National Aeronautics and Space Administration

Planetary Rover Simulation for Lunar Exploration Missions

Mark Allan, Uland Wong, Michael Furlong,
Arno Rogg, Scott McMichael, Terry Welsh,
Ian Chen, Steven Peters, Brian Gerkey, Morgan Quigley,
Mark Shirley, Matthew Deans, Howard Cannon, Terry Fong

3/1/2019

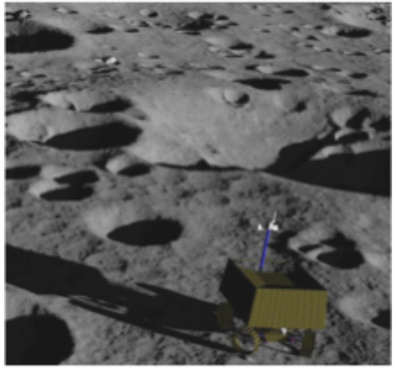
Resource Prospector Driving Concept of Operations Simulator

- 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

Simulator



Rover and Instrument Commands

Real Software and Systems

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

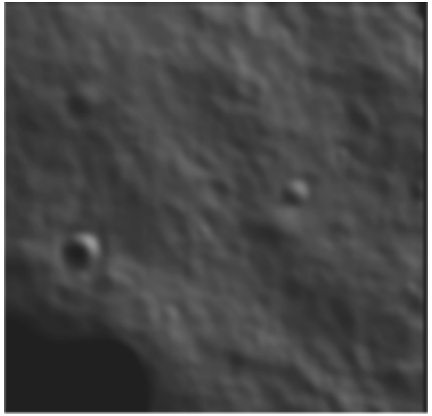
End-to-End Rover Driving Simulation

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

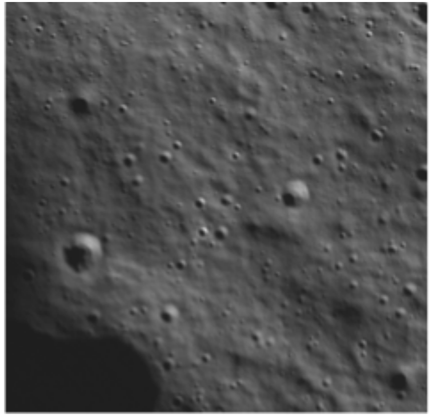
Synthetic Lunar Terrain

- 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)



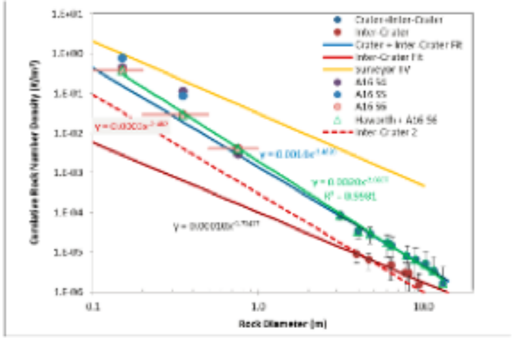
Stereo/SfS DEM (1m)



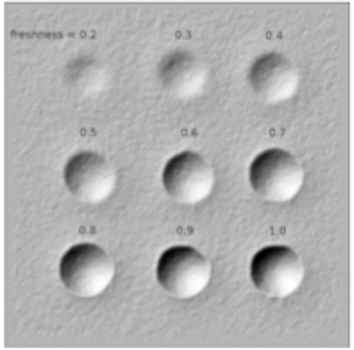
LRO NAC Image

Synthetic Lunar Terrain

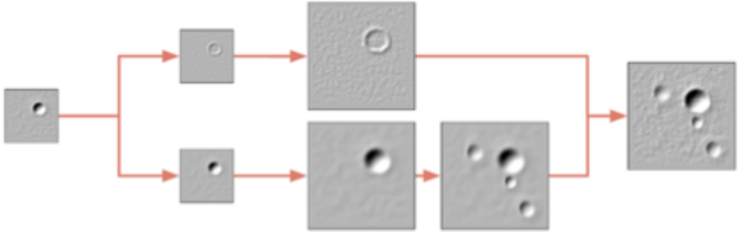
- Artificially enhanced Lunar DEMs
  - Fractal synthesis used to increase DEM resolution
  - Craters and rocks inserted based on size-frequency distributions and shape models from science team



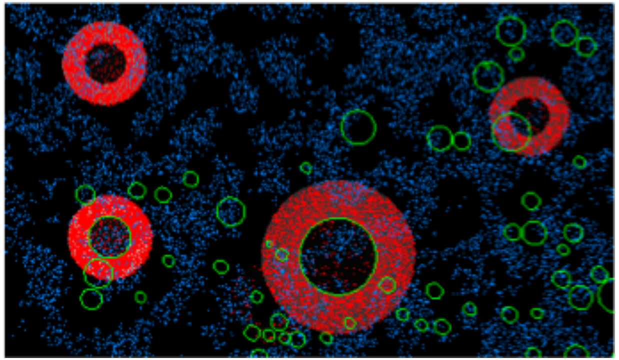
Lunar rock size-frequency distributions



Crater shape



DEM upscaling process



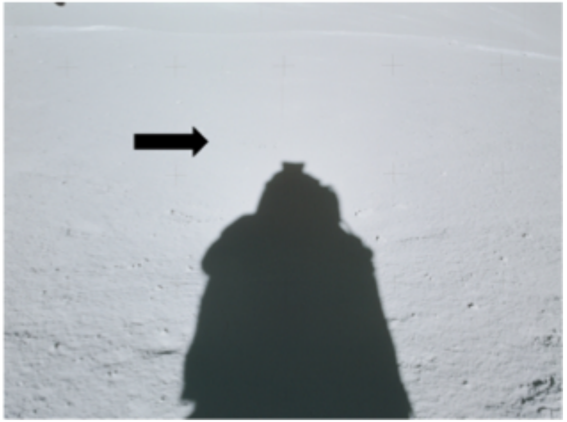
Crater and rock placement

End-to-End Rover Driving Simulation

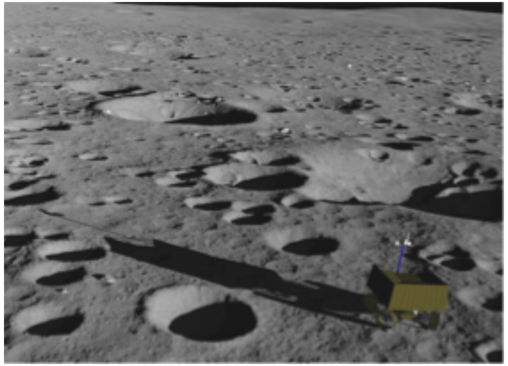
- Simulator Elements
  - Synthetic Lunar Terrain
  - Visual Simulation
  - Rover Mechanism & Software Simulation
  - Physical Simulation
  - Comm Simulation
  - Science Data Simulation
  - Mission Operations Software Tools

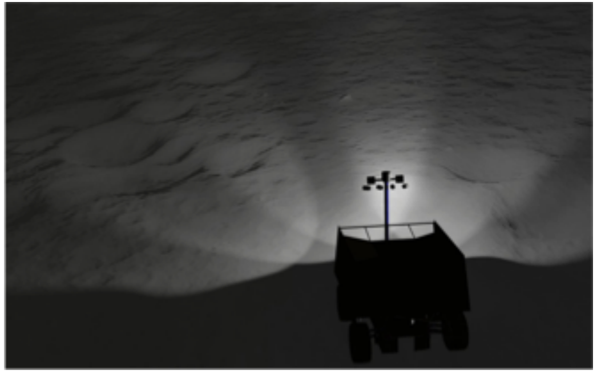
Visual Simulation

- 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

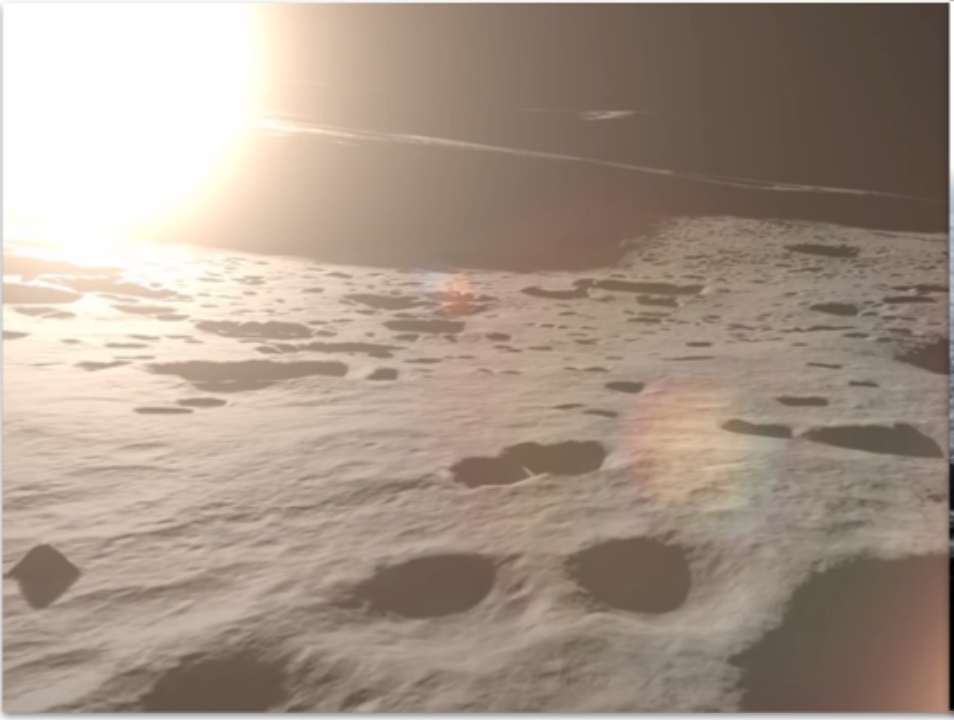


Opposition Effect





Visual Simulation



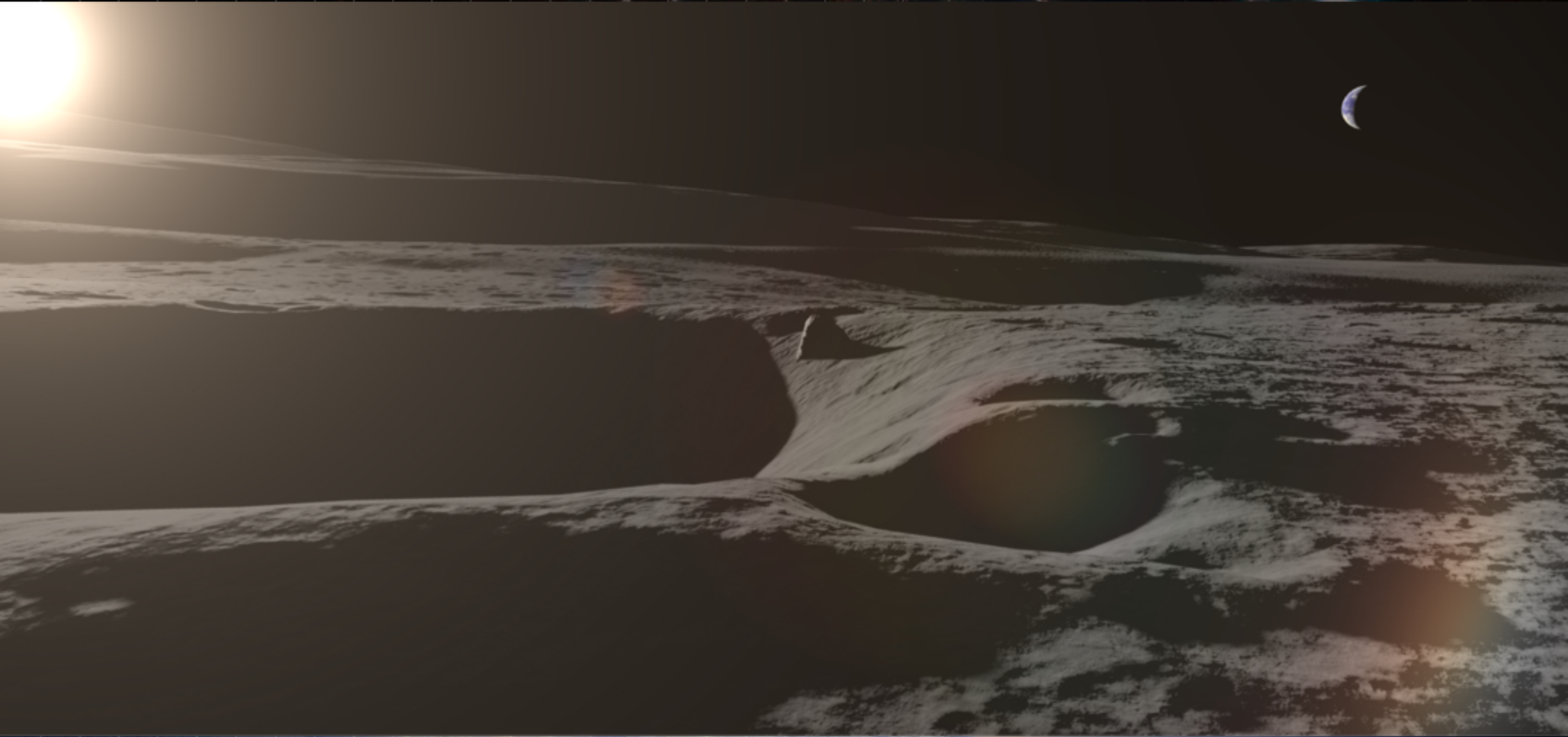
Lunar scene from simulator

Lunar scene from Apollo 12 mission

Visual Simulation

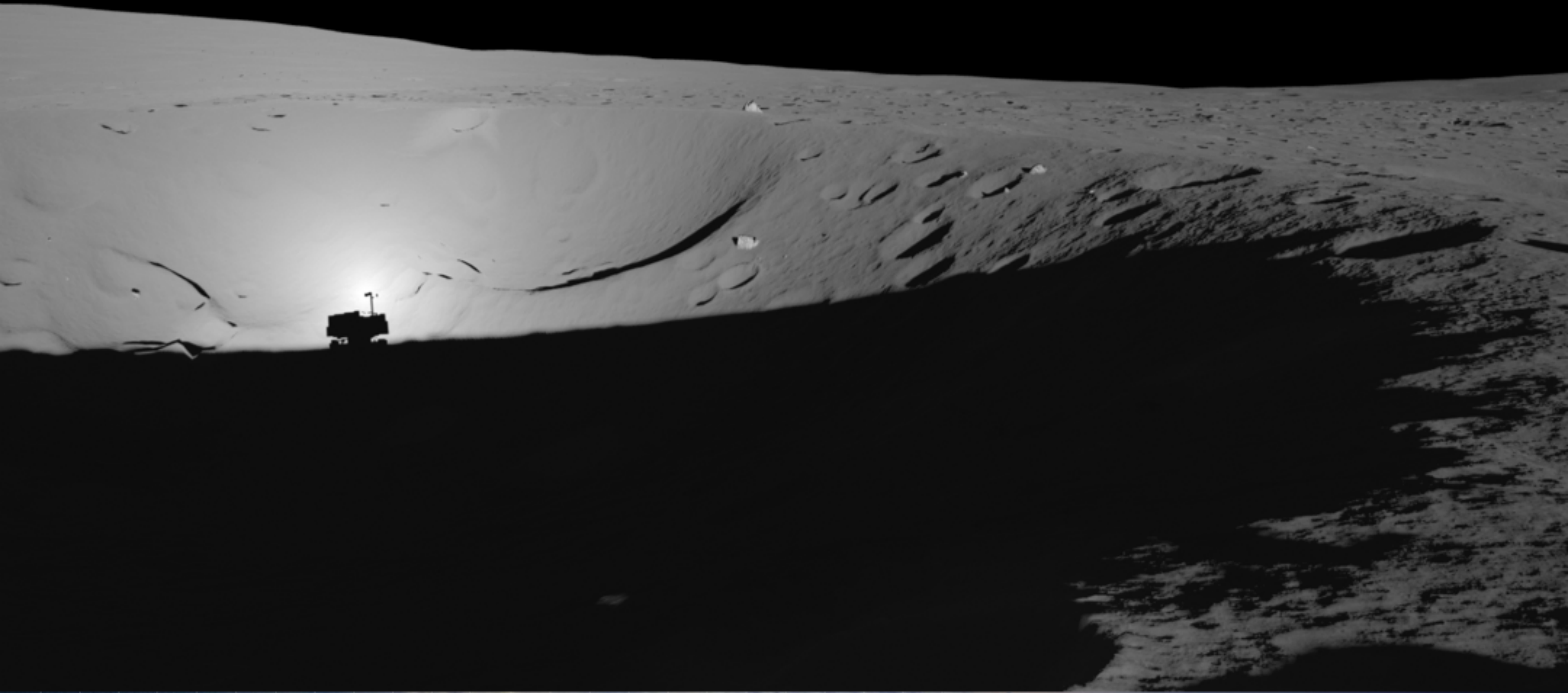
- Significant enhancements to core Gazebo visualization capabilities, including
  - Support for high resolution terrains
  - Support for custom terrain appearance shaders
  - Improved real time shadows
  - Rover wheel tracks in regolith
  - Vehicle mounted lighting with customizable beam pattern
  -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

Visual Simulation Images

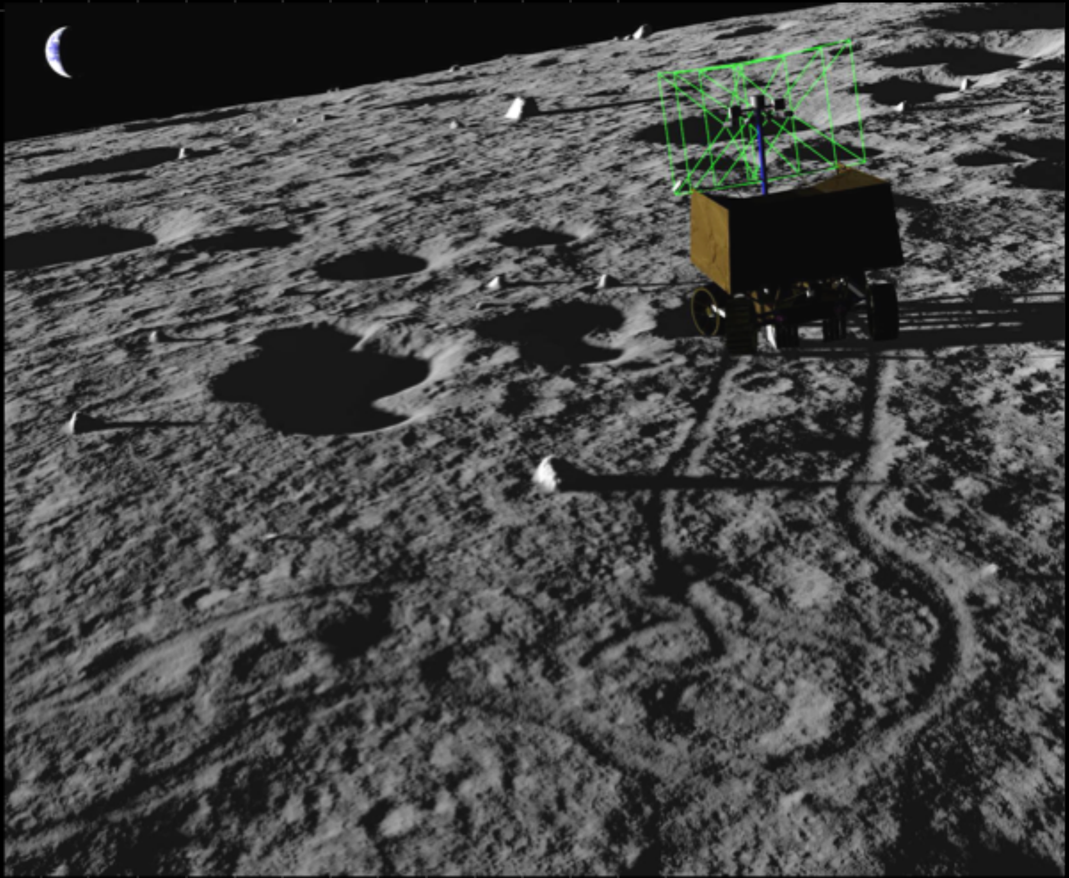


Visual Simulation Images

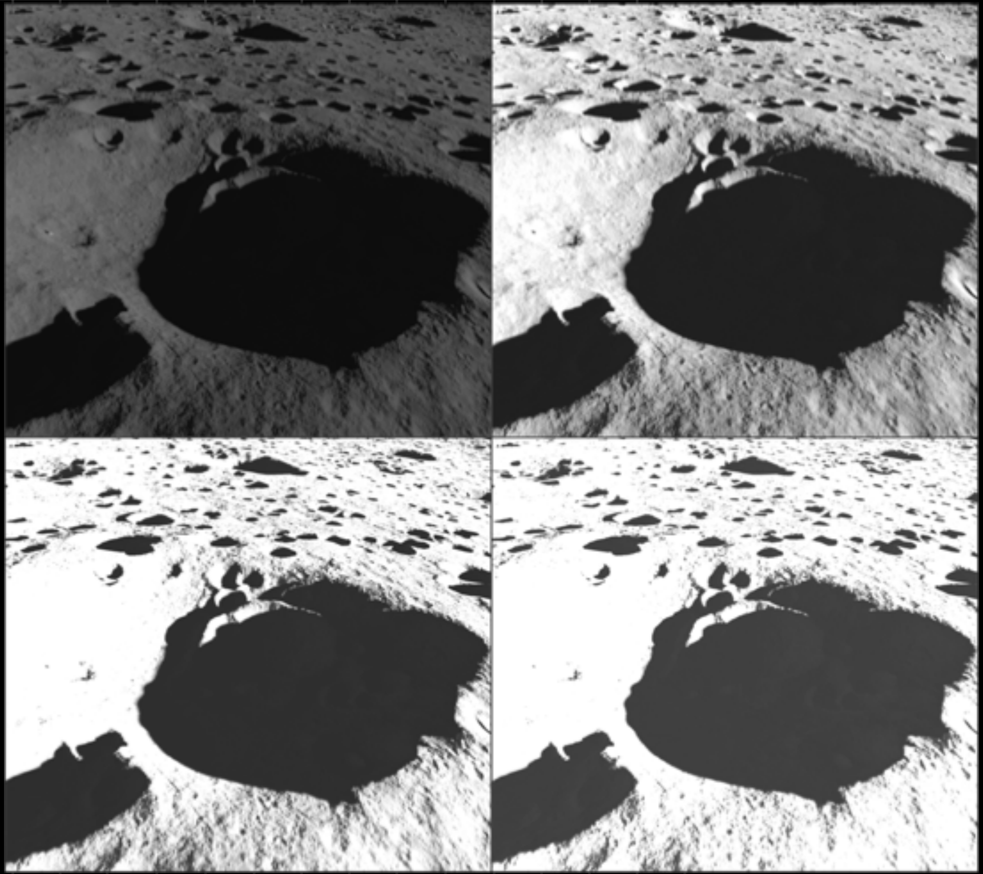
Visual Simulation Images



Visual Simulation - wheel tracks



Visual Simulation - high dynamic range

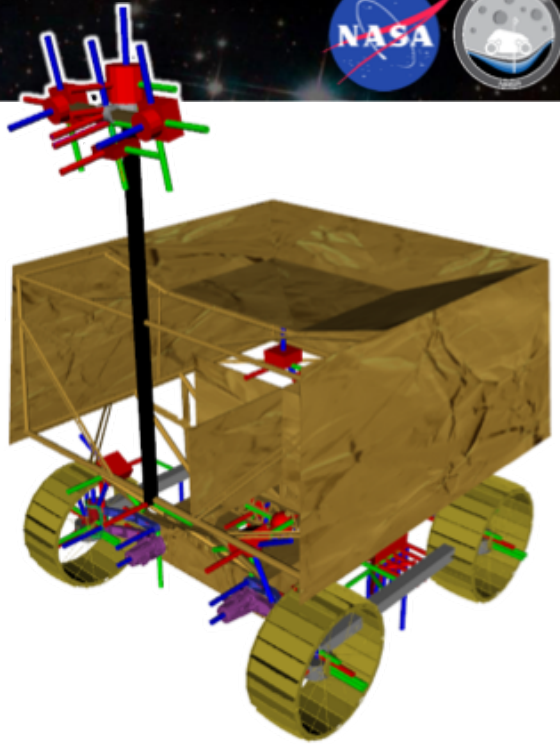


End-to-End Rover Driving Simulation

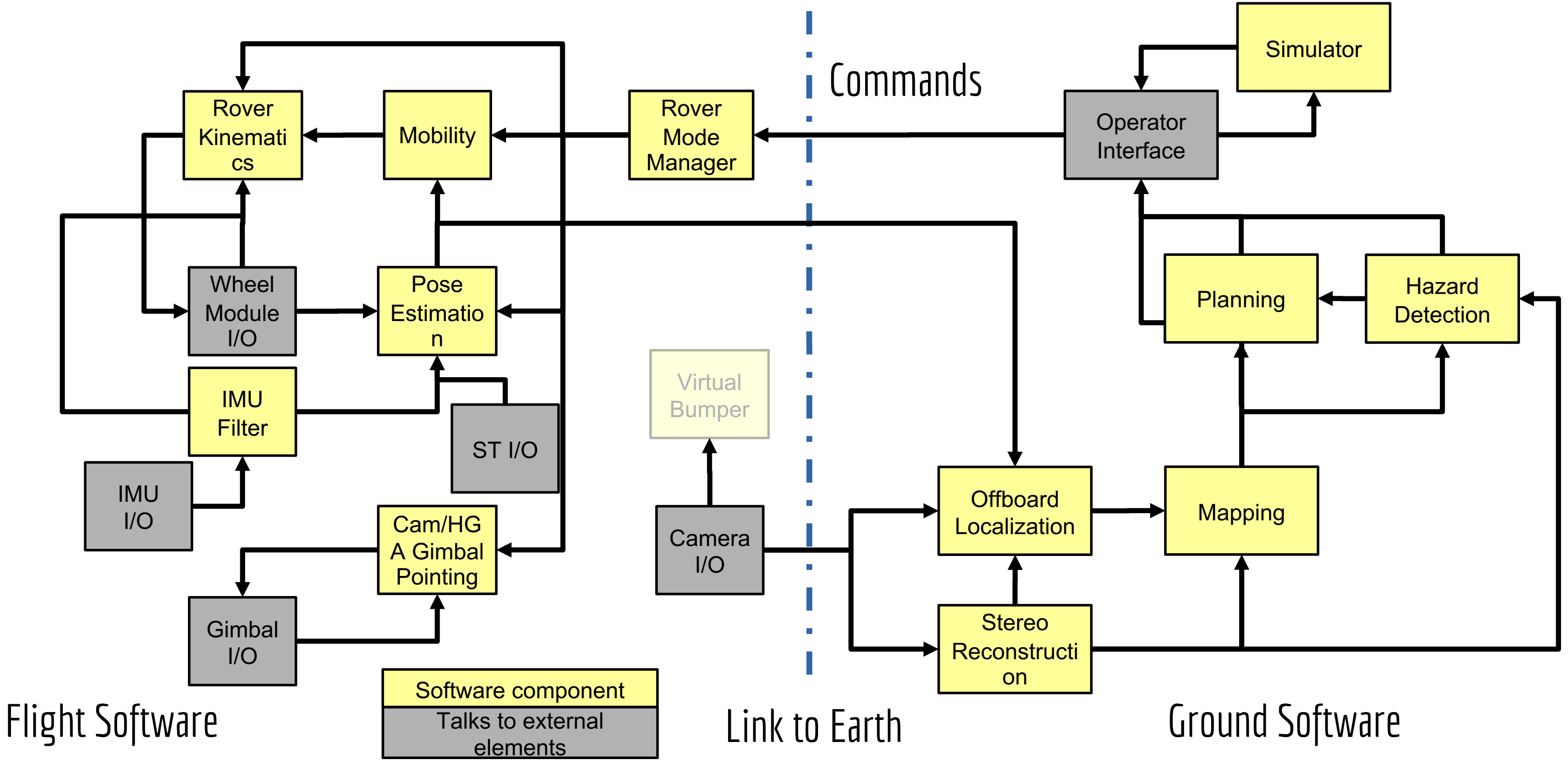
- Simulator Elements
  - Synthetic Lunar Terrain
  - Visual Simulation
  - Rover Mechanism & Software Simulation
  - Physical Simulation
  - Comm Simulation
  - Science Data Simulation
  - Mission Operations Software Tools

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



Lunar Operations Enable Distributed Autonomy

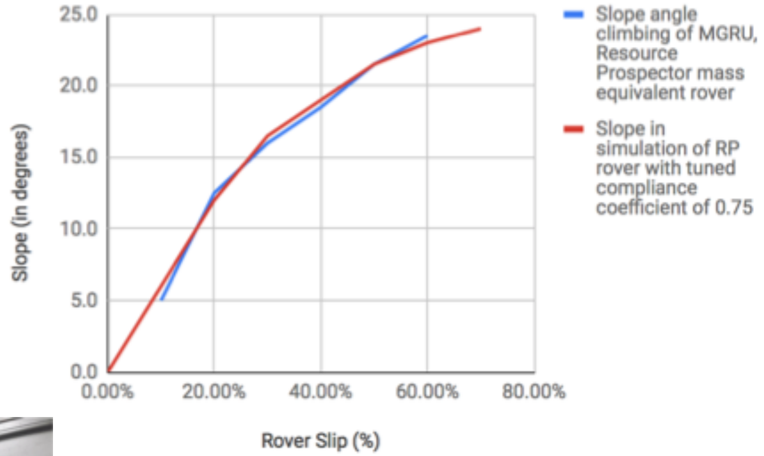


End-to-End Rover Driving Simulation

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

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

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

Comm Simulation

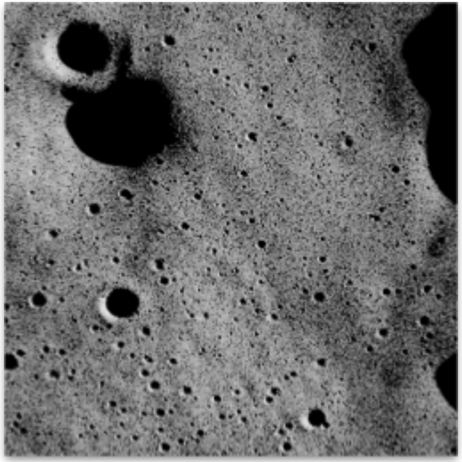
- Asymmetric, bidirectional time delay
  - Time-of-flight
  - Anticipated Deep Space Network (DSN) processing time
  - Telemetry size
- Variable jitter

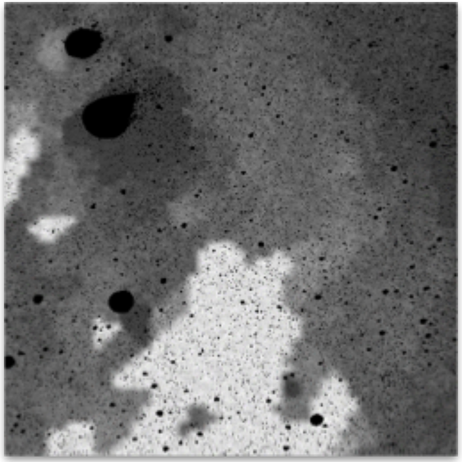
End-to-End Rover Driving Simulation

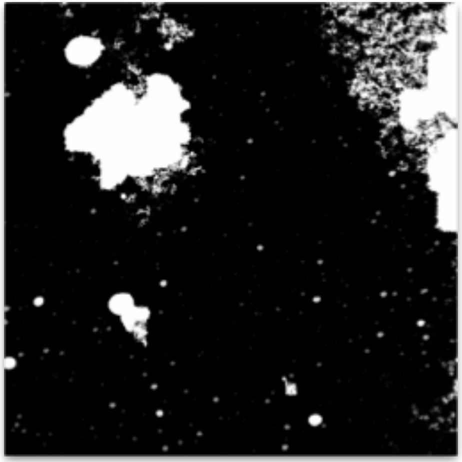
- Simulator Elements
  - Synthetic Lunar Terrain
  - Visual Simulation
  - Rover Mechanism & Software Simulation
  - Physical Simulation
  - Comm Simulation
  - Science Data Simulation
  - Mission Operations Software Tools

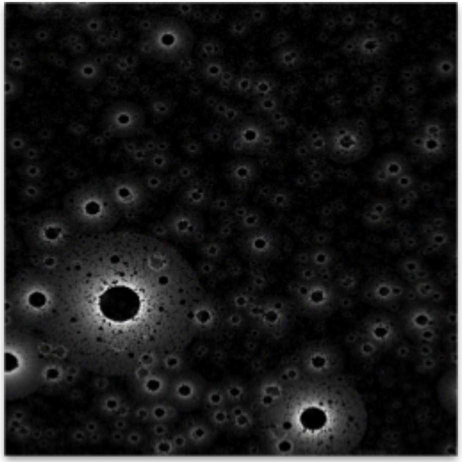
Science Data Simulation

- 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

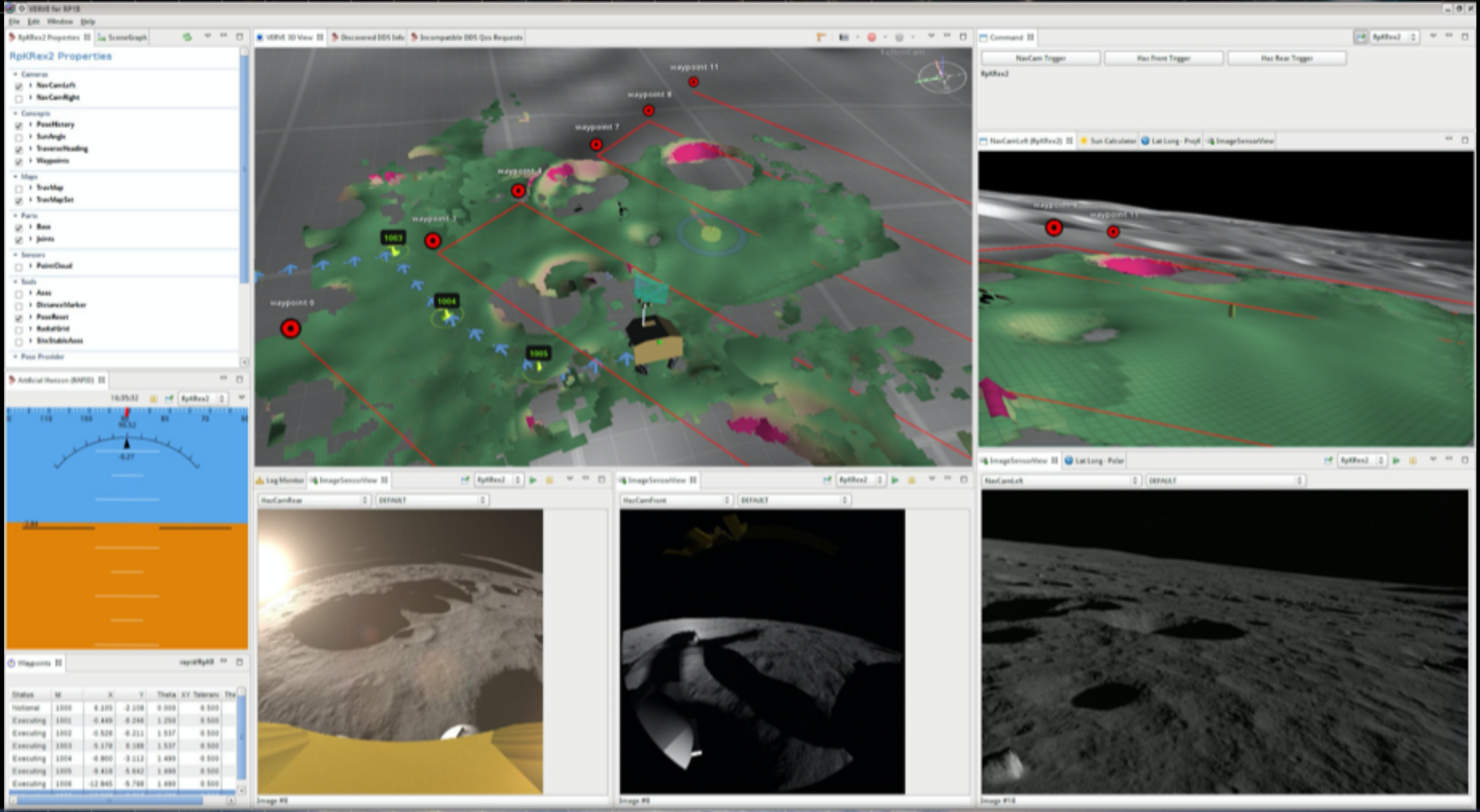
- Simulator Elements
  - Synthetic Lunar Terrain
  - Visual Simulation
  - Rover Mechanism & Software Simulation
  - Physical Simulation
  - Comm Simulation
  - Science Data Simulation
  - Mission Operations Software Tools

Mission Operations Software Tools

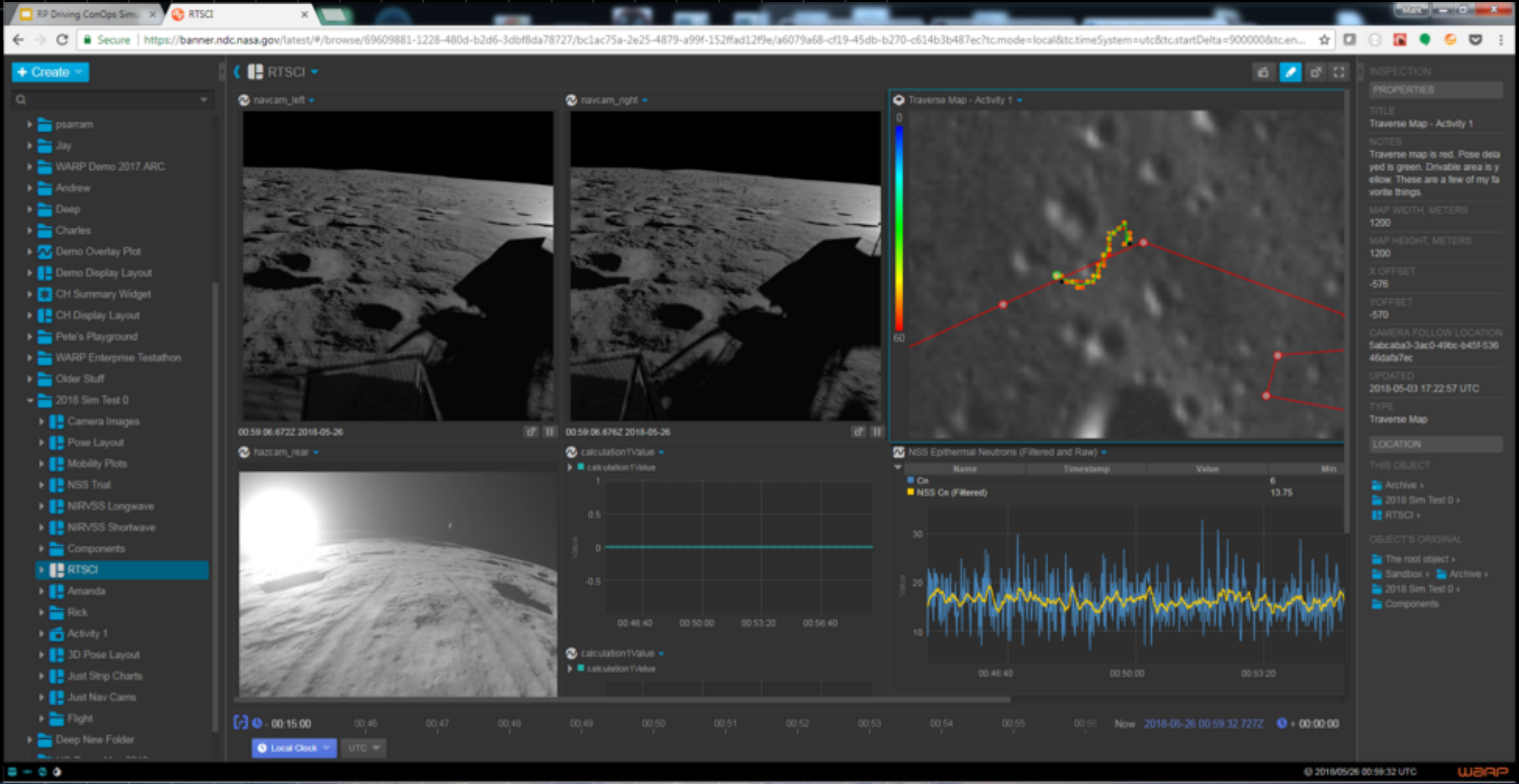
- Mix of development versions of Mission Operations software tools and stand-ins
- Configuration as flight-like as possible
- Simulation experiments inform software design

  - RDT (Rover Driving Tools)
    - Interactive 3D command interface
  - WARP (Ground Data System)
    - Web based telemetry visualization interface
  - Science Displays

Rover Driving Tools



WARP/OpenMCT



Science Displays

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