

Space Robotics: The Next Generation

Astrobee, CADRE, and VIPER

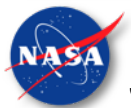
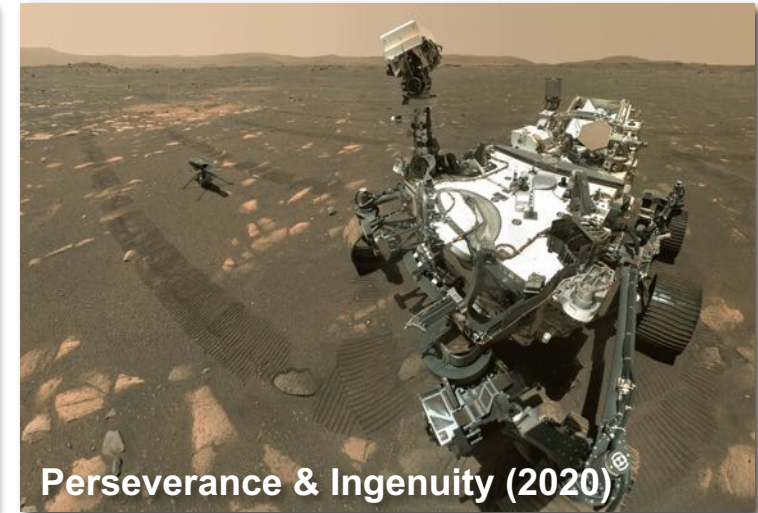
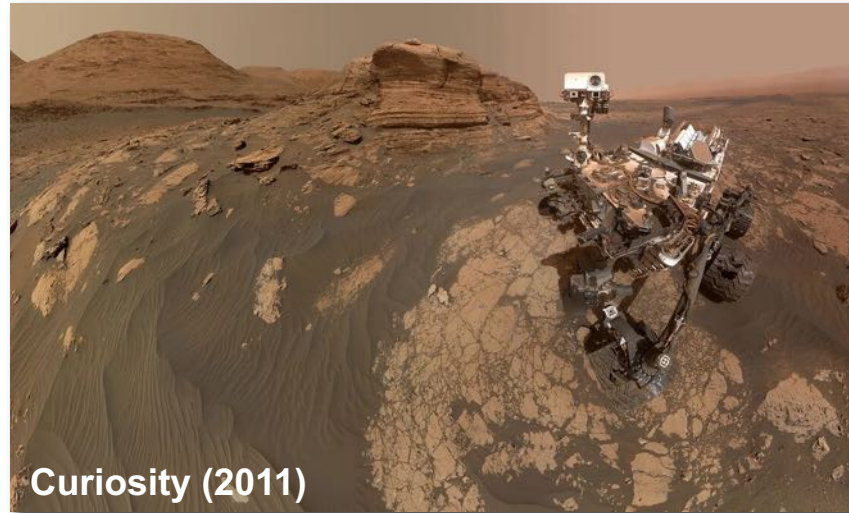
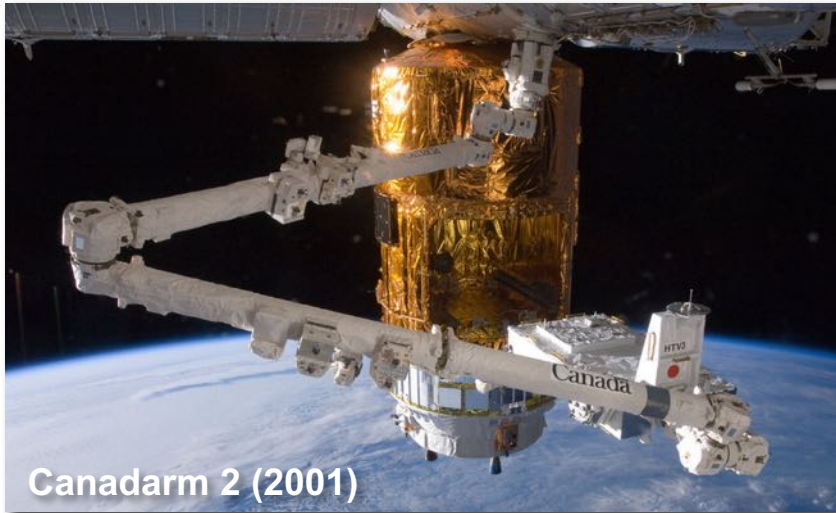
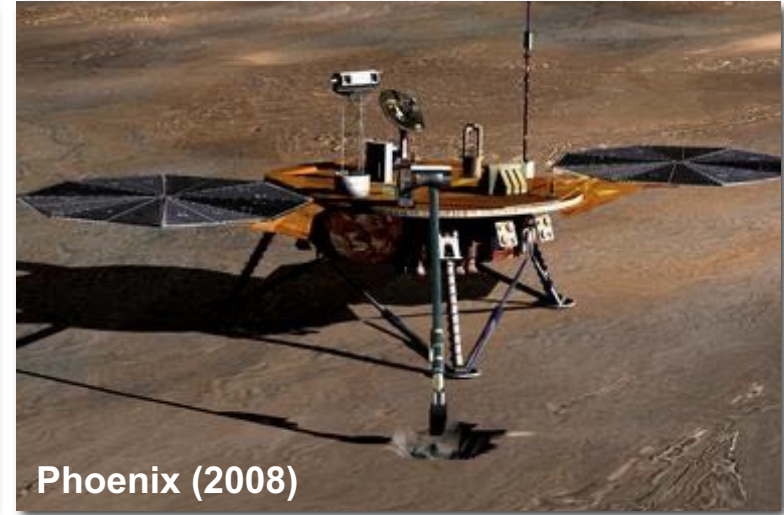


Terry Fong

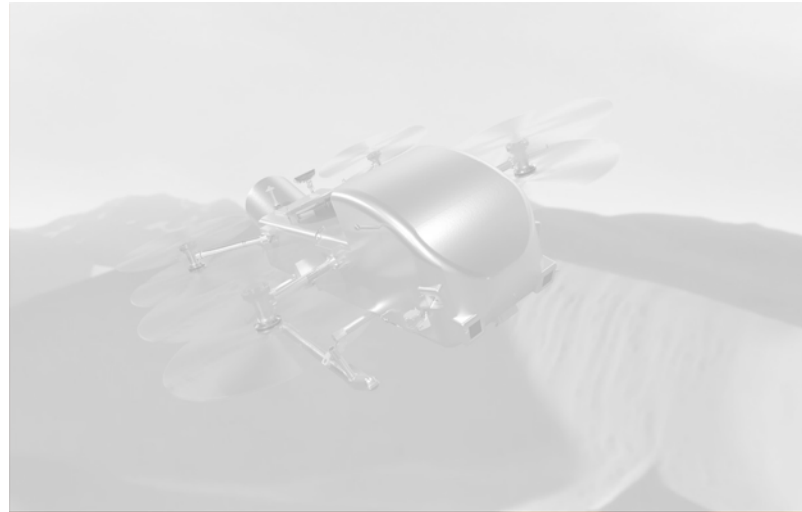
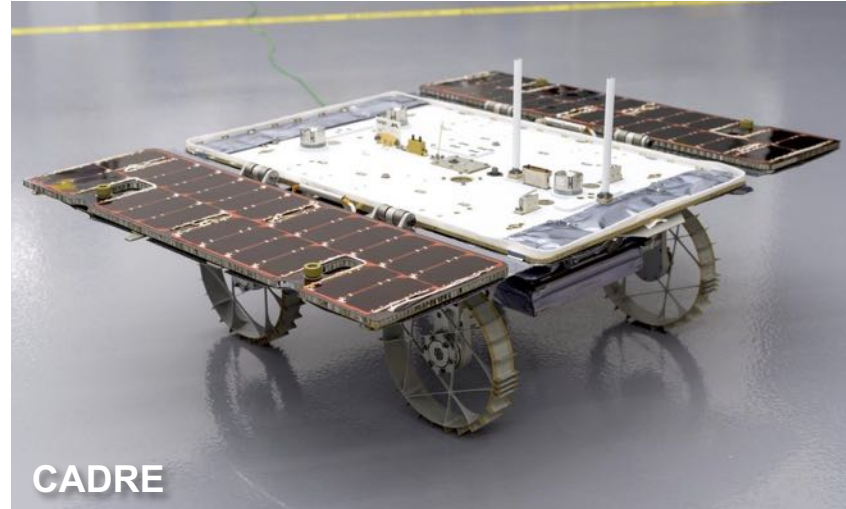
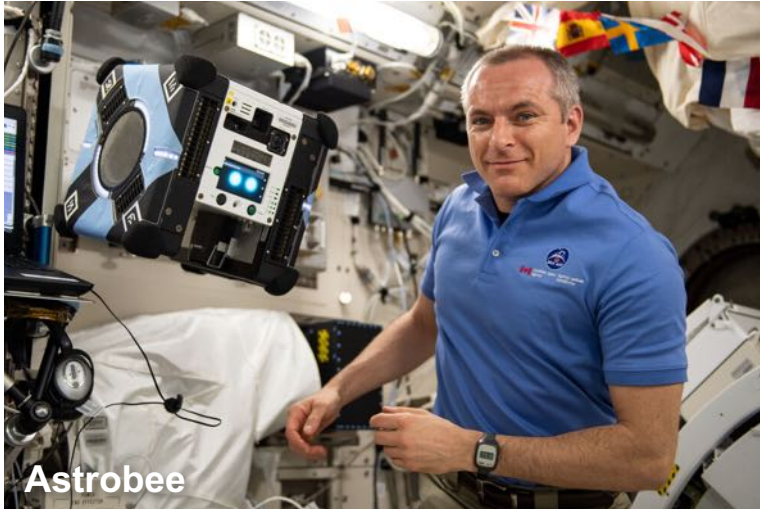
Chief Roboticist
NASA Ames Research Center
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2024-10-11

Space Robotics



(Some of) The Next Generation





Astrobee

**Free-Flying Robots on the
International Space Station**

Astrobee

Applications

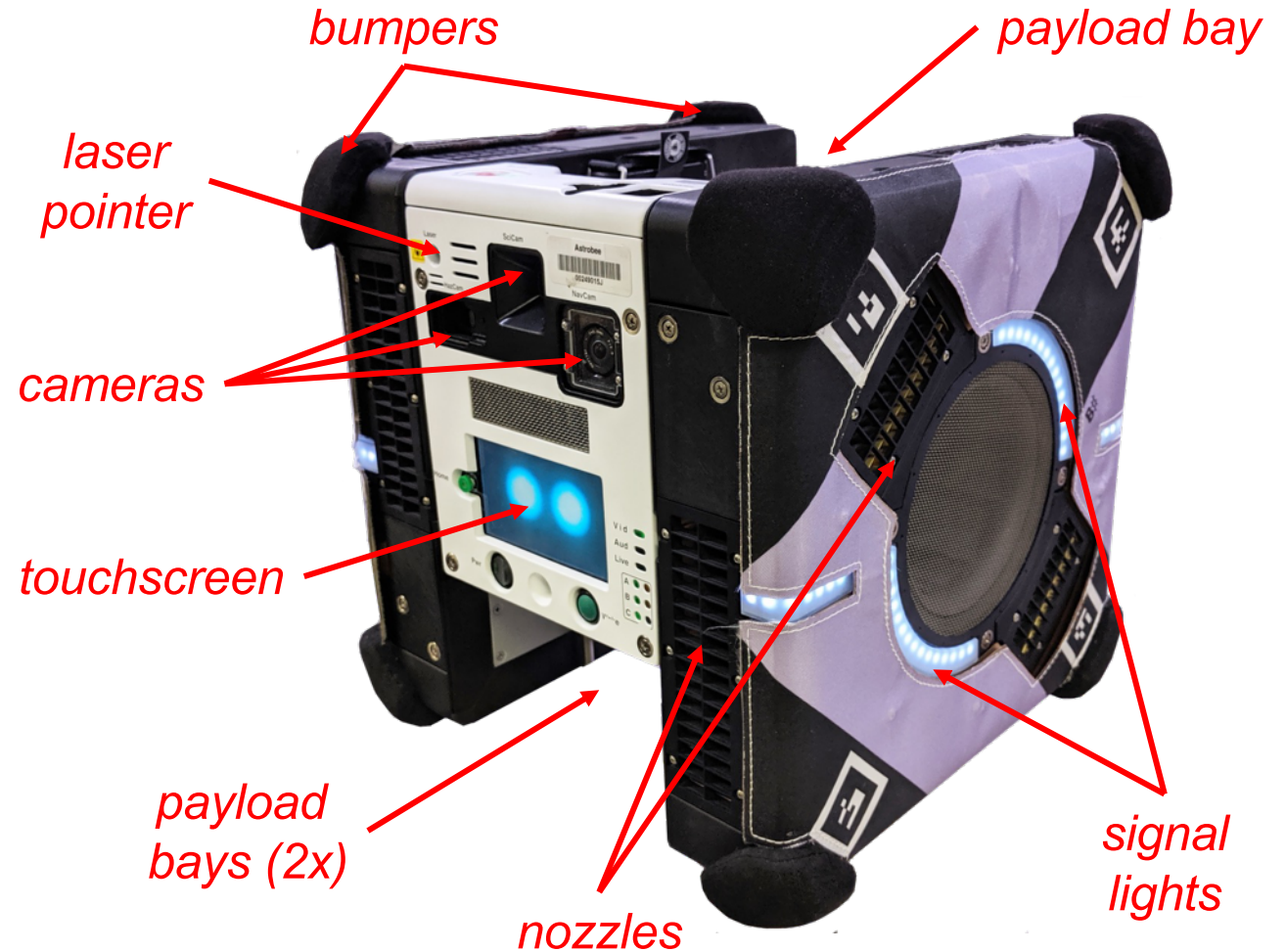
- Microgravity robotics research
- Mobile sensor (inventory, etc.)
- Remotely operated camera

Specs

- 10 kg, 32 x 32 x 32 cm
- All electric, fan-based propulsion
- Robot arm for “perching”
- Three smartphone computers
- Open-source software (with simulator)

New technology

- Autonomous docking & recharge
- Autonomous perching
- Vision-based navigation



<https://www.nasa.gov/astrobee>



A photograph taken from the International Space Station (ISS) showing a view of Earth from space. The Earth's surface is covered in blue oceans and white clouds. The horizon of the planet is visible, curving away from the viewer. In the upper center, a portion of the station's structure is visible. On the right side, a solar panel array is partially visible. The text "VICE PRESIDENT HARRIS CALLS NASA ASTRONAUTS" is overlaid in large, white, bold, sans-serif capital letters across the center of the image.

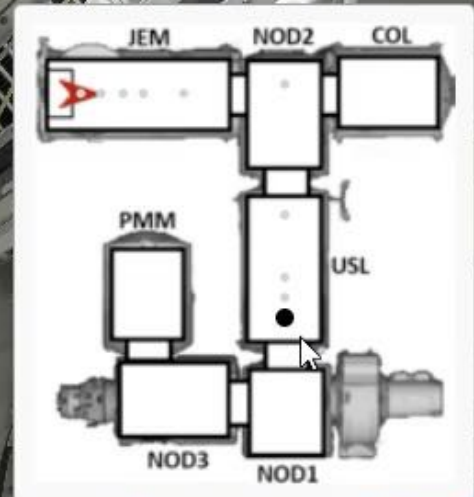
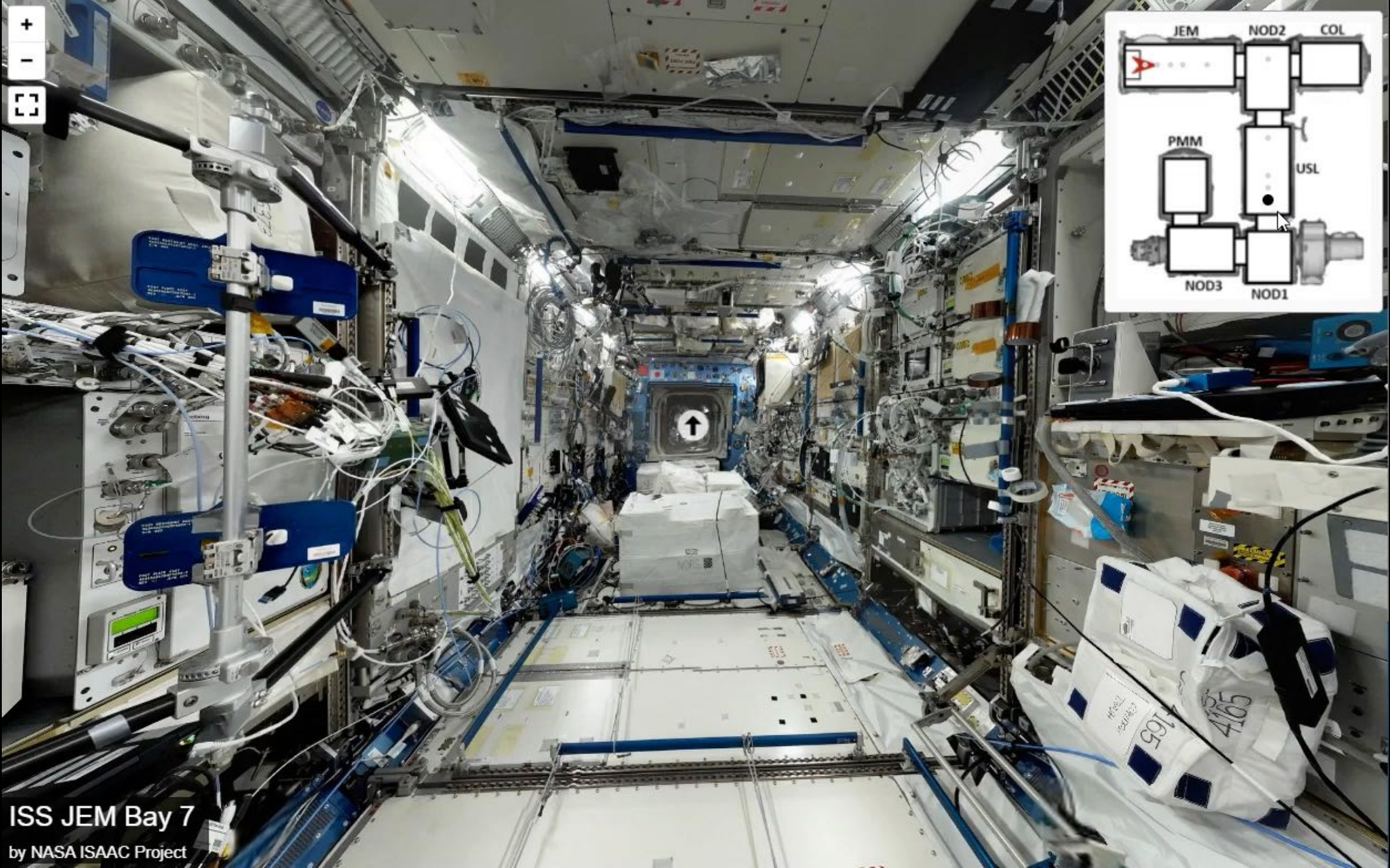
VICE PRESIDENT HARRIS CALLS NASA ASTRONAUTS



Astrobee 1st Autonomous Survey

2022-04-07 ISAAC-6

4 crew members working independently



ISS JEM Bay 7
by NASA ISAAC Project

Survey Data Analysis

Label search

- Perform image-to-text conversion and indexing
- Enables search by label text to find 3D locations with matching imagery
- Supports spacecraft monitoring

Switch state identification

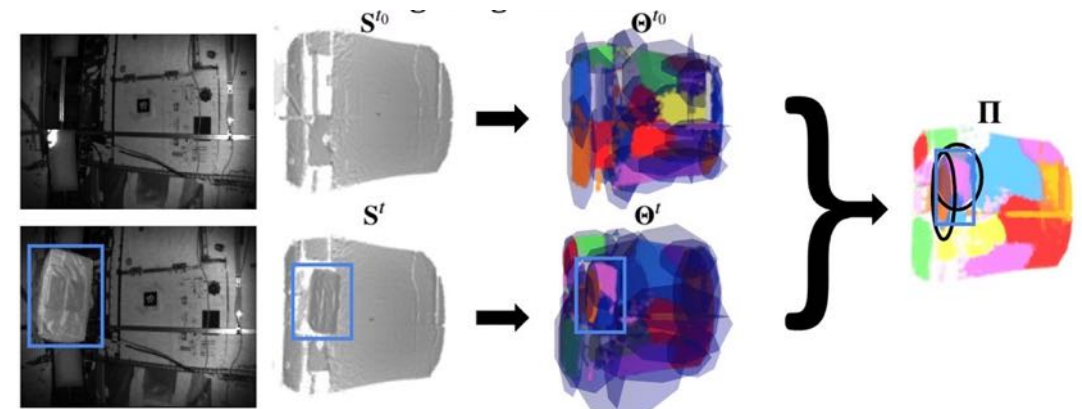
- Identify switch panels and individual switches
- Automatically classify switch state
- Supports spacecraft monitoring

Change detection

- Compare current and historical imagery
- Automatically detect objects added, removed, or relocated
- Supports logistics management



Examples of switch patches extracted from larger images and classified on/off. Credit: Tim Rehnstroem.



Before-and-after change detection successfully finds the location of a cargo bag added to the scene. Credit: Santos, et al.

Hatch Seal Inspection



Divot and cut
~1.8 x 1.5 mm



Divot
~0.7 x 0.3 mm



CADRE

COOPERATIVE AUTONOMOUS DISTRIBUTED ROBOTIC EXPLORATION

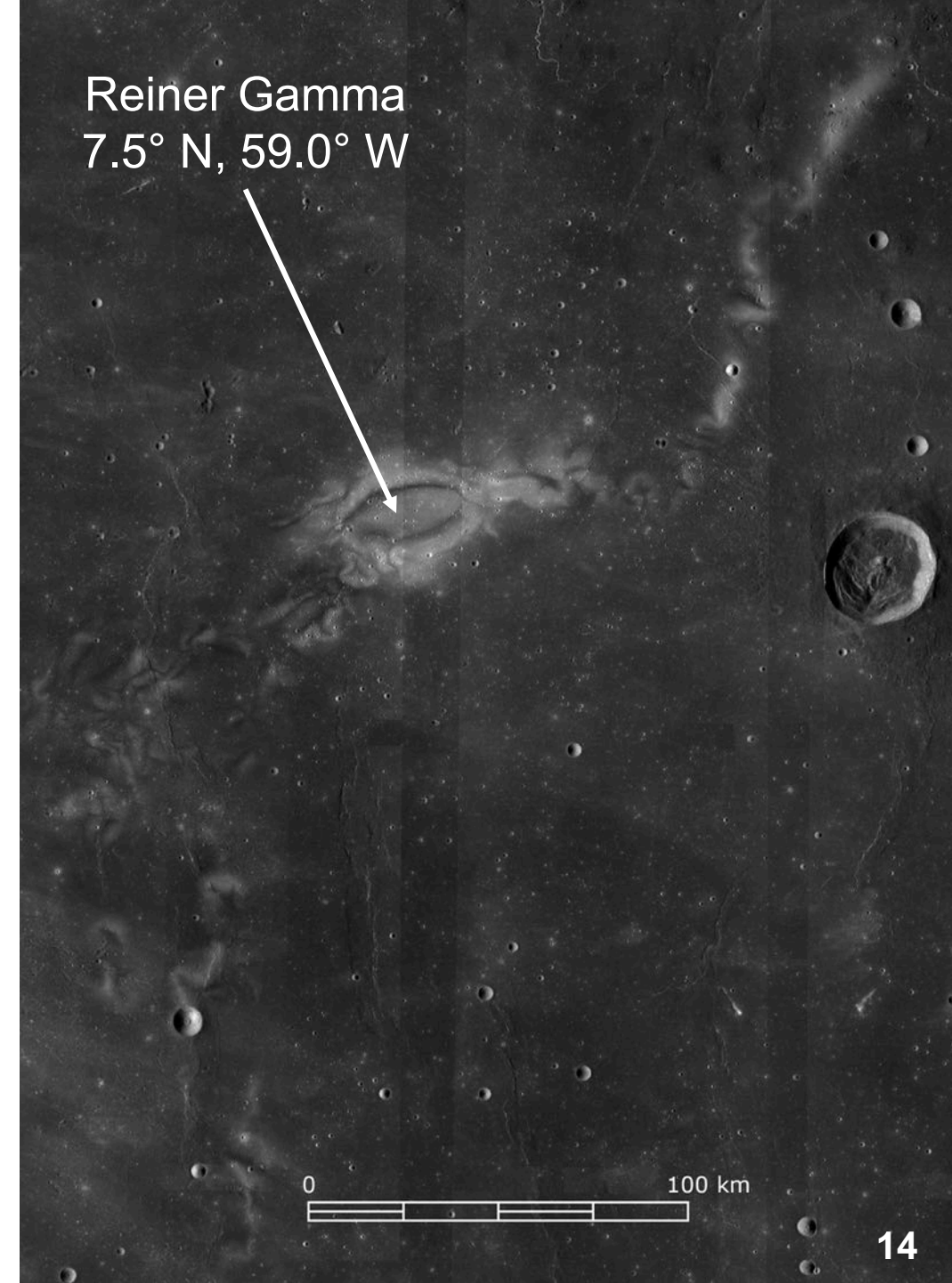
JEAN-PIERRE DE LA CROIX, **Principal Investigator**
SUBHA COMANDUR, **Project Manager**

Jet Propulsion Laboratory, California Institute of Technology

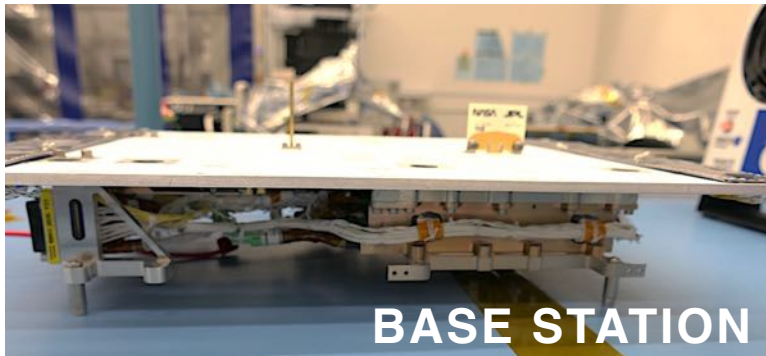
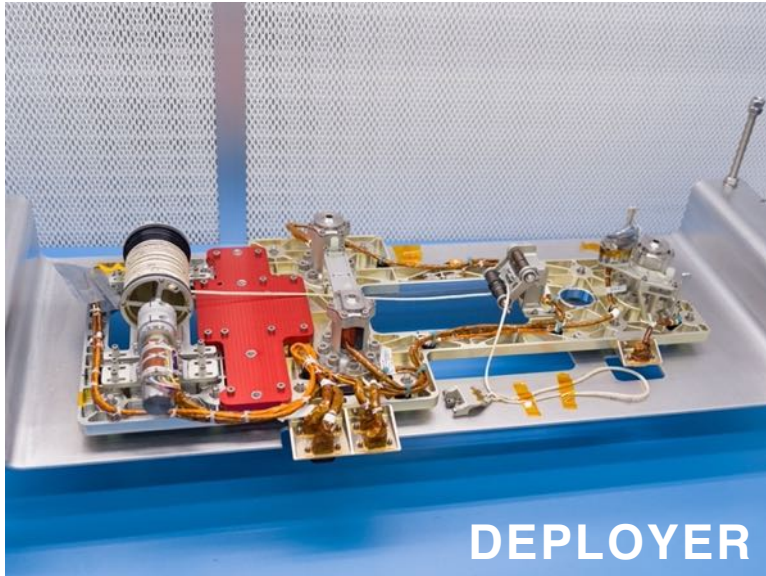


MISSION OVERVIEW

- CADRE will demonstrate multi-agent autonomy on the Moon.
- CADRE is manifested as a payload on a commercial lunar payload service (CLPS) Intuitive Machine's IM-3 mission, and is headed to the Reiner Gamma "lunar swirl" magnetic anomaly.
- CADRE's technology demonstration will focus on cooperative exploration and distributed measurements using multiple ground penetrating radars (GPRs).



CADRE SYSTEM

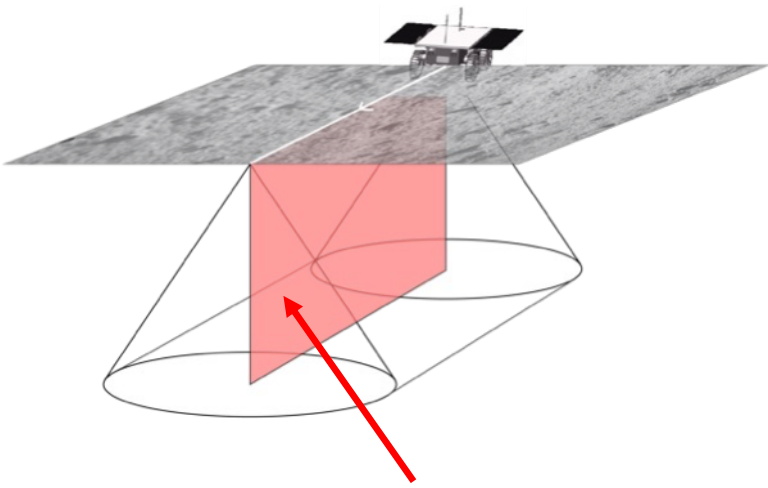


APPLICATION

Multi-static Ground Penetrating Radar

Today

Single Monostatic Measurements



2-DIMENSIONAL DATA ONLY

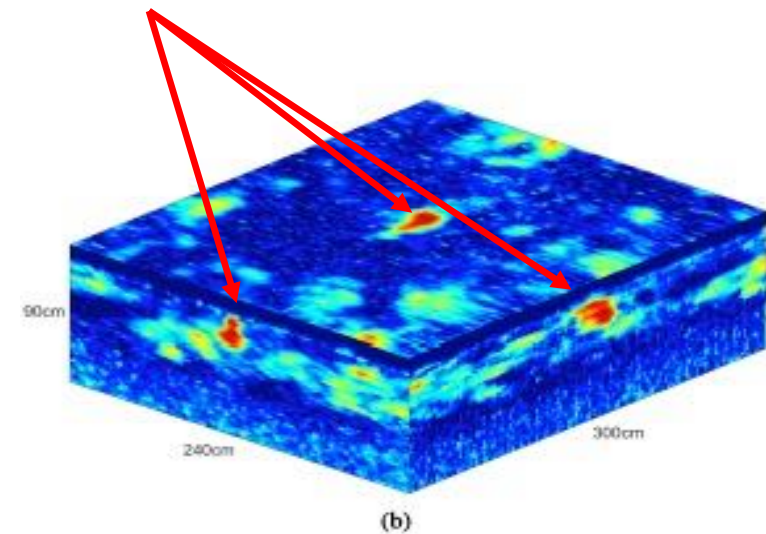
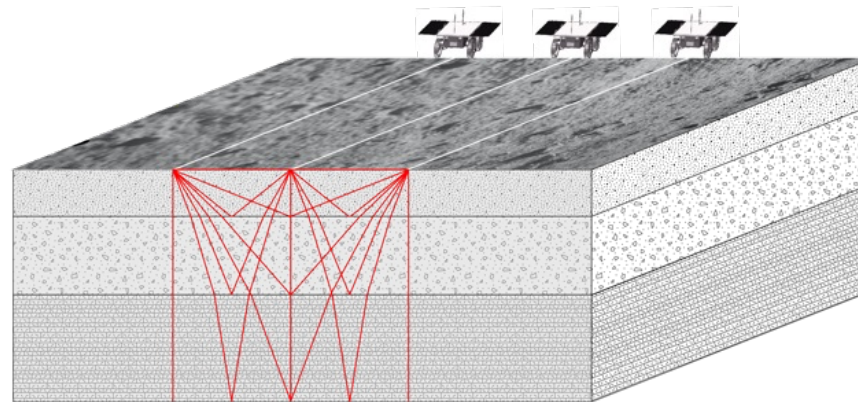
State-of-the-Art:

- Chang'e 3 and 4 Lunar Penetrating Radar on the Moon
- Perseverance RIMFAX on Mars

Tomorrow

Distributed & Adaptable Multi-Static Measurements

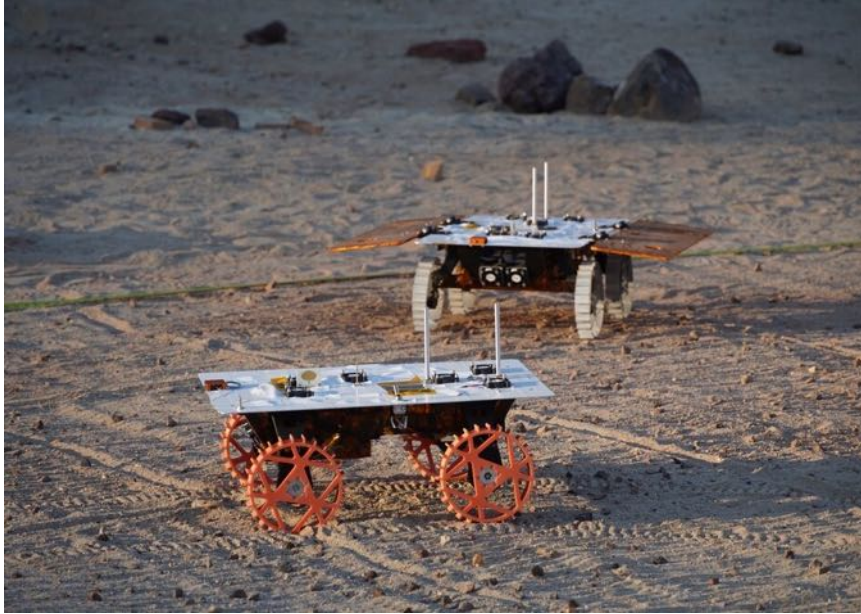
3D SUBSURFACE IMAGERY FROM MULTIPLE GPRs WORKING TOGETHER



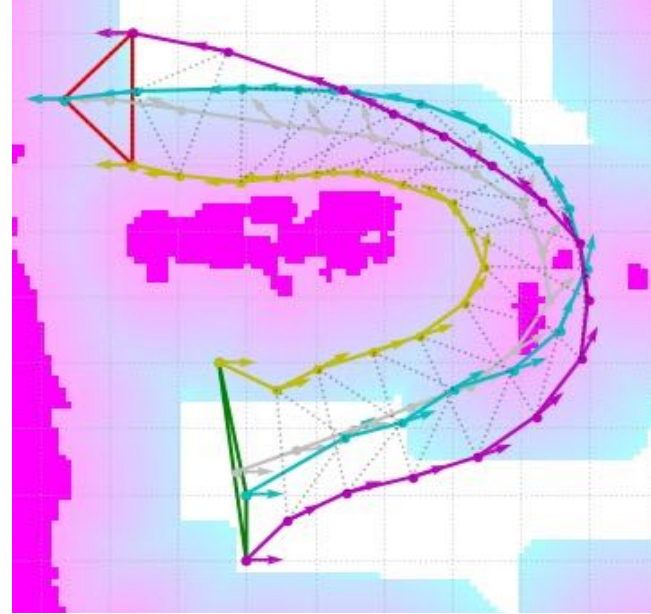
Rovers have to:

- (1) navigate across the lunar surface in a specific formation
(depth measurement dictated by rover separation) and
- (2) maintain this formation within a certain threshold
(derived from required measurement Signal to Noise Ratio)

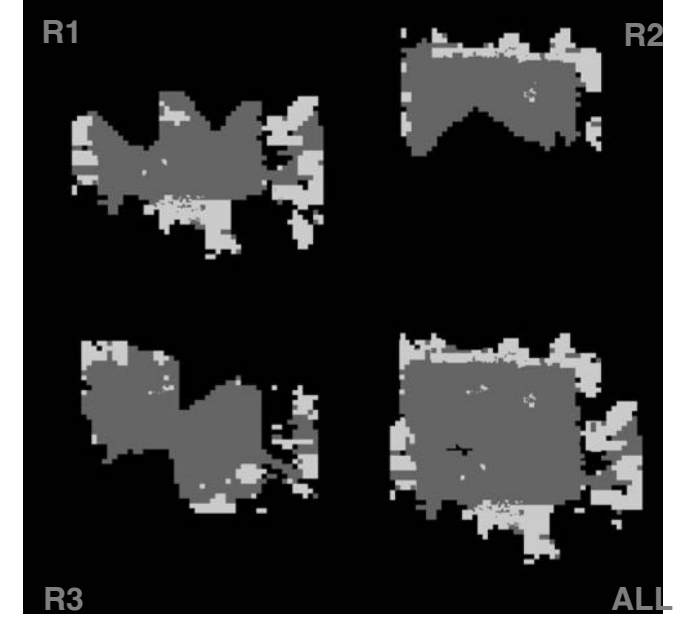
COORDINATION & COOPERATION



Relative Position Determination of the team of rovers relative to the lander using on-board state estimation and inter-rover distance measurements.



Coordinated Behaviors and Motion Planning to enable exploration and formation driving for distributed measurements.



Knowledge Building of the local environment merged and maintained from sensor data on-board each rover.

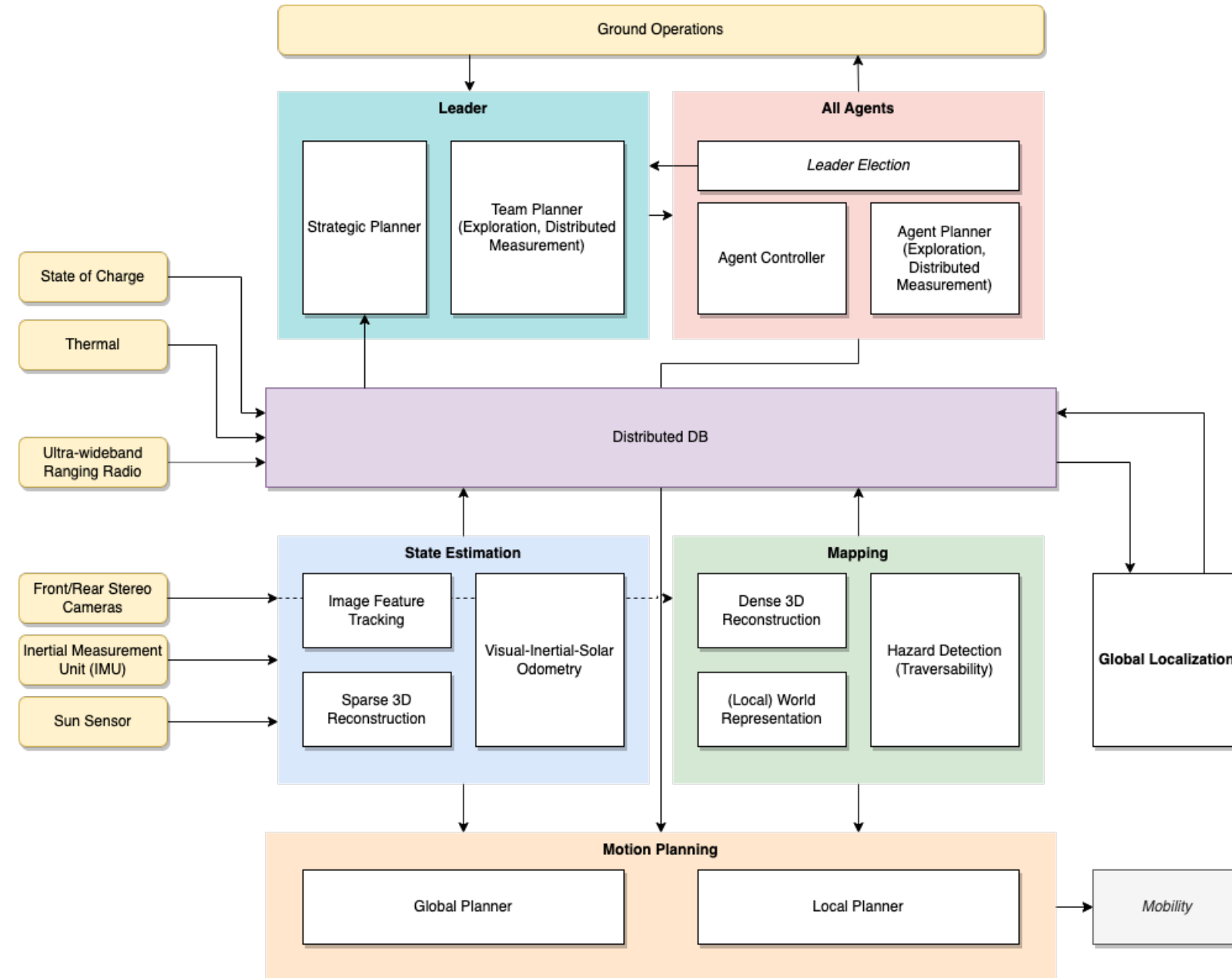
Plus:

- Global Pose Optimization (GPO) to correct for drift across the team
- Multi-resolution traversability mapping
- Optimization-based motion planner to track trajectories (space and time)

Plus:

- Distributed database with replication (maps, localization)
- Autonomous, multi-robot strategic planning based on real time resource constraints (state of charge, thermal conditions, etc.)
- Leader election with designator survivor

MULTI-AGENT AUTONOMY



Ground Provide goals:
Explore this region
Follow this path in formation

Leader Decide:
What can I do with all available resources?
Who goes where?

Every Rover Communicate:
What do we all know?

Estimate:
Where am I?

Estimate:
What does the Moon look like?

Decide:
How to get there?

National Aeronautics and
Space Administration

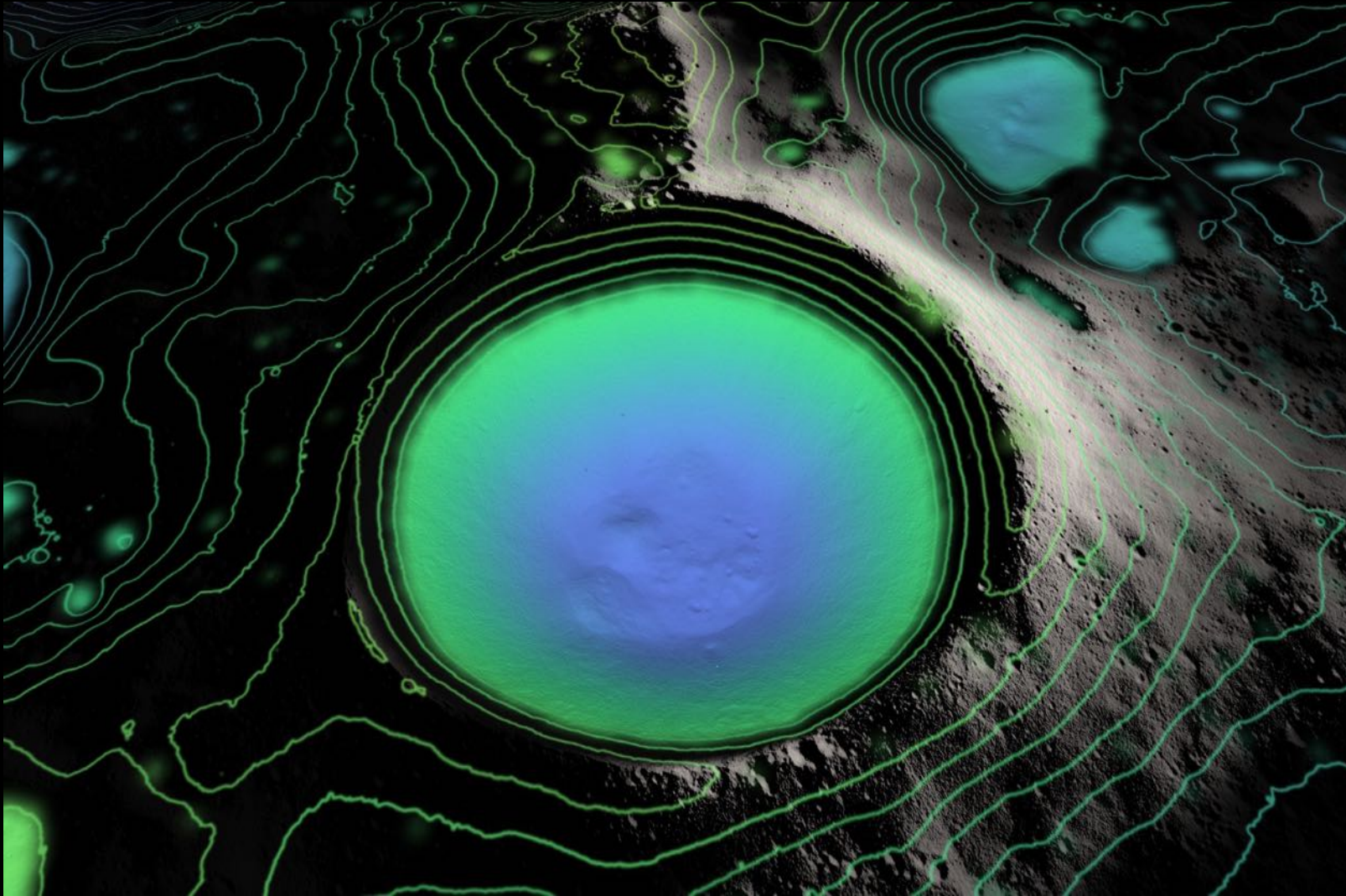


Volatiles Investigating Polar Exploration Rover

Ames Research Center (ARC)
Johnson Space Center (JSC)
Kennedy Space Center (KSC)

Project Manager: Dan Andrews (ARC)
Project Scientist: Tony Colaprete (ARC)

Water-ice exists in the polar regions of the Moon



- Polar region craters sit in permanent or near-permanent shadow, because of the low angle to the Sun
- No sun means water-ice can be protected from sublimation
- Permanently Shadowed Regions (PSRs) cover an area of 10^4 km^2 (~100x San Francisco)



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



The next great leap in understanding lunar water's potential is to map these volatiles at large scale



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

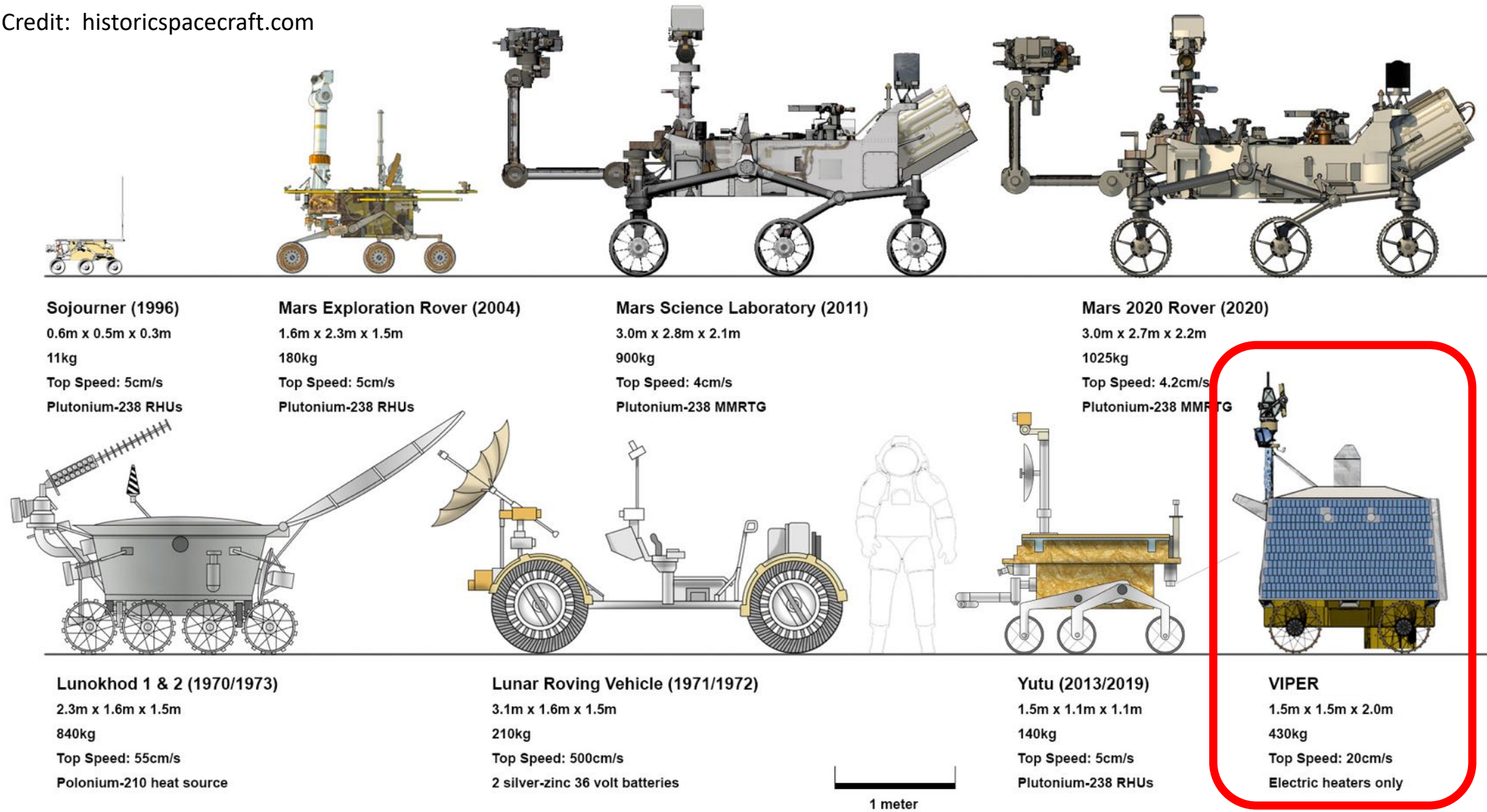
- “Real-time” mission control: rover operations + science team
- Single waypoint driving (approx. 4 m / command cycle)
- Hybrid of human exploration (Shuttle, Space Station) and Mars rover mission operations

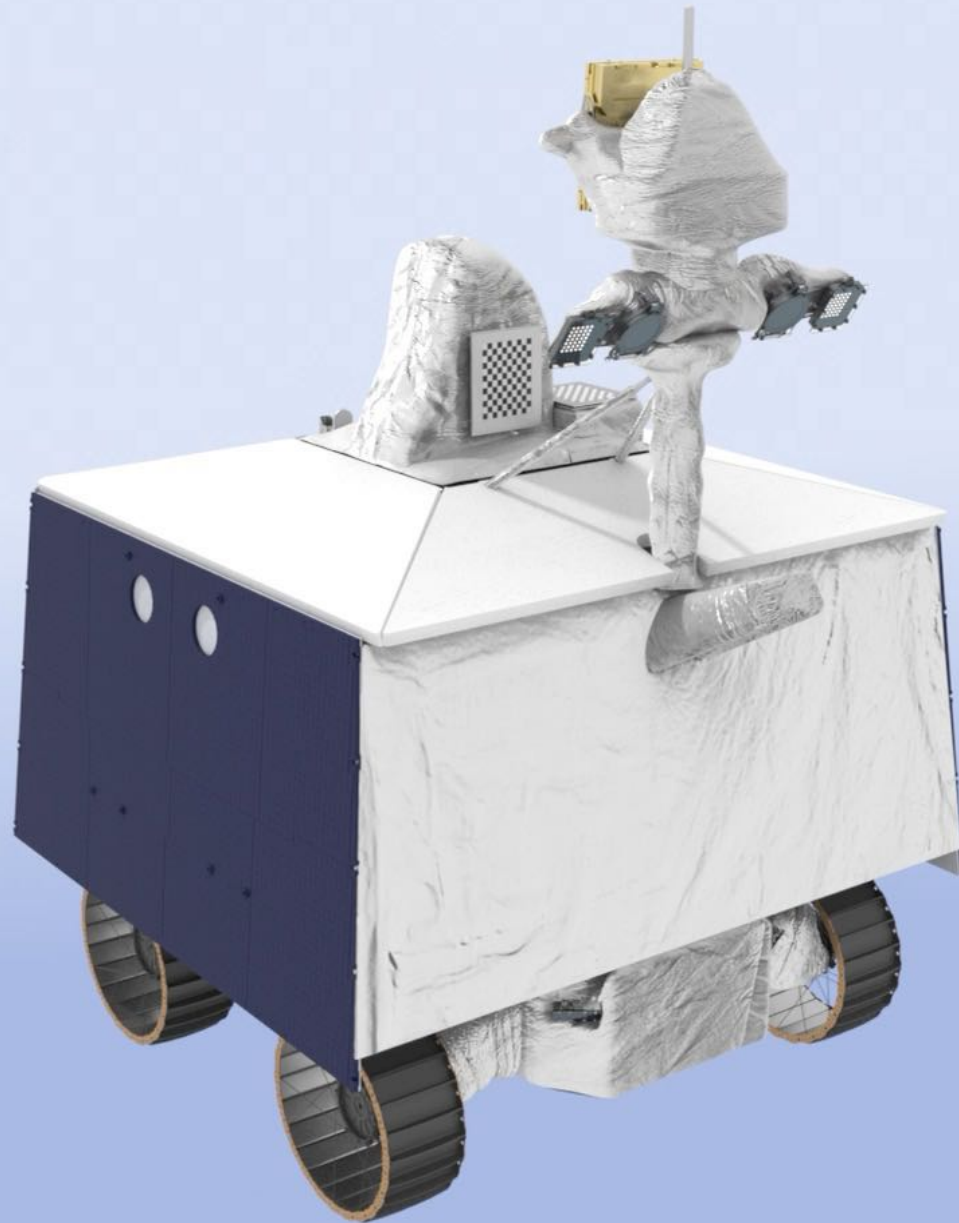
Hybrid avionics and software

- 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)

Rover Comparison

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

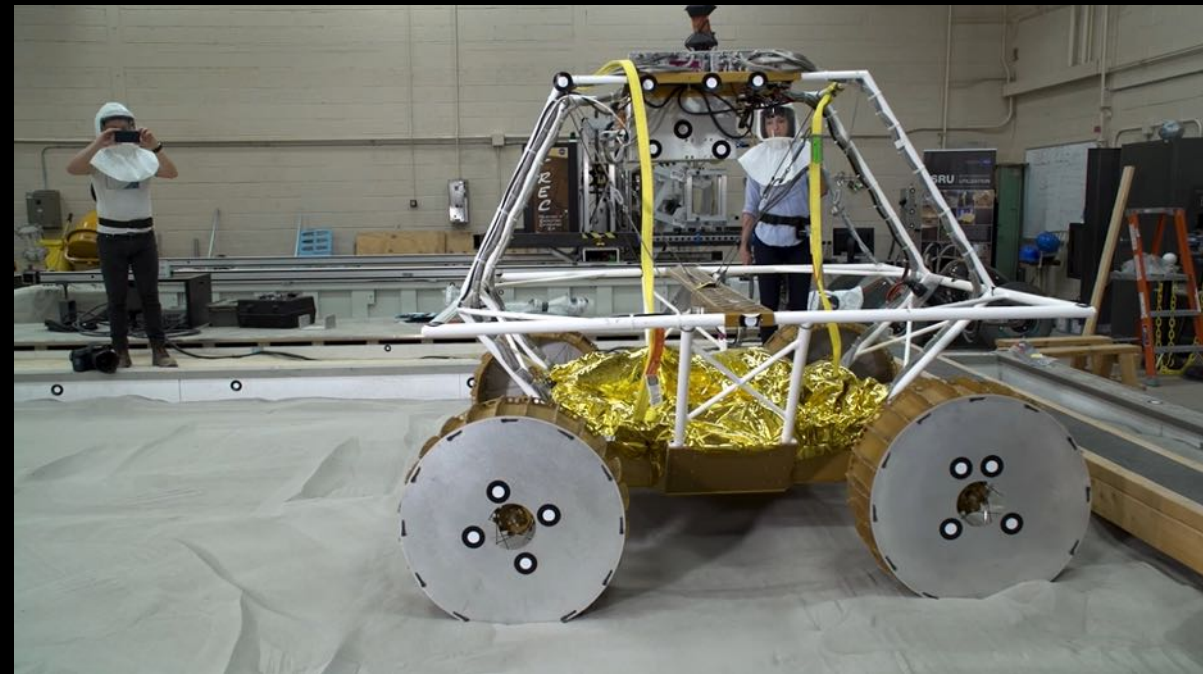




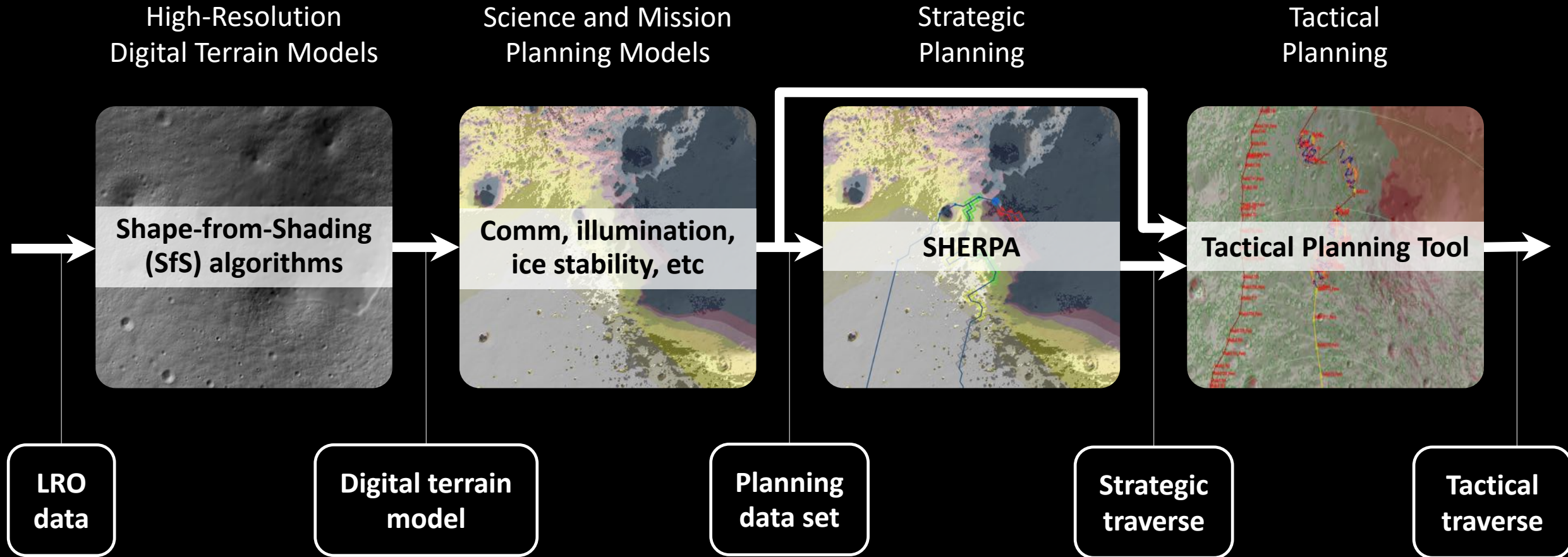
Hybrid Locomotion



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



VIPER Surface Mission Planning Process



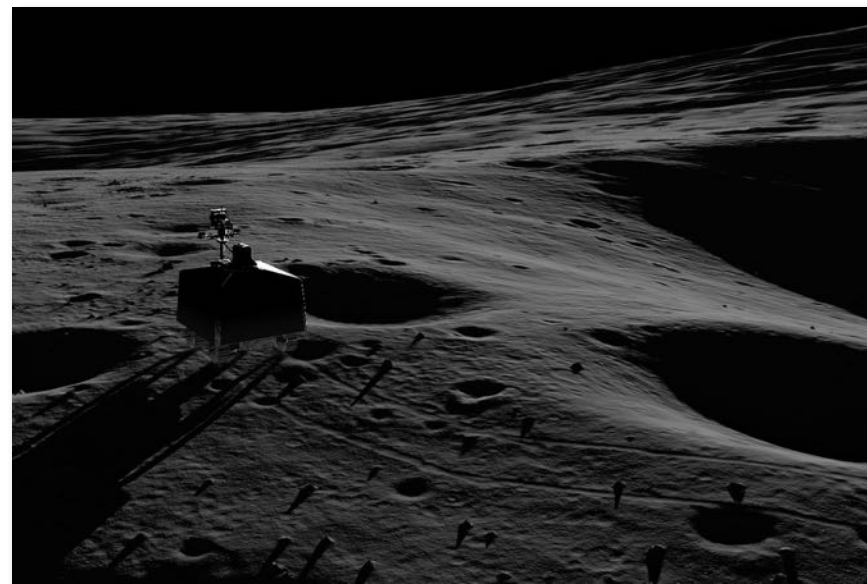
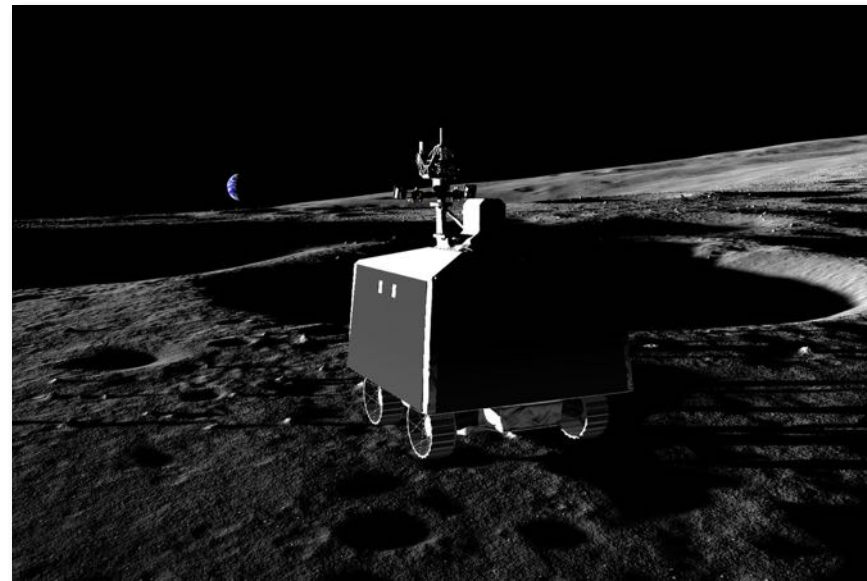
2023-11-23
to
2024-03-07

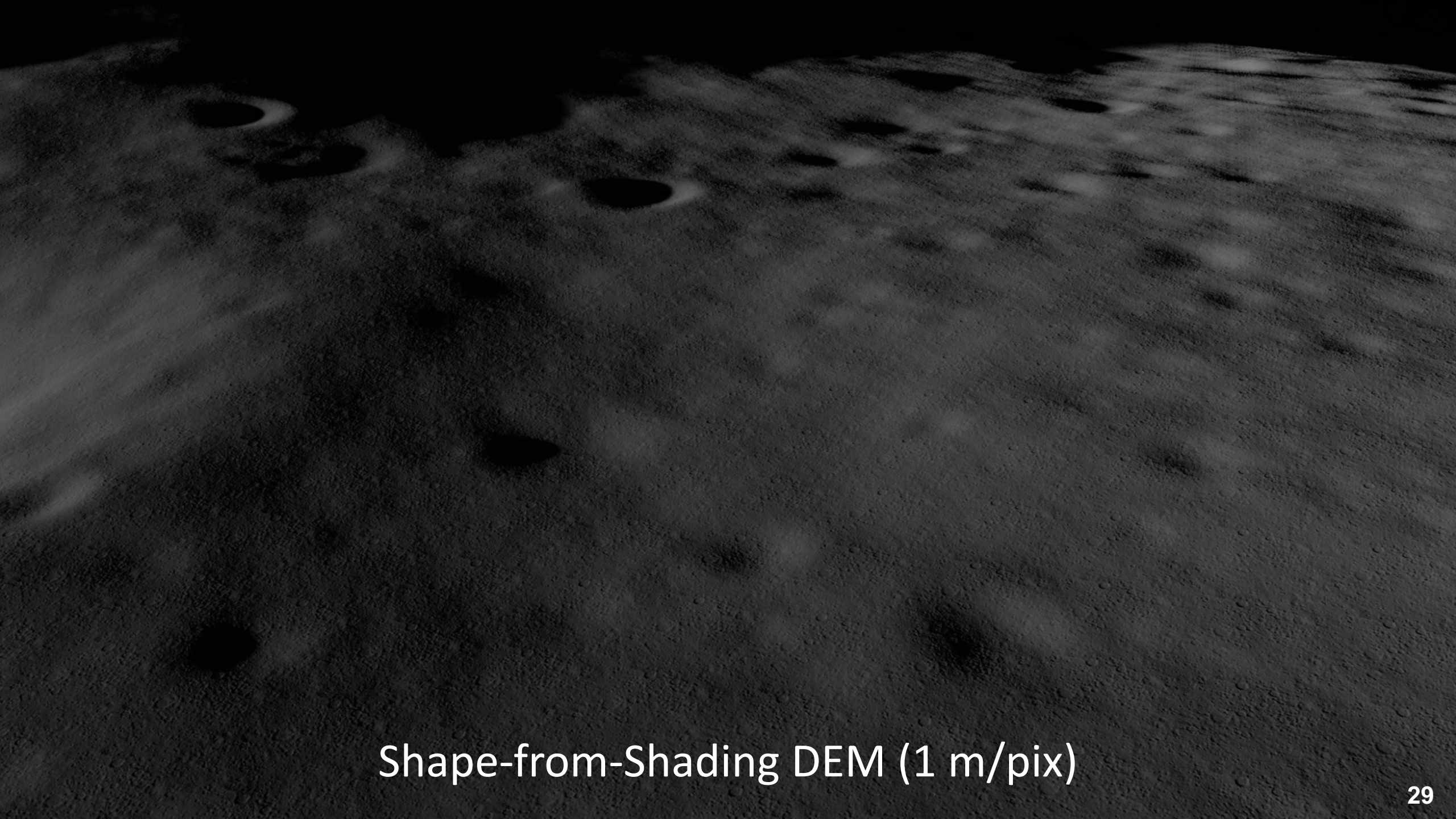


Simulator (“RSIM”)

Key Features

- High dynamic range rendering
- Real-time shadows
- Support for high resolution terrains
- Rover wheel tracks and slip modeling
- Rover lights with custom pattern
- High-fidelity camera modeling
- Lunar regolith reflectance model
- Accurate Sun & Earth ephemeris
- Based on Gazebo Classic r11 (with many customizations)



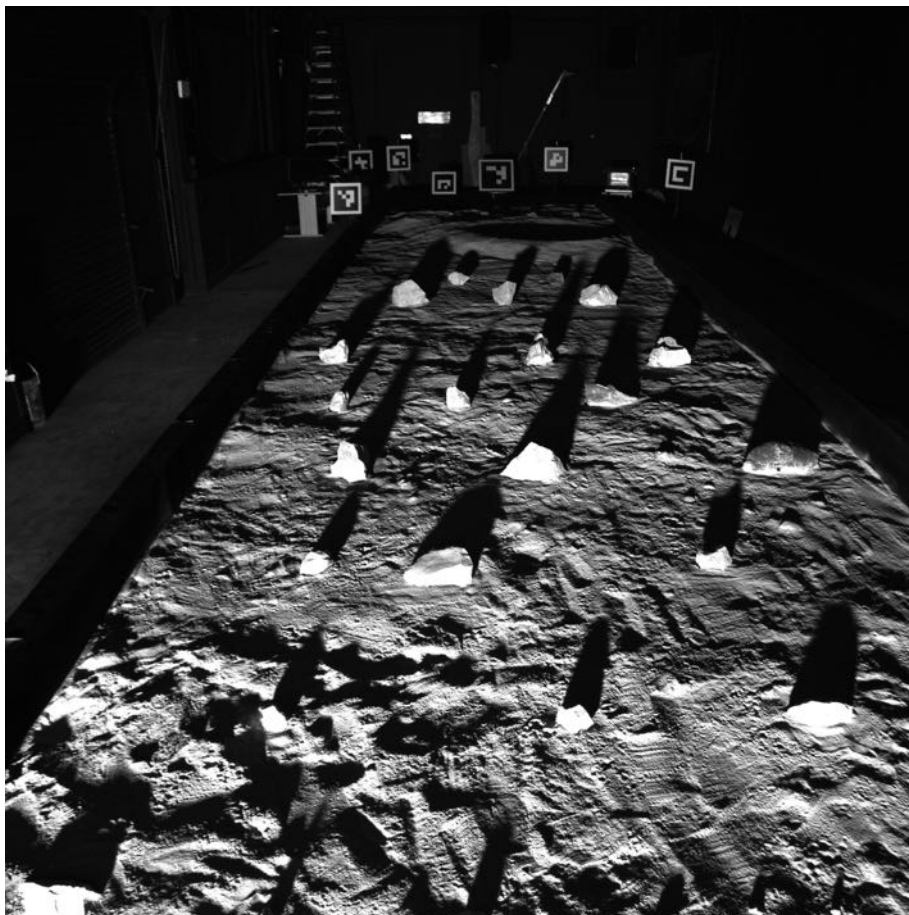


Shape-from-Shading DEM (1 m/pix)

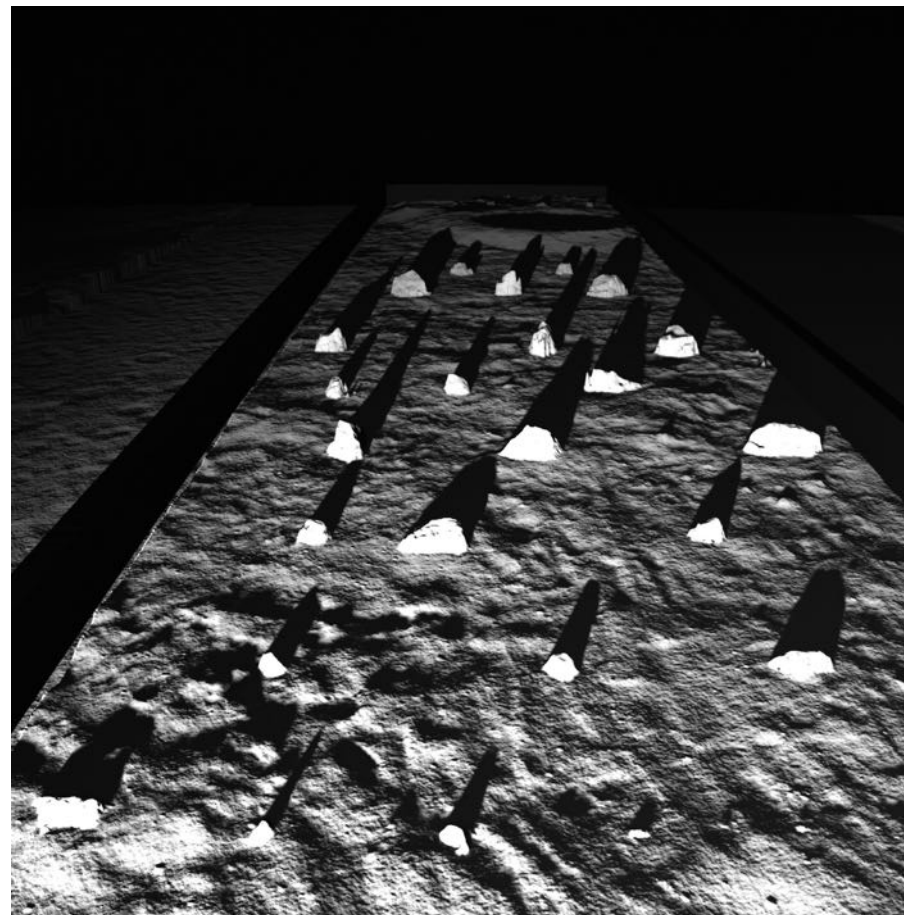


Synthetic DEM (4 cm/pixel)

Camera Simulation Results



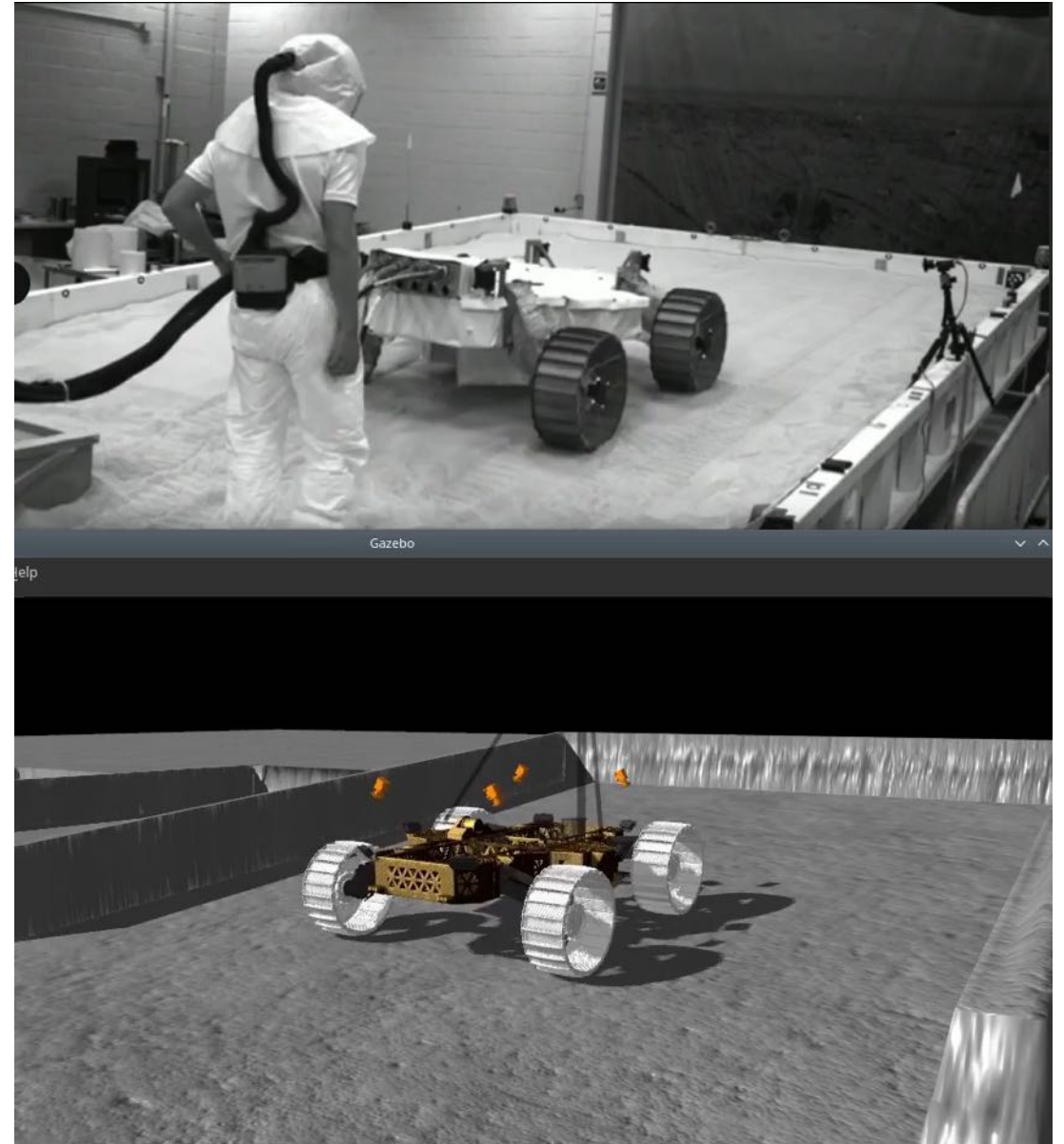
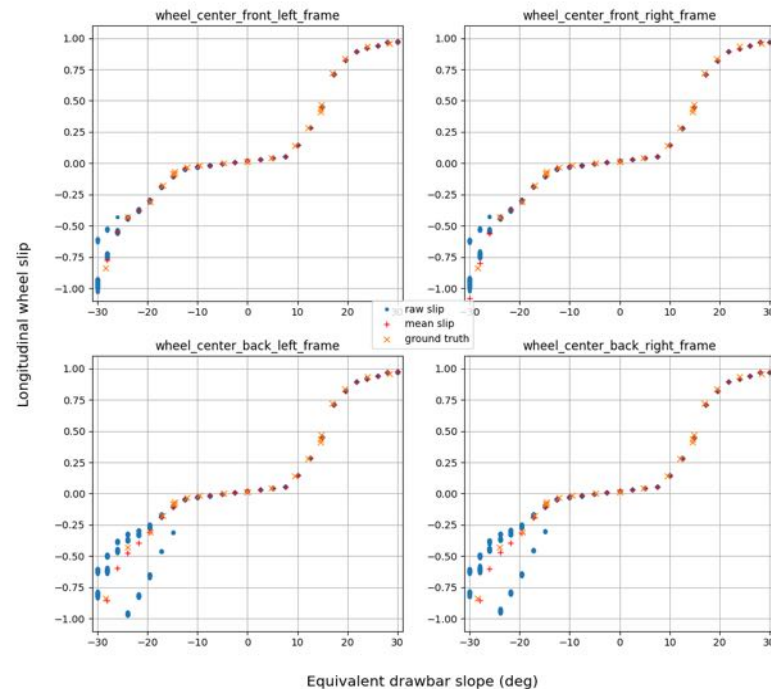
ARC "Lunar Lab"
LHS-1 simulant + rocks +
simulated solar illumination



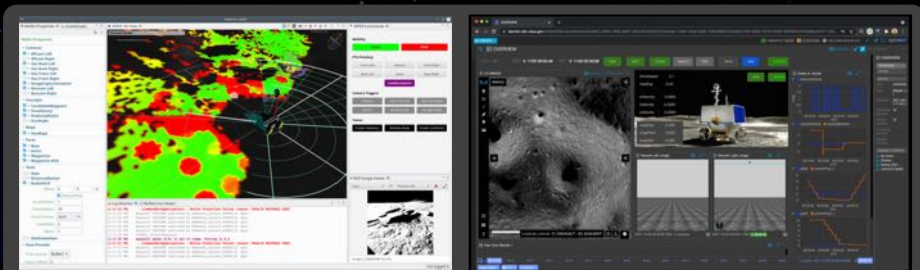
RSIM
3D point cloud data +
camera image + light model

Rover Physics

- Multibody dynamics using Open Dynamics Engine
- Real-time wheel slip
- Slip compliance and friction modulated per-wheel
- Tuned to physical testing

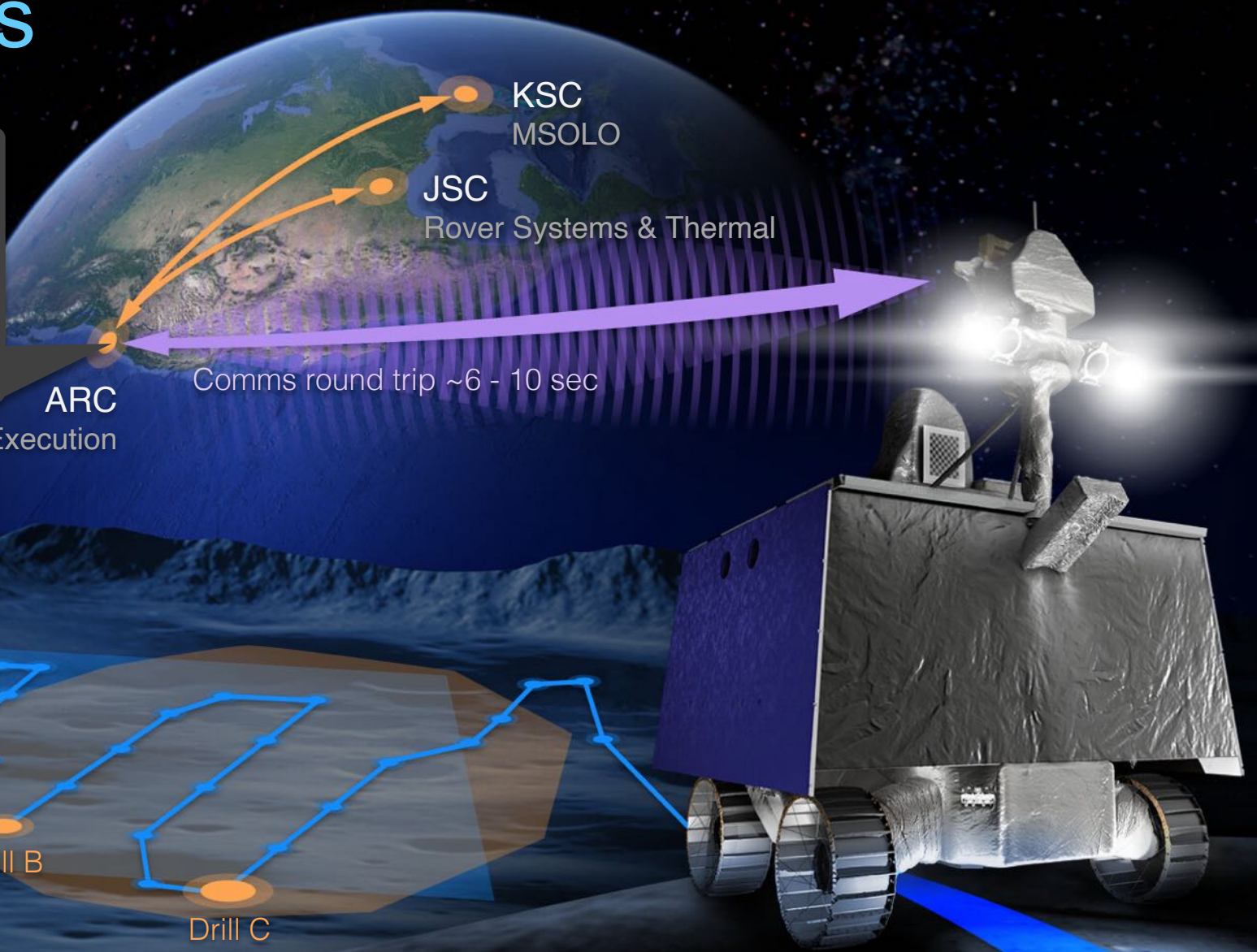


Mission Operations



Rover Driving

Mission Monitoring



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

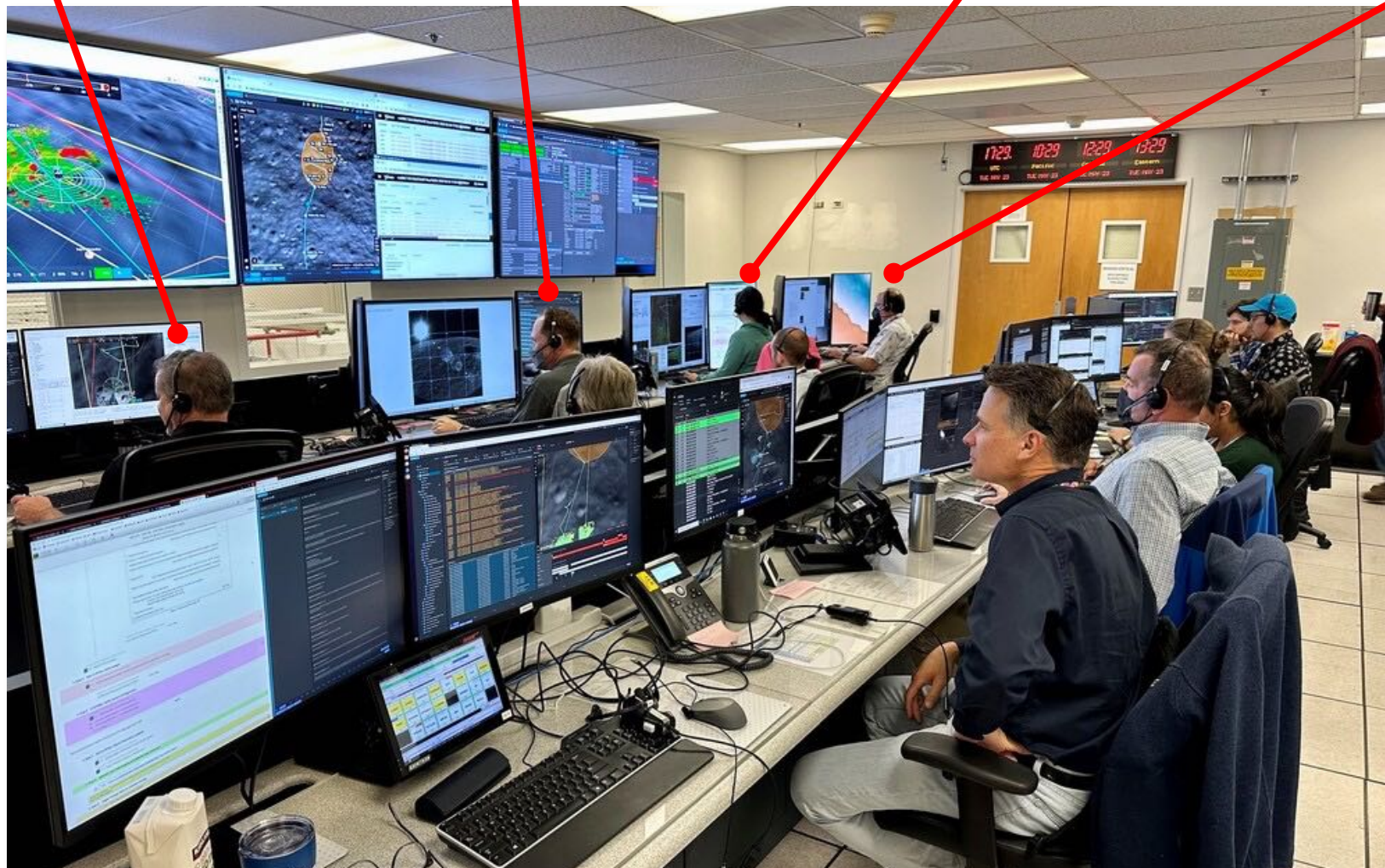
Mission Ops “Drive Team”

Real-Time Science

Driver

Co-Driver

Navigator



VERVE + RSIM (Assess terrain + place waypoint)

The image displays the Verve + RSIM interface, which is used for assessing terrain and placing waypoints. The interface is divided into several panels:

- VERVE 3D View:** A 3D terrain map showing a rover (labeled 1013) on a surface. A yellow arrow points to a specific location on the map.
- VERVE Command Monitor:** A table showing the status of various commands and waypoints.
- VERVE Suspension View:** A diagram showing the suspension angles and dimensions of the rover.
- VERVE Sensor Sample Manager:** A panel for managing sensor data.
- VERVE Waypoint Manager:** A panel for managing waypoints.
- VERVE Image Viewer:** A panel showing the rover's camera feed.
- VERVE Waypoint Manager:** A panel showing the rover's current position and waypoints.

The **VERVE Command Monitor** table is as follows:

Started	Command	Est Dur	Status
01:50:33	Waypoint 1010	00:00:02	Completed
01:50:49	Set Pan/Tilt (-11.2°/-21.1°)	+00:31:57	Overdue
01:50:56	Nav-1010-A [NavCam Default*] [Nav Lights ...]	+00:02:39	Completed
01:53:23	Waypoint 1011	00:00:08	Completed
01:53:47	Set Pan/Tilt (-22.7°/-13.2°)	+00:28:59	Overdue
01:53:49	Nav-1011-A [NavCam Default*] [Nav Lights ...]	+00:08:11	Completed
02:01:49	Waypoint 1012	00:00:08	Completed
02:01:58	Set Pan/Tilt (2.6°/-17.2°)	00:00:09	Completed
02:02:05	Nav-1012-A [NavCam Default*] [Nav Lights ...]	+00:00:49	Completed
02:03:20	Set Pan/Tilt (-42.3°/-16.4°)	00:00:11	Completed
02:03:27	Nav-1012-B [NavCam Default*] [Nav Lights ...]	+00:13:37	Completed
02:10:28	Waypoint 1013	00:00:06	Completed
02:17:19	Set Pan/Tilt (21.8°/-25.2°)	00:00:08	Completed
02:17:30	Nav-1013-A [NavCam Default*] [Nav Lights ...]	+00:02:48	Overdue
02:19:56	Set Pan/Tilt (-50.7°/-14.6°)	00:00:09	Completed
02:20:10	Set Pan/Tilt (-45.3°/-15.9°)	+00:02:35	Overdue
02:20:37	Nav-1013-B [NavCam Default*] [Nav Lights ...]	00:00:19	Executing

The **VERVE Suspension View** diagram shows the following data:

- ROLL: 0.0°
- PITCH: -5.3°
- SUSP ANGLE A: -11.3°
- SUSP ANGLE B: 8.4°
- SUSP ANGLE C: 12.1°
- SUSP ANGLE D: 31.5°
- Wheel L: 135.7 cm
- Wheel R: 132.5 cm

The **VERVE Image Viewer** shows the rover's camera feed, with the text "RSIM" overlaid in the bottom right corner.

The **VERVE Waypoint Manager** shows the rover's current position and waypoints, with the text "Driver" and "ROS Time" at the bottom.

VERVE + RSIM (Refine waypoint + drive)

The image displays the Verve + RSIM interface, which is used for controlling a rover. The main window shows a 3D terrain map with a rover's position and a path. The map includes a color-coded elevation scale from -400 to 0. The interface is divided into several panels:

- VERVE 3D View:** The main 3D terrain map showing the rover's position and a path.
- VERVE Commands:** A panel for controlling the rover's mobility and PTU pointing. It includes buttons for Drive, STOP, PTU A, PTU Default, PTU C, PTU B, PTU to Cal, PTU D, and PTU Absolute/Relative. It also has a Camera Trigg... section with checkboxes for Haz A, Haz B, Haz C, Haz D, NavCam Stereo, and AltCam Stereo.
- VERVE Precision Drive View:** A panel for controlling the rover's precision drive. It includes buttons for DRIVE_CART, SUSP_CART, DET_ON, ATT_ON, and ATT_OFF. It also has a Z Offset section with a slider and a button for ATT_ON/ATT_OFF.
- VERVE Command Monitor:** A table showing the status of various commands. The table has columns for Started, Command, Est Dur, and Status.
- VERVE Image Viewer:** A panel showing a real-time video feed of the rover's camera. It includes a play button and a Real Time Factor slider.
- VERVE Sensor Sample Manager:** A panel for managing sensor samples. It includes a table with columns for Filters, Columns (7/7), Sensors (10/10), Edit, Hazard Maps, and Photo Quads.

The RSIM (Refine waypoint + drive) interface is shown in the top right corner, displaying a real-time video feed of the rover on a planetary surface. The rover is a small, boxy vehicle with a camera and a solar panel. The surface is dark and rocky. The RSIM interface includes a play button and a Real Time Factor slider.

Flight Rover



Assembly complete (6/4/2024)



Thermal-vacuum testing (9/2024)

Interested in Space Robotics ?

NASA Space Technology Graduate Research Opportunities (NSTGRO)

- Graduate student fellowships (1 to 4 yr support) for US citizens and permanent residents
- \$84,000 per year + 10 weeks per year at NASA + collaborate with NASA staff
- Deadline: **November 1, 2024 (at 3p Pacific)**
- <https://tinyurl.com/NASA-NSTGRO25>

Research grants

- Solicitations issued by many different parts of NASA throughout the year
- AIST, ECF, ESI, PSTAR, ULI, etc.
- <https://nspires.nasaprs.com>

NASA small business grants (SBIR / STTR)

- Develop new robotics technology for use in space and on Earth
- \$150,000 (Phase 1: 6 to 13 mo) + \$850,000 (Phase 2: 24 mo) + multiple follow-on options
- Next cycle starts: **January 2025**
- <https://sbir.nasa.gov>



Questions?



Astrobee "Bumble Bee"
1st On-Orbit Activities
Astronauts Anne McClain,
David Saint-Jacques, & Christina Koch

VIPER Navigation Testing

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



Mission Planning

Objectives

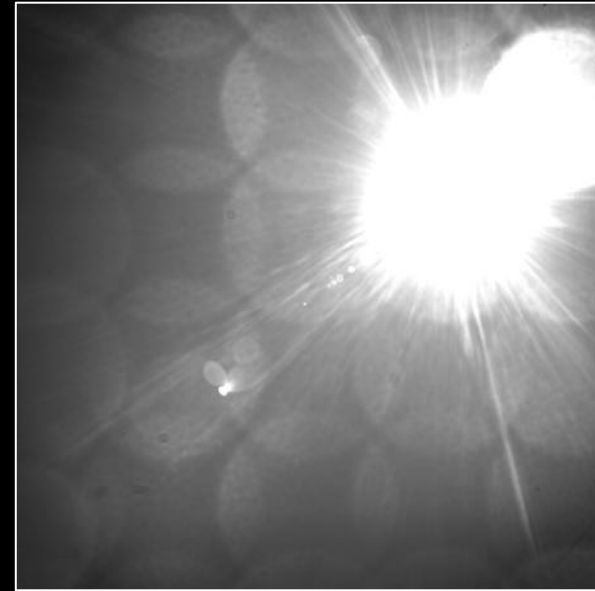
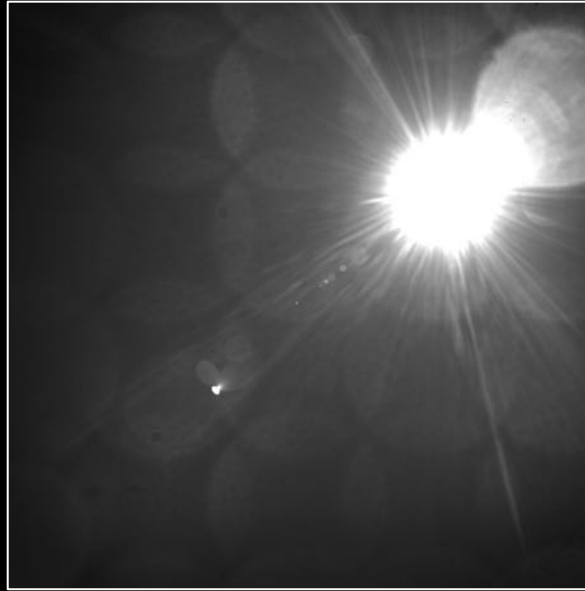
- Develop activity, resource, and traverse plans
- Strategic and tactical plans, including contingency handling
- Robustly achieve full science success under uncertainty
- Real-time replanning, particularly when operating in science stations

(A few) constraints

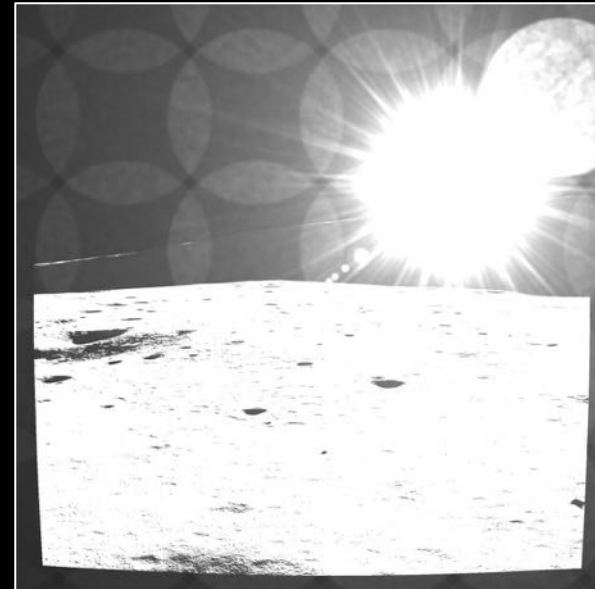
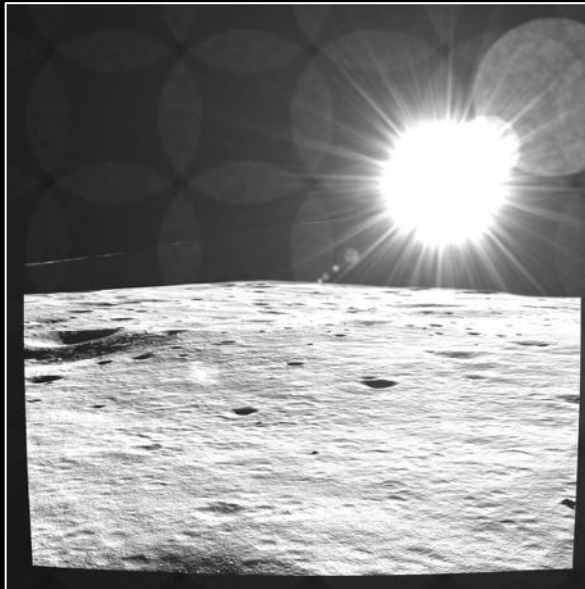
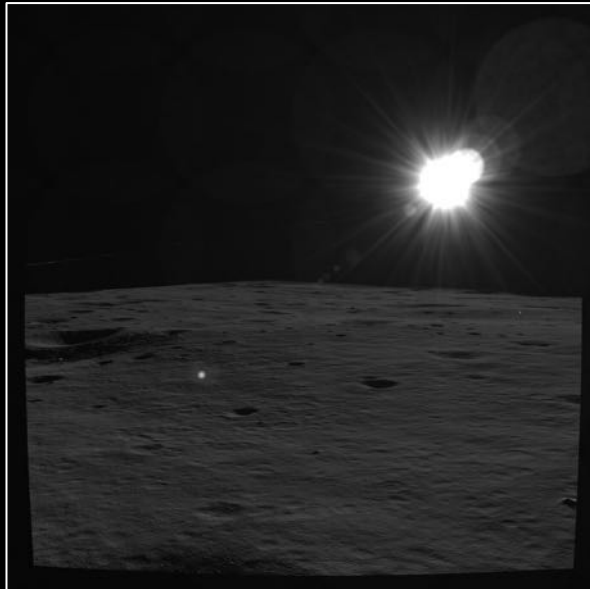
- Measure distribution and state of lunar polar volatiles
- Solar-powered rover with limited battery (shadow endurance)
- Lunar summer “season” (~100 Earth days max)
- Line-of-sight data communications to Earth
- 20 km max drive, 15 deg slopes, 20 cm step obstacles (design limit)
- 10 cm/s drive speed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

Lens Flare

Real



RSIM



VIPER Mission Control Center



Rover Driving Interface (VERVE)

