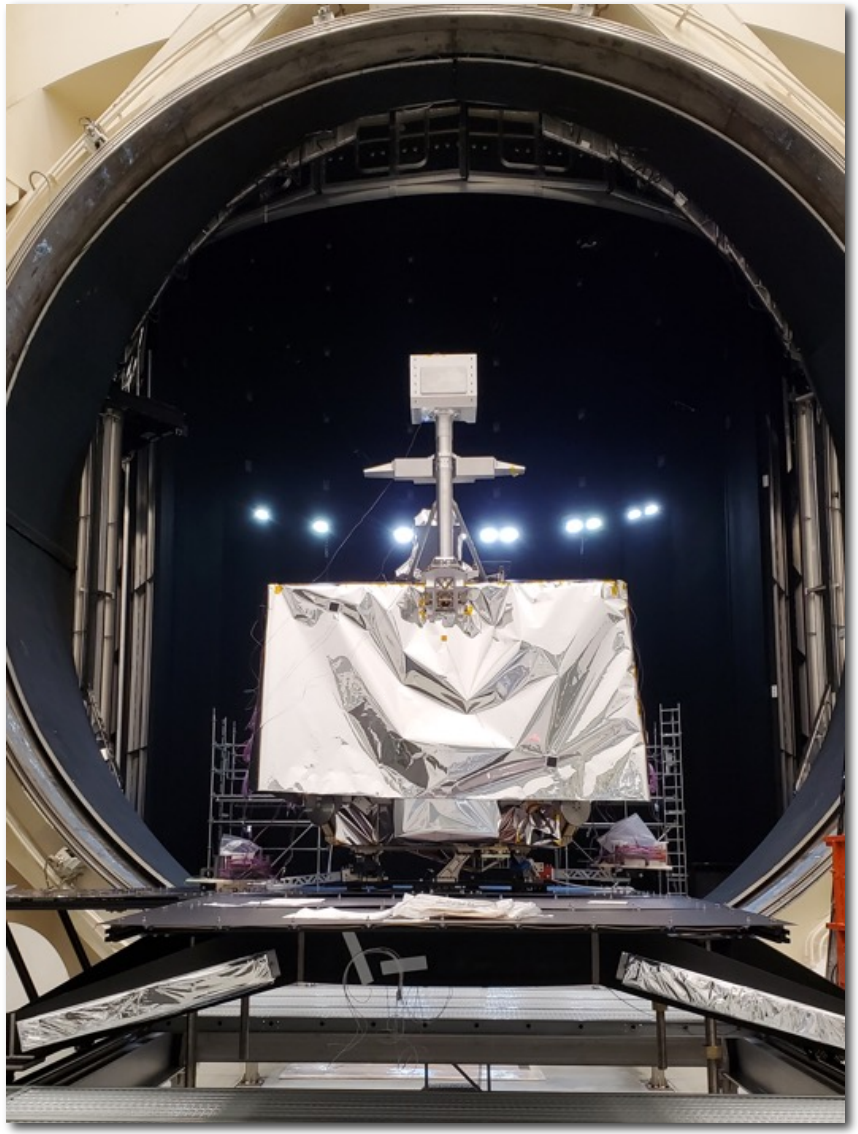
Not your usual NASA mission

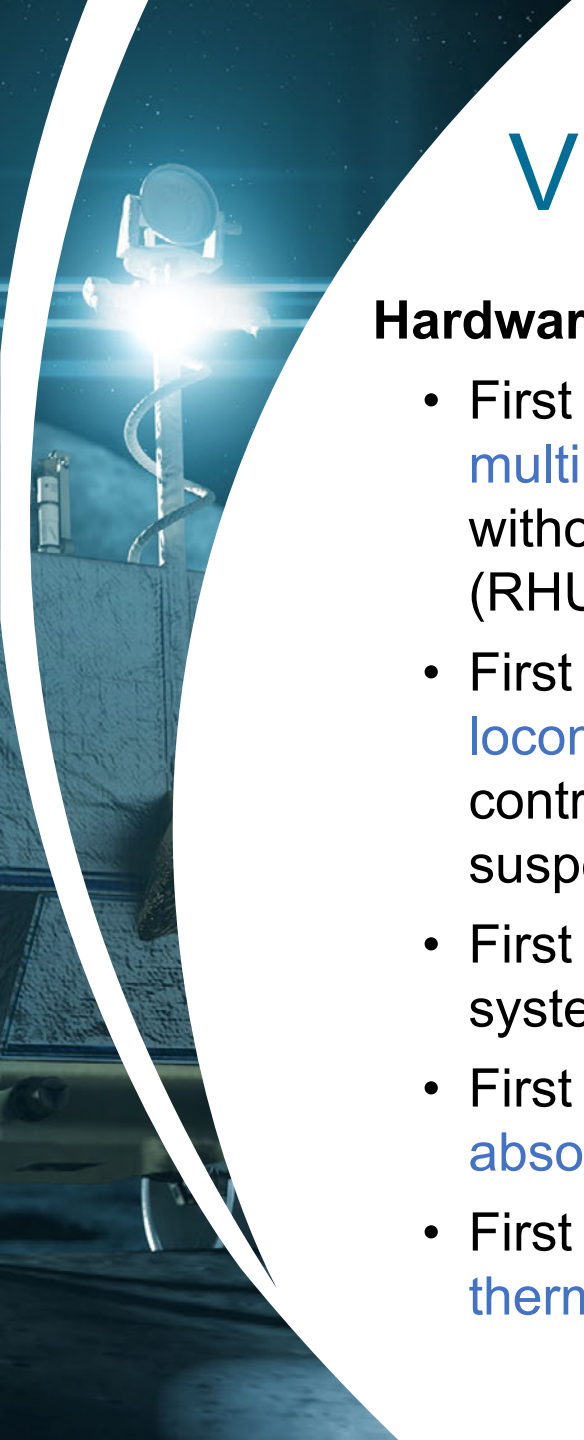
Research & Tech (R&T) mission

- Significant tailoring of traditional NASA flight requirements for cost & schedule savings
  NPR 7120.8, not 7120.5
- VIPER managed as a low-cost, risk-tolerant pathfinder mission

Significant commercial engagement

- Instruments developed with industry (SBIR/STTR program)
- First major ($500M) NASA mission to rely on CLPS program for launch and landing service





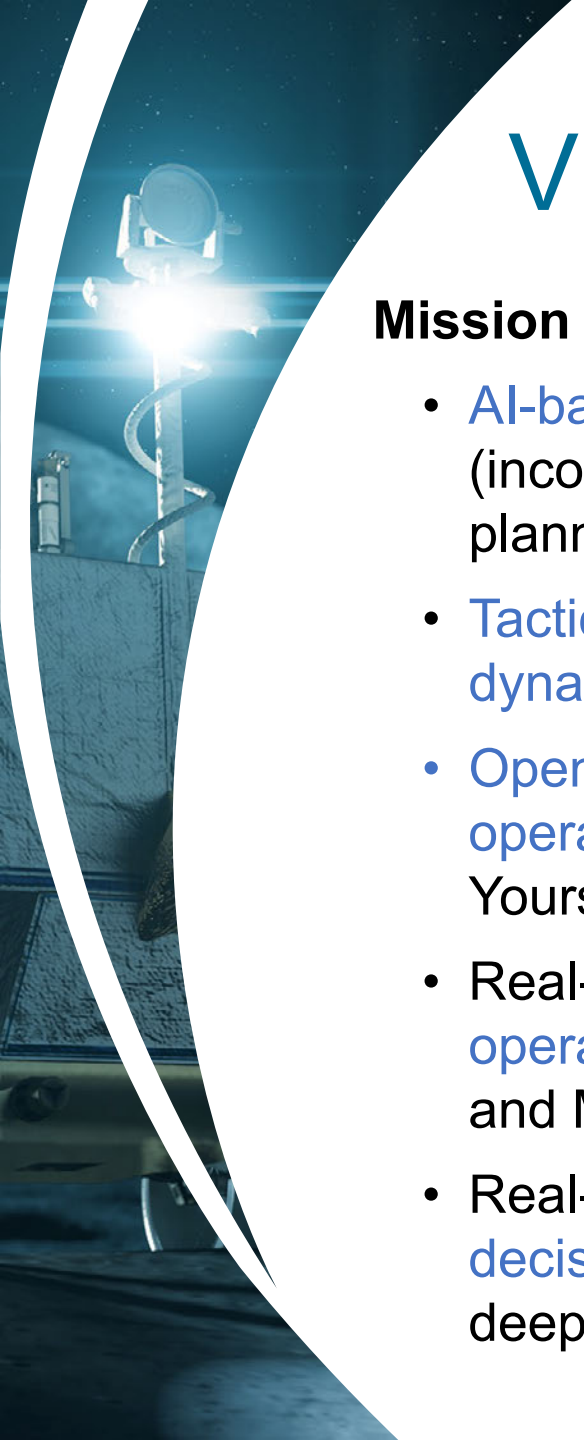
VIPER Innovations

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

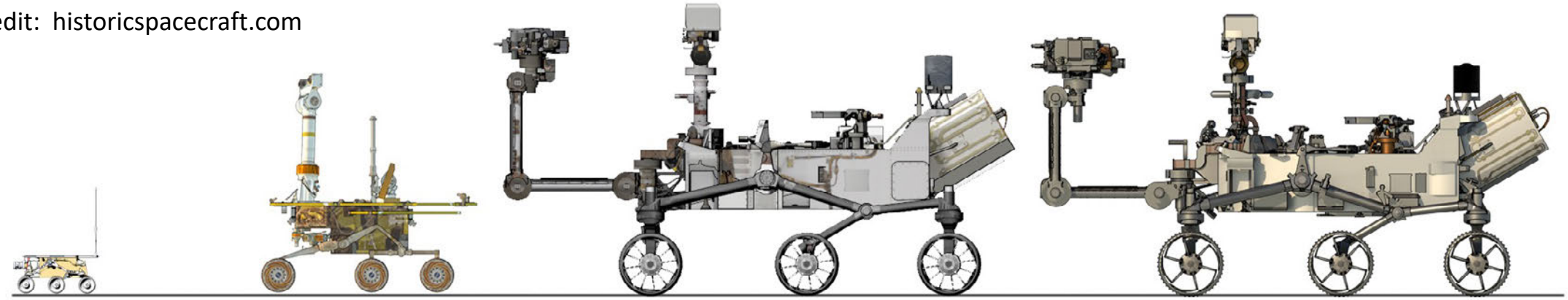
- AI-based strategic traverse planning (incorporates multiple solvers and planning under uncertainty)
- Tactical planning technology for dynamic operational environment
- OpenMCT open-source mission operator interfaces (including "Do It Yourself" public mission control)
- Real-time interactive rover 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 (TRACLabs, SBIR)

Rover Comparison

Credit: historicspacecraft.com

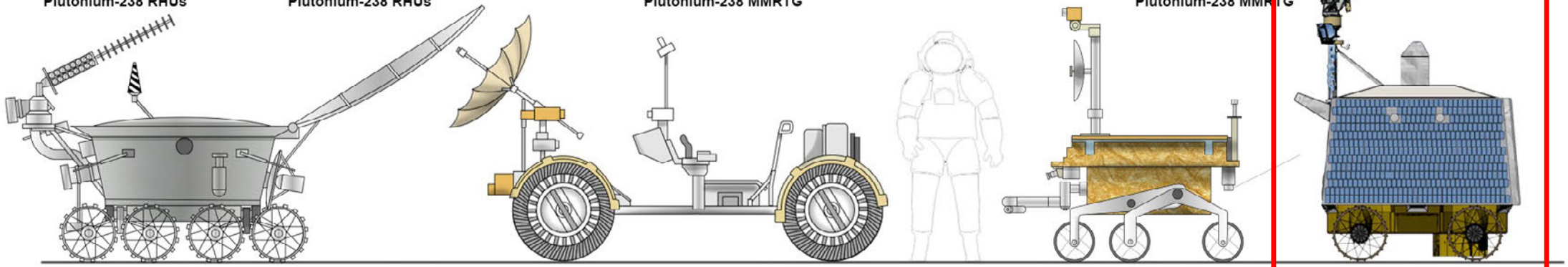


Sojourner (1996)
0.6m x 0.5m x 0.3m
11kg
Top Speed: 5cm/s
Plutonium-238 RHUs

Mars Exploration Rover (2004)
1.6m x 2.3m x 1.5m
180kg
Top Speed: 5cm/s
Plutonium-238 RHUs

Mars Science Laboratory (2011)
3.0m x 2.8m x 2.1m
900kg
Top Speed: 4cm/s
Plutonium-238 MMRTG

Mars 2020 Rover (2020)
3.0m x 2.7m x 2.2m
1025kg
Top Speed: 4.2cm/s
Plutonium-238 MMRTG



Lunokhod 1 & 2 (1970/1973)
2.3m x 1.6m x 1.5m
840kg
Top Speed: 55cm/s
Polonium-210 heat source

Lunar Roving Vehicle (1971/1972)
3.1m x 1.6m x 1.5m
210kg
Top Speed: 500cm/s
2 silver-zinc 36 volt batteries

1 meter

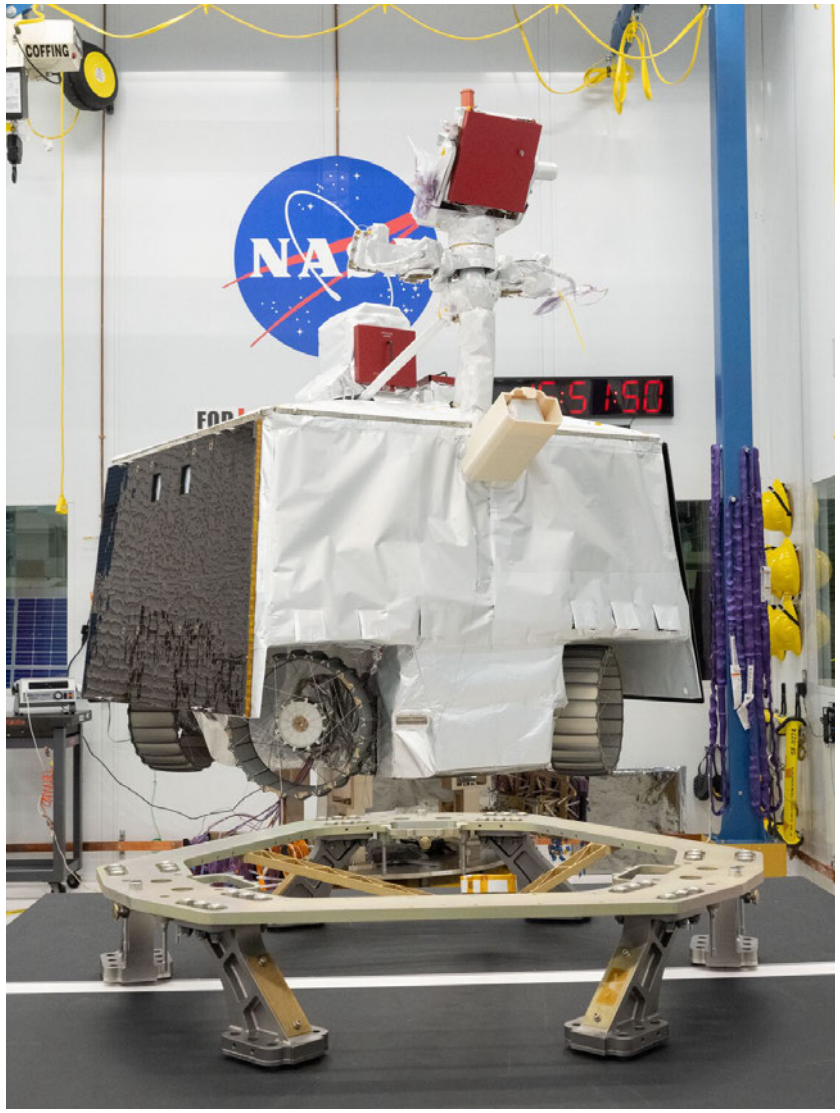
Yutu (2013/2019)
1.5m x 1.1m x 1.1m
140kg
Top Speed: 5cm/s
Plutonium-238 RHUs

VIPER
1.5m x 1.5m x 2.0m
430kg
Top Speed: 20cm/s
Electric heaters only



Flight Rover



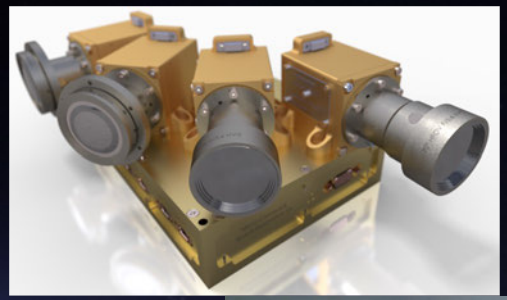


Assembly complete
4 June 2024

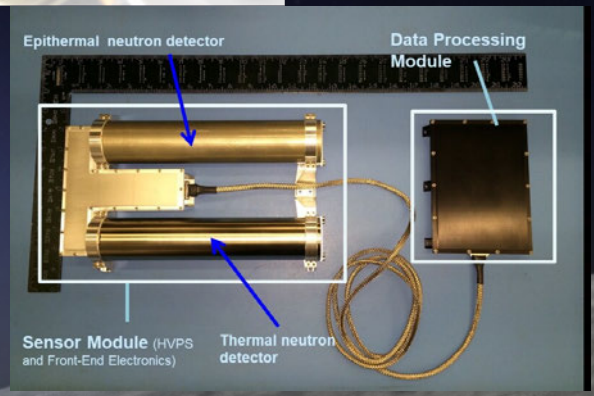
Instruments



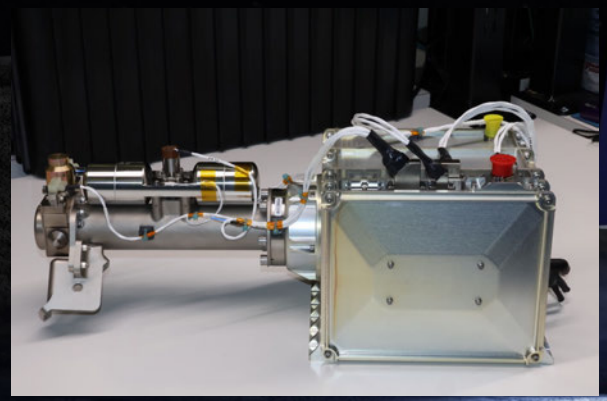
Subsurface excavation
TRIDENT Drill



Imaging Science
VIS

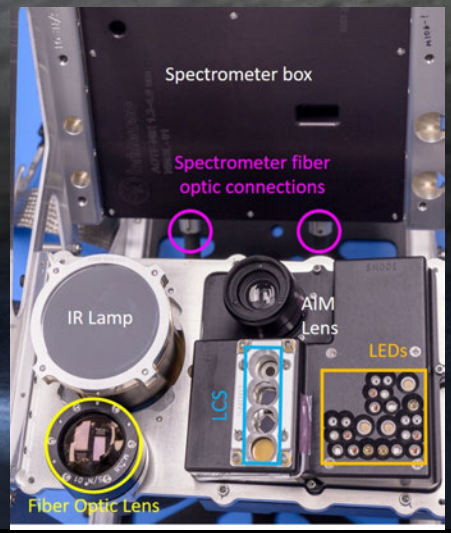


Prospecting
Neutron Spectrometer System (NSS) Instrument





Subsurface Sounding
Rover IMU



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

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

Mobility Architecture

Independent Wheel Modules (4x)

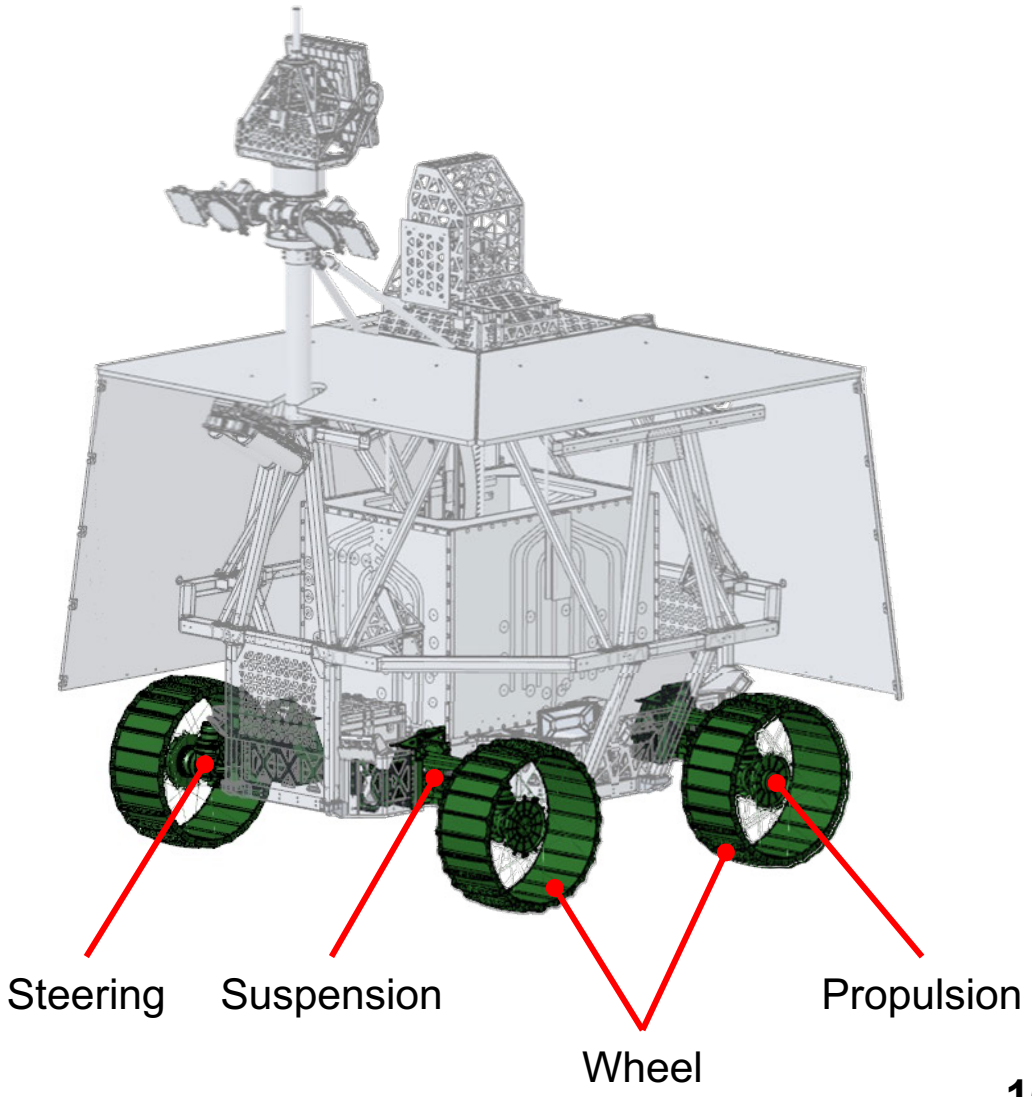
- Suspension: ± 40º, 200 N·m torque
- Steering: ± 50º, 130 N·m torque
- Propulsion: 20 cm/s, 200 N·m torque

Wheels (4x)

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

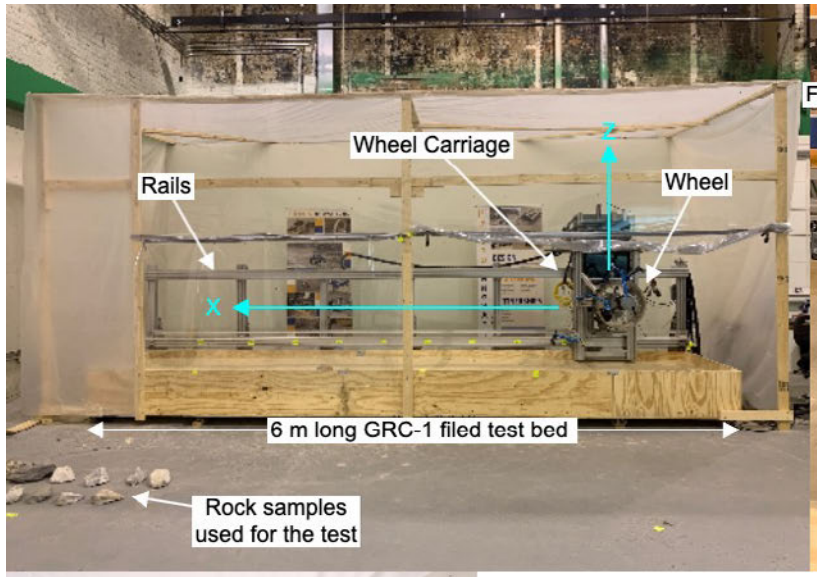
Capabilities

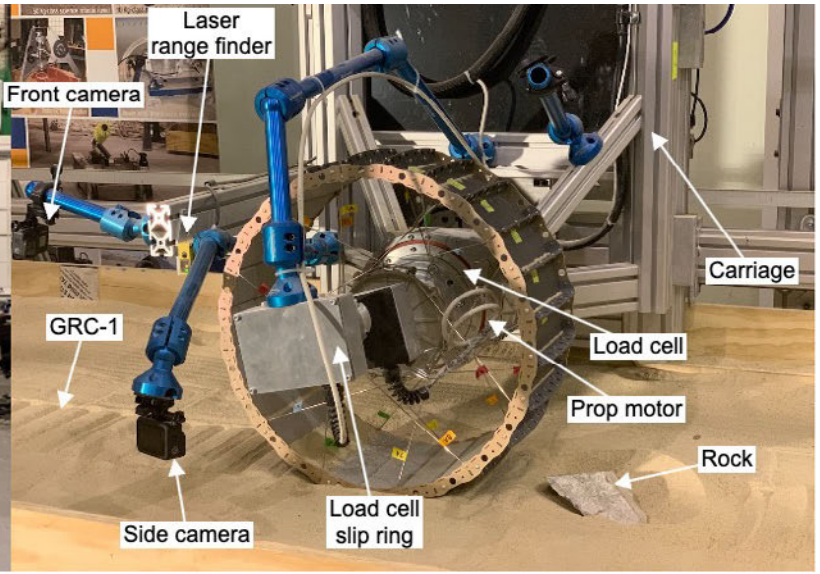
- Actuated suspension enables body attitude and clearance control
- Explicit steering and skid steering
- Alternate mobility

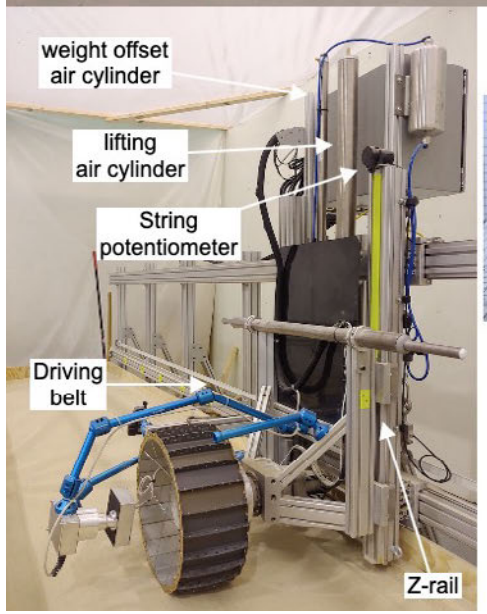



NASA

Wheel Lifecycle Testing (40 km)





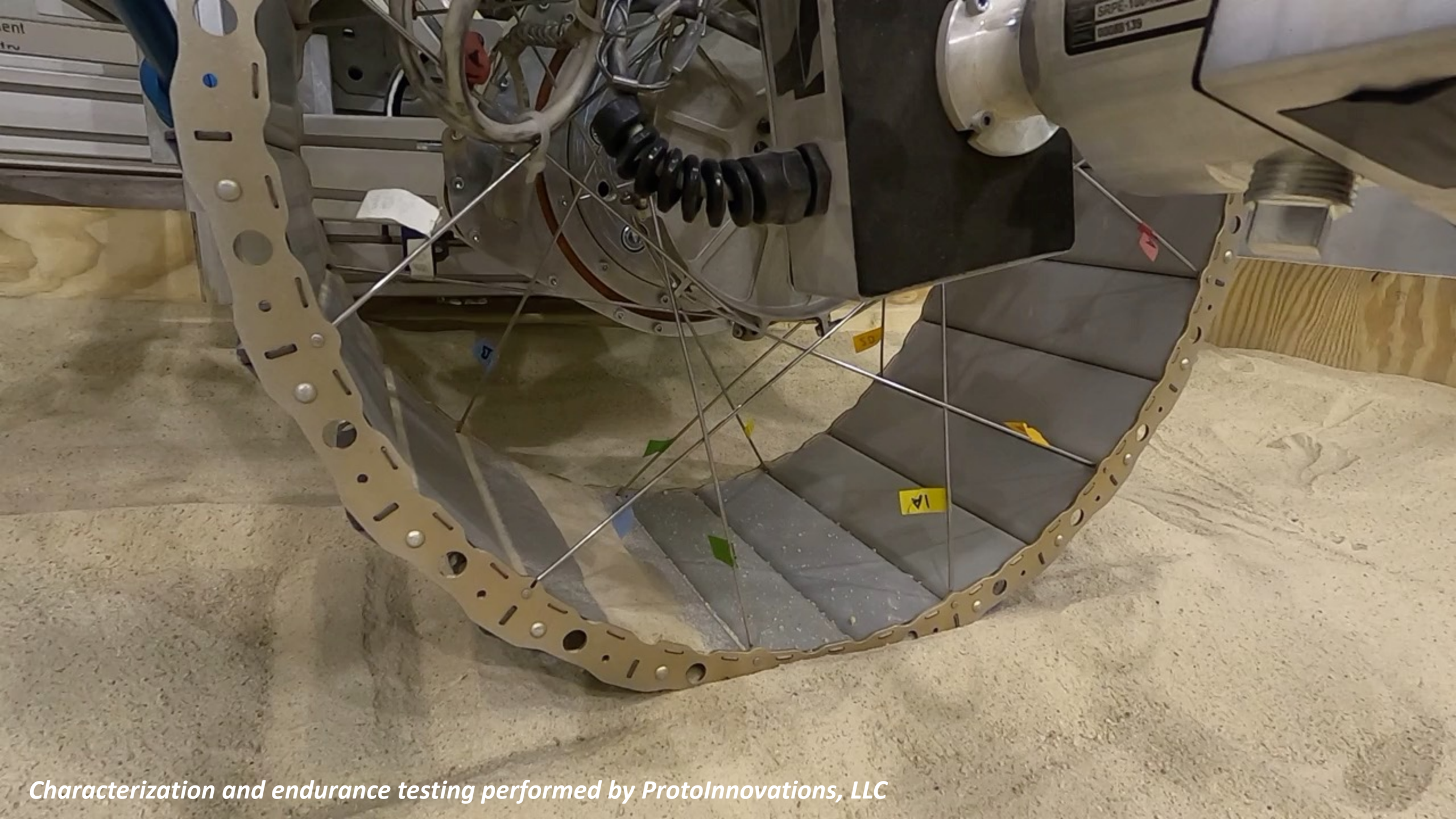


Anorthosites Rocks



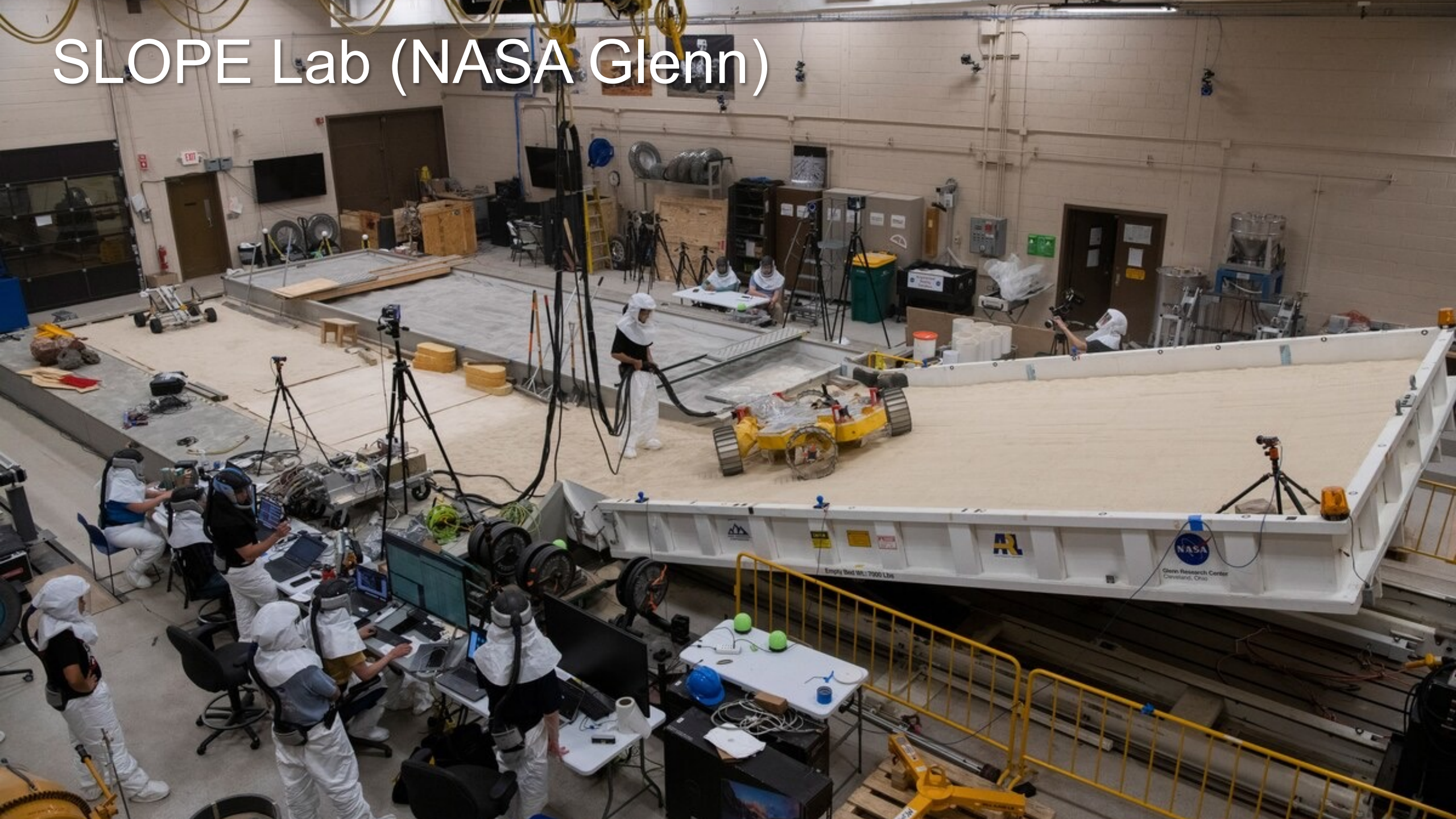
Basalt Rocks





Characterization and endurance testing performed by ProtoInnovations, LLC

SLOPE Lab (NASA Glenn)



Rock Traversal Testing



Crater Traversal Testing




4x speed

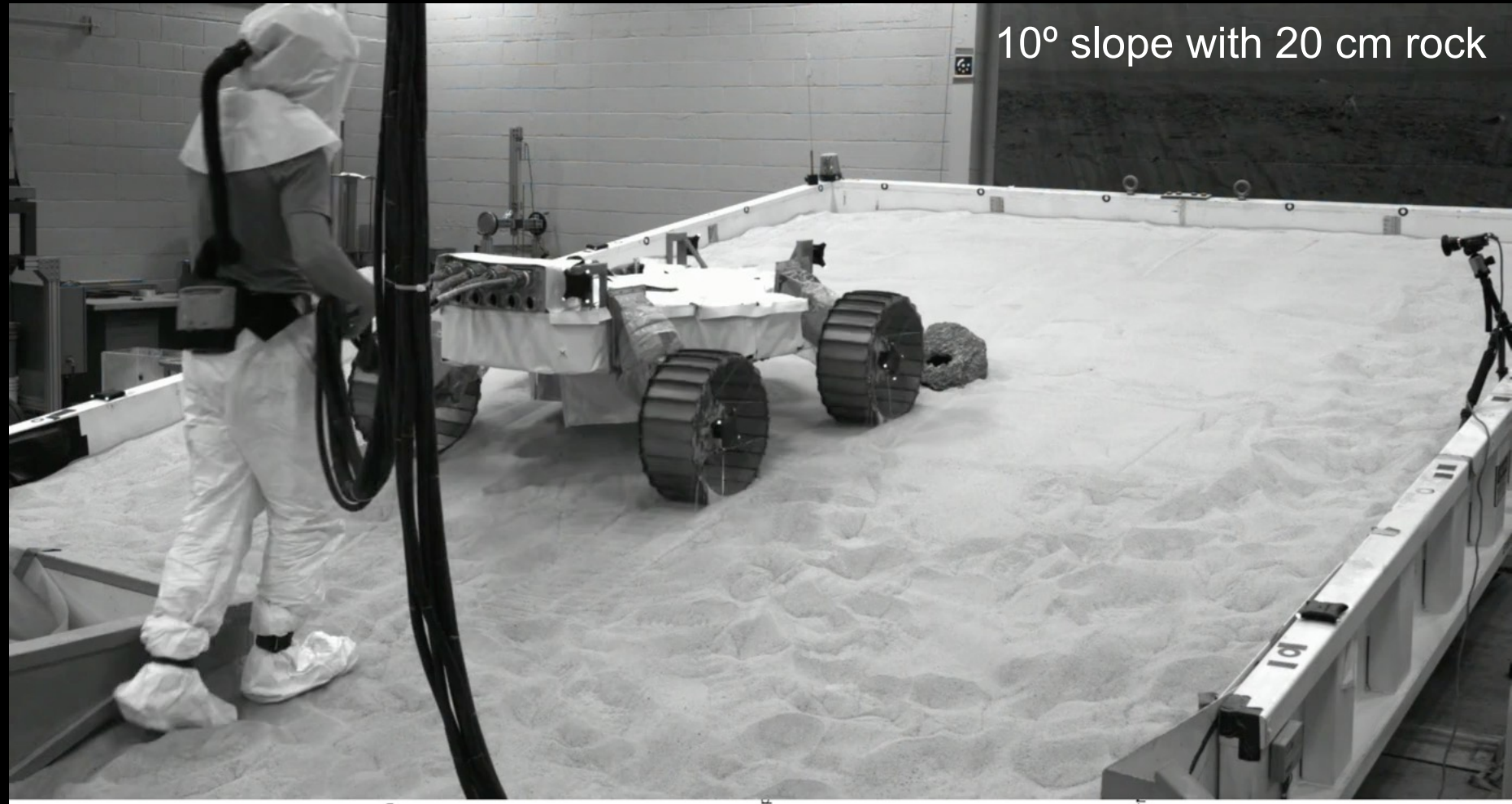
Slip Testing (30° Slope)

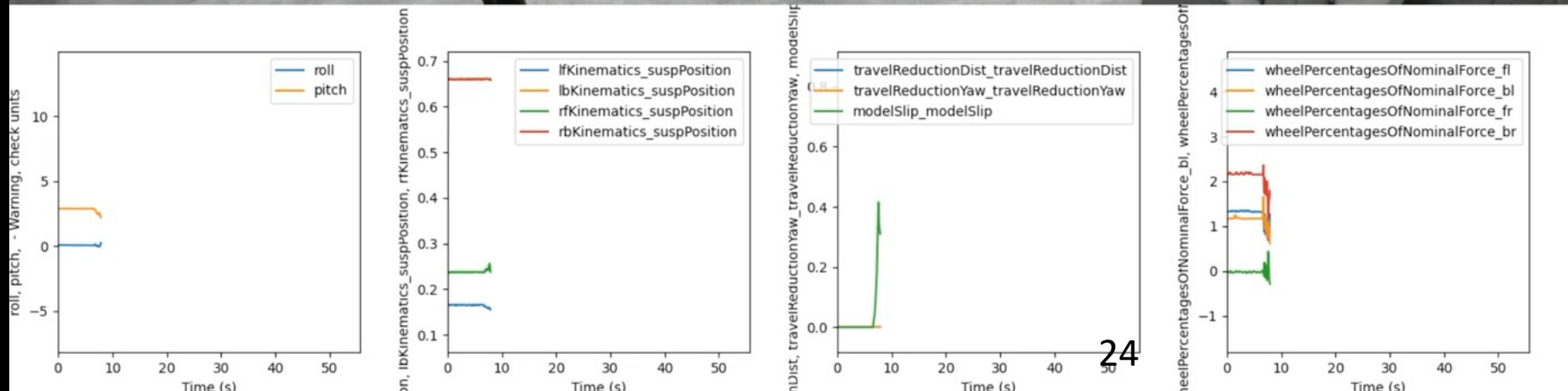




Slip Detection

- 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





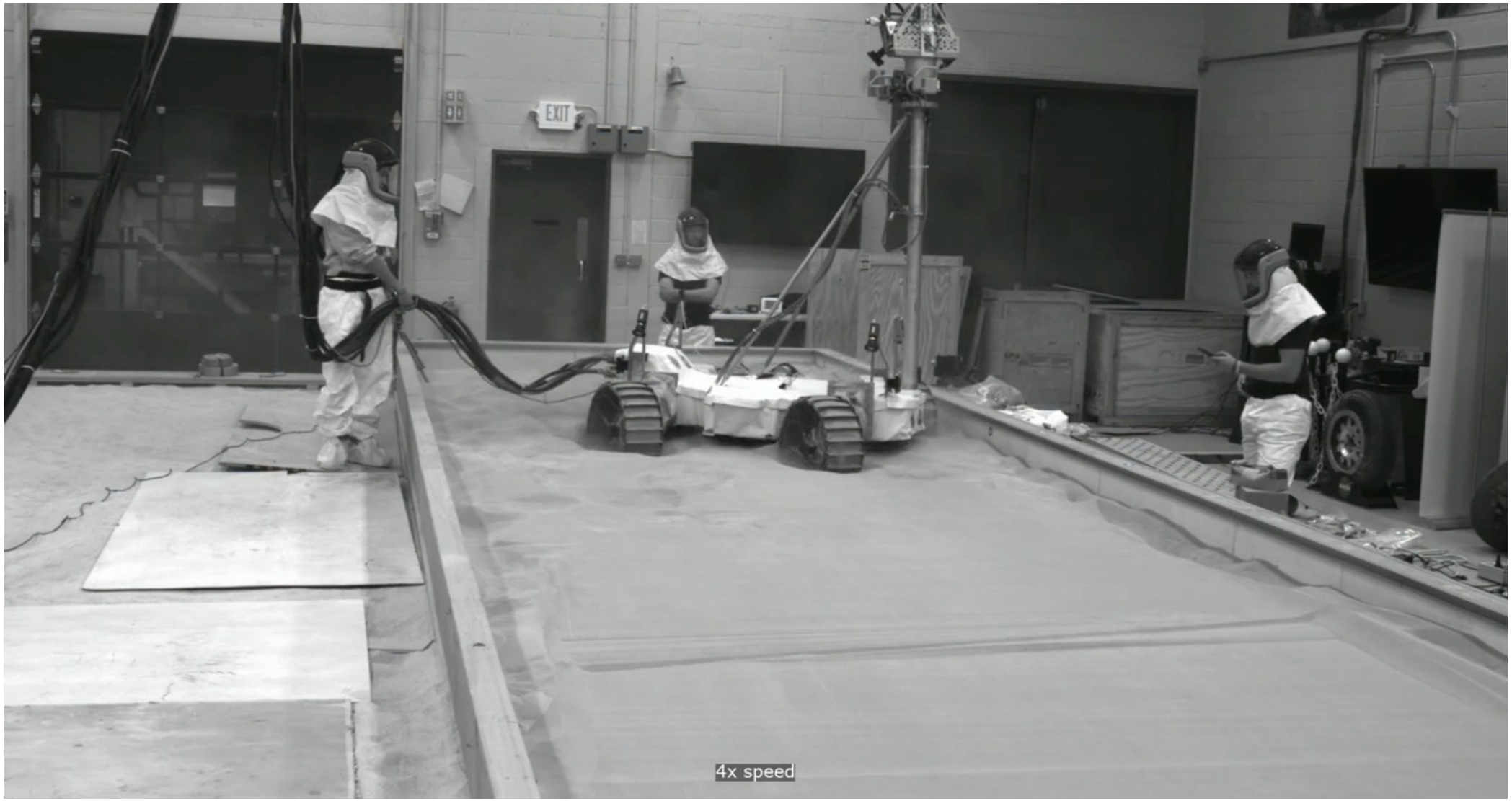
Entrapment Testing



Entrapment Testing

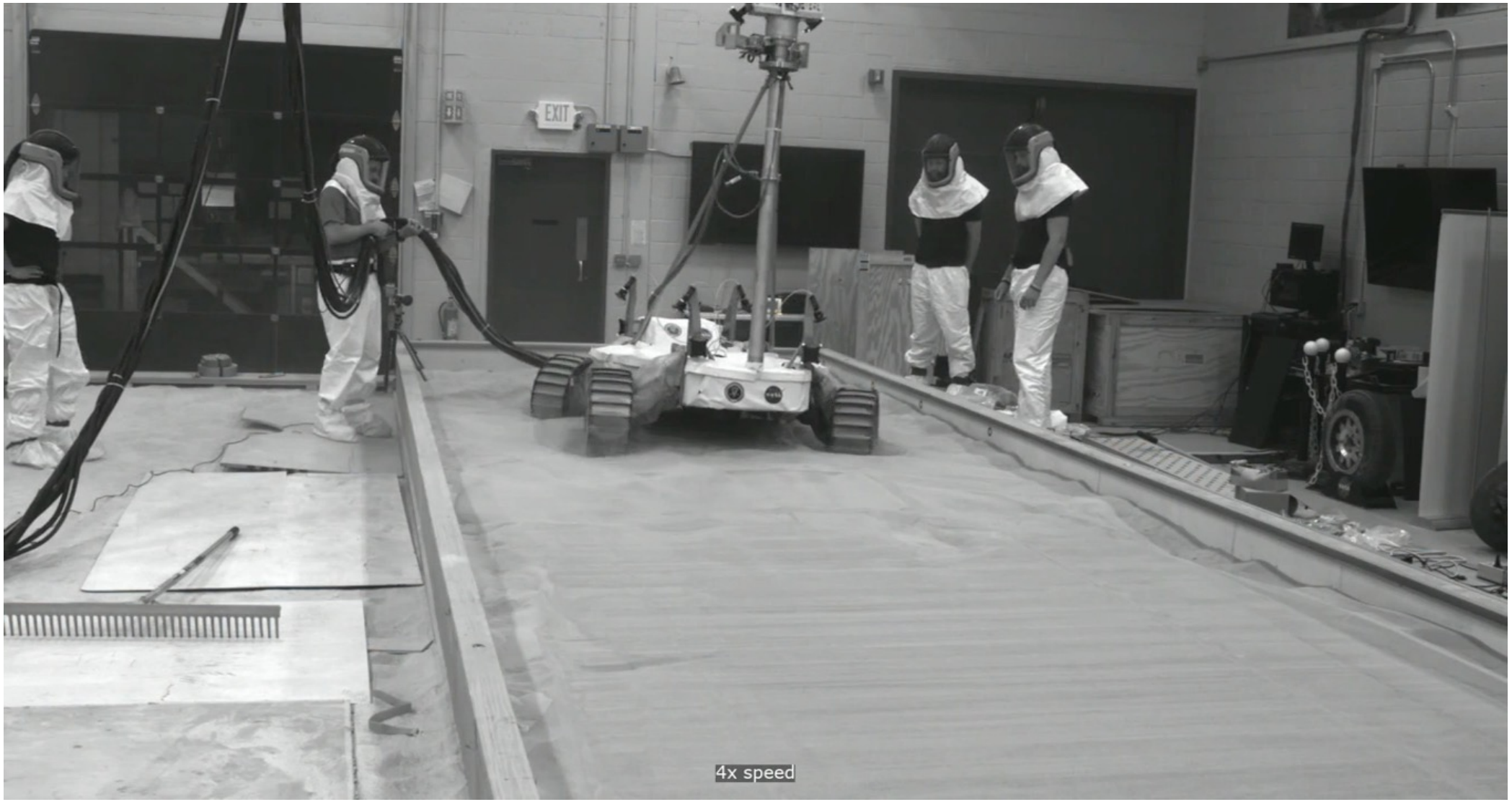


Alternate Mobility Modes



“Inchworm”

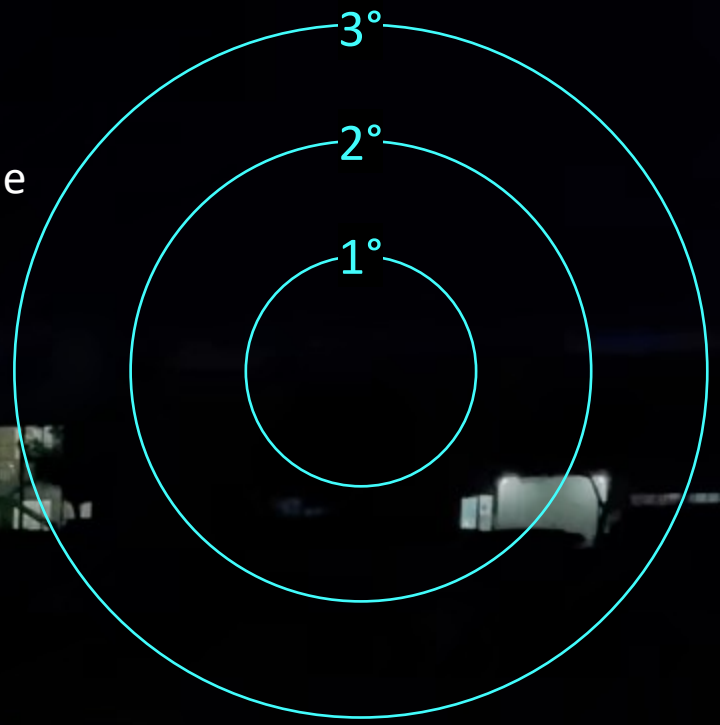
Alternate Mobility Modes



“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



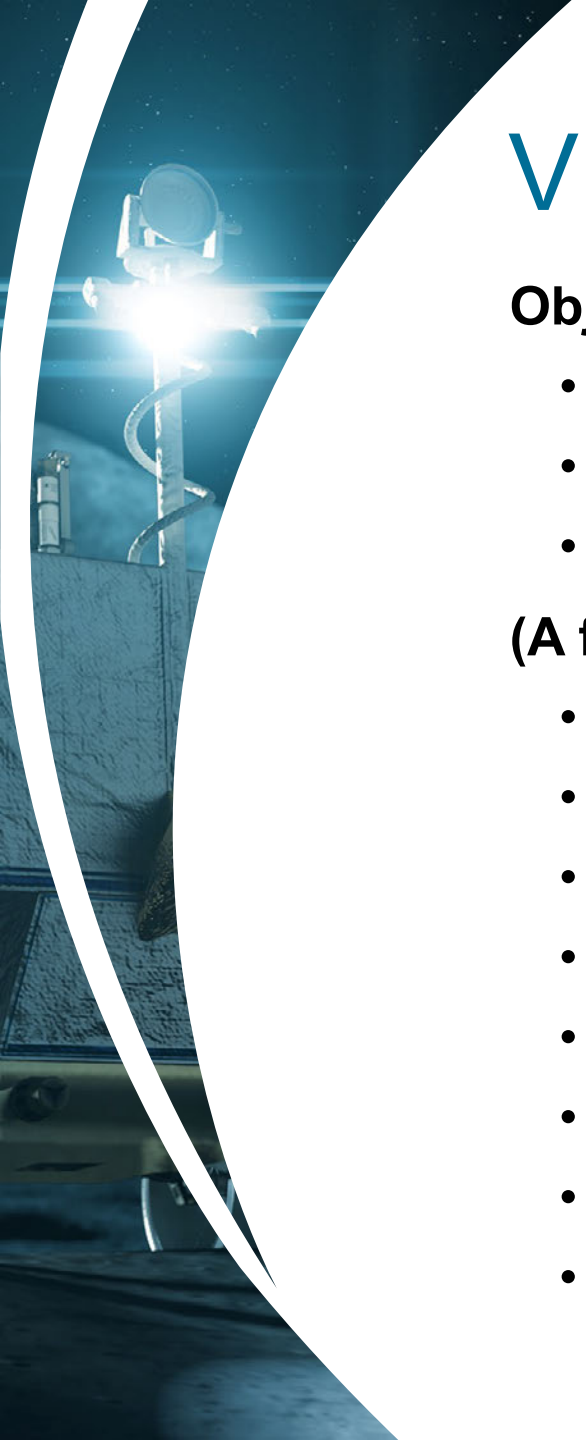


Sliding gantry over LHS-1 terrain

NASA Ames “Lunar Lab”



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



VIPER Mission Planning

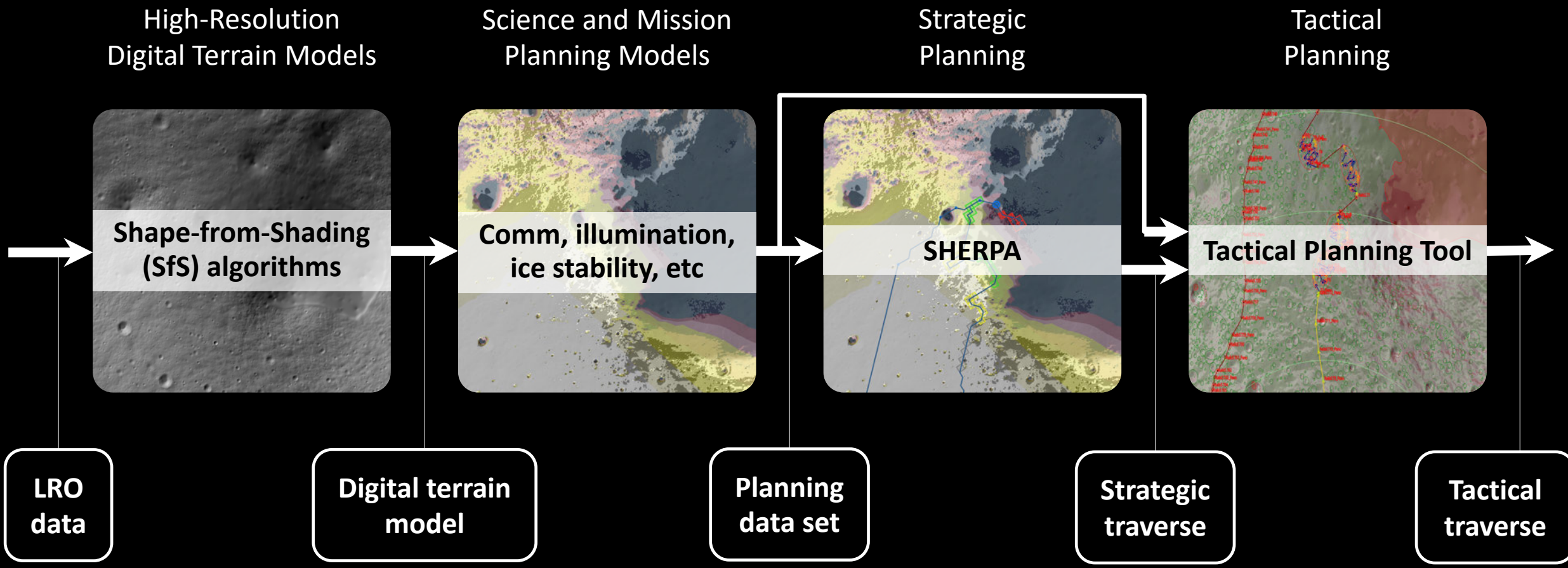
Objectives

- 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)

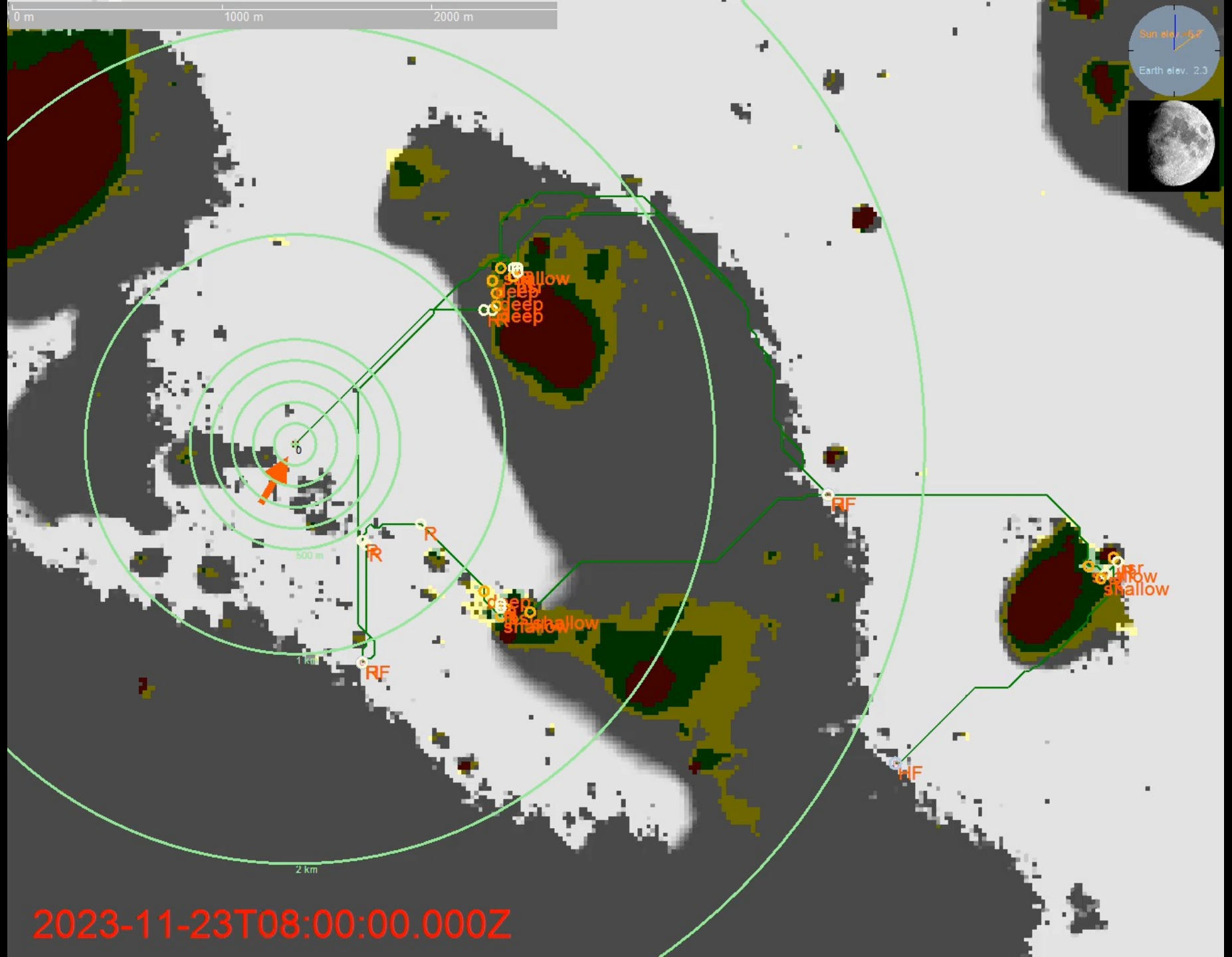
Planning Process



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

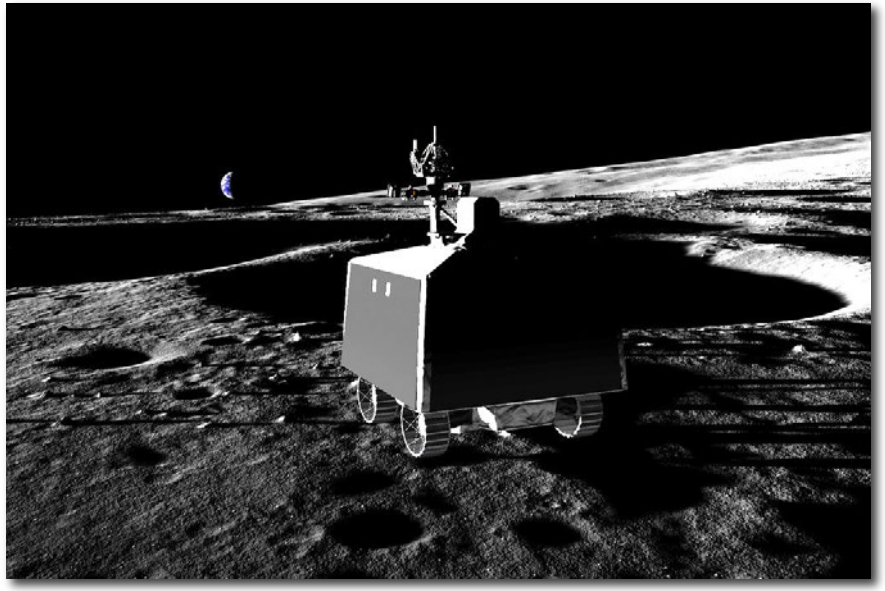
- Exposure, distortion, flare, fixed pattern noise, pixel defects, bit depth, read noise, etc.
- Tuned using NASA Ames “Lunar Lab” tests with camera/light EDUs

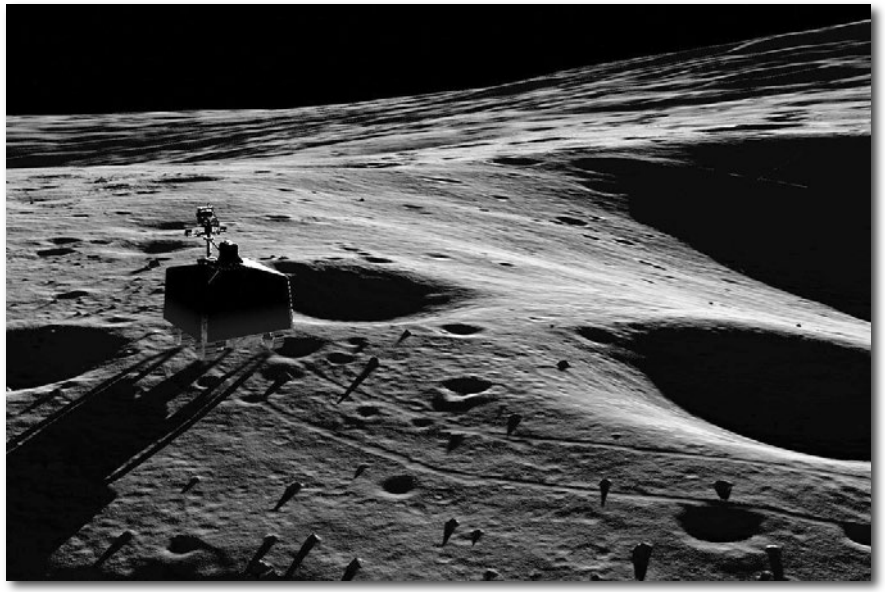
Real-time slip modeling

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

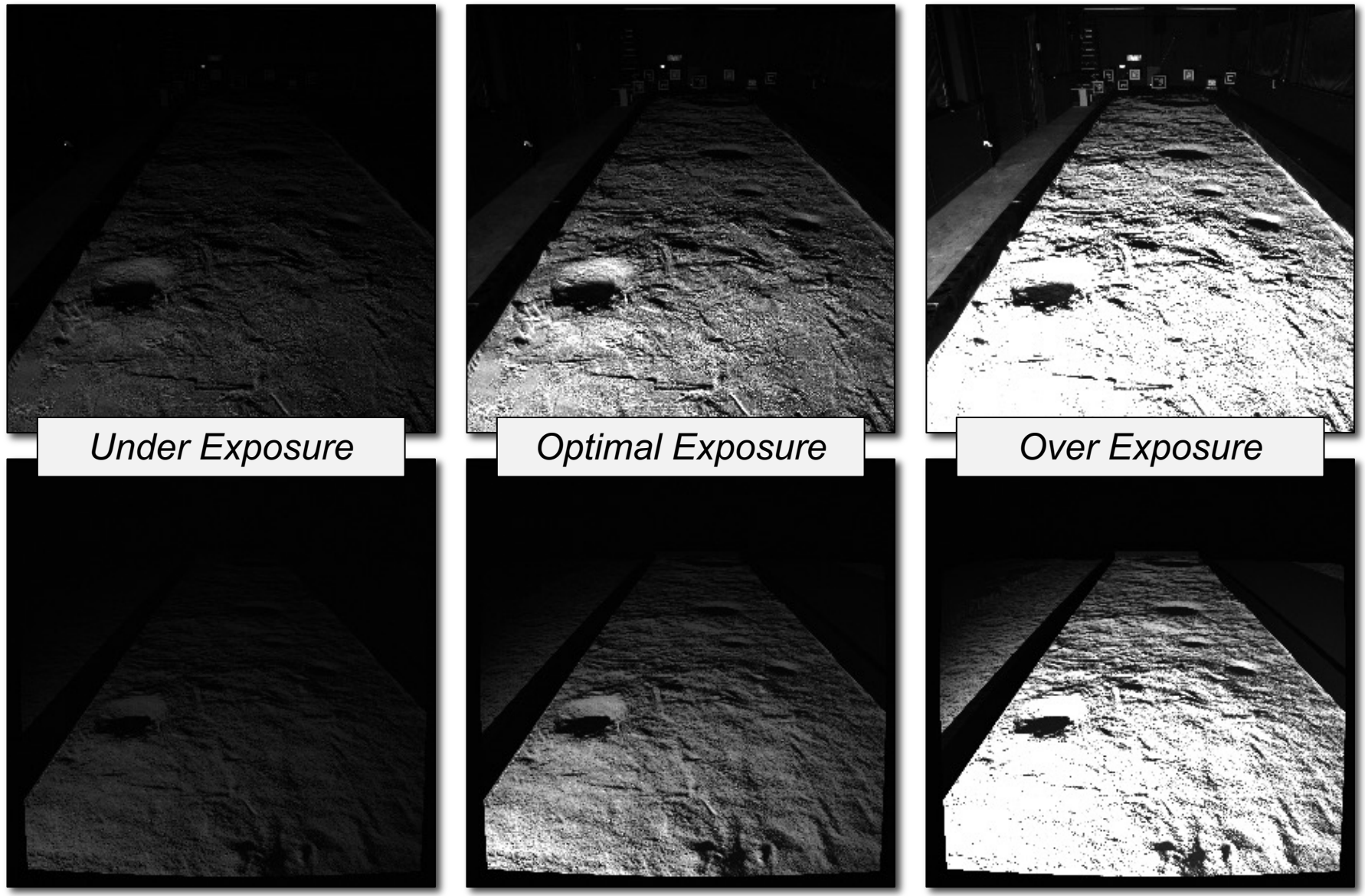
High-resolution lunar terrain models

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



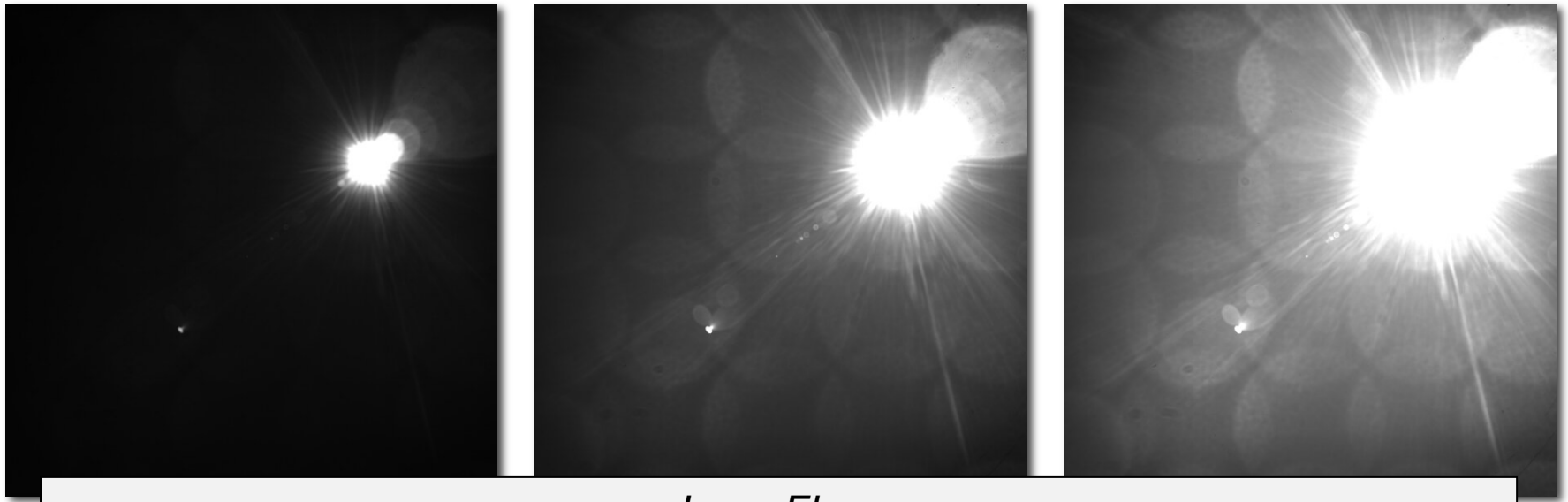


High-fidelity Camera Models



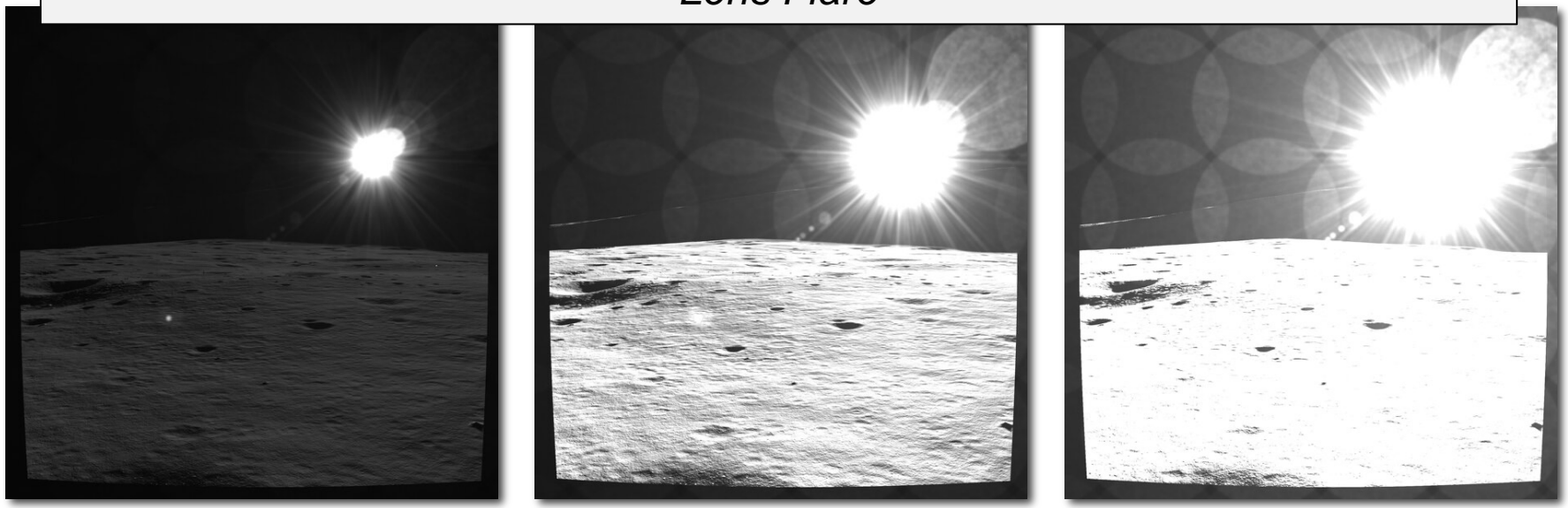
High-fidelity Camera Models

Lunar Lab

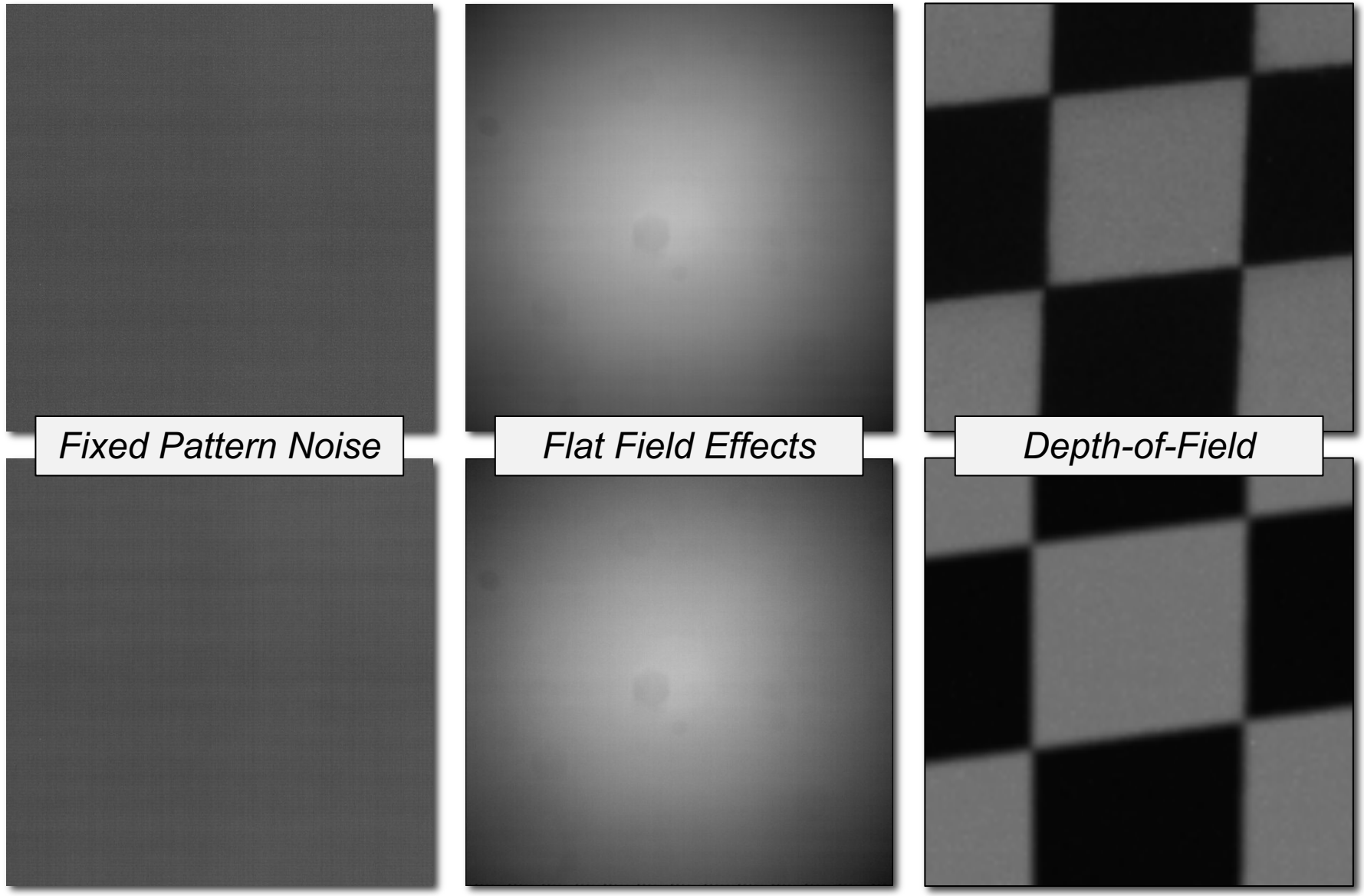


Lens Flare

RSIM



High-fidelity Camera Models



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**

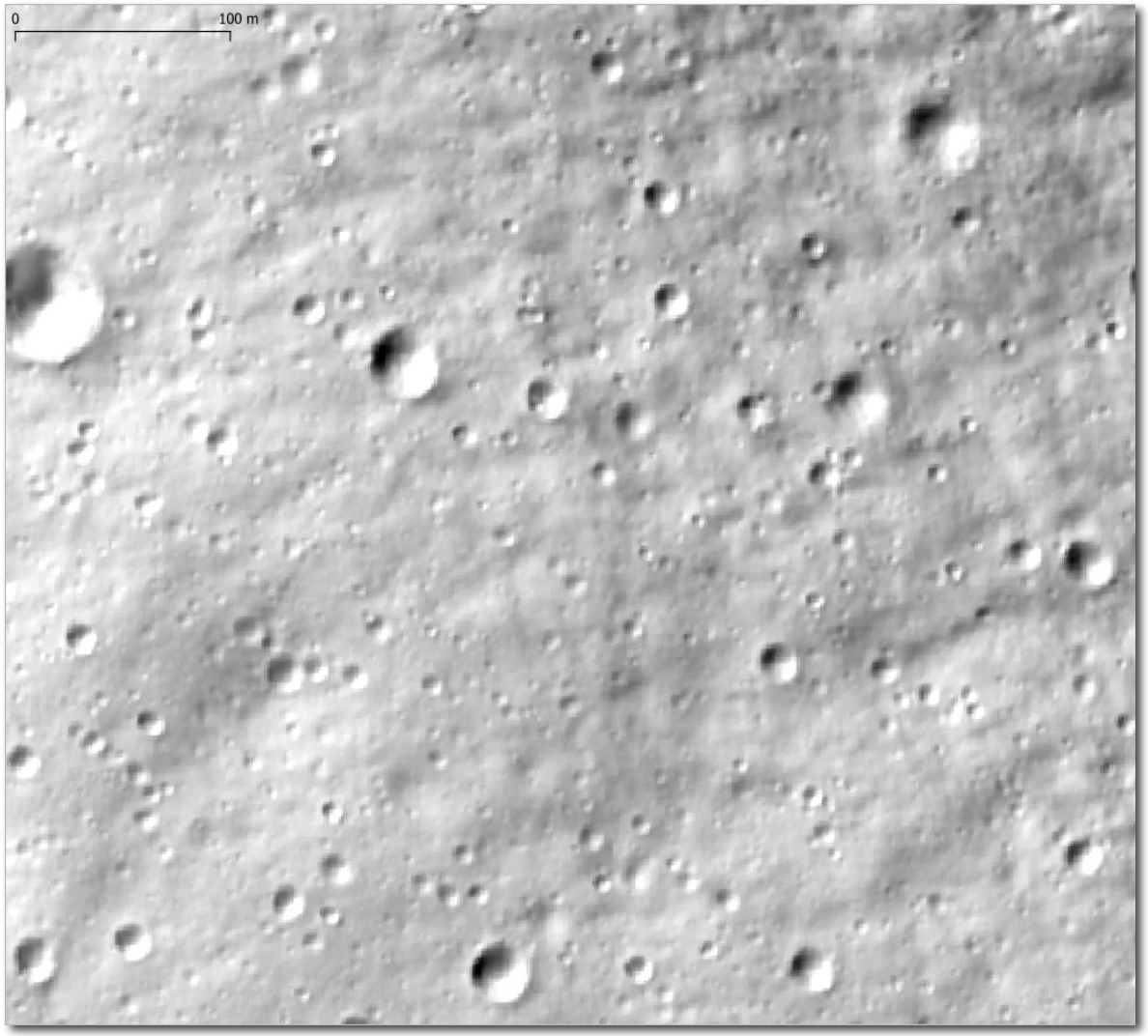


DEM based on LRO LOLA at 5 m/pixel

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

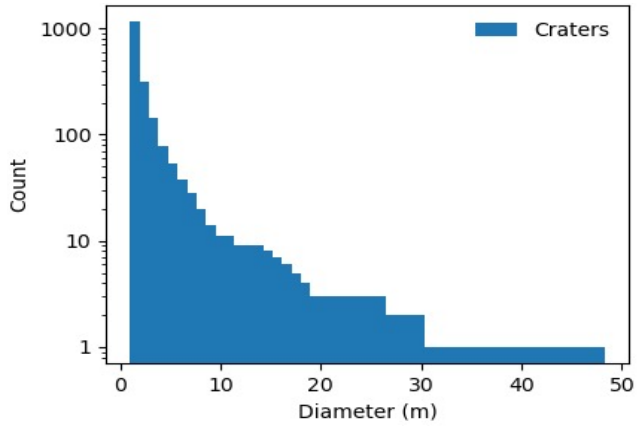
VIPER Synthetic Terrain Tools

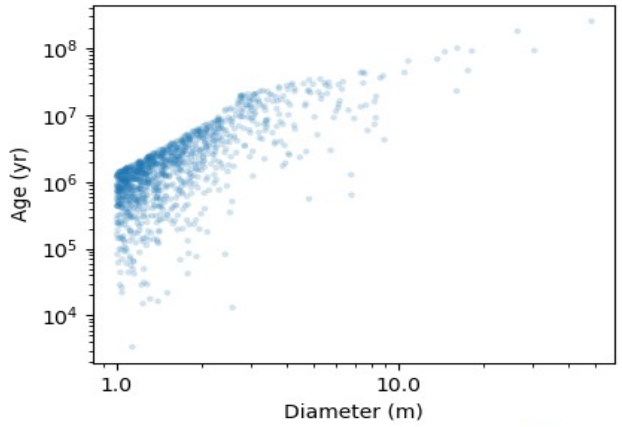
Objective

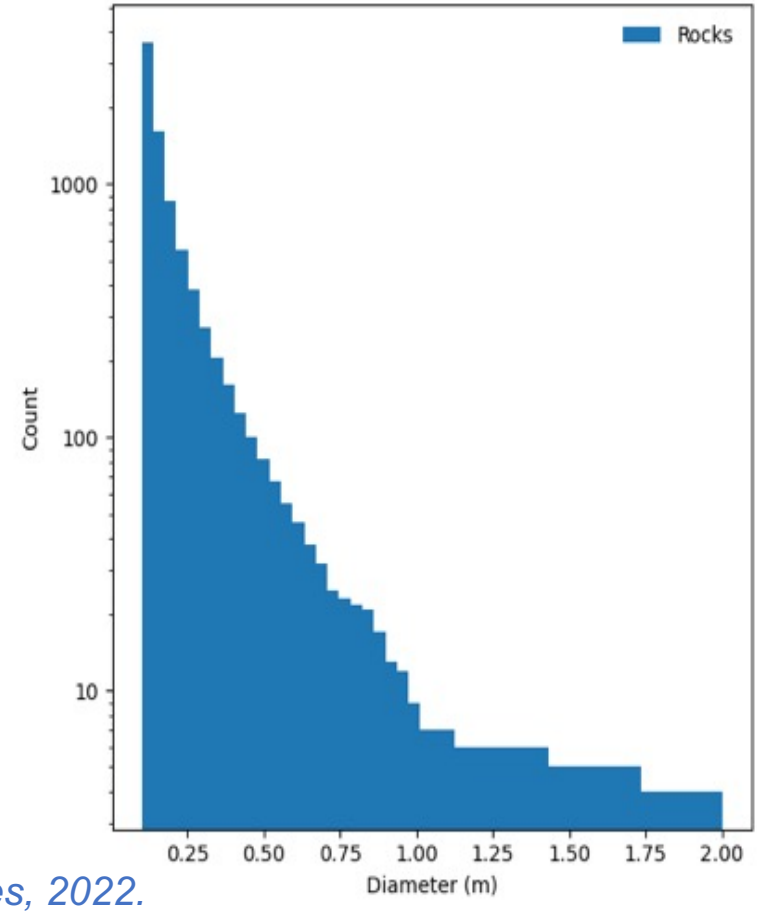
- Produce **scientifically plausible,** very high-resolution (**cm/pixel**) DEMs

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)

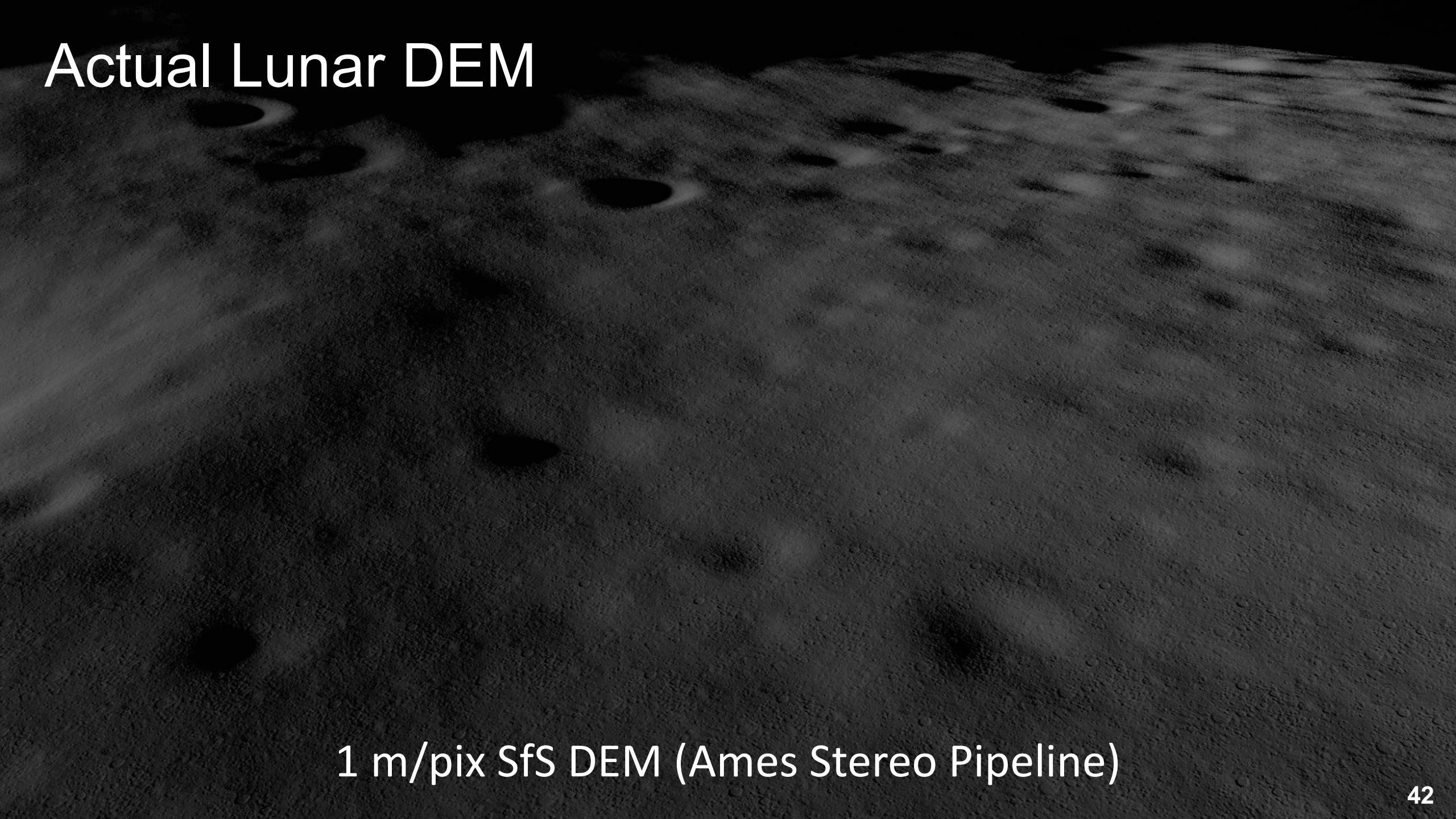






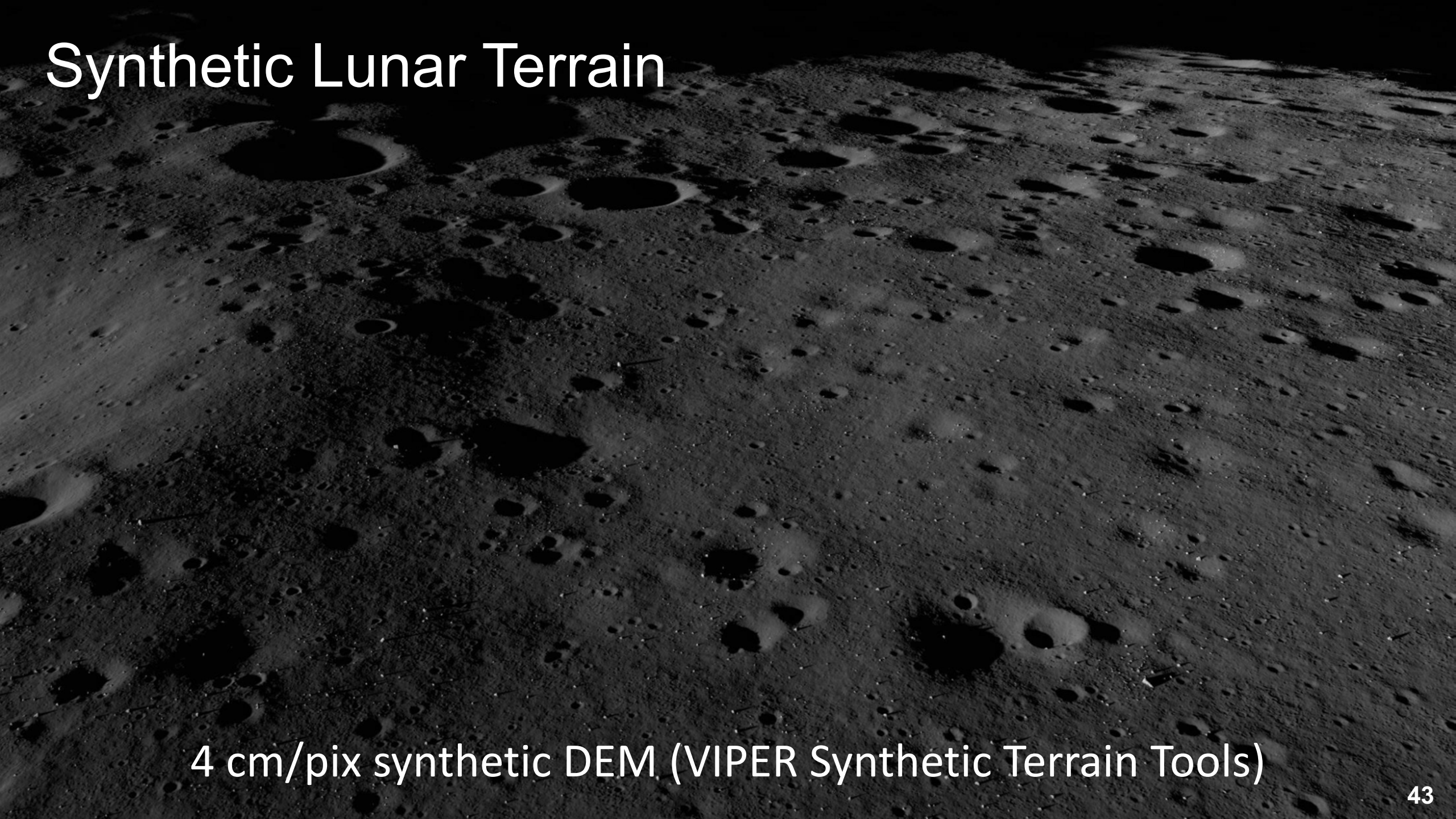
VIPER Environmental Specification, VIPER-MSE-SPEC-001, NASA Ames, 2022.

Actual Lunar DEM



1 m/pix SfS DEM (Ames Stereo Pipeline)

Synthetic Lunar Terrain

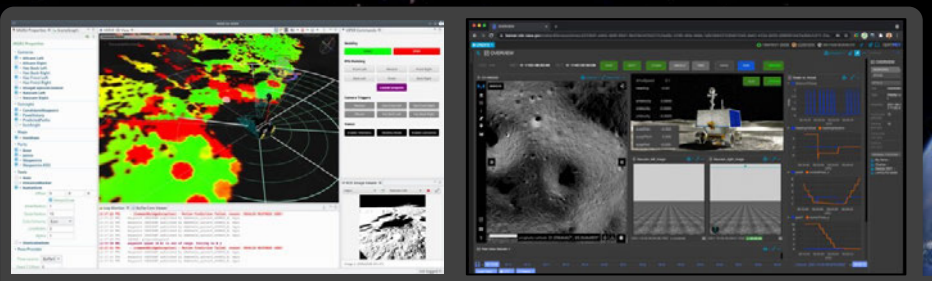


4 cm/pix synthetic DEM (VIPER Synthetic Terrain Tools)



Real-time lunar surface simulation (VIPER RSIM)

Mission Operations



Rover Driving

Mission Monitoring

KSC
MSOLO

JSC
Rover Systems & Thermal

ARC
Systems & Execution

Comms round trip ~6 - 10 sec

Lander

Science Station

Waypoints
~ 5 m

Traverse Points
~ 50 m

Drill A

Drill B

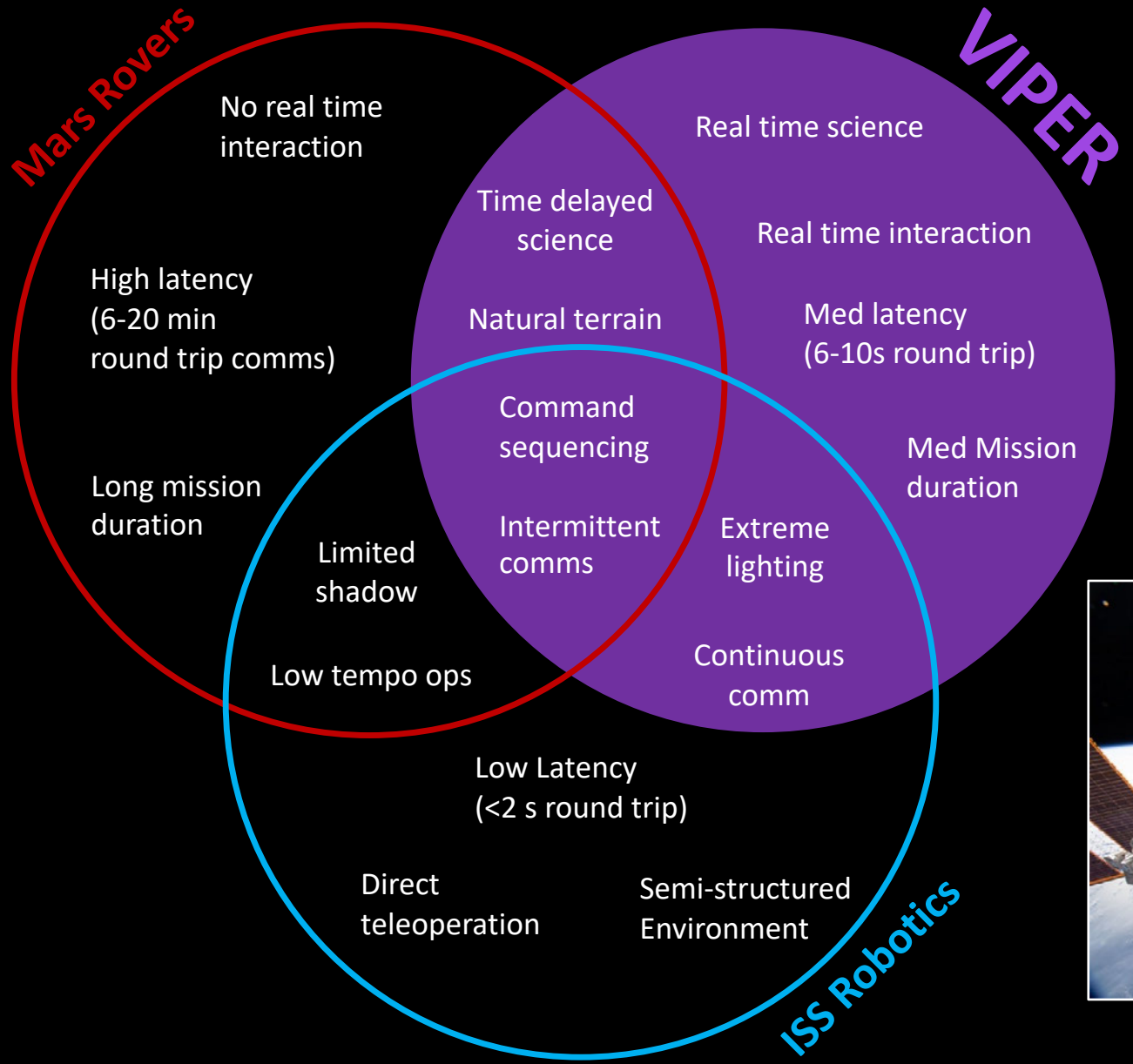
Drill C

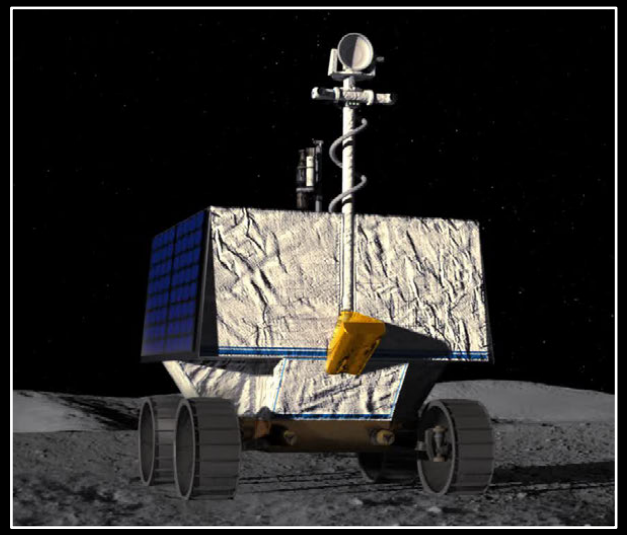
Science Station

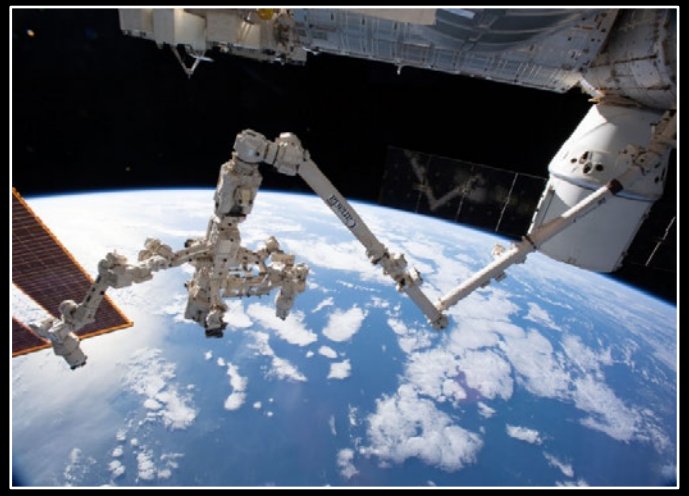
Mons Mouton (84.6°S, 31.0°W)
near Nobile Crater

VIPER vs ISS vs Mars Rovers





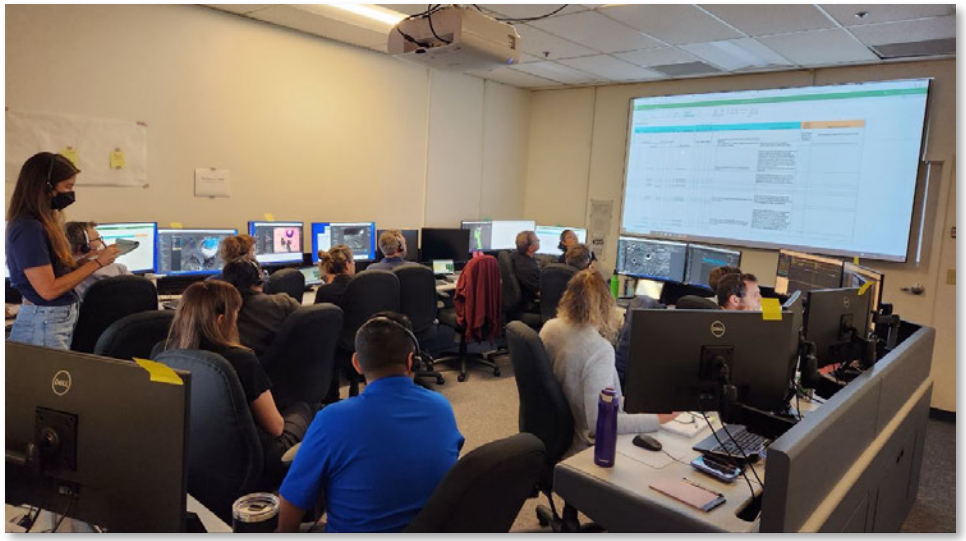




Real-Time Science Operations

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**



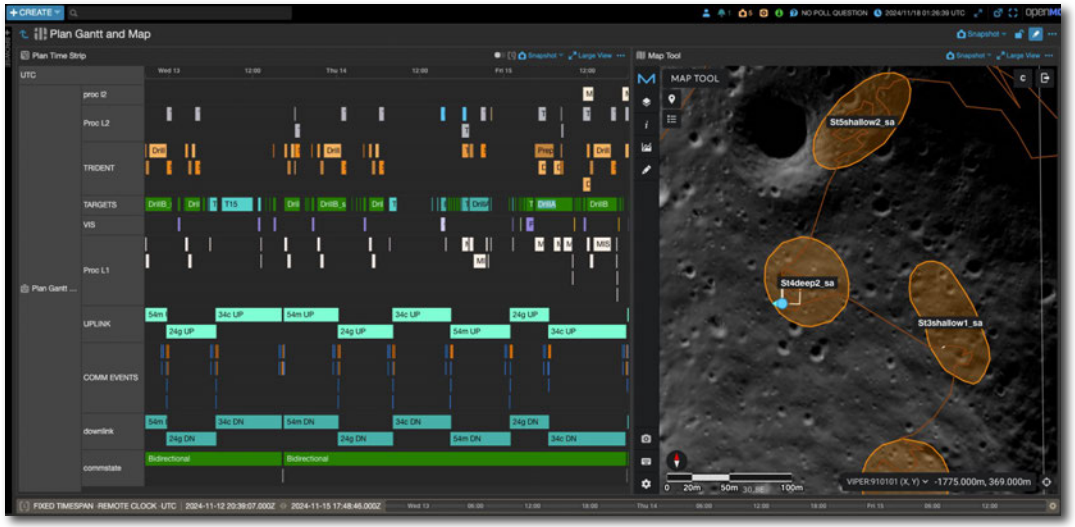


VIPER Mission Science Center (NASA Ames)

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

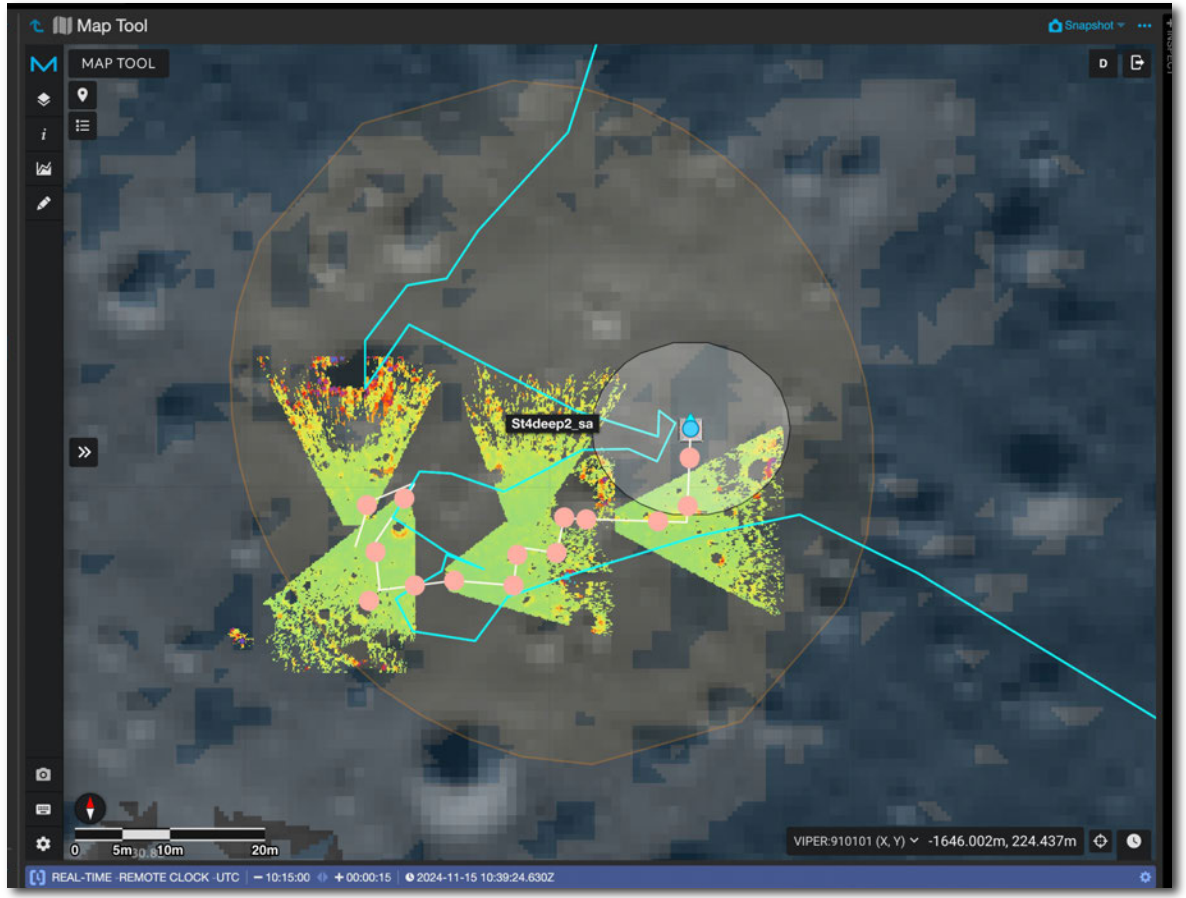


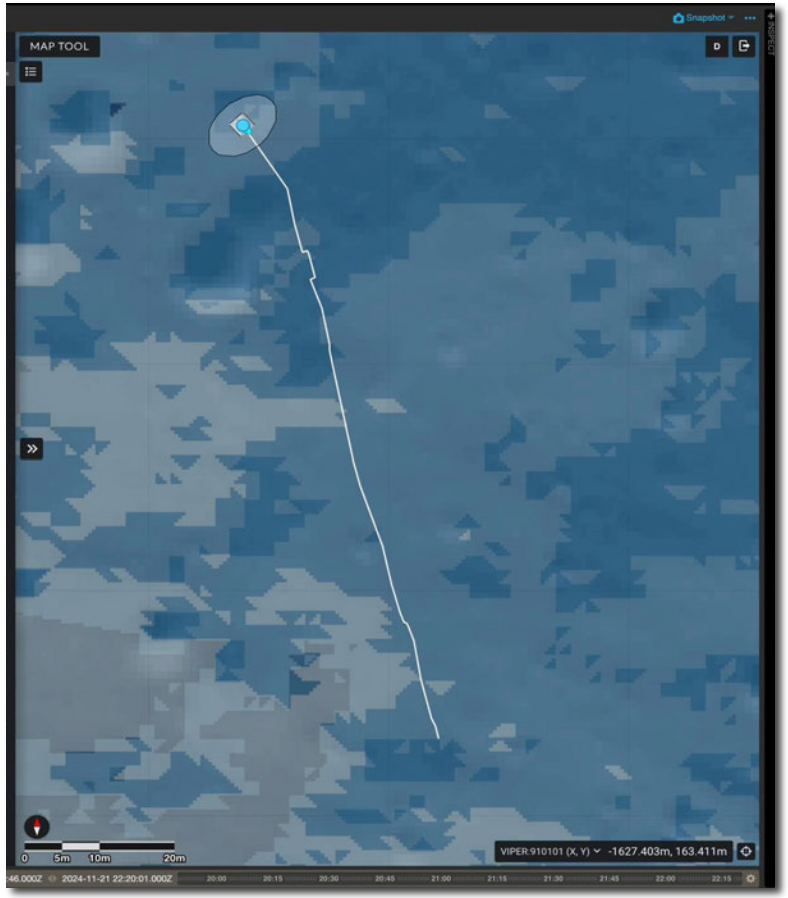


MMGIS

Map-based Geographic Information System tool

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



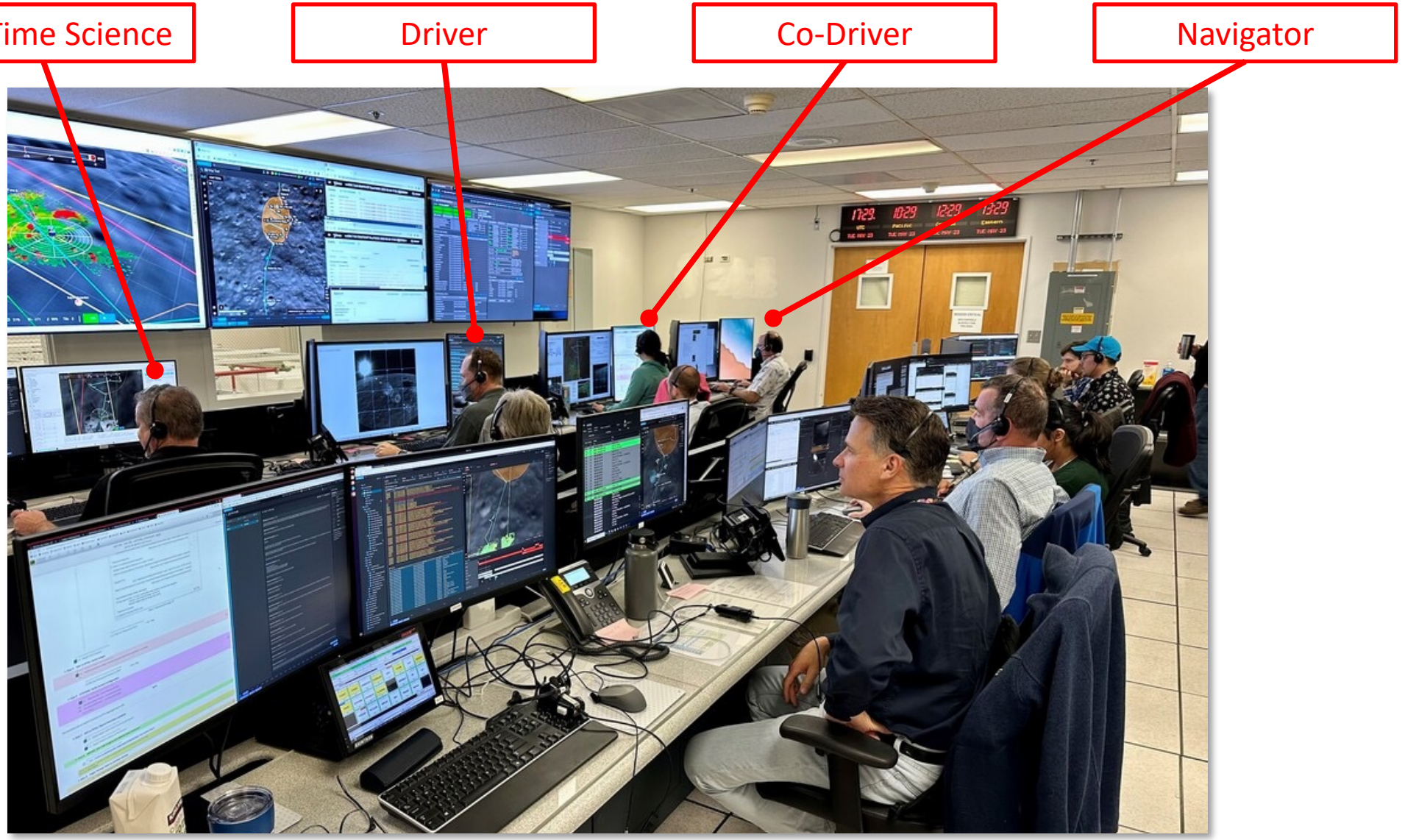


Rover Operations



VIPER Mission Operations Center (NASA Ames)

“Drive Team”





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

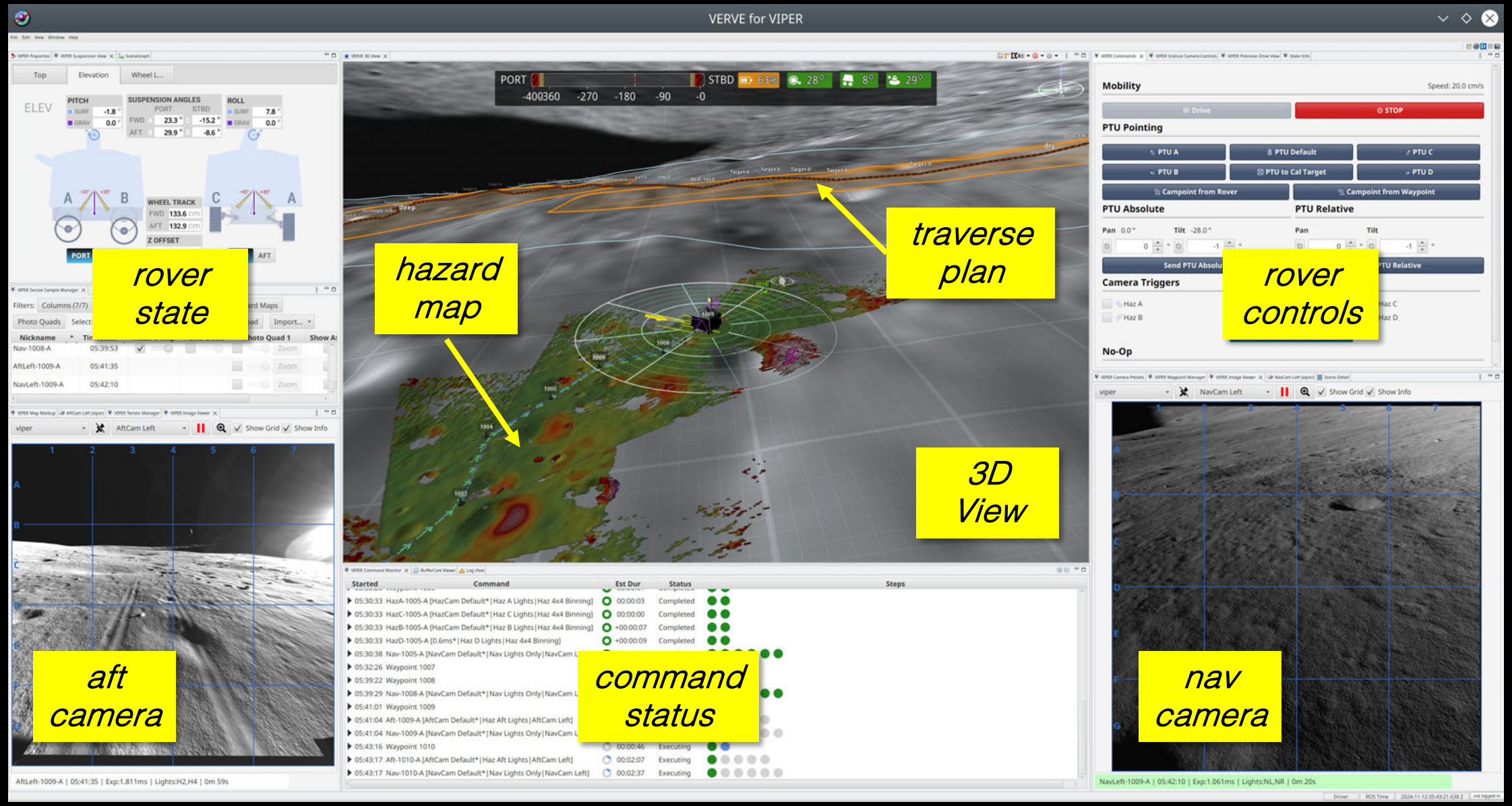
- Interactively command rover to drive to a waypoint 4-8m away
- Rover on-board control achieves the waypoint
- Employ a variety of tactical driving techniques to handle different surface conditions and environments (slopes, craters, shadows, etc)

Drive Team Command Cycle Tasks

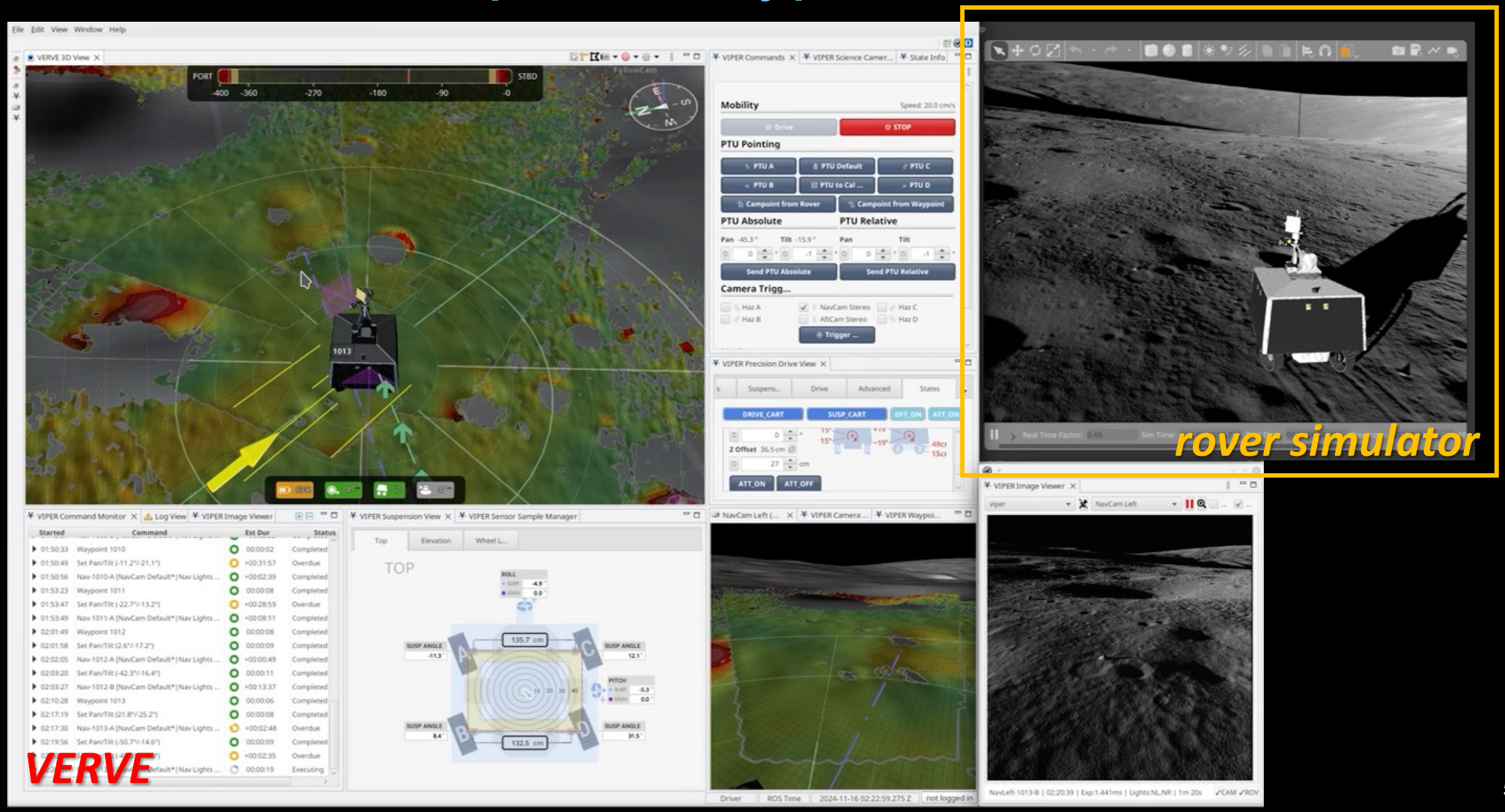
Task	Driver	Co-Driver	Navigator	Real-Time Sci
Assess rover state	Review mobility state Review mobility health Review current pose	*Shadow driver (when possible)*	Review nav sensor state Review nav sensor health Review localization quality	
Assess terrain hazards	Assess geometric hazards Assess non-geometric hazards (near/mid-field)	*Shadow driver (when possible)*	Assess data 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 movement (posture or pose change, drive mode, etc)	Sanity check (concur)		
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	*Call halt if needed*	*Call halt if needed*	*Call halt if needed*
Command navigation imaging	Confirm imaging is authorized Countdown to command Execute command	*Call halt if needed*	*Call halt if needed*	*Call halt if needed*

5 min duration

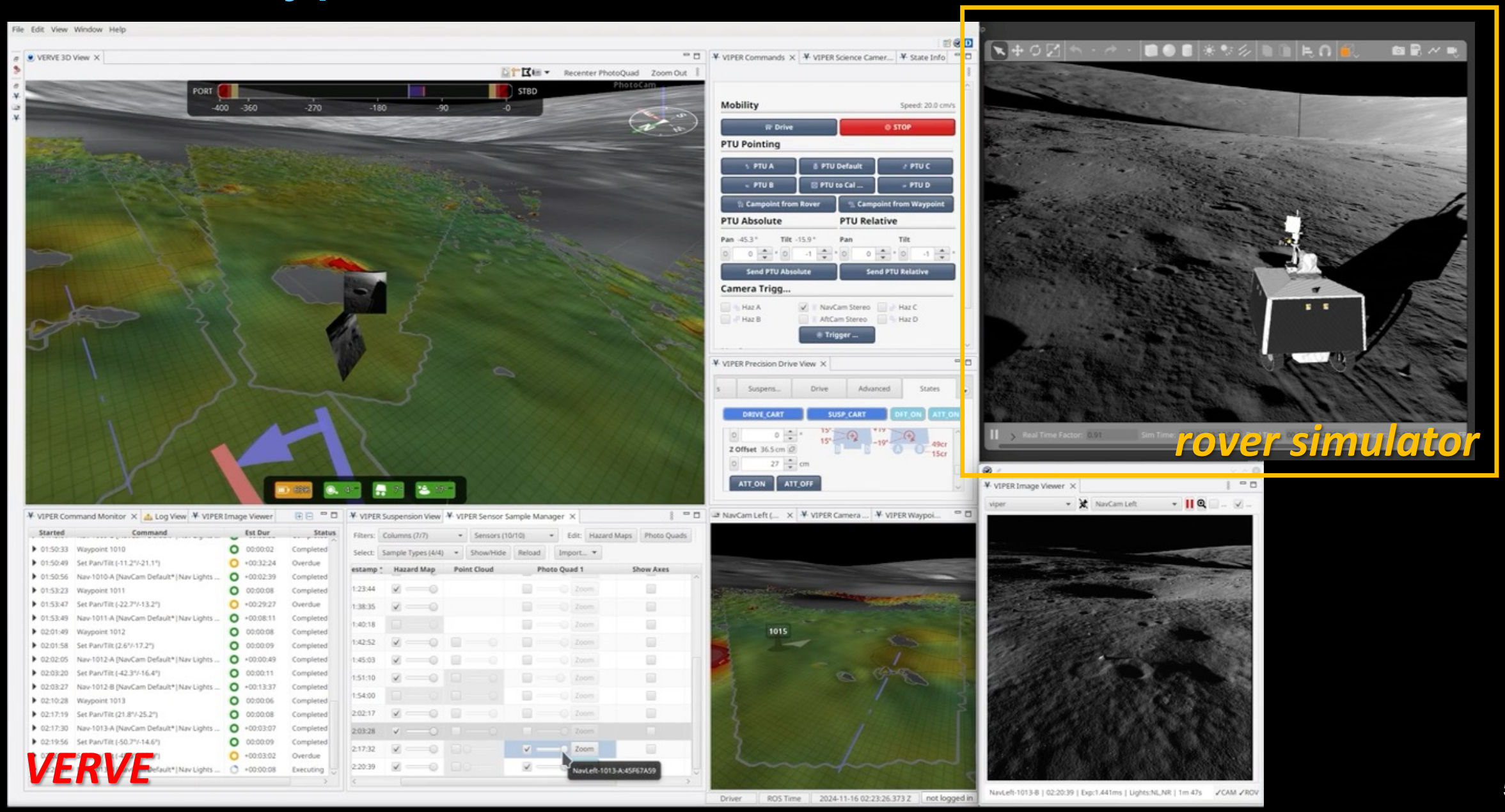
Rover Driving Interface (VERVE)

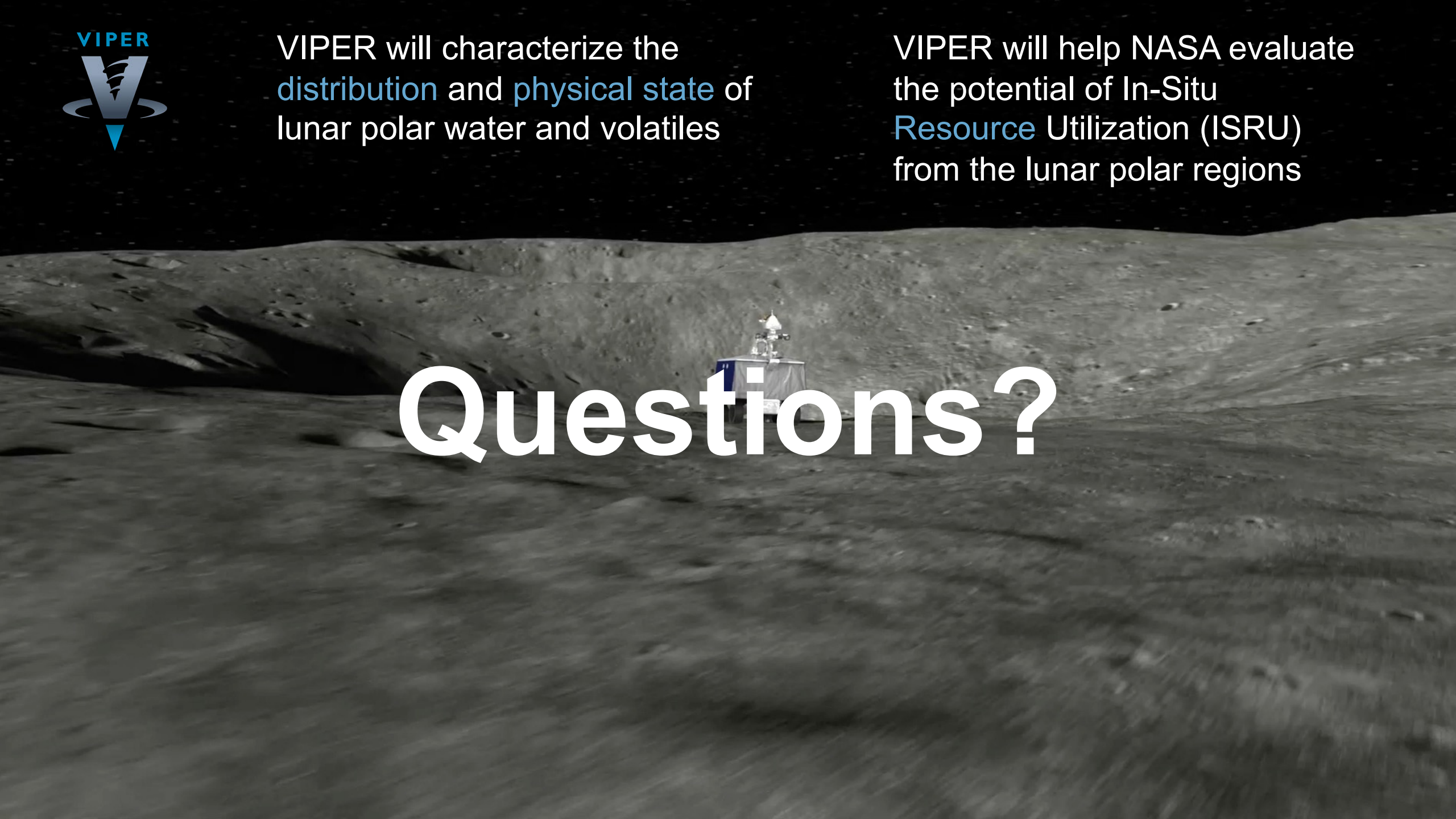


Assess terrain + place waypoint



Refine waypoint + command motion




VIPER
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
Questions?