

National Aeronautics and  
Space Administration



# Volatiles Investigating Polar Exploration Rover

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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)**



# 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

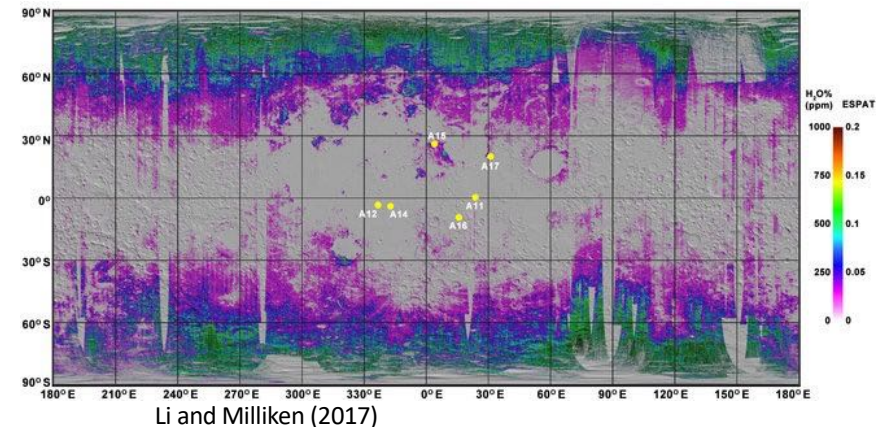
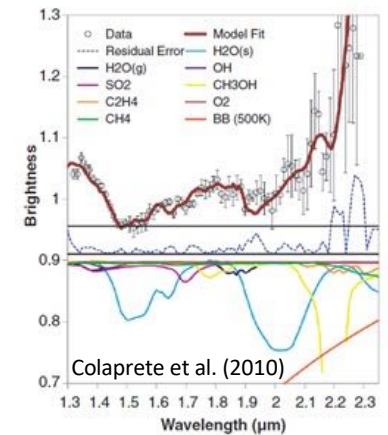
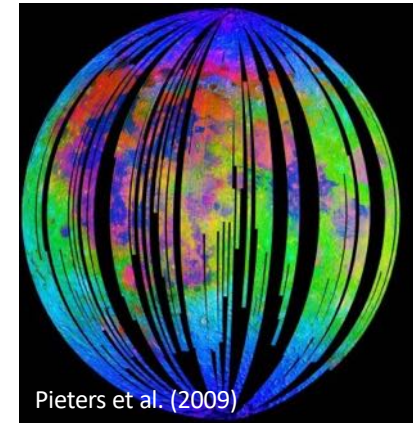
**BUT:** *Do not yet understand the concentration, evolution and interrelated dynamics of these varied sources of water*

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





# VIPER Mission

## Lunar south pole

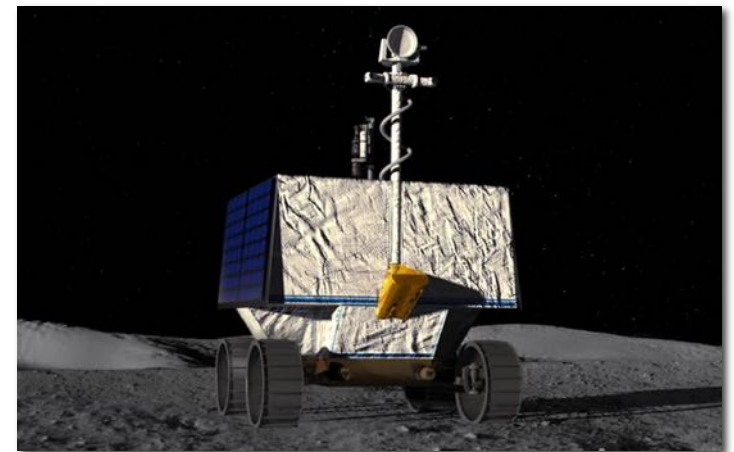
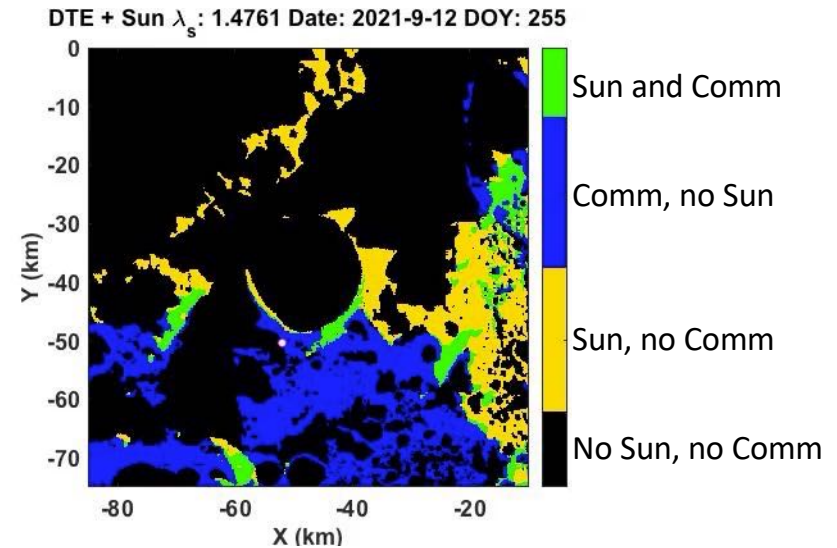
- Commercial launch and landing
- 100+ day mission (including extended survival periods)
- Up to 20 km total drive

## Science objectives

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

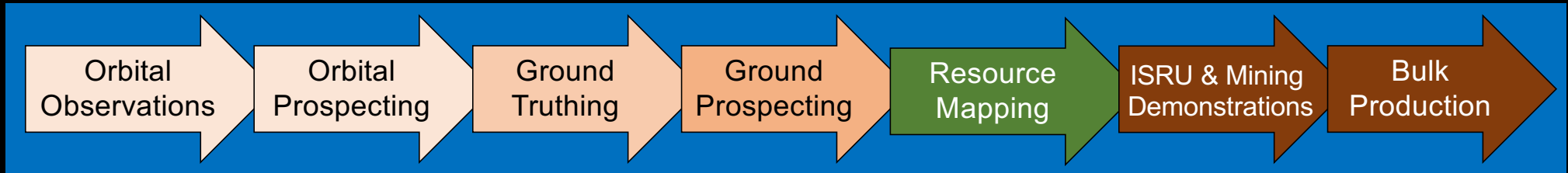
## A few unique challenges (among many...)

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

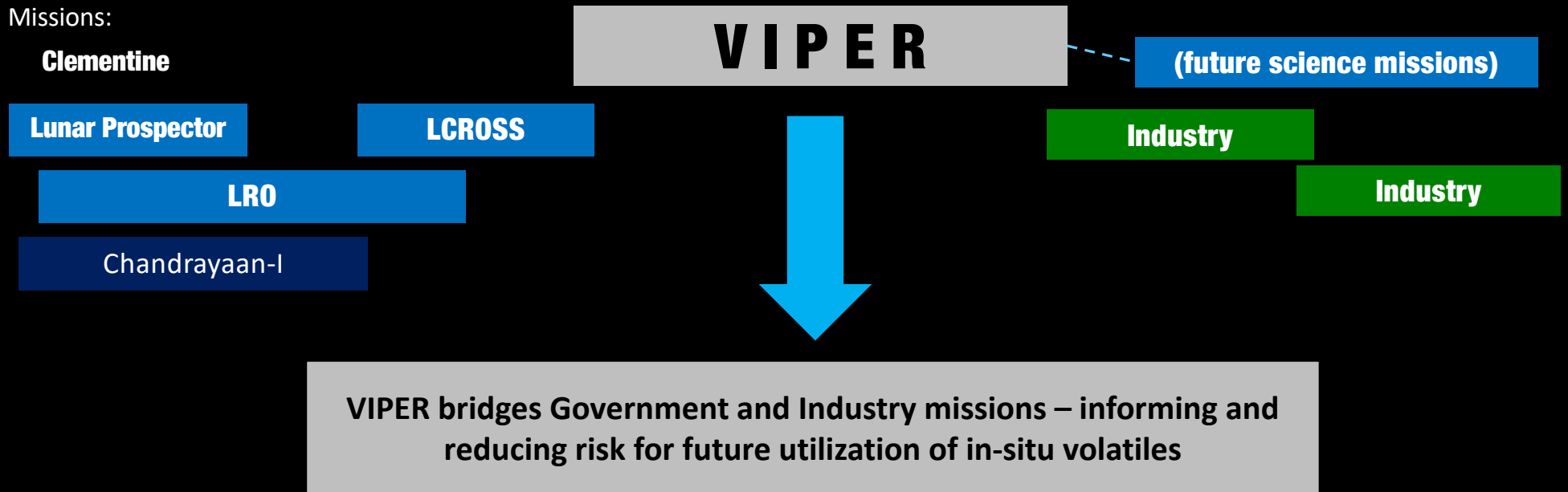


# The Big Picture of Lunar Resources

US Lunar Goals:



Missions:



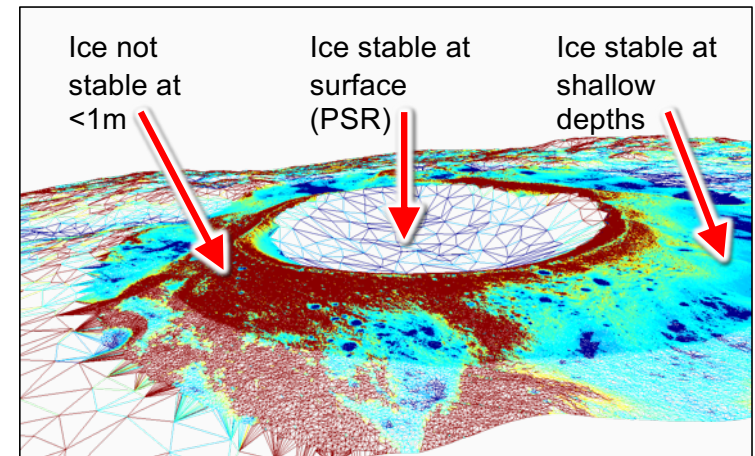
# Where is water (ice) at the lunar poles?

## Environmental factors

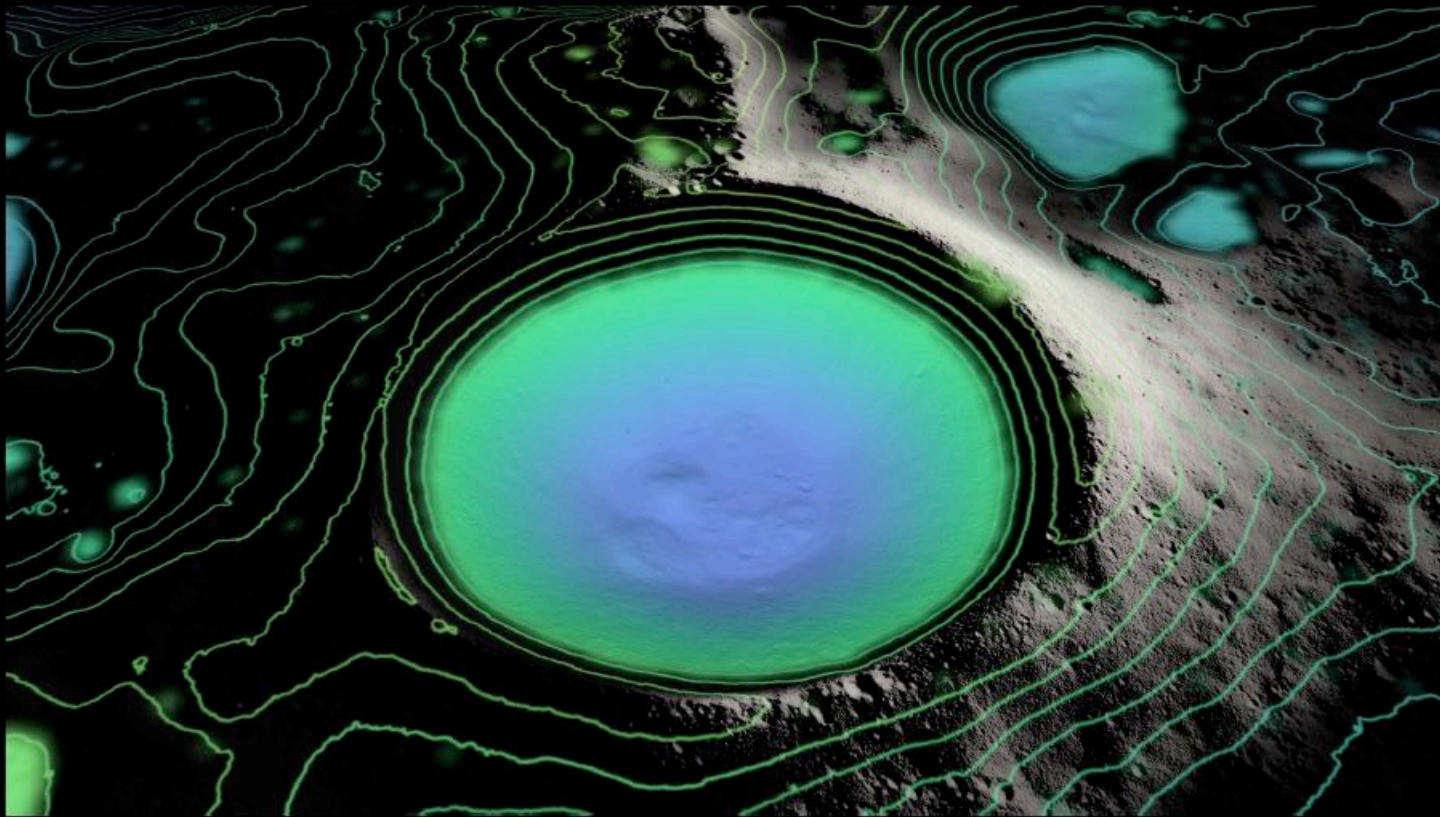
- Temperatures (surface or subsurface) must be low enough to retain water ice
- Geophysical properties (topography, materials, depth, etc.)

## 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”)

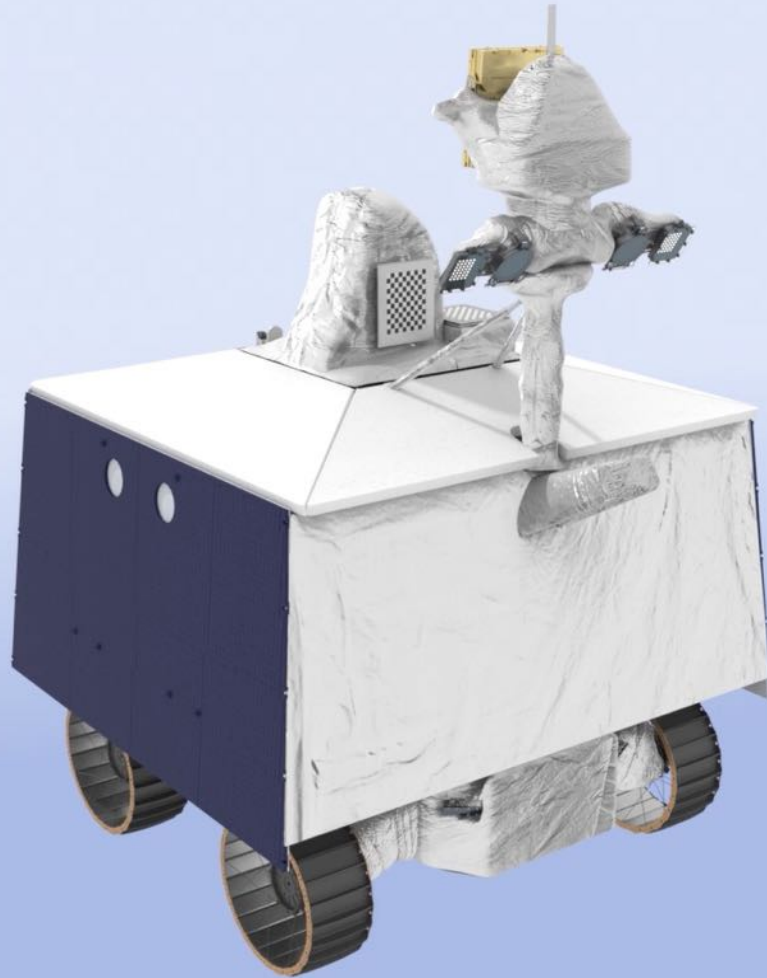


# Permanently Shadowed Regions on the Moon



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

# VIPER Rover



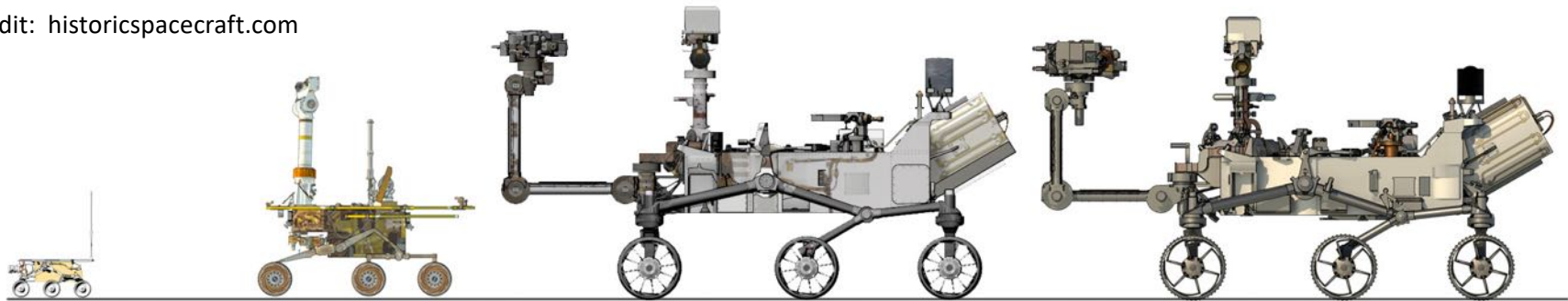
# Flight Rover Assembly



100%  
complete  
(4 June 2024)

# Rover Comparison

Credit: historic spacecraft.com

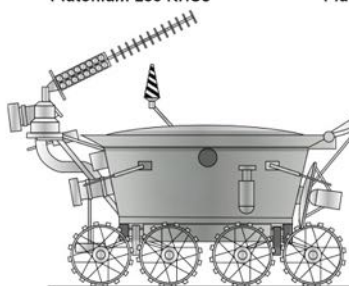


**Sojourner (1996)**  
 0.6m x 0.5m x 0.3m  
 11kg  
 Top Speed: 5cm/s  
 Plutonium-238 RHUs

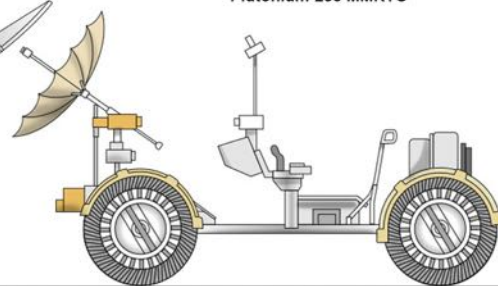
**Mars Exploration Rover (2004)**  
 1.6m x 2.3m x 1.5m  
 180kg  
 Top Speed: 5cm/s  
 Plutonium-238 RHUs

**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



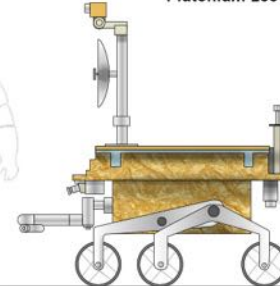
**Lunokhod 1 & 2 (1970/1973)**  
 2.3m x 1.6m x 1.5m  
 840kg  
 Top Speed: 55cm/s  
 Polonium-210 heat source



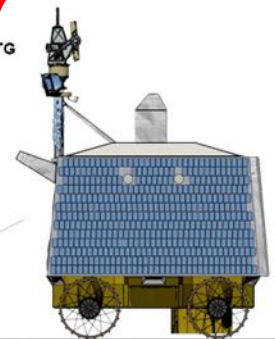
**Lunar Roving Vehicle (1971/1972)**  
 3.1m x 1.6m x 1.5m  
 210kg  
 Top Speed: 500cm/s  
 2 silver-zinc 36 volt batteries



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



# 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)

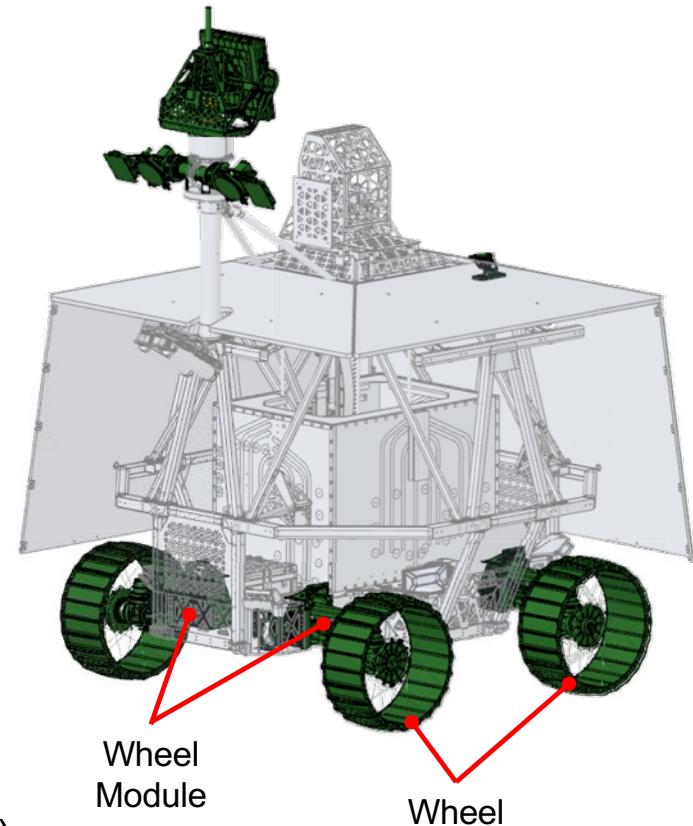
- Suspension
- Steering
- Propulsion

## Wheels (4x)

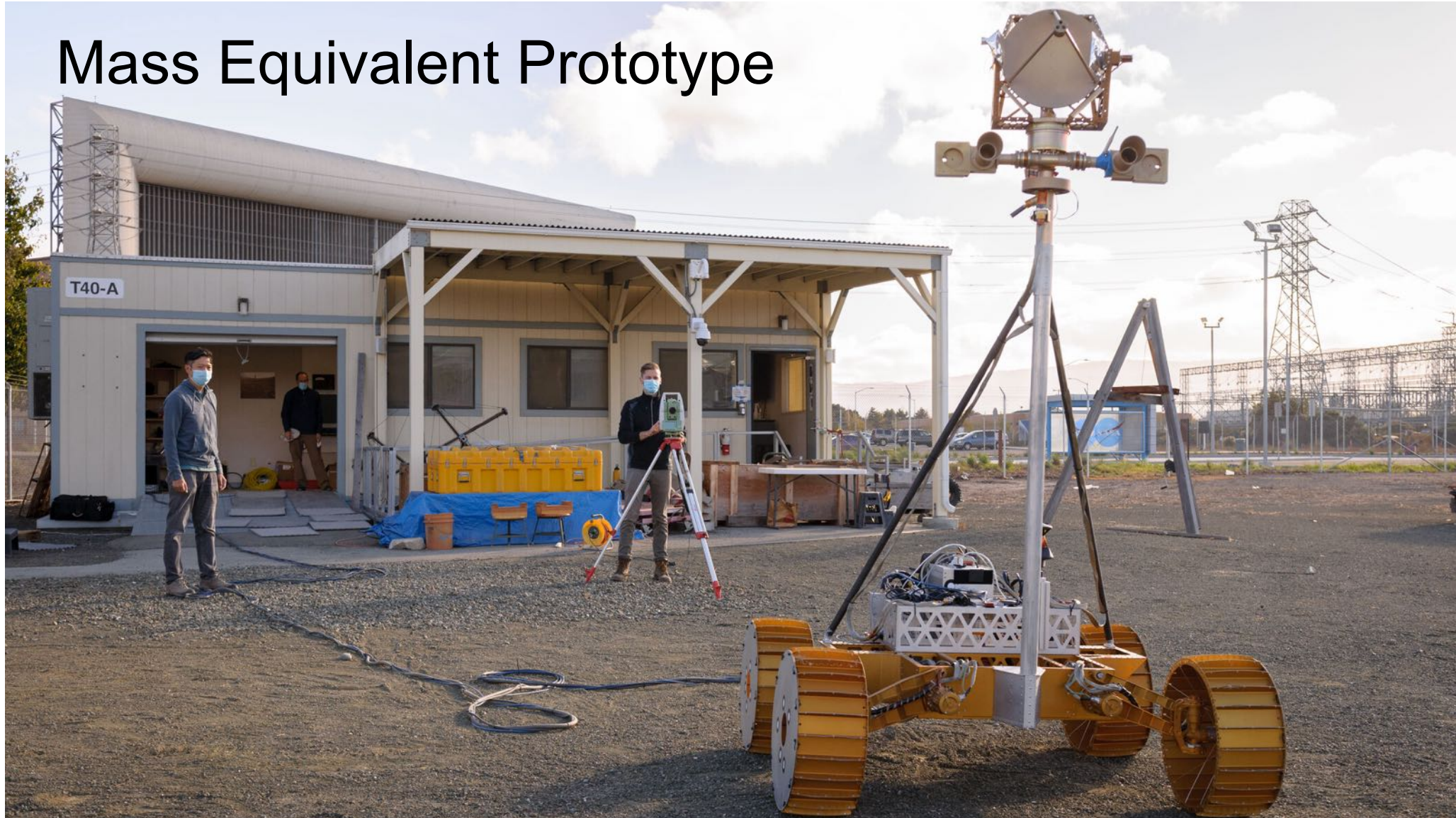
- 50 cm diameter, 20 cm wide
- Rigid sheet metal with spokes
- Rim grousers

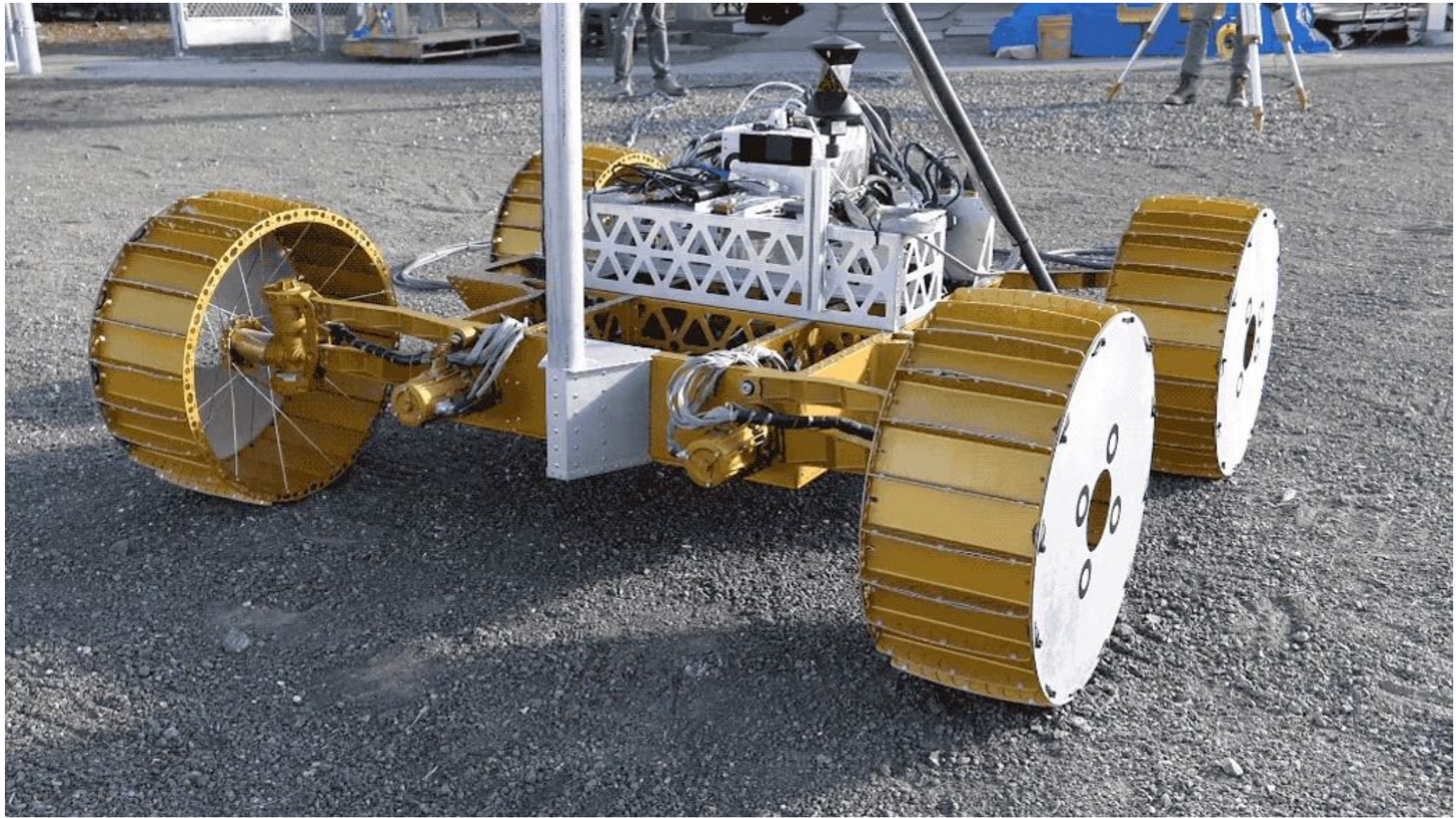
## Capabilities

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

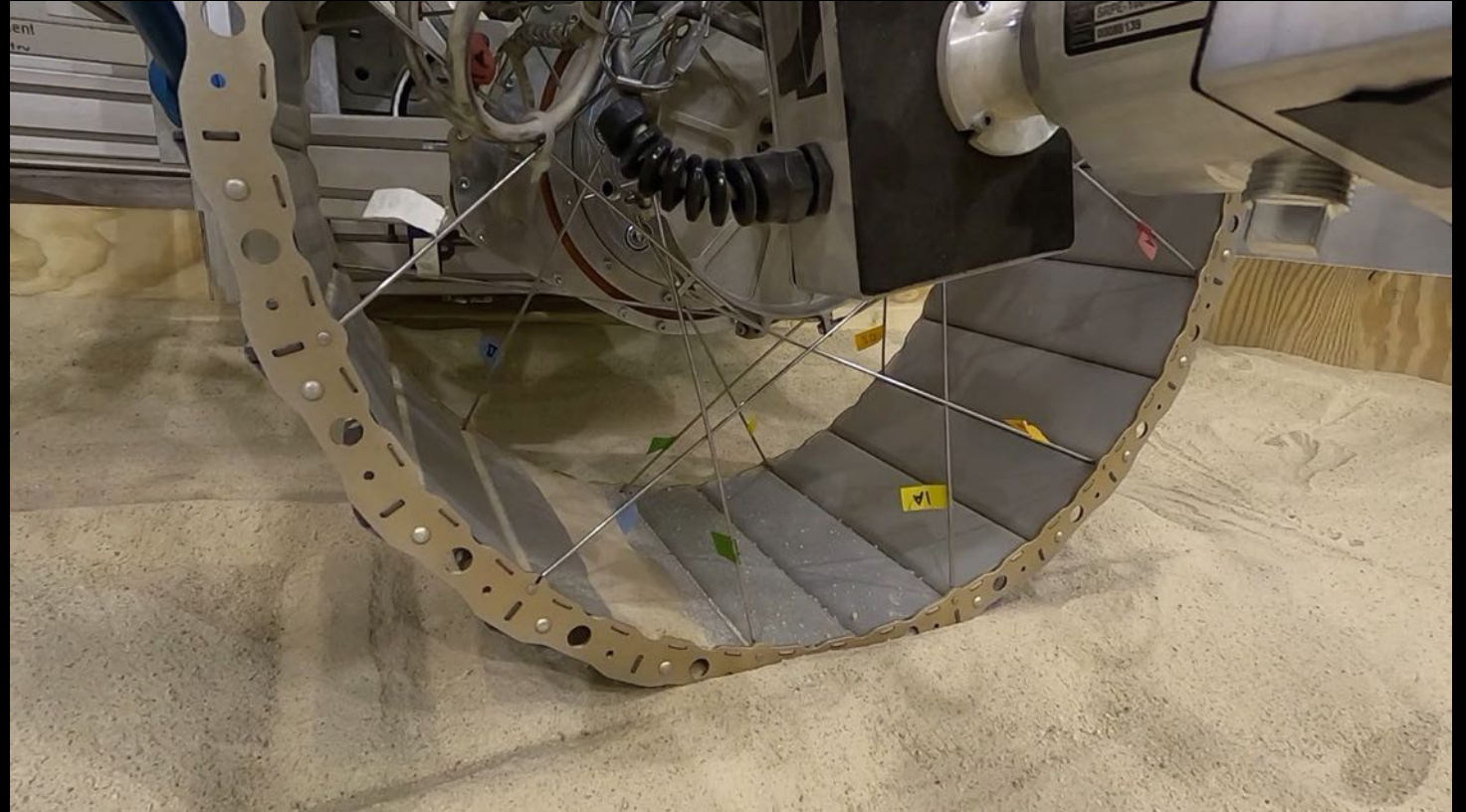


# Mass Equivalent Prototype





# Wheel Prototype Testing



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

# SLOPE Lab (NASA Glenn)

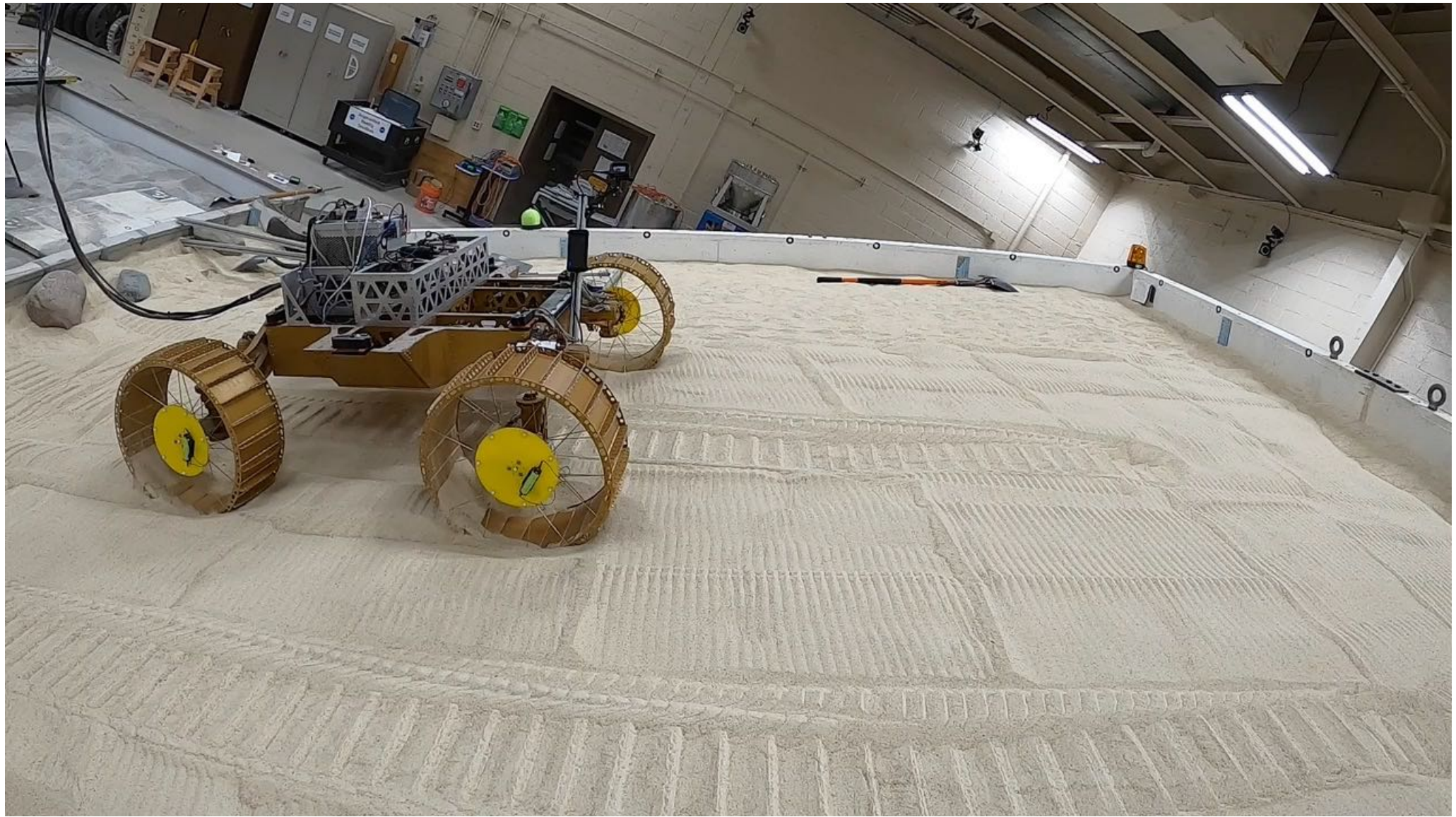


# Entrapment Testing



# Slip Testing



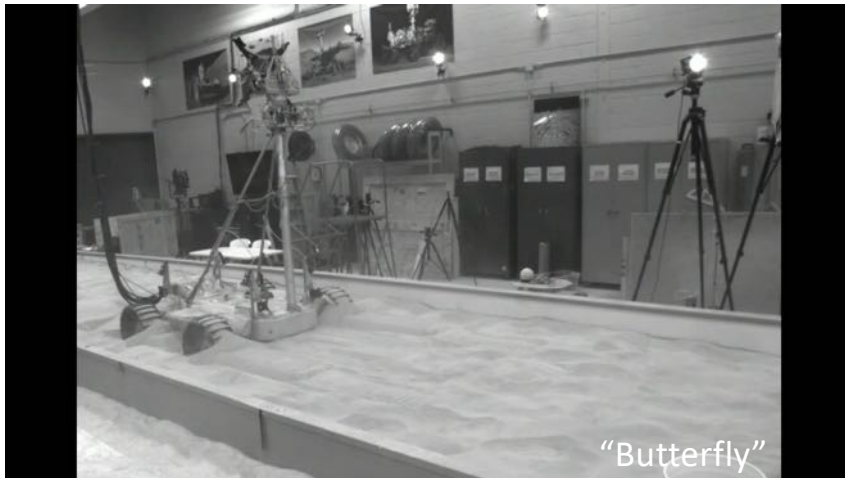


# Crater Traversal Testing



# Alternate Mobility Modes

*8x speed*



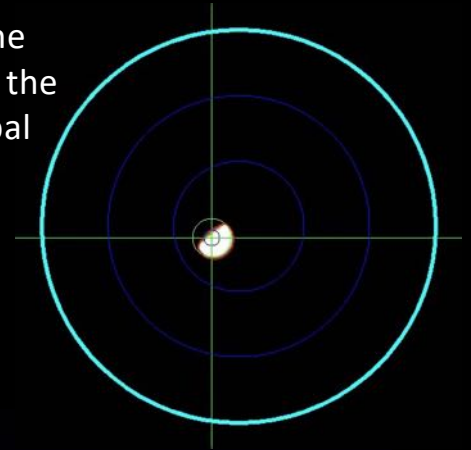
# Lander Egress Testing (NASA Johnson)



# 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

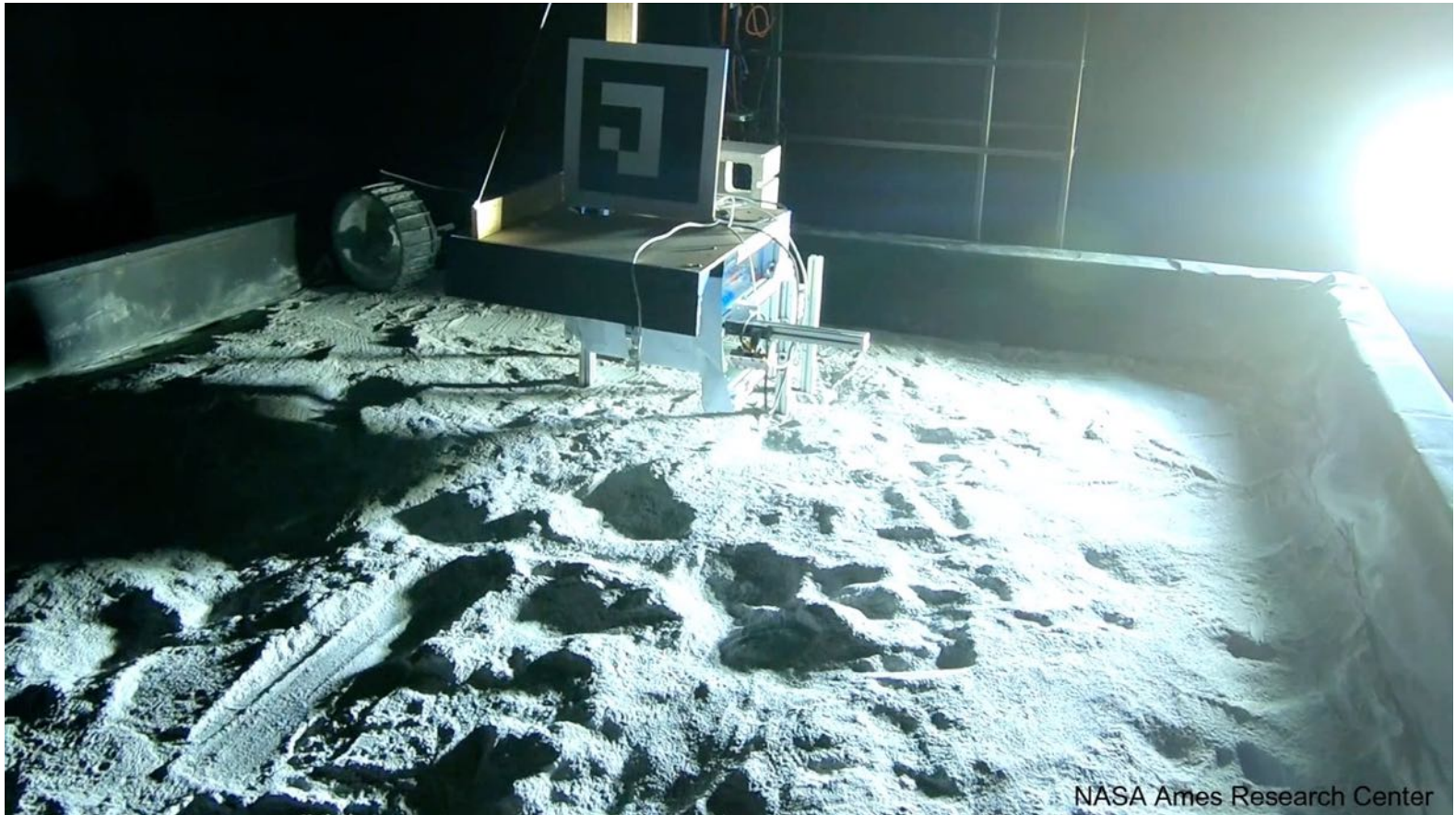


Engineering Unit Rover NavCam view with Sun Simulator from behind



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

# Camera & Light Testing Facility



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



# VIPER Mission Planning

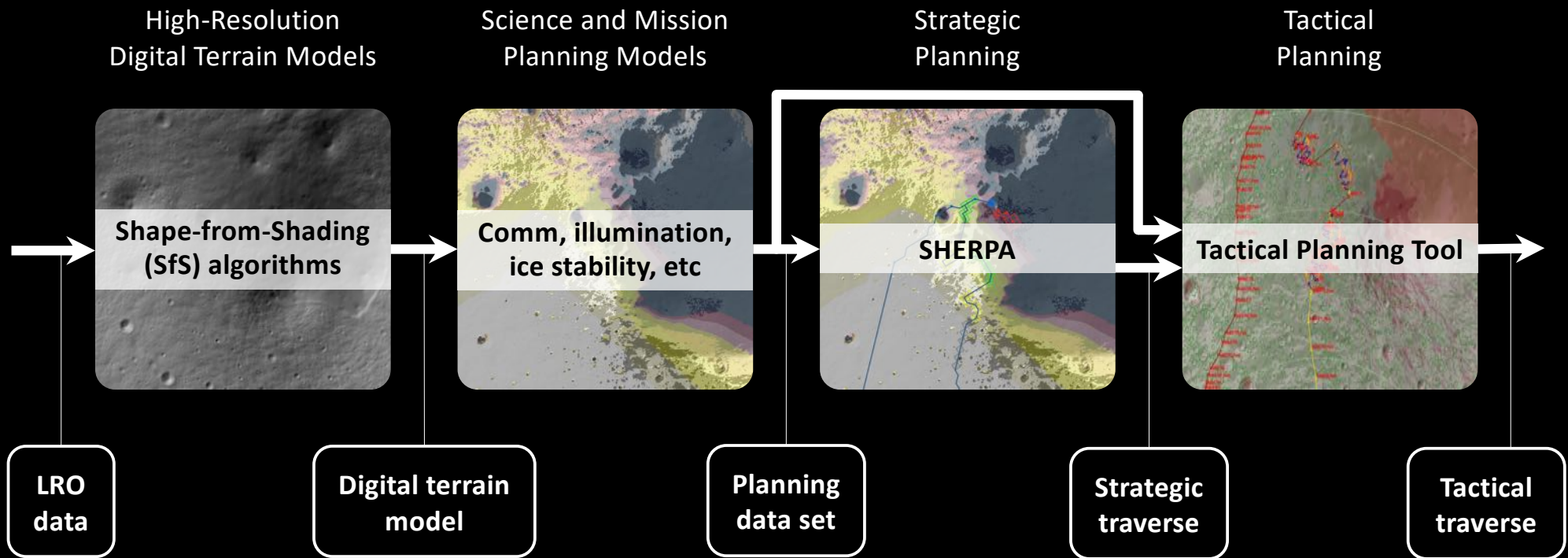
## Objectives

- 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

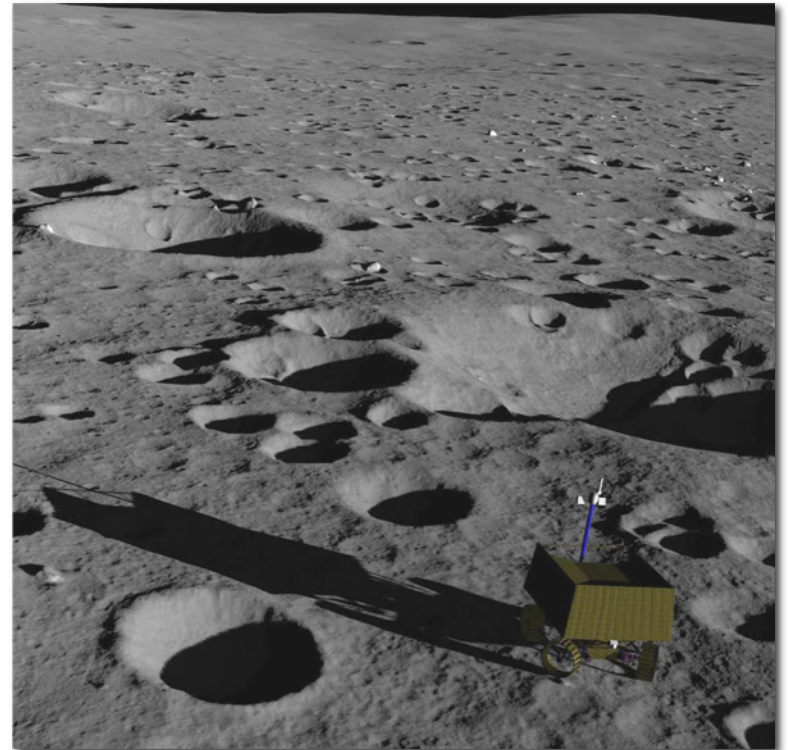




# VIPER RSIM (Rover Simulator)

## 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 ephemeris



*Lunar surface simulator  
based on Gazebo*



# Real-time Simulation Needs

## **ConOps Design**

- New type of robotic exploration mission
- Designed for the dynamic lunar environment
- Emphasis on high operational cadence and traverse speed

## **Software Development**

- Rapid technology development requires prototyping environment
- Agile software engineering requires continuous integration & testing
- Some planetary surface mission V&V can only be done in simulation

## **Mission operations training**

- “Real-time” mission control: rover operations + science team
- Hybrid of human exploration (Shuttle, Space Station) and Mars rover mission operations
- Mission ops development (procedures, flight rules, etc) best performed with continuous, high-fidelity mission simulation



# Real-time Simulation Innovations

## High-quality lighting

- Physics-based rendering (coherent backscatter / “opposition effect”)
- Direct + indirect solar illumination + “Earth-shine”
- Rover lights

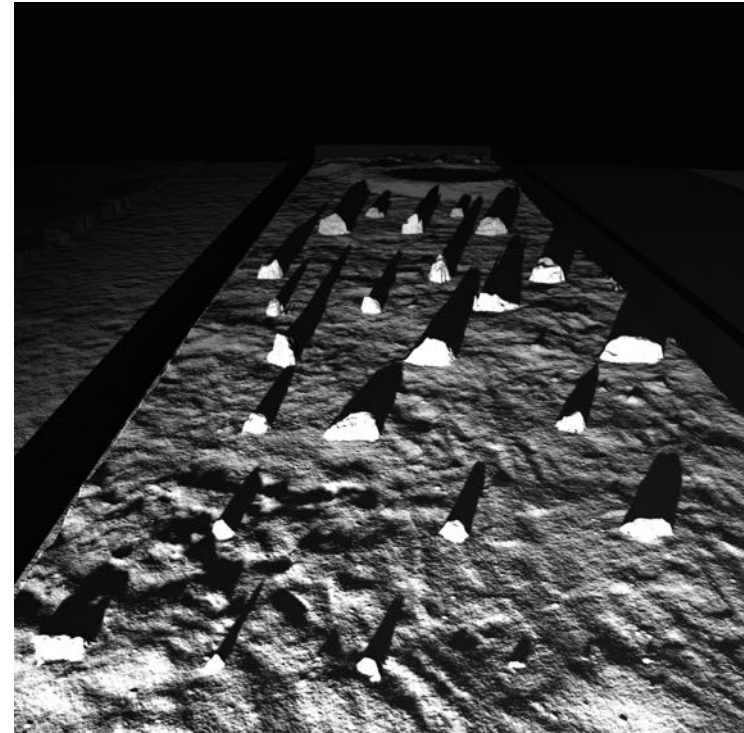
## High-quality camera models

- Produce images representative of what we expect during flight from both **human operator** and **computer vision** perspectives
- Models include:
  - Aperture
  - Depth of Field
  - Exposure
  - Focal Length
  - Lens Distortion
  - Optical Center
  - Vignetting
  - Bit Depth
  - Dark Current Noise
  - Fixed Pattern Noise
  - Modulation Transfer Function
  - Photon Shot Noise
  - Pixel Defects
  - Read Noise

# Simulation Results



*ARC "Lunar Lab"  
LHS-1 simulant + rocks +  
simulated solar illumination*



*RSIM  
3D (stereo vision) data +  
camera/light model*



# Synthetic Terrain

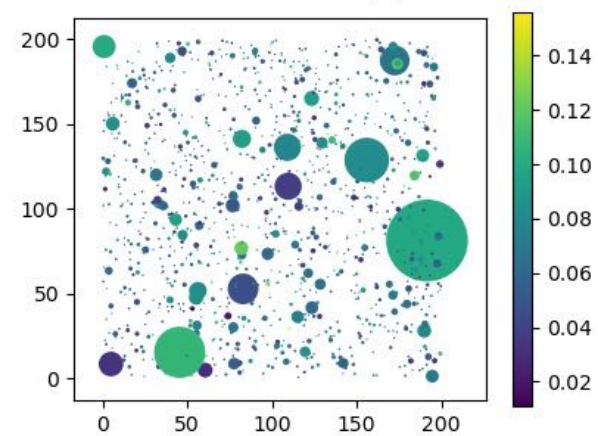
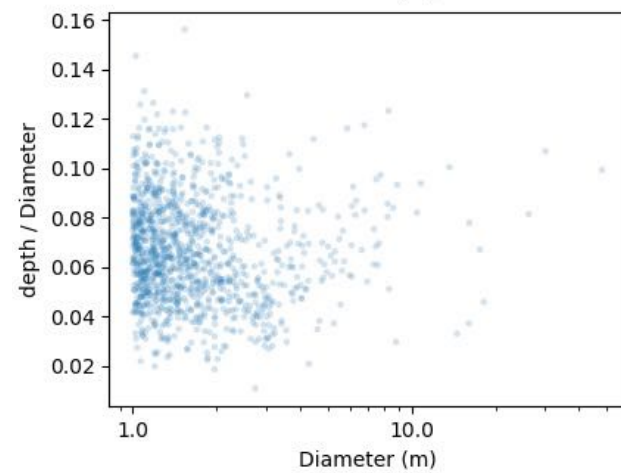
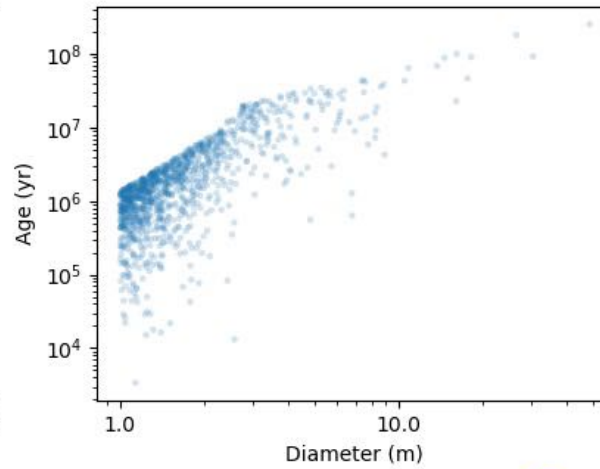
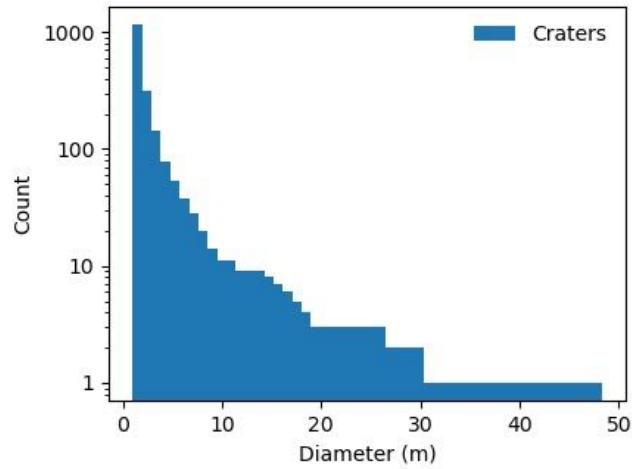
## **Purpose**

- Orbital data has limited spatial scale (generally 50 cm/pixel max image resolution and 2-3 m/pixel terrain model)
- Higher-resolution maps and terrain data are needed for conops studies, development of surface navigation systems, mission simulations, etc.

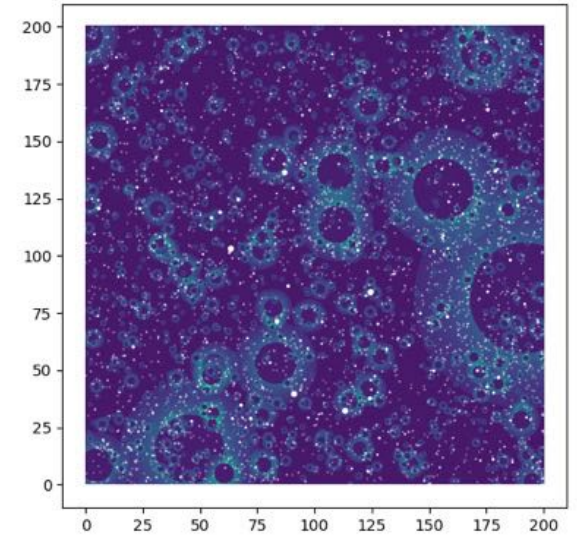
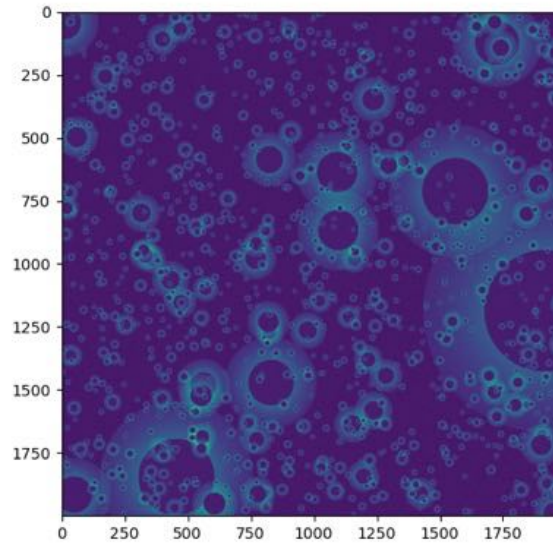
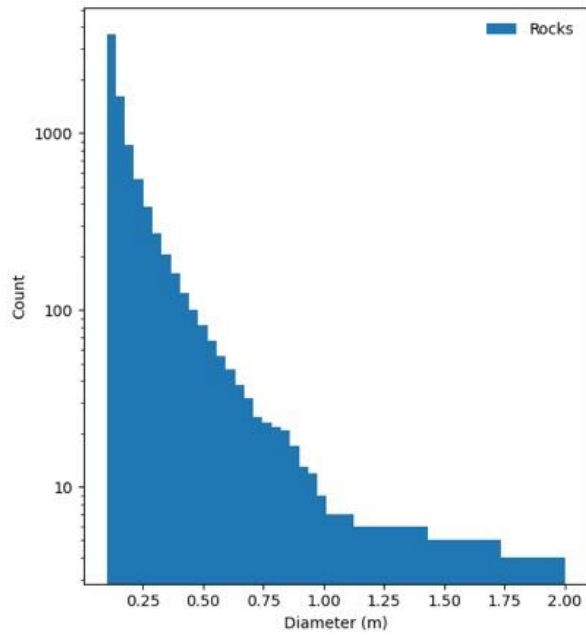
## **Scientifically plausible terrain models**

- Begin with highest resolution maps (source) derived from orbital data
- Use the last 60 years of planetary science research to:
  - Infer crater size-frequency distributions to small scales
  - Infer rock size-frequency distributions to small scales
- Synthetically enhance source maps via fractal synthesis (not interpolation) to create high-resolution maps
- Add synthetic craters and rocks based on size-frequency distributions
- Apply landscape diffusion to appropriately age shape of degraded craters

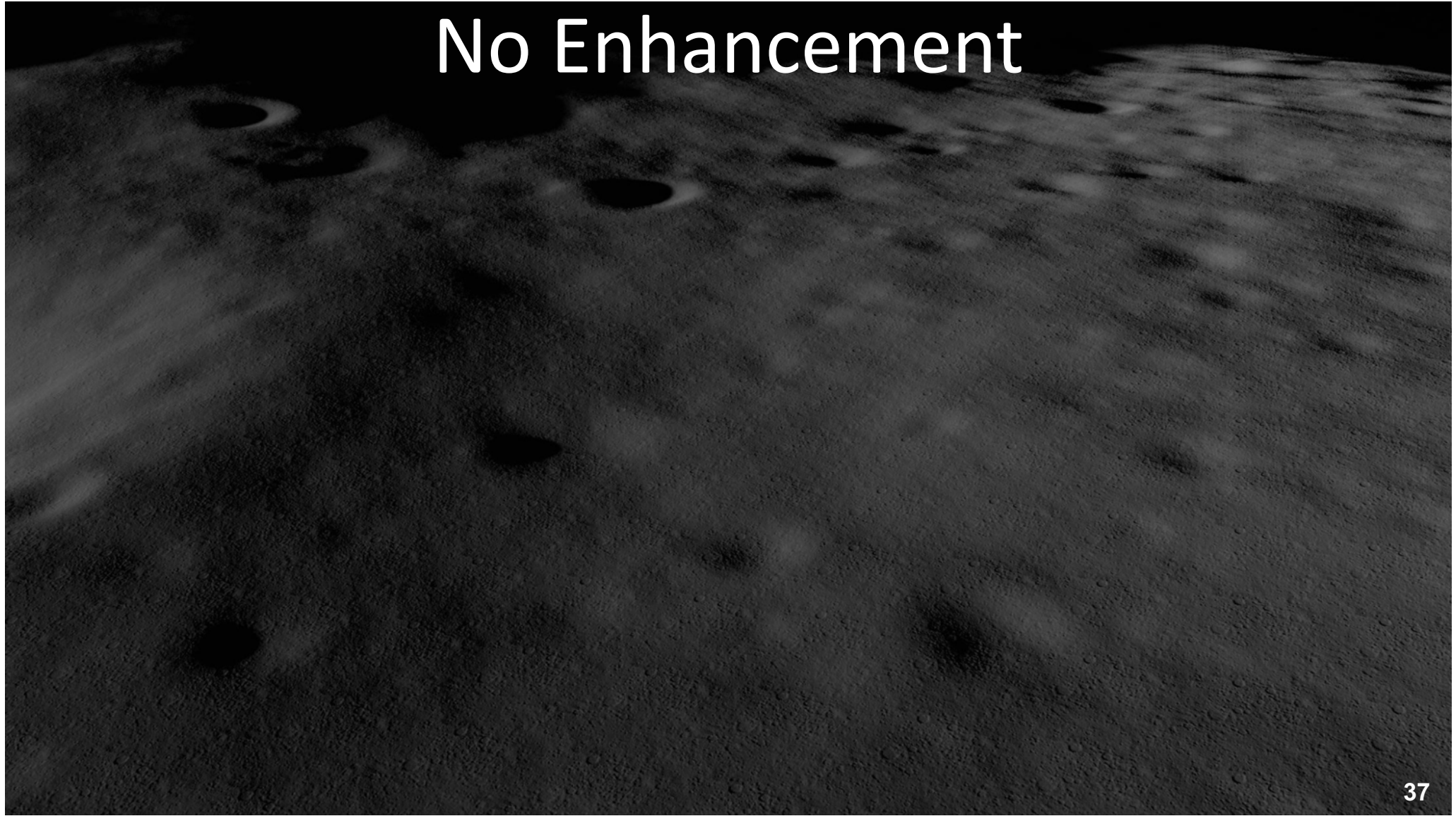
# Lunar Crater Models



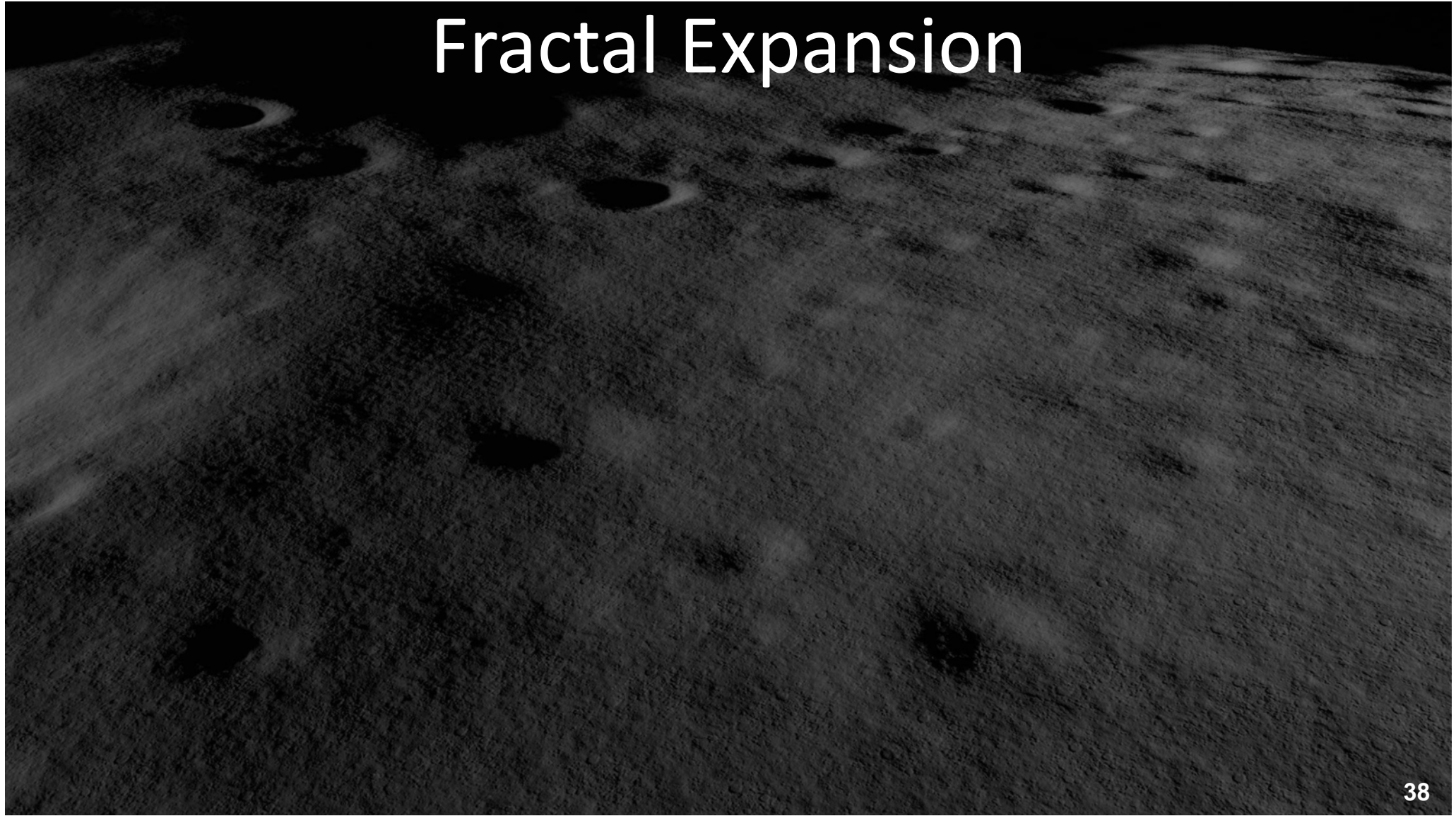
# Lunar Rock Models



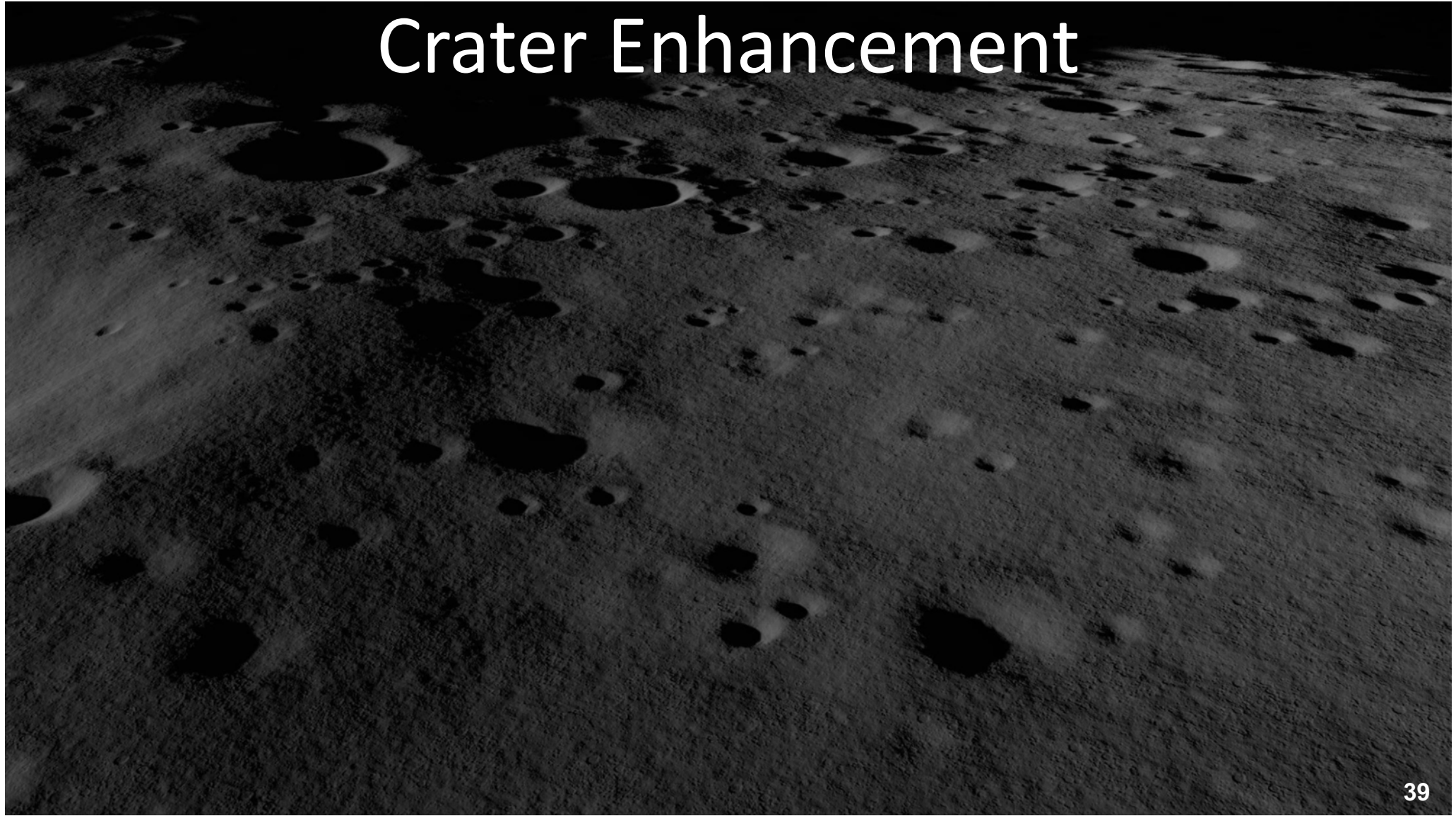
# No Enhancement



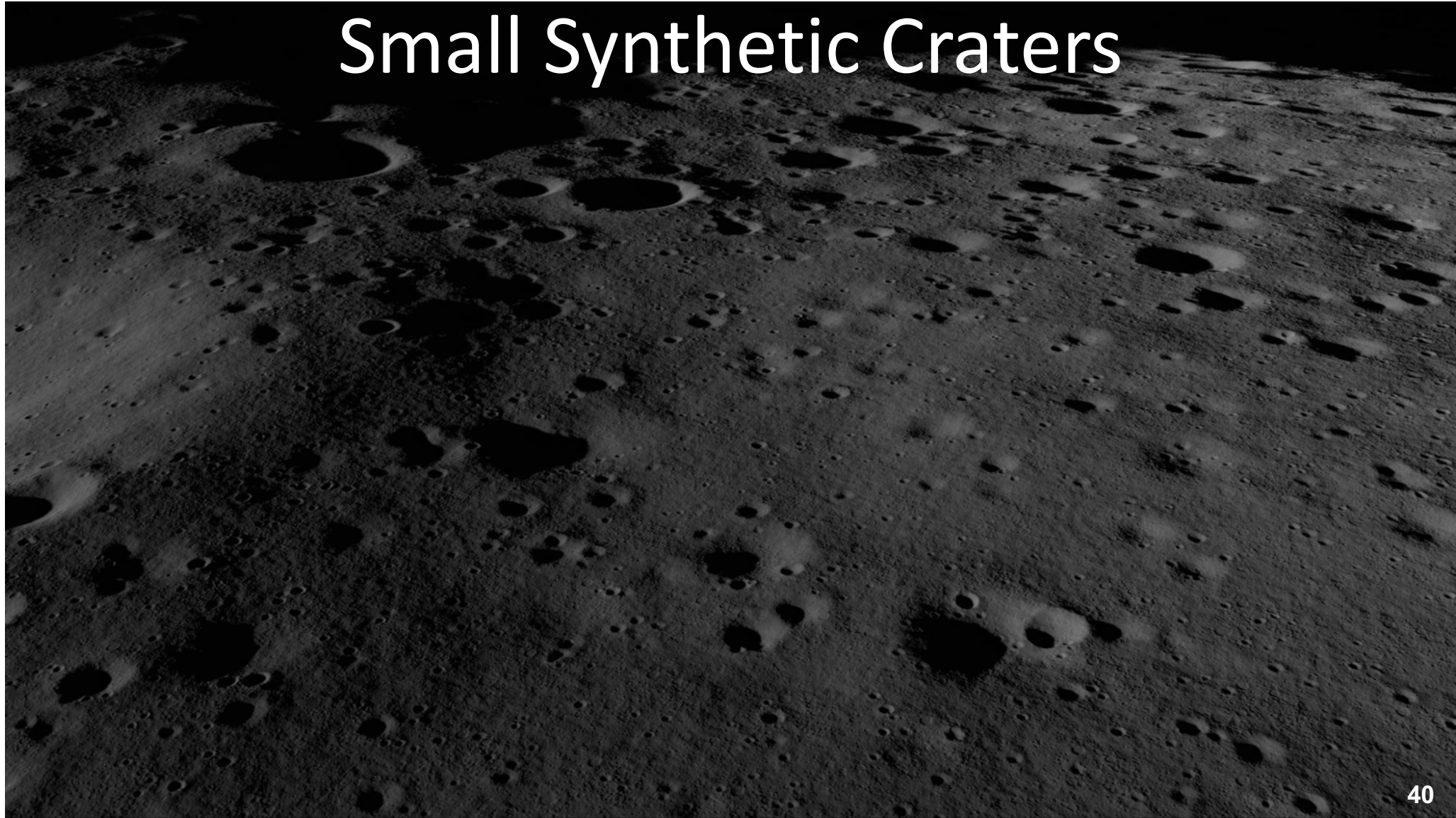
# Fractal Expansion



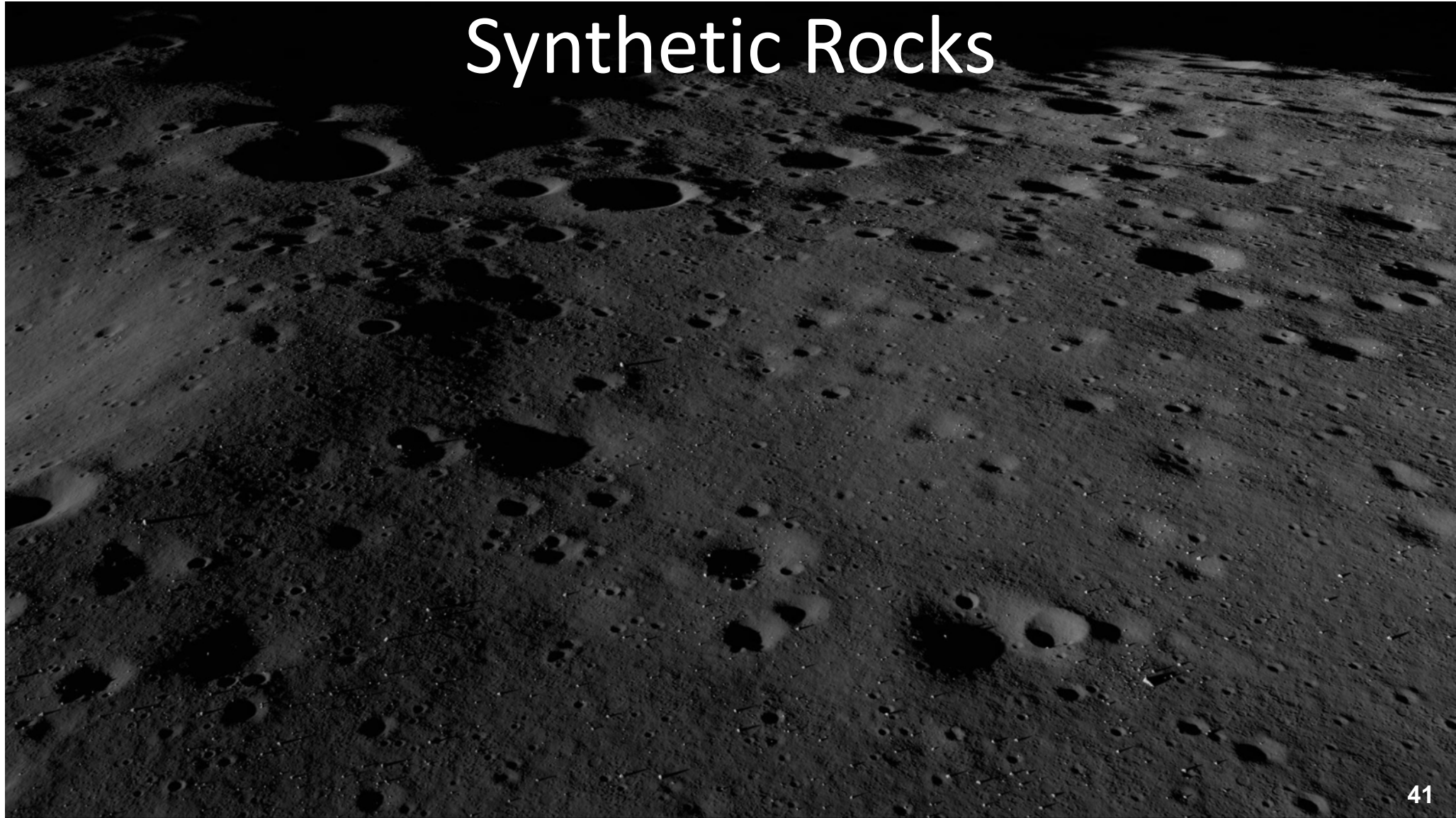
# Crater Enhancement



# Small Synthetic Craters



# Synthetic Rocks



A dark, high-contrast photograph of the lunar surface. The terrain is covered in numerous craters of various sizes, some with distinct shadows. In the lower-left quadrant, there are faint, winding tracks and a small, dark, rectangular object, likely a prototype rover, as mentioned in the caption. The overall scene is dimly lit, emphasizing the textures and shadows of the lunar landscape.

*Real-time shadows, rover tracks, prototype rover (2020)*

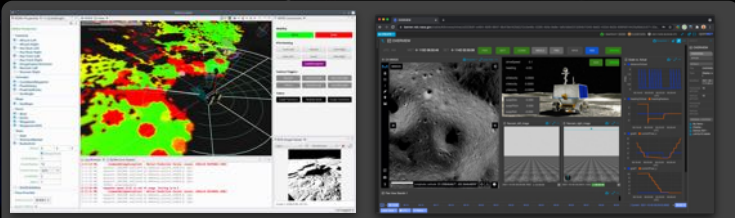


*High-resolution synthetic terrain & flight rover (2023)*

# Mission Operations Training



# VIPER Surface Mission



*Rover Driving*

*Mission Monitoring*

ARC

Systems & Execution

KSC  
MSOLO

JSC  
Rover Systems & Thermal

Comms round trip ~6 - 10 sec



Lander

Science Station

Traverse Points  
~ 50 m

Waypoints  
~ 5 m

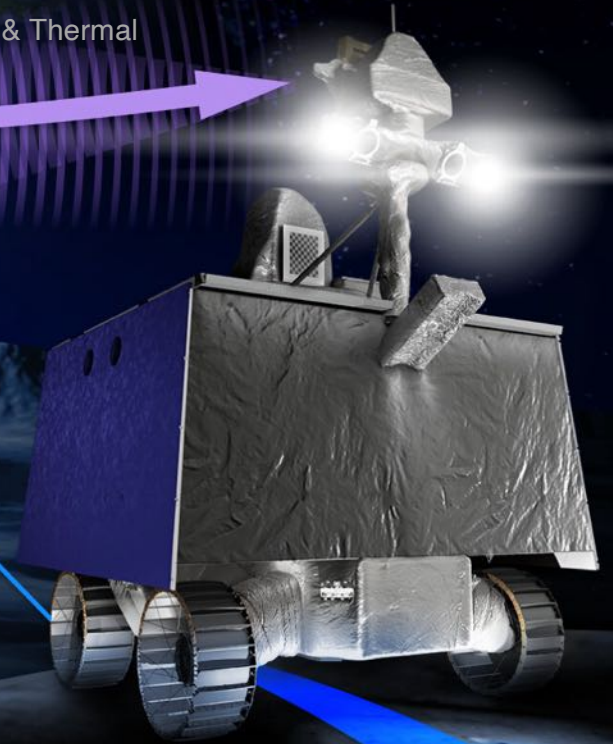
Drill A

Drill B

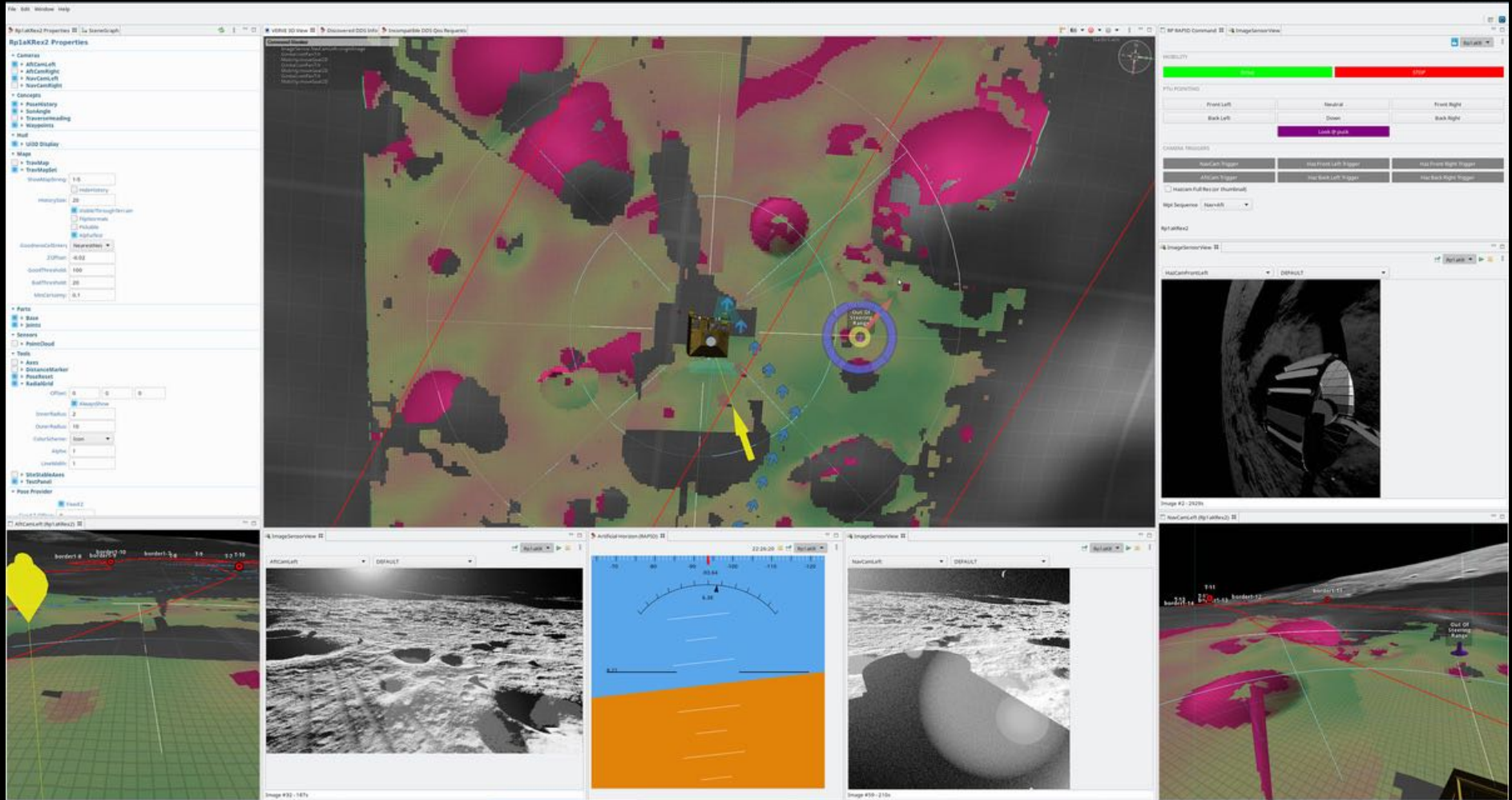
Drill C

Science Station

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



# VERVE: Rover Driving Interface



VERVE 3D View | Discovered DDS Info | Incompatible DDS Qos Requests

FollowCam

Commanded Initiator

- ImageSensor.RearCamLeftImage
- GimbalSetPanTilt
- ImageSensor.NavCamLeftImage
- ImageSensor.NavCamLeftImage
- GimbalSetPanTilt
- MobilizeMoveGoal2D
- GimbalSetPanTilt

RP RAP... | Image...

Rp1aKR

NavCam ont Left | Haz Fro | Haz Fro

Rear Car ear Left | Haz Rez ar Right

Neutral | T Down | PT Zero

STOP

Exp:Low | xp:Med | xp:High | Exp:Ext

ights On | ights Off | Fake Pa

Rp1aKRex2

ImageSensorView

Rp1aKR

NavCe | DEFAI

Image #6

ImageSenso... | ImageSenso... | ImageSensorView

RearCam | DEFAULT

HazCamf | DEFAULT

Artificial Horizon (RA...)

20:12:38 | Rp1aKR

-40 -50 -60 -70 -80 -90

163.64

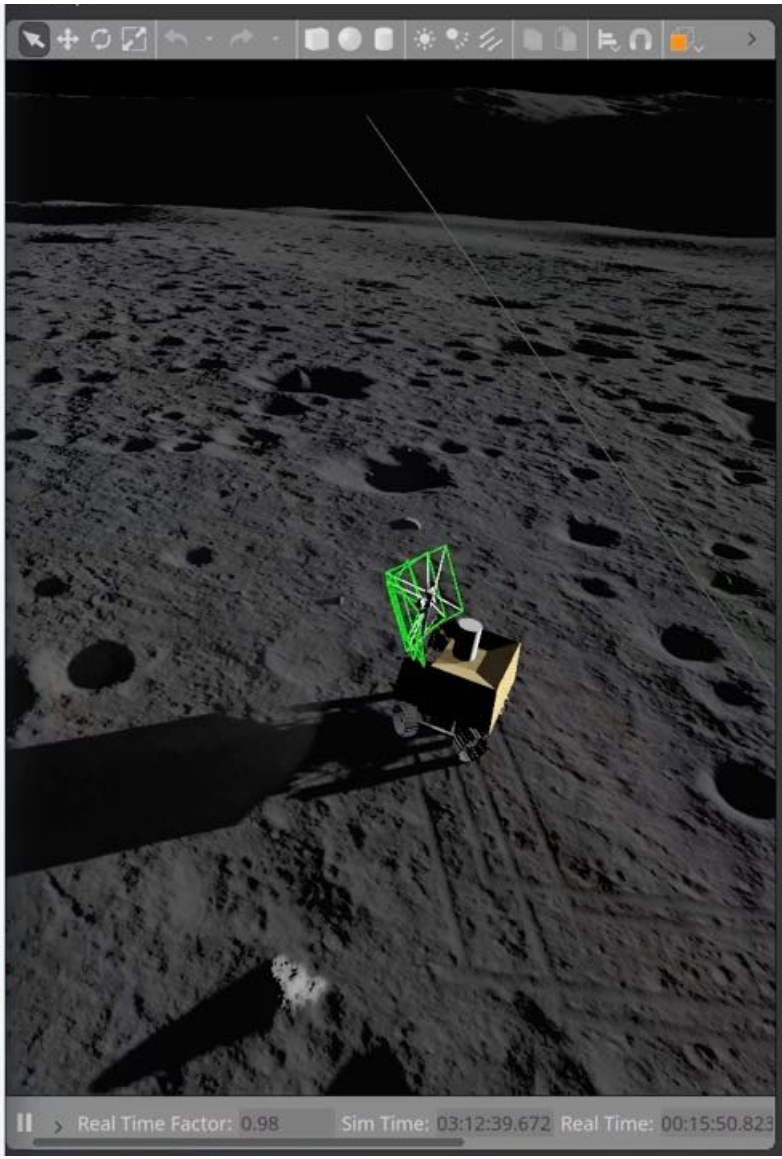
9.38

4.92

Image #4

Image #2

Image... | NavCa...





[www.nasa.gov/viper](http://www.nasa.gov/viper)

*Image courtesy of Astrobotic*