



# Planetary Rover Simulation for Lunar Exploration Missions

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# Resource Prospector Driving Concept of Operations Simulator



- End-to-end Lunar rover driving simulation to assist in the development and refinement of the RP ConOps
- Created simulated Lunar environment and rover simulation to develop and test Mission Software components

\*create diagram w/ simulator, ops room, flight software, etc

# End-to-End Simulation for Developing Concept of Operations



Rover and Instrument  
Commands



Simulated mission data

# Resource Prospector - A NASA Lunar Rover Mission Concept



- **Goal:** characterize subsurface water distribution at Lunar poles
- **Mission duration:** 7-10 Earth days during single Lunar day
- **Rover:**
  - Solar powered
  - Direct-To-Earth communication
- **Science payload:**
  - Neutron Spectrometer, Visible to Near-IR Spectrometer
  - Soil Sampling with Drill
  - Volatile Analysis with Gas Chromatogram and Mass Spectrometer



# Resource Prospector Proposed a New Mission Model



- High tempo, human-in-the-loop operations
- Science representative integrated into driving team
- Split Autonomy
  - Low level functions onboard rover (e.g. waypoint following, relative pose)
  - High level functions on ground (e.g. terrain analysis, absolute localization)
- Reliance on both human and machine perception to navigate

# End-to-End Rover Driving Simulation



- Simulator Elements
  - Synthetic Lunar Terrain
  - Visual Simulation
  - Rover Mechanism & Software Simulation
  - Physical Simulation
  - Comm Simulation
  - Science Data Simulation
  - Mission Operations Software Tools

# End-to-End Rover Driving Simulation

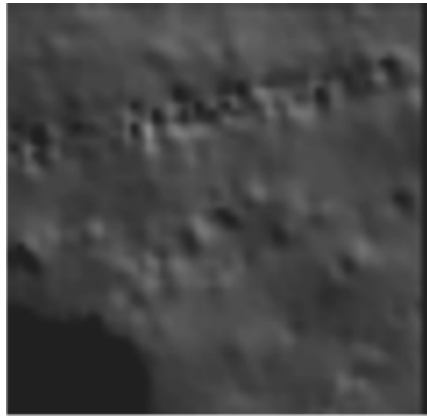


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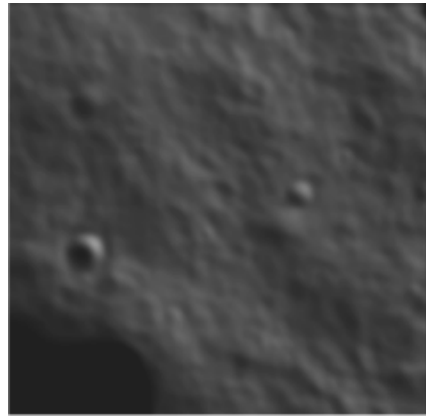
# Synthetic Lunar Terrain



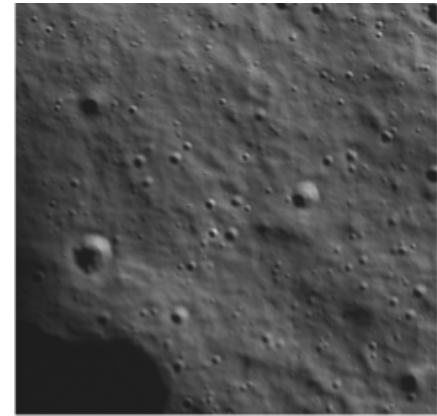
- Existing Lunar Digital Elevation Models (DEMs) are too coarse for driving simulation
  - Best-available DEMs are 1-10m resolution and typically noisy
  - 100x better resolution required to reproduce rover-scale hazards



LOLA DEM (10m)



Stereo/SfS DEM (1m)



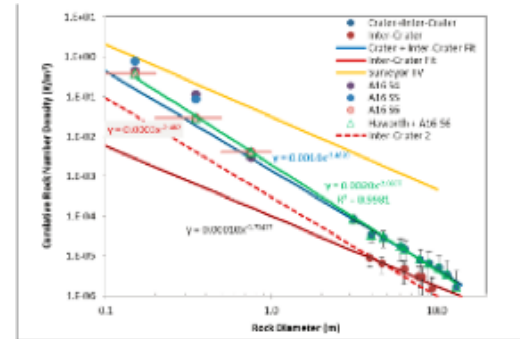
LRO NAC Image



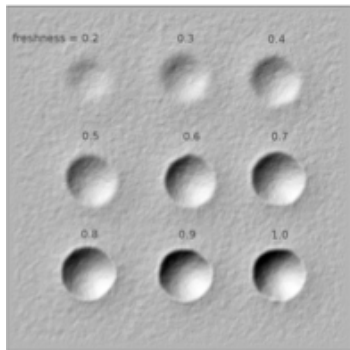
# Synthetic Lunar Terrain



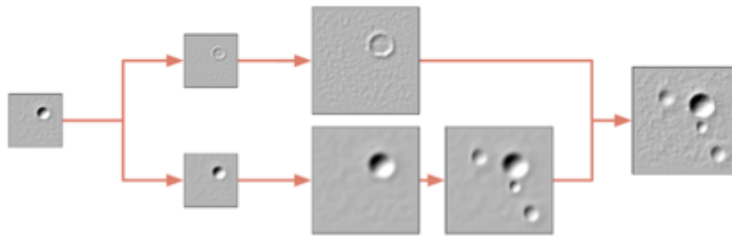
- Artificially enhanced Lunar DEMs
  - Fractal synthesis used to increase DEM resolution
  - Craters and rocks inserted based on size-frequency distributions and shape models from science team



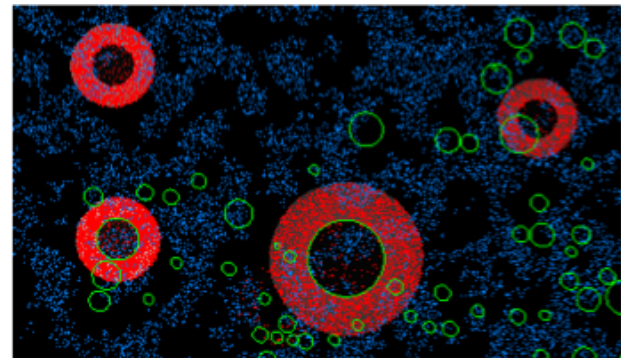
Lunar rock size-frequency distributions



Crater shape



DEM upscaling process



Crater and rock placement

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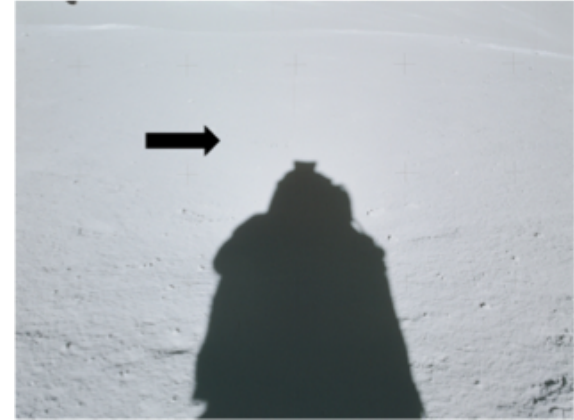


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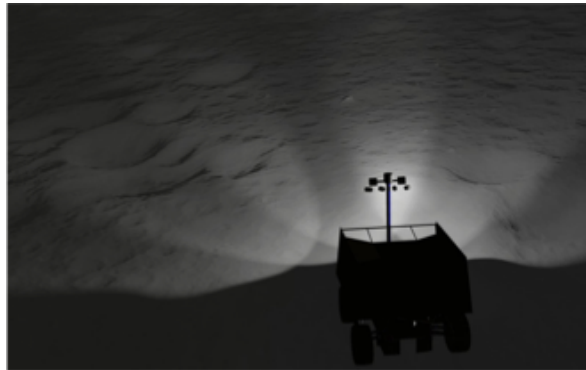
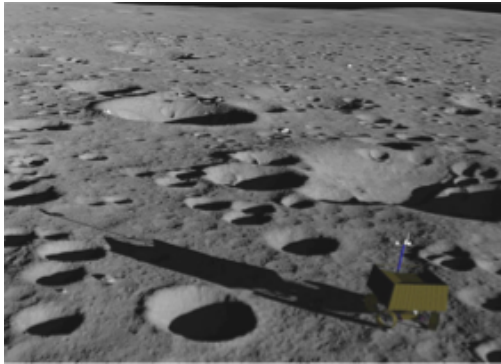
# Visual Simulation



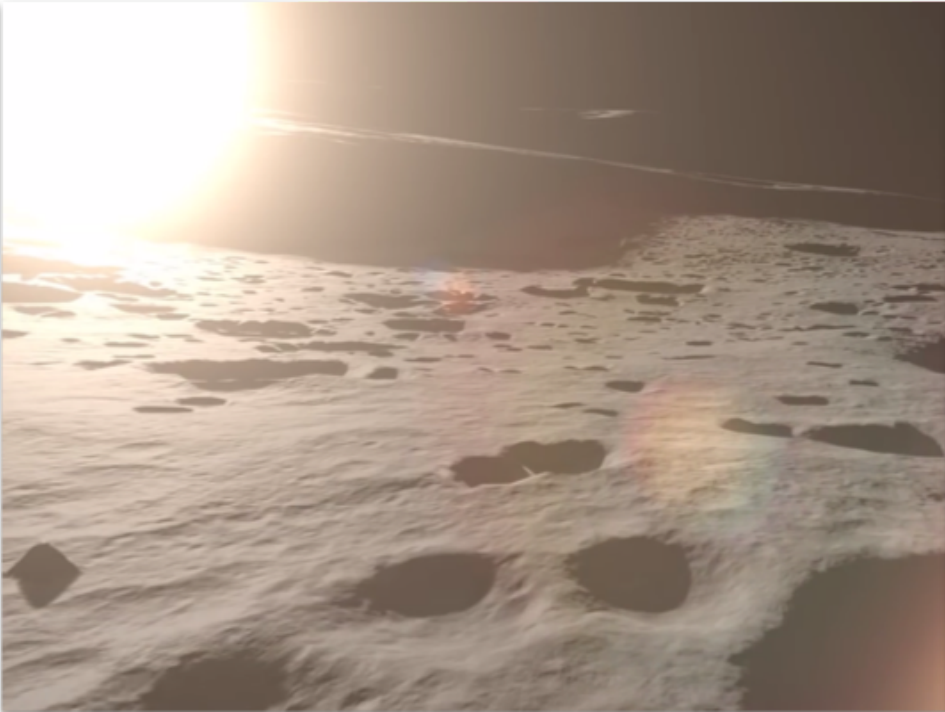
- High fidelity visual simulation critical to human driver perception as well as machine perception
- Lunar regolith
  - Hapke BRDF
- Accurate placement of Sun and Earth from ephemeris models
  - Sun extremely low on horizon at poles
  - Earth location critical for comm



Opposition Effect



# Visual Simulation



Lunar scene from simulator



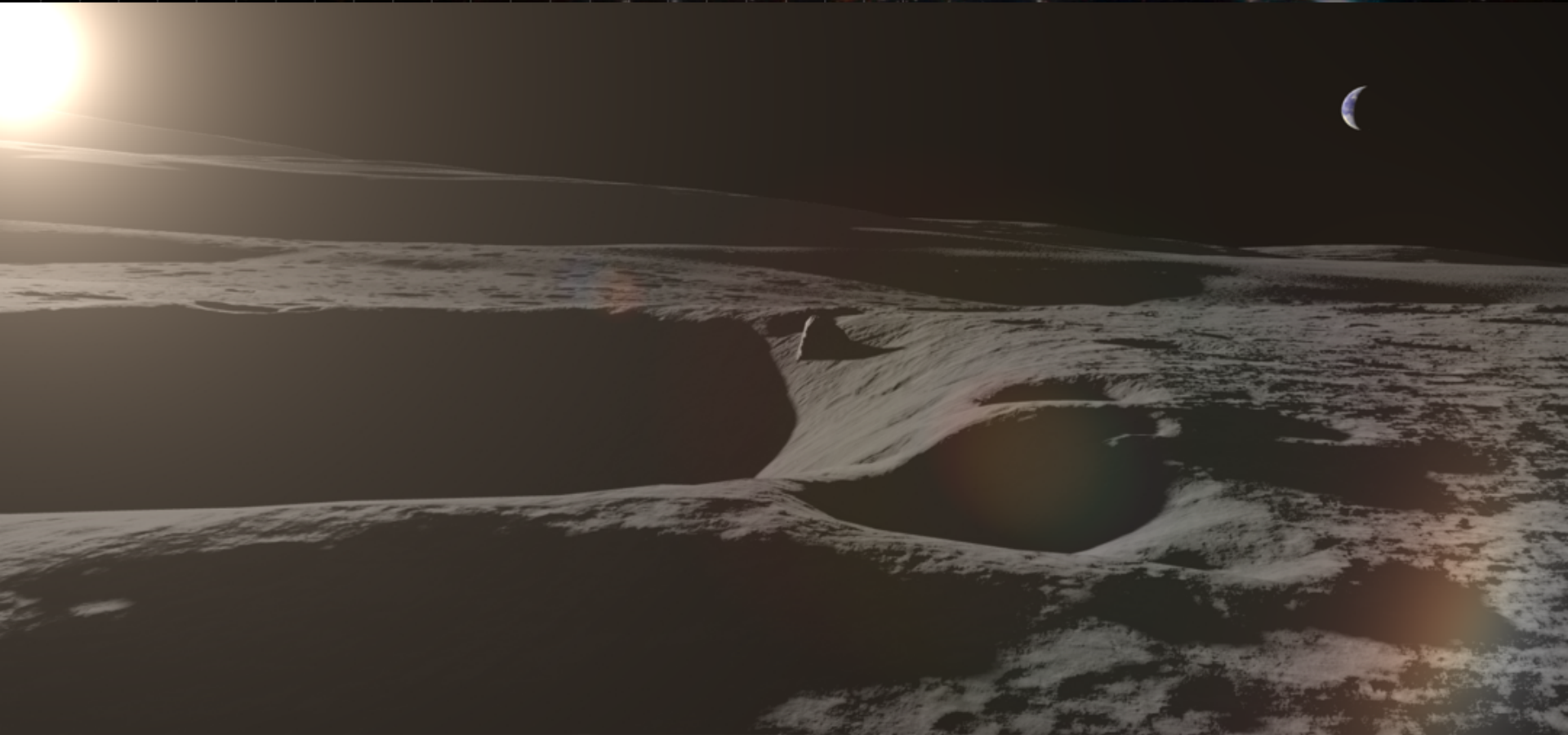
Lunar scene from Apollo 12 mission



- Significant enhancements to core Gazebo visualization capabilities, including
  - Support for high resolution terrains
  - Support for custom terrain appearance shaders
  - Improved real time shadows
  - Rover wheel tracks in regolith
  - Vehicle mounted lighting with customizable beam pattern
  - Lensflares and enhanced camera noise model
  - High dynamic range image rendering



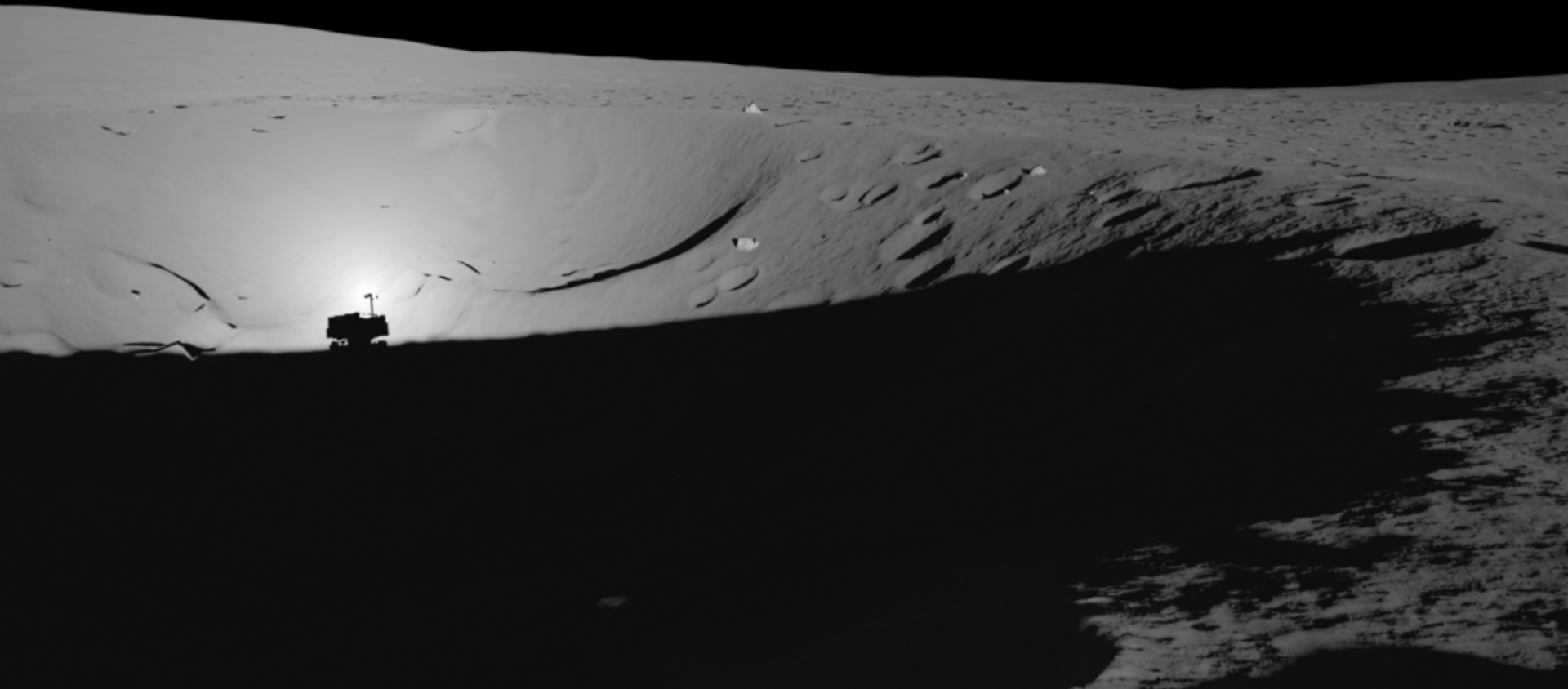
# Visual Simulation Images



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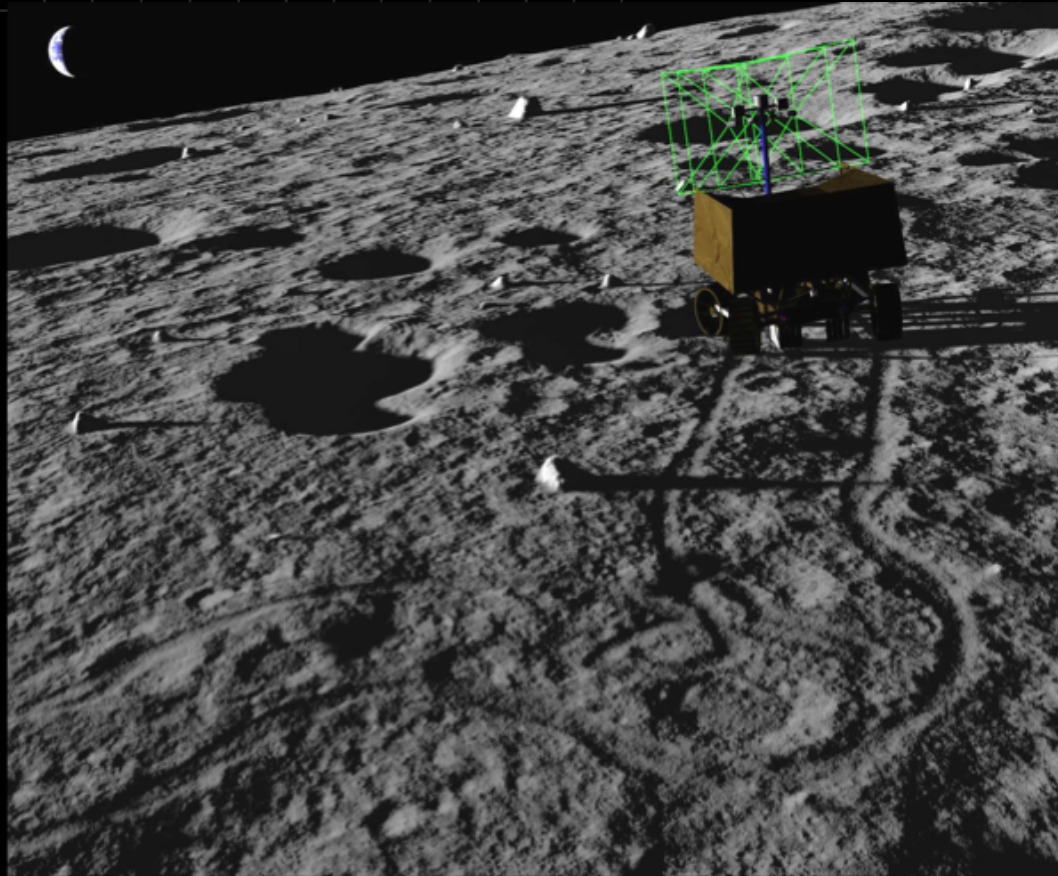


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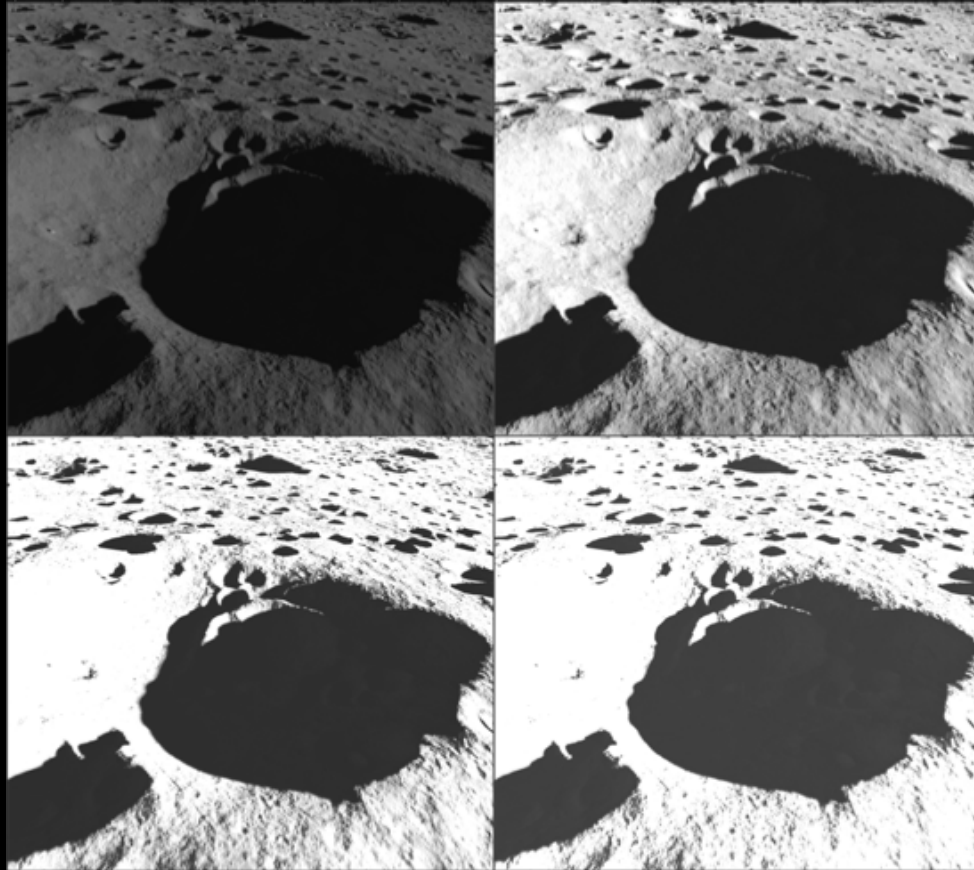




# Visual Simulation - wheel tracks



# Visual Simulation - high dynamic range



# End-to-End Rover Driving Simulation

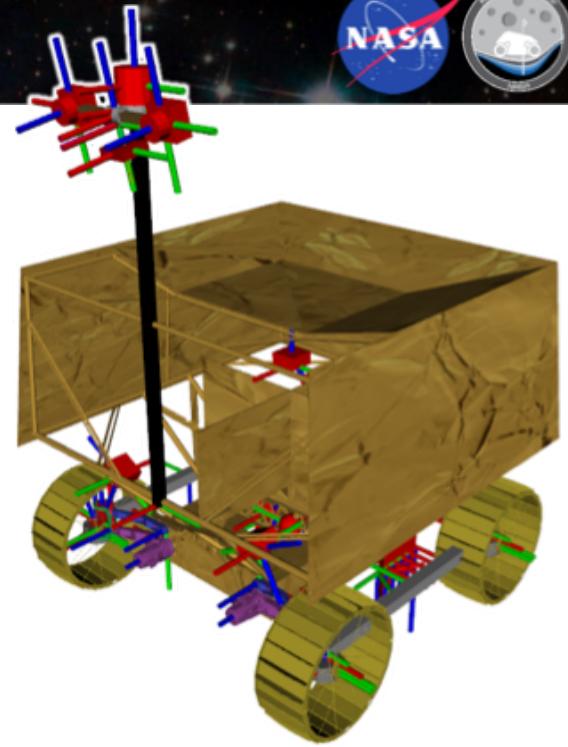


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# Rover Mechanism & Software Simulation

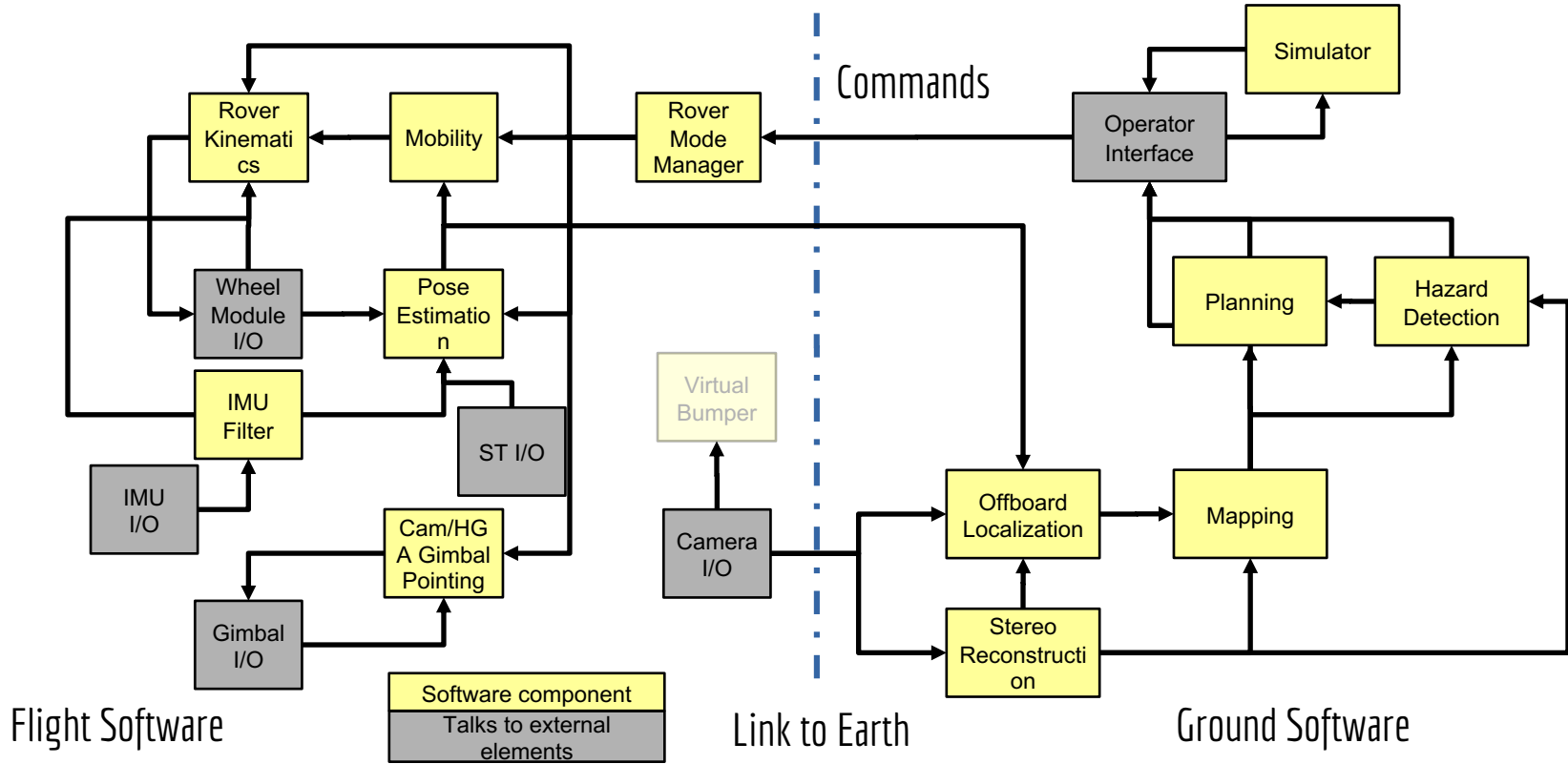


- Rover Mechanism
  - 4 wheel explicit steer platform simulated in Gazebo,
  - Scaled vehicle to RP rover size, added RP chassis and mast
  - Added slip module to Gazebo for increased driving realism
- Rover Software
  - Emulating Flight and Ground Software with ROS (Robot Operating System)
  - ROS provided stand-ins for flight software functionality



ROS

# Lunar Operations Enable Distributed Autonomy



# End-to-End Rover Driving Simulation

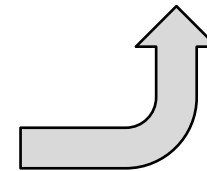
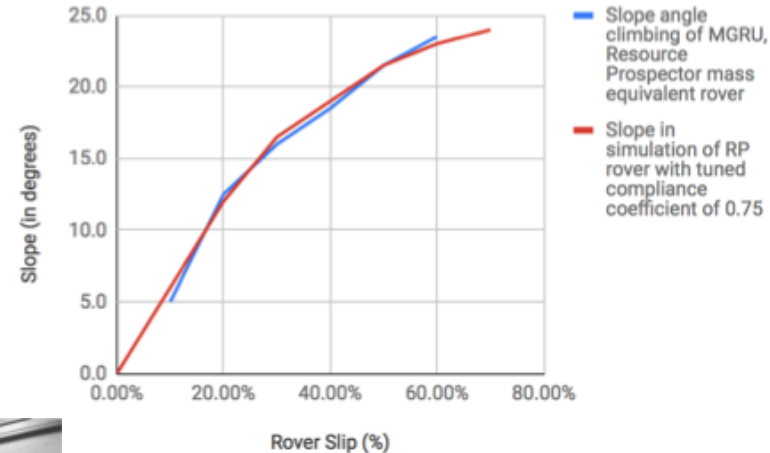


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# Physical Simulation



- Gazebo simulation platform with ODE (Open Dynamics Engine)
- Wheel slip plugin
  - First order approximation of wheel slip on unconsolidated soil
  - Tuned using test results from physical testbeds



# End-to-End Rover Driving Simulation



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- Asymmetric, bidirectional time delay
  - Time-of-flight
  - Anticipated Deep Space Network (DSN) processing time
  - Telemetry size
- Variable jitter

# End-to-End Rover Driving Simulation

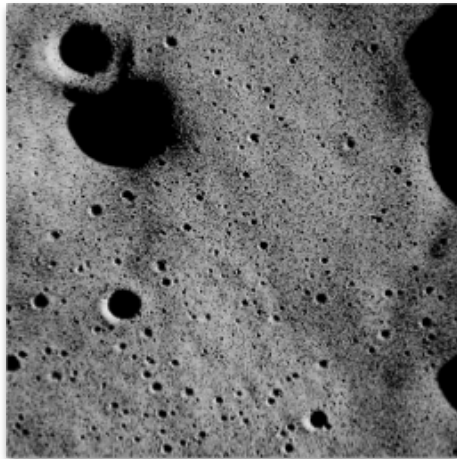


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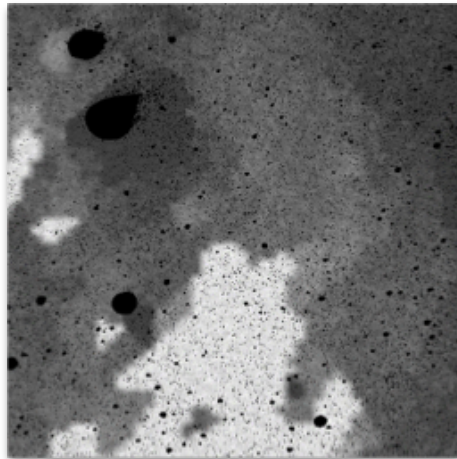
# Science Data Simulation



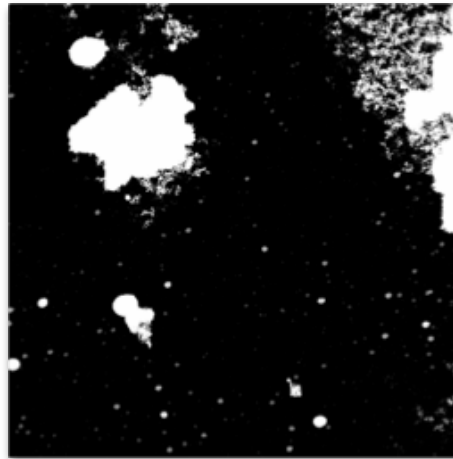
- Synthetic "ground truth" maps created for science data
- Real time instrument readings based on rover location



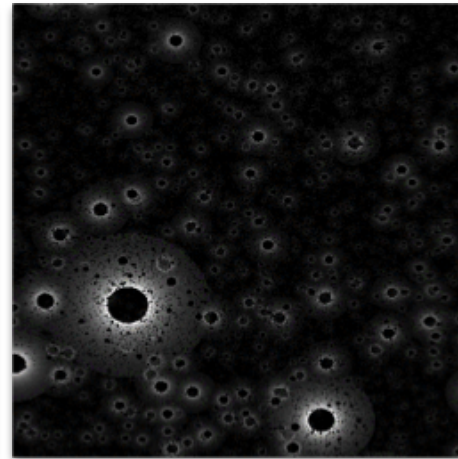
Surface Temperature



Depth of Dry Layer



Surface Frost



Subsurface Ice Concentration

# End-to-End Rover Driving Simulation



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# Mission Operations Software Tools



- Mix of development versions of Mission Operations software tools and stand-ins
- Configuration as flight-like as possible
- Simulation experiments inform software design
  - RDT (Rover Driving Tools)
    - Interactive 3D command interface
  - WARP (Ground Data System)
    - Web based telemetry visualization interface
  - Science Displays

# Rover Driving Tools



The screenshot displays the RPL software interface for rover navigation. The main window shows a 3D terrain map of a Martian surface with a planned path and several waypoints (0 through 11). A rover model is positioned on the terrain. The interface is divided into several panels:

- RptRex2 Properties:** A tree view on the left showing various rover components like cameras, sensors, and tools.
- Command:** A console at the top right for sending commands to the rover.
- Log Monitor:** A panel at the bottom left showing system logs.
- Image Views:** Three camera views at the bottom right showing the rover's perspective from different angles.

At the bottom left, a table lists waypoints with their coordinates and altitudes:

Station	X	Y	Theta	XZ Distance	Alt
Waypoint 0	1000	0.000	0.000	0.000	0.000
Waypoint 1	1001	0.449	0.246	1.200	0.000
Waypoint 2	1002	0.528	0.211	1.537	0.000
Waypoint 3	1003	0.178	0.188	1.537	0.000
Waypoint 4	1004	-0.890	0.112	1.400	0.000
Waypoint 5	1005	0.468	0.842	1.400	0.000
Waypoint 6	1006	-0.240	0.730	1.400	0.000

# WARP/OpenMCT



The screenshot displays the WARP/OpenMCT interface for a lunar simulation. The browser address bar shows a URL from banner.ndc.nasa.gov. The interface is divided into several panels:

- Left Panel:** A tree view showing the simulation's structure, including folders for 'psarram', 'Ray', 'WARP Demo 2017 ARC', and '2018 Sim Test 0'. The 'RTSCI' folder is currently selected.
- Top Center:** Two camera views labeled 'navcam\_left' and 'navcam\_right', showing a first-person perspective from the lunar surface. Below them is a third camera view labeled 'hazzcam\_near'.
- Bottom Center:** A timeline and playback controls. The current time is 00:59:32.727Z on 2018-05-26.
- Right Panel:** A 'Traverse Map - Activity 1' showing a path on a grayscale map of the lunar surface. A color scale on the left indicates values from 0 to 60. Below the map is a table of data for 'NSS Epithermal Neutrons (Filtered and Raw)'.

Name	Timestamp	Value	Min
Cn			6
NSS On (Filtered)		13.75	

Below the table is a plot of the 'NSS On (Filtered)' data over time, showing a fluctuating signal between 10 and 30.
- Far Right:** A 'PROPERTIES' panel for the 'Traverse Map - Activity 1' object, listing metadata such as title, notes, map dimensions, offsets, and location.





# Video



# Take Home Message



- Created End-to-End Simulation for Lunar Driving Operations
  - Produced realistic visual environment
  - Improved slip models
- Pushed improvements to Gazebo to the public
- Demonstrated use in missions operation tests
- Allowed Mission Operations team to:
  - Build intuition
  - Test out operations concepts

# Thank you

