

National Aeronautics and Space Administration

NASA

VIPER

Volatiles Investigating Polar Exploration Rover

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

8 April 2024

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)**



Toward Understanding Lunar Water

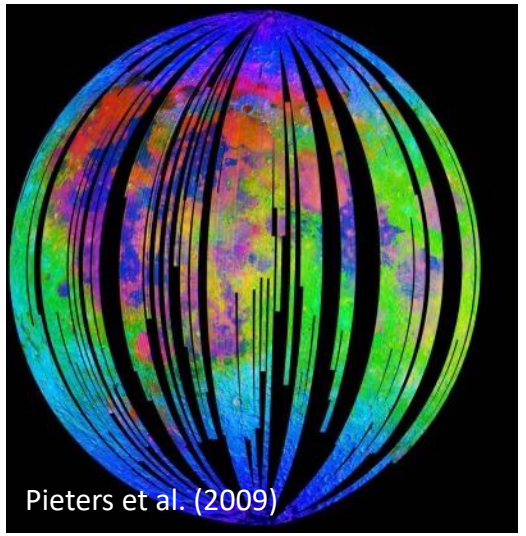
Moon now known to host all three forms of Solar System water *: (1) internal – primordial / endogenic, (2) external sequestered – delivery by asteroids/comets, and (3) in-situ – surficial "frosts" due to solar wind plasma

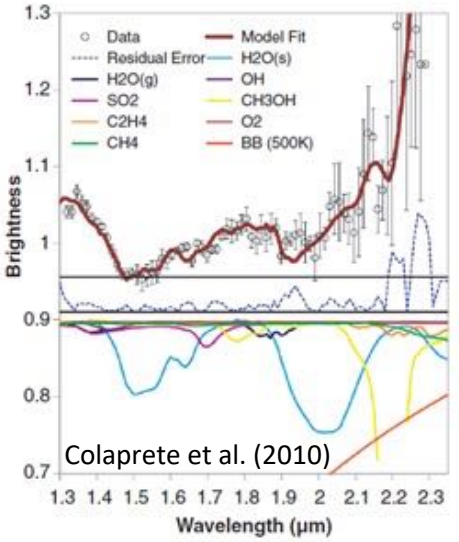
BUT: *Do not yet understand the concentration, evolution and interrelated dynamics of these varied sources of water*

Understanding the distribution, both laterally and with depth, addresses key exploration and science questions

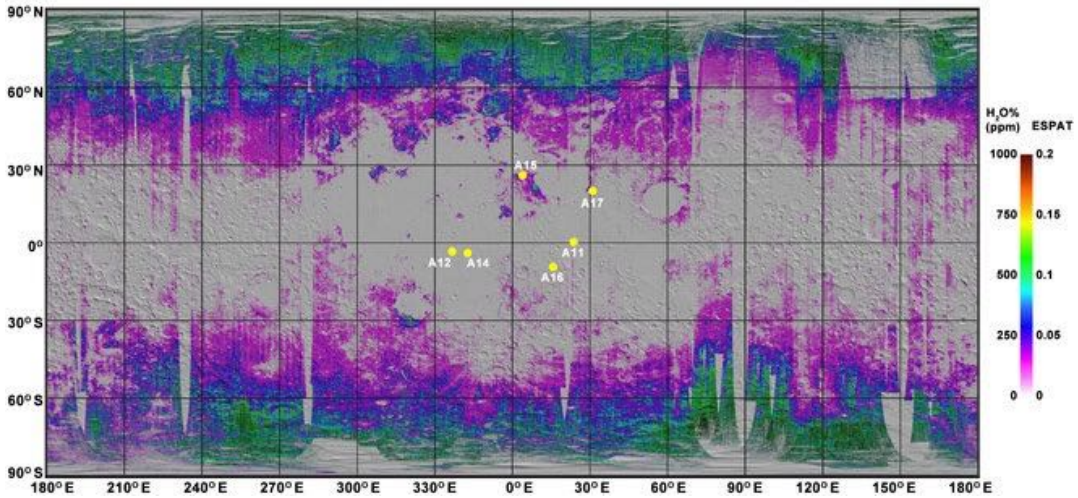
BUT: *Surface measurements are necessary to characterize the spatial distribution and state of the water*

"Prospecting" for lunar water at poles is the next step in understanding the resource potential and addressing key theories about water emplacement and retention


Pieters et al. (2009)



Colaprete et al. (2010)



Li and Milliken (2017)

*Pieters, Canup, et al. (2018), Transformative Lunar Science



VIPER Mission

Lunar south pole

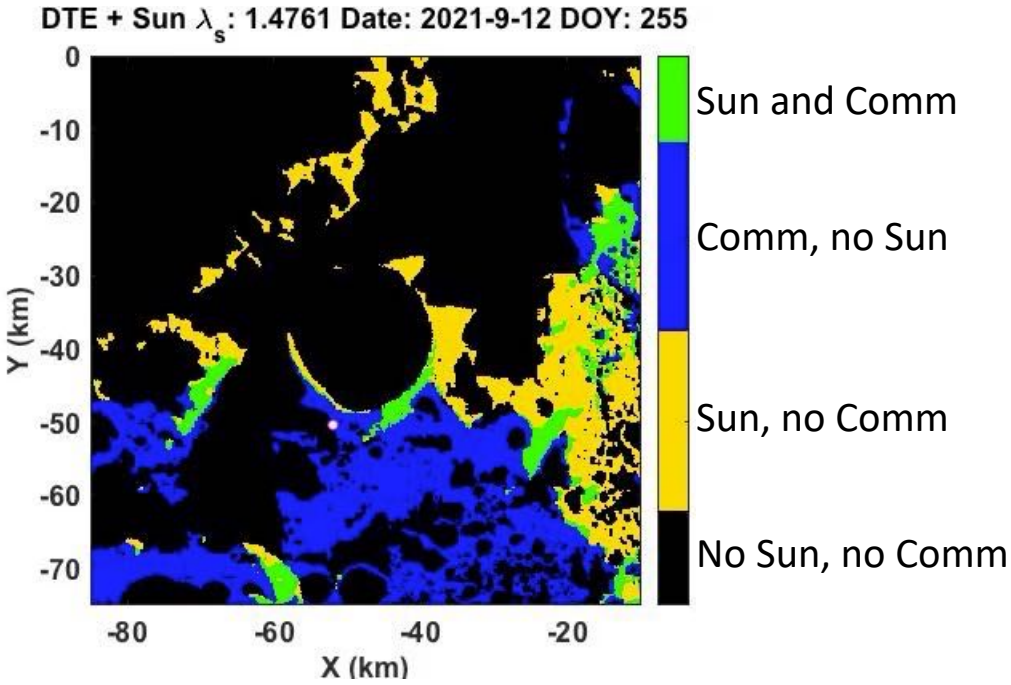
- Commercial launch and landing
- 100+ day mission (including extended survival periods)
- Up to 20 km total drive

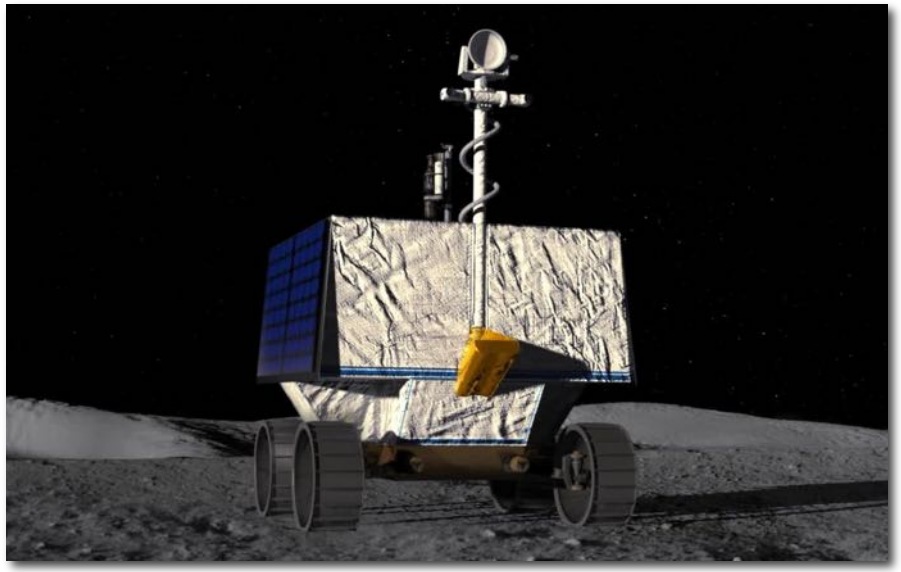
Science objectives

- Characterize distribution and physical state of volatiles (water ice, etc)
- Provide data to evaluate the potential for lunar in-situ resource utilization

A few unique challenges (among many…)

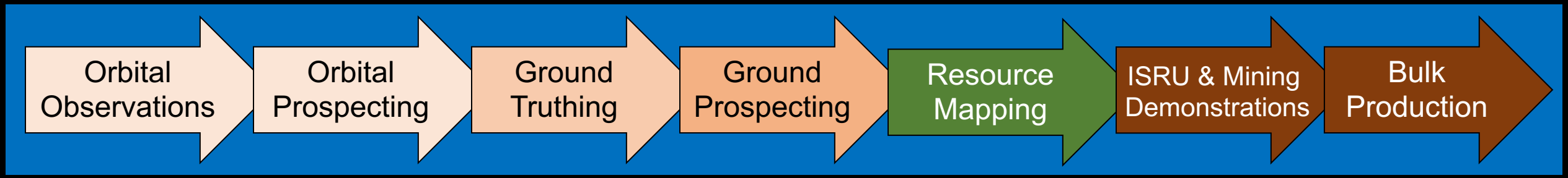
- Dynamic environment: light + shadows
- Real-time mission ops and science
- Prospecting & “speed made good”





The Big Picture of Lunar Resources

US Lunar Goals:



Missions:

Clementine

Lunar Prospector

LCROSS

LRO

Chandrayaan-I

VIPER

(future science missions)

Industry

Industry

VIPER bridges Government and Industry missions – informing and reducing risk for future utilization of in-situ volatiles

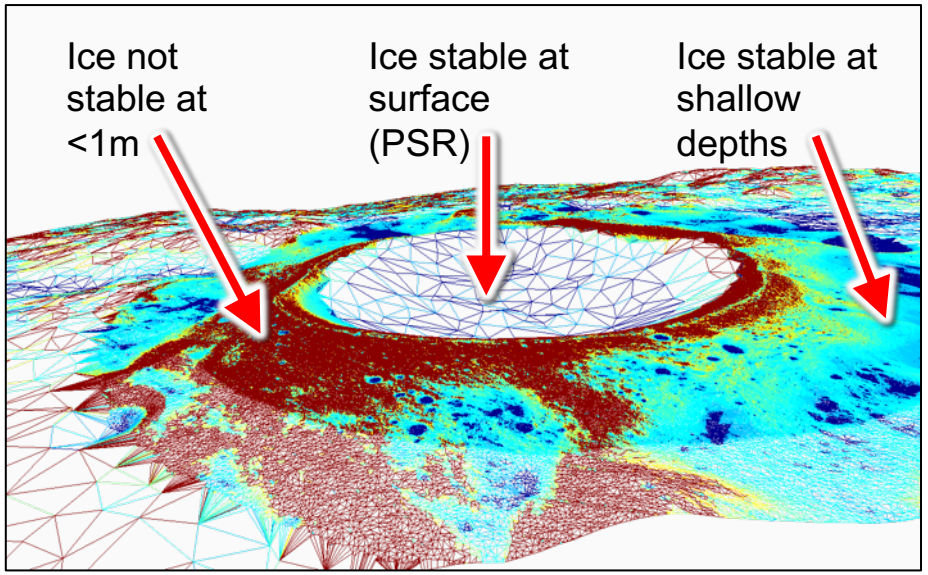
Where is water (ice) at the lunar poles?

Environmental factors

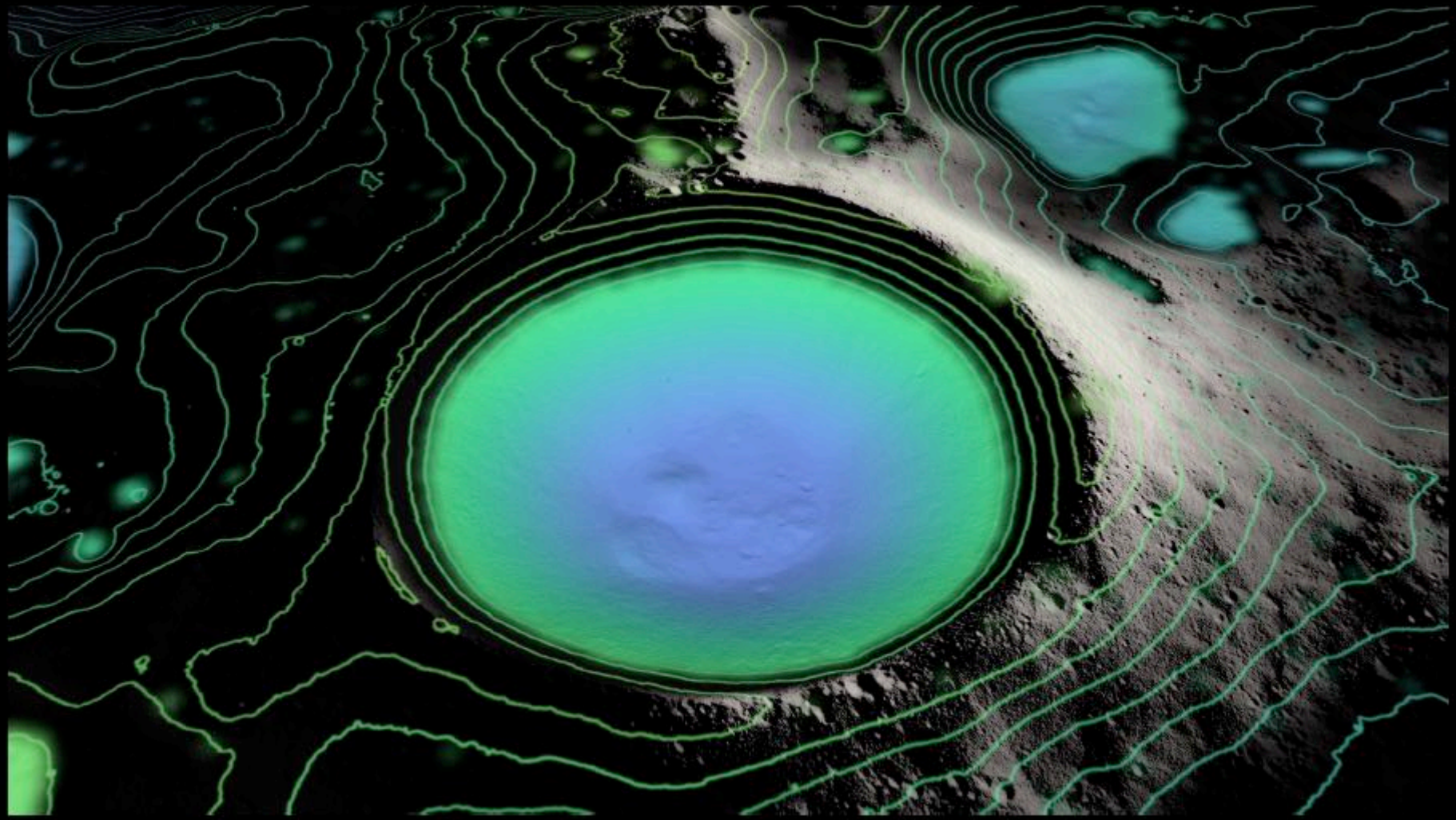
- Temperatures (surface or subsurface) must be low enough to retain water ice
- Geophysical properties (topography, materials, depth, etc.)

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 (e.g., within a Permanently Shadowed Region or “PSR”)



Permanently Shadowed Regions on the Moon



- Low obliquity.
- At high latitudes, topography creates permanently shadowed regions.
- >10^4 km^2 area of PSR.
- These exist on size scales ranging from sub-mm to 10 km.

NASA SVS

https://svs.gsfc.nasa.gov/4043

VIPER Rover



Flight Rover Assembly

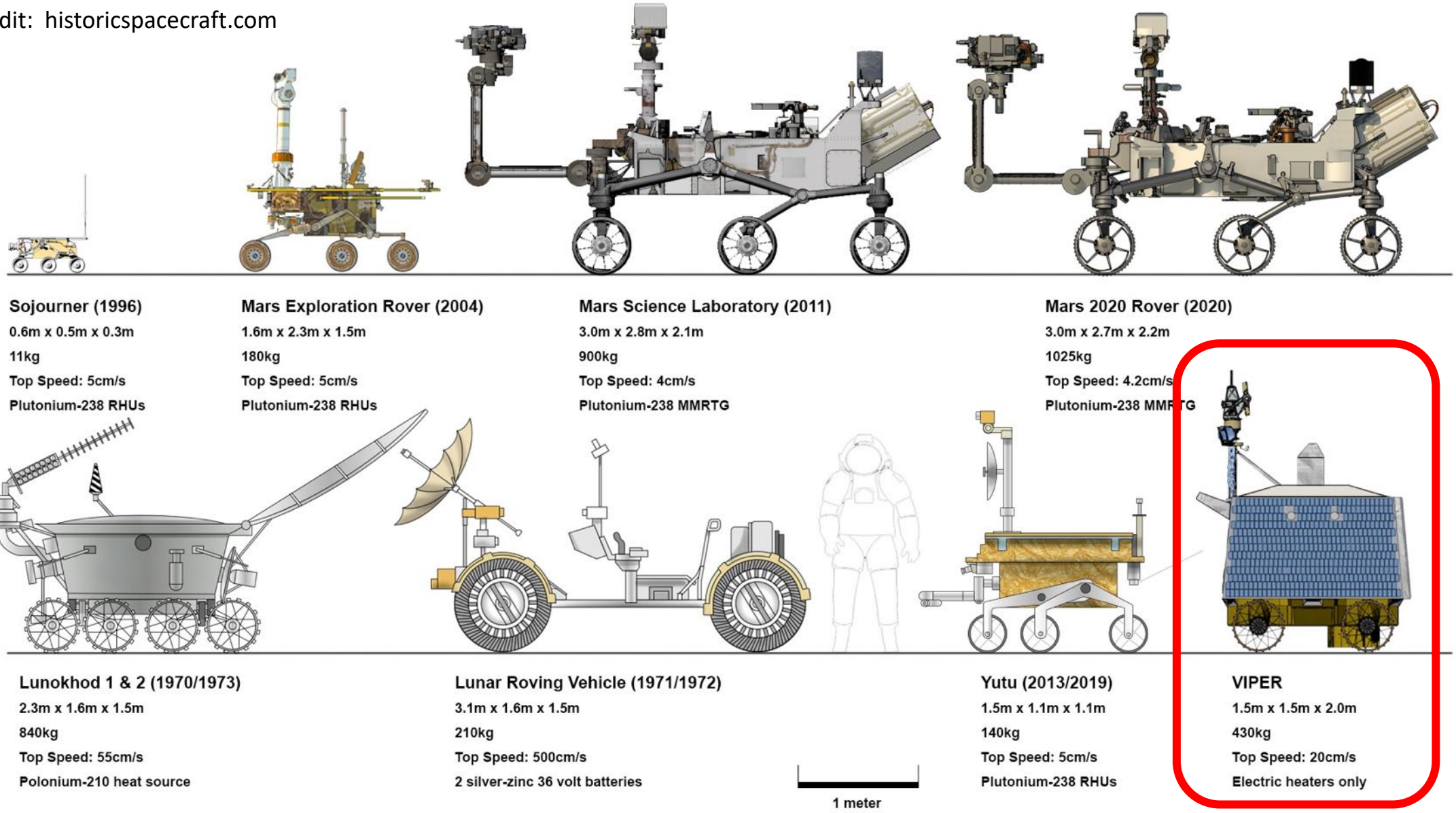




90%
complete
(8 April 2024)

Rover Comparison

Credit: historicspacecraft.com





A new type of planetary rover

First NASA lunar rover

- Designed for the “dynamic” lunar environment
- Emphasis on high operational cadence and traverse speed
- Significantly lower cost than Mars rovers (but higher risk)

Interactive operations

- “Real-time” mission control: rover operations + science team
- Single waypoint driving (approx. 4 m / command cycle)
- Hybrid of human exploration (Shuttle, Space Station) and Mars rover mission operations

Hybrid avionics and software

- BAE RAD 750 v3 (rad-hard, 198 MHz PPC, similar to 1997 PowerMac G3) + SP0 (rad-tolerant, 1 GHz PPC, similar to 2010 iPhone 4) computing
- Flight software is split between on-board and ground
- Ground software uses Robot Operating System 2 (ROS2)

Mobility Architecture

Independent Wheel Modules (4x)

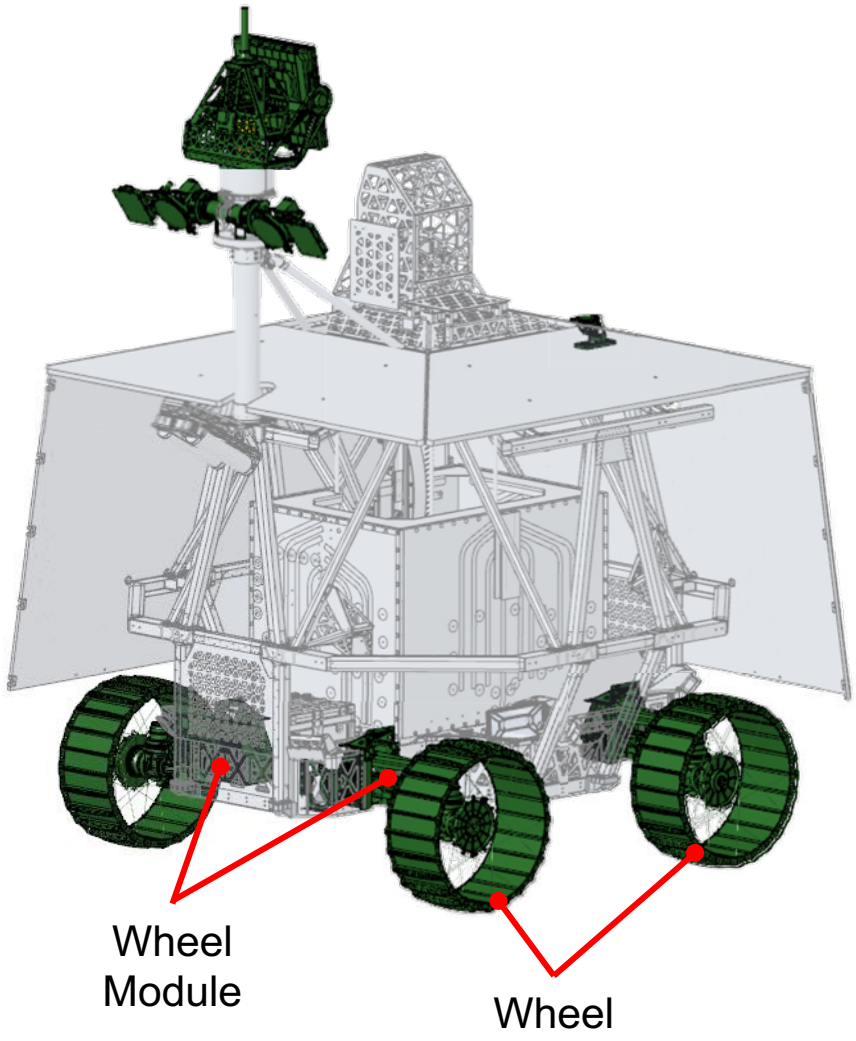
- Suspension
- Steering
- Propulsion

Wheels (4x)

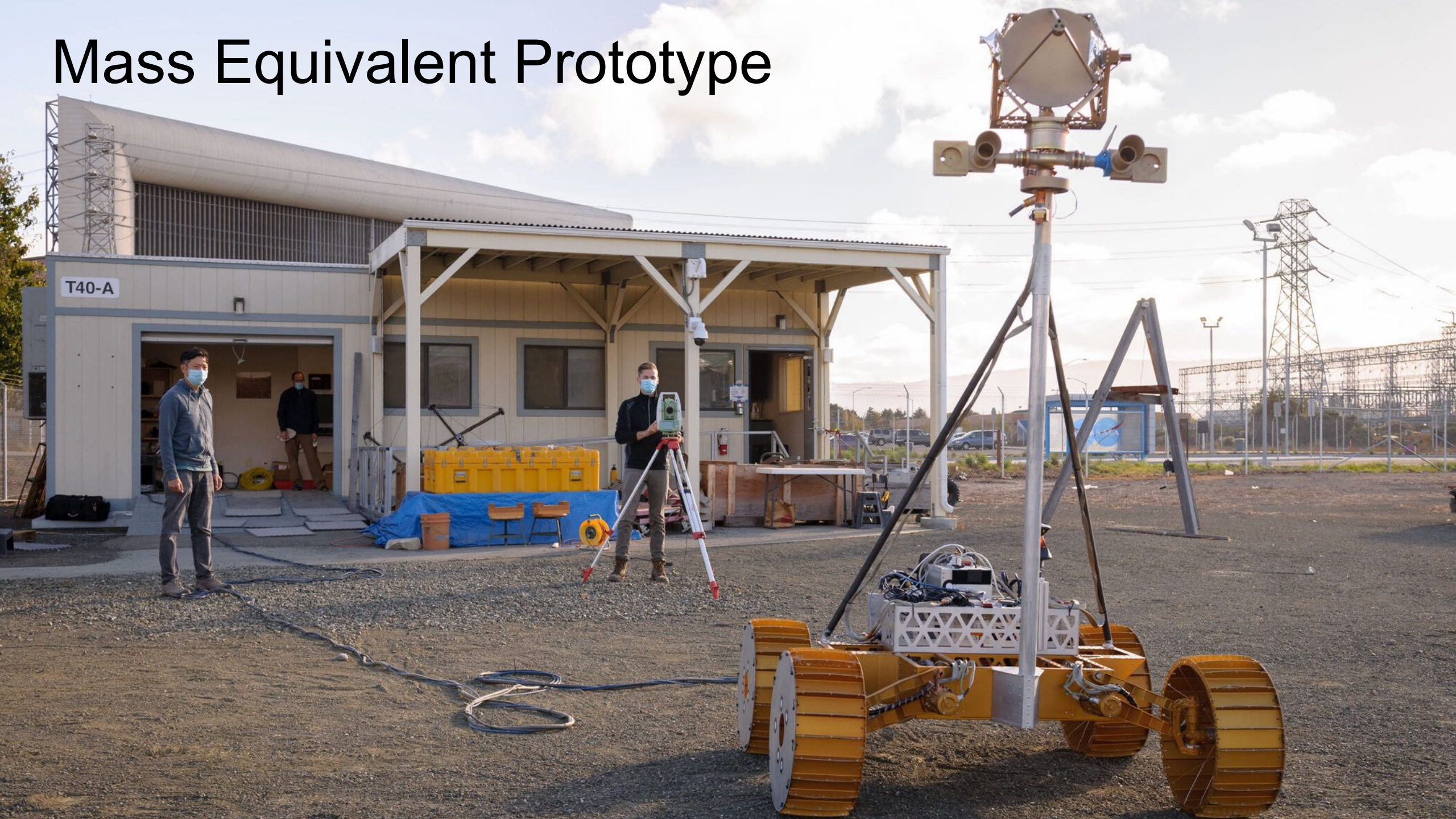
- 50 cm diameter, 20 cm wide
- Rigid sheet metal with spokes
- Rim grousers

Capabilities

- Actuated suspension enables body attitude and clearance control
- Explicit steering (with sufficient torque to perform skid steering)
- Alternate mobility (e.g., “inchworming”)

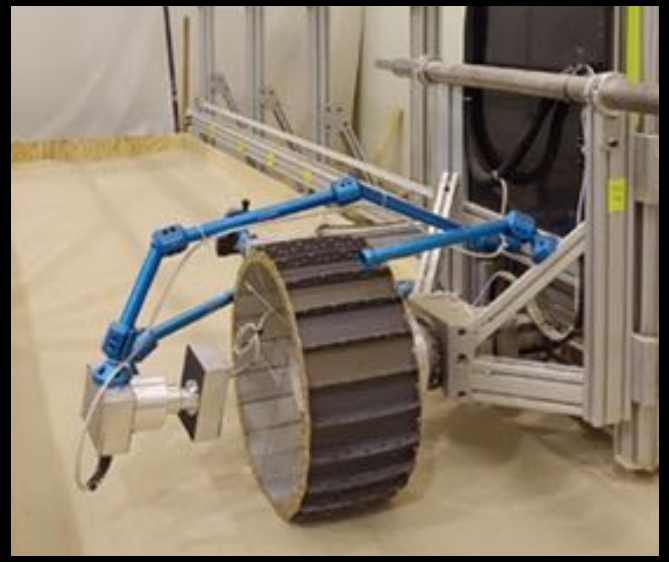


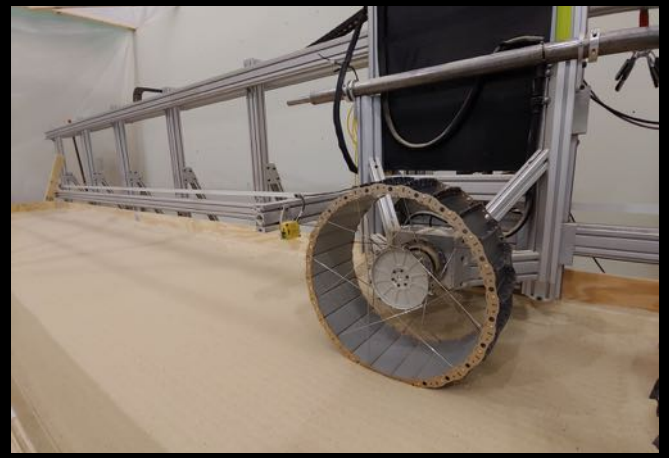
Mass Equivalent Prototype

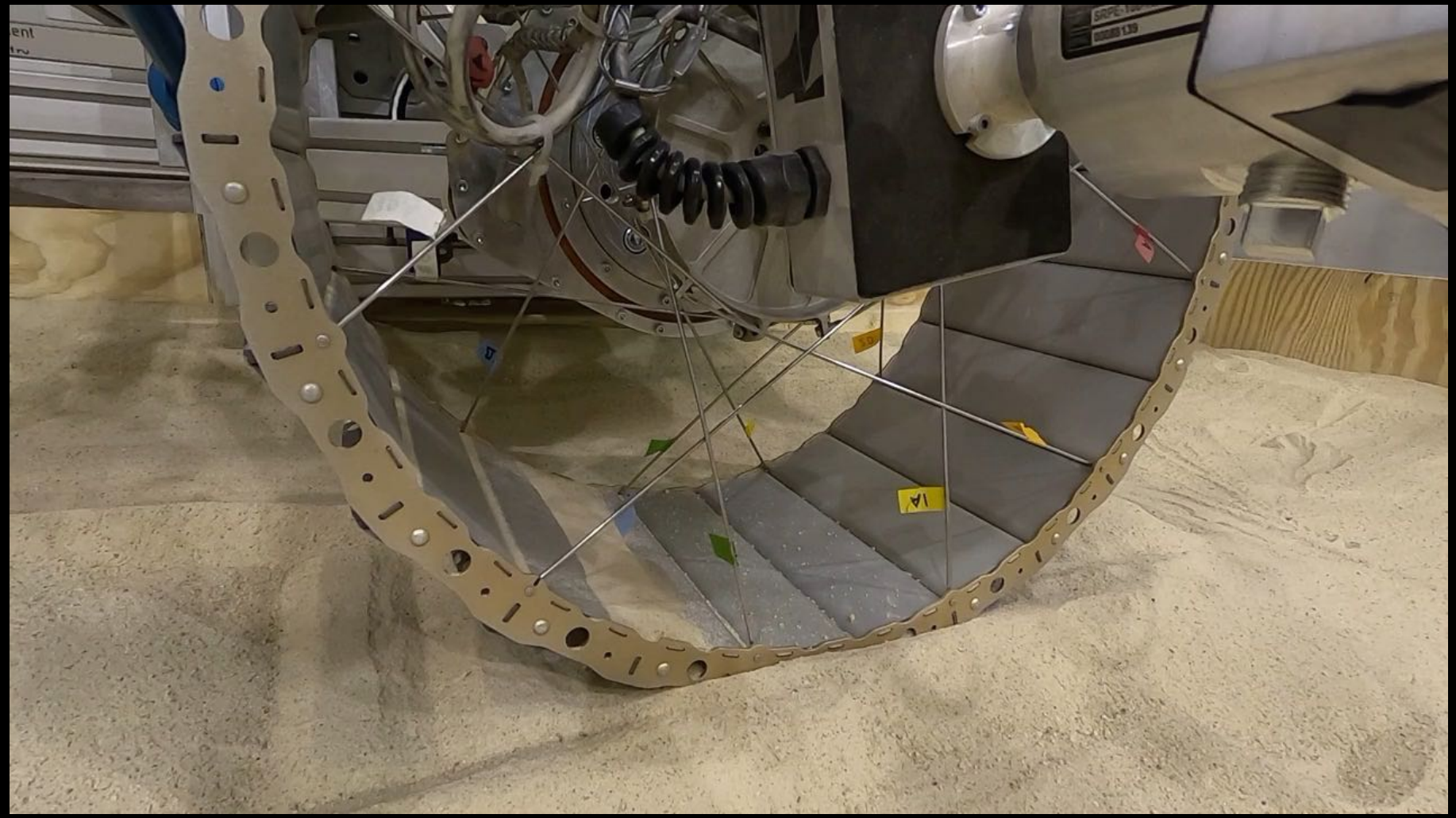




Wheel Prototype Testing







Characterization and endurance testing performed by ProtoInnovations, LLC (Pittsburgh)

SLOPE Lab (NASA Glenn)

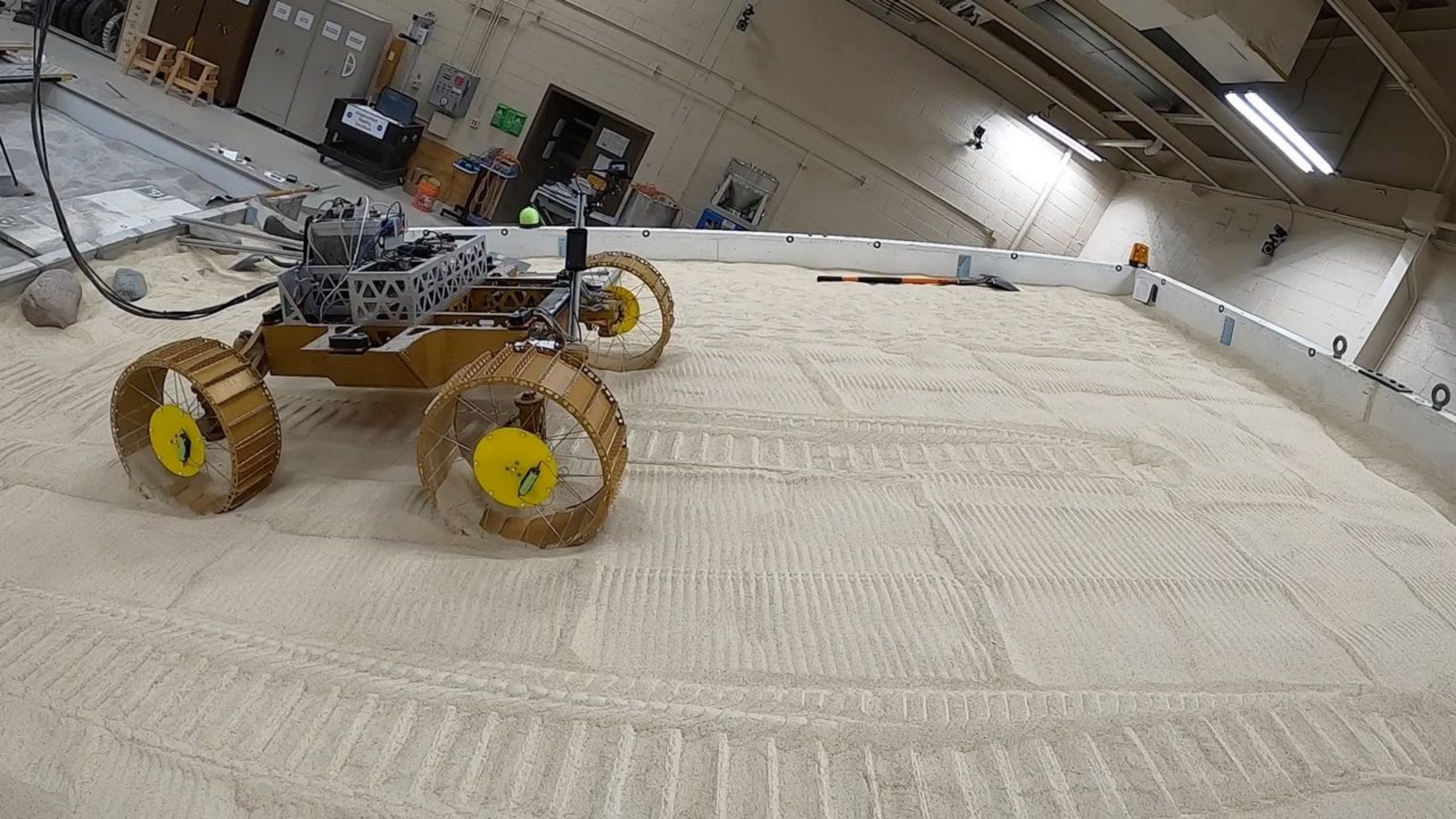


Entrapment Testing



Slip Testing





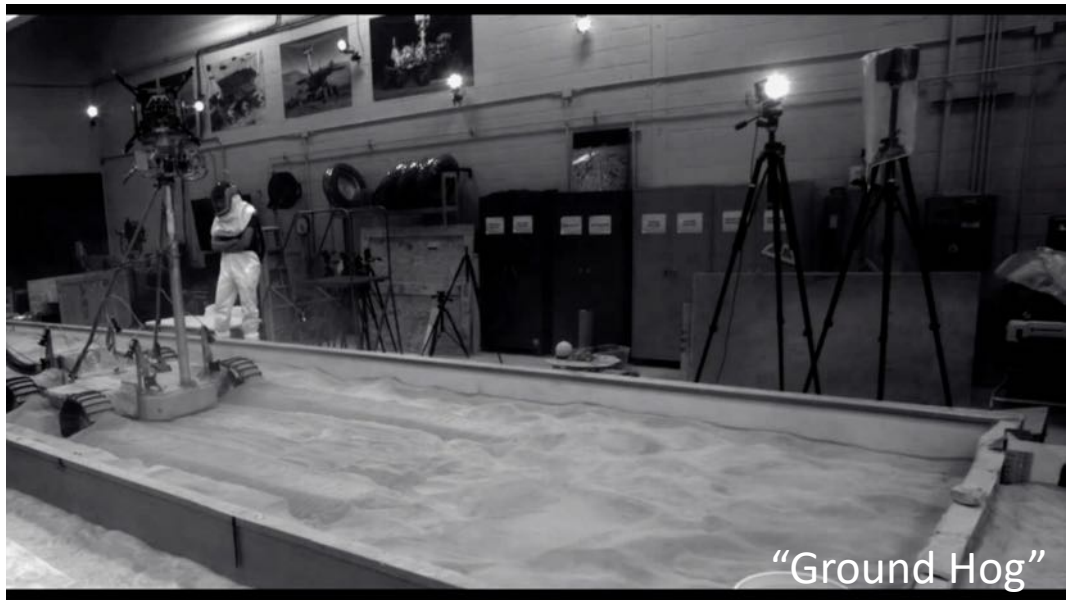
Crater Traversal Testing

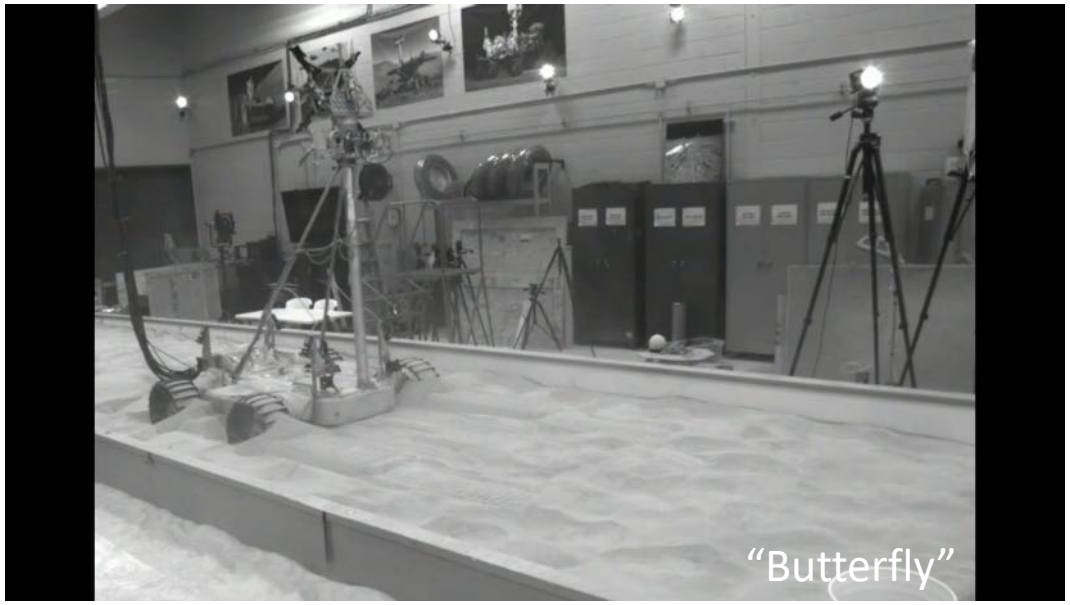


Alternate Mobility Modes

8x speed

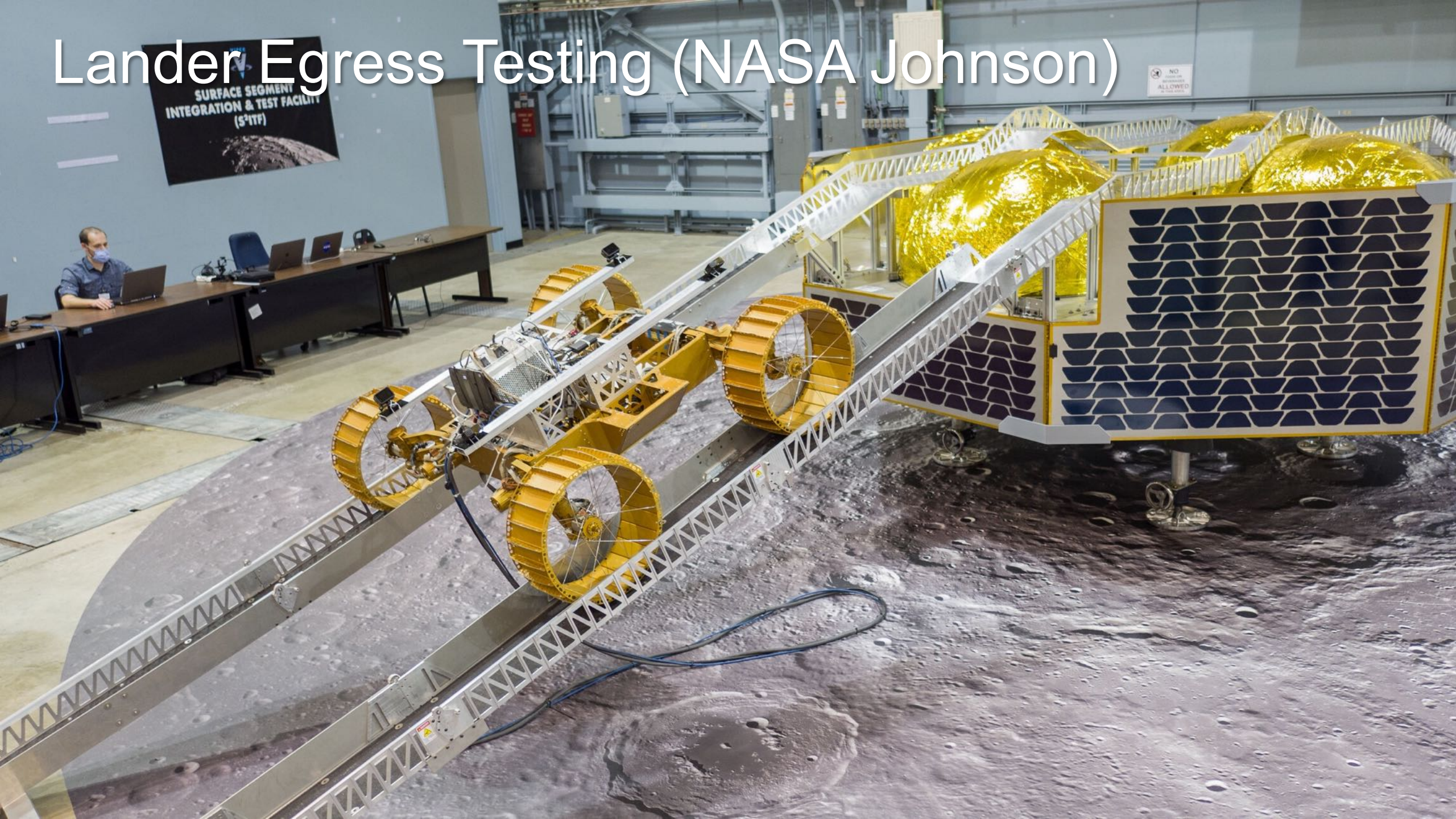








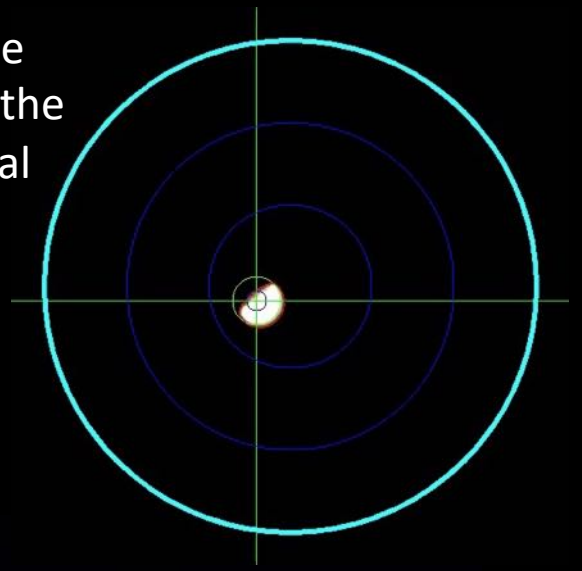
Lander Egress Testing (NASA Johnson)



High Gain Antenna Testing – Pointing Under Motion



view of the Moon from the HGA gimbal





Camera/Light Testing (NASA Ames)

Engineering Unit Rover in front of slopes with craters



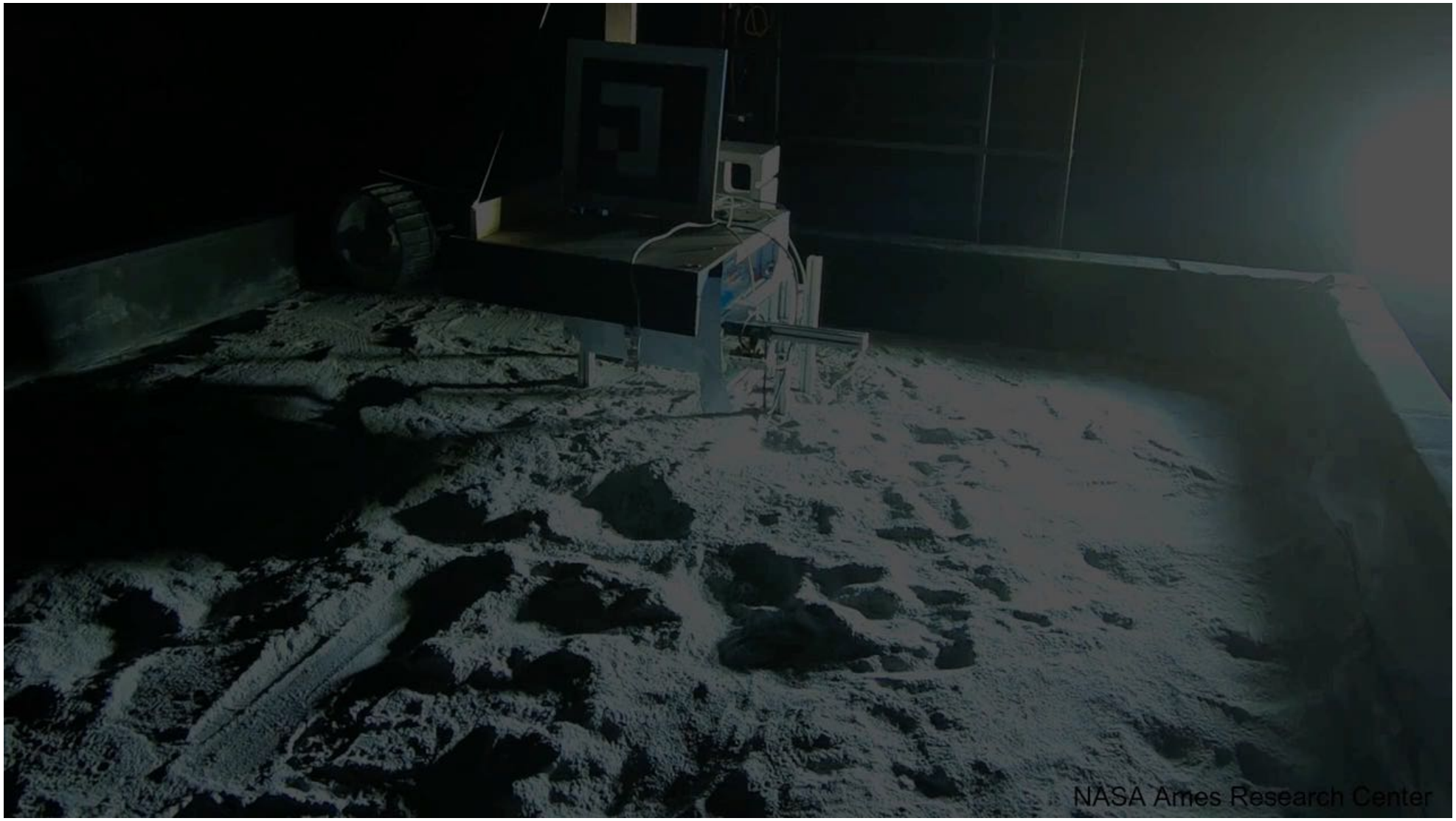


Rock field for hazard map testing with sun simulator on the right

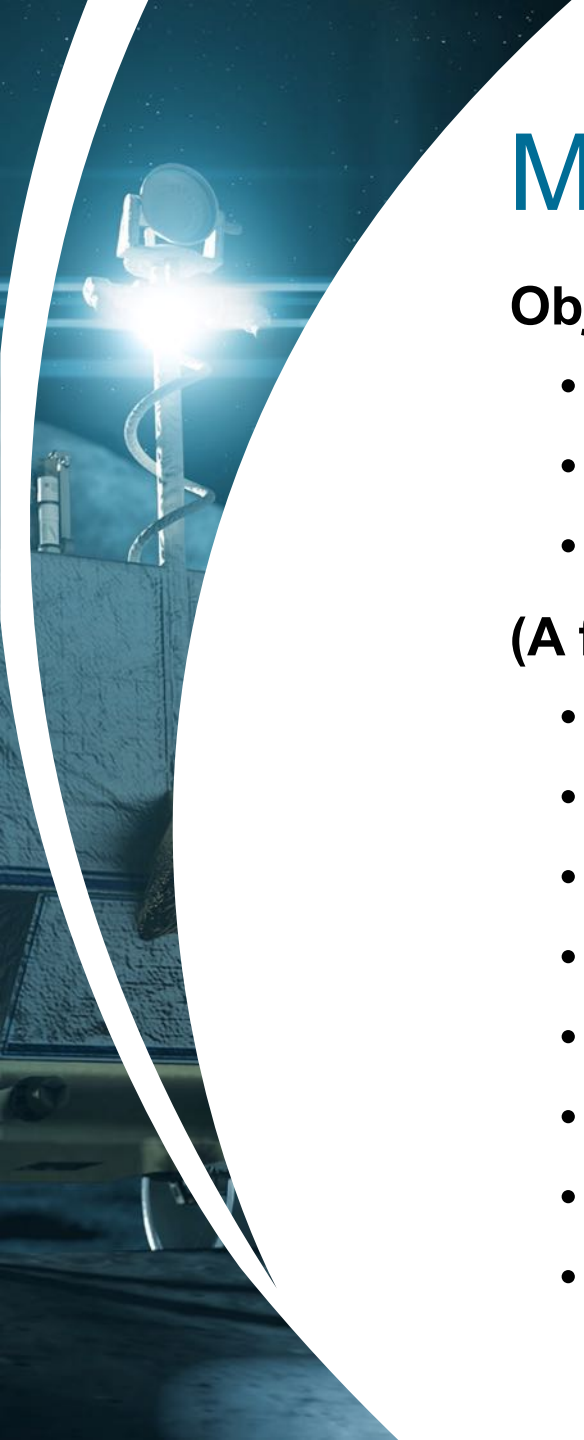
Engineering Unit Rover NavCam view with Sun Simulator from behind



Camera & Light Testing Facility



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



Mission Planning

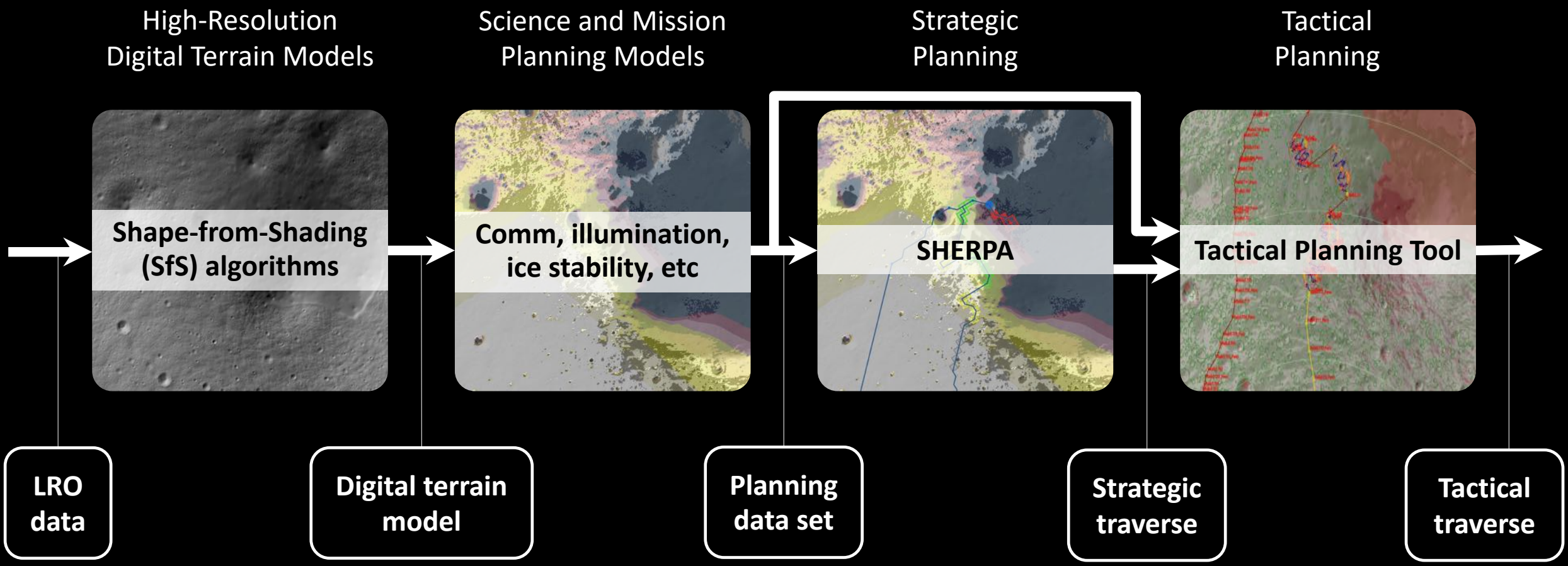
Objectives

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

(A few) constraints

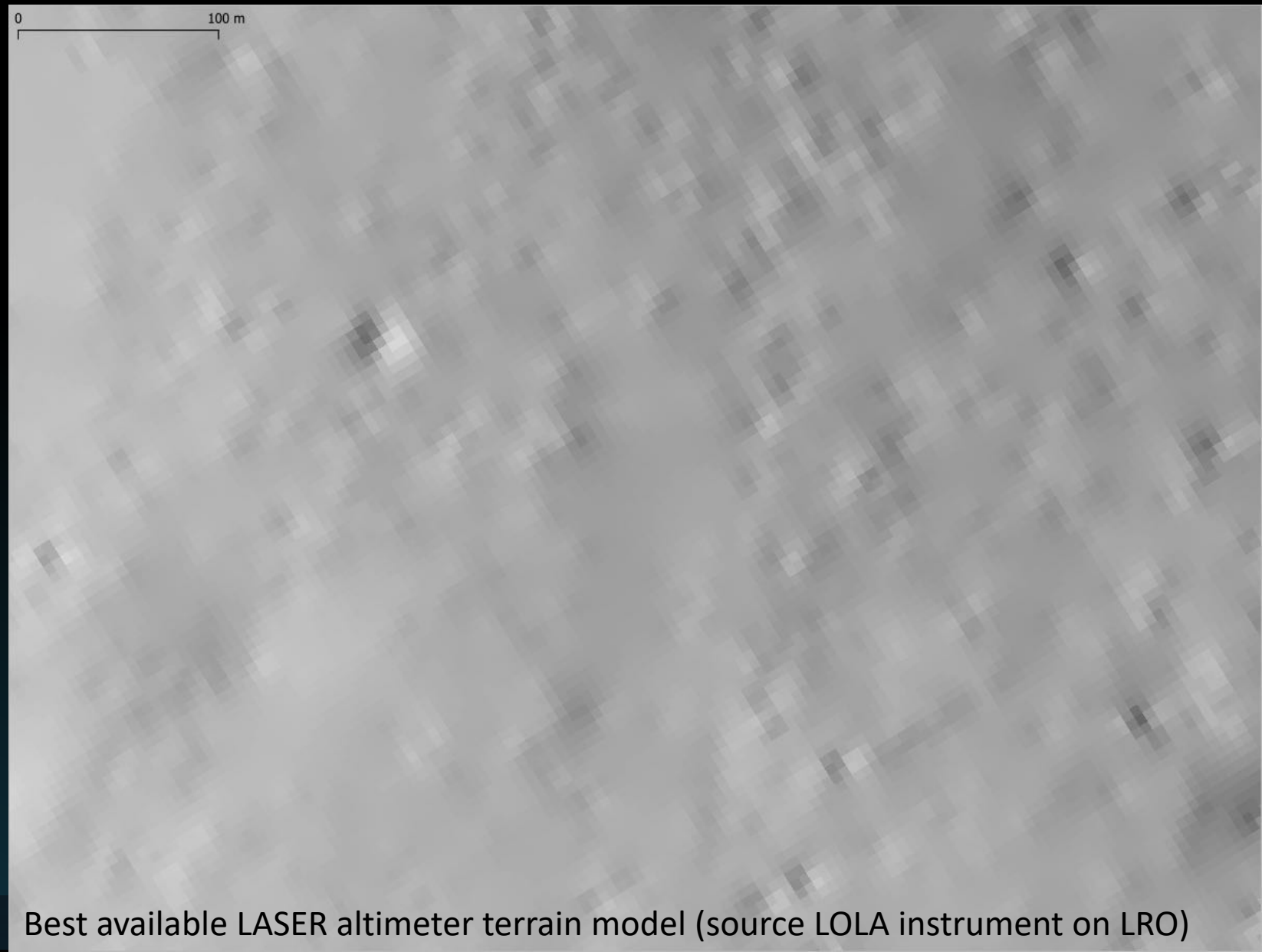
- Measure distribution and state of lunar polar volatiles
- Solar-powered rover with limited battery (shadow endurance)
- Lunar summer “season” (~100 Earth days max)
- Line-of-sight data communications to Earth
- 20 km max drive distance (design limit)
- 15 deg slopes + 20 cm step obstacles (design limit)
- 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



High-Resolution Digital Terrain Models

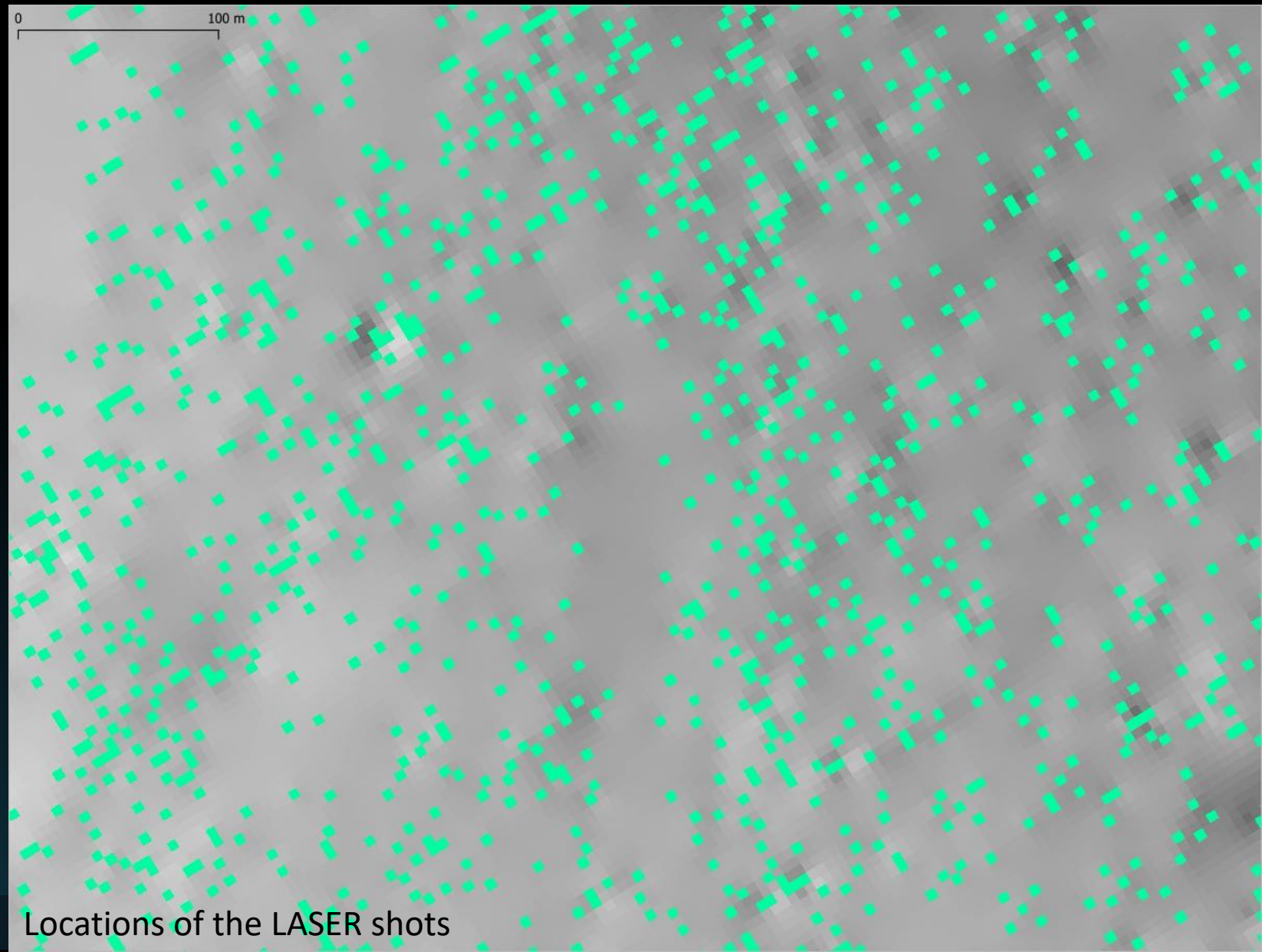
- LASER altimeter terrain 5m/pixel



Best available LASER altimeter terrain model (source LOLA instrument on LRO)

High-Resolution Digital Terrain Models

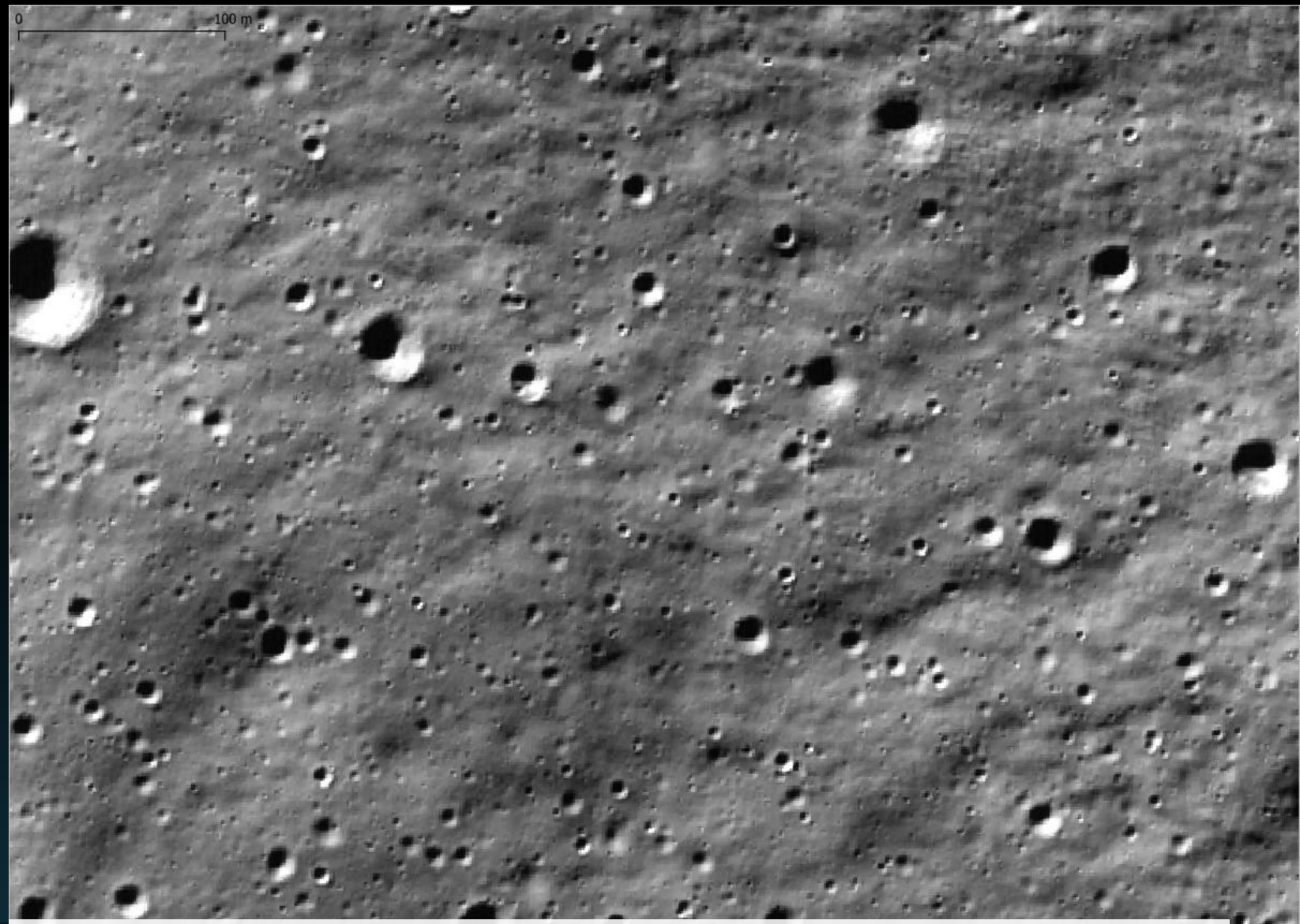
- LASER altimeter terrain 5m/pixel
- Much of the terrain model is interpolated



Locations of the LASER shots

High-Resolution Digital Terrain Models

- LASER altimeter terrain 5m/pixel
- Much of the terrain model is interpolated
- The best available photographs are 1m/pixel (5x the resolution)



Best available orbital photograph (source LROC narrow angle camera on LRO)

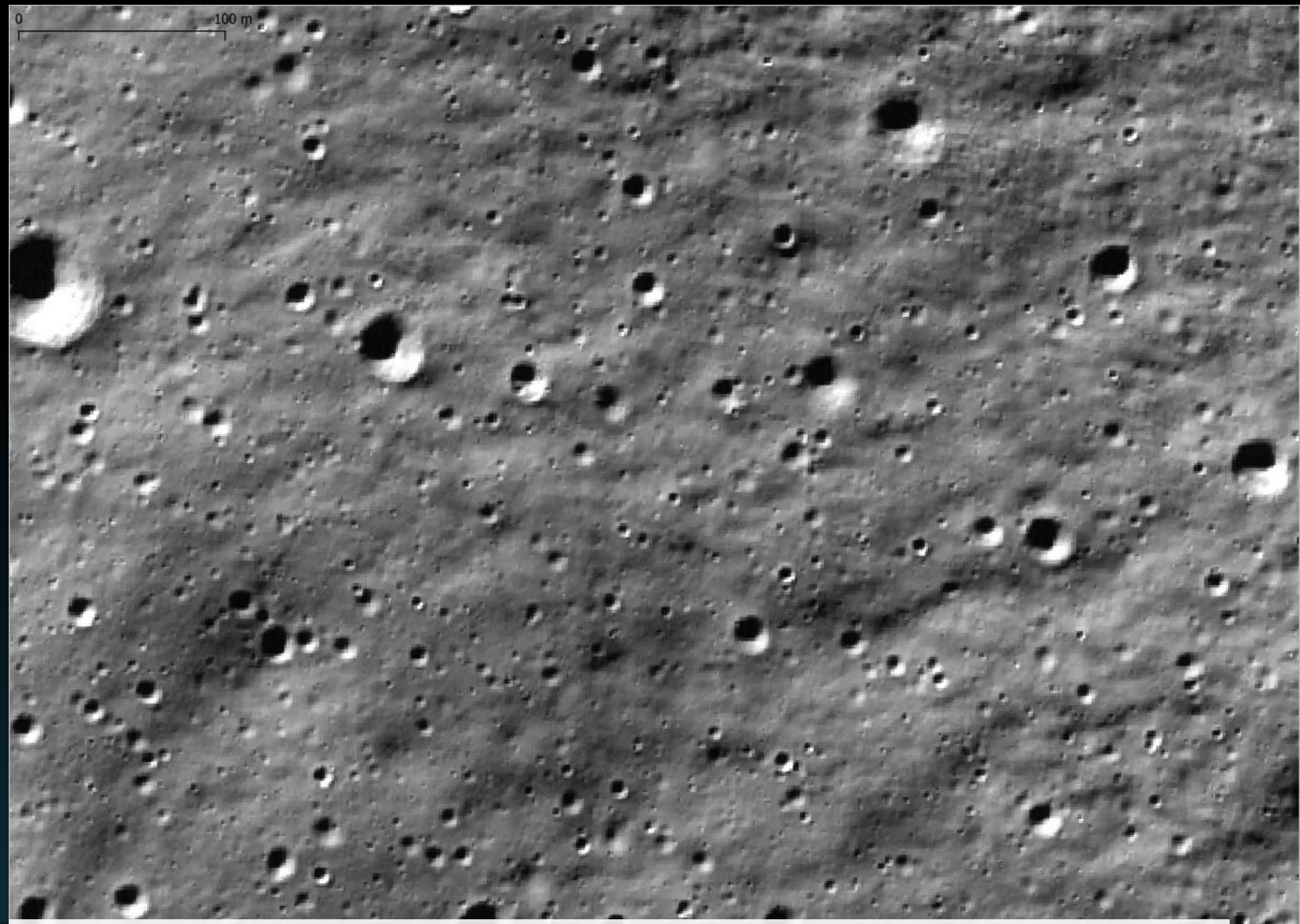
High-Resolution Digital Terrain Models

- LASER altimeter terrain 5m/pixel
- Much of the terrain model is interpolated
- The best available photographs are 1m/pixel (5x the resolution)
- Shape-from-shading

  Estimate slope of each pixel from its shading in multiple images

  Combine to model terrain at 1m/pixel

  VIPER worked out how to use this method at scale for lunar polar images



Best available orbital photograph (source LROC narrow angle camera on LRO)

High-Resolution Digital Terrain Models

- LASER altimeter terrain 5m/pixel
- Much of the terrain model is interpolated
- The best available photographs are 1m/pixel (5x the resolution)
- Shape-from-shading

  Estimate slope of each pixel from its shading in multiple images

  Combine to model terrain at 1m/pixel

  VIPER worked out how to use this method at scale for lunar polar images



Shape-from-shading terrain model

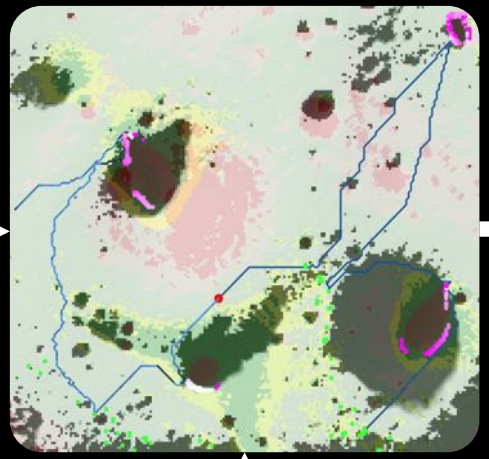
Strategic Planning

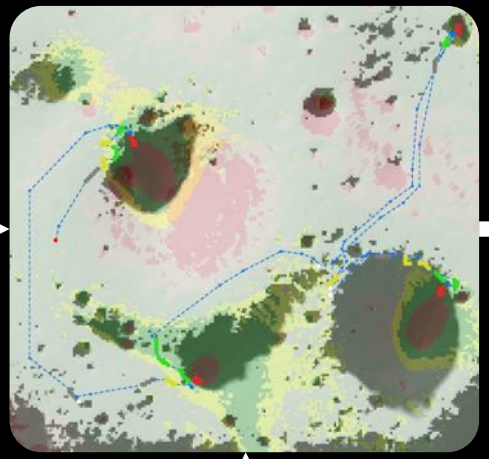
Traverse outlining

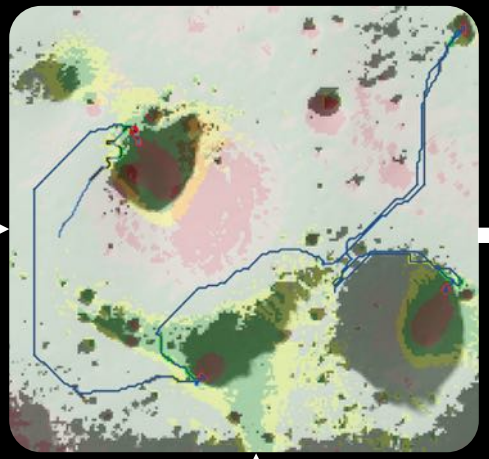
Traverse templating

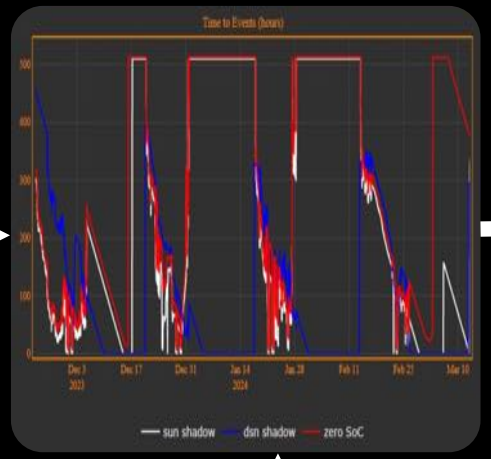
Traverse synthesis

Traverse evaluation









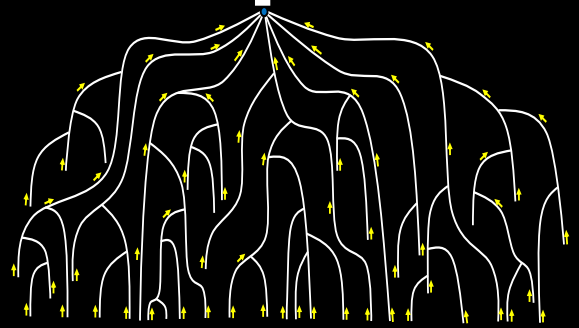
Planning inputs

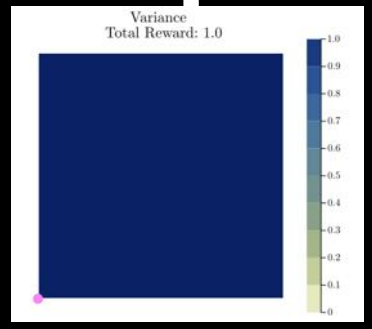
Traverse outline

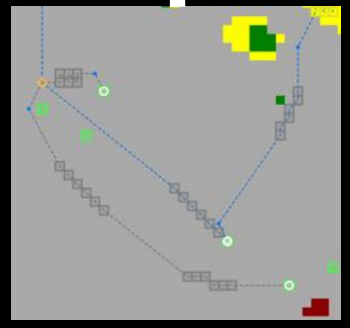
Template (optionally customized by user)

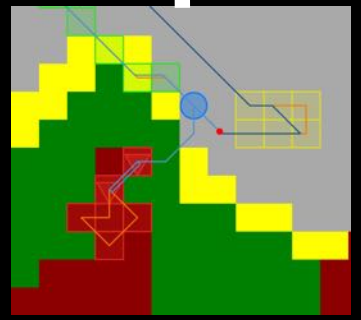
Traverse specification

Evaluation statistics

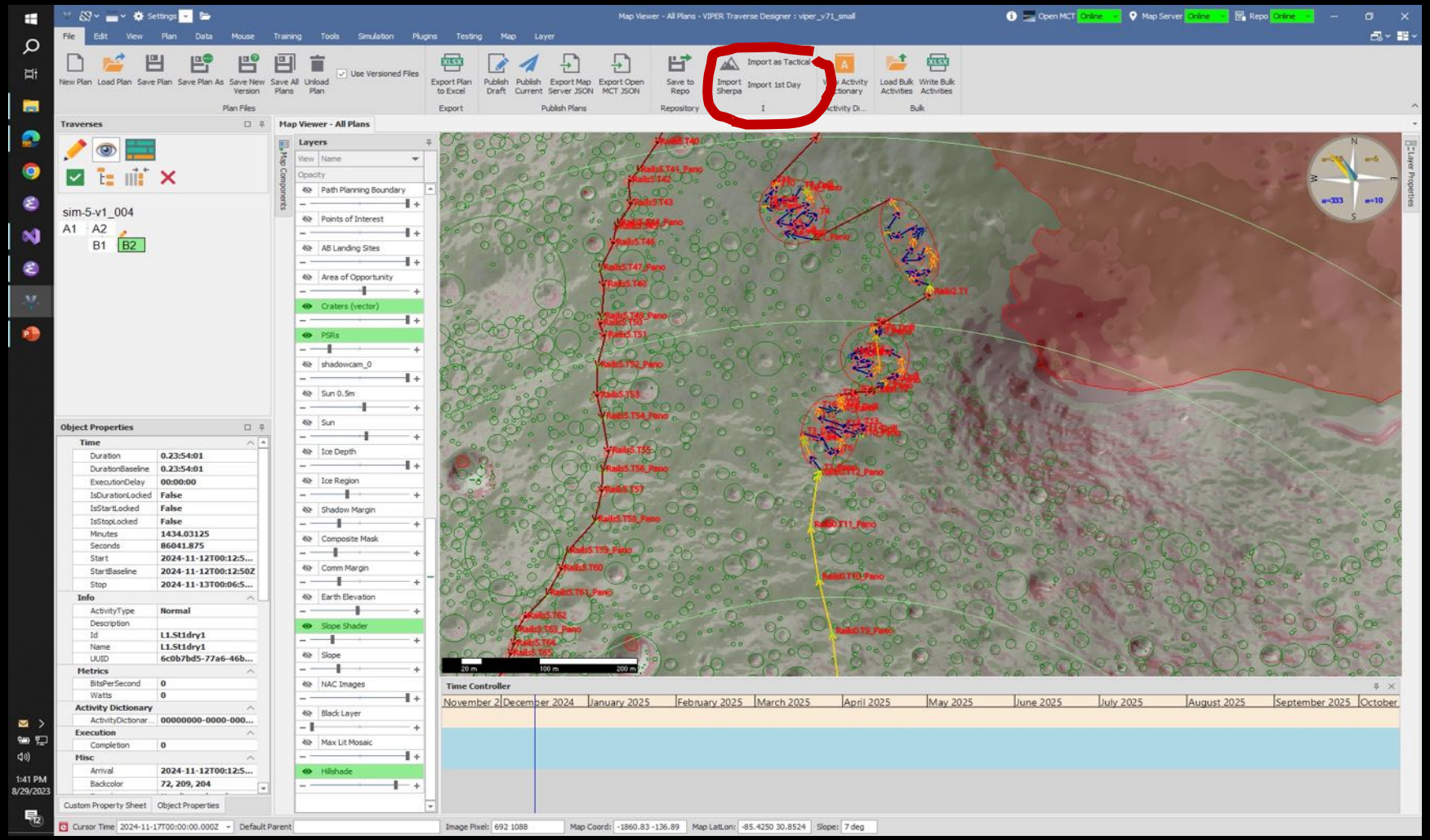






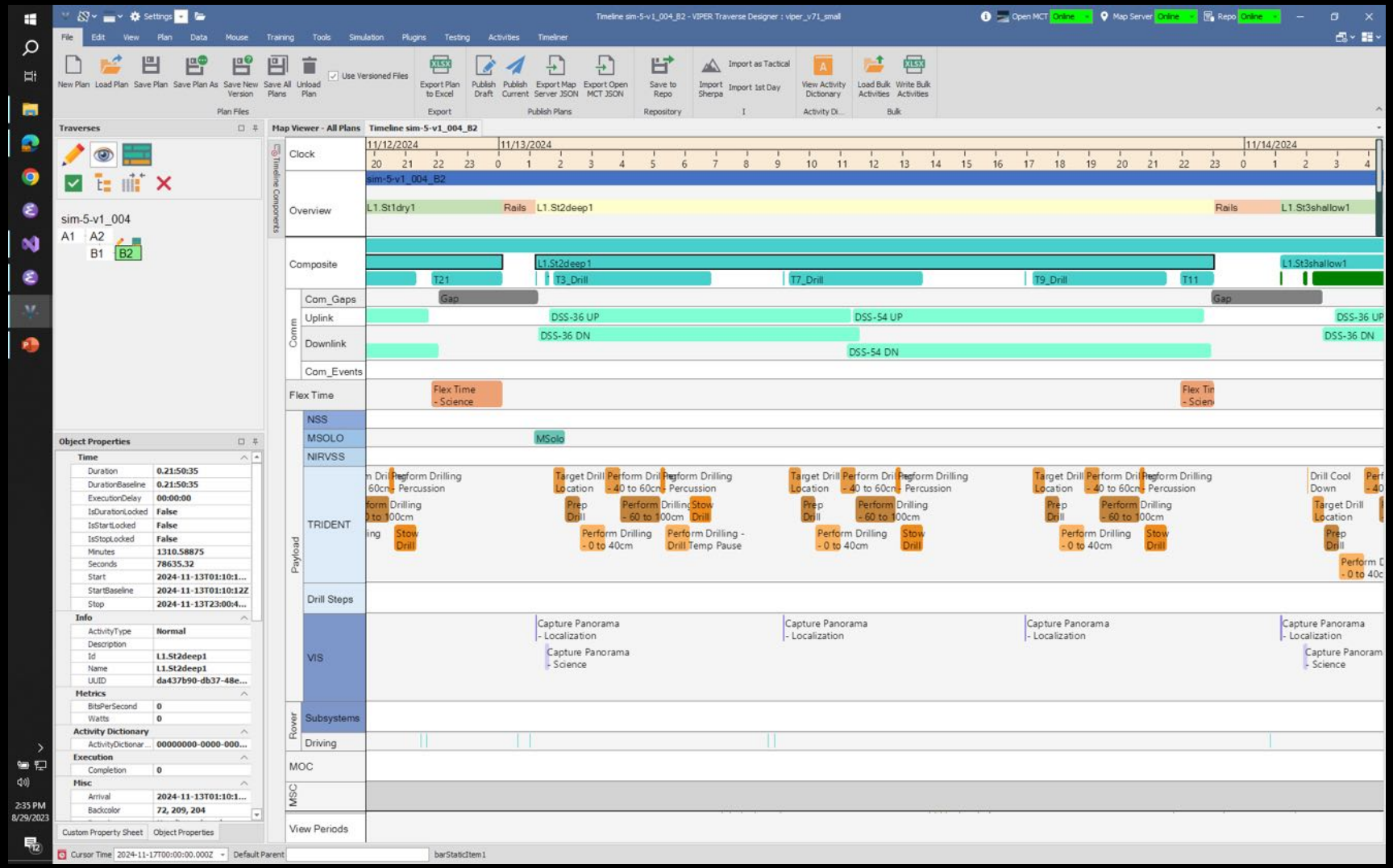


Tactical Planning



- Supporting tools for generating lighting and communications time-series maps.
- Tools for generating maps combining conditions and constraints, e.g., locations that experience at most N hours of shadow in a given period.
- Automated deterministic route planning between targets.

Tactical Planning

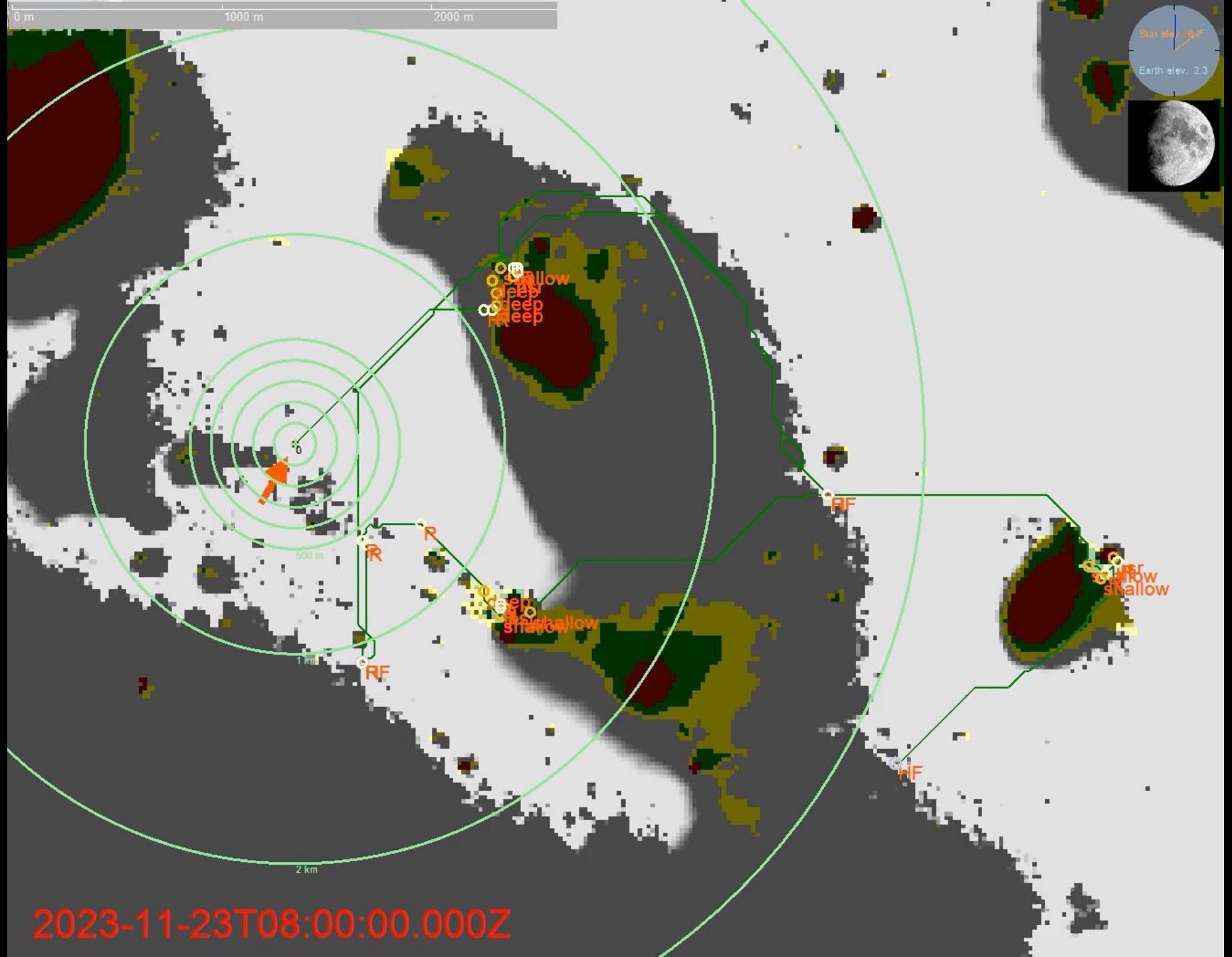


- Coordinated editing of the rover's route and operational schedule
- Mode for monitoring and updating the plan's timing during execution
- Simple and extensible flight rule checking

Example Traverse Plan

2023-11-23
to
2024-03-07

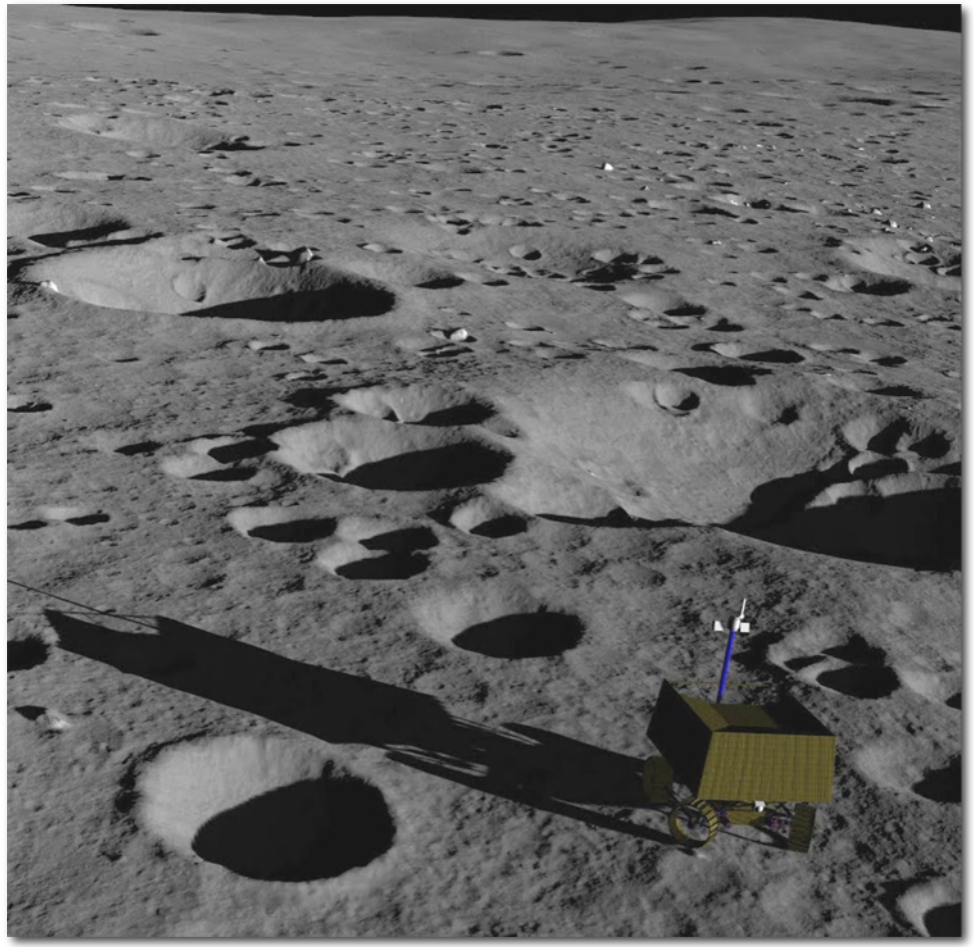
106 days



Lunar Surface Simulation

Key Features

- High dynamic range rendering
- Real-time shadows
- Support for high resolution terrains
- Support for custom terrain appearance
- Rover wheel tracks and slip modeling
- Rover lights with custom pattern
- Simulated lens flare and noise
- Lunar regolith reflectance model
- Accurate Sun & Earth emphemeris



Lunar surface simulator based on Gazebo



Synthetic Lunar Terrain Modeling

Need

- High-resolution DEMs (10 cm/post) are needed for conops studies, development of rover navigation systems, mission simulations, etc.
- Best-available lunar DEMs are 1-10 m/post and typically noisy

Typical model

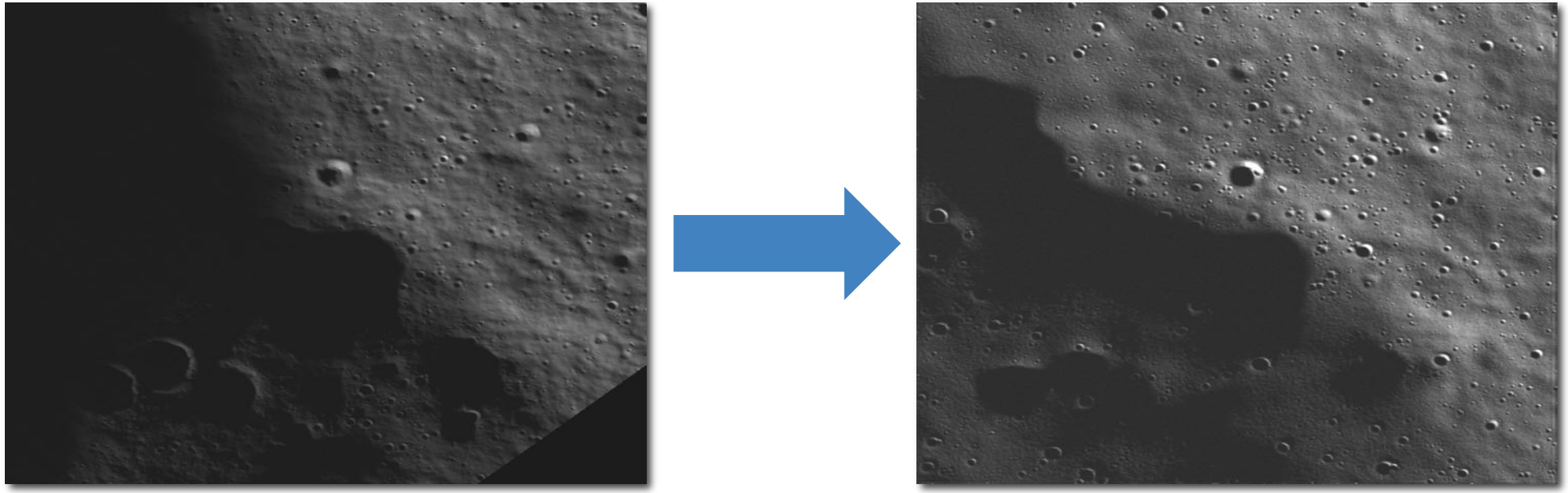
- 1 km x 1 km area, high-latitude site
- 4 cm / post

Disclaimer

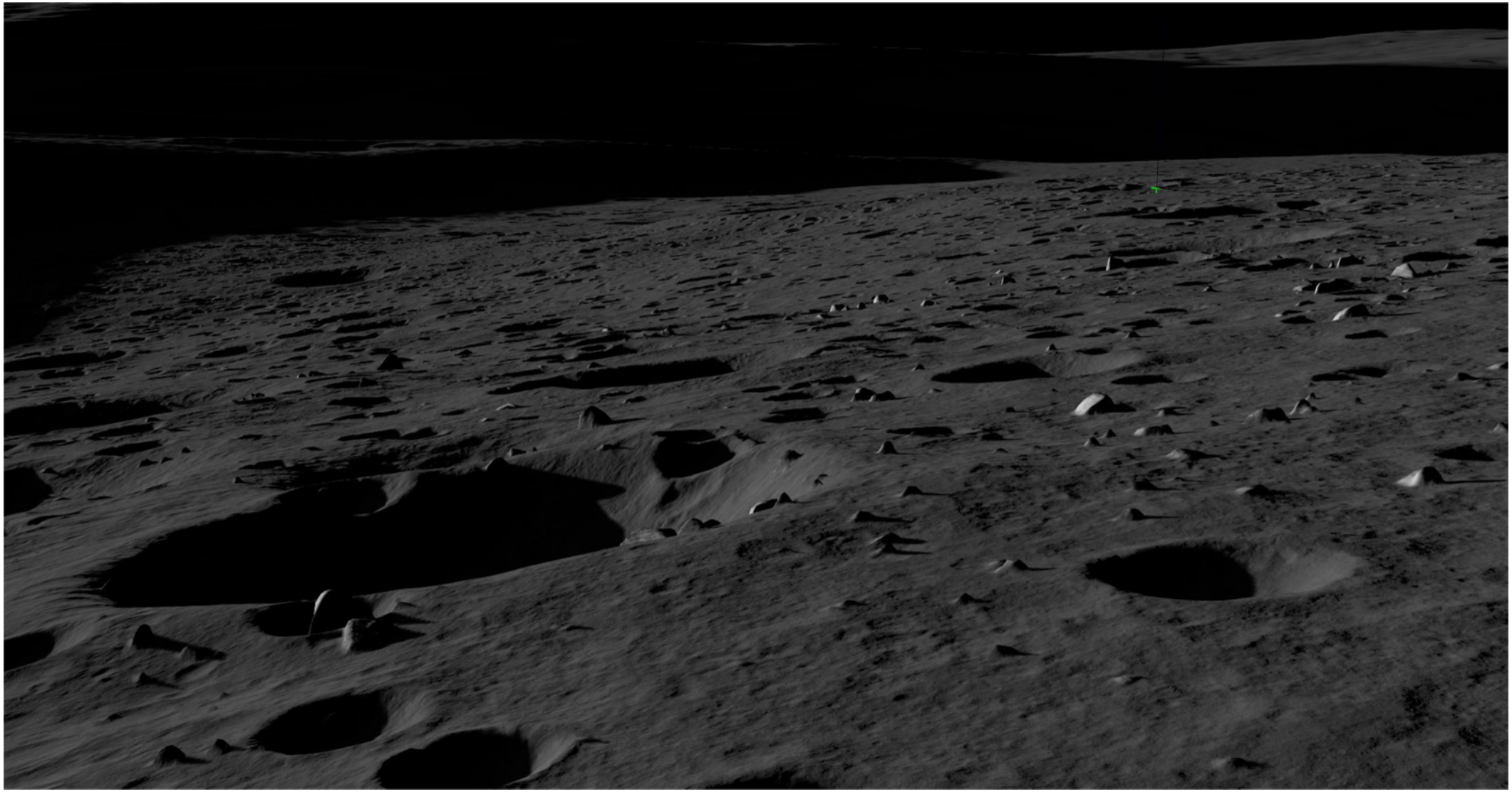
- NOT an accurate measurement of the actual lunar terrain
- NOT appropriate for lunar mission planning or operations
- Suitable for education use, outreach activities, research, or simulation

Synthetic DEM Generation Process

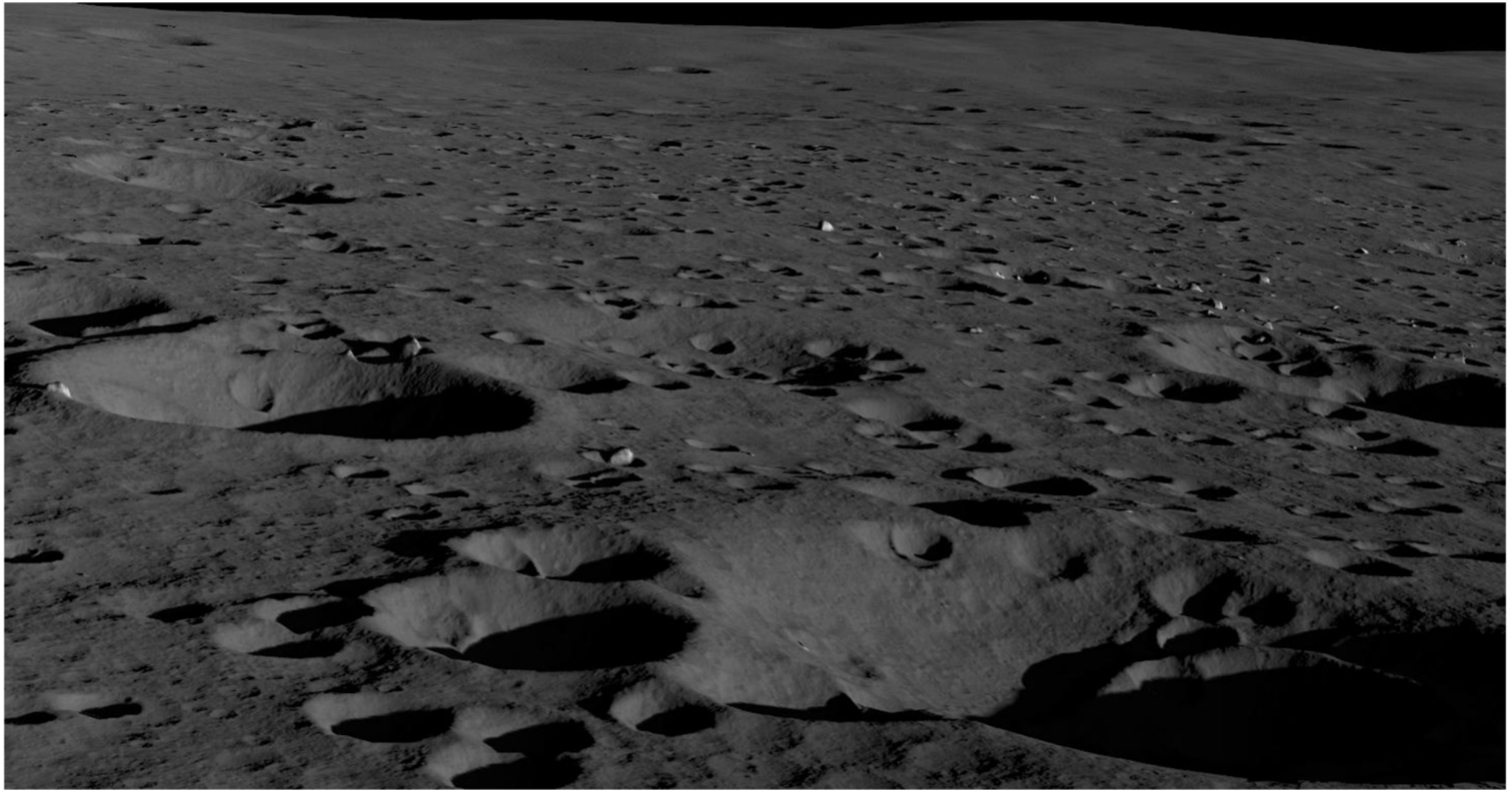
- LROC-NA Images and LOLA laser altimetry
- Create initial DEM with 1 m/post using photoclinometry
- Synthetically enhance DEM via fractal synthesis to create high-resolution surface detail that is consistent with lunar morphology
- Add synthetic craters and rocks using a parametric shape model with size-frequency distributions to control density



Synthetic Terrain Results



Synthetic Terrain Results



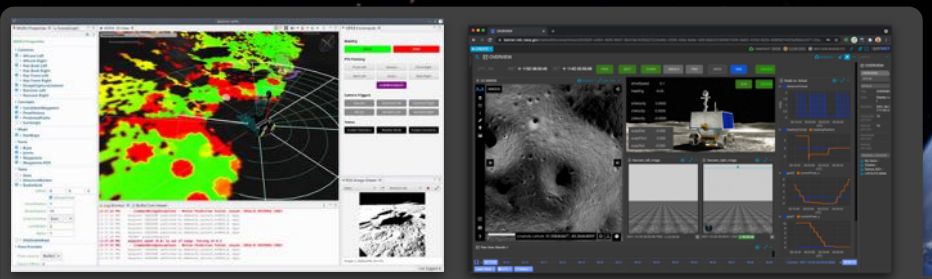


Mission Operations Training





VIPER Surface Mission



Rover Driving

Mission Monitoring

KSC
MSOLO

JSC
Rover Systems & Thermal

Comms round trip ~6 - 10 sec

ARC
Systems & Execution

Science Station

Lander

Waypoints
~ 5 m

Traverse Points
~ 50 m

Drill A

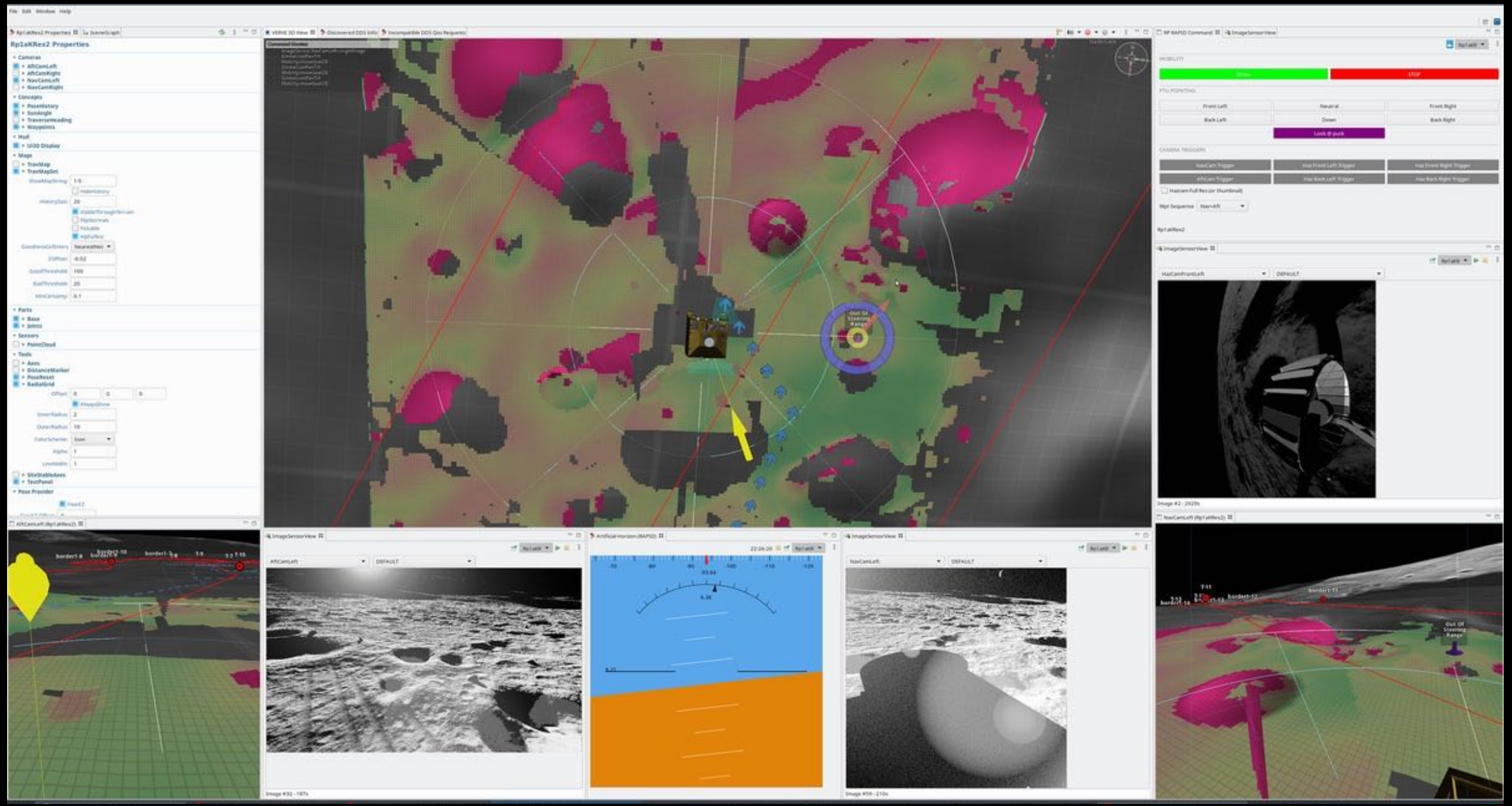
Science Station

Drill B

Drill C

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

VERVE: Rover Driving Interface



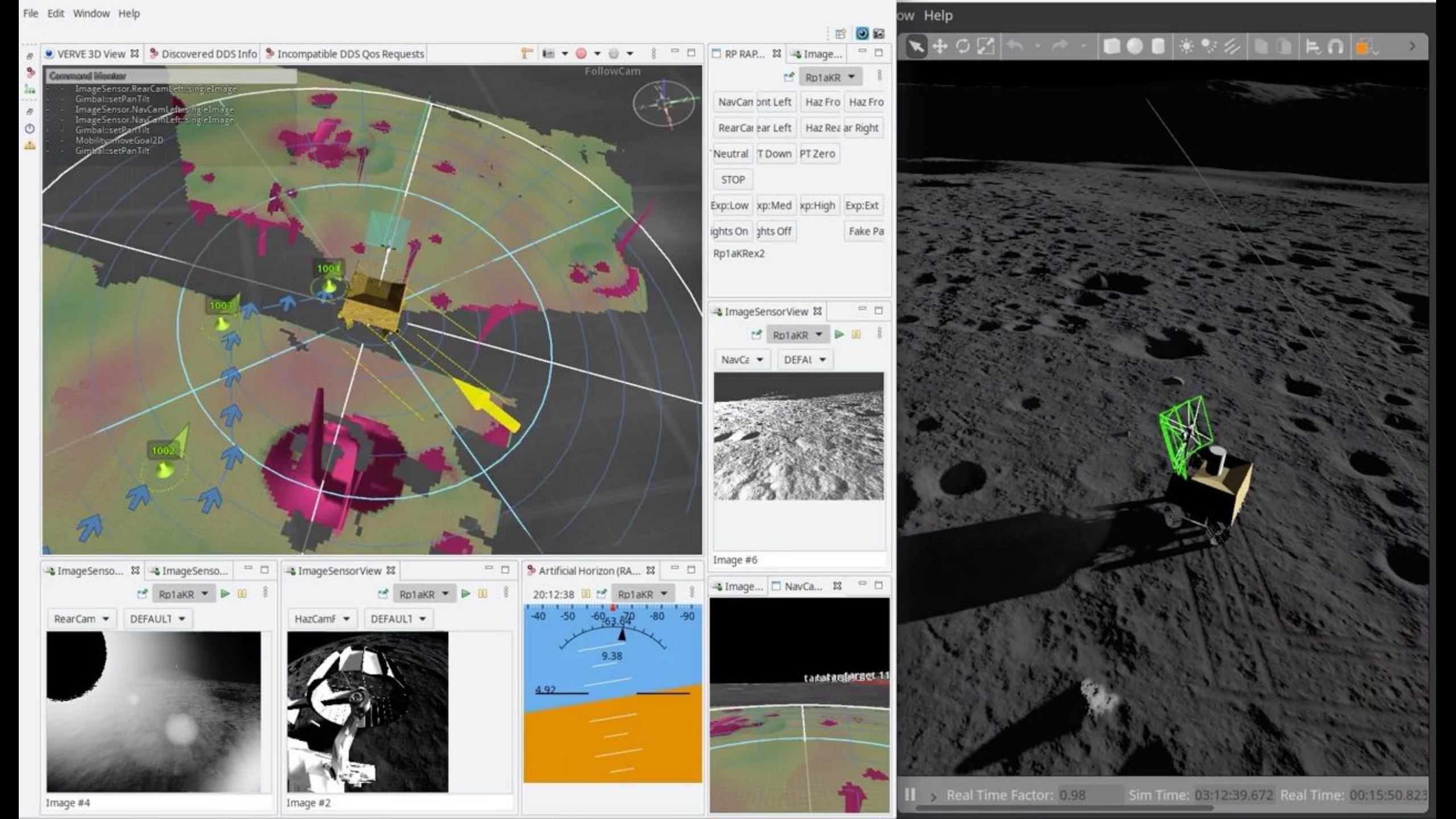

File Edit Window Help
VERVE 3D View
Discovered DDS Info
Incompatible DDS Qos Requests
FollowCam
Command Monitor
ImageSensor.RearCamLeft::singleImage
Gimbal::setPanTilt
ImageSensor.NavCamLeft::singleImage
ImageSensor.NavCamLeft::singleImage
Gimbal::setPanTilt
MobilityMoveGoal2D
Gimbal::setPanTilt
1004
1003
1002
RP RAP...
Image...
Rp1aKR
NavCam ont Left
Haz Fro
Haz Fro
RearCar ear Left
Haz Rea ar Right
Neutral T Down
PT Zero
STOP
Exp:Low xp:Med xp:High
Exp:Ext
ights On ghts Off
Fake Pa
Rp1aKRex2
ImageSensorView
Rp1aKR
NavCa
DEFAL
Image #6
ImageSenso...
ImageSenso...
Rp1aKR
RearCam
DEFAULT
Image #4
ImageSensorView
Rp1aKR
HazCamF
DEFAULT
Image #2
Artificial Horizon (RA...
20:12:38
Rp1aKR
-40 -50 -60 -70 -80 -90
-63.64
9.38
4.92
Image...
NavCa...
Real Time Factor: 0.98
Sim Time: 03:12:39.672
Real Time: 00:15:50.823



Image courtesy of Astrobotic