National Aeronautics and Space Administration

VIPER Lunar Surface Simulator

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RSIM Lead

Resource Prospector Driving Concept of Operations Simulator

Lunar Surface Simulation

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

Lunar Surface Simulation

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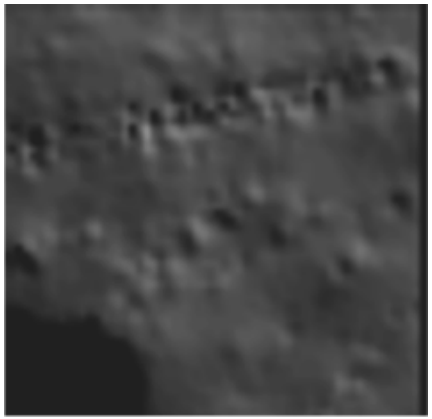
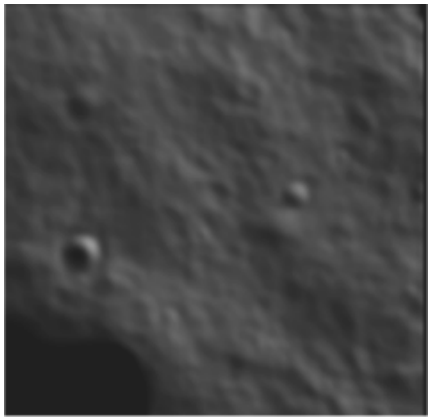
Synthetic Lunar Terrain

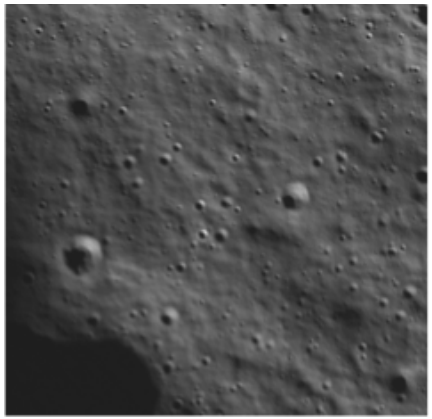
- Existing Lunar Digital Elevation Models (DEMs) are too coarse for driving simulation
  - Best-available DEMs are 1-10 meter resolution and typically noisy
  - Centimeter resolution required to reproduce **rover-scale hazards**



LOLA DEM (10m)



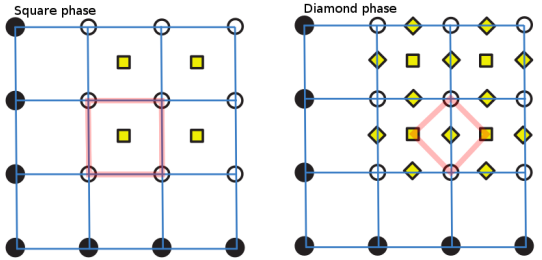
Stereo/SfS DEM (1m)

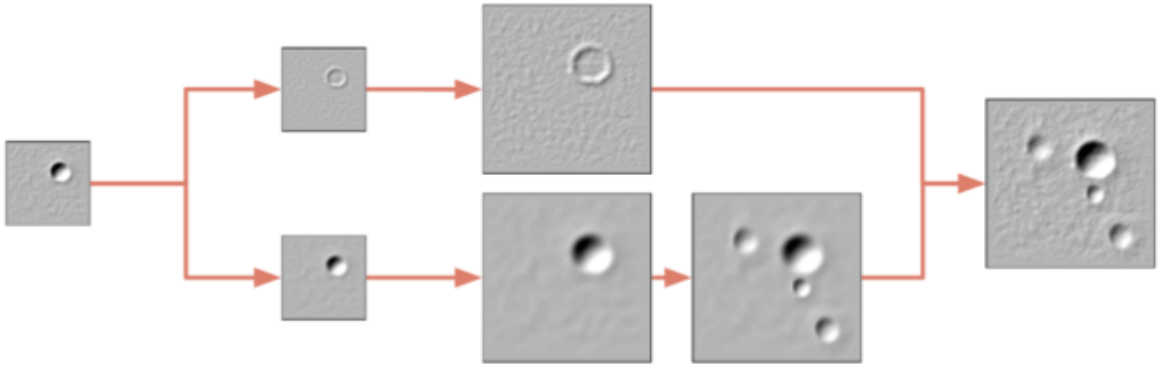


LRO NAC Image

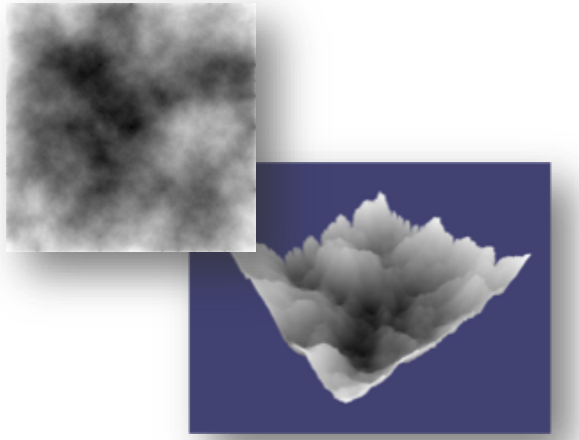
Synthetic Lunar Terrain

- Artificially enhanced Lunar DEMs
  - Fractal synthesis used to **increase DEM resolution**
  - **Insert craters and rocks** based on models from Environmental Spec



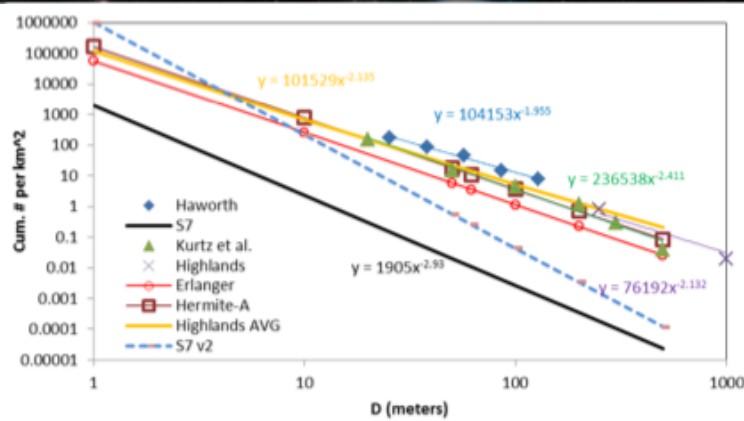


DEM upscaling process

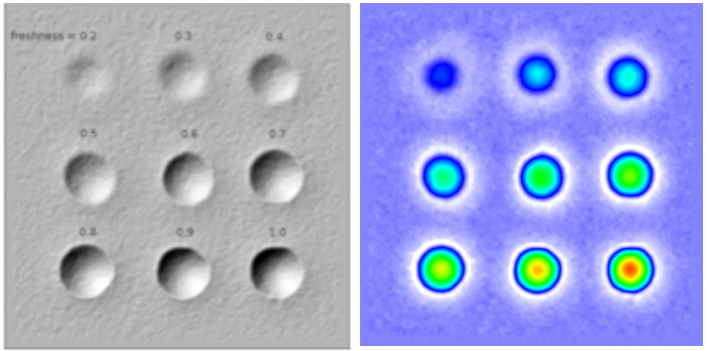


Synthetic Lunar Terrain - Craters

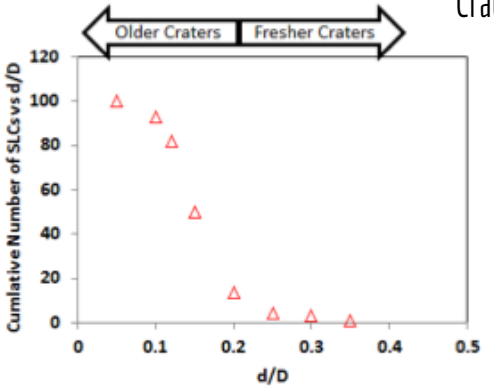
- Crater placement is random, spatially uniform
  - Sampled from size-frequency distribution
- Depth/Diameter distribution determines crater shape



Crater size-frequency distributions



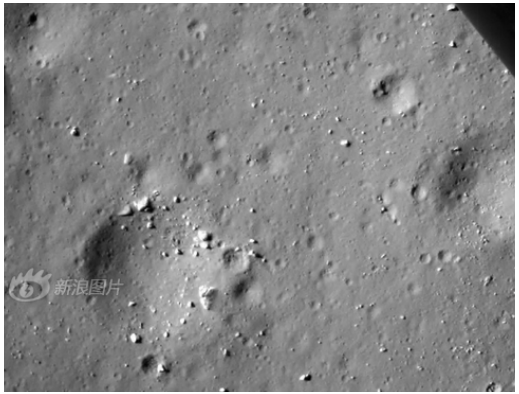
Crater shape



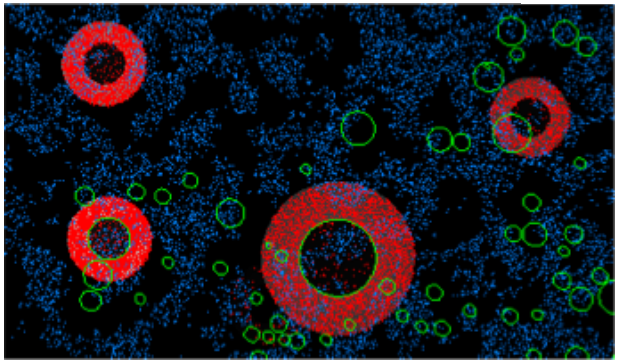
Depth/Diameter distribution

Synthetic Lunar Terrain - Rocks

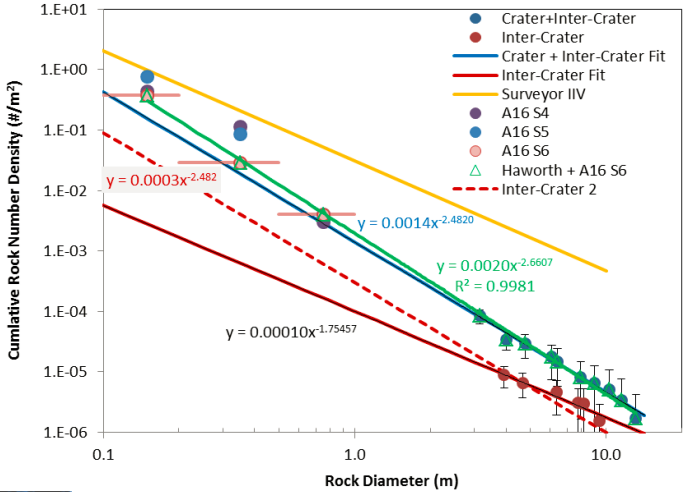
- Rock placement is *not* spatially uniform
  - Sampled from "around crater" and "between crater" size-frequency distributions
  - Fractal "clumping" parameter



Chang-e descent image



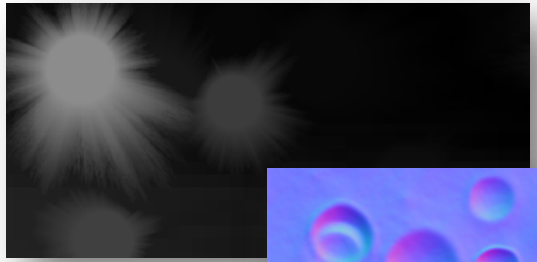
Rock Placement
Red: intra-crater distribution
Blue: inter-crater distribution
Green: crater rims



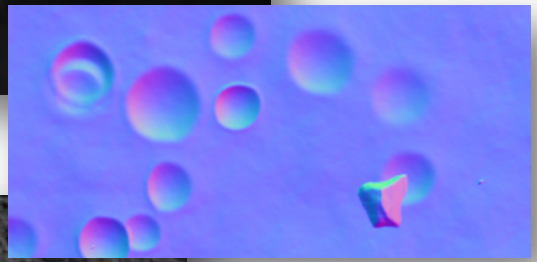
Rock size-frequency distributions

Synthetic Lunar Terrain

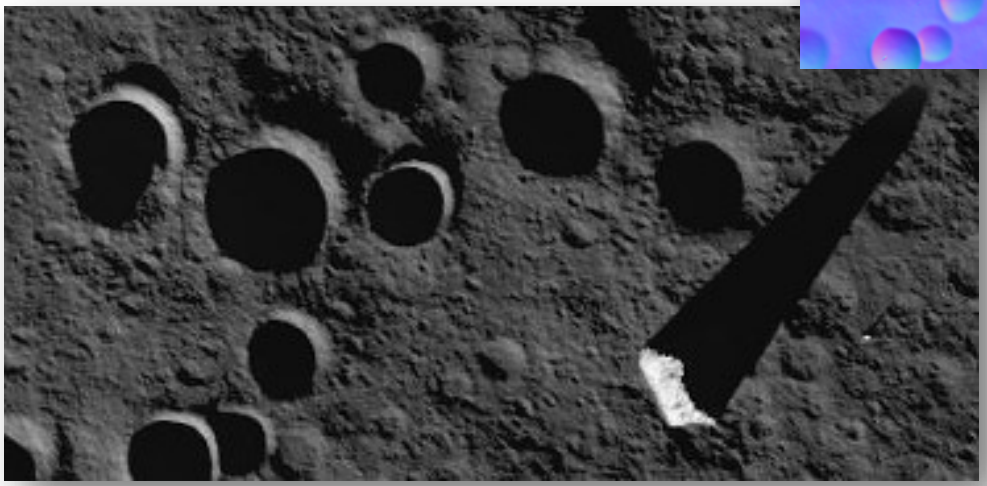
- DEMs can be generated at arbitrary resolution
  - 4 cm/pixel used for simulation
- Additional outputs
  - Albedo map
  - Normal map
  - Rock mask



Albedo



Normals

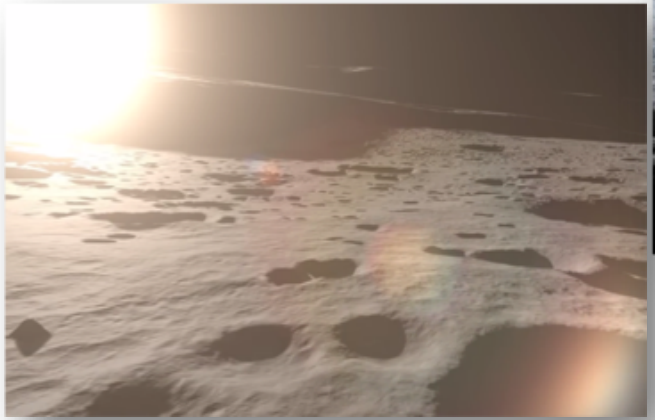


Lunar Surface Simulation

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

Visual Simulation

- **High fidelity visual simulation** critical to **human perception** as well as **machine perception**
  - Rover driver situational awareness
  - RGSW test data



Lunar scene from simulator

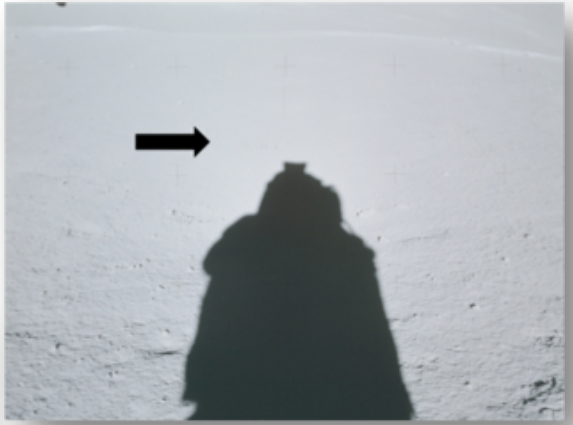
Lunar scene from Apollo 12 mission

Visual Simulation

- **Gazebo Simulation Platform**
- Collaborated with Open Robotics to enhance Gazebo visualization capabilities, including
  - Support for custom terrain appearance shaders
  - Support for high resolution terrains
  - Improved real time shadows
  - Rover wheel tracks in regolith
  - Vehicle mounted lighting with customizable beam pattern
  - Lensflares
  - Enhanced camera noise model
  - High dynamic range image rendering

Visual Simulation – Regolith Reflectance

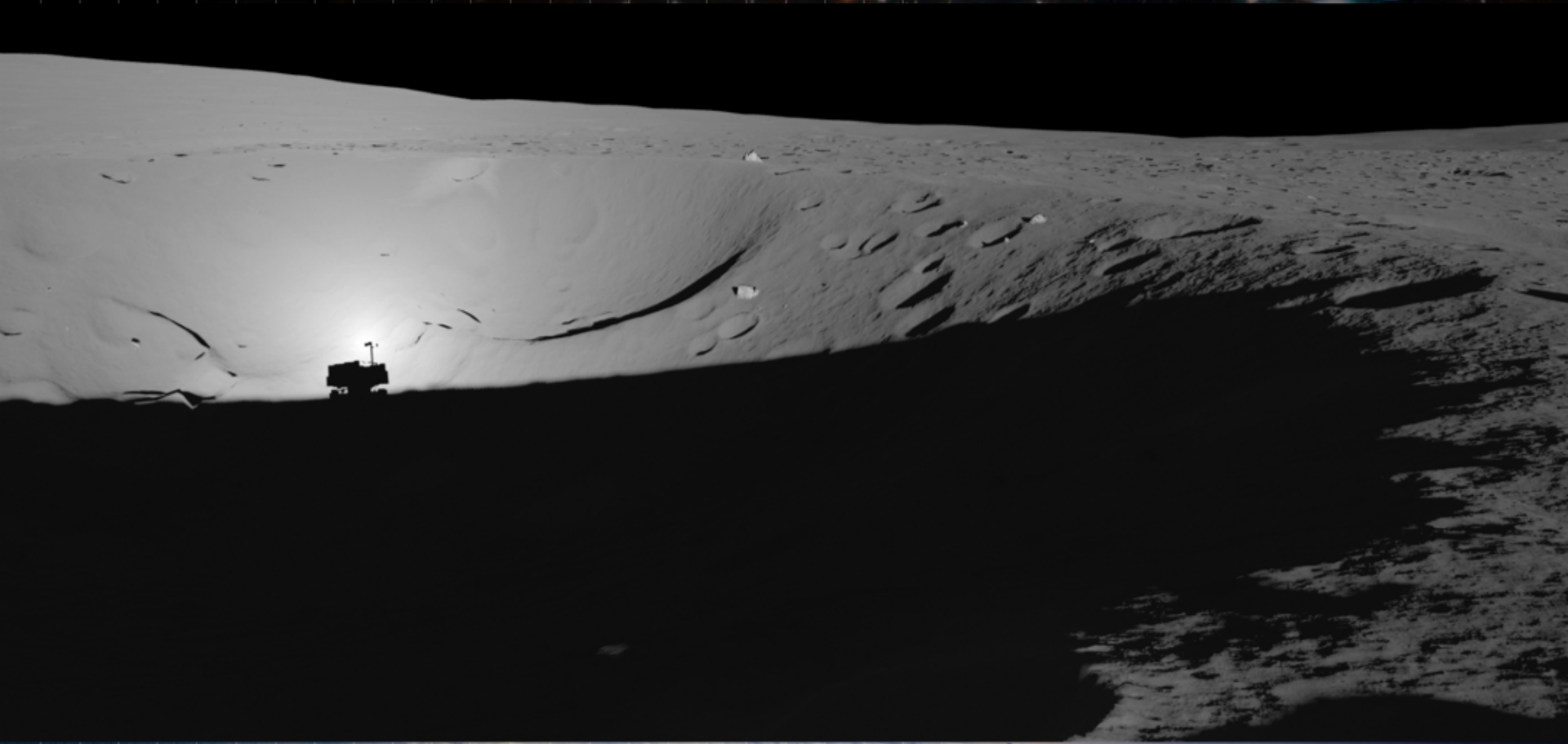
- Lunar regolith exhibits moderately strong **opposition effect**
- Occurs when view angle coincides with illumination angle
- Terrain shader implements Hapke Bidirectional Reflectance Distribution Function (BRDF)



Opposition Effect

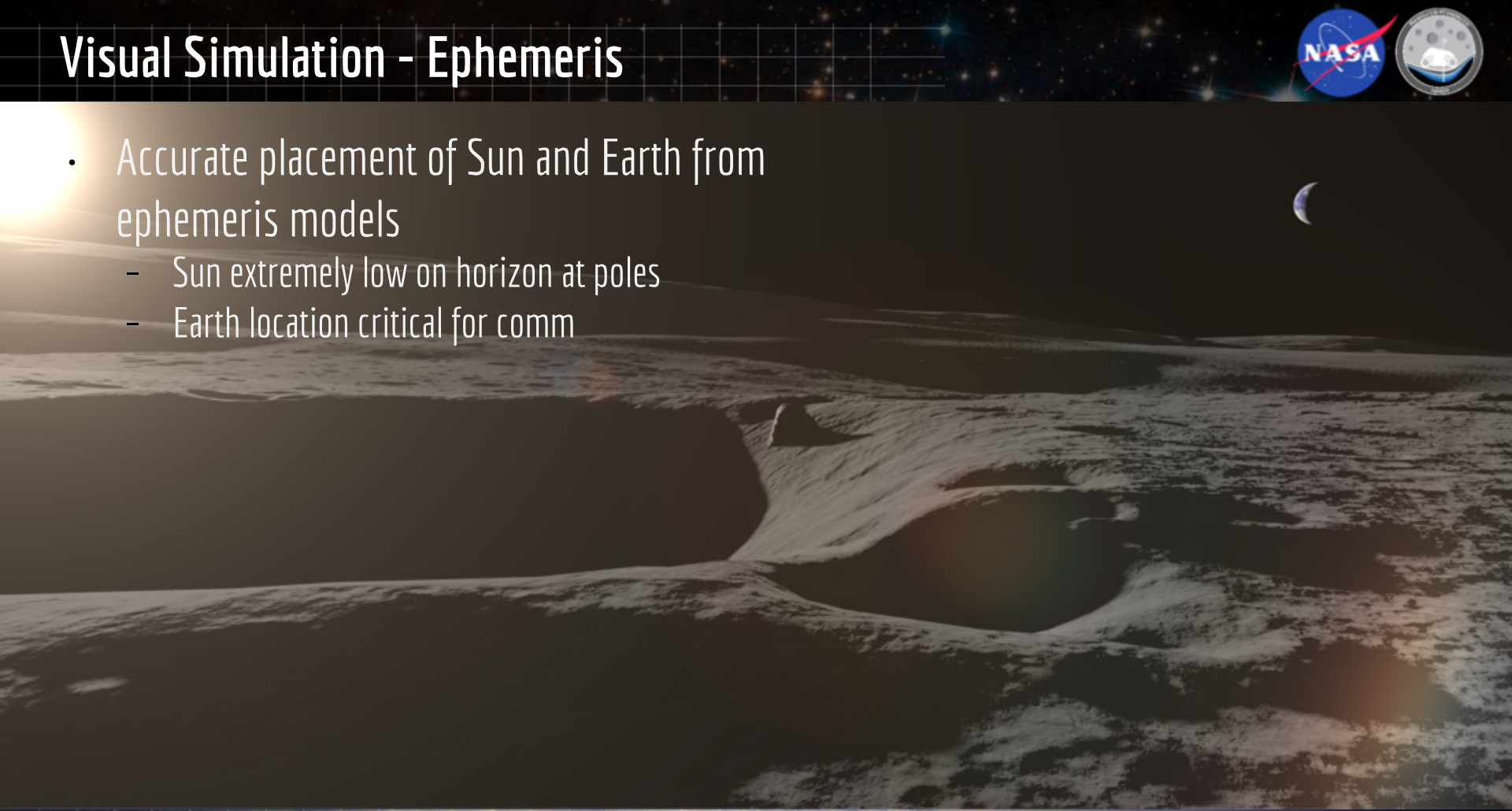
Visual Simulation – Regolith Reflectance

Visual Simulation – Regolith Reflectance



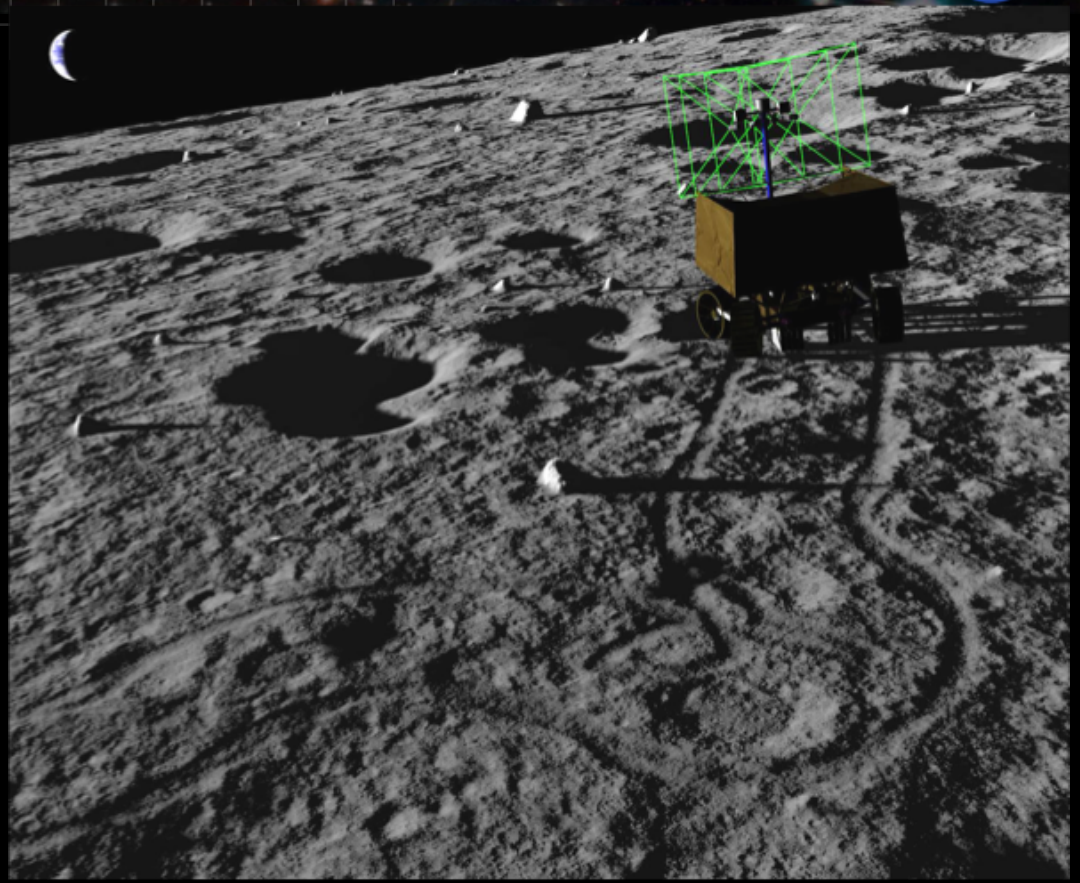
Visual Simulation - Ephemeris

- Accurate placement of Sun and Earth from ephemeris models
  - Sun extremely low on horizon at poles
  - Earth location critical for comm



Visual Simulation - wheel tracks

- Wheel Tracks drawn into terrain
  - Essential visual cue for drivers

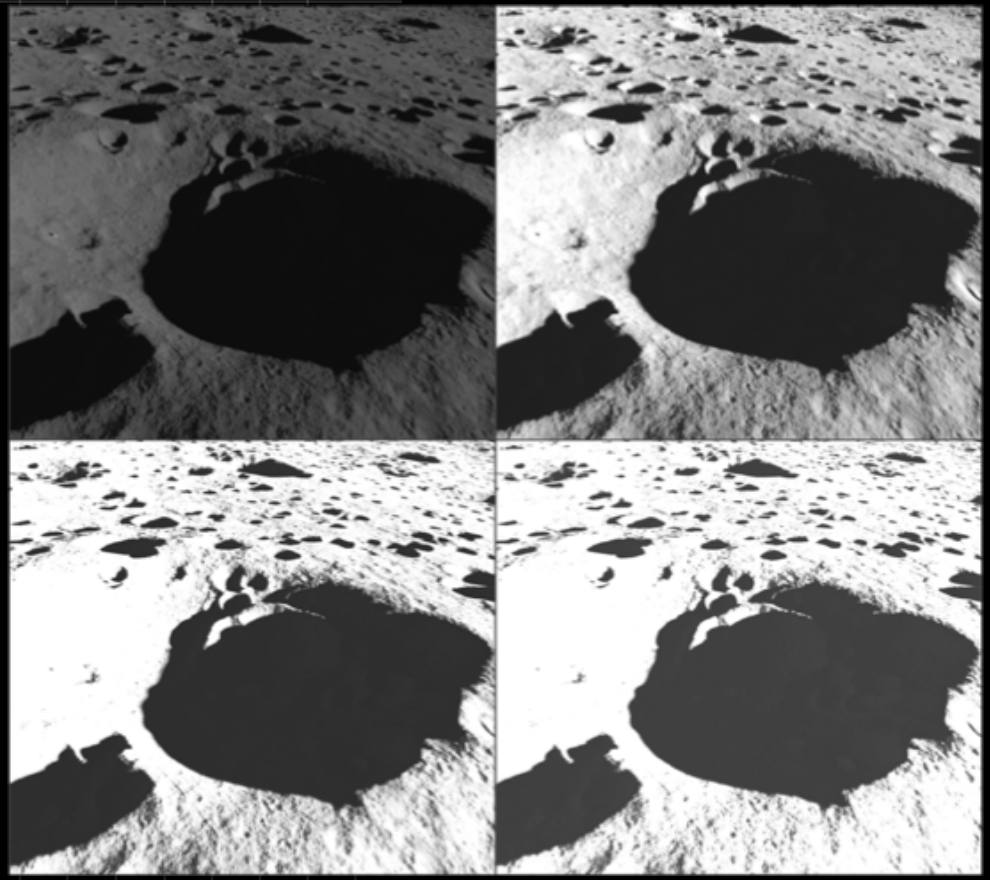


Visual Simulation – vehicle lighting

Vehicle mounted lighting with customizable beam patterns

Visual Simulation - high dynamic range

- High dynamic range rendering
  - Mission cameras expected to be 12 bit/pixel minimum
- Approximation of global illumination



End-to-End Rover Driving Simulation

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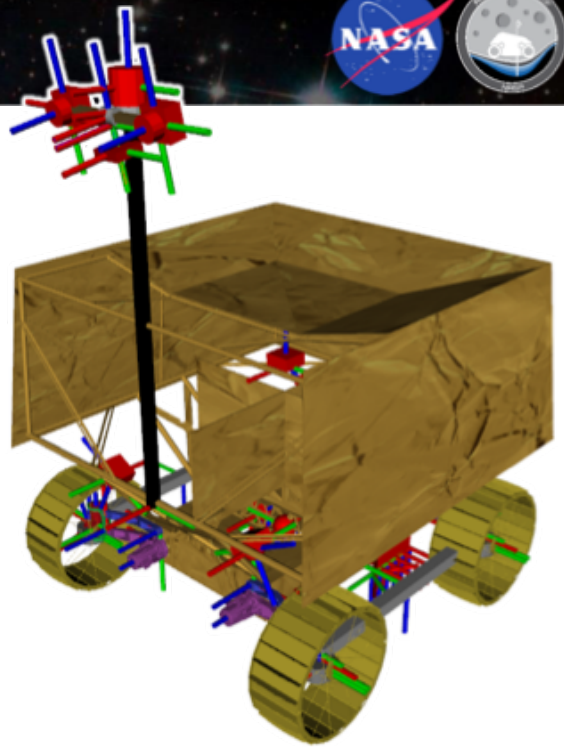
Simulated Mechanism & Software

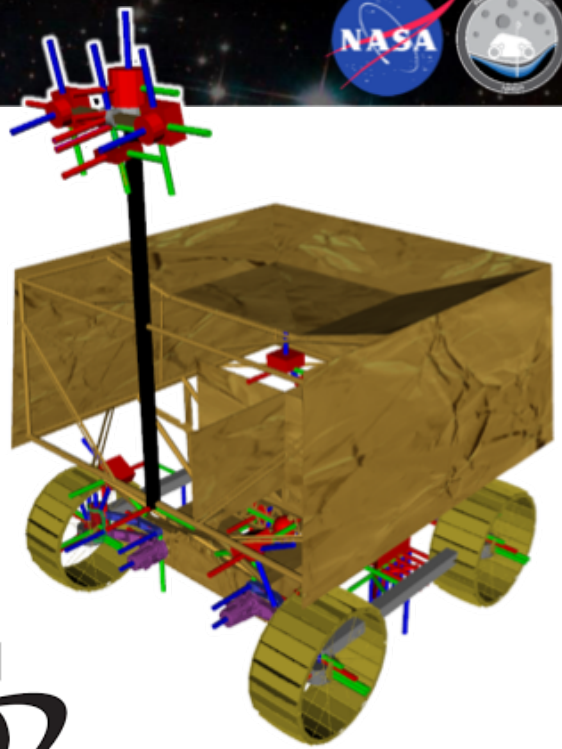
- Rover Mechanism
  - 4 wheel explicit steer platform simulated in Gazebo,
  - Scaled vehicle to RP rover size, added RP chassis and mast

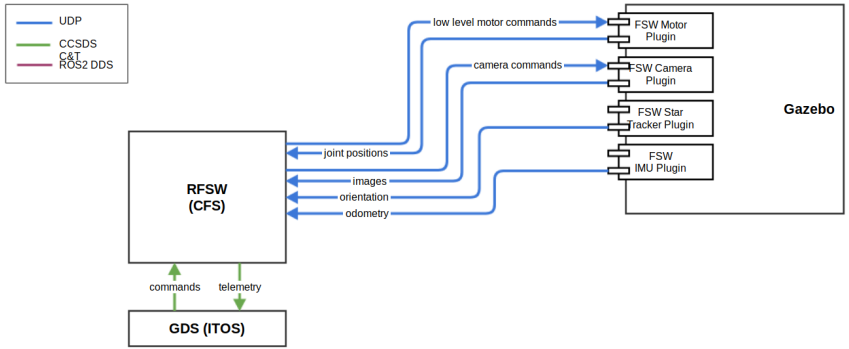
- Rover Software
  - Emulating Flight and Ground Software with ROS (Robot Operating System)
  - ROS provided stand-ins for flight software functionality



Flight-Forward Mechanism & Software

- Rover FSW communicates directly with Gazebo
- FSW CCSDS telemetry bridged to Rover GSW ROS2

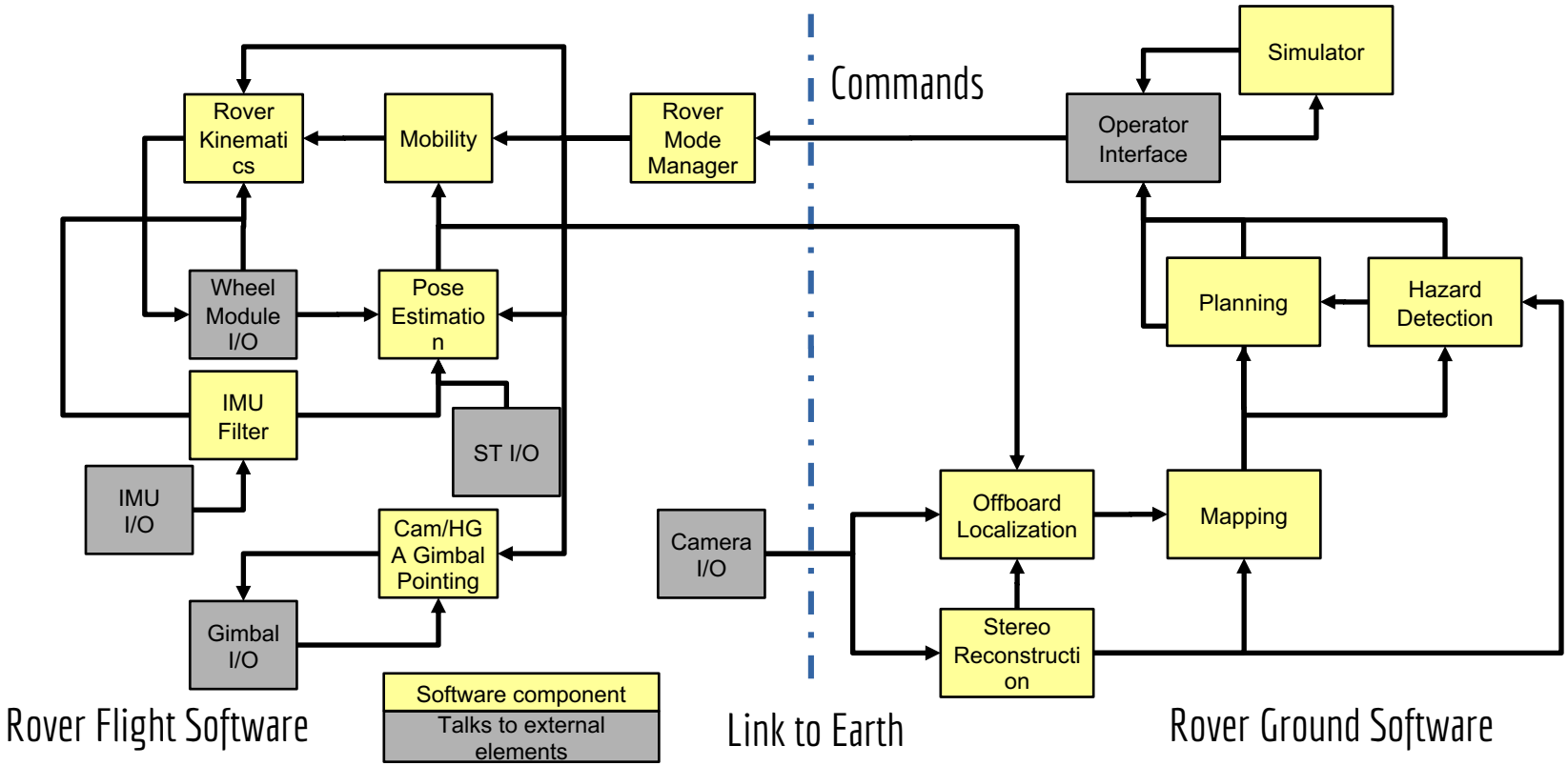




NASA cFS core Flight System

ROS 2

Distributed Rover Software Architecture



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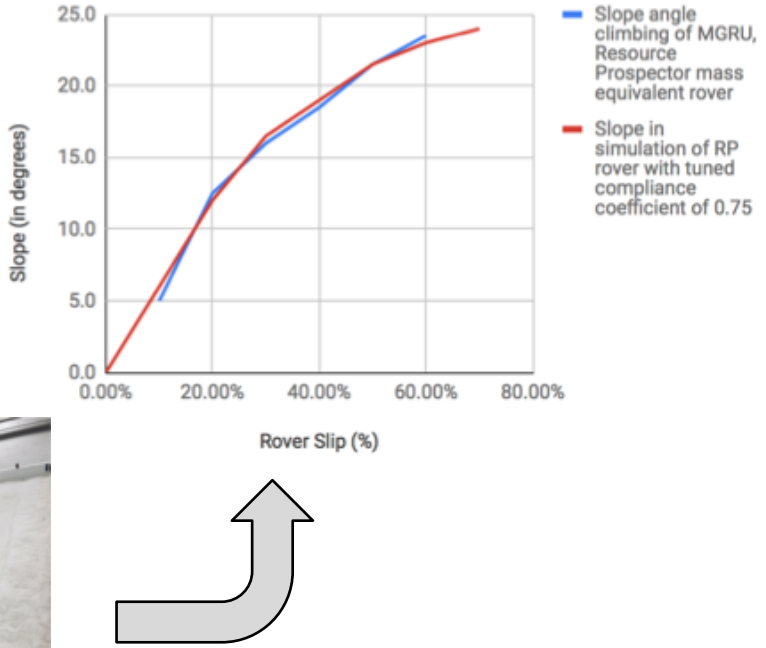
Physical Simulation

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



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Comm Simulation

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

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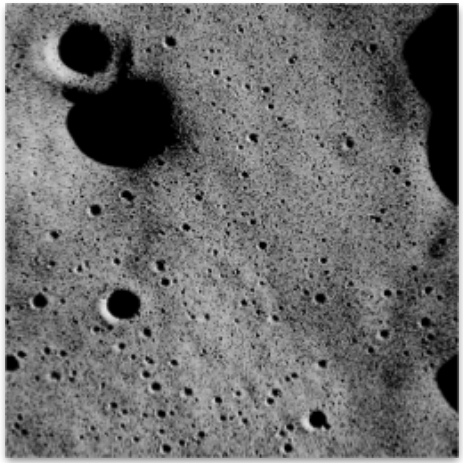
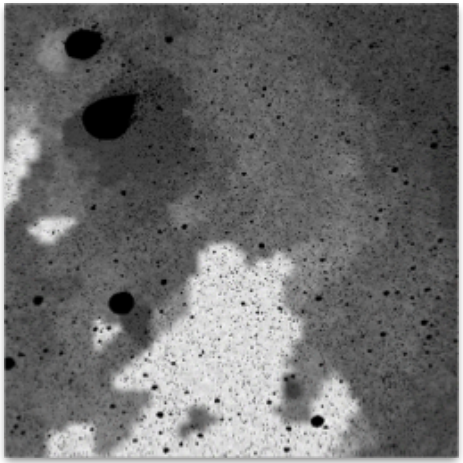
Science Data Simulation

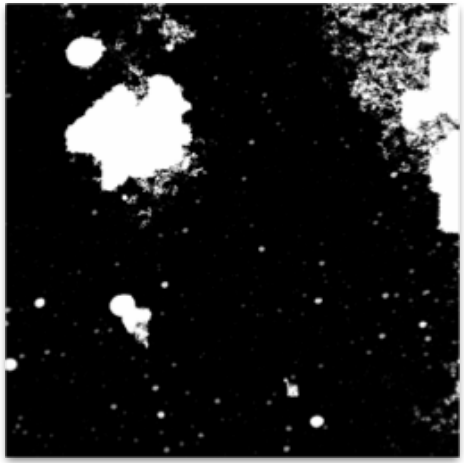
- Synthetic "ground truth" maps created for science data
- Real time instrument readings based on rover location



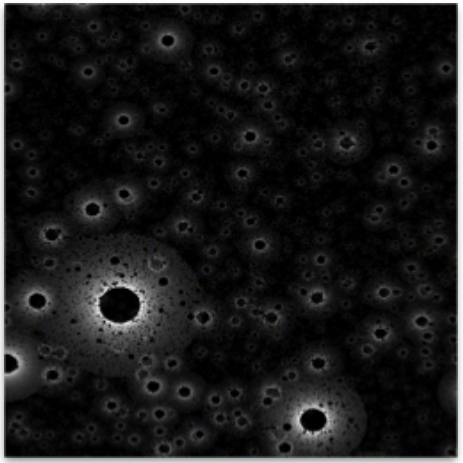
Surface Temperature



Depth of Dry Layer



Surface Frost



Subsurface Ice Concentration

Thank you