

National Aeronautics and Space Administration

VIPER

Volatiles Investigating Polar Exploration Rover

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NASA Ames Research Center

June 28, 2023

Just Two Decades Ago…

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

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

The ”general” thinking was:

- Surface was relative constant
- Thin exosphere of Argon, Sodium and Potassium
- Bone dry (~100 ppm of water in soils)



Some believed water could exist on the Moon

1961 JGR

The Behavior of Volatiles on the Lunar Surface[1]

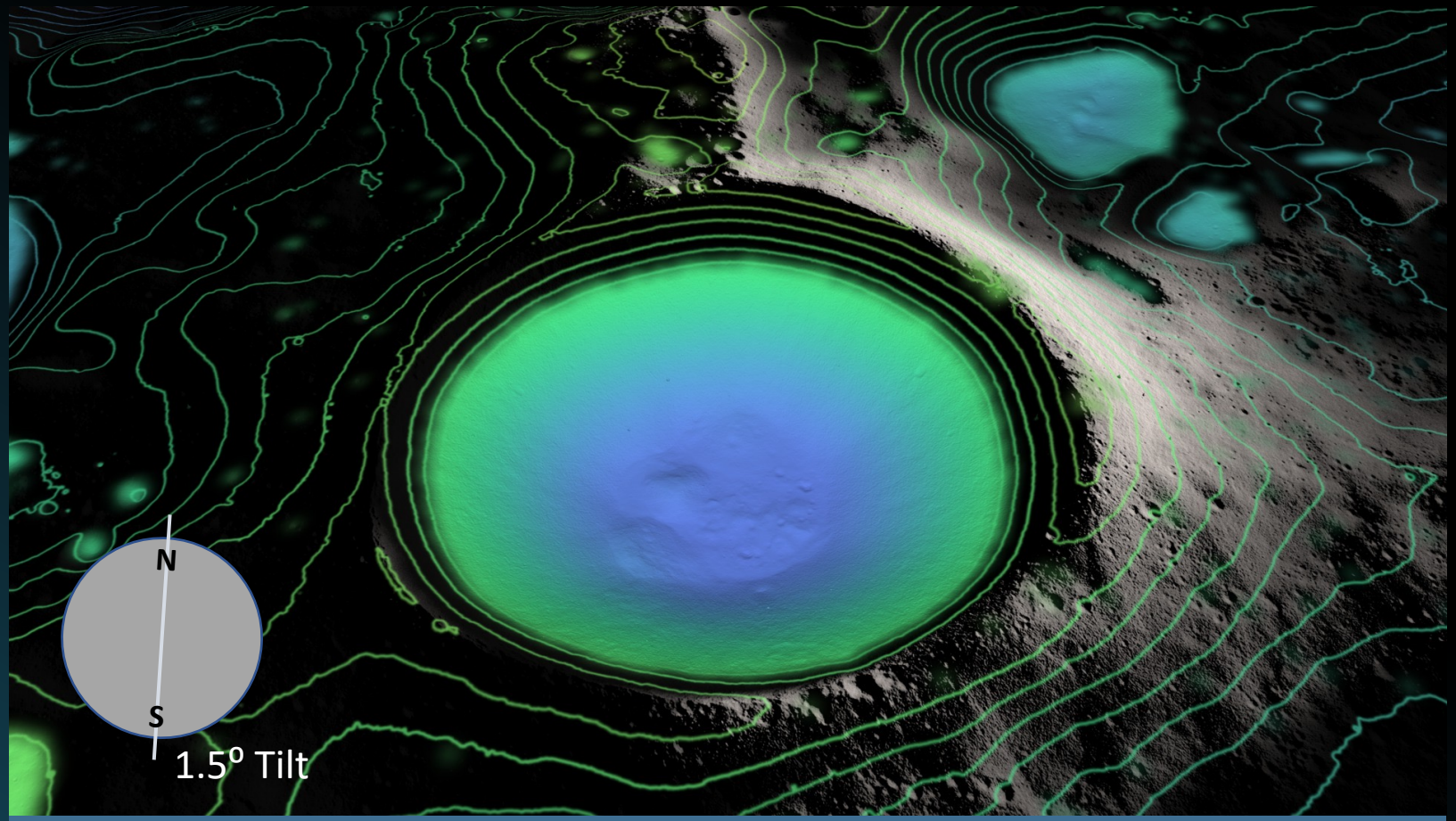
KENNETH WATSON, BRUCE C. MURRAY, AND HARRISON BROWN

Division of Geological Sciences, California Institute of Technology
Pasadena, California

Abstract. Volatiles, and water in particular, have been thought to be unstable on the lunar surface because of the rapid removal of constituents of the lunar atmosphere by solar radiation, solar wind, and gravitational escape. The limiting factor in removal of a volatile from the moon, however, is actually the evaporation rate of the solid phase, which will be collected at the coldest points on the lunar surface. We present a detailed theory of the behavior of volatiles on the lunar surface based on solid-vapor kinetic relationships, and show that water is far more stable there than the noble gases or other possible constituents of the lunar atmosphere. Numerical calculations indicate the amount of water lost from the moon since the present surface conditions were initiated is only a few grams per square centimeter of the lunar surface. The amount of ice eventually detected in lunar 'cold traps' thus will provide a sensitive indication of the degree of chemical differentiation of the moon.

Watson et al. 1961 set expectations that the Moon's poles might hold volatiles including water

Permanently Shadowed Regions (PSRs) on the Moon



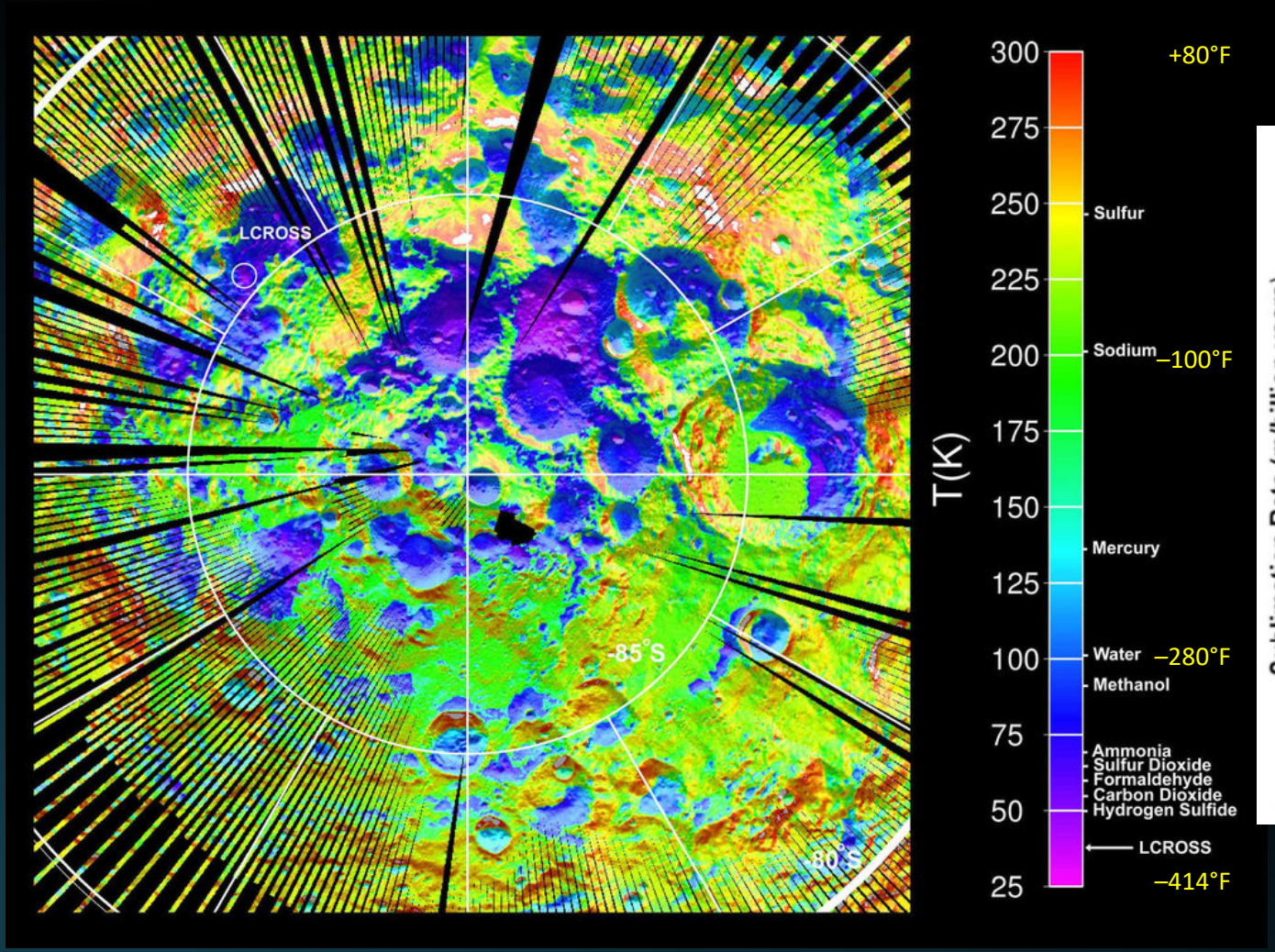


Near the pole, Sun against topography casts long shadows

- Low Moon inclination
- At high latitudes, topography creates permanently shadowed regions
- >10^4 km^2 area
- Exist on size scales ranging from the sub-mm (micro) to 10 km

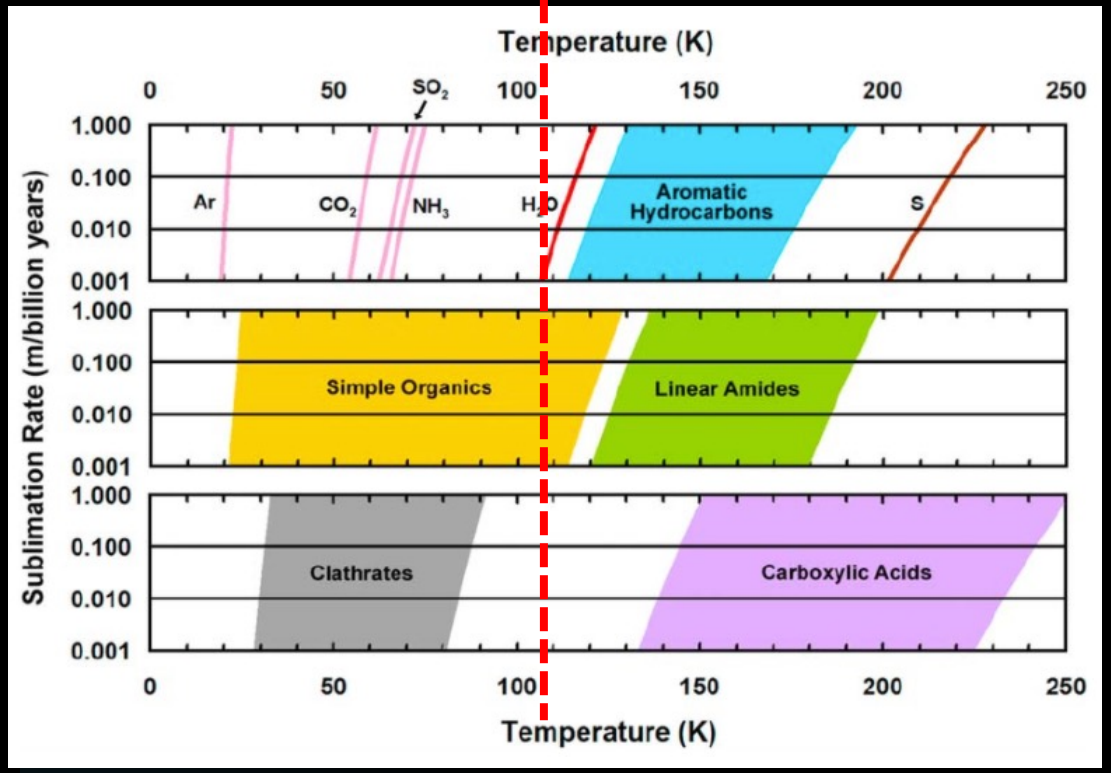
https://svs.gsfc.nasa.gov/4043

Temperature and Volatile Stability



Paige et al. 2010

more volatile than water | less volatile than water



Zhang & Paige 2009



Clementine (1994):
Bi-static radar tests revealed curious findings at the poles... *Water-ice?*

Lunar Prospector (1998): Neutron measurements reveal shadowed craters contain elevated Hydrogen levels… *Water-ice?*

LCROSS/LRO (2009):
Shadowed Crater Impactor confirms **subsurface water-ice**. *How is the water-ice distributed?*

Chandrayaan-1 (2018):
M^3 instrument confirms **surface ice** at the poles. *How is the water-ice distributed?*

VIPER (2024–2025):
Will prospect for water-ice on human scales, creating water resource maps of the polar regions

The Hunt for Lunar Volatiles

VIPER Science Objectives

National Aeronautics and Space Administration



- Characterize the distribution and physical state of lunar polar water and other volatiles in lunar cold traps and regolith to understand their origin.
- Provide the data necessary for NASA to evaluate the potential return of in-situ resource utilization (ISRU) from the lunar polar regions.

VIPER will make those desired surface (and subsurface) water ice measurements

Resource Mapping

Sufficiently characterize an area to evaluate the resource potential and/or physical processes that govern distribution

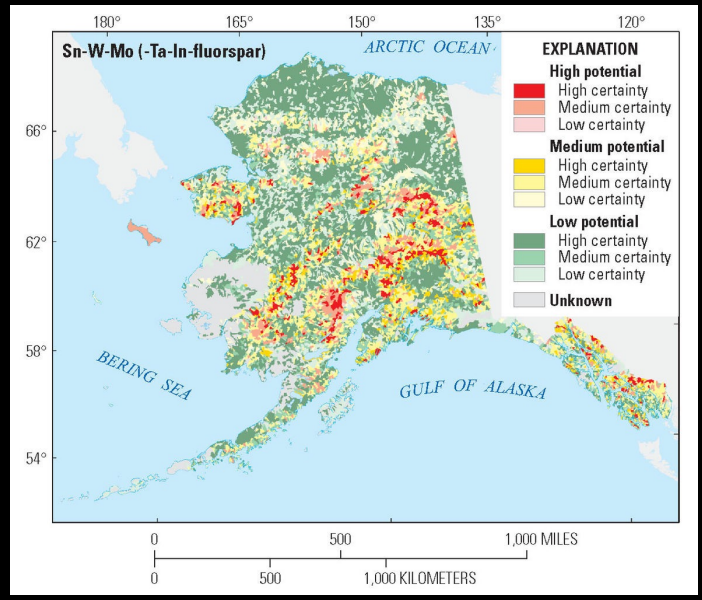
- Terrestrial mining companies develop “Mineral Models” for production evaluation
- The “Mineral Model” for lunar water is uncertain, but the same techniques can be applied

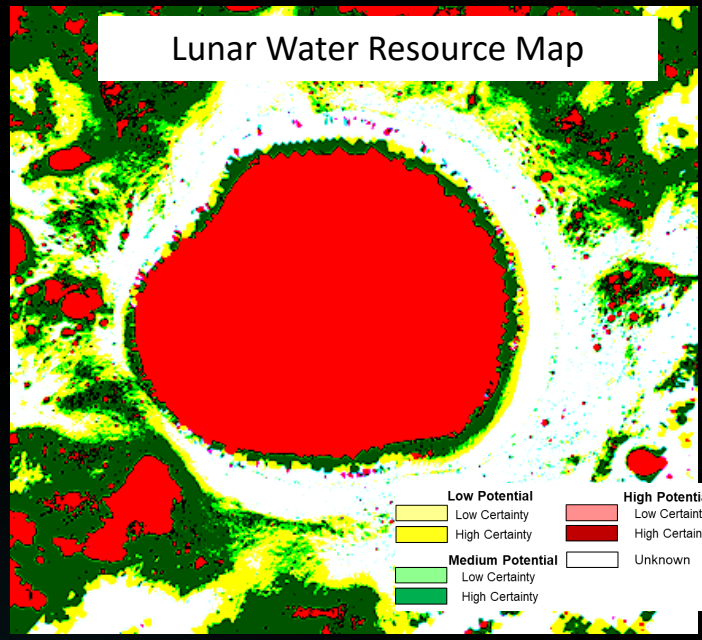
Demonstrated (e.g., USGS) Methods to Characterizing a Resource

- Gather data – map where the materials are
- Explore spatial variability – horizontal and vertical distribution
- Develop and test empirical and theoretical models and validate

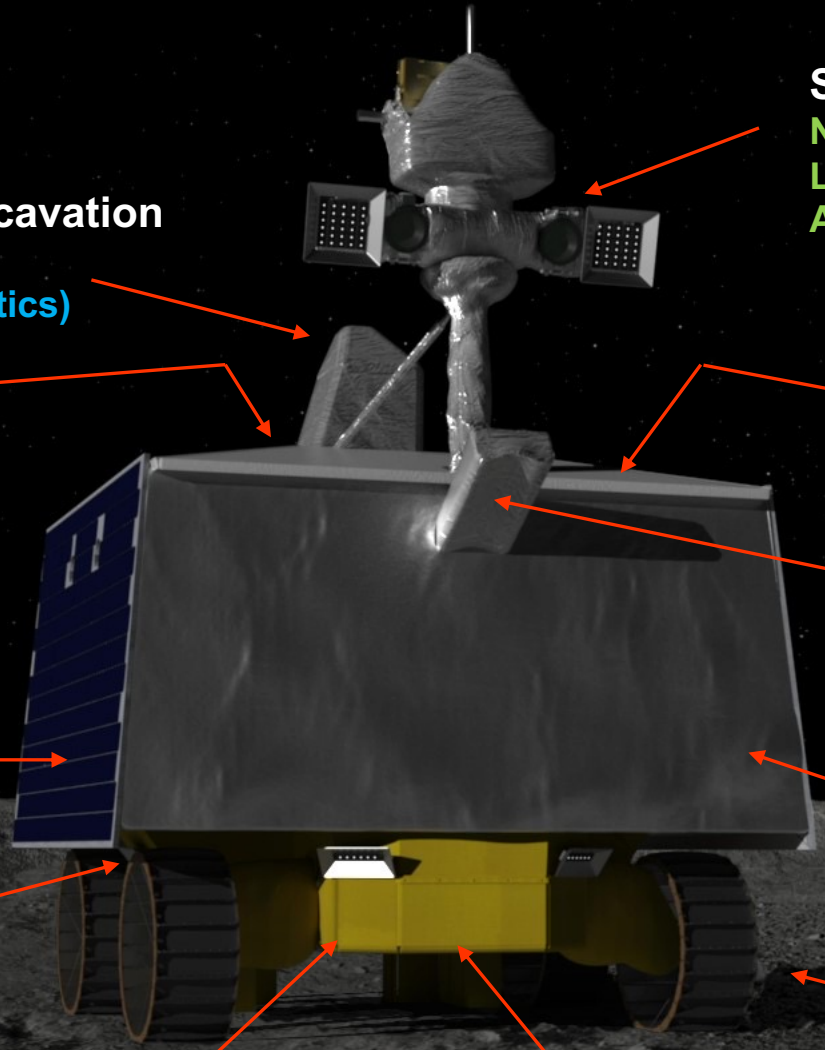
Requirements for the mission

- Wide-ranging mobile rover, with (relatively) fast speed
- Instruments that can detect water and other volatiles while driving
- Ability to sample the subsurface
- Need to survive for weeks, through communication loss and darkness
- Investigate 4 potential ice stability types: surface, shallow, deep, dry





VIPER Rover



Situational Awareness & Comm
Nav Cams (1pr)
Lights (1pr)
Antenna Mast

Subsurface excavation
TRIDENT Drill
(Honeybee Robotics)

Localization
Star tracker

Heat Rejection
Radiator (on top)

Situational Awareness
Aft Cams (1pr)
(in back)

Prospecting
Neutron Spectrometer System (NSS) Instrument
(Ames Research Center)

Power
Solar Array (3-sides)

“Warm Box” (internal)
Flight Avionics
Instrument Avionics

Situational Awareness
Hazard Cams (2 cams x 2 sides)

Mobility (x 4)
Steerable Wheel
Adjustable Suspension

VIPER Rover
(JSC h/w, Ames s/w)

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

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

As part of the Commercial Lunar Payload Services (CLPS) program
NASA has selected Astrobotic Technology to deliver VIPER
to the lunar South Pole in late-2024 aboard their Griffin Lander

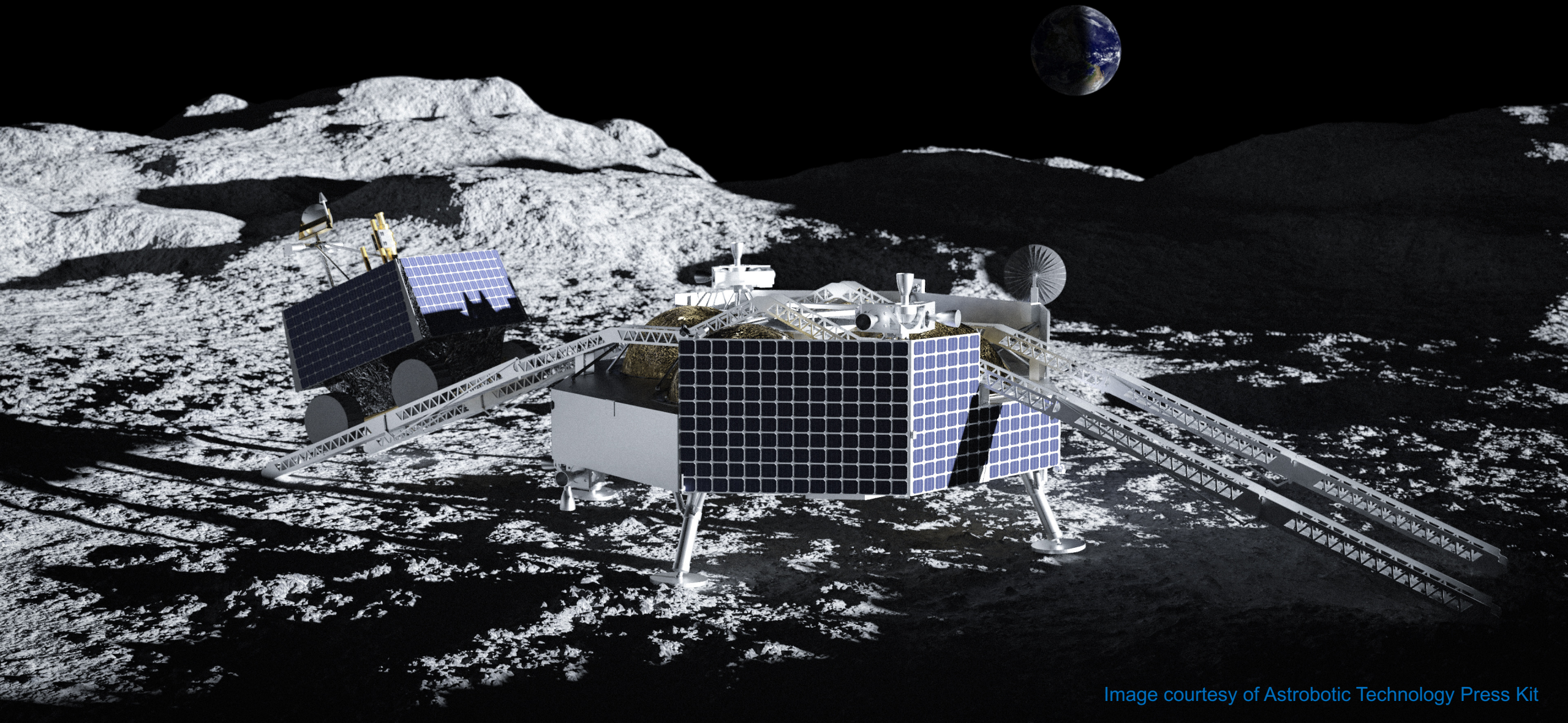
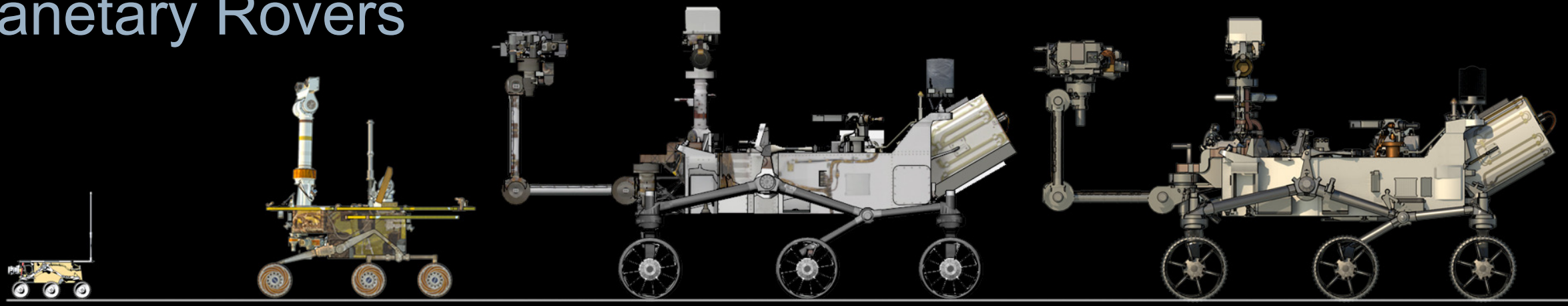


Image courtesy of Astrobotic Technology Press Kit

Planetary Rovers

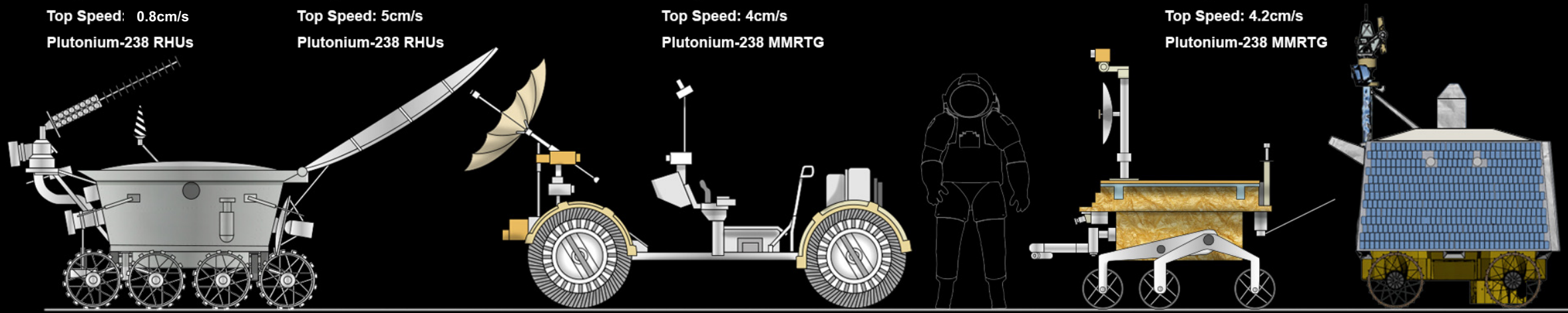


Sojourner (1996)
0.6m x 0.5m x 0.3m
11kg
Top Speed: 0.8cm/s
Plutonium-238 RHUs

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



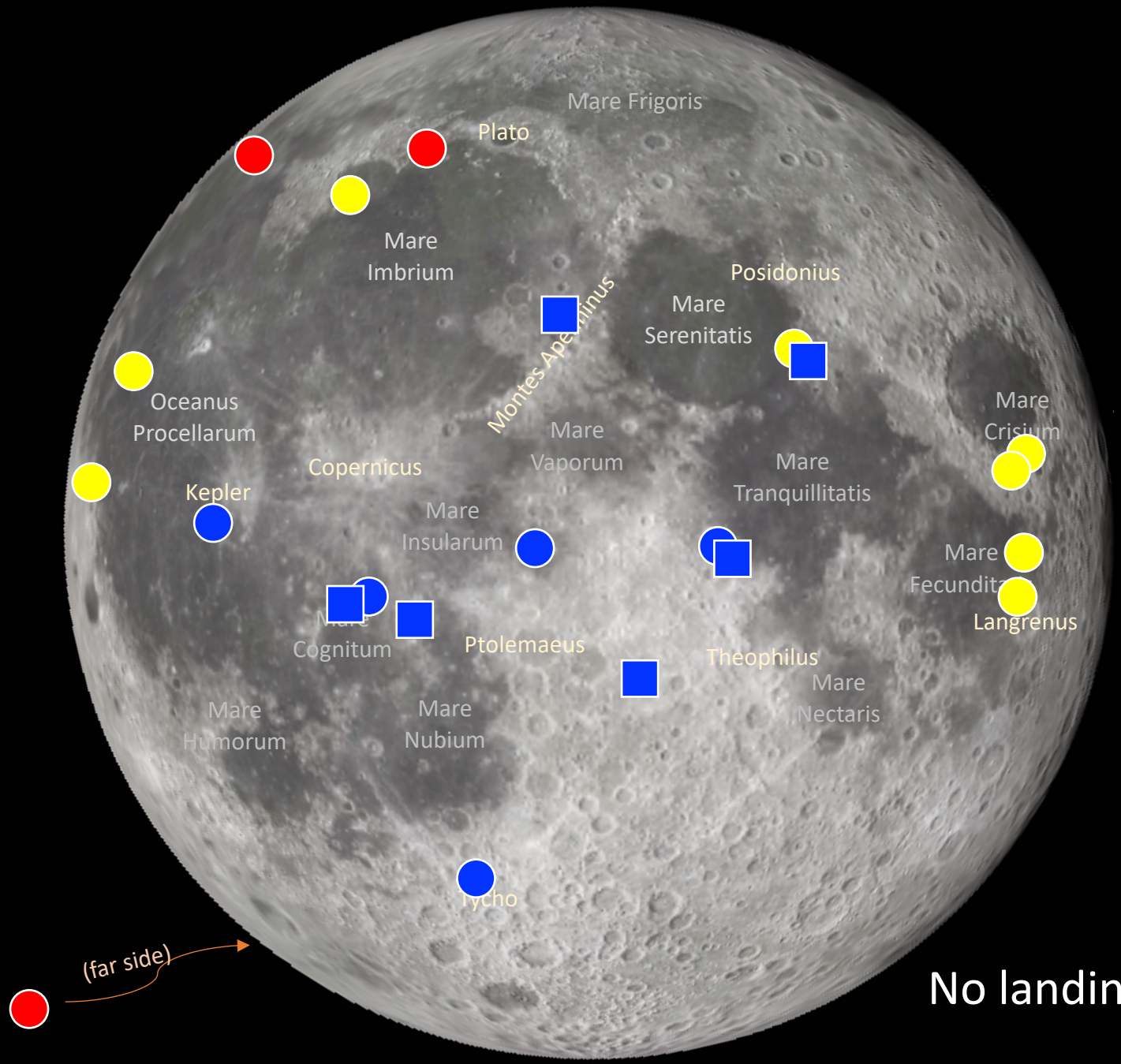
Lunokhod 1 & 2 (1970/1973)
2.3m x 1.6m x 1.5m
840kg
Top Speed: 55cm/s
Polonium-210 heat source

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 (2023)
1.5m x 1.5m x 2.0m
430kg
Top Speed: 20cm/s
Electric heaters only



Human

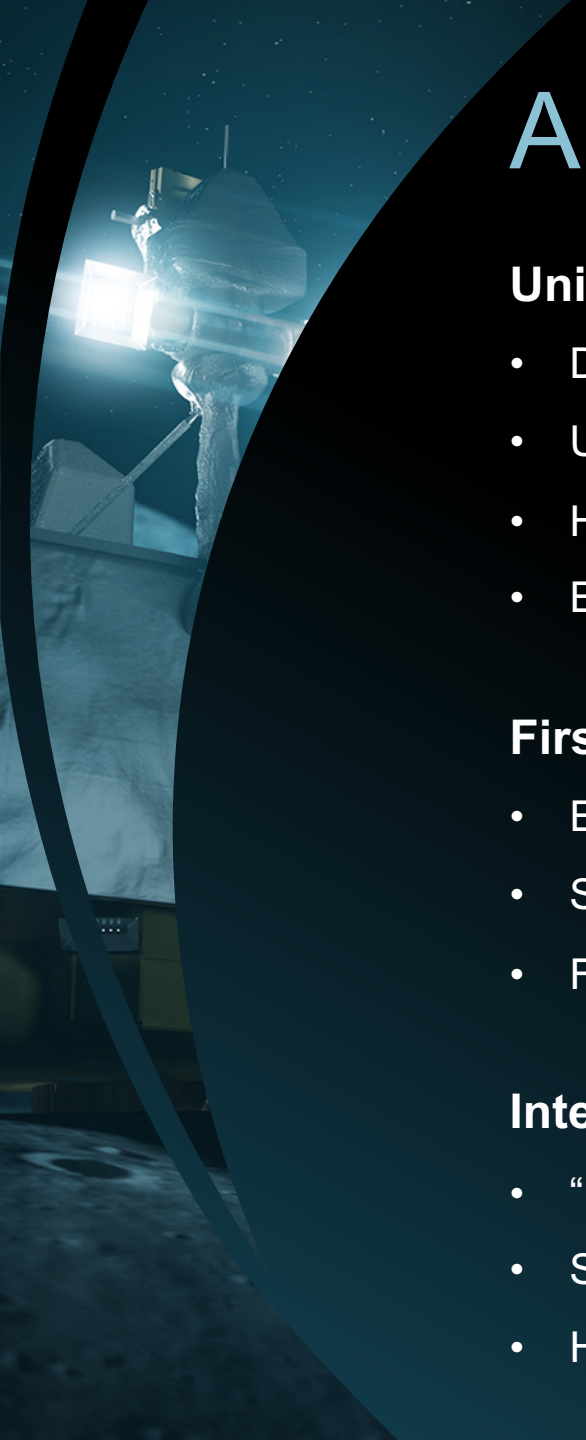
Robotic

USA

USSR

China

No landings yet on the poles



A New Type of Planetary Rover

Unique challenges

- Demanding lighting environment – sharp contrasts, long shadows
- Uncertain lunar pole “trafficability”
- Highly variable temperatures – ~40K (–390F) in PSR, to 300K (+80F) in sun
- Earth communication only about half each lunar day

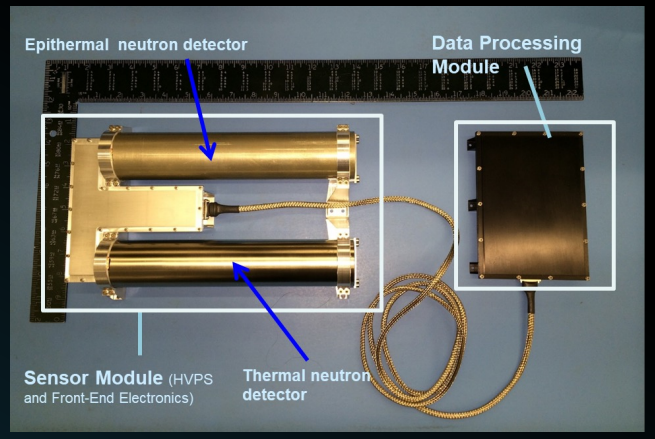
First NASA lunar rover

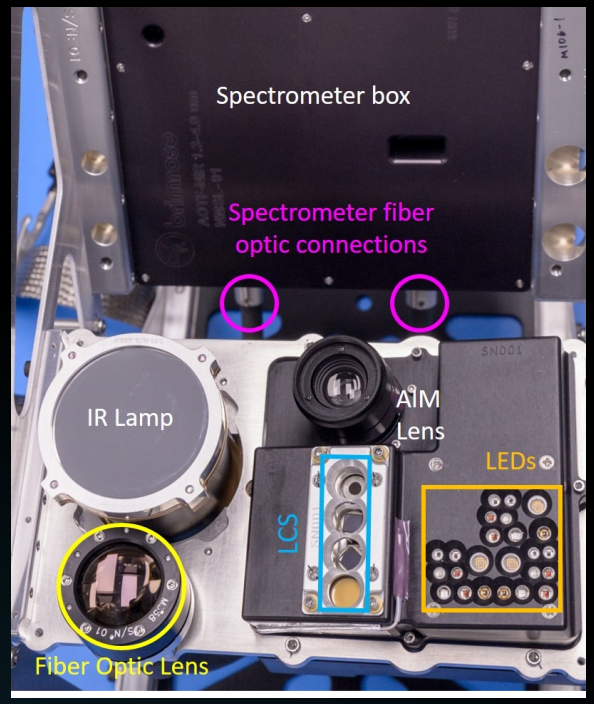
- Emphasis on high operational cadence and traverse speed
- Significantly lower cost than Mars rovers (but higher risk)
- Flight software split between on-board and ground

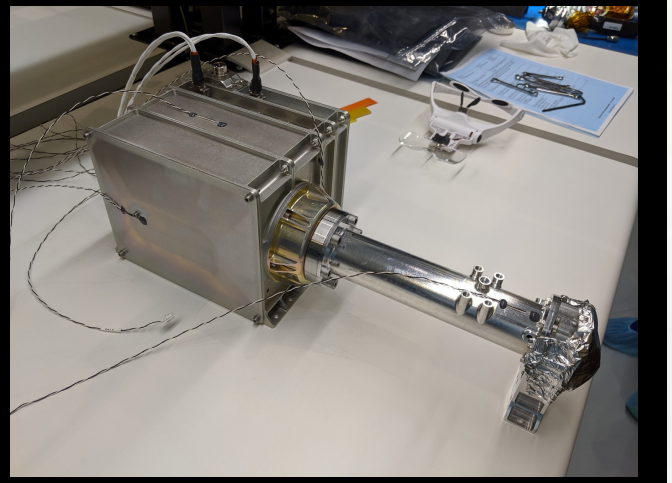
Interactive operations

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

VIPER Science Payload

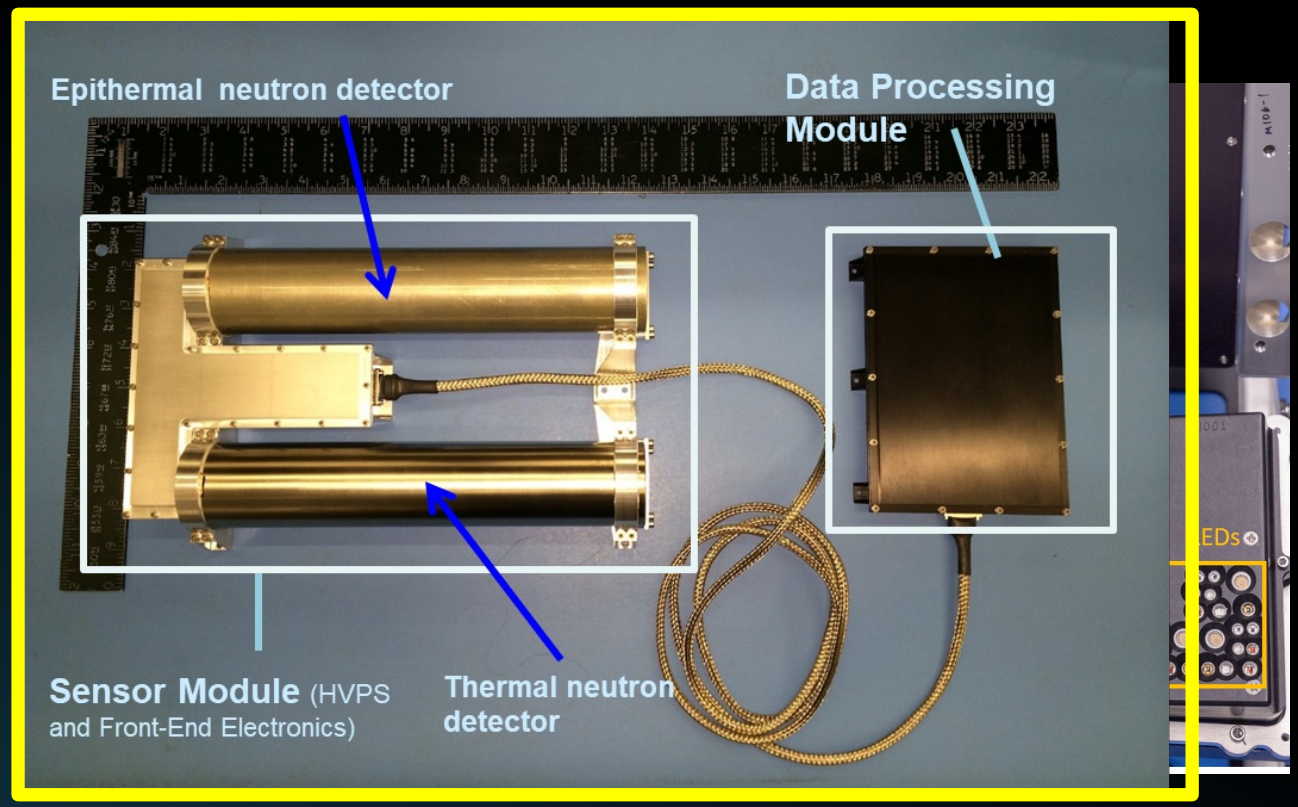


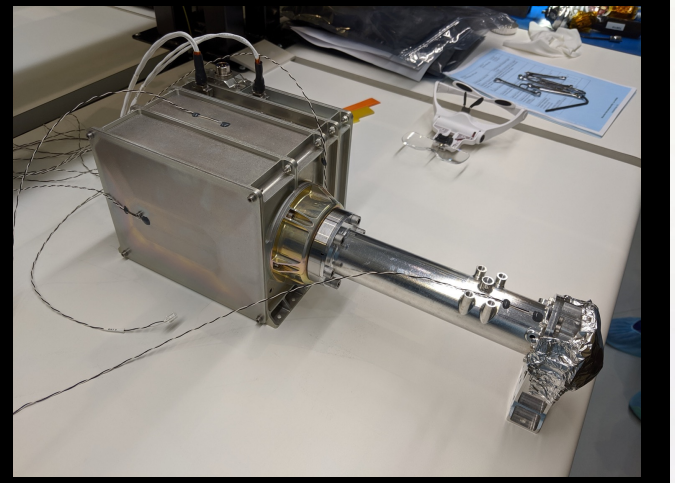






VIPER Science Payload



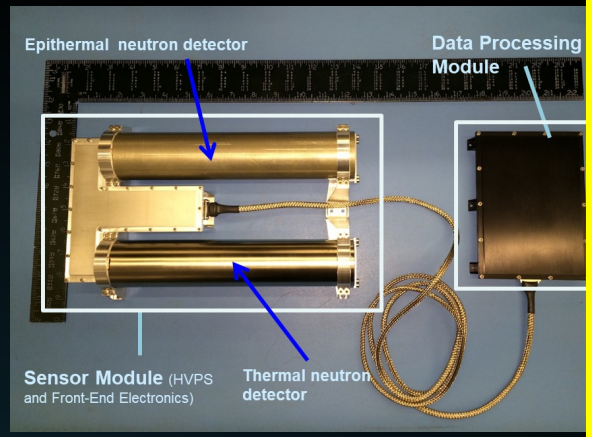


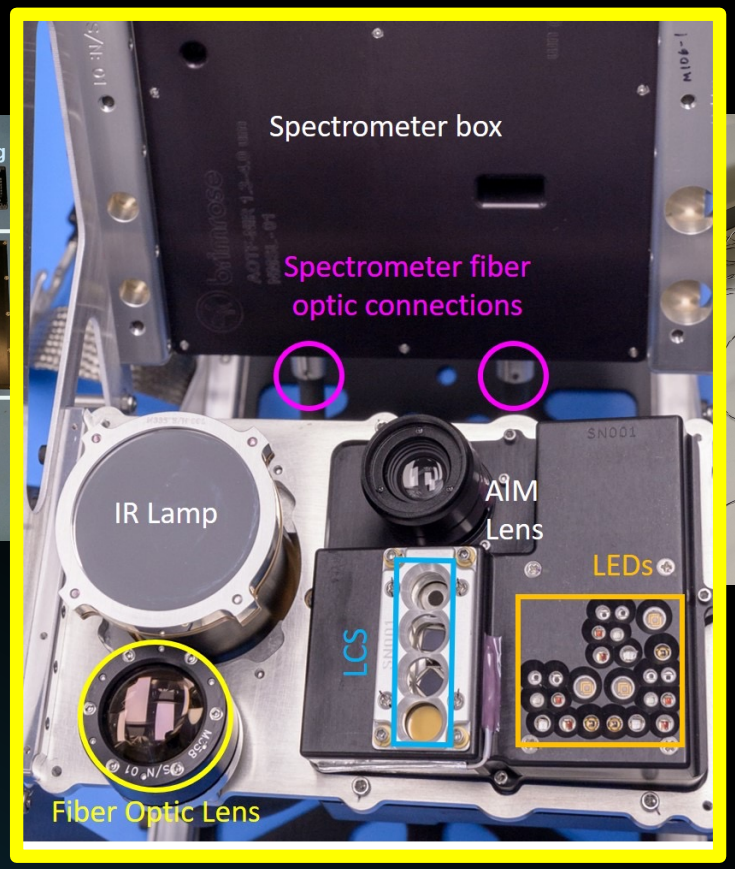


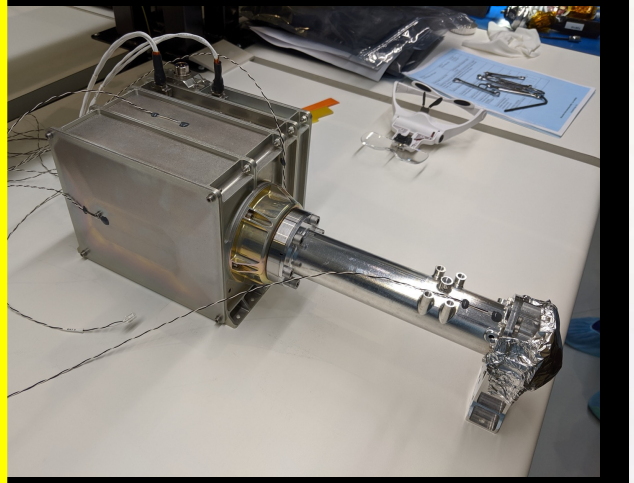
Neutron Spectrometer System (NSS)

- **NASA Ames Research Center, Lockheed Martin ATC**
- **Instrument Type:** Two channel neutron spectrometer
- **Key Measurements:** Assess hydrogen and bulk composition in the top meter of regolith, measuring down to 0.5% (wt) WEH to 3σ while roving

VIPER Science Payload





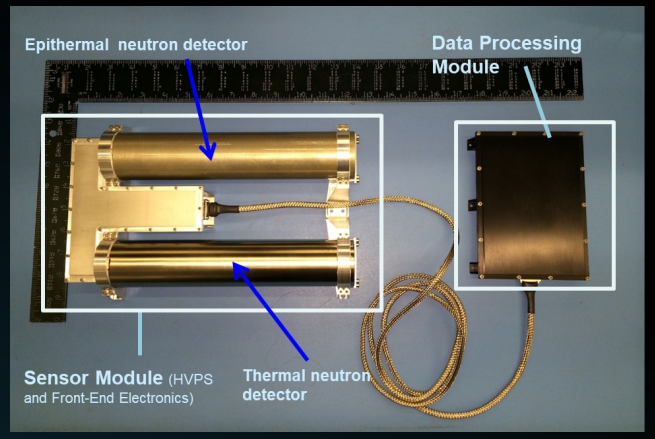


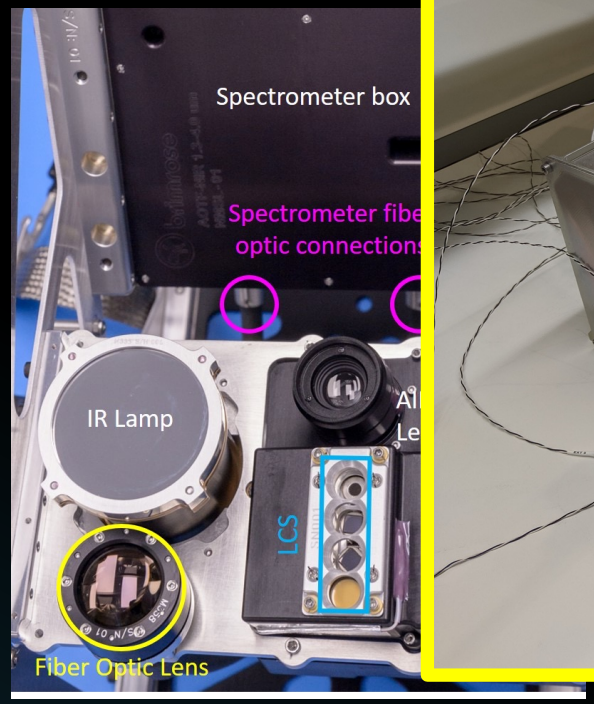


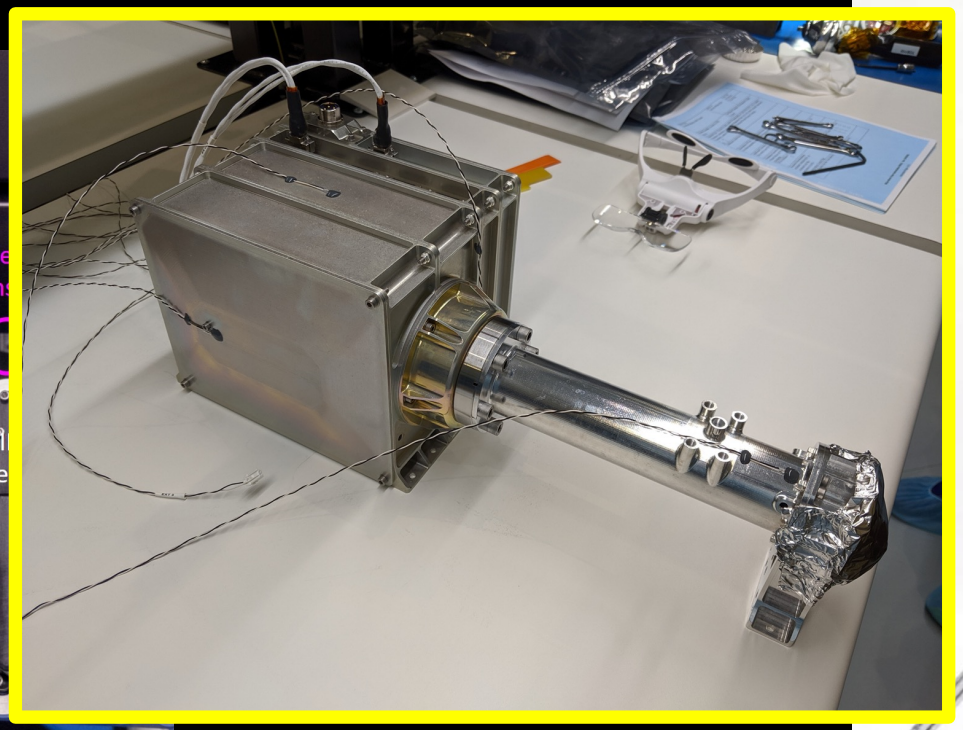
Near Infrared Volatiles Spectrometer System (NIRVSS)

- **NASA Ames Research Center, Brimrose Corporation**
- **Instrument Type:** NIR Spectrometer (1200-4000 nm), 4Mpxl visible imager with 7 color LEDs, four channel thermal radiometer
- **Key Measurements**: Volatiles including H_2O, OH, NH_3, H_2S and CO_2, mineralogy, surface morphology and temperatures

VIPER Science Payload





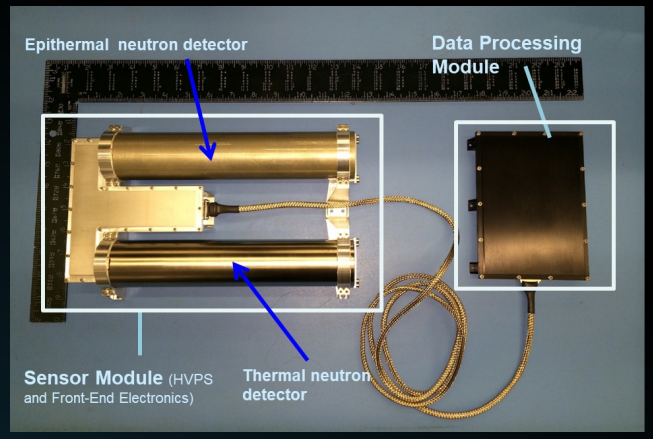


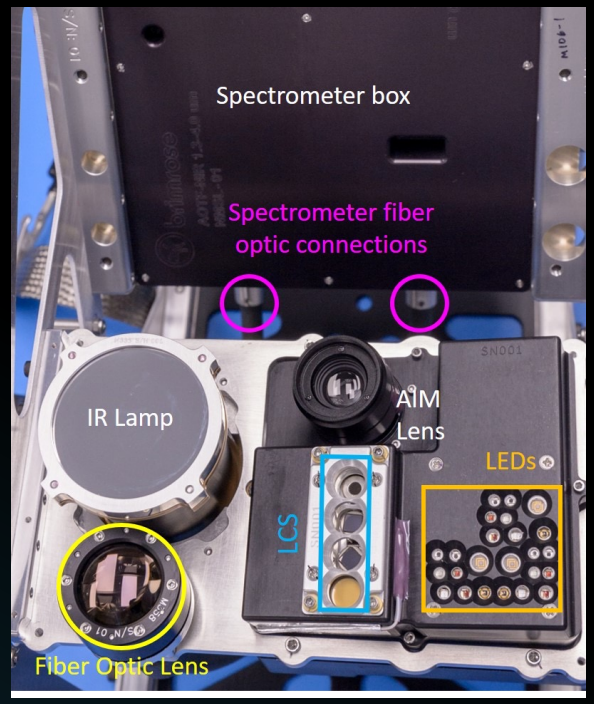


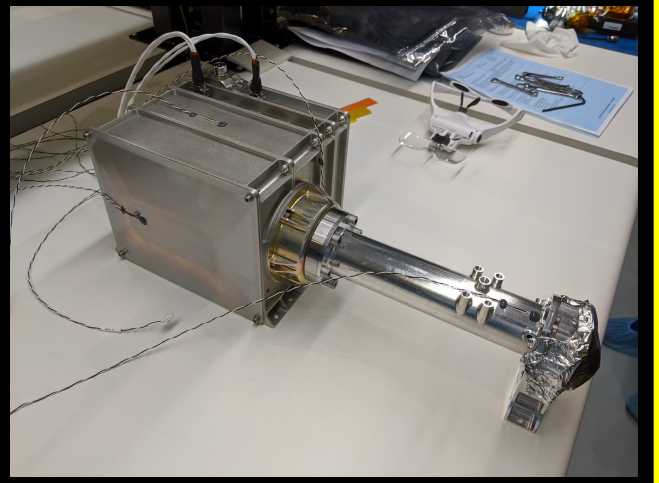
Mass Spectrometer Observing Lunar Operations (MSolo)

- **NASA Kennedy Space Center, INFICON**
- **Instrument Type:** Quadrupole mass spectrometer
- **Key Measurements**: Identify low-molecular weight volatiles between 1-100 amu, unit mass resolution to measure isotopes including D/H and O^{18}/O^{16}

VIPER Science Payload







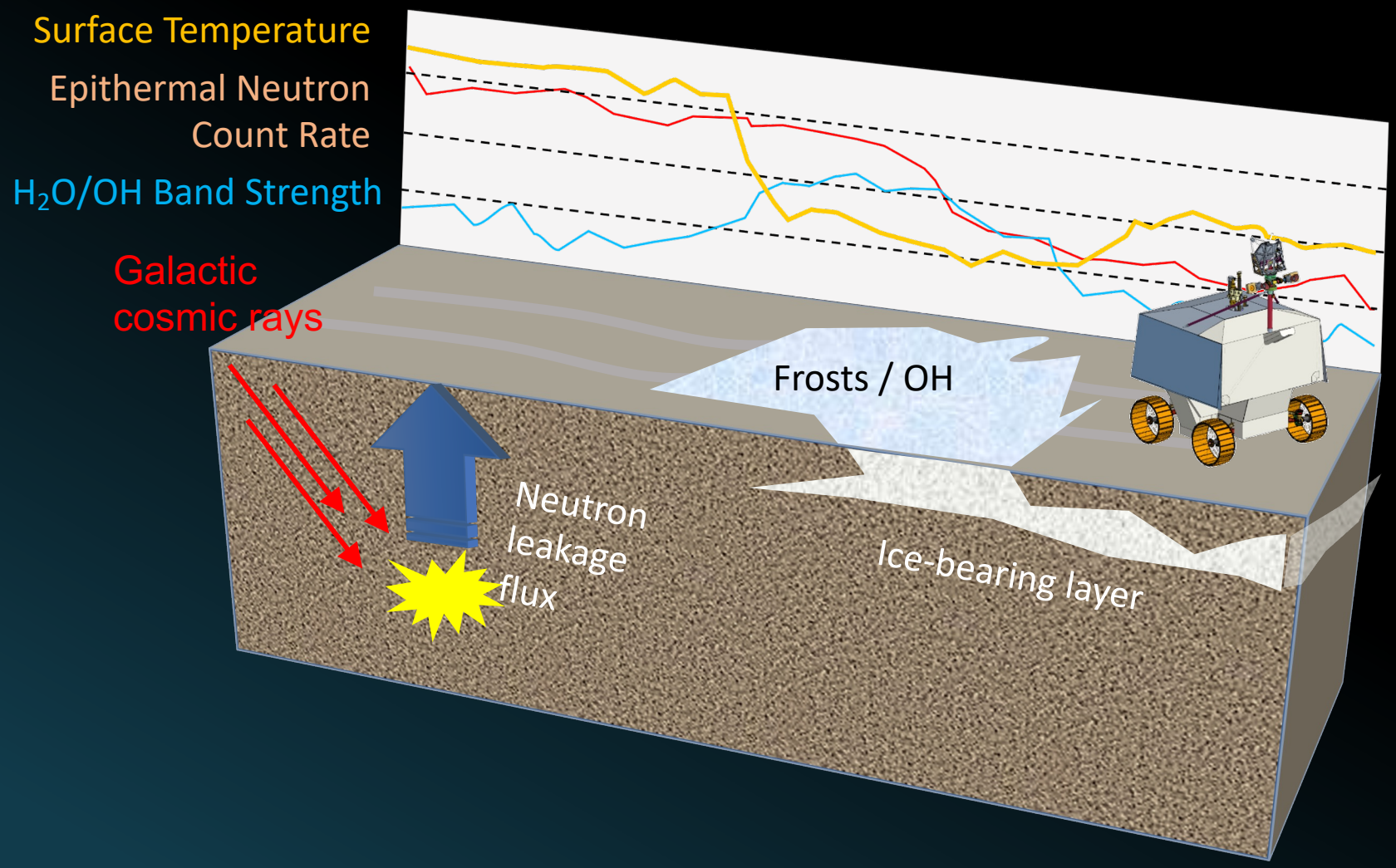


The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT)

- **Honeybee Robotics**
- **Instrument Type:** 1-meter rotary-percussive drill
- **Key Measurements**: Excavation of subsurface material to 100 cm, subsurface temperature vs depth, strength of regolith vs depth (info on ice-cemented ground vs. ice-soil mixture)

Prospecting & Subsurface Activities (drilling)

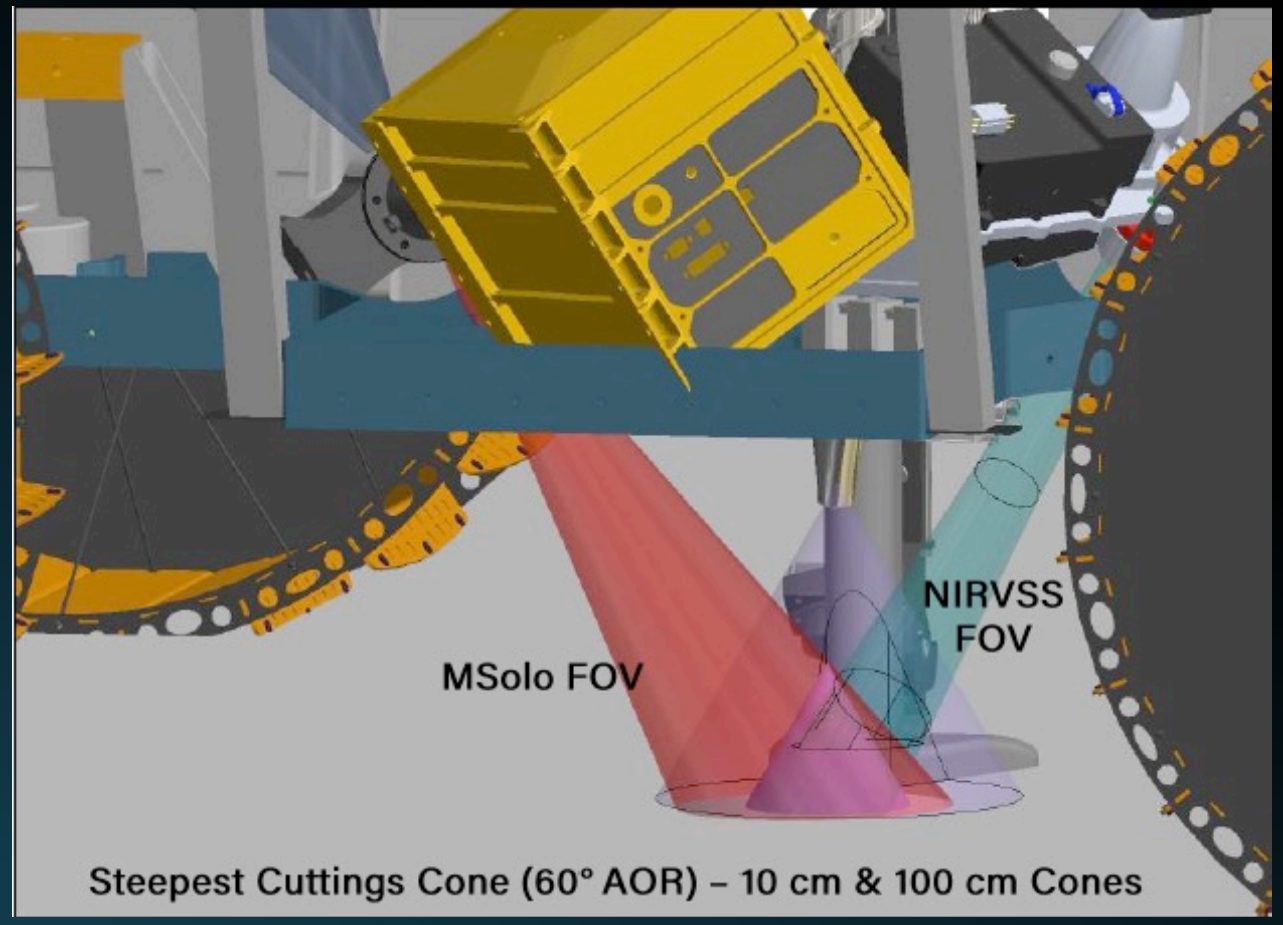
Prospecting: NSS, NIRVSS & MSolo



- NSS, NIRVSS & MSolo take data continuously while roving or parked
- NSS Neutron flux variations identify abundance and burial depth of hydrogenous materials
- NIRVSS NIR surface reflectance identifies surface and excavated hydration
- MSolo detects subliming gasses (H_2 or H_2O vapor) identify surface and excavated hydration
- TRIDENT excavates subsurface materials/ice

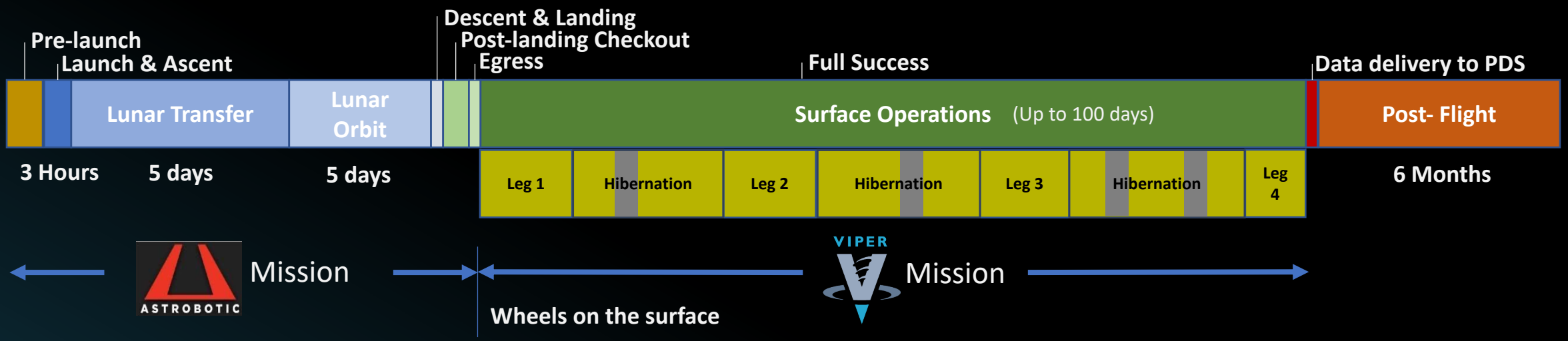
Sampling: TRIDENT, NIRVSS and MSolo

Sampling via the TRIDENT, MSolo and NIRVSS profile water
(and other volatiles with depth, tying down NSS derived concentrations)



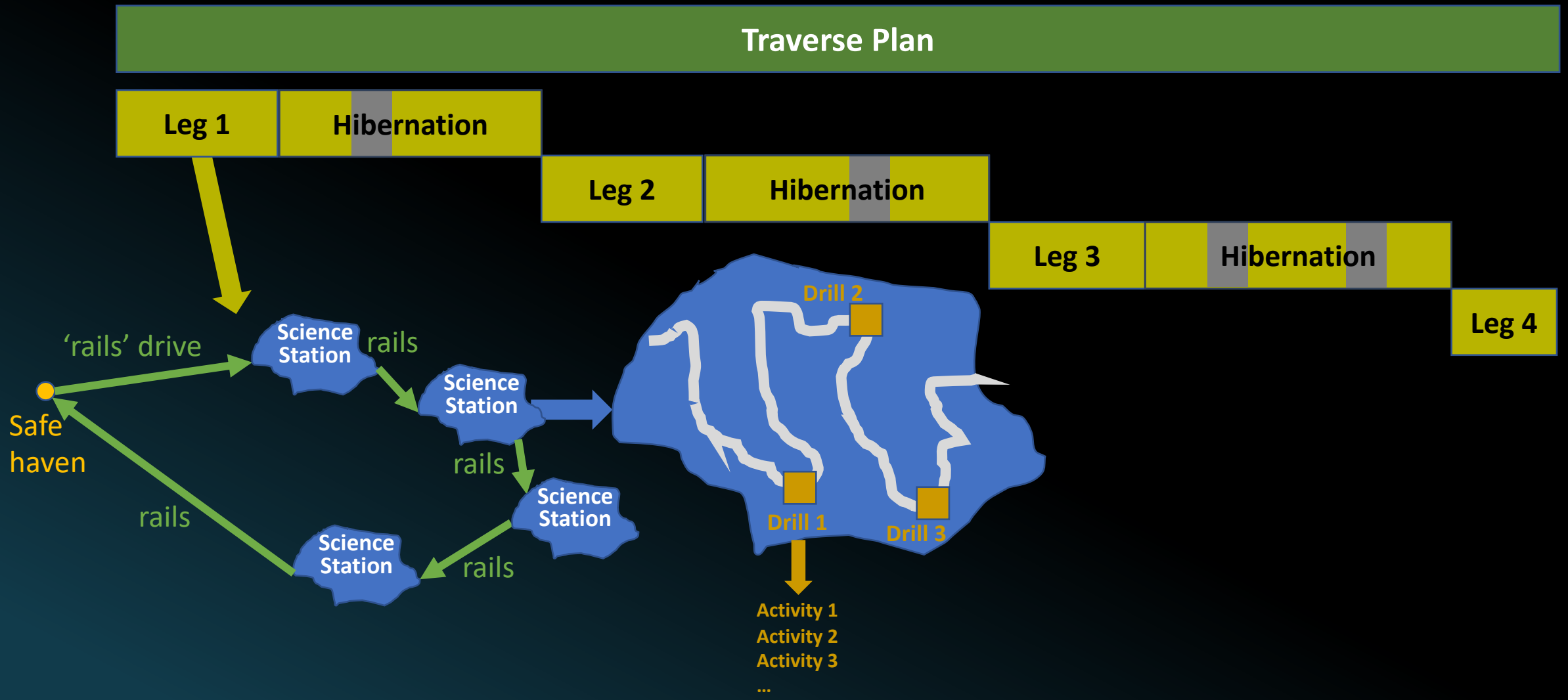
- TRIDENT samples in 10 cm “bites” down to 1 meter, using a simple auger bit
- Each 10 cm sample can be brushed to the surface for inspection by NIRVSS and MSolo
- NIRVSS images the cuttings at multiple wavelengths (providing context for NIRVSS and MSolo observations) and measures the scene temperature
- This process identifies the stratification of hydrogen bearing volatiles, “tying down” NSS measurements

VIPER Mission Phases



- Surface Ops consist of periods of activity (“traverse legs”) and periods of inactivity (“hibernations”)
  - Traverse legs are in view of Earth and sun (except for planned shadow (PSR) ops (<8 hours))
  - Hibernations are NOT in view of Earth, but in view of sun, with periods of sun shadow (<72hrs)
  - Lunar Day (28 days) = one Traverse Leg + one Hibernation

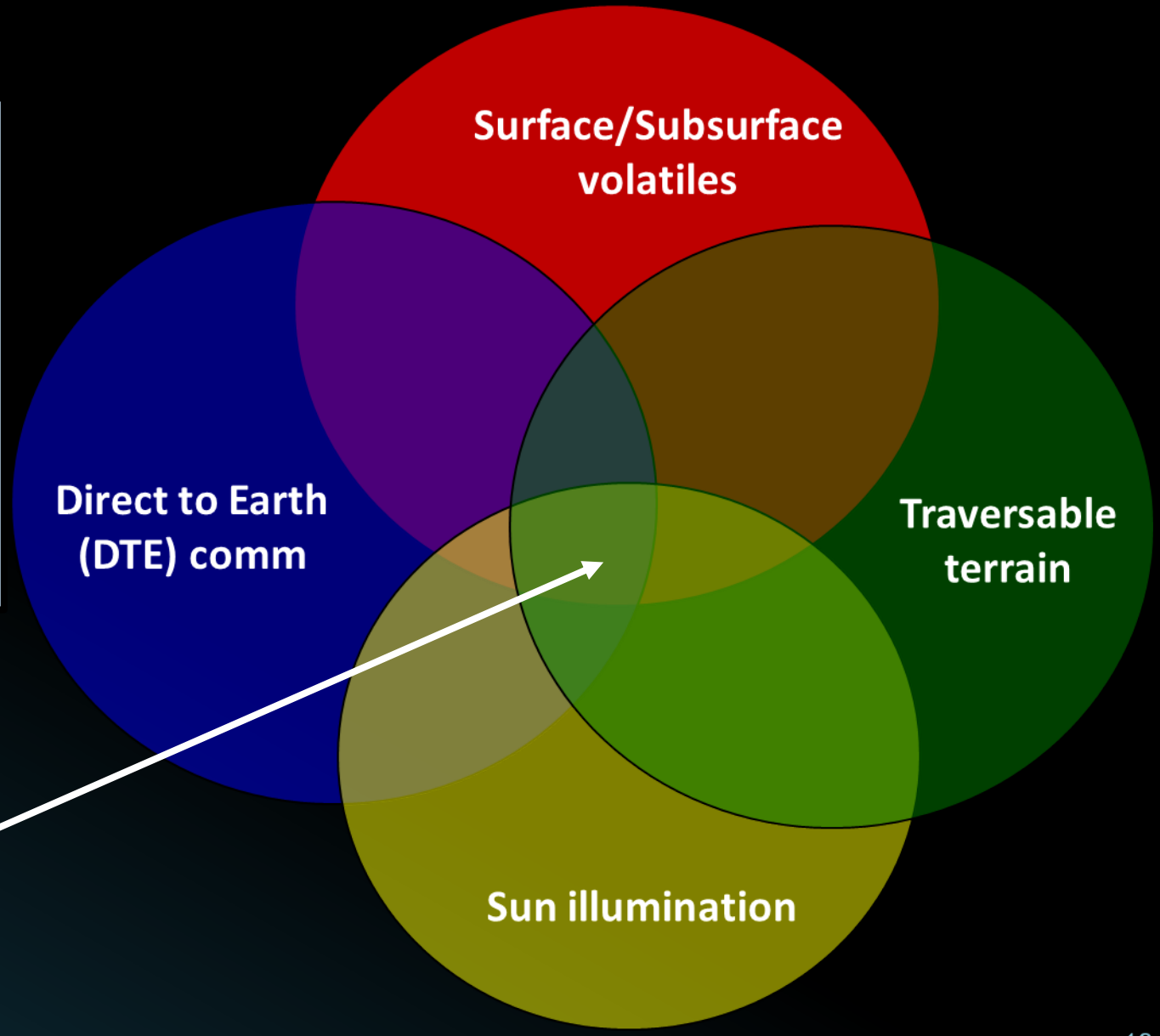
VIPER Surface Operations



Landing Site Requirements: Where are We Going?

Candidate polar landing sites meet these four criteria:

1. Plausible surface/subsurface volatiles
2. Reasonable terrain for landing and traverse
3. Direct view to Earth for communication
4. Sunlight for power

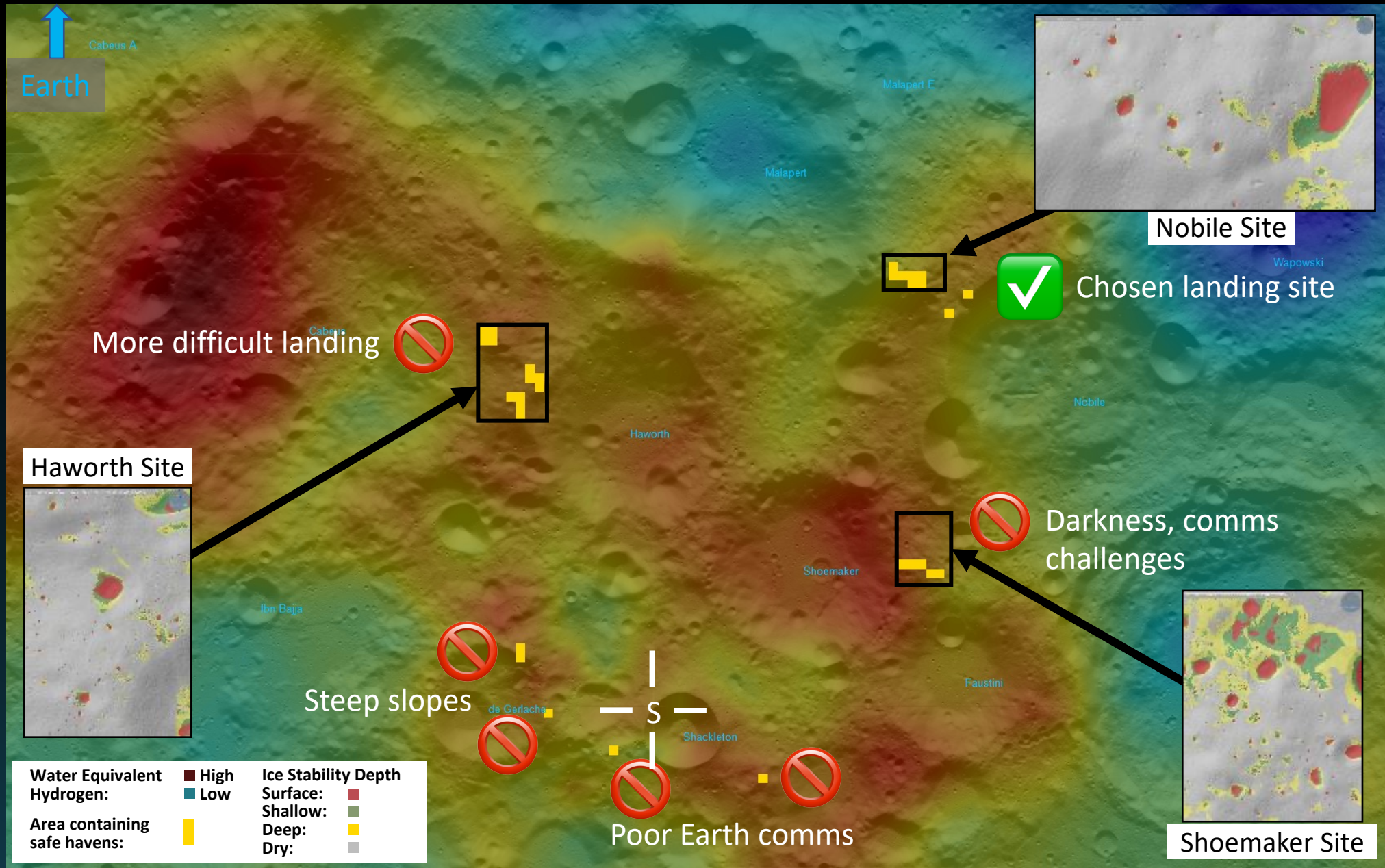


VIPER needs to find the intersection of these constraints

Three locations for traverse studies

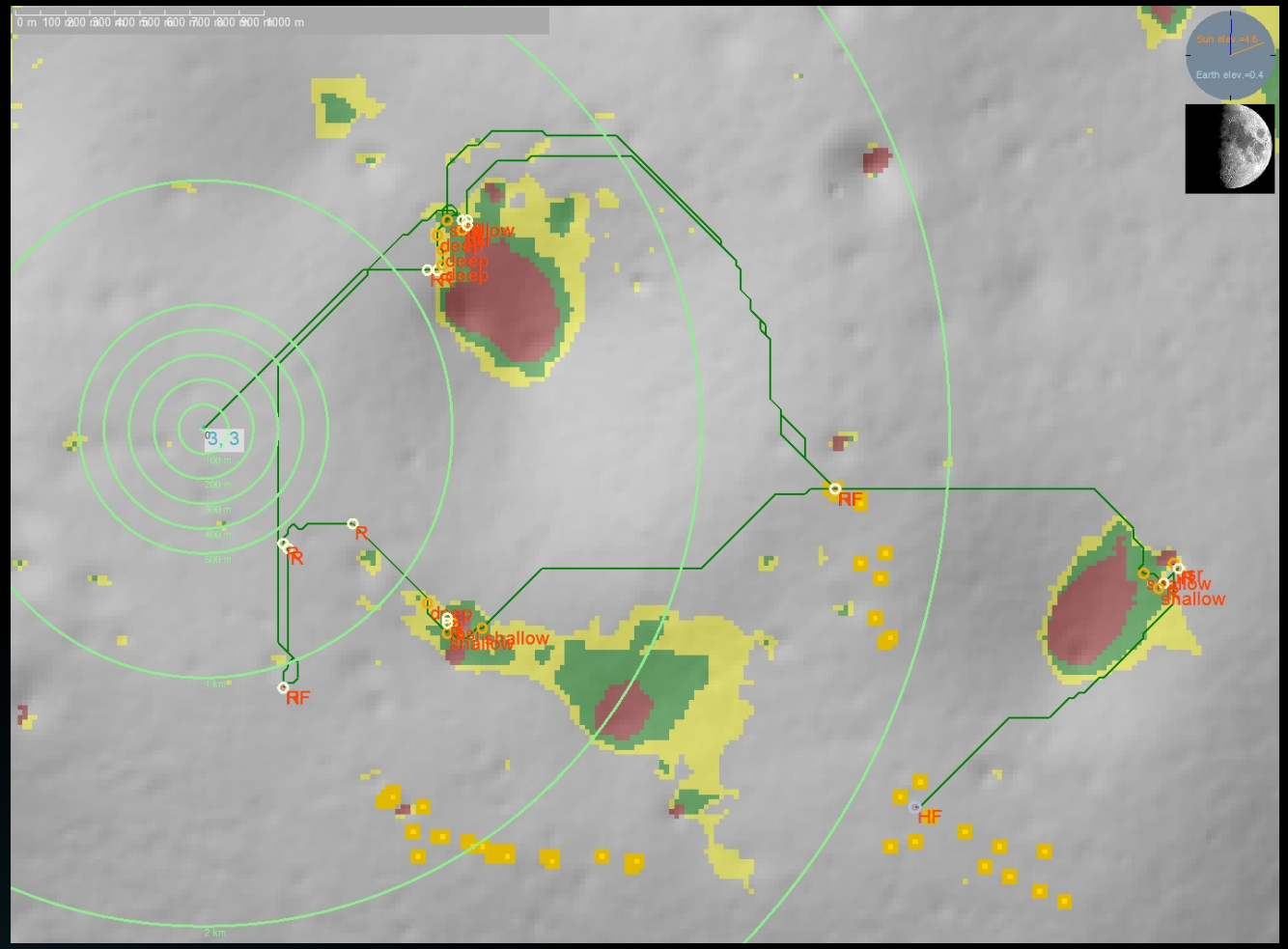
Needed: locations with …

- High water-equivalent hydrogen (background map)
- A variety of thermal environments using ice stability depth as an indicator (insets)
- Periods of shadow short enough for the rover to survive (yellow blocks)
- Unobscured line-of-site to Earth for communications



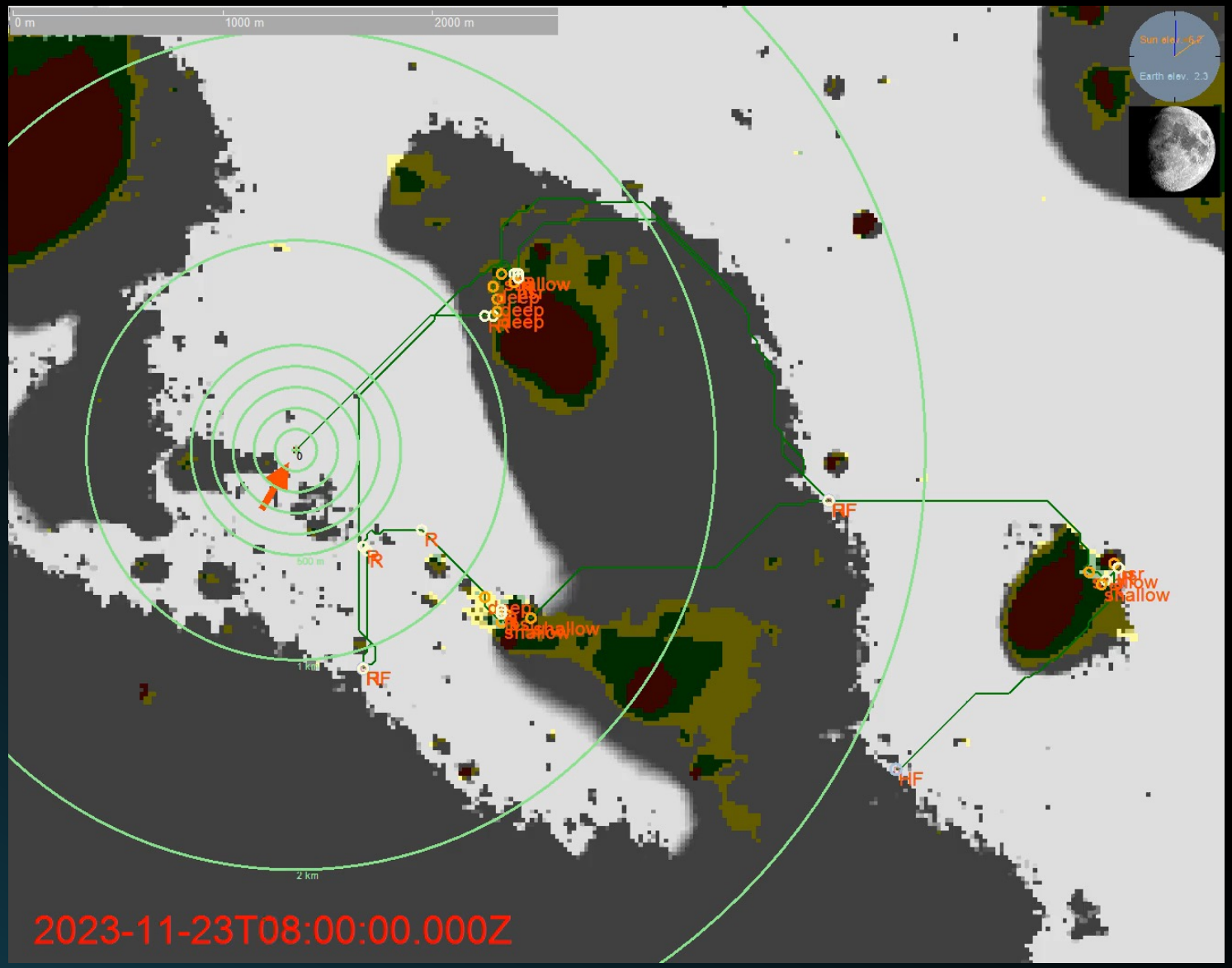
Sample Nobile Traverse

Key Parameter	Value		
Launch Date (est)	3 pm 11/10/2023 (all times UTC)		
Lunar transfer duration	5 days		
Lunar Orbit Insertion (est)	10:45pm 11/15/2023		
Lunar orbit duration	7 days		
Landing time	8 am 11/23/2023		
Total mission duration	106 days + option for 28 more		
Surface mission duration	94 days + option for 28 more		
Active days on the surface	45 days + option for 10 more (but limited science)		
Landing location	85.449452S, 31.064135E		
Average slope at landing site	5°		
Light and comm at landing site	12 days		
Total driving distance	4.4 km prospecting, 27.4 total		
Max distance from landing site	3 km		
Science Stations	12	2 psr	4 shallow
		4 deep	2 dry
Full mission success reached	Day 37, near end of 2nd lunar day		
Driving Speed	0.813 cm/s normal 0.613 cm/s sunward		



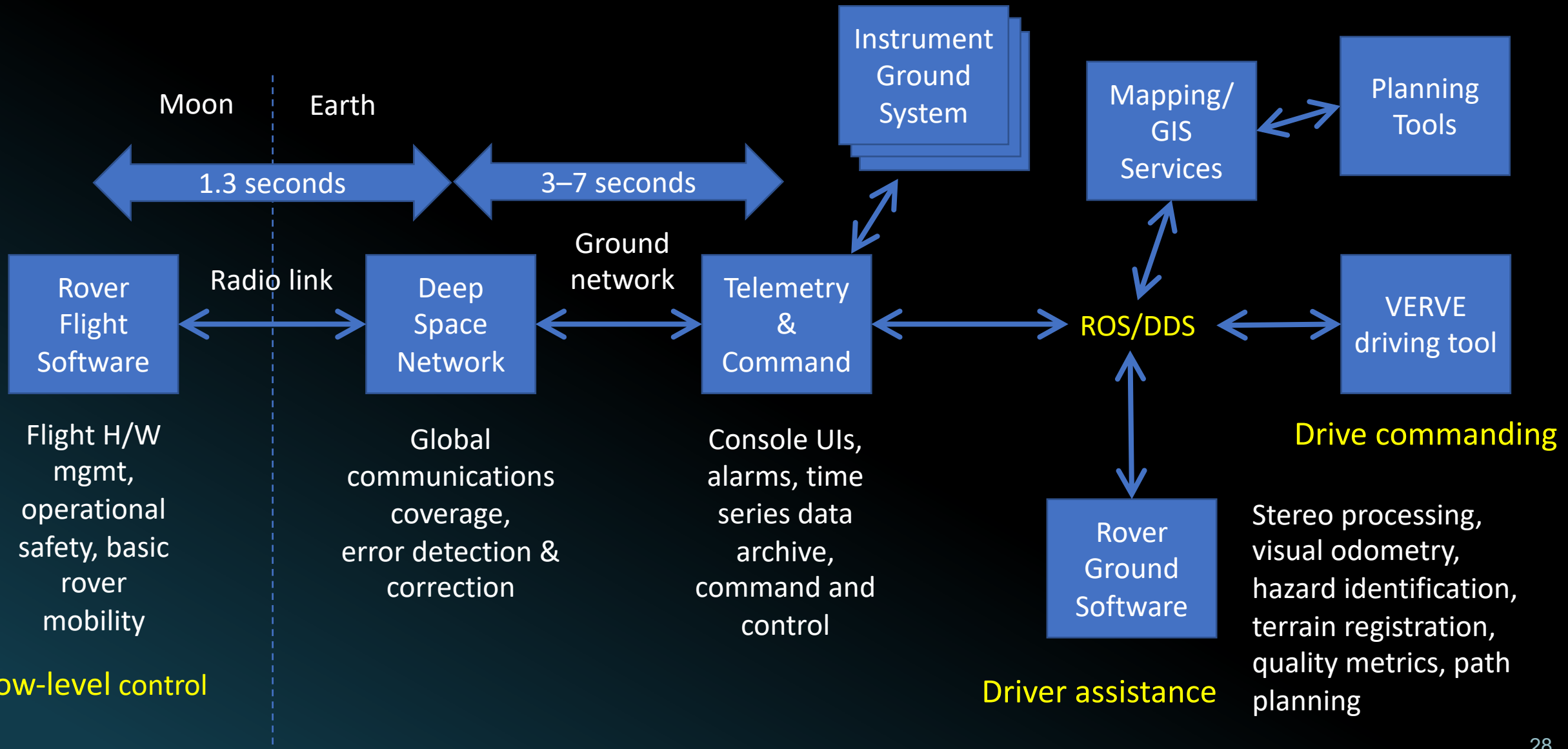
- Surface Ice Depth (PSR)
- Shallow Ice Depth (< .5 m)
- Deep Ice Depth (< 1 m)
- Dry (deeper than 1 m)

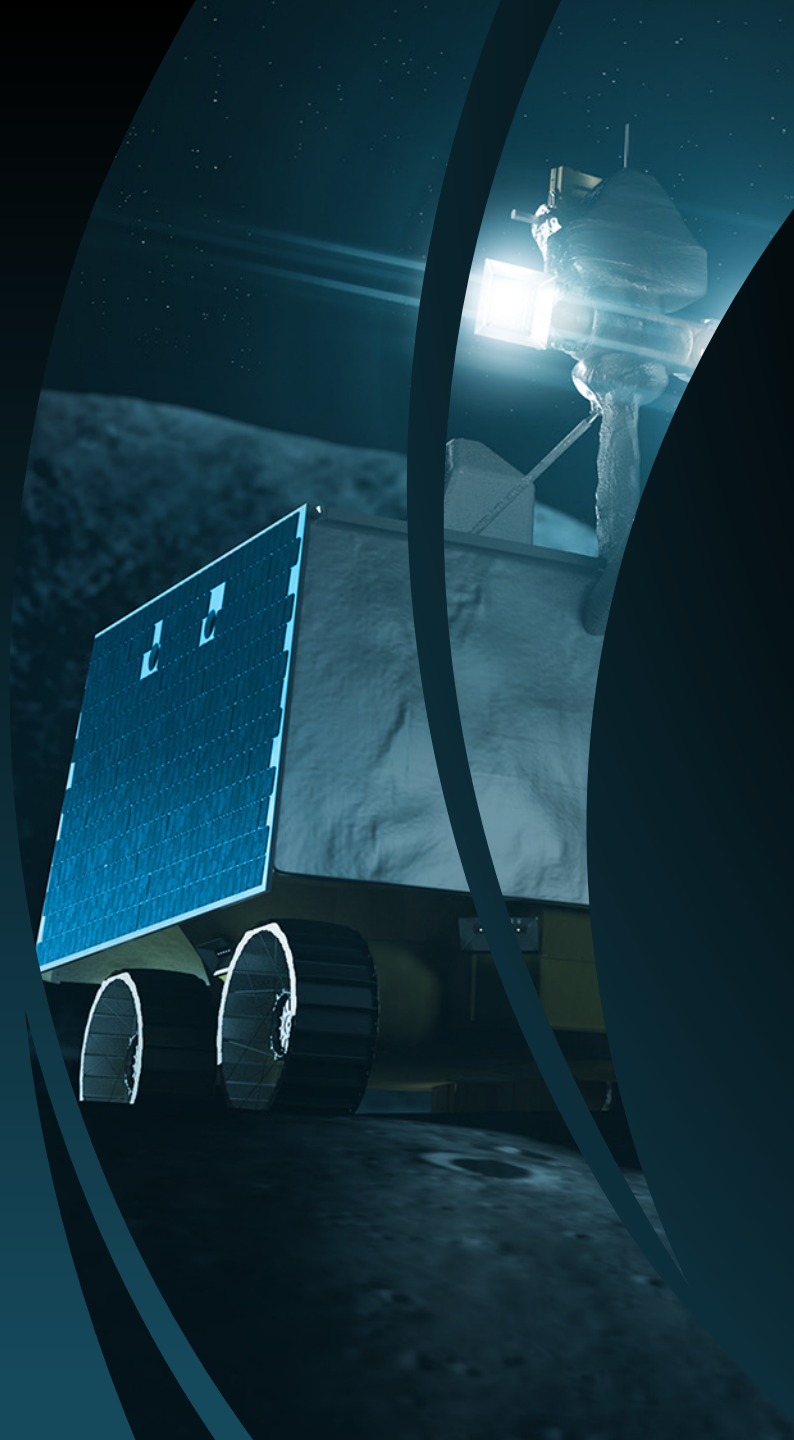
Nobile Traverse Animation



VIPER distributed architecture

Moon- and Earth-based components





Open-source & reused software

cFS – NASA Core Flight System – framework for flight s/w

Yamcs – telemetry and command system

OpenMCT – NASA browser telemetry viewing application

ROS – Robotic Operating System – framework for robotics

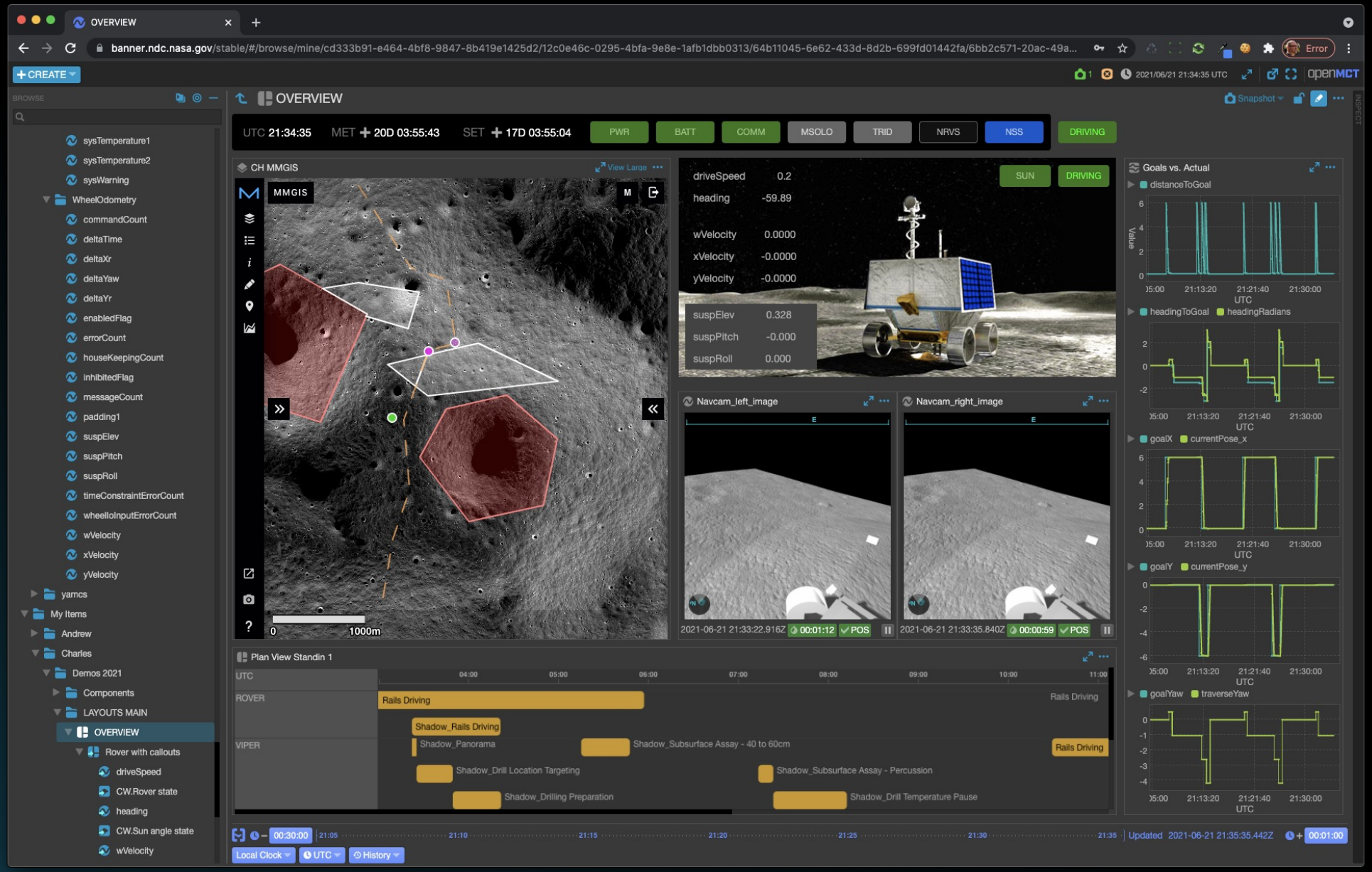
VERVE – Ames robot driver console

MMGIS – JPL GIS system for map services

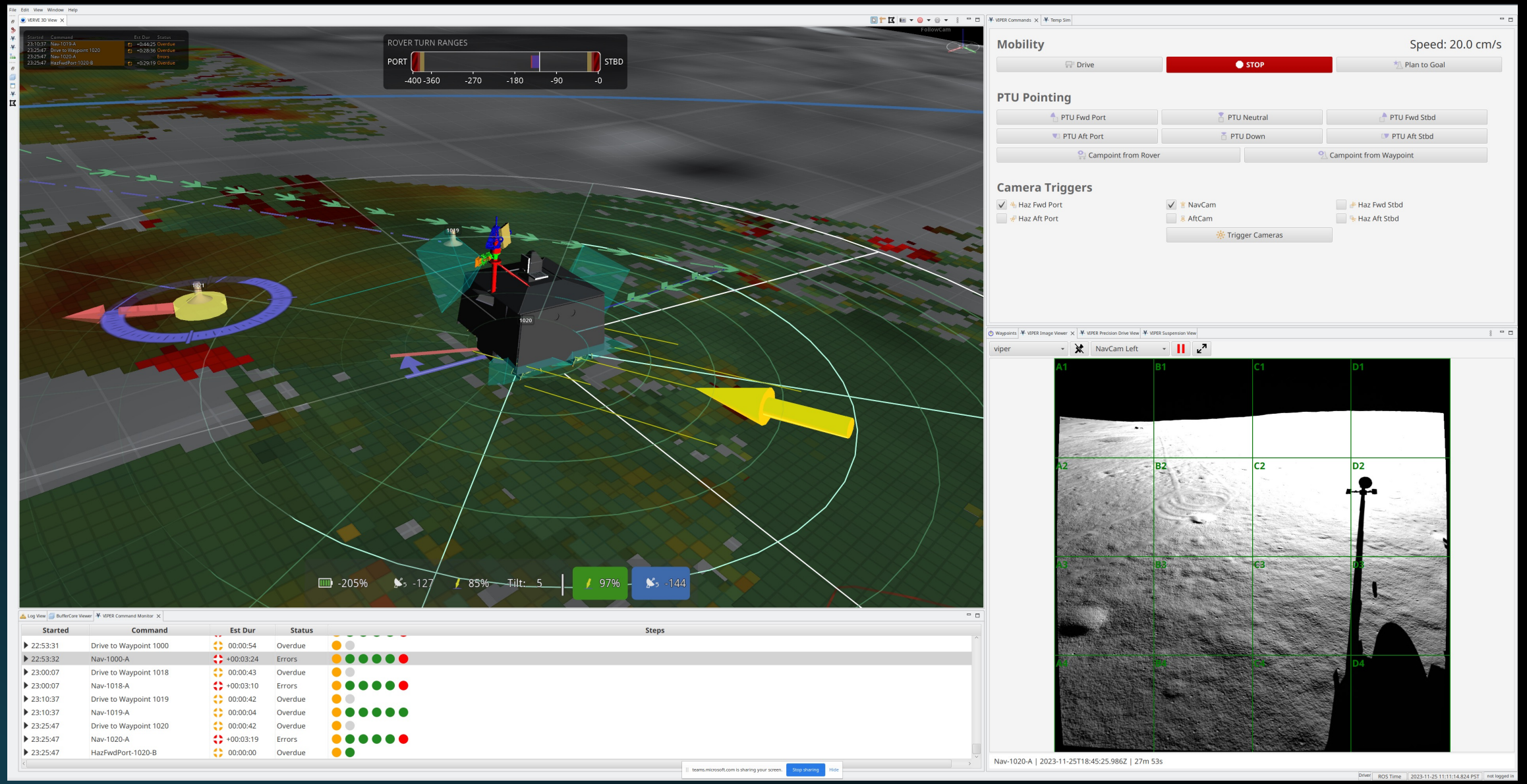
ICER – JPL image compression library

Ames Stereo Pipeline – stereo image processing

OpenMCT – browser telemetry display



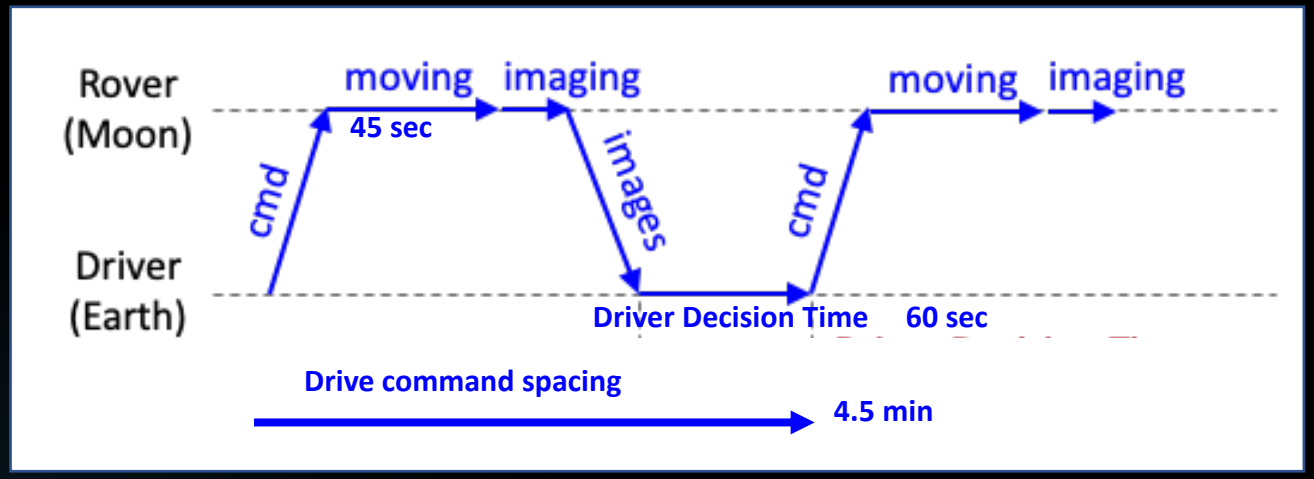
VERVE – rover driver console



Simulating the mission and environment

Key operational challenges

Rover is idle 90% of the time while drivers make decisions and wait for images

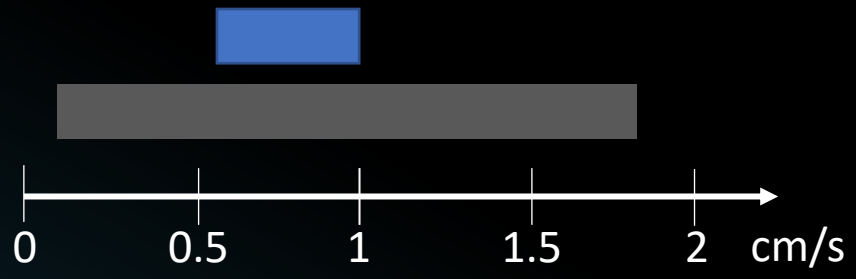


Teleoperation uplink / downlink cycle

Thus, rover and shadows (sun and radio) move at comparable speeds

The rover's avg speed: 0.6 – 1.0 cm/s

Shadow edges' speed: 0.1 – 1.8 cm/s

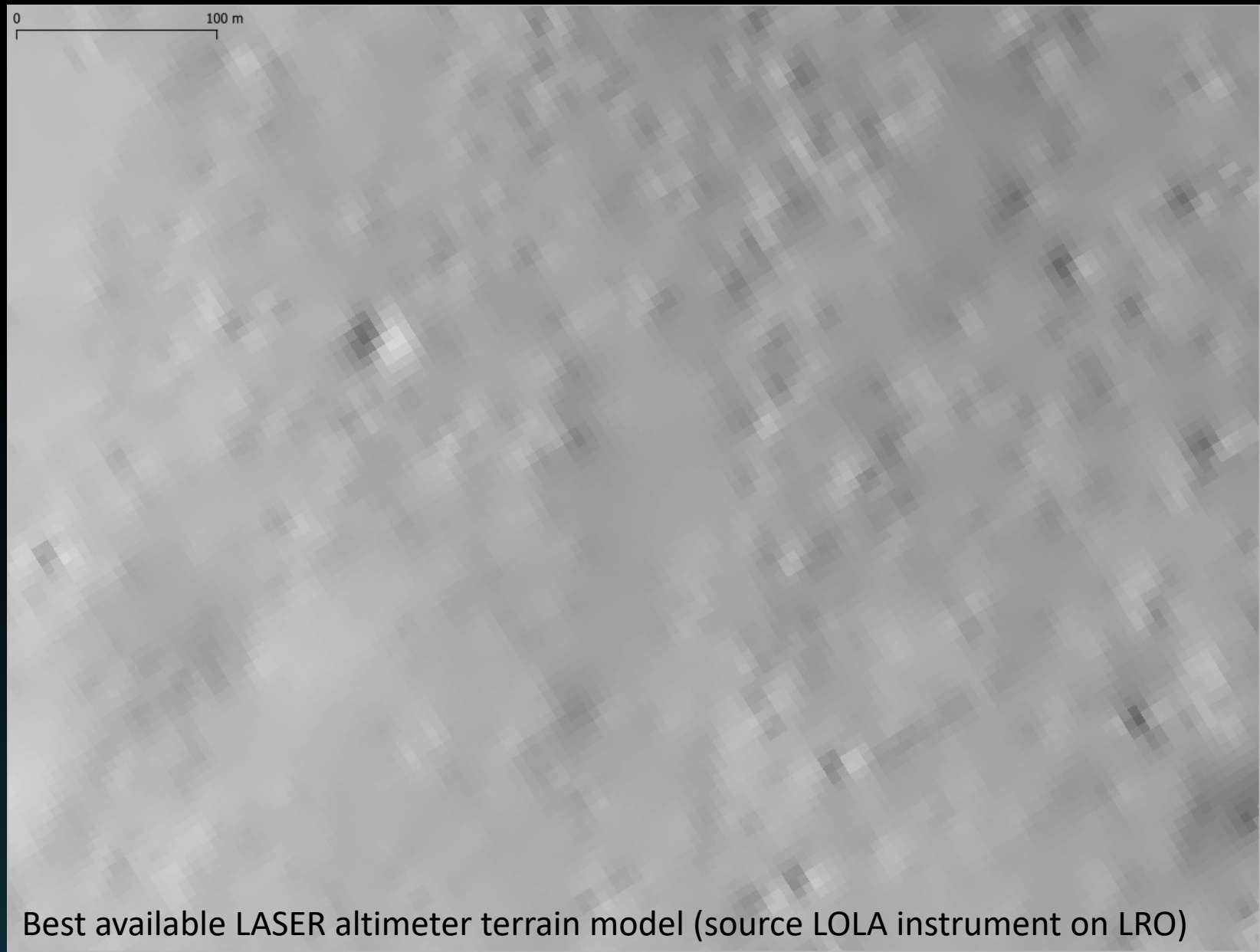


Innovations to address challenges

Problem	Innovation
Accurately predicting shadow location and movement	High-resolution terrain (1 meter/pixel), 5x more than previous
Rover effective speed is sensitive to obstacles too small to see from orbit	Synthesize scientifically-plausible terrain for driving simulations
Anomalous situations could cause rover to get trapped by shadows	Risk-aware route planning

High-Resolution Digital Terrain Models

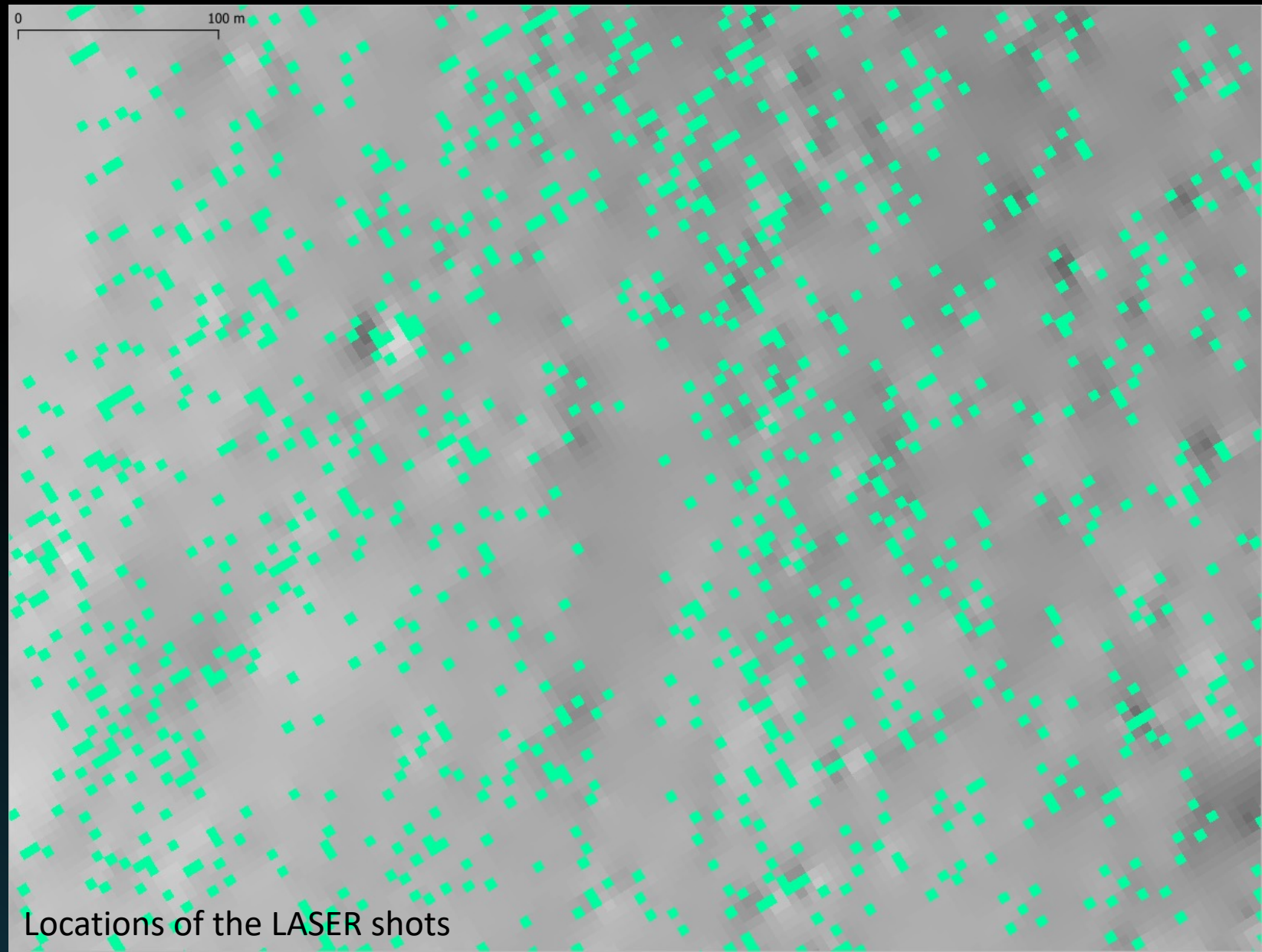
- LASER altimeter terrain 5m/pixel



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

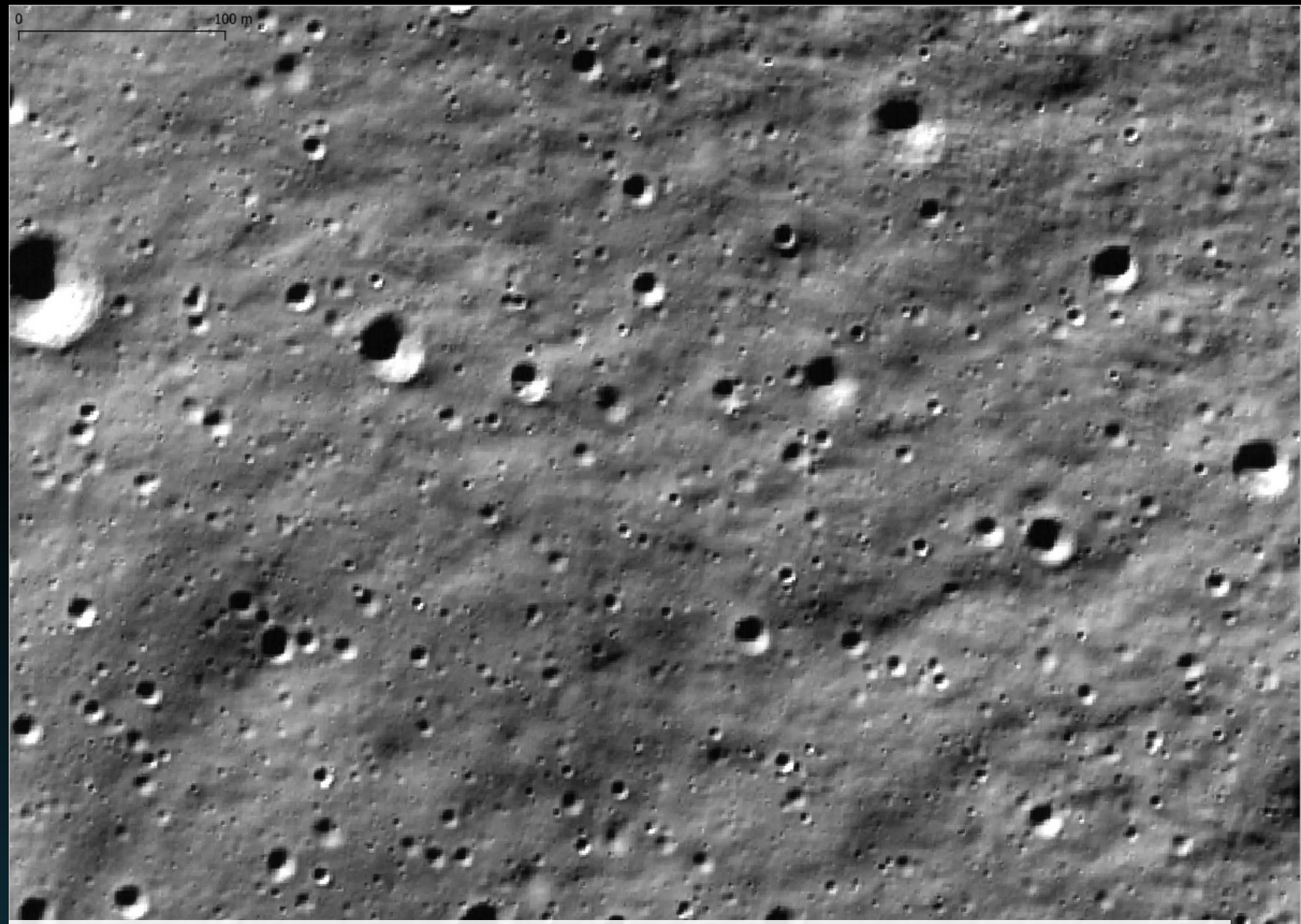
High-Resolution Digital Terrain Models

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



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)

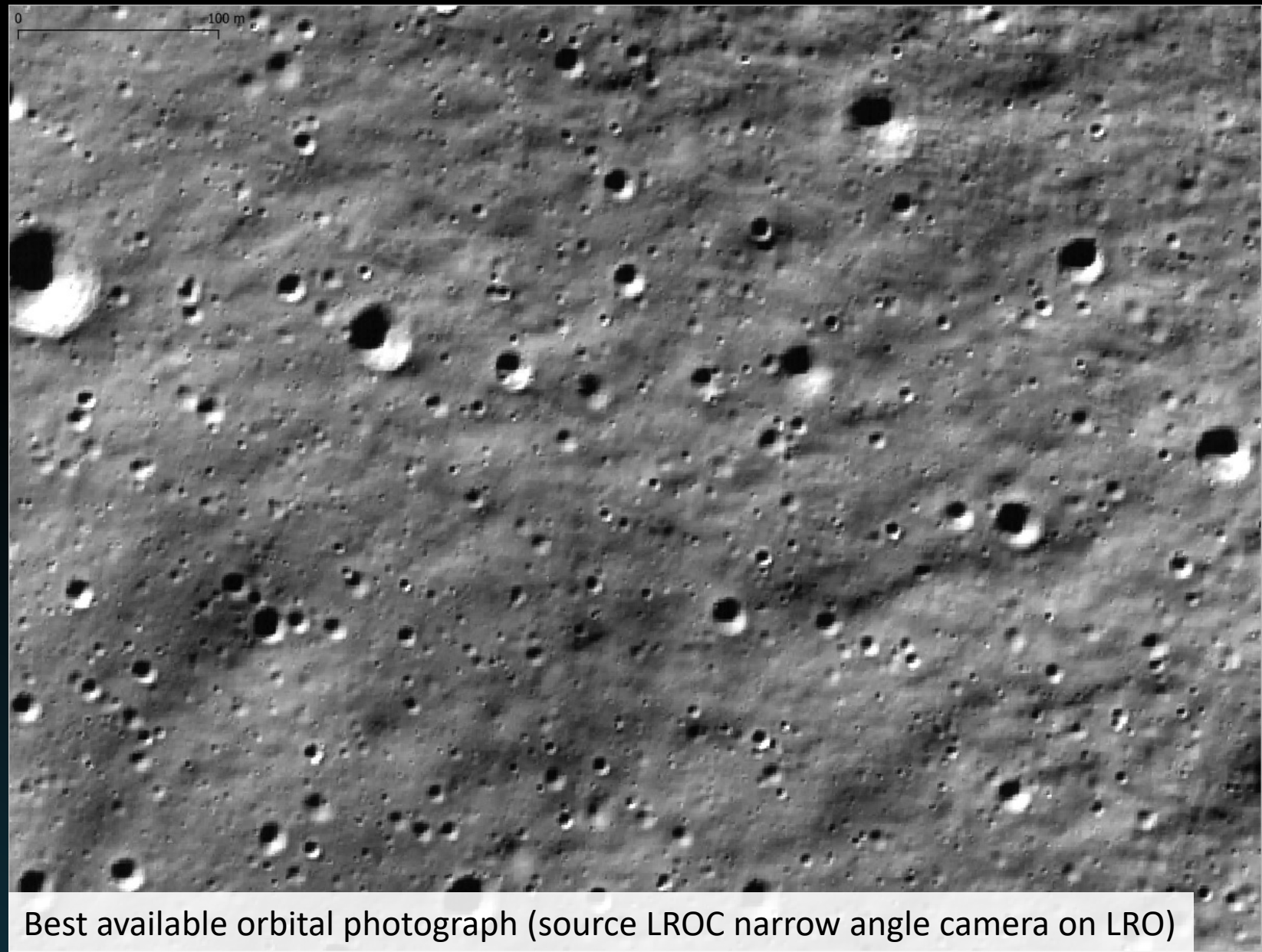
High-Resolution Digital Terrain Models

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- 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



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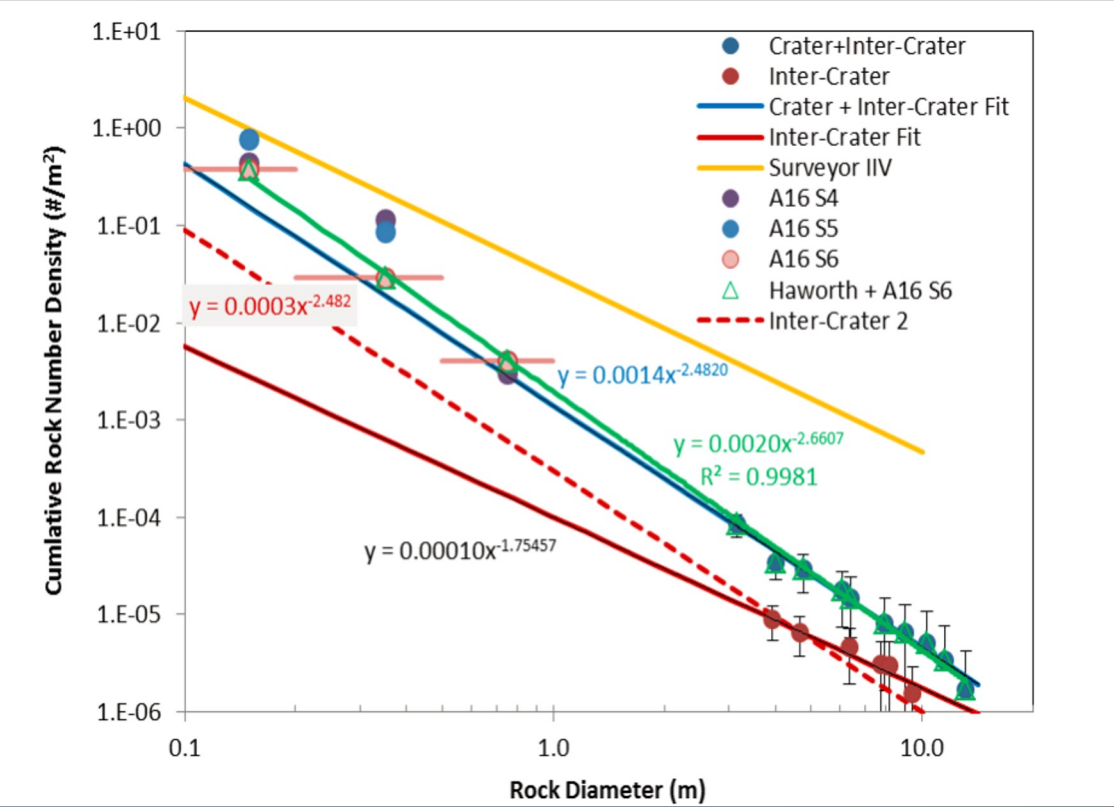
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Shape-from-Shading (SfS) on the Moon, Oleg Alexandrov and Ross Beyer, Lunar and Planetary Science Conference, 2017

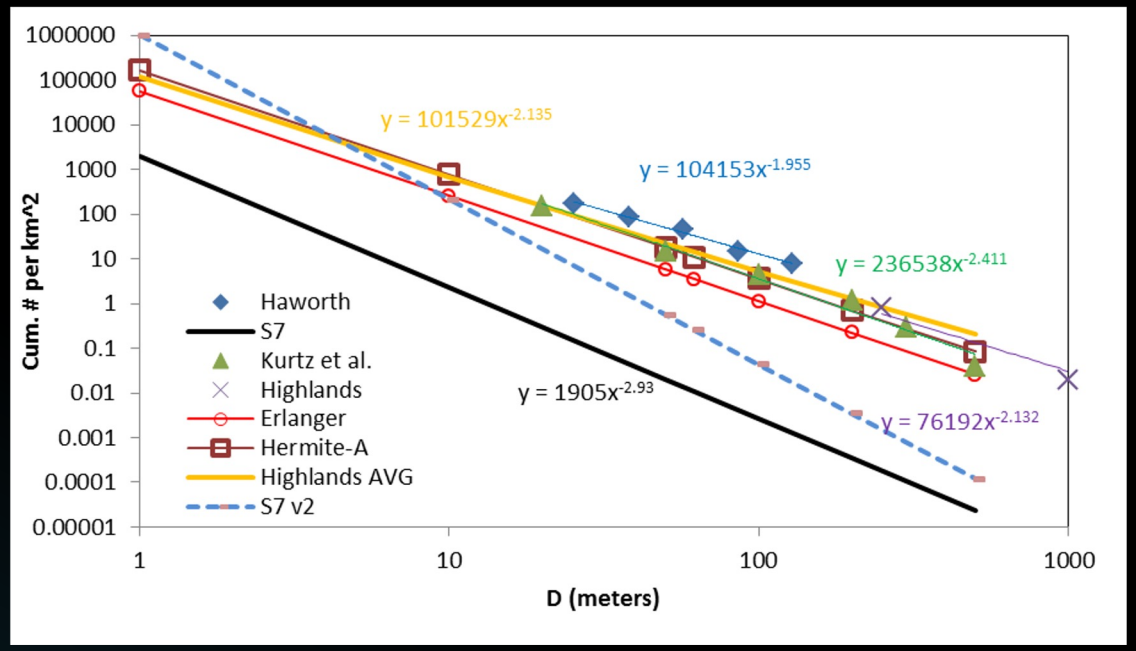


Shape-from-shading terrain model

Models of rock and crater distribution

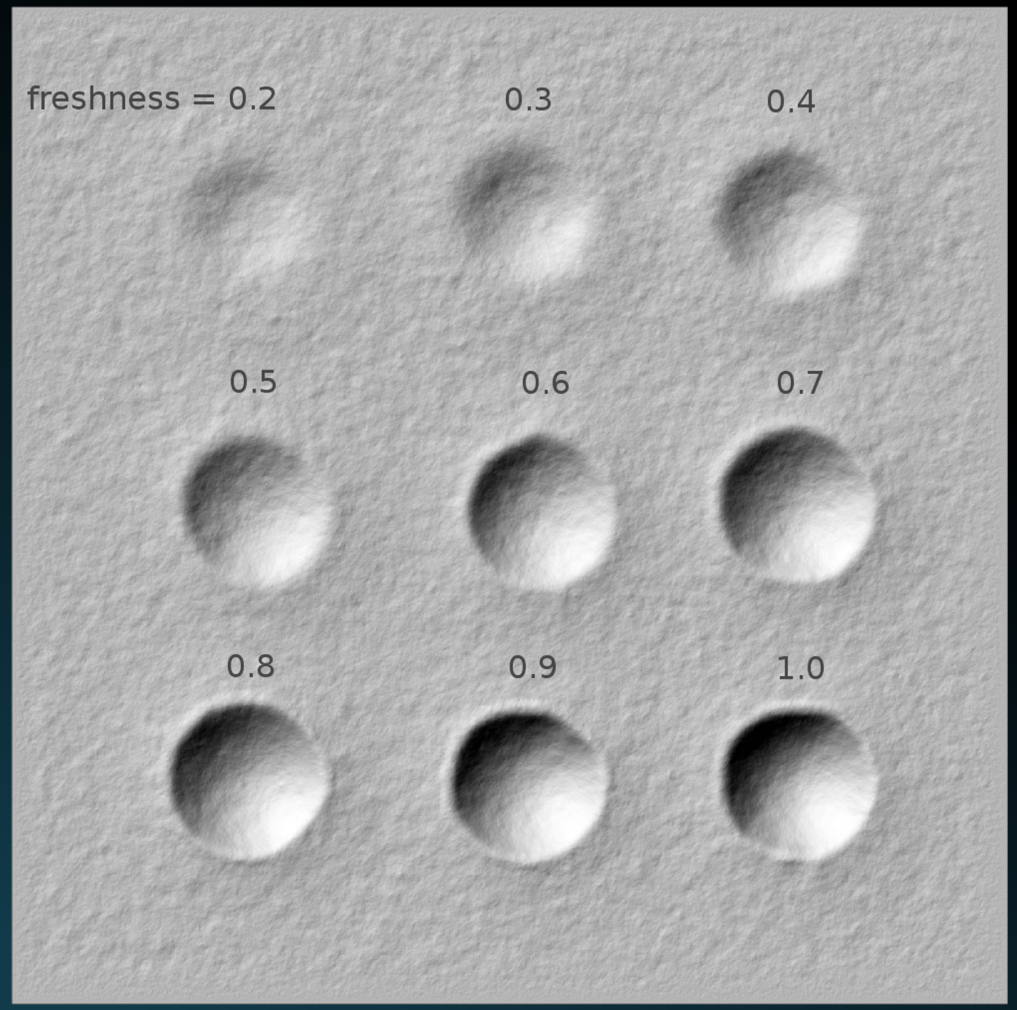


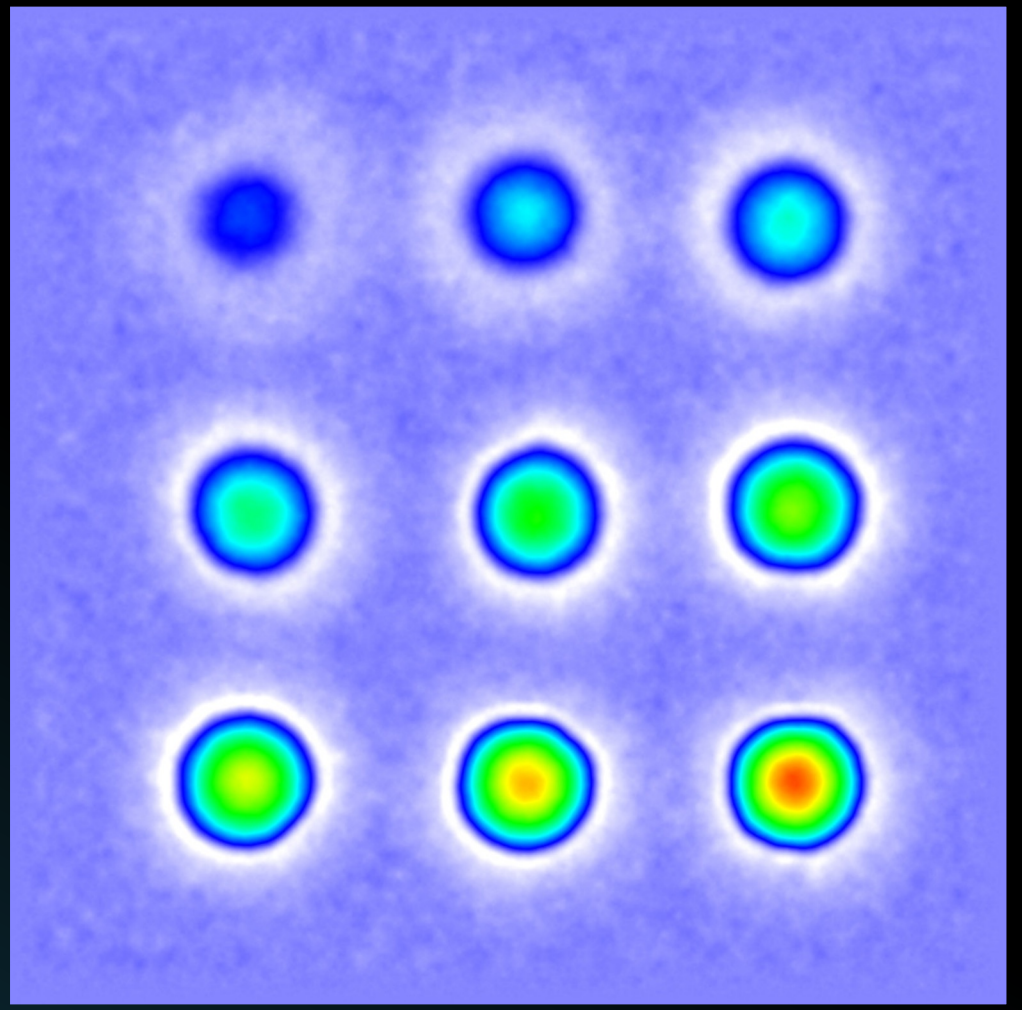
Rock distribution



Crater distribution

Adjusting for crater age: freshness parameter

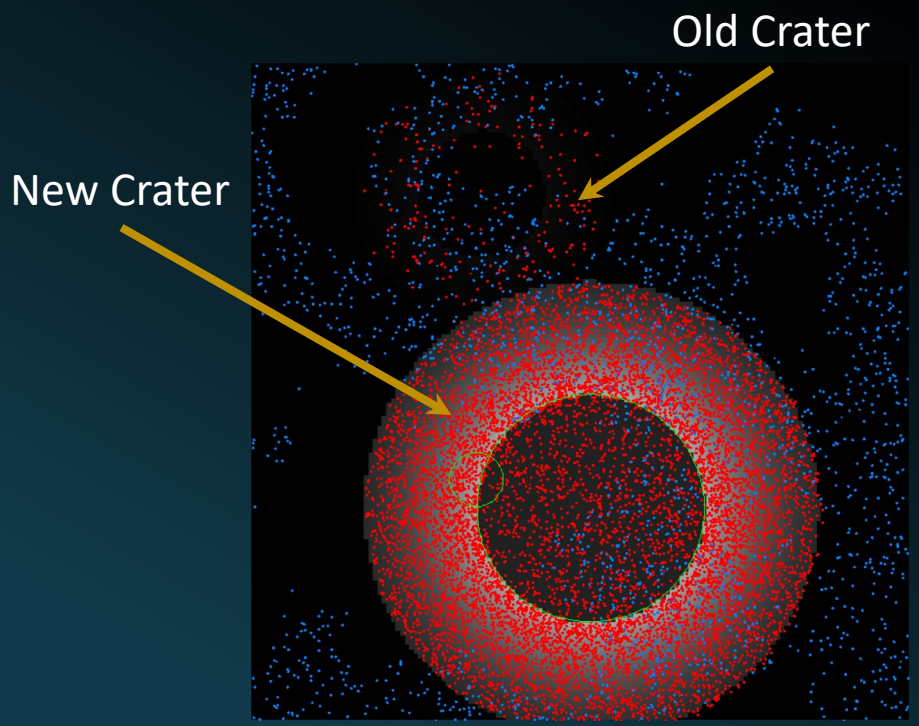


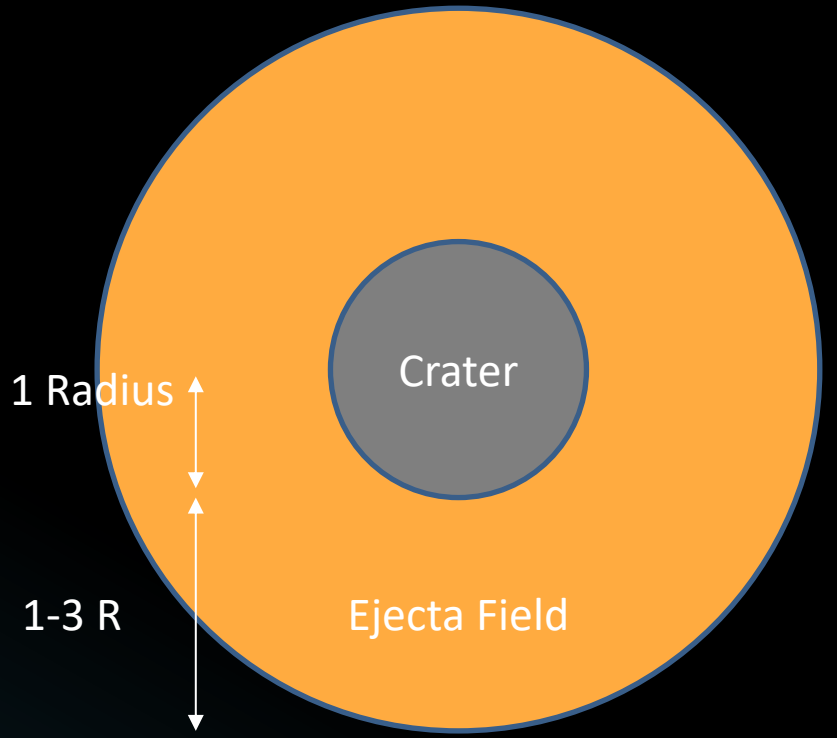


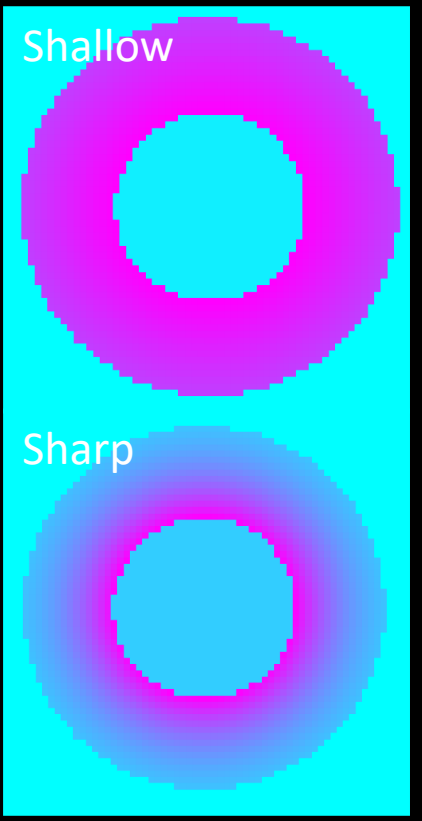
80m diameter craters
Max depth 24m
Freshness 1.0 ~ d/D 0.3

Adding crater ejecta

- Older craters have less rocks than newer craters
- Number of “visible” rocks decays as a power of age







Parameters control the spatial size of ejecta field.

Camera & lighting model calibration

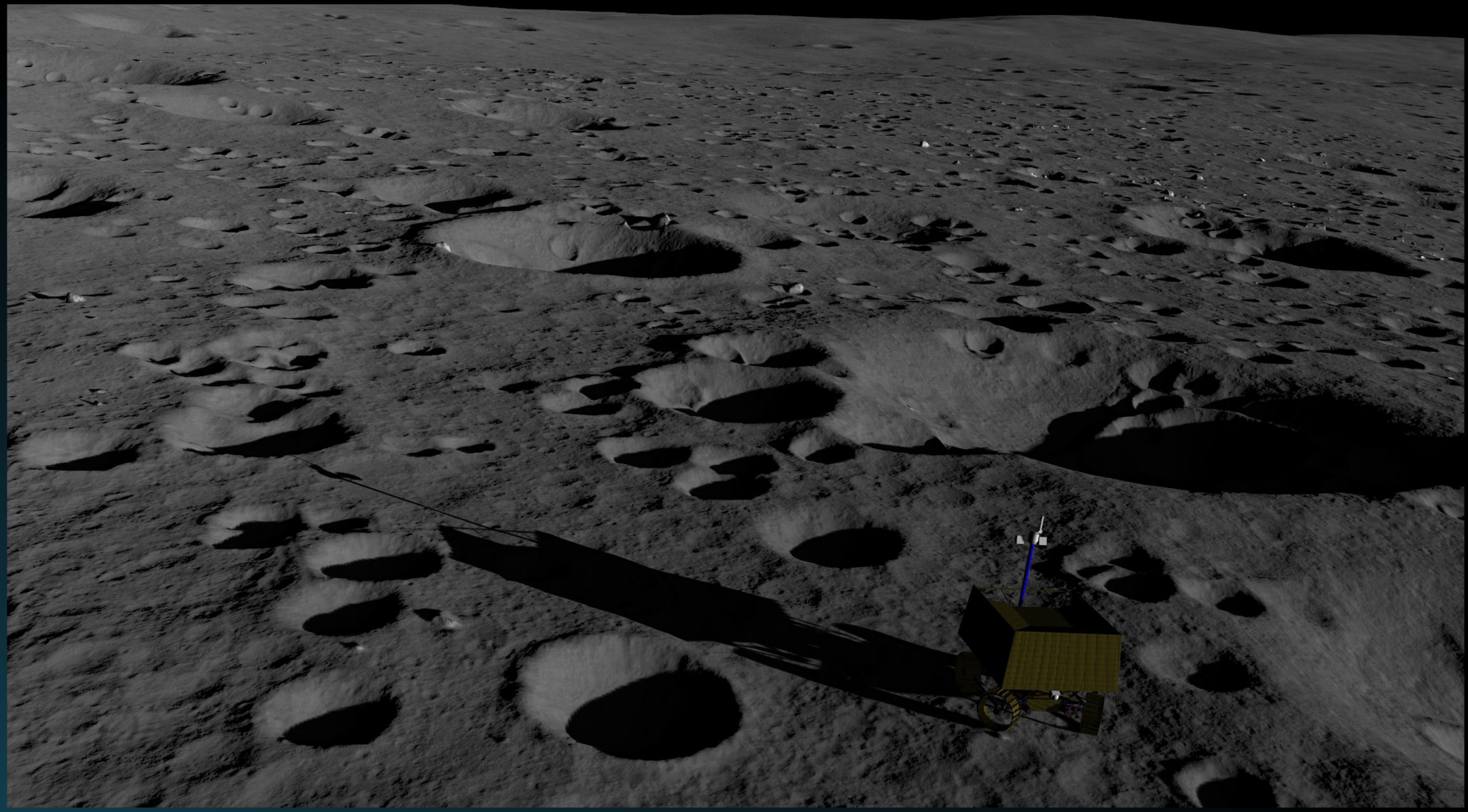


Simulated image

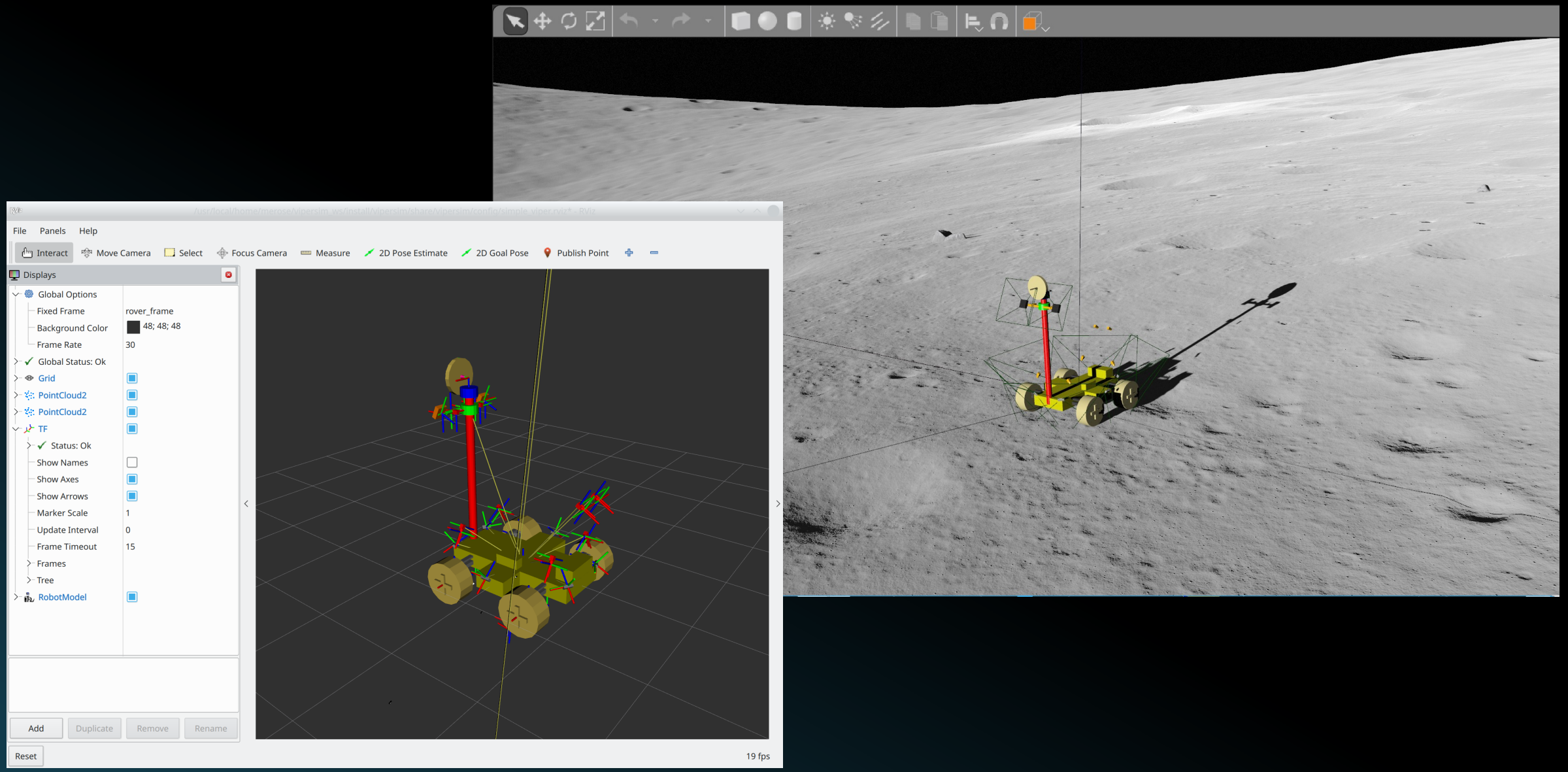


Synthetic Lunar Terrain for Driving Simulation, Mark Allan et. al., Workshop on Lunar Mapping for Precision Landing, 2021

Simulated image

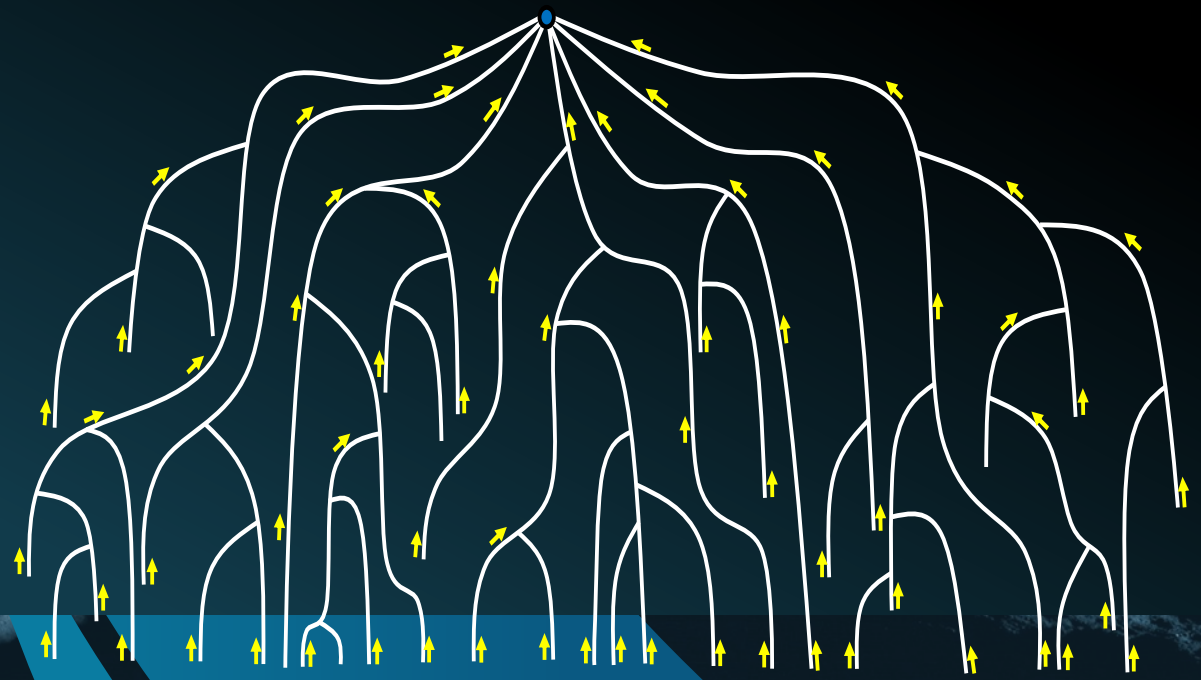


Simulated terrain in Gazebo



Risk-Aware Route Planning

- We address the complexity of planning for moving shadows by using automation to generate traverse candidates
- The automation optimizes science productivity while minimizing risk
- Each route is simulated many times under different performance and anomaly conditions
- Results reviewed by the science and ops teams



Uncertainties considered

- Landing and egress delays
- Initial battery charge
- Power draw
- Average driving speed
- Other execution-time delays
- DSN connection availability
- Solar Energetic Proton (SEP) events

Generates

- Routes with the highest probability of success

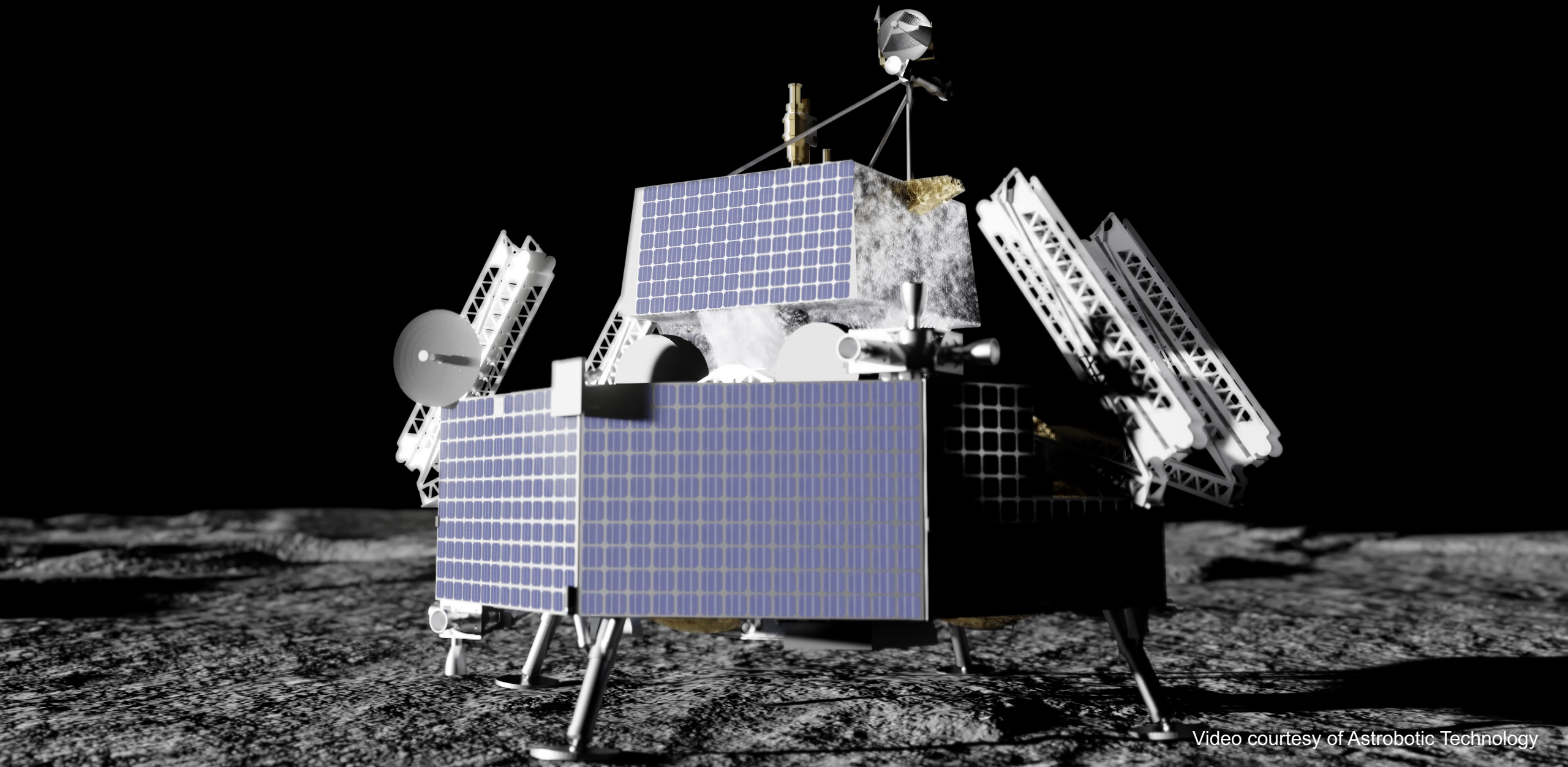
Tool: SHERPA
E. Balaban

Image gallery



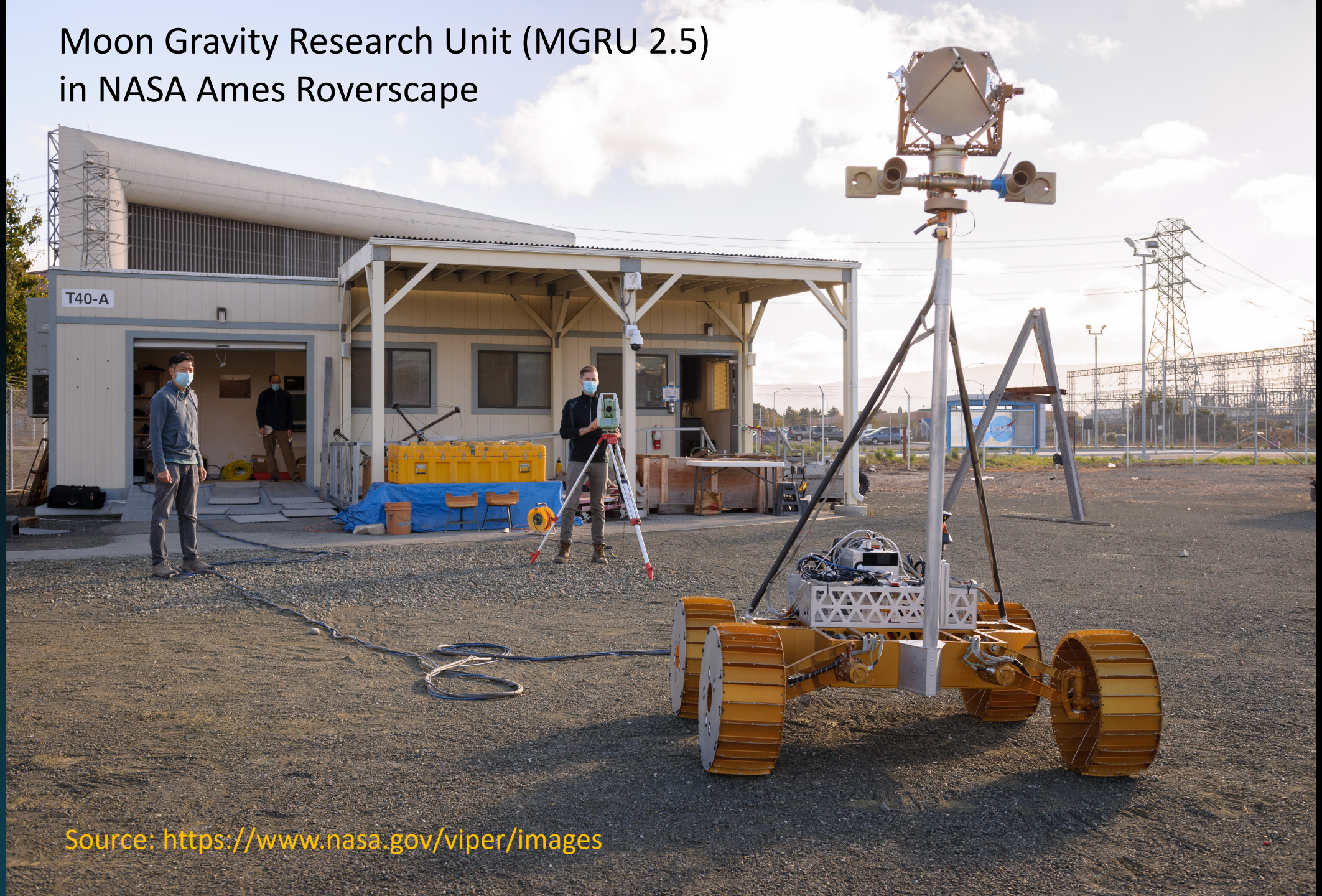
ASTROBOTIC

The NASA CLPS program has selected Astrobotic Technology, (Pittsburgh, PA, USA) for delivery of VIPER to the lunar South Pole in late-2023 aboard their Griffin Lander

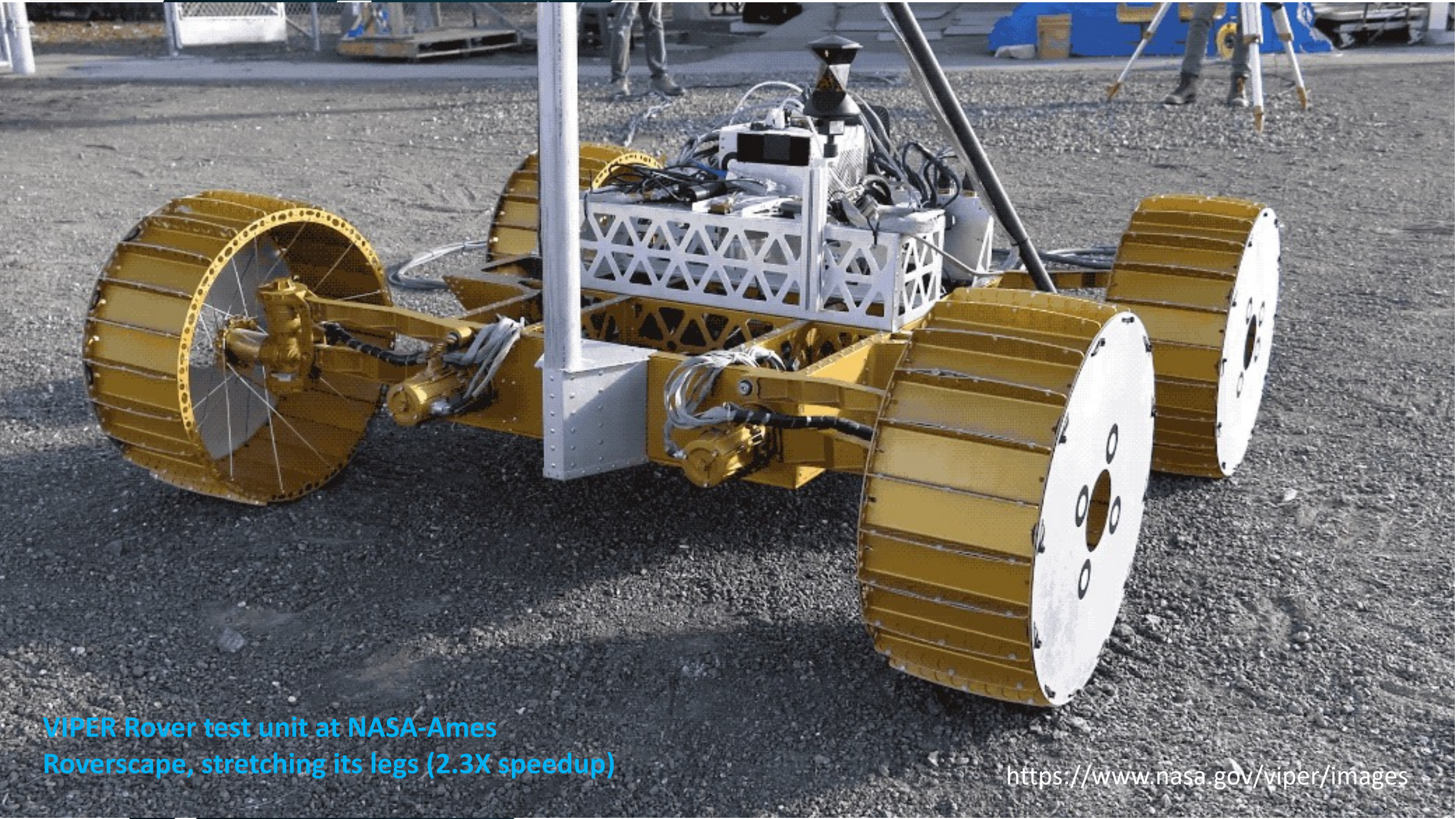


Video courtesy of Astrobotic Technology

Moon Gravity Research Unit (MGRU 2.5) in NASA Ames Roverscape

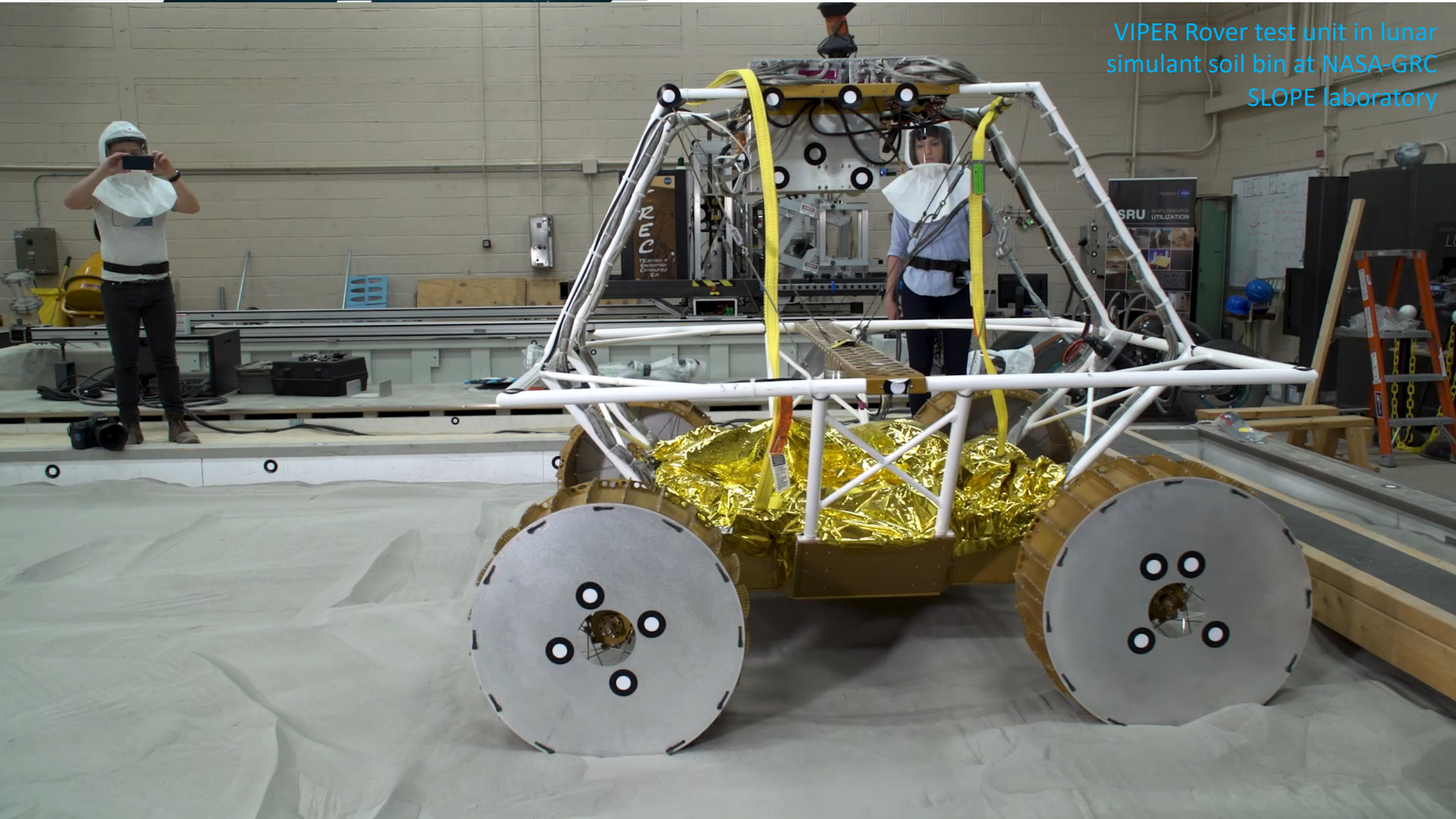


Source: https://www.nasa.gov/viper/images



VIPER Rover test unit at NASA-Ames
Roverscape, stretching its legs (2.3X speedup)

https://www.nasa.gov/viper/images

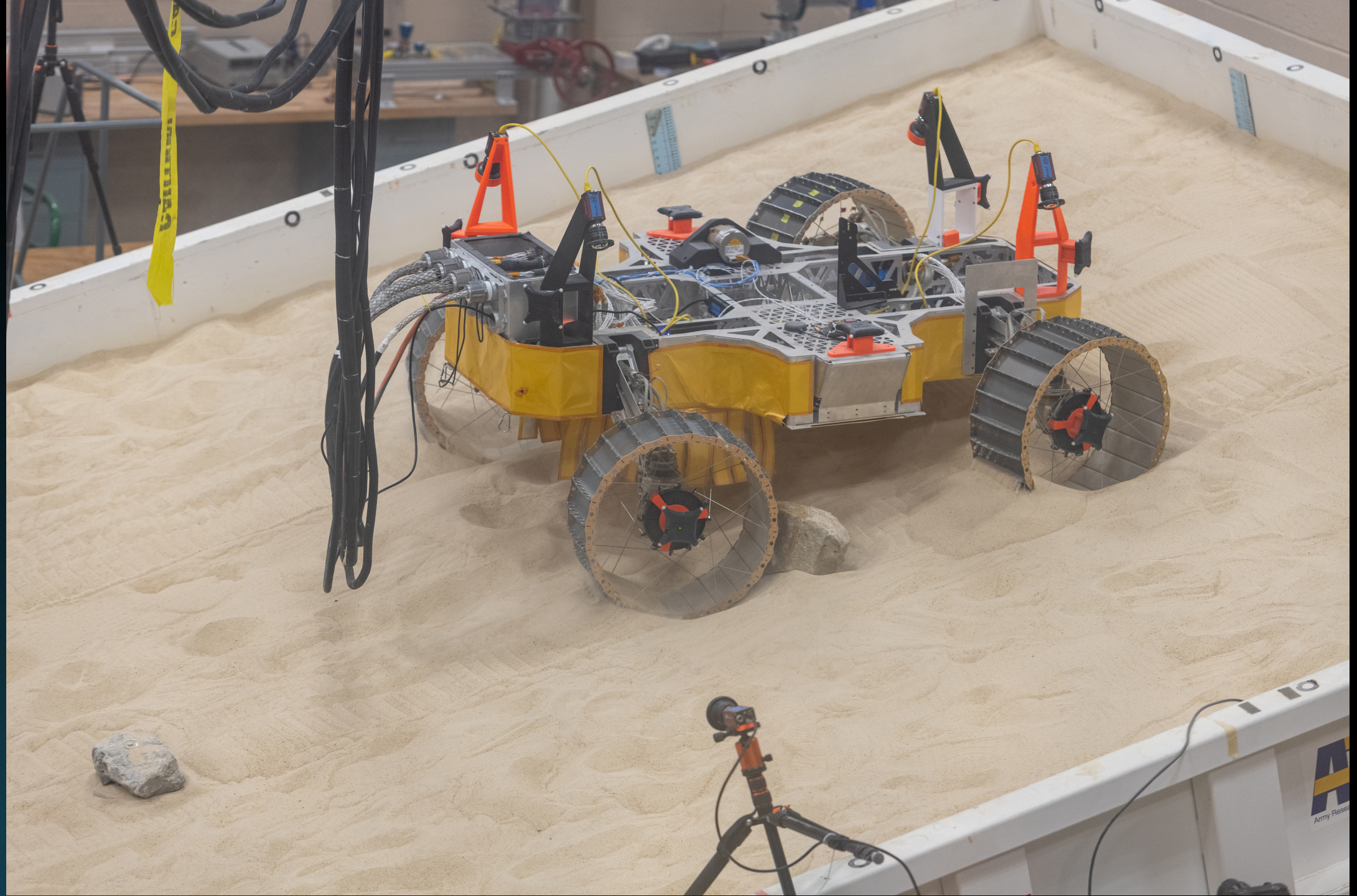


VIPER Rover test unit in lunar simulant soil bin at NASA-GRC SLOPE laboratory

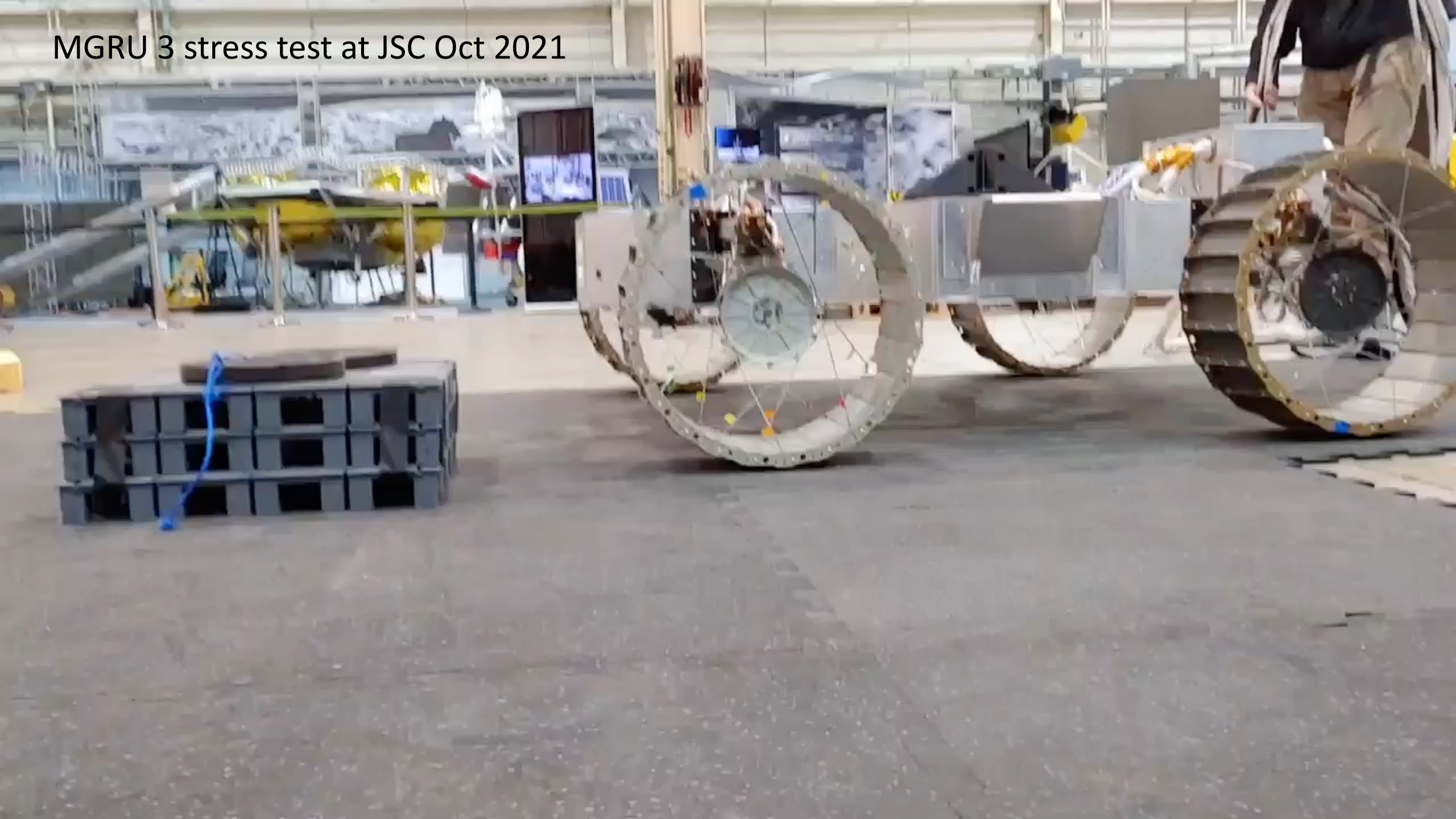
MGRU 3 at GRC SLOPE lab Nov 2021




CAUTION
DANGER
Empty Bed Wt.: 7000 Lbs

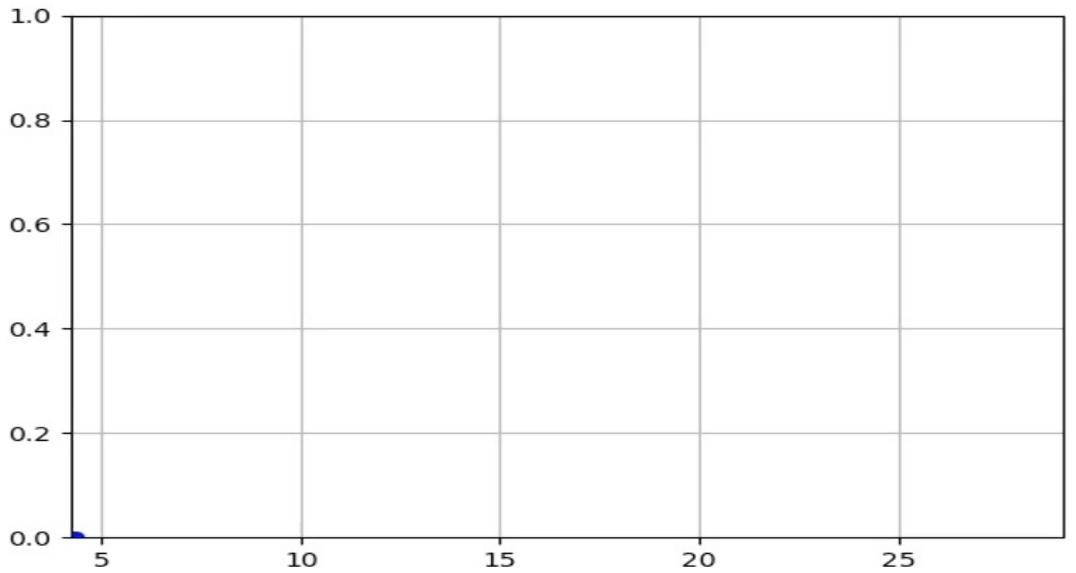


MGRU 3 stress test at JSC Oct 2021



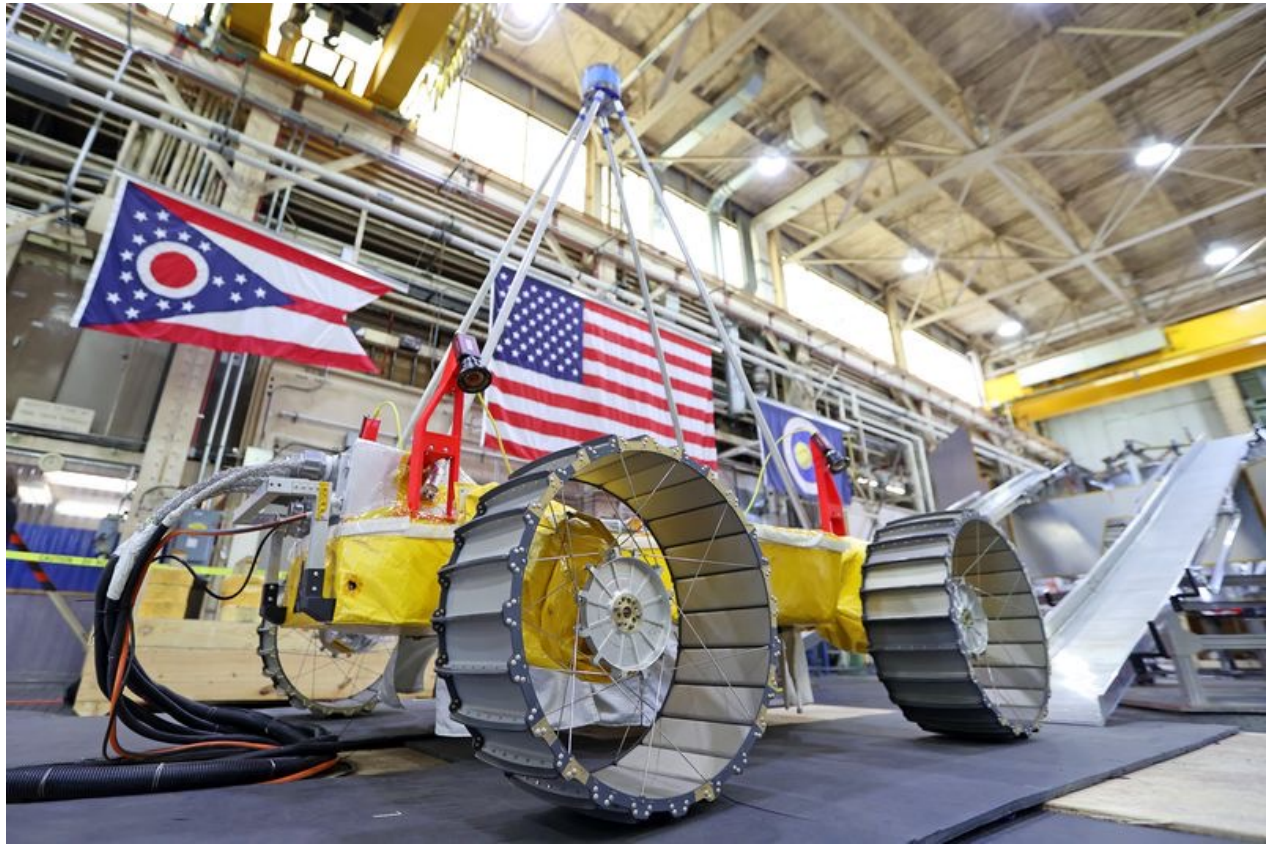
Automatically detecting wheel embedding





Egress Testing – June 2, 2022

At NASA Glenn Research Center



Joshua Gunter, cleveland.com


KONECRANES
MANUFACTURING FACILITY

Moon Water

The past decade of observations have built a fascinating and complicated story about lunar water.

From “frosts” to buried ice blocks, there appears to be water everywhere, but its nature and distribution is very uncertain.

The next steps in exploration require surface assets, including surface mobility.

VIPER is that mission to conduct exploration science, modeled after terrestrial resource exploration processes and techniques.

https://www.nasa.gov/viper

Launch Oct/Nov 2024




Questions?