

National Aeronautics and
Space Administration



NASA Ames Lunar Rover Technologies

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VIPER Rover

First NASA lunar rover

- Designed for the “dynamic” lunar environment
- Emphasis on high operational cadence and traverse speed

Interactive operations

- “Real-time” mission control: rover operations + science team
- Hybrid of ISS robotics and Mars rover mission operations

Hybrid avionics and software

- BAE RAD 750 v3 (rad-hard) + AiTech SP0-S (rad-tolerant) computing
- “Flight” software split between on-board and ground



*100% assembled
(4 June 2024)*



Lunar Rover Technologies (1)

Rover Software

- Hybrid flight software designed for lunar rovers
 - On-board built on cFS/CFE (VIPER “RFSW”)
 - Off-board (ground) built on ROS2 (VIPER “RGSW”)
 - Includes suspension and mobility control, absolute/relative localization, terrain hazard assessment, continuous Earth antenna pointing during motion over rough terrain, slip detection & embedding recovery
- High-fidelity real-time lunar rover & surface simulator (VIPER “RSIM”)

Lunar Surface Navigation

- Lunar rover navigation hardware expertise, including cameras, star tracker, IMU, and lights
- Lunar rover localization using visual odometry, terrain registration, high-resolution mapping, and real-time sensor data



Lunar Rover Technologies (2)

Lunar Mapping

- 1 m/pixel lunar maps (basemaps and DEMs) produced via the Ames Stereo Pipeline (including "shape from shading" algorithms)
- 4 cm/pixel synthetic, scientifically-plausible lunar maps (DEMs) for dev, V&V, & training produced with Ames SynthTerrain & RSIM map tools

Mission Planning

- AI-based strategic mission planning software (SHERPA), including activity and traverse planning for the dynamic lunar environment
- AI-based tactical mission planning software, including integrated multiple map (lighting, comms, terrain hazards, etc) visualization

Rover Operations

- 3D rover operator interface (VERVE) for interactive lunar rover remote operations, including real-time map markup, multiple hazard map layers, etc
- Lunar rover mission operations expertise, including conops and ops products for real-time remote rover driving and interactive science



Lunar Rover Development Support

Facilities

- Ames "Lunar Lab" regolith testbeds (highlands, mare, and deep bed) for high-fidelity lunar surface appearance testing of cameras and lights
- Ames "Roverscape" outdoor testbed including 10 kW sun simulator for simulated lunar polar operations testing

Engineering

- Lunar environmental knowledge and expertise (including topography, surface processes, lunar resources, illumination)
- VIPER "Environmental Specification" – supplements DSNE & Lunar Sourcebook with lunar polar analysis (small crater & rock size-frequency distributions, detailed slope analysis, etc)

A background image of the VIPER rover on the lunar surface, with a bright light source creating a lens flare effect on the left side of the slide.

VIPER Rover Software

Rover Flight Software (**RFSW**)

- Runs on-board the rover on radiation hardened (RAD 750) and radiation tolerant (AiTech SP0-S) CPUs
- Utilizes Core Flight System (cFS)
- Provides low-level hardware interfaces, mobility control, waypoint driving, odometry, error checking, and device/payload services

Rover Ground Software (**RGSW**)

- Runs at mission control on Earth using commodity desktop computing
- Implemented as an ensemble of Robot Operating System 2 (ROS2) nodes
- Performs navigation, mapping, and generation of rover driver decision support data

Rover Simulator (**RSIM**)

- Integrated lunar surface mission simulator
- Built on modified ROS (Robot Operating System) Gazebo framework with Lunar plugins and communicates with modules developed for RFSW and RGSW
- Used for VIPER software development + mission ops training



RFSW Functions

System Services and Apps

- Set of basic middleware services

Mode Management

- Puts the vehicle into known states (modes) for operations, and for automatic fault responses

Comm Management

- Commanding, configuration, monitoring and selection of the rover communication paths

Power Management

- Manages the rover charge and power distribution

Thermal Management

- Maintains the correct temperature of the rover critical systems, and reports the thermal state of the rover to the ground

Mobility Management

- Responsible for the motion of the rover chassis. Manages low-level motion (individual motor control) and high-level motion (waypoint driving)

Navigation Management

- On-board Localization to support antenna tracking and mobility functions.
- On-board camera Management and image processing to support ground localization function

Data Management

- Handles up-link of commands and data, down-link of telemetry and files, and on-board data management

Fault Management

- Contain, prevent, detect, isolate, diagnose, respond to and recover from conditions that may interfere with nominal mission operations

Platform Management

- Manage the rover IAU from reset/powerup to a fully configured hardware system and booted operating system kernel

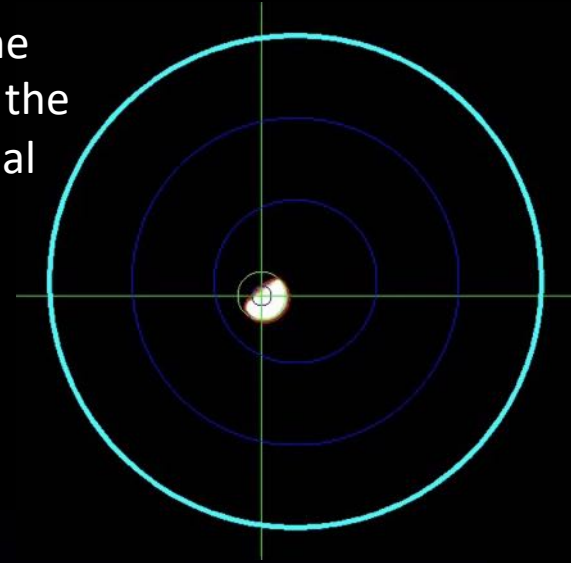
Gimbal Management

- Manages the two gimbals located at the top of the rover mast

High Gain Antenna Testing – Pointing Under Motion



view of the
Moon from the
HGA gimbal





RGSW Functions

3D Terrain Map

- Generates a digital elevation model (DEM) of the local terrain from a given input point cloud

Frame Store

- Provides a service to which allows clients to retrieve transformations between coordinate frames

Hazard Map

- Produces a map indicating "traversability" of terrain

Orthoprojection

- Produces orthographically projected surface maps from stereo camera point clouds

Path Planner

- Finds a path from a starting location to a goal location chosen by operators

Planetary Frame Provider

- Provides transformations between planetary body-centered frames, local-level surface frames, and map frames

Pose Corrector

- Utilizes inputs from visual odometry and terrain registration to improve on the flight software rover localization output

Rover Motion Predictor

- Predicts the expected trajectory and endpoint that the Rover will achieve given a waypoint command and a model of the terrain

Stereo Image Processing

- Computes 3D point clouds from rover stereo images

Terrain Registration (TR)

- Estimates the absolute position of the rover in the map coordinate frame by aligning rover stereo data to an orbital lunar DEM

Visual Odometry

- Estimates the relative vehicle pose (position and orientation) between successive stereo image captures to improve the Pose Corrector's estimation of vehicle position and pose



RSIM Functions

RSIM Lunar Terrain Modeling

- Synthesizes large scale, very high-resolution Digital Elevation Map (DEM) models of Lunar terrain with rover-scale hazards
- Synthetic terrains are representative of the geomorphology expected at the Lunar poles.

RSIM Rover Models

- Converts the rover structure and mechanisms of the flight design (VIPER) and mobility test units (MGRU 2.5 and MGRU 3) to a model that can be simulated in RSIM

RSIM Rover Physics

- Models the multibody dynamics of the VIPER rover driving
- Wheel slip (nonlinear slip compliance and plowing effect) model tuned to match physical rover

RSIM Visual Simulation

- Renders images of the lunar environment such that human operators can be trained to perceive hazards and maintain situational awareness

RSIM NavHW Modeling

- Provides more realistic simulated NavHW components (cameras, IMU, star tracker, and lights) for development and testing of localization in RFSW and RGSW

RSIM RFSW Integration

- Provides interfaces that mimic the flight hardware communication protocols

RSIM Payload Simulators

- Provides communication protocol level simulation of instruments for development and test of RFSW Payload command and data handling

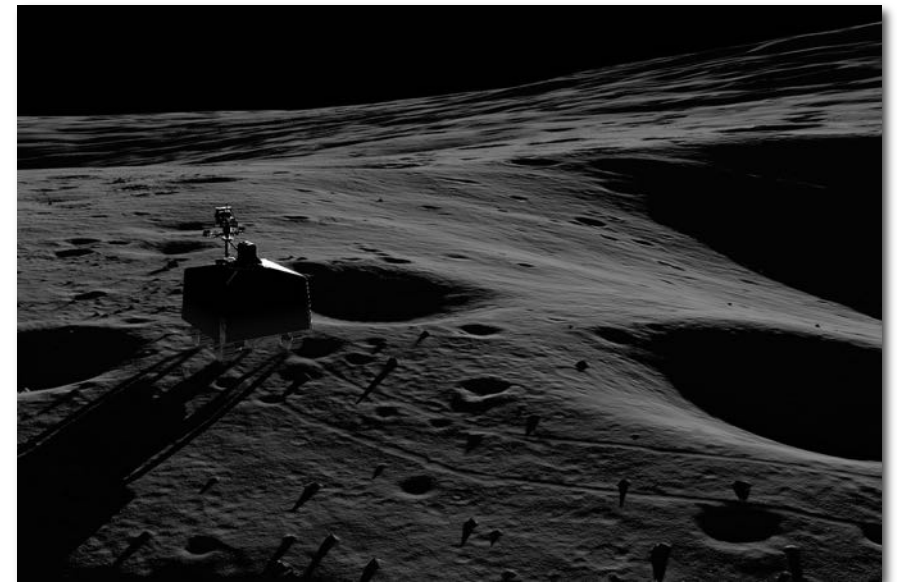
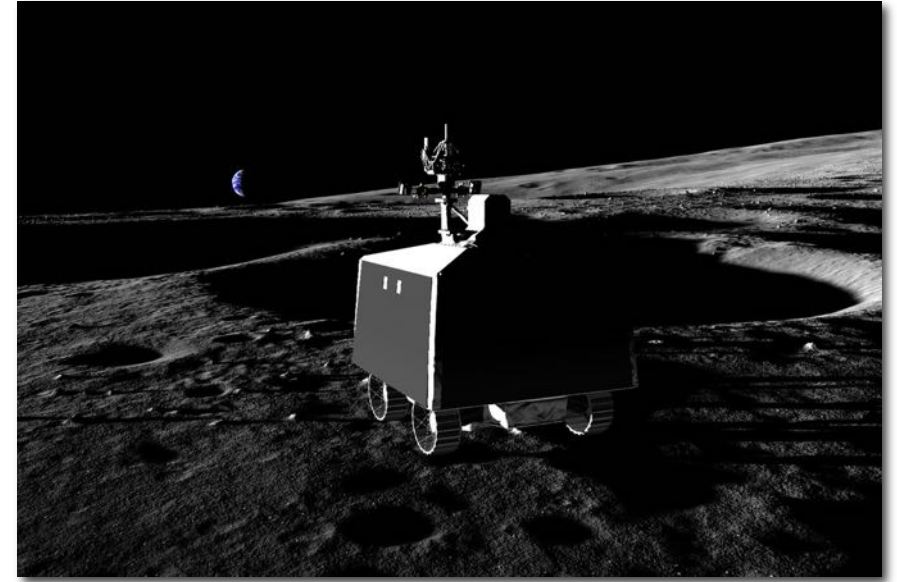
RSIM Fault Injection

- Provides an interface for users to trigger off-nominal events in the simulated environment
- Telemetry override – ability to override any telemetry point being sent from RSIM to RFSW

RSIM (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
- Based on Gazebo Classic r11 (with many lunar customizations)





Real-time Simulation Innovations

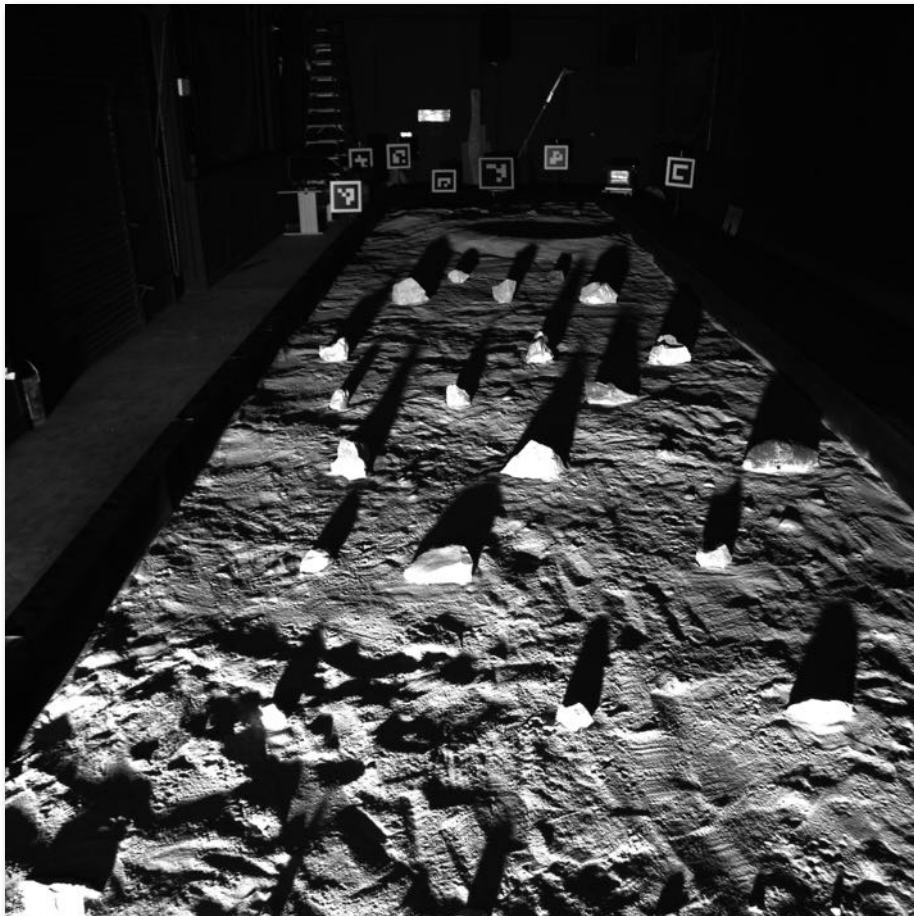
High-quality lighting

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

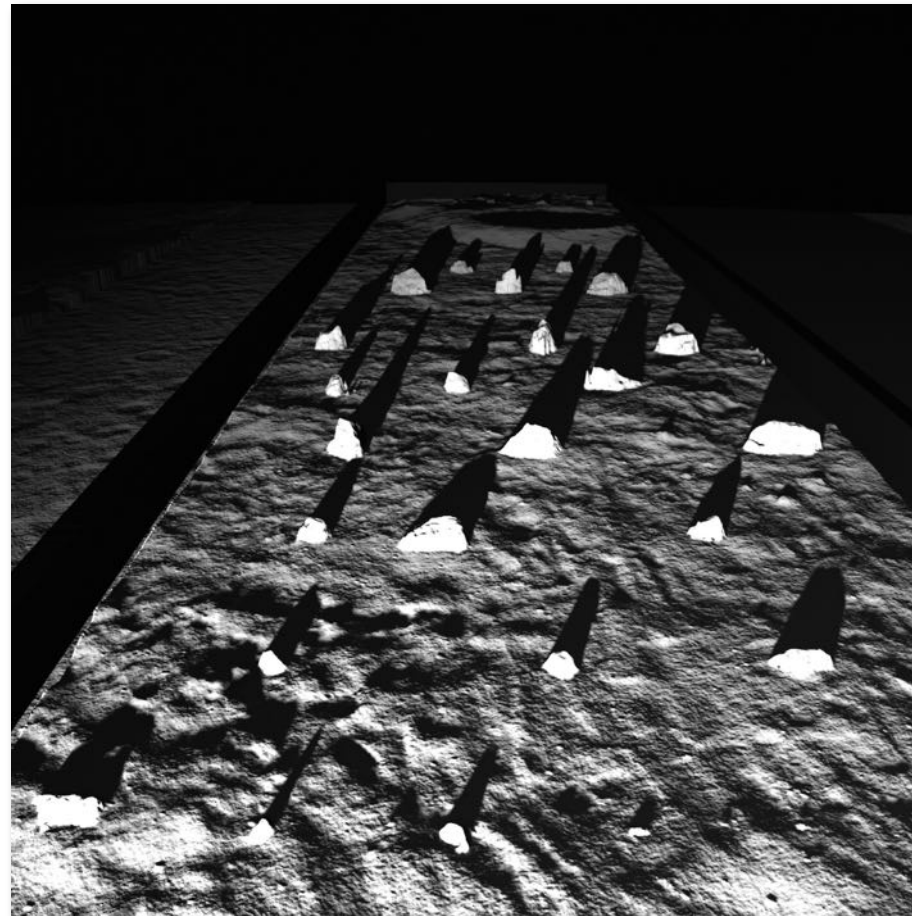
High-quality camera models

- 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



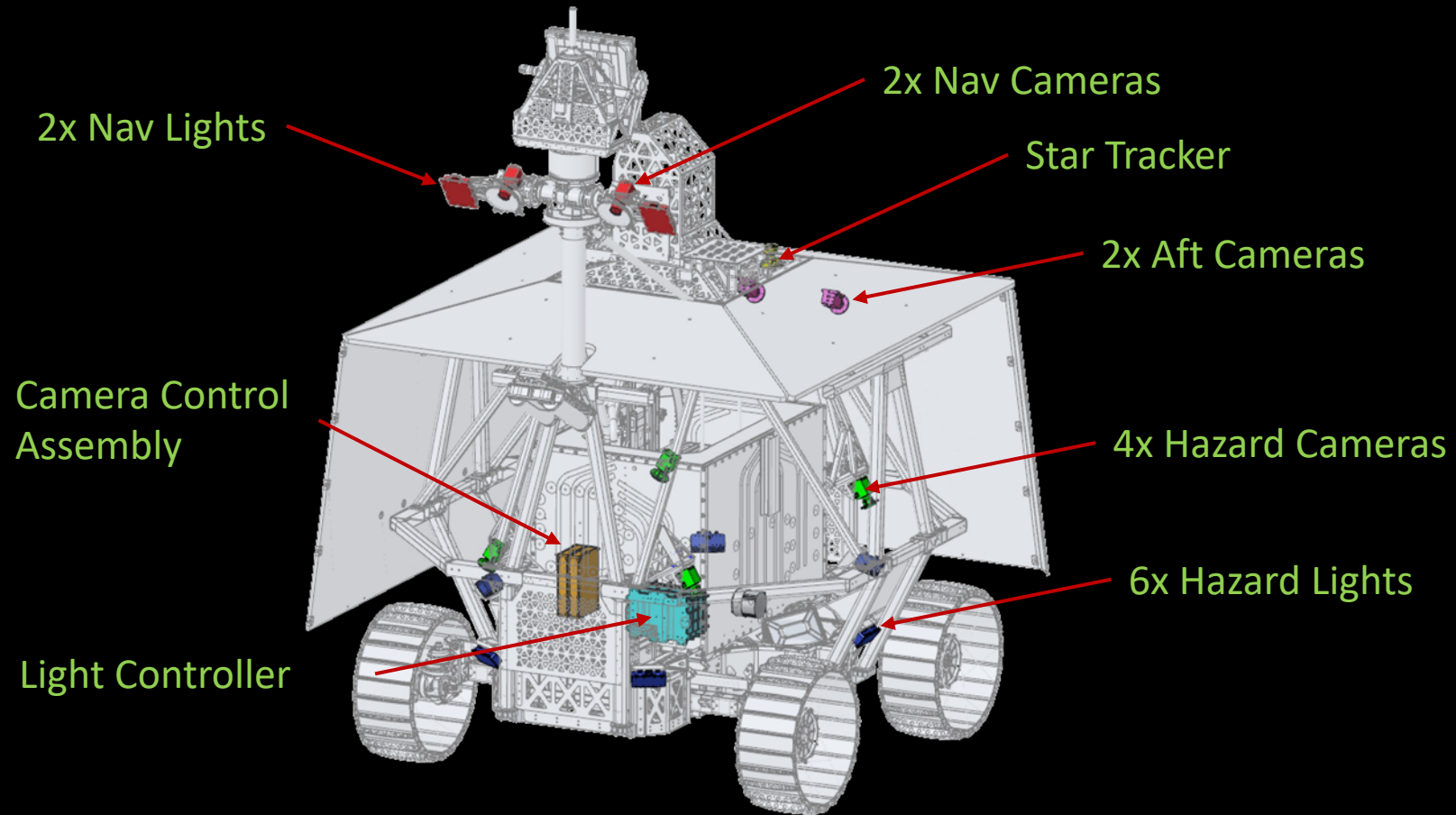
ARC "Lunar Lab"
LHS-1 simulant + rocks +
simulated solar illumination



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



VIPER Navigation System



Lunar Surface 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

Camera Qualification and Calibration

VIPER Visible Imaging System (VIS)

- 8x cameras: 2x NavCams, 4x HazCams, and 2x AftCams
- In-house lens/body integration and flight qualification of NavCams

Testing & Calibration

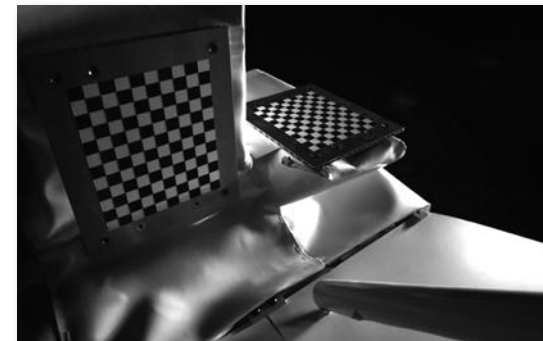
- Acceptance testing of MTF, depth of field, and field of view; geometric calibration for all cameras
- Pre-launch calibration of optical geometry (all cameras)
- In-mission calibration of NavCams using rover-mounted “checker board” targets



NavCam lens close-up



Camera MTF testing



Rover “checker board” calibration targets

Lunar Rover Lights

VIPER Lighting System

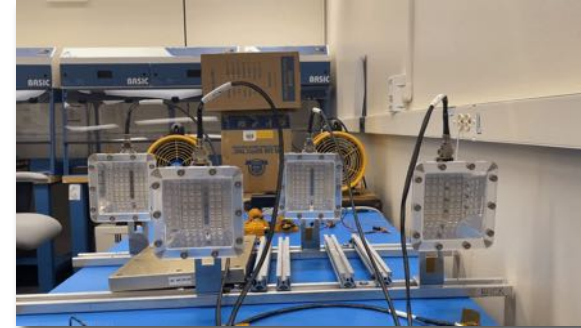
- Lighting for human driving and robot navigation in PSRs
- 8x LED-array lights and avionics qualified for Lunar polar conditions
- Blue wavelength tuned for sensitivity in Permanently Shadowed Regions.

NavLights

- “Headlights” tuned for long-range stereo imaging and decision making

HazLights

- “Parking lights” provide near-field illumination needed for maneuvering and inspection of wheels



NavLights flashing during burn-in tests

Avionics box during vibration testing



HazLights covering terrain near wheels

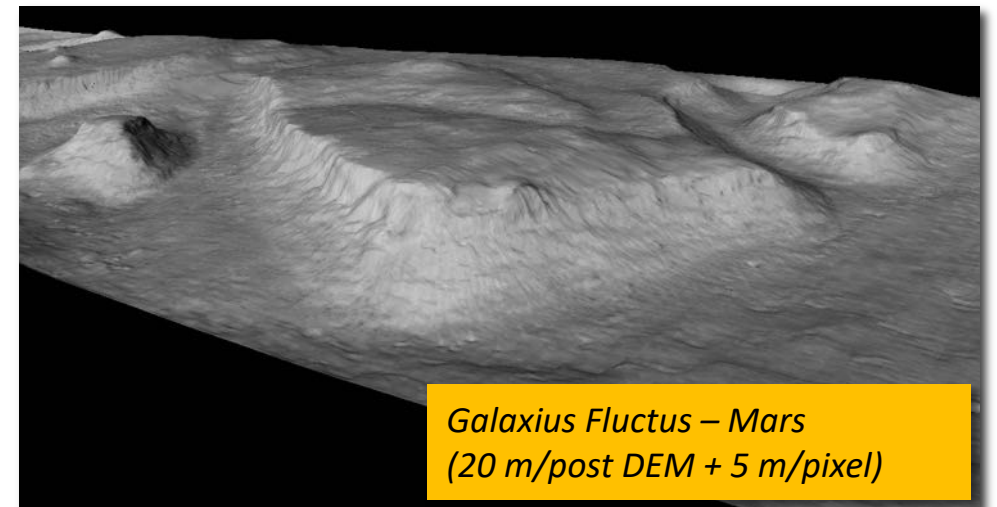
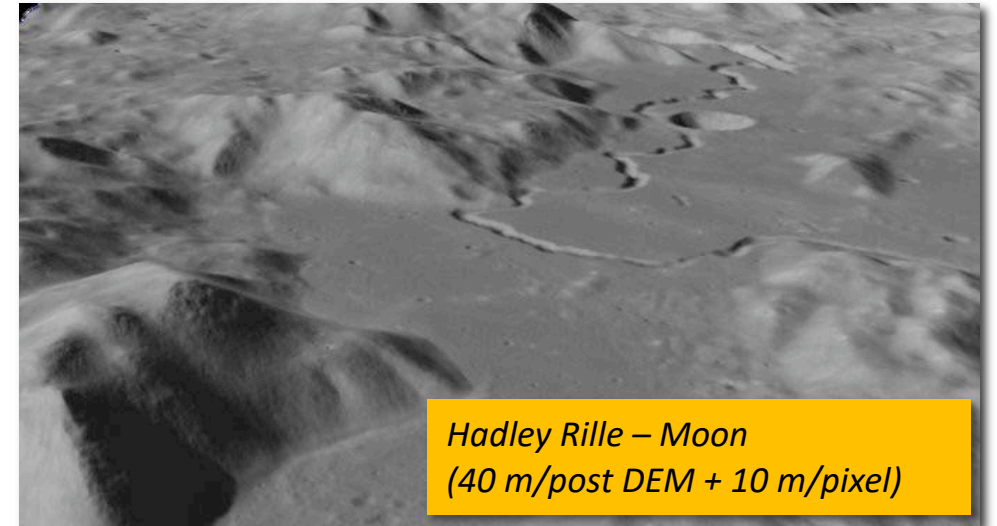
Ames Stereo Pipeline (ASP)

Automated stereogrammetry

- Command-line processing tools (including bundle adjustment, albedo reconstruction, etc.)
- C++ code hosted on GitHub (Apache 2 license)
- Linux and OS-X binaries

Planetary data

- Apollo Metric Camera
- Lunar Reconnaissance Orbital Camera (LROC-NA)
- Mars High Resolution Imaging Science Experiment (HiRISE)
- Mars Orbiter Camera (MOC)
- MRO Context Camera (CTX)



High-Resolution Digital Terrain Models

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



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

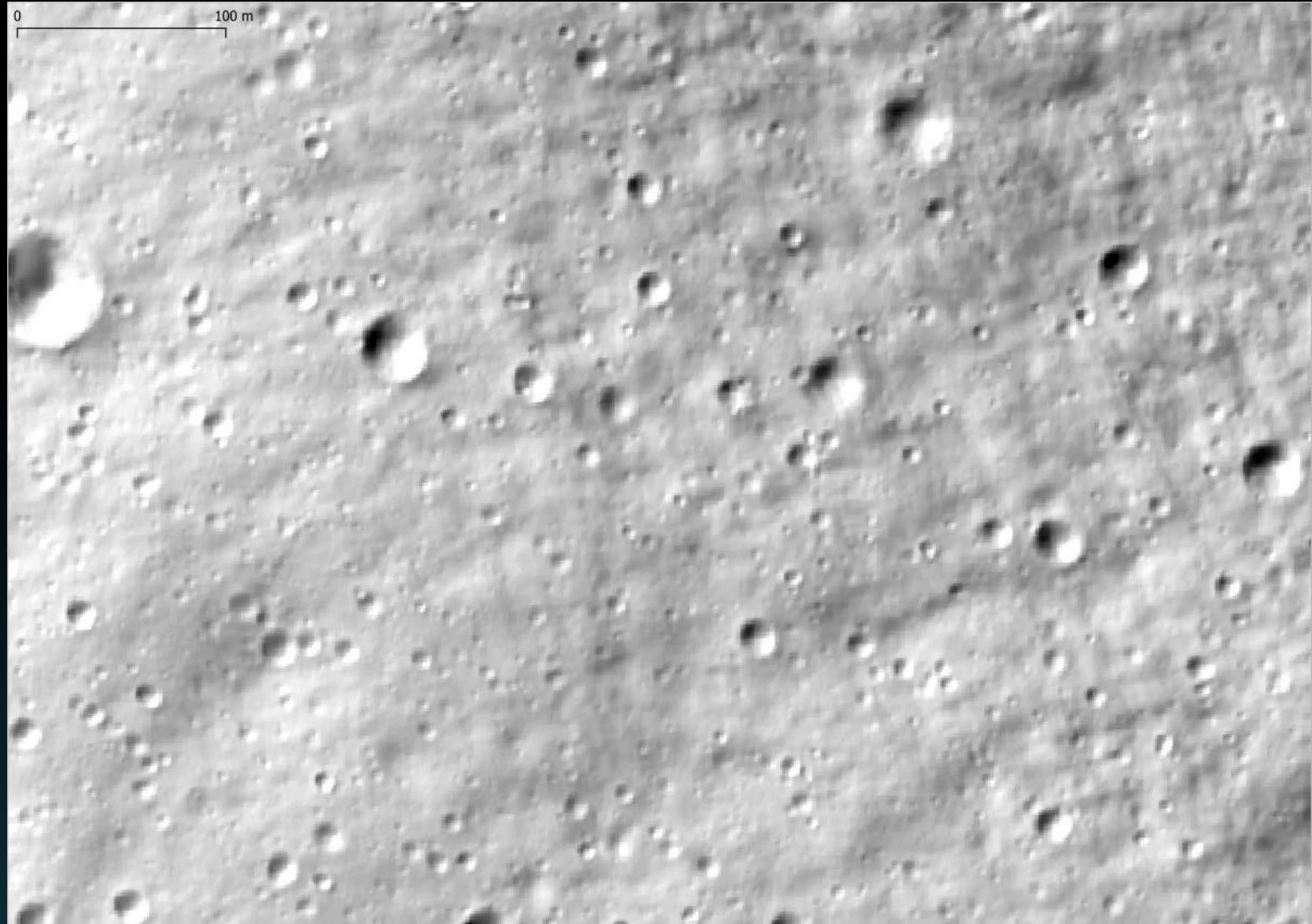
High-Resolution Digital Terrain Models

- 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 produced by Ames Stereo Pipeline



Synthetic Terrain

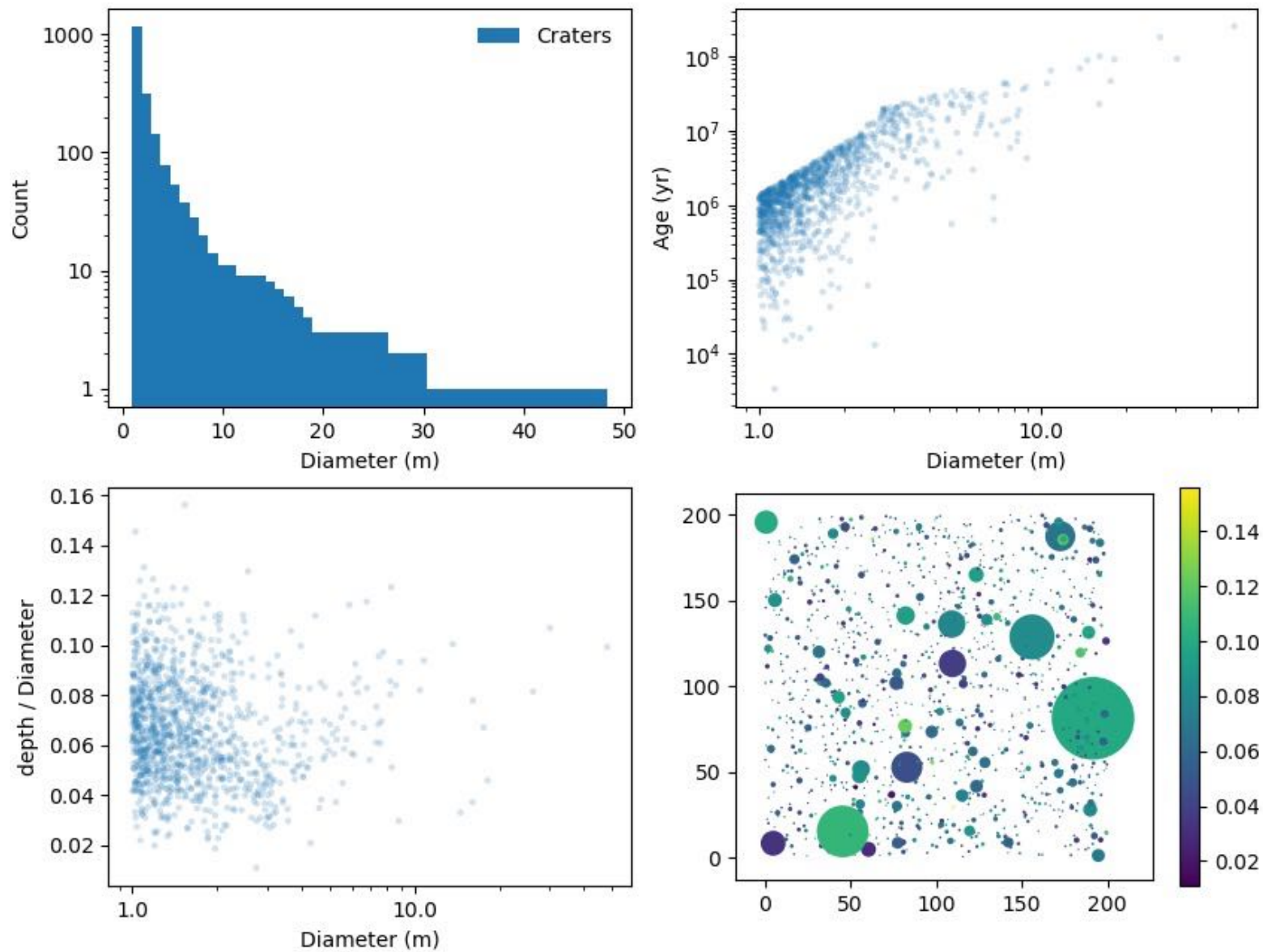
Purpose

- 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, software development (e.g., navigation), V&V, mission simulations, etc.
- Synthetic terrain must be **scientifically plausible**

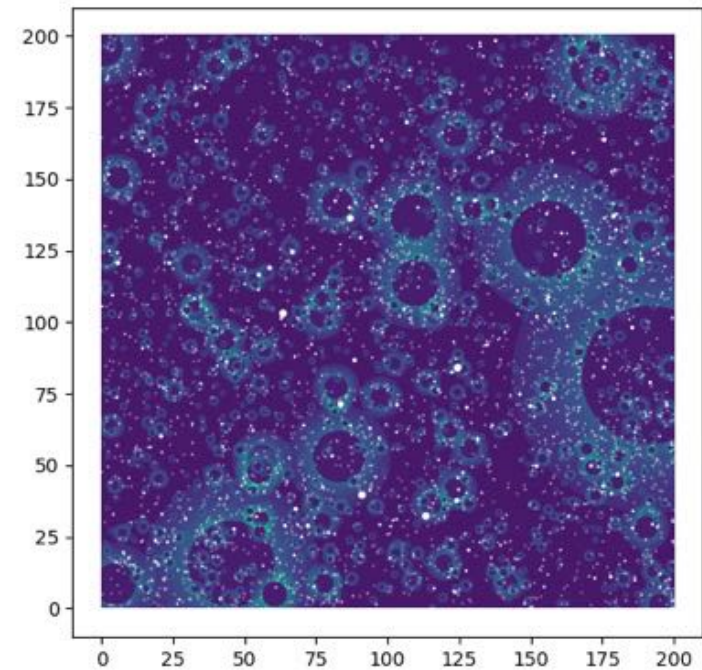
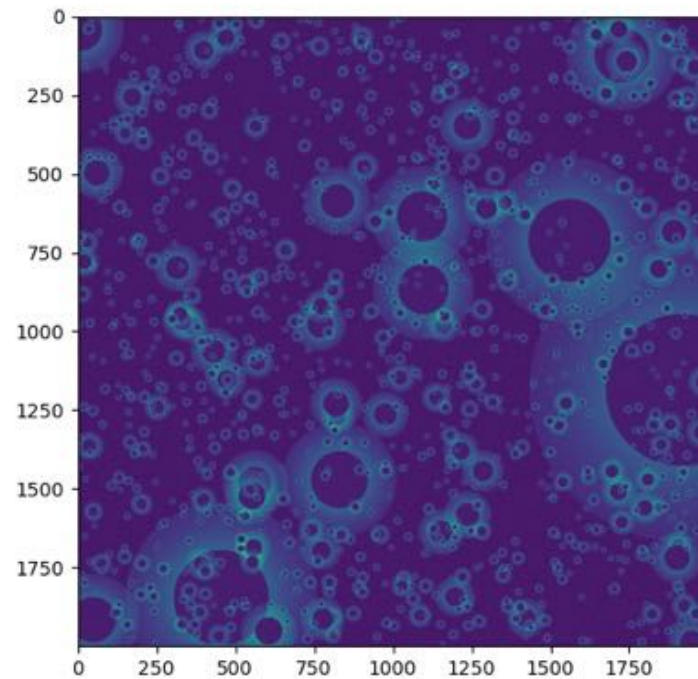
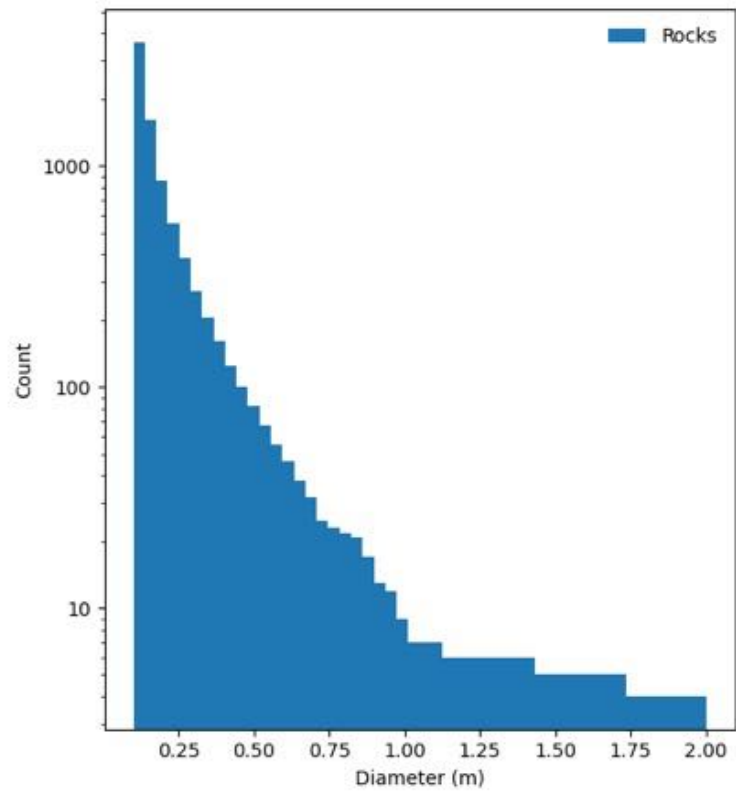
Synth Terrain + RSIM map tools

- Begin with highest resolution maps (source) derived from orbital data
- Use the last 60 years of planetary science research to infer **crater** and **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

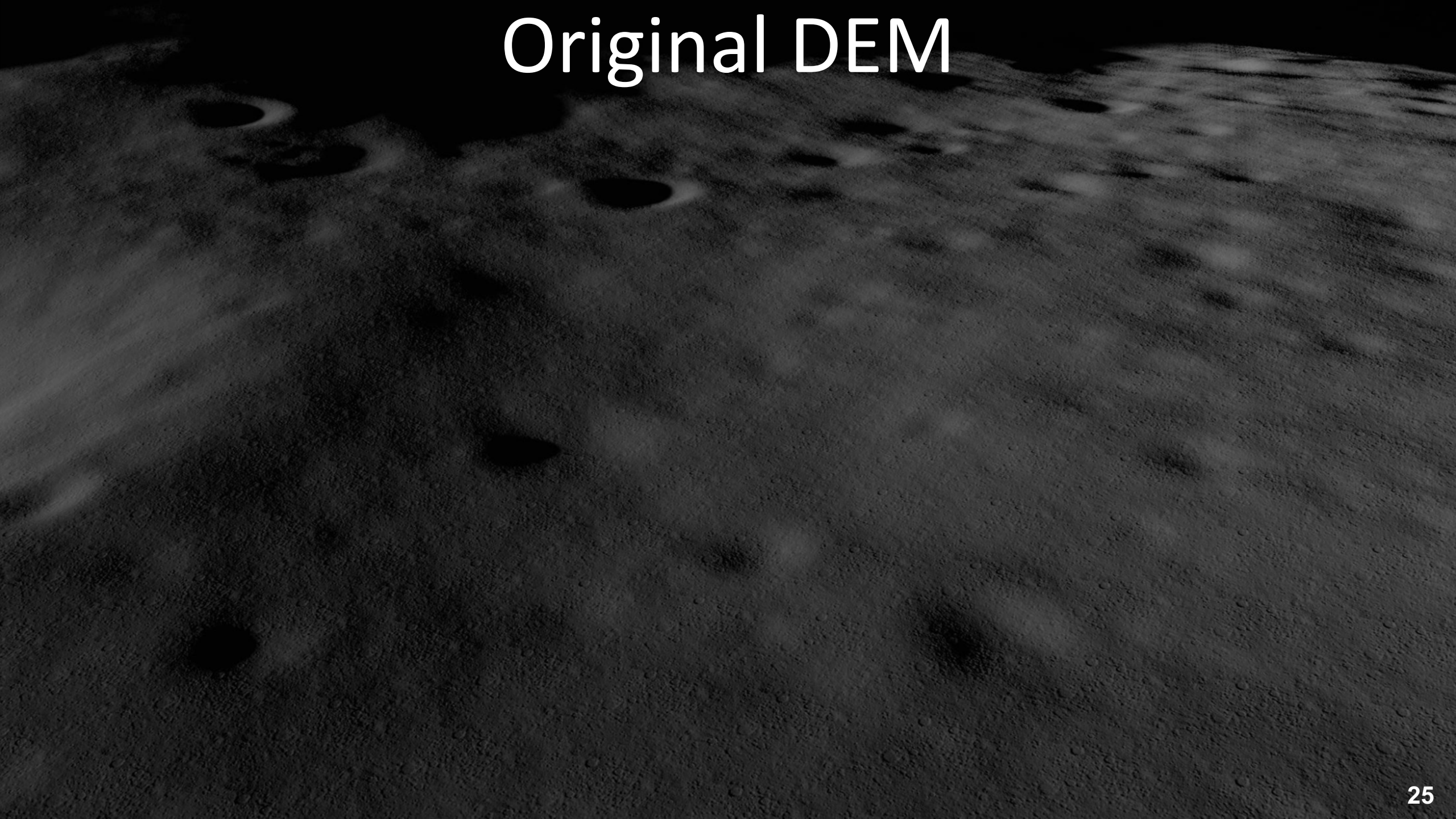
Lunar Crater Models



Lunar Rock Models



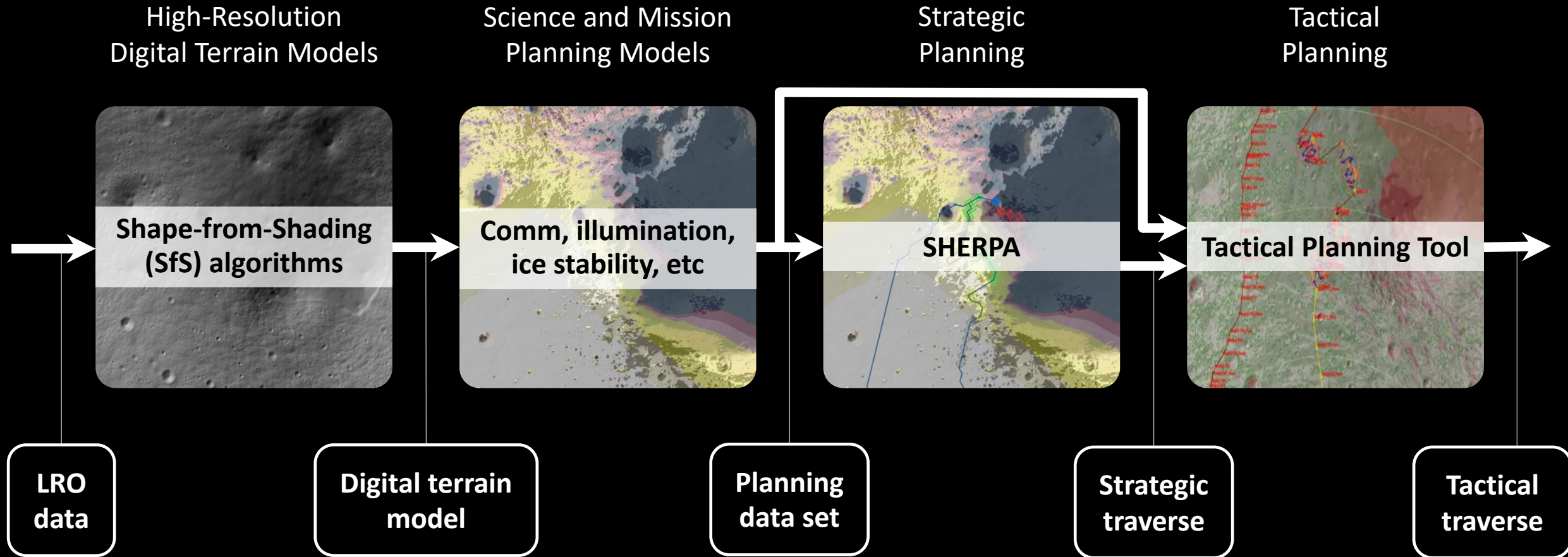
Original DEM



Synthetic 4 cm/pixel



VIPER Surface Mission Planning Process



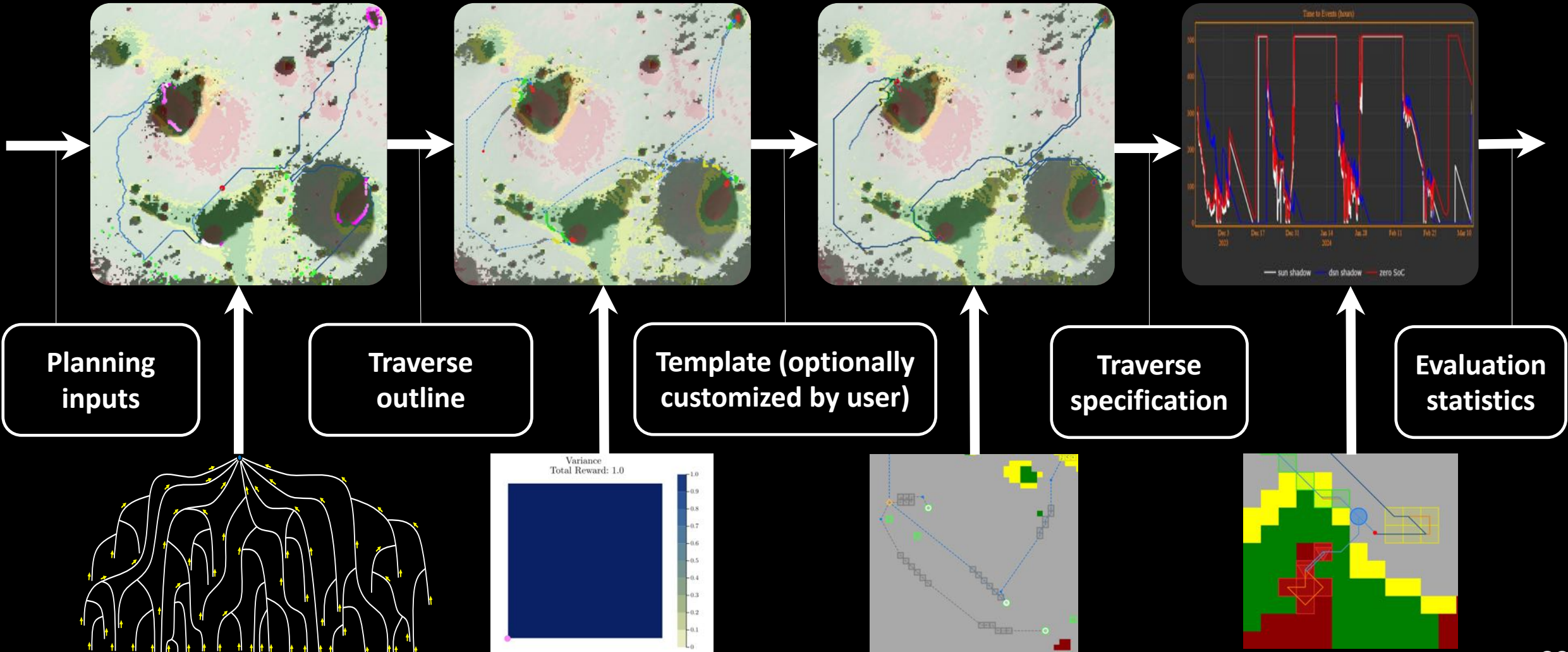
VIPER Strategic Planning (SHERPA)

Traverse
outlining

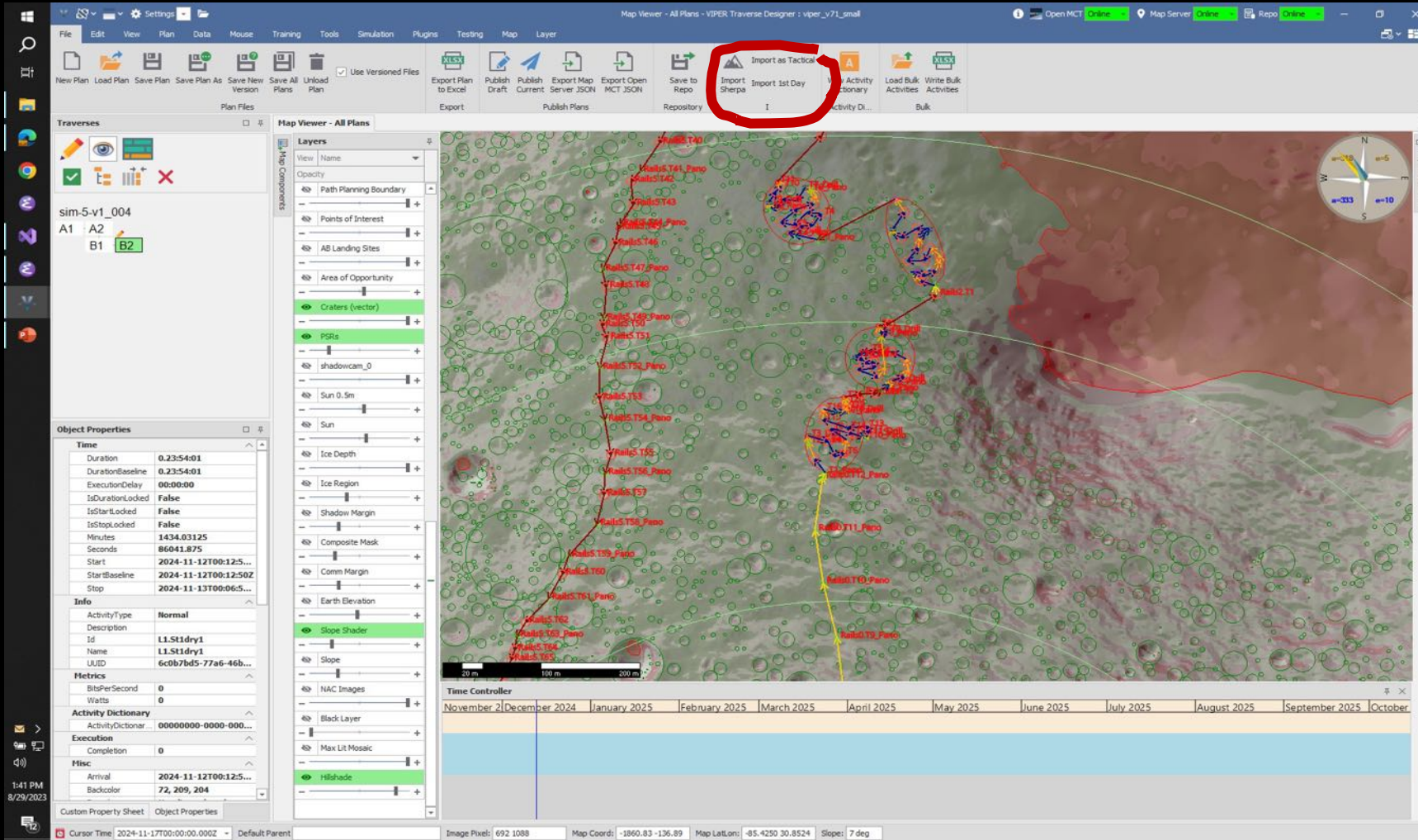
Traverse
templating

Traverse
synthesis

Traverse
evaluation



VIPER Tactical Planning Tool



- 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.

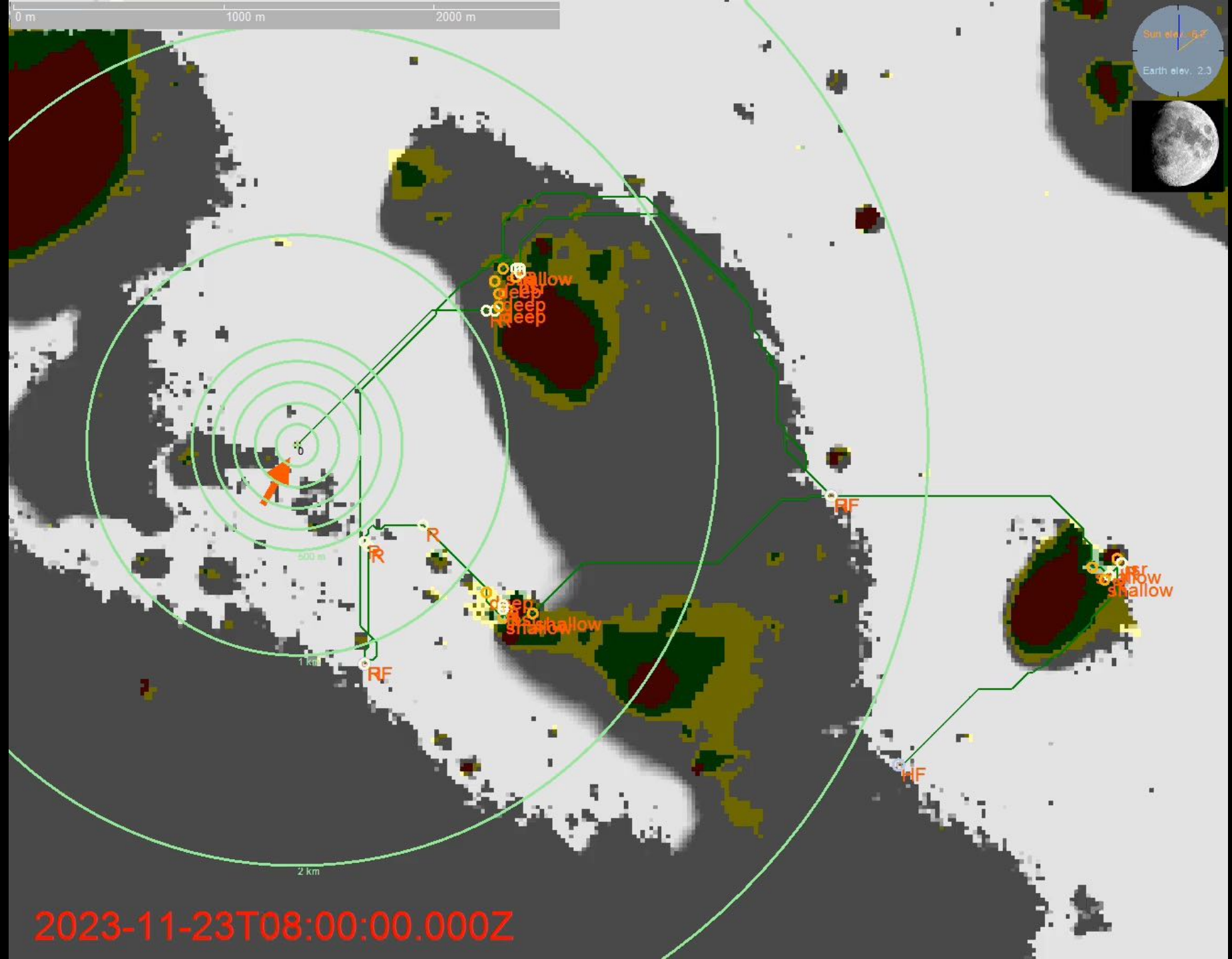
VIPER Tactical Planning Tool

- 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

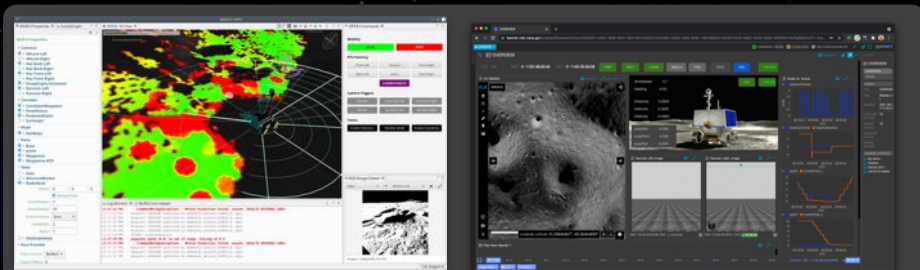
Example Traverse Plan

2023-11-23
to
2024-03-07

106 days

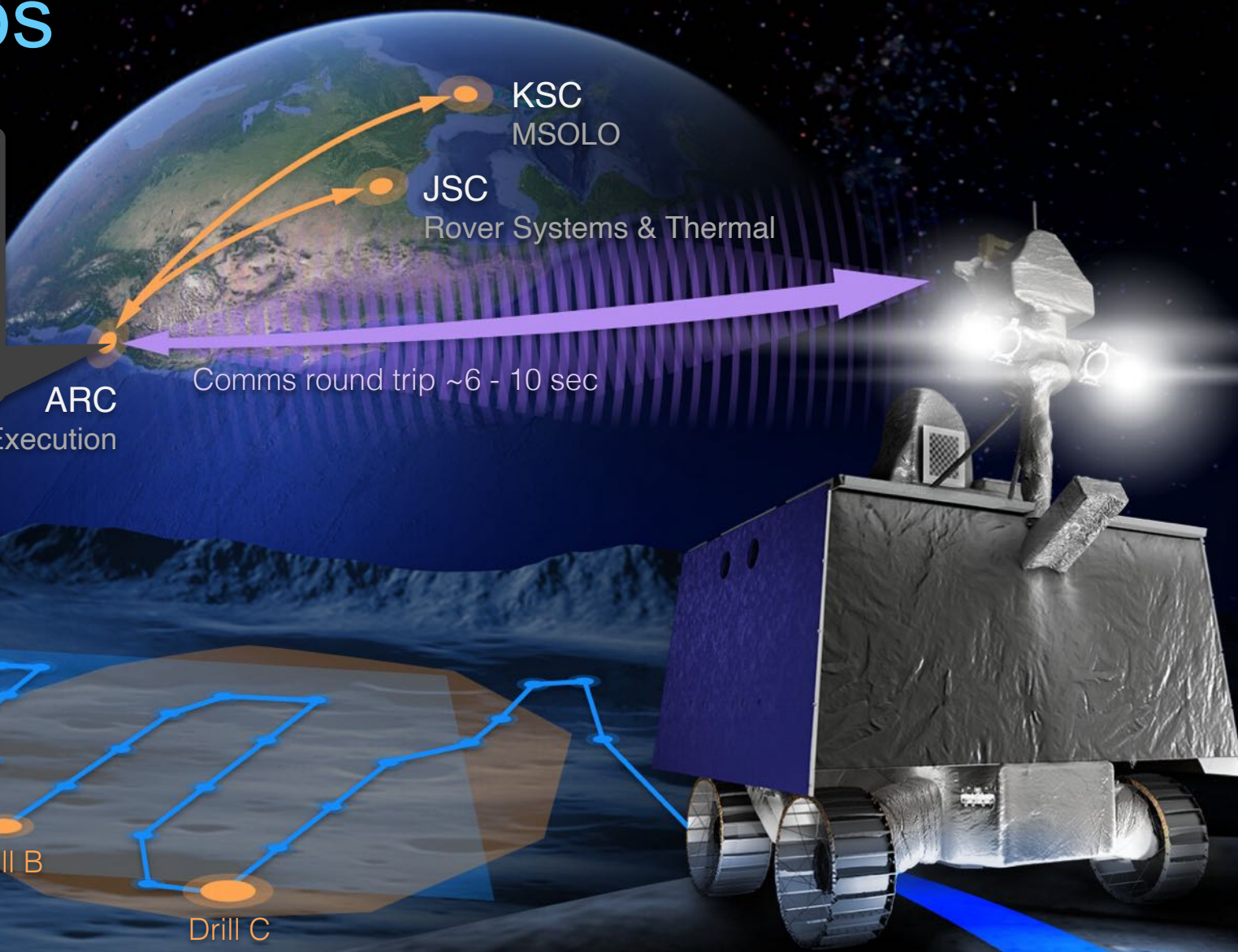


VIPER Mission Ops



Rover Driving

Mission Monitoring



Lander

Science Station

Waypoints
~ 5 m

Traverse Points
~ 50 m

Drill A

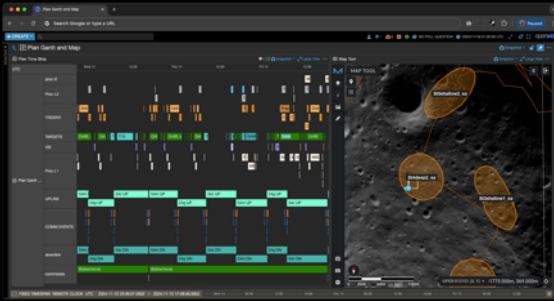
Drill B

Drill C

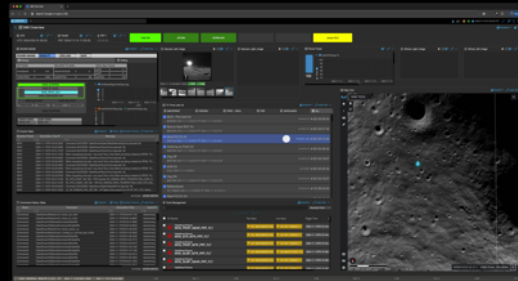
Science Station

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

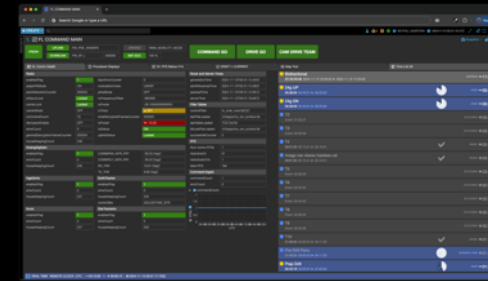
Mission Ops Tools



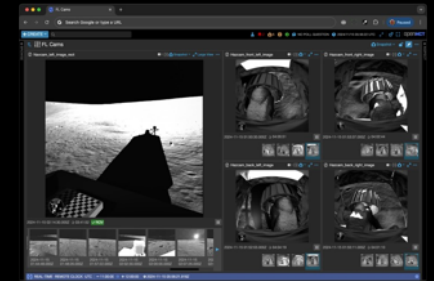
Planning Timeline and Map



Mission Manager Integrated Overview



Situational Awareness and Activities



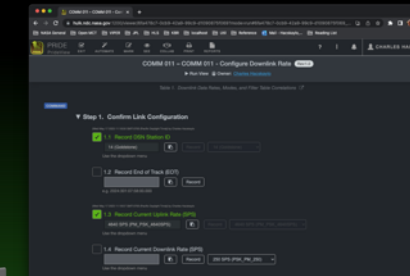
Nav and Haz Cameras



Instrument Health and Status

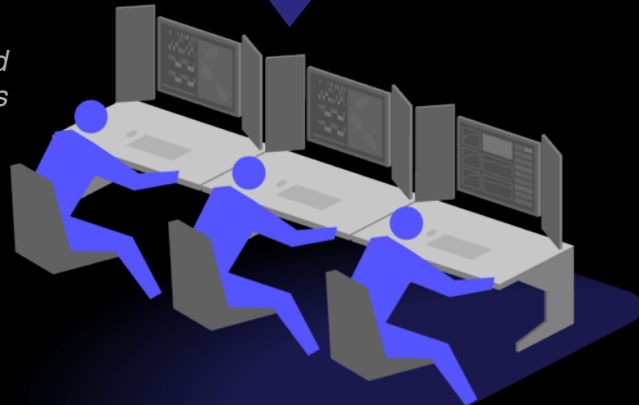


VERVE Driving Software



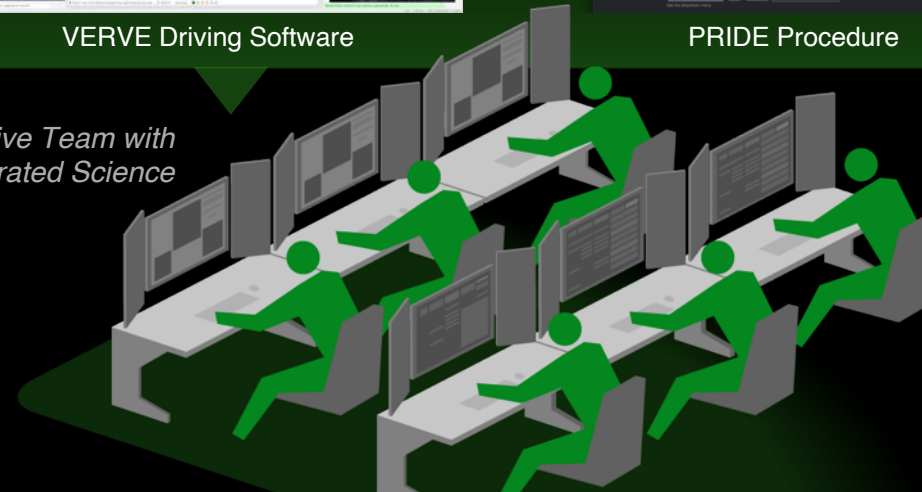
PRIDE Procedure

*Instrument and
Planning Teams*



Payload Operations

*Drive Team with
Integrated Science*

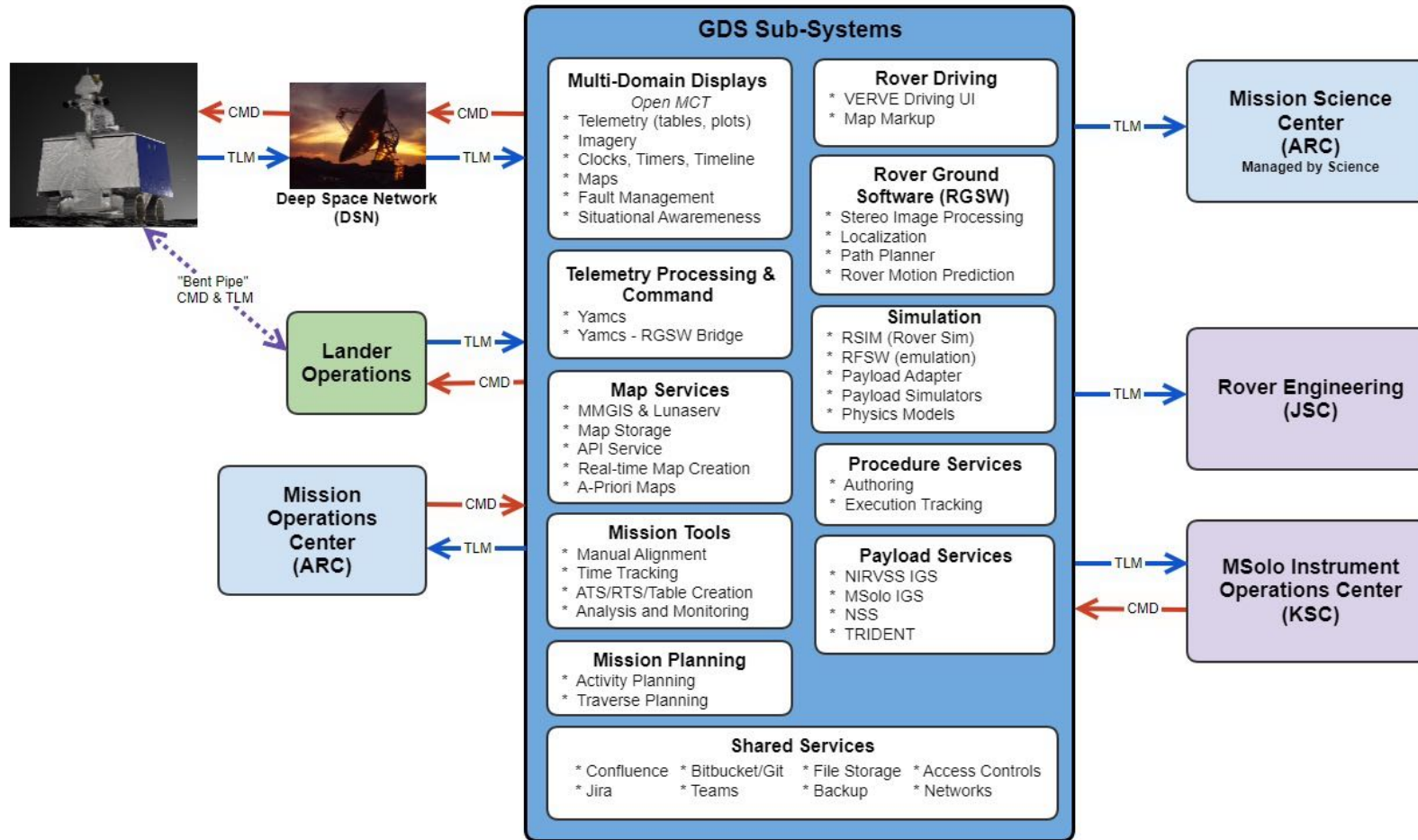


Rover Operations

*Mission and
Engineering Team*

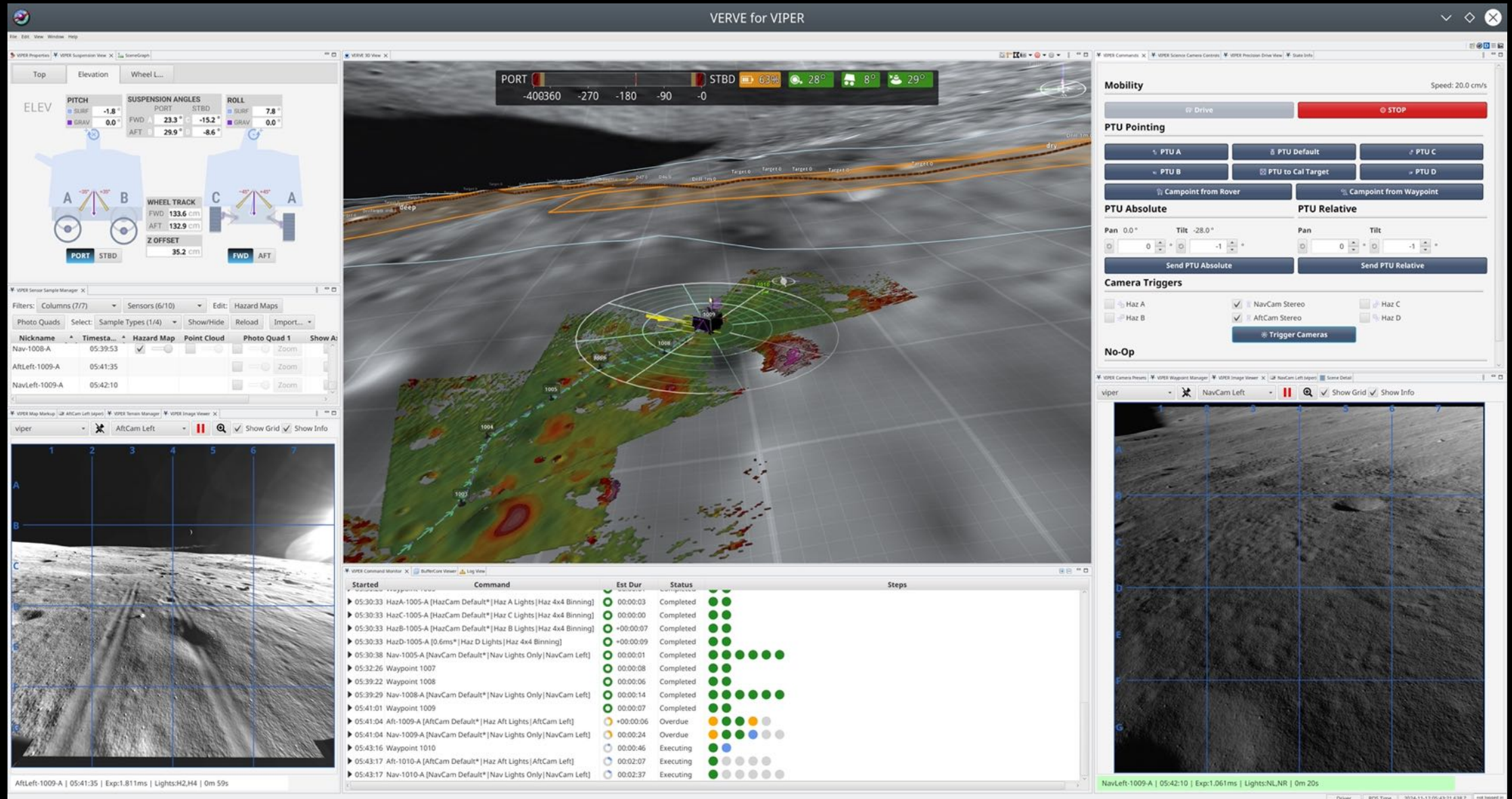
Ground Data System

GDS Overview Diagram

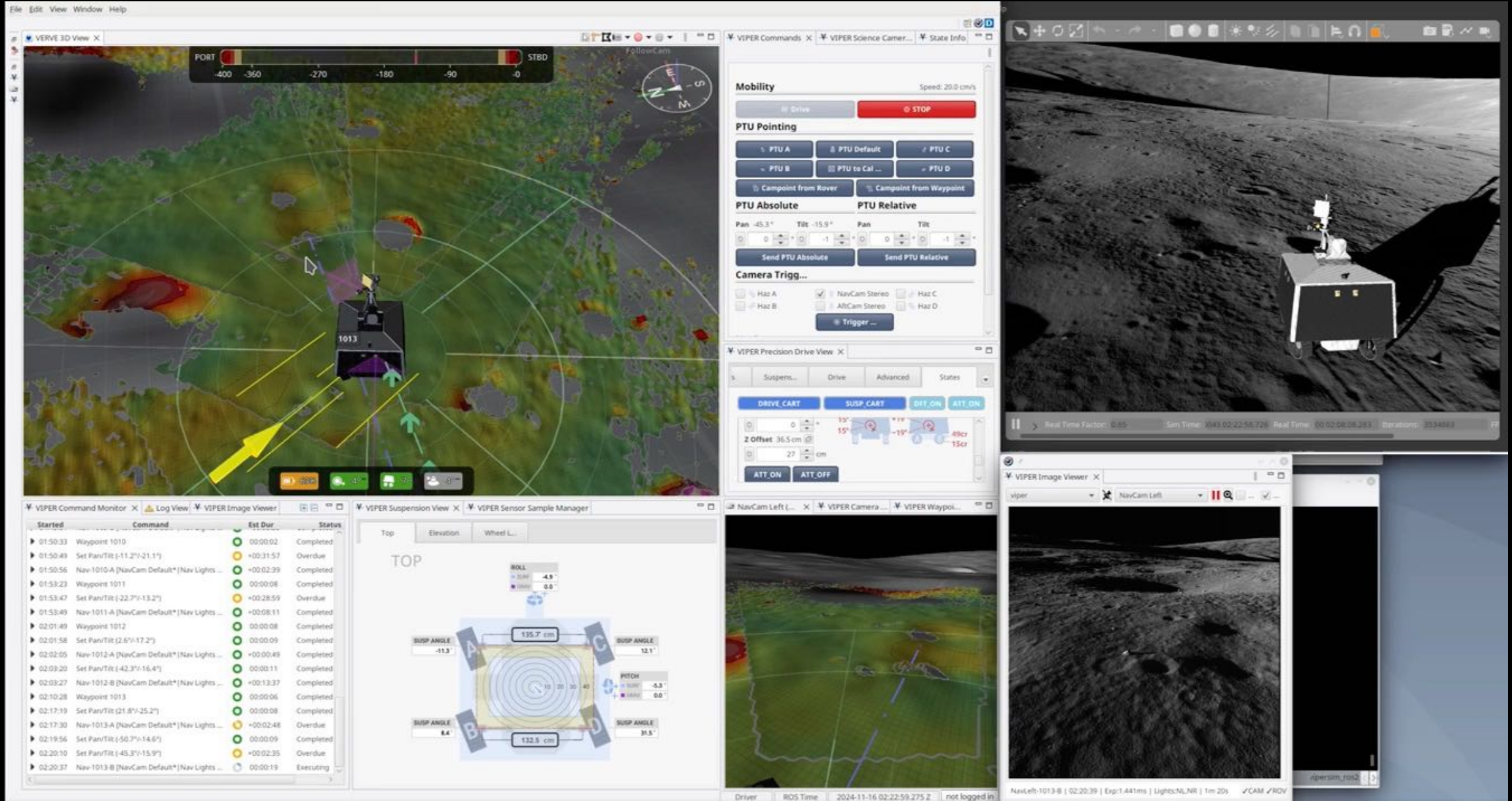


- Build 9 – feature complete
- Integrated into operational environment across operational positions
- Tested in Activity-Based Operational Thread Tests
- Tested in Integrated Simulations
- Integrated testing underway with flight hardware
- Full Verification Testing planned for November 2024

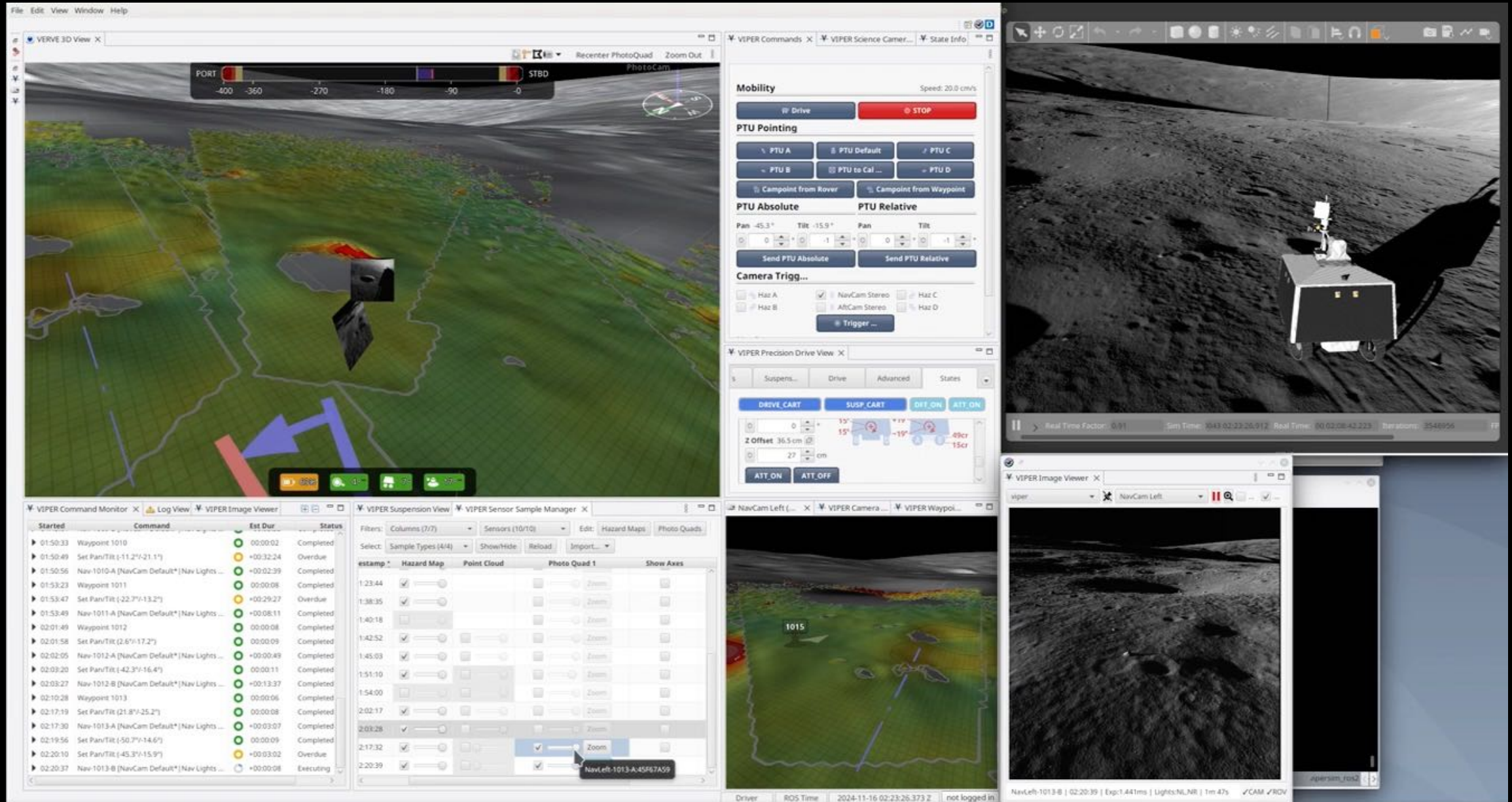
Rover Driving Interface (VERVE)



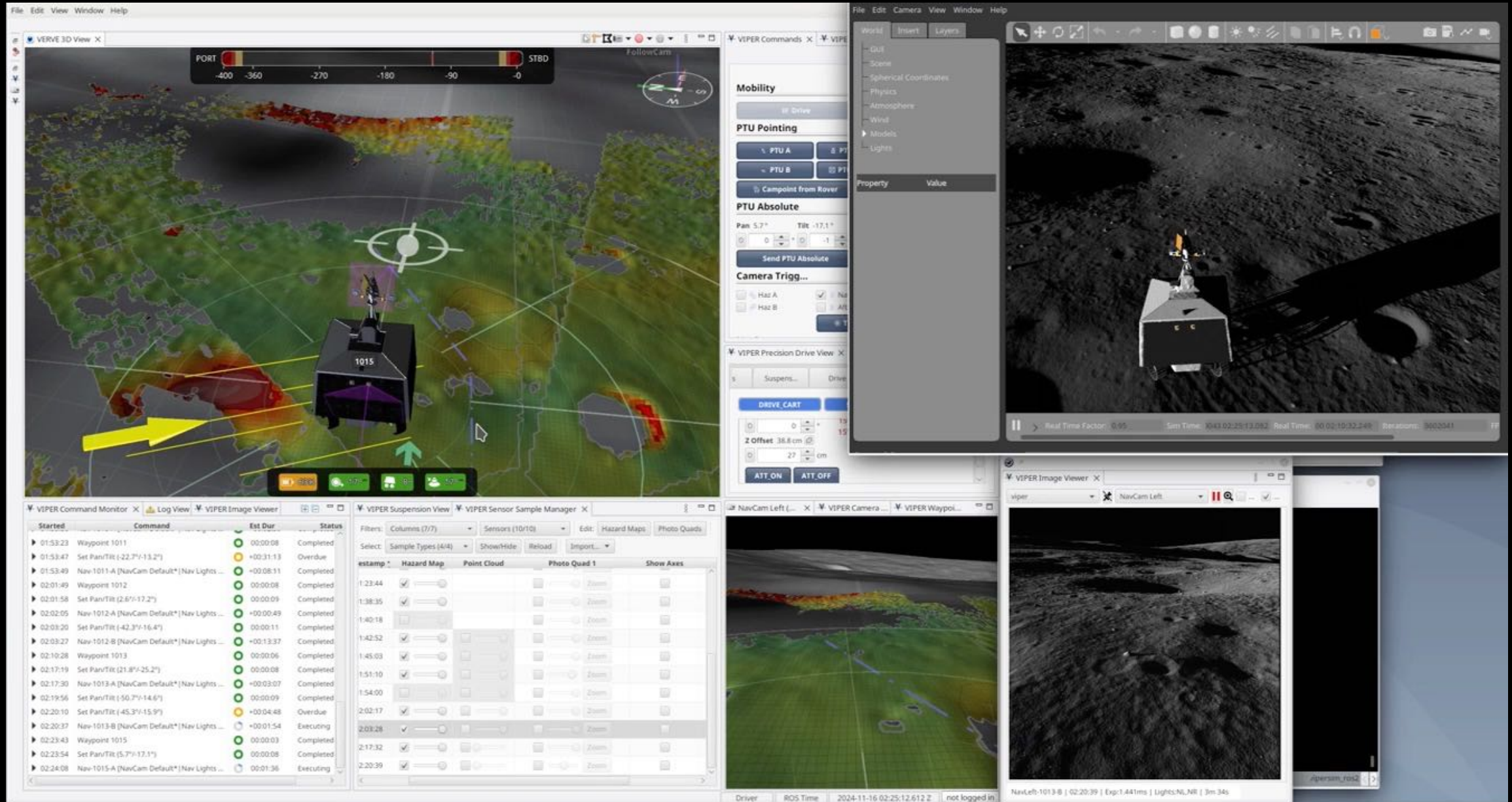
VERVE + RSIM (Assess terrain + place waypoint)



VERVE + RSIM (Refine waypoint + drive)



VERVE + RSIM (Repeat drive loop)



NASA Ames “Lunar Lab”

High-fidelity surface appearance testbed

- Supports camera, light, and navigation testing across a variety of lunar terrain
- Highlands: 12 tons of LHS-1 simulant in a 4x20 meter sandbox
- Mare: 8 tons of JSC-1A simulant in a 4x4 meter sandbox
- Terrain can be shaped and dusted to mimic micro-meteorite surface texture

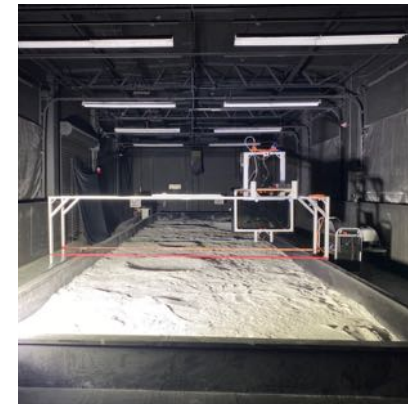
Experimental setup

- Sun simulators for lunar polar lighting
- Sliding gantry provides non-contact data collection for optical sensors
- High accuracy (survey grade) lidar and positioning system for ground truthing



Simulated polar lighting on LHS-1 terrain

*Appearance of
VIPER rover wheel
and tracks*



*Sliding gantry over
LHS-1 terrain*

NASA Ames “Lunar Lab”



NASA Ames Research Center

4m x 20m sandbox with 12 tons of LHS-1 lunar regolith simulant

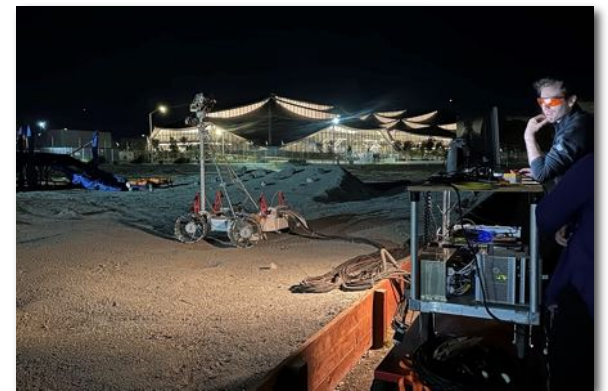
NASA Ames “Roverscape”

Outdoor planetary rover test facility

- Supports testing of rover locomotion, navigation, and surface operations
- 11,500 m² (two American football fields)
- Variety of terrain features: craters, boulder field, unconsolidated soil, etc.
- Most of the Roverscape is covered by 10 cm of highly compacted quarry fines

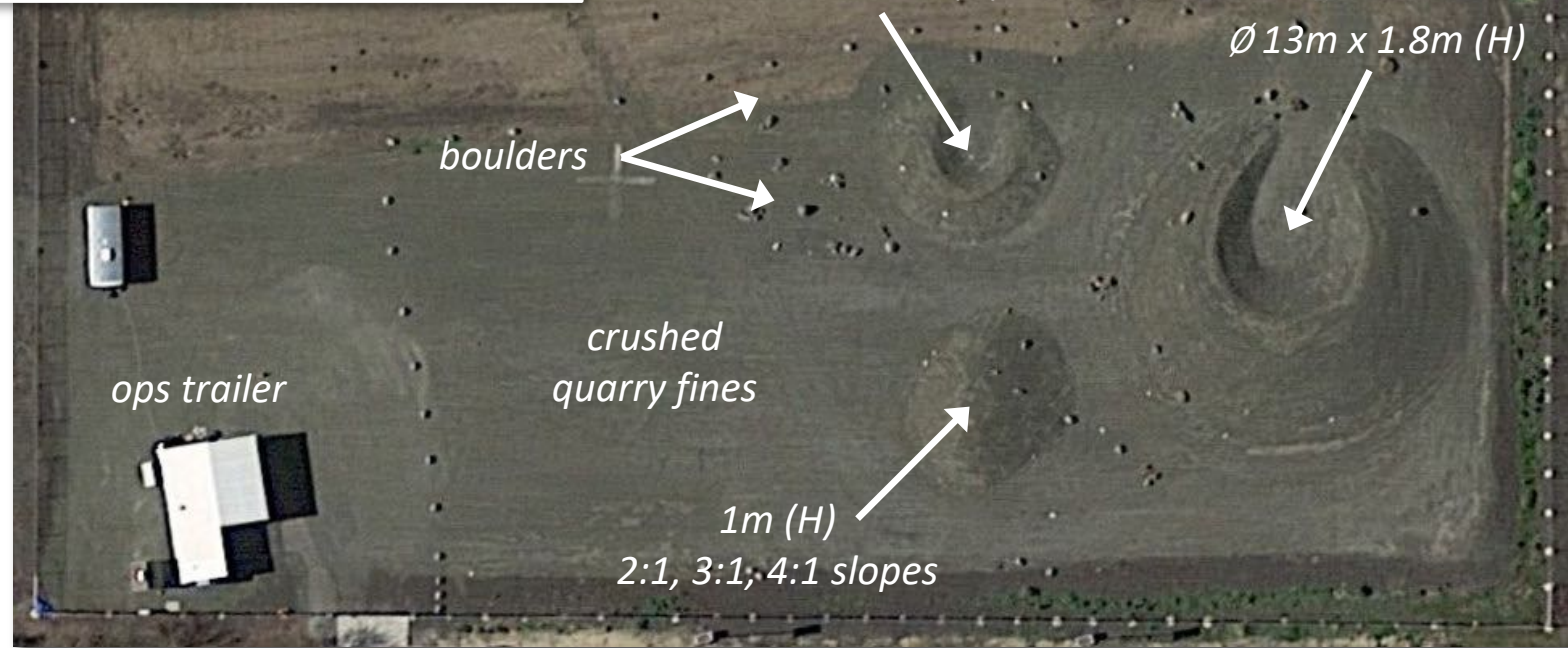
Experimental setup

- Sun simulator for lunar polar lighting
- High accuracy (survey grade) lidar and positioning system for ground truthing
- Operations trailer provides electrical power, wireless network, and workspace



VIPER rover testing in the Roverscape

NASA Ames "Roverscape"



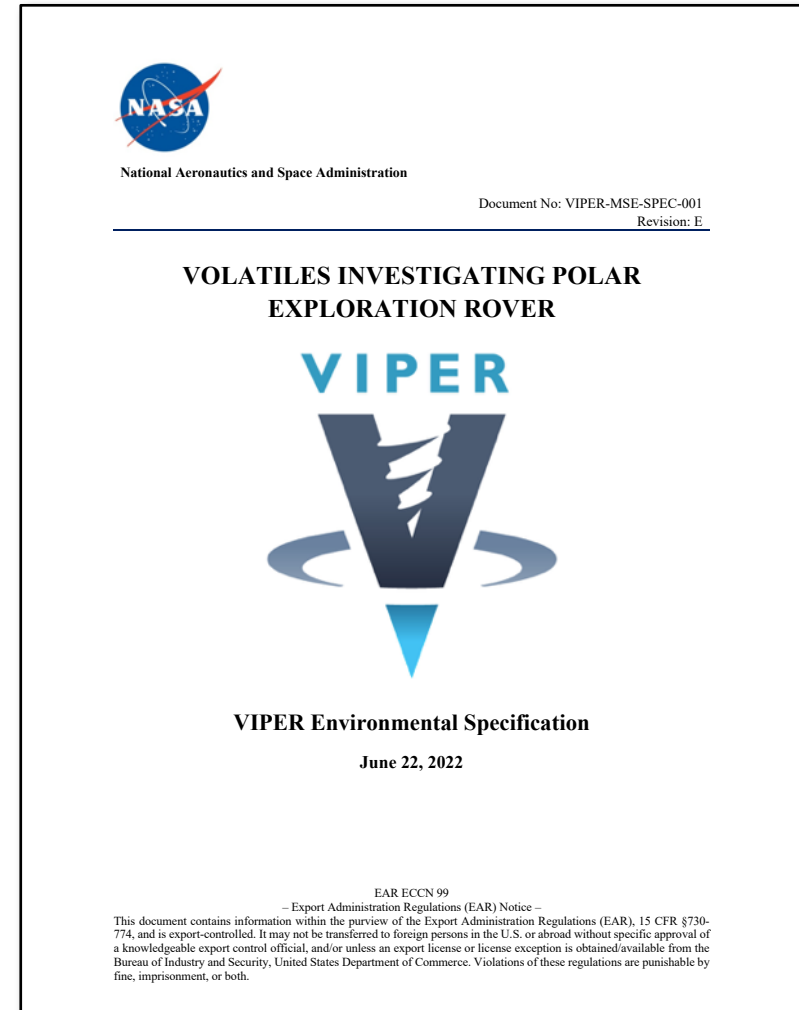
VIPER Environmental Spec (Rev E)

Key points

- Defines the natural and self-induced environments occurring over the VIPER life-cycle (ground, launch, transit, descent, landing, surface)
- Complements and augments:
 - SLS-SPEC-159 (DSNE)
 - MIL-STD-461G
 - Lunar Sourcebook

Lunar surface traversability section

- Lunar soil properties
- Rock and crater properties
- Slope properties



For additional information:

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