National Aeronautics and Space Administration



Synthetic Lunar Terrain for Driving Simulation

Mark Allan, Uland Wong,
Terry Welsh, Michael Furlong, Larry Edwards

2017

Driving Simulation Environment

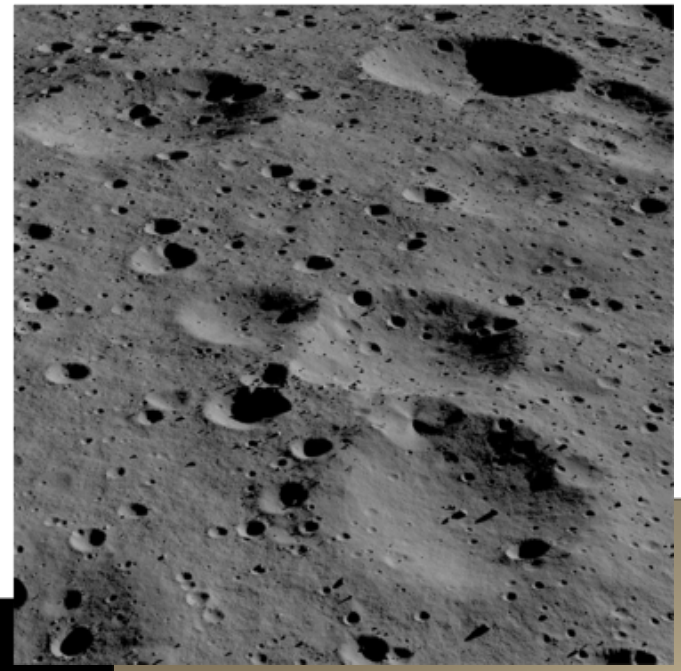
Requires representative terrain with expected density of positive and negative obstacles

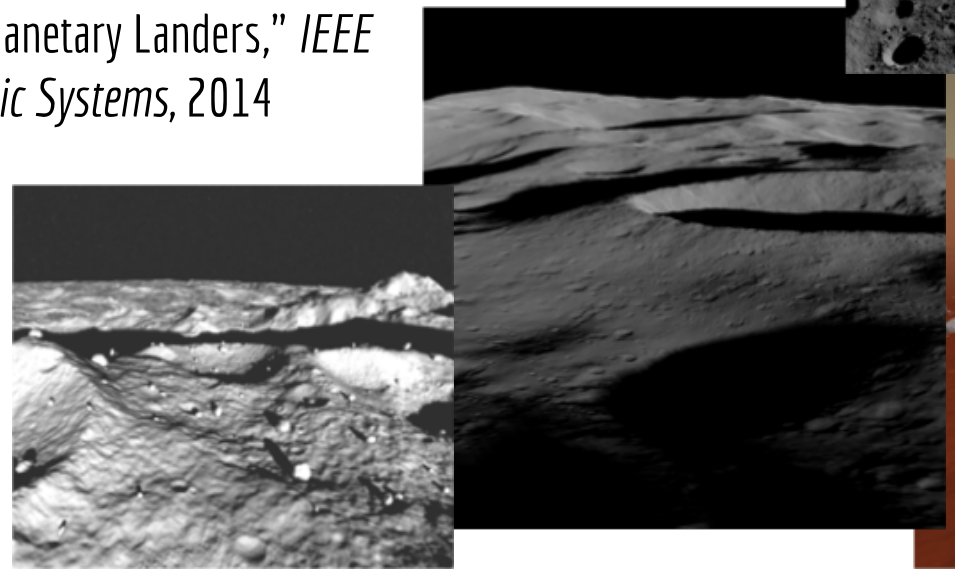
- Resolution of best available lunar DEMs is 1m
  - …but positive obstacles ›10cm are considered hazards…
- Need to generate terrain at appropriate resolution
- Build or buy?

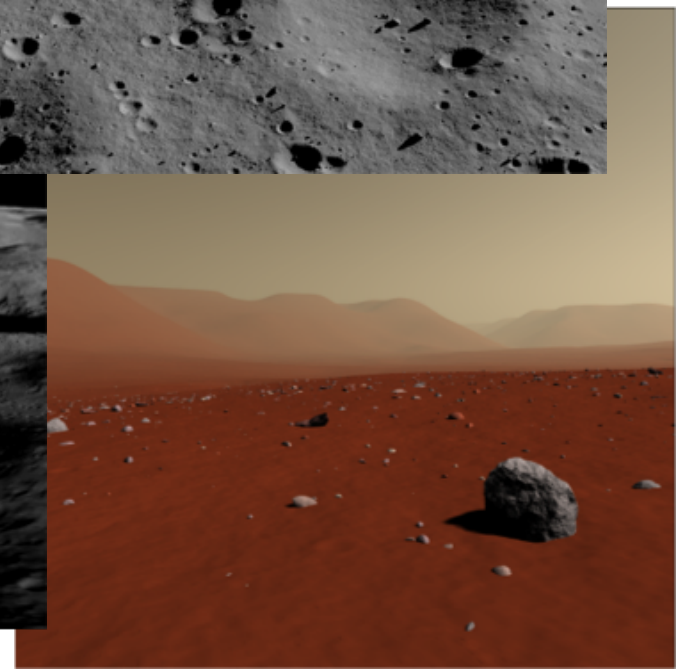
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PANGU

- PANGU (Planet and Asteroid Natural Scene Generation Utility)
  - Developed at University of Dundee, funded by ESA
  - Commercialized by Star-Dundee
- Unfortunately, PANGU produces *images* not terrains
  - Does not directly support generating DEMs
  - Closed source, so no tweaking possible
- Developers authored:
  - Martin, S. Parkes and M. Dunstan, "Modeling Cratered Surfaces with Real and Synthetic Terrain for Testing Planetary Landers," *IEEE Transactions on Aerospace and Electronic Systems*, 2014







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Lunar Terrain Synthesis

1. Expand existing DEM using fractal synthesis

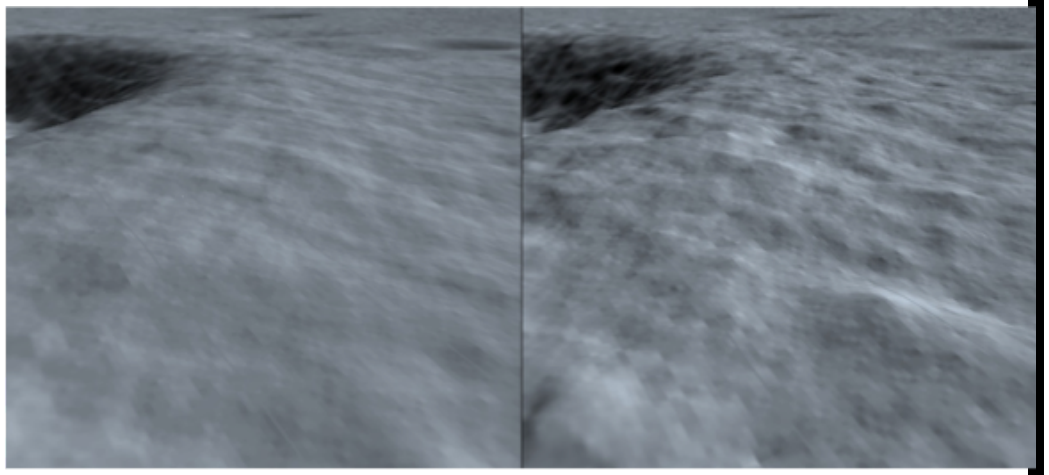
1. Insert craters

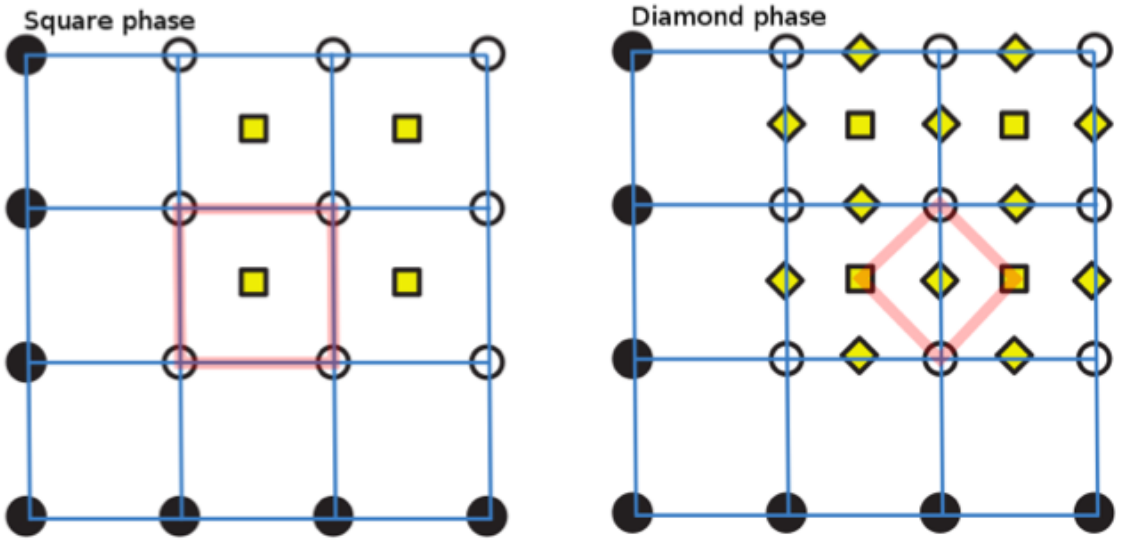
1. Insert rocks

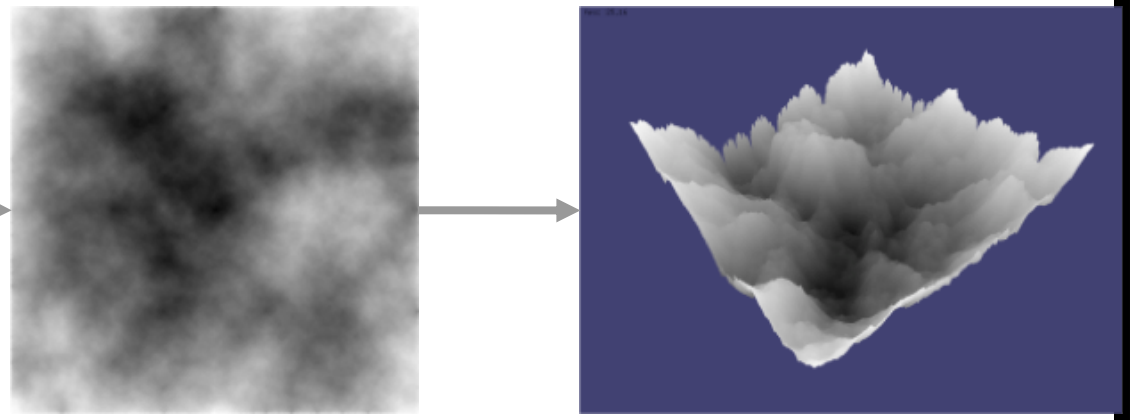
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Fractal Expansion

- Fractal expansion of DEMs using modified Diamond-Square algorithm
  - AKA Plasma Fractal, Random Midpoint Displacement
- Iteratively interpolate intermediate values and add a little noise
- Fractal dimension controls roughness of added terrain





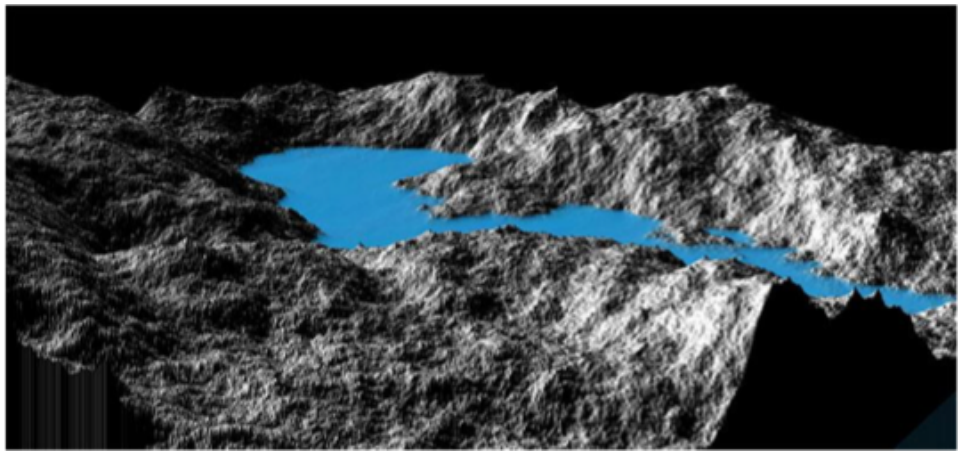


https://danielbeard.wordpress.com/2010/08/07/terrain-generation-and-smoothing/

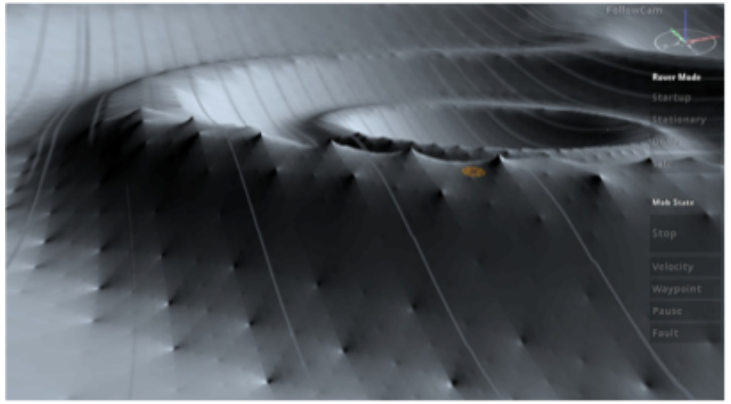
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Fractal Expansion - Diamond-Square Algorithm

- **Pros**
  - Simple
  - **Maintains original DEM postings**
    - Intermediate pixels interpolated with a small amount of noise added
- **Cons**
  - Resulting terrains not very "lunar-like"
    - ...but we only need a little bit filled in
    - DEMs provide overall shape of terrain, fractal noise fills in details
  - **Creasing artifacts** when constrained
    - Especially bad on smooth features like craters
    - PANGU paper briefly mentions the artifacts but did not offer a solution...





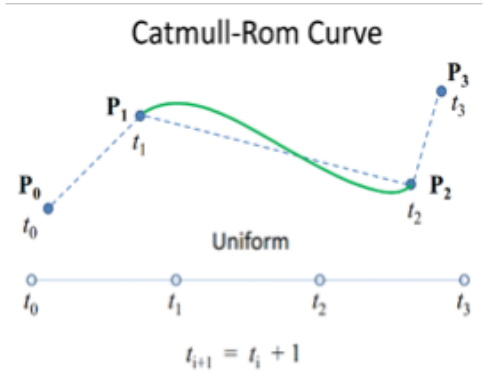


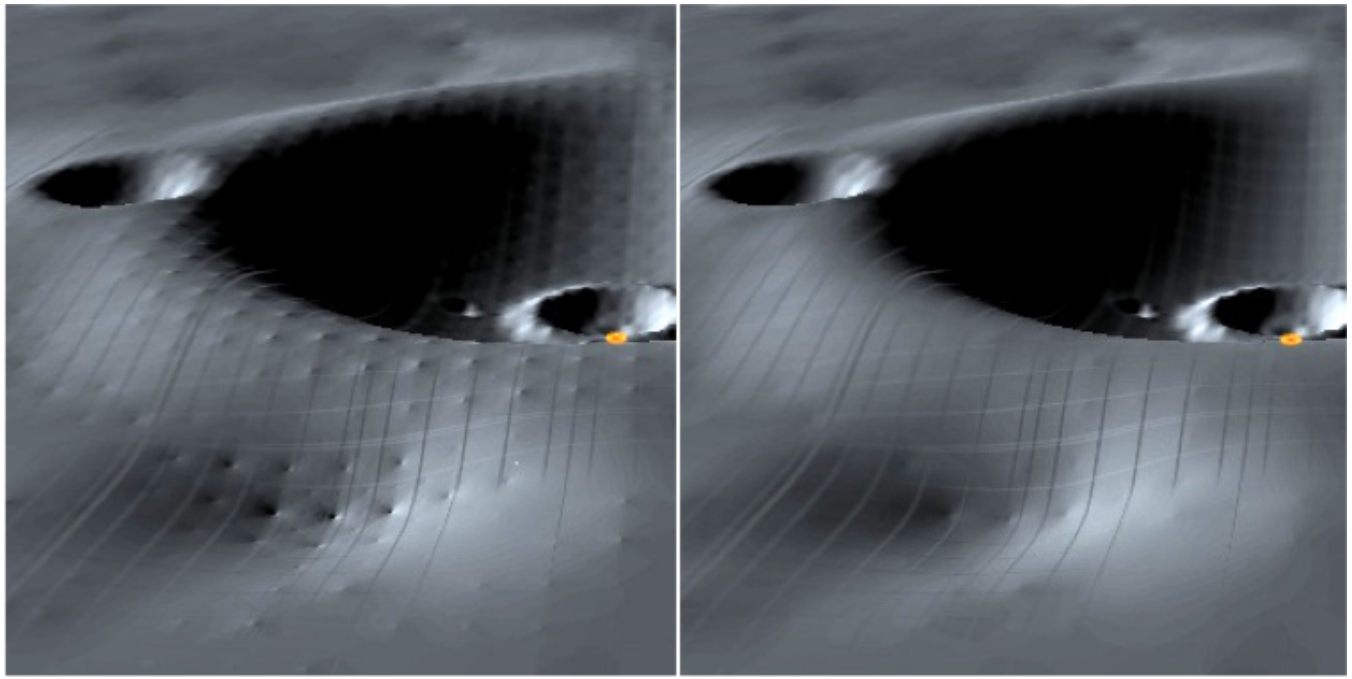
Miller, Gavin S.P., "The definition and rendering of terrain maps" *ACM SIGGRAPH Computer Graphics 1986*

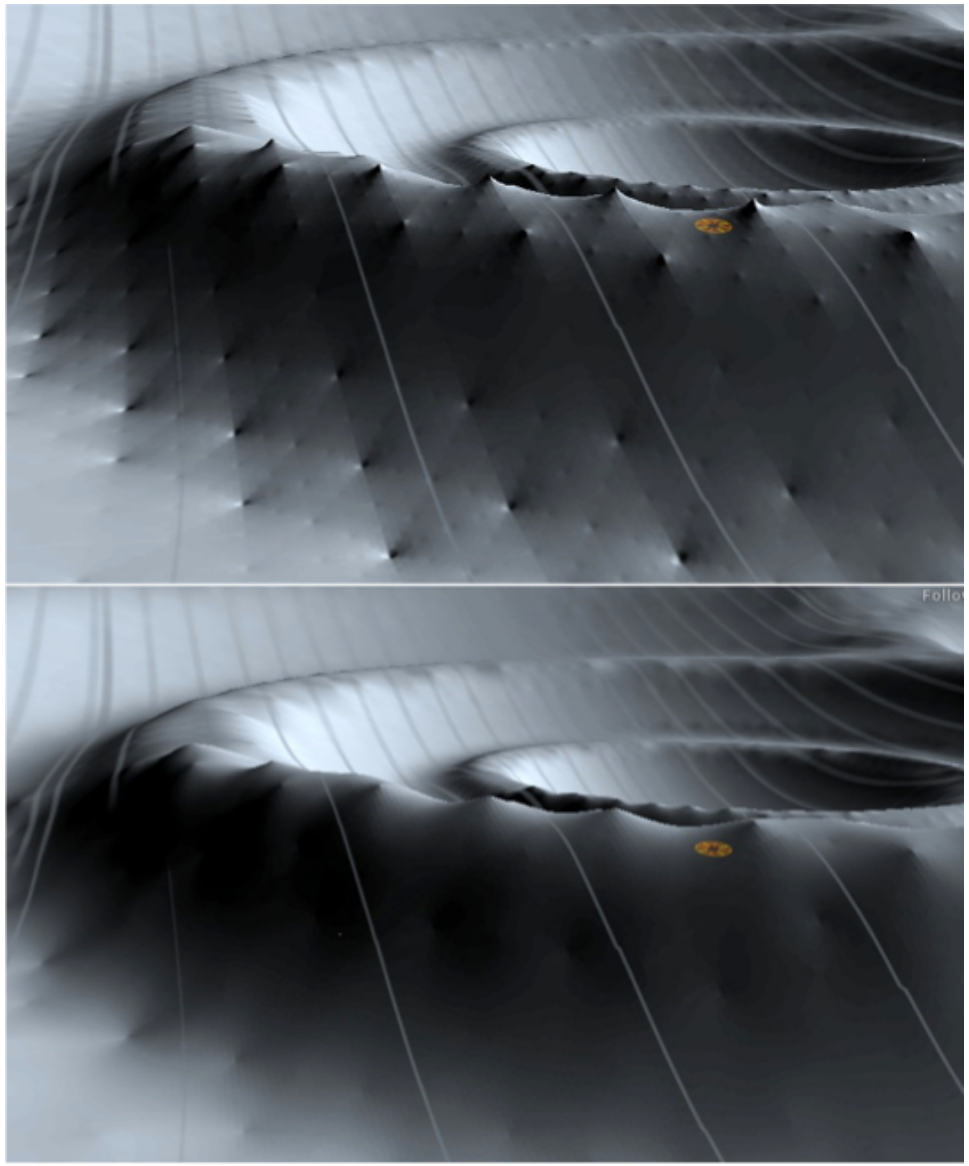
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Fractal Expansion - Artifact Mitigation

- Improve Interpolation:
  - Replace linear interpolation with Catmull-Rom splines in Diamond-Square algorithm
    - Decreases severity of artifacts but does not eliminate them







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Fractal Expansion - Artifact Mitigation

- Avoid fractal expansion on low-frequency features by decomposing terrain into high- and low-frequency DEMs
  - Gaussian blur original DEM [-->low-frequency DEM]
  - Subtract low-frequency DEM from original DEM [-->high-frequency DEM]
  - Fractal expansion in high-frequency DEM
  - Scale low-frequency DEM by 2x (bicubic)
  - Insert craters into low-frequency DEM
  - Add high-frequency and low-frequency DEMs to get final

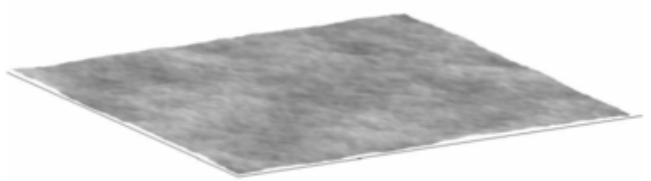
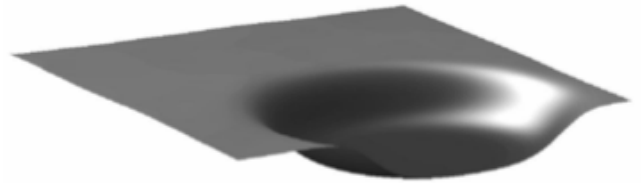
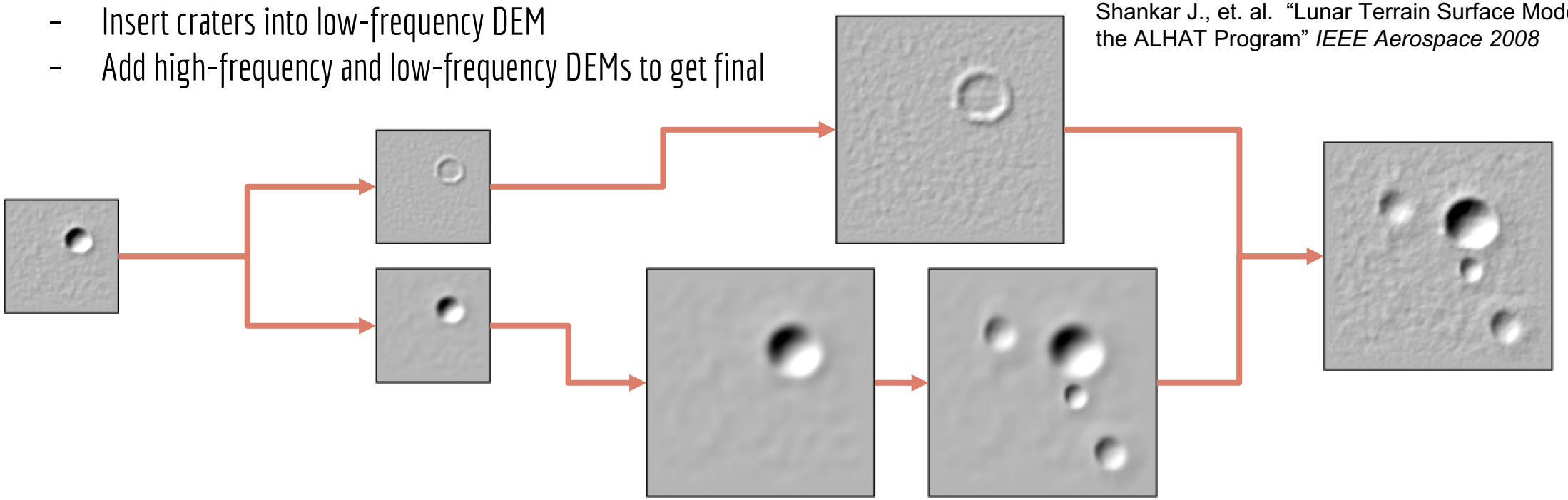


Figure 2. DEM-Maker—Fractal terrain created from low-resolution DEM



Shankar J., et. al. "Lunar Terrain Surface Modeling for the ALHAT Program" *IEEE Aerospace 2008*



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Crater Insertion

- We attempt to generate craters with the right*
  - Size-frequency distribution
  - Shape profile
  - Age distribution
    - Bulk slope (Depth to Diameter ratio - d/D)

* "right" as per RP Environmental Spec

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RP Environmental Specification

Purpose

- Defines the environmental characteristics that will be encountered during mission life cycle
- Used to develop engineering requirements to successfully survive and operate in the appropriate environments
- Definitive reference for the mission environment

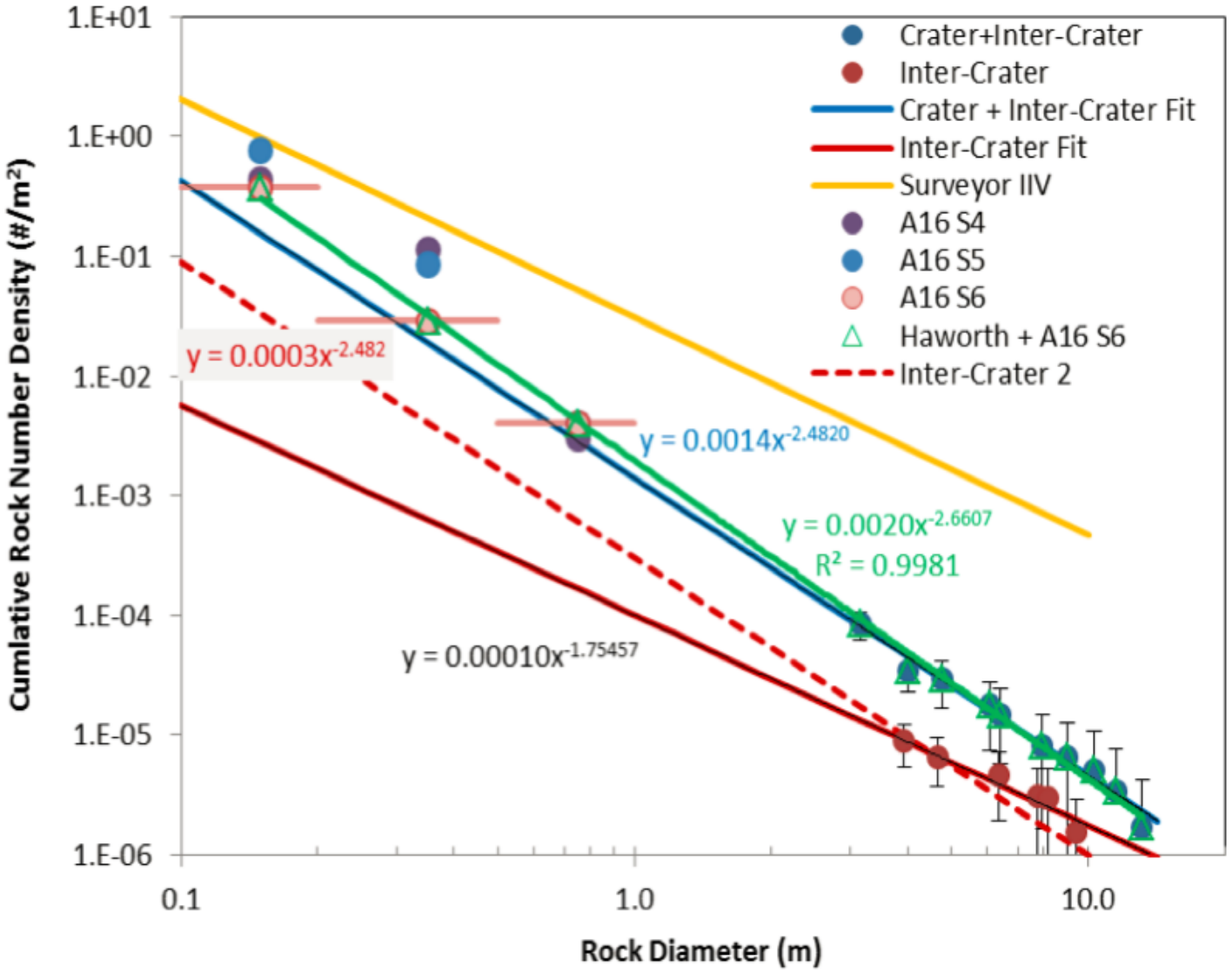
Caveats

- The lunar poles are not well understood environments
- Due to disparate sources of data and uncertainty, parameters sometimes contradict
- (Extreme) extrapolation is used to get parameters at scales we are interested in

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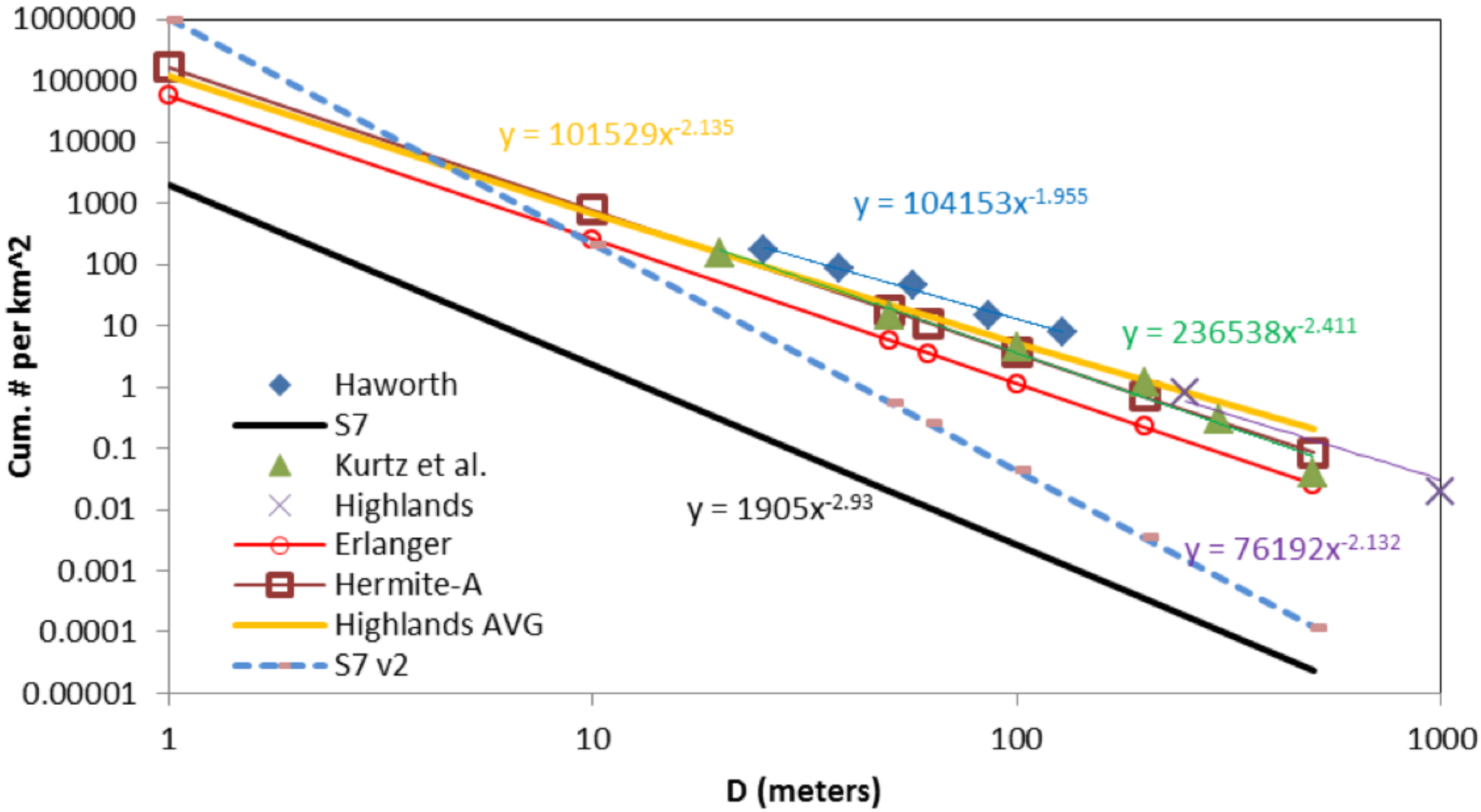
Environmental Spec Size-Frequency Distributions

- Power Law Parameterization [Shoemaker, et al. 1968] is used for size-frequency distribution
  - $Y = \xi \cdot X^{\lambda}$
- In log-log space, this is a linear fit with slope (ξ) and y-intercept (λ)
- X axis is the observed object diameter
- Y axis is the observed cumulative density per m^2



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Crater Size-Frequency Distribution

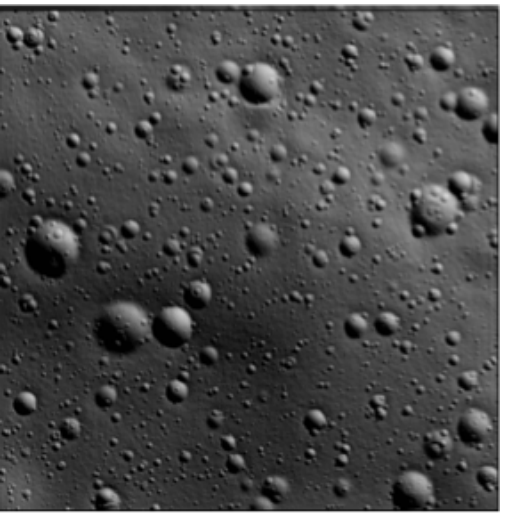


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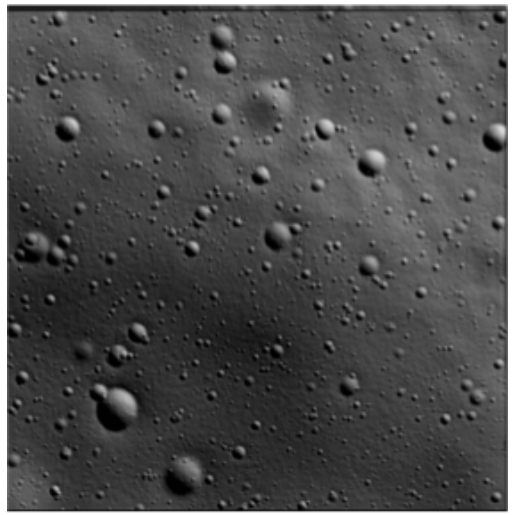
Crater Size-Frequency Distribution

- Small changes in power law parameters greatly affect the appearance of the scene:

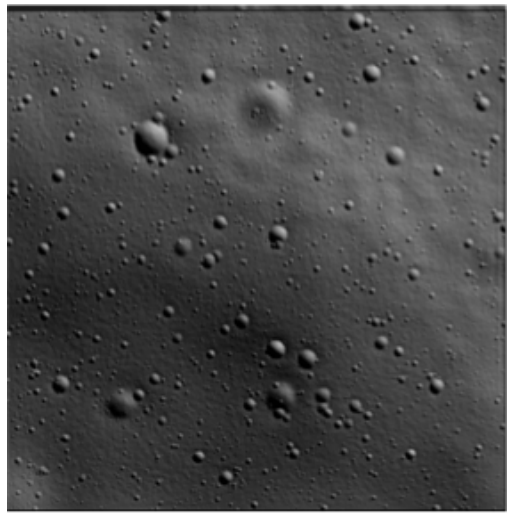
λ=2.1



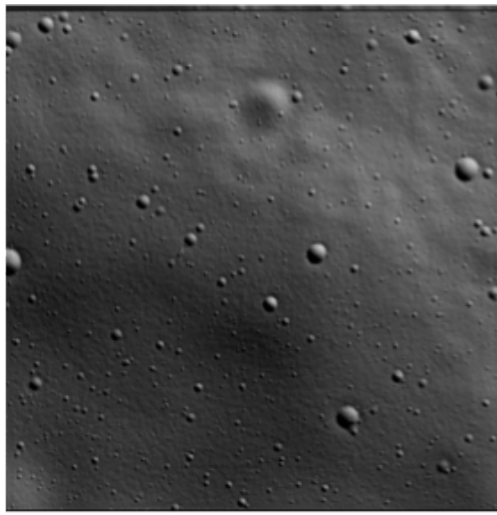
λ=2.4



λ=2.6



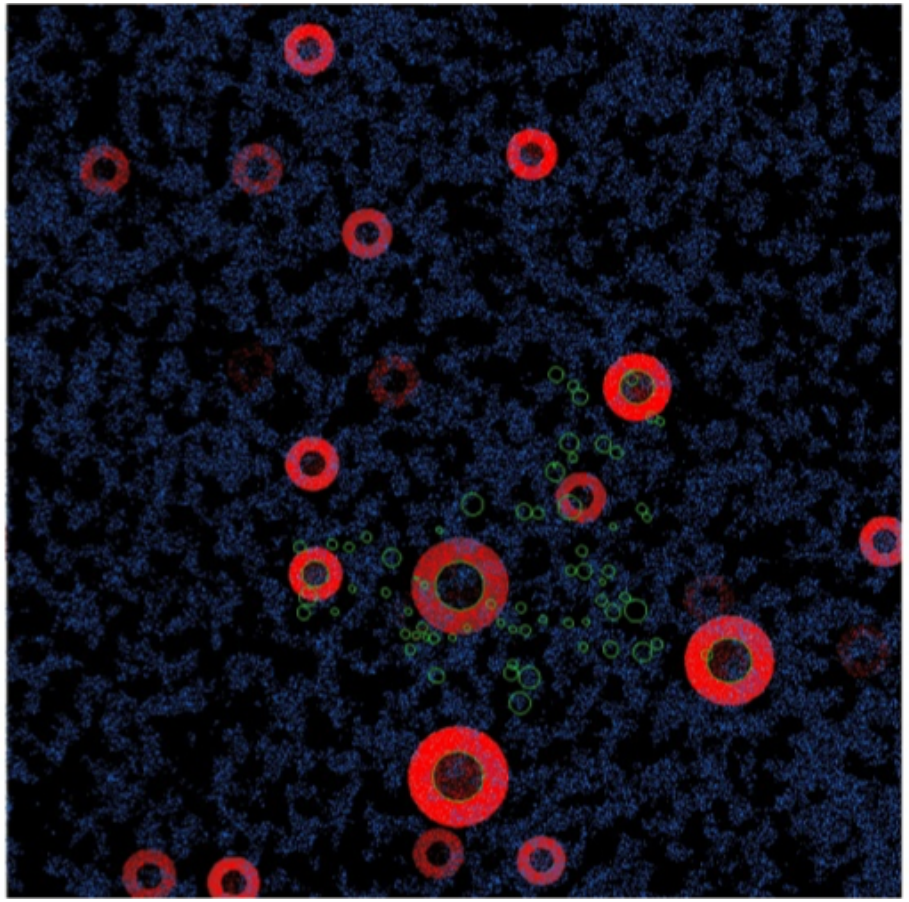
λ=2.9



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Crater Placement

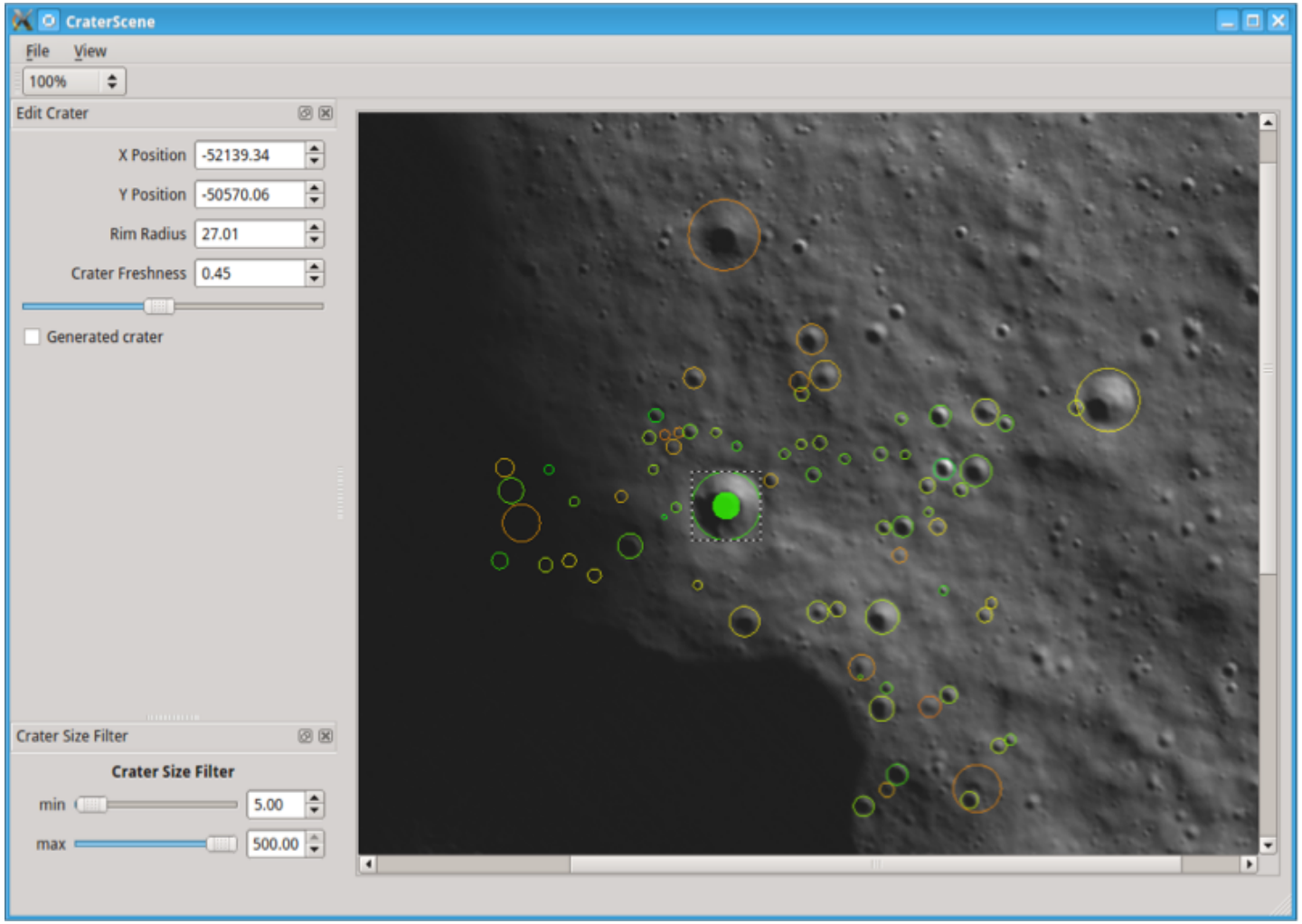
- Placement is **spatially uniform**, completely random, controlled by seed
- Craters **added in order of old to new**, so that older craters are slowly "overwritten" (via weighted blending) and old rock fields are slowly destroyed
  - Larger new craters overwrite smaller old ones
  - Smaller new craters excavate into larger old ones
- Craters can also be **manually placed** to match orbital imagery



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Crater Marking Tool

- Tool to specify
  - Location
  - Size
  - Freshness
- Manual craters are counted against the cumulative frequency distribution.
  - i.e. if you identify all large craters, the sim will only generate smaller ones
- Biased spatial distribution is not yet implemented.
  - i.e. if you hand mark a bunch of craters in one corner of a dem, that corner will still have craters generated and will be more dense than desired



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Crater Shape Profile

- Crater profile is from [Martin, et al 2014]
  - Defined by 4 constrained polynomials
  - Integrates quadratic bowl shape mode (Melosh) and ejecta profile (McGetchin rim degredation model (Ross)
  - Degredation (crater age) controlled by "Freshness" parameter

*time permitting, we will replace this model with a library of bezier-curve profiles created by lunar scientists

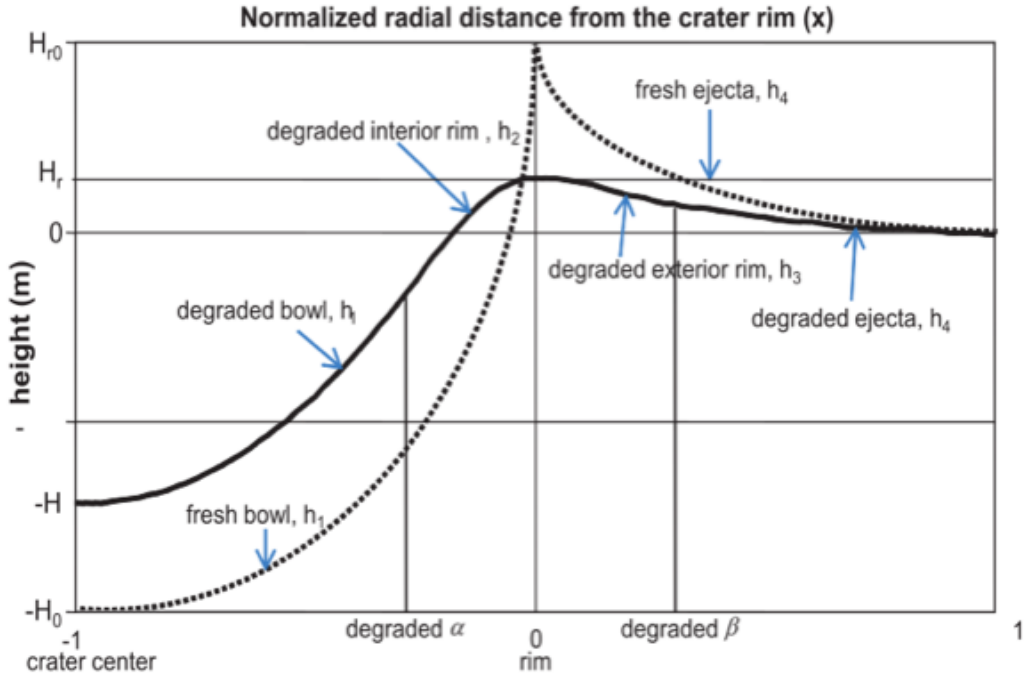


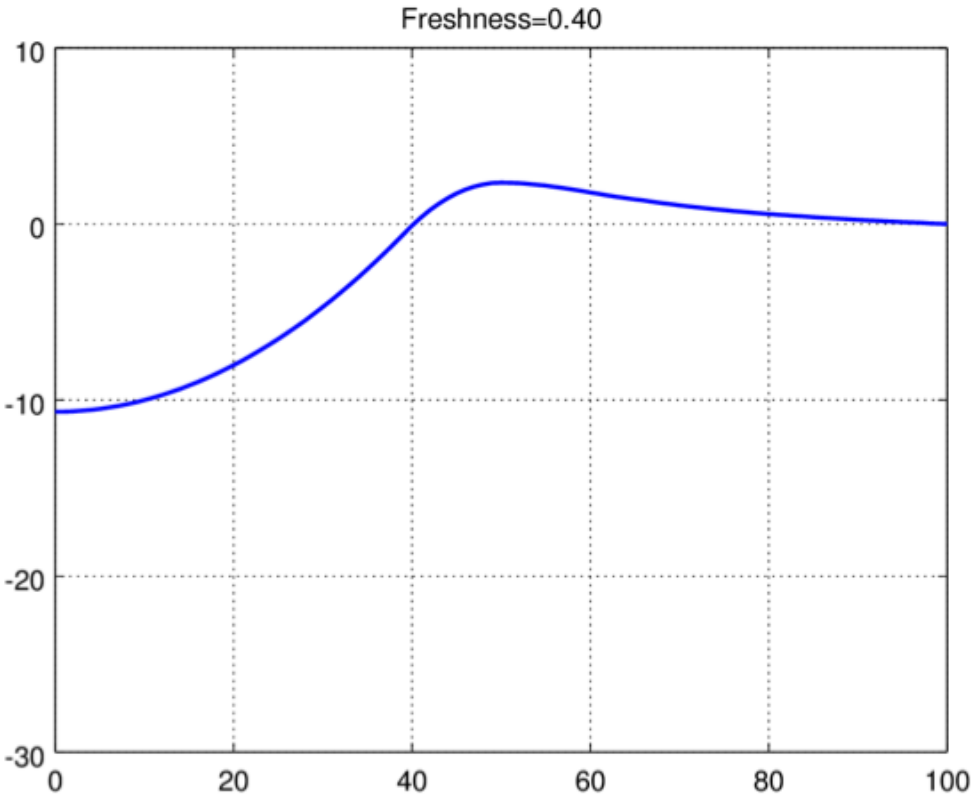
Fig. 3. Fresh and degraded crater profiles.

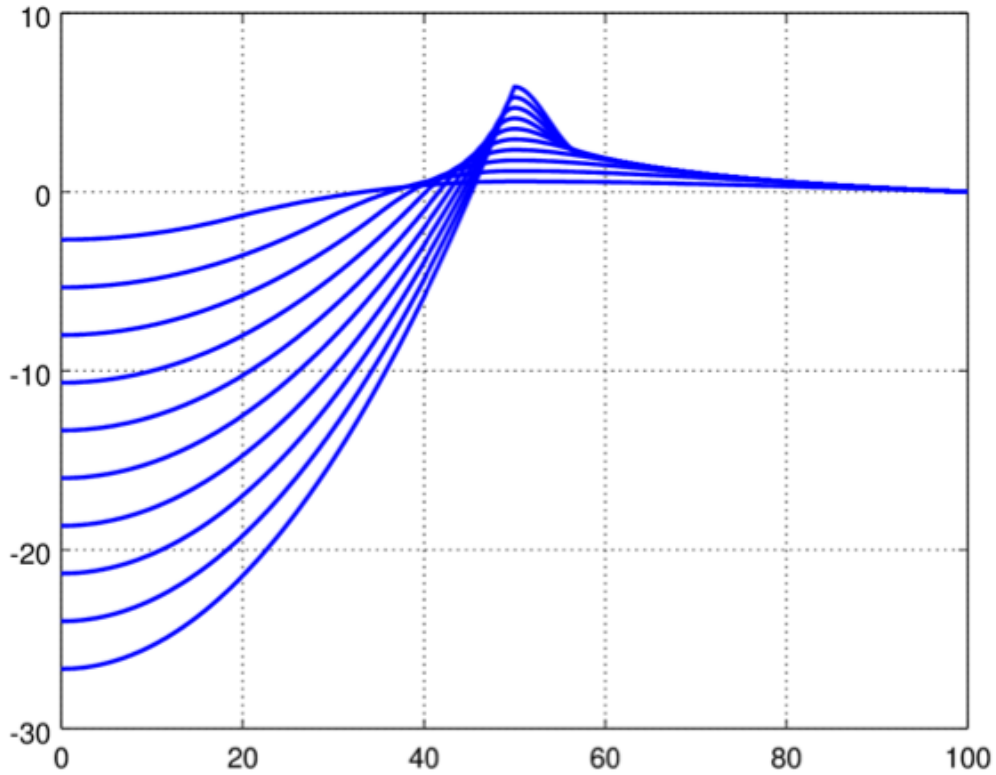
* Martin, et. al. *Modeling Cratered Surfaces With Real and Synthetic Terrain for Testing Planetary Landers*, 2014

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Crater Shape Profile - Freshness Parameter

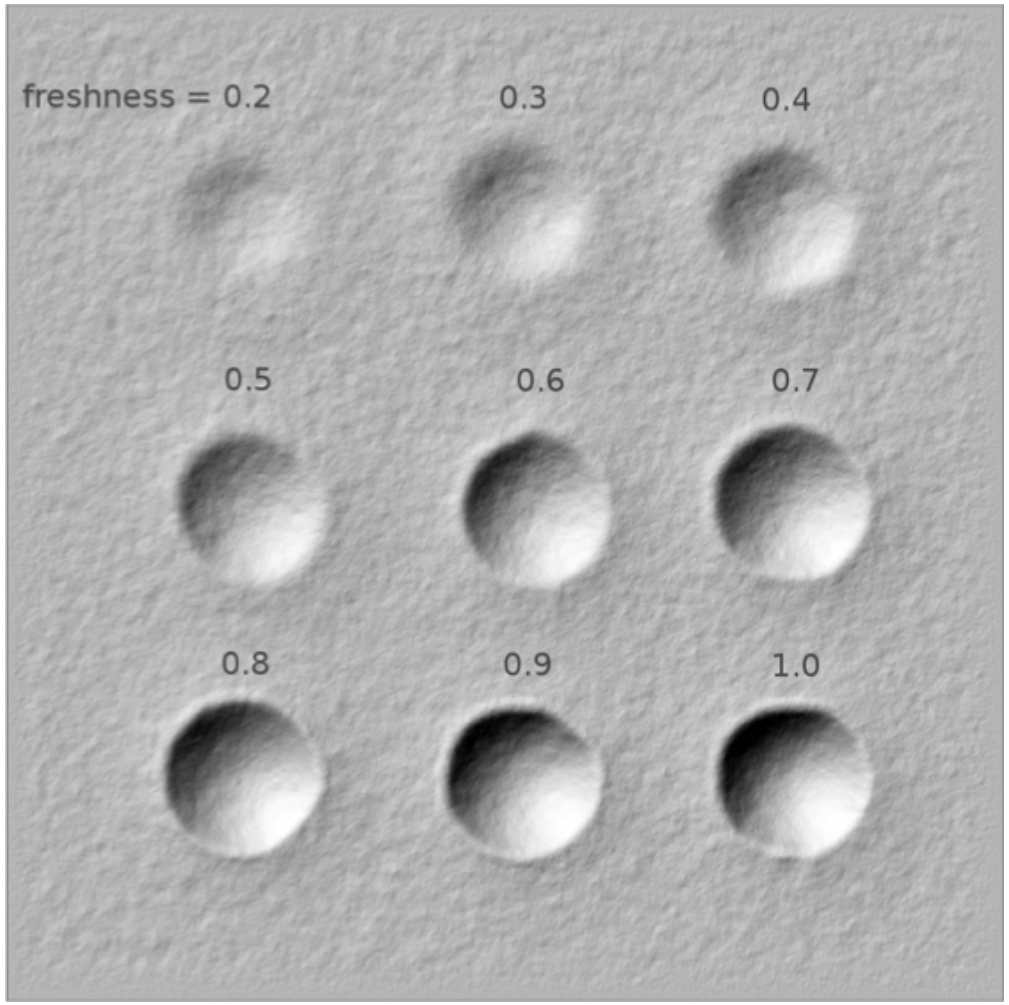
- "Freshness" (age) parameter determines profile and d/D

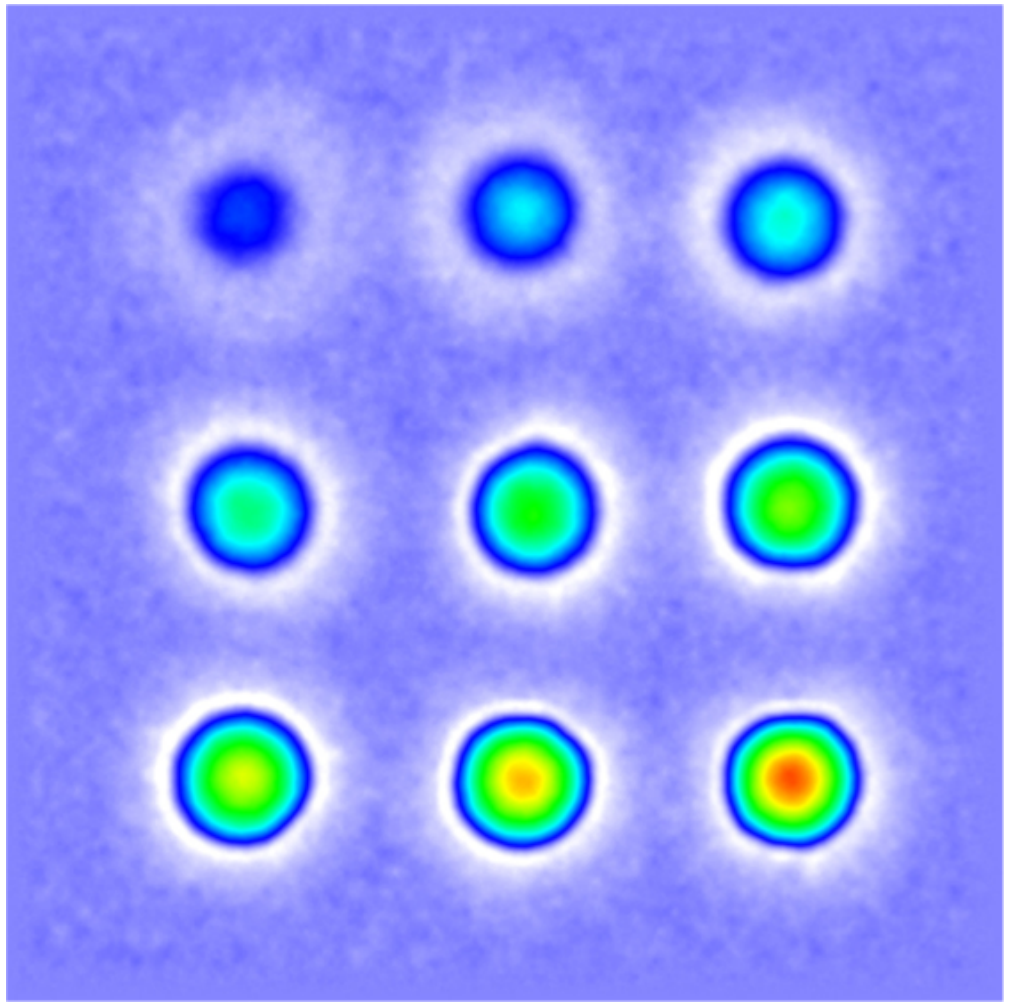




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Crater Shape Profile - Freshness Parameter



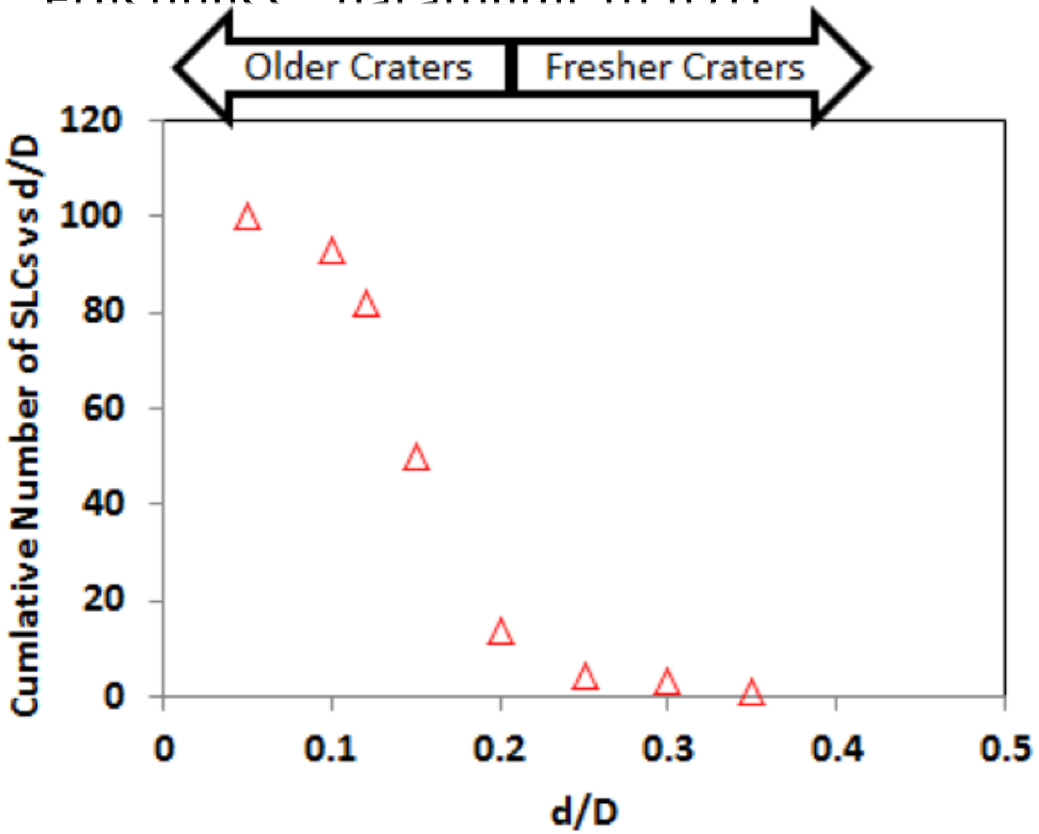


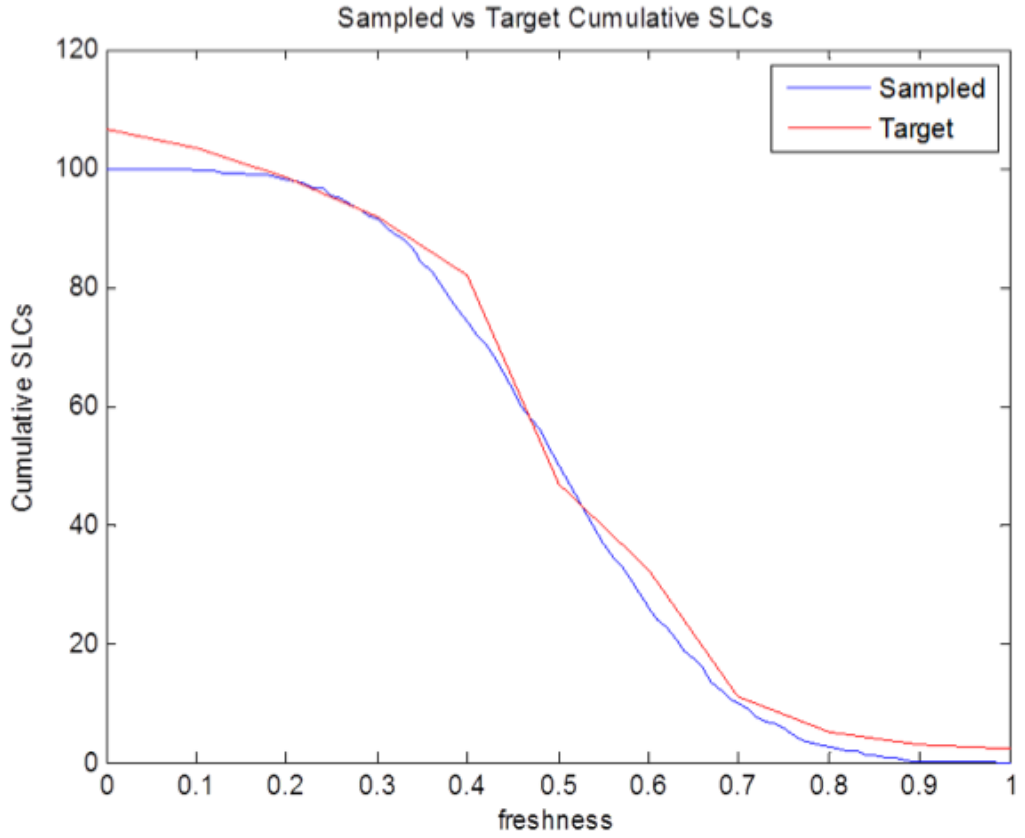
80m diameter craters
Max depth 24m
Freshness 1.0 ~ d/D 0.3

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Crater Depth/Diameter Ratio

- Env spec provides distribution of d/D for small lunar craters (<100m) [Mahanti et al., 2015]
- Map "Freshness" parameter to d/D

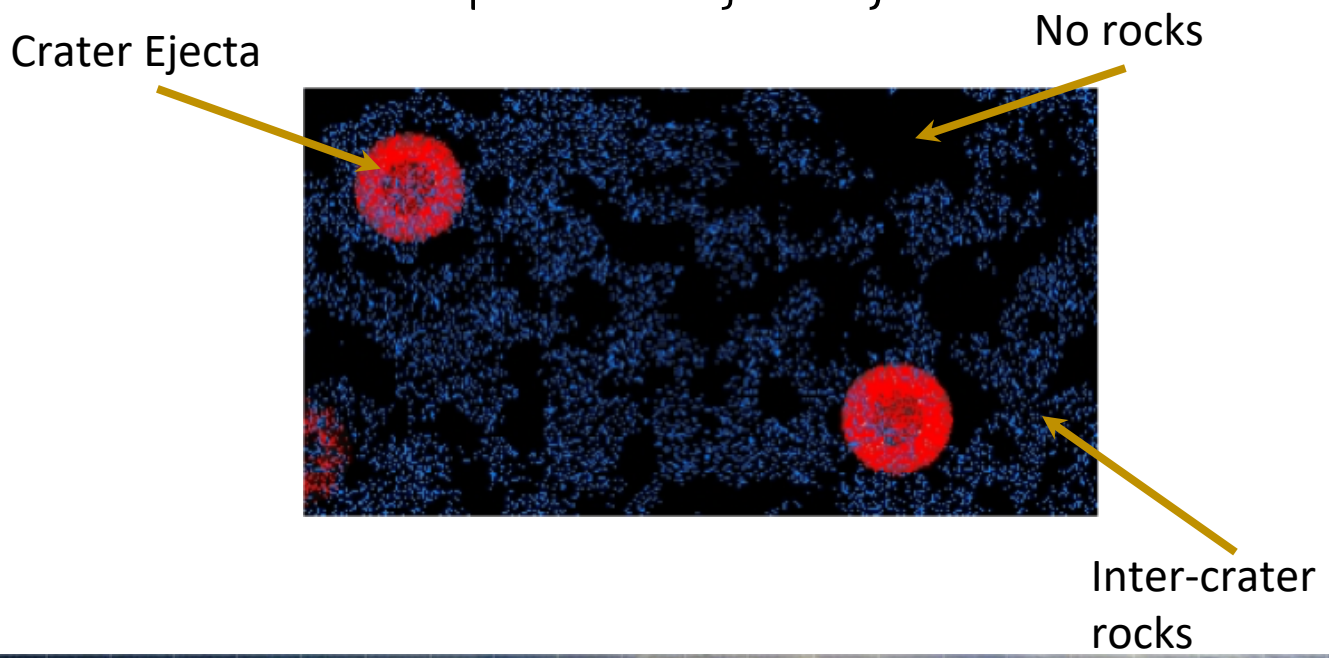




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Rock Placement

- Placement is *not* **spatially uniform**
  - High density near fresh crater rims
  - Low density between craters (background distribution)
  - Random "clumping" parameter to control spatial uniformity (Perlin noise)
  - No attempt to model ejecta rays



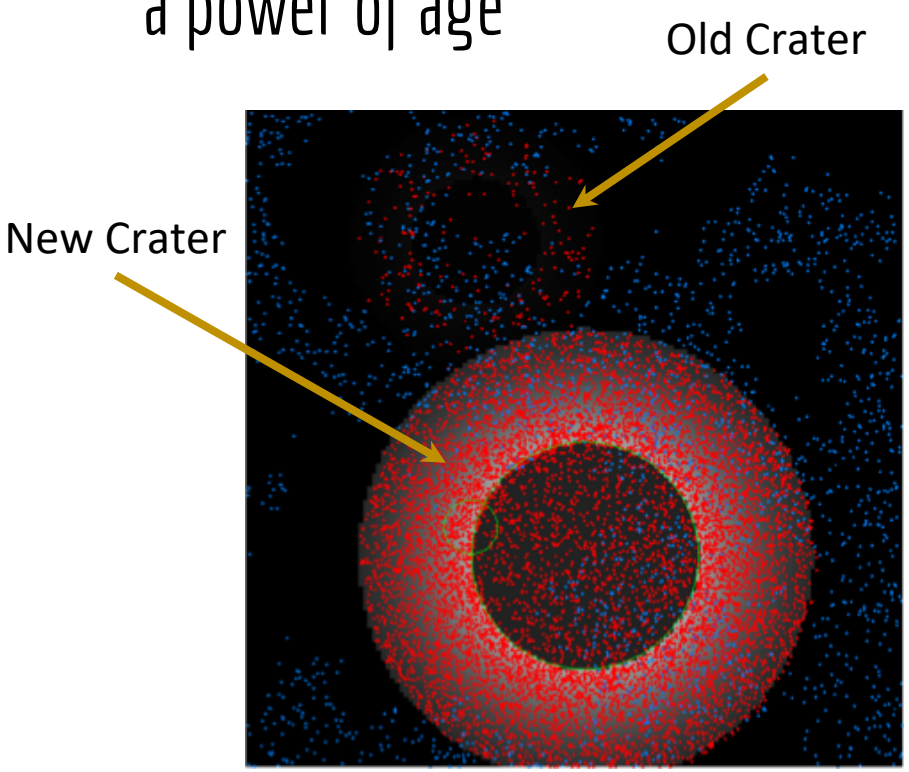


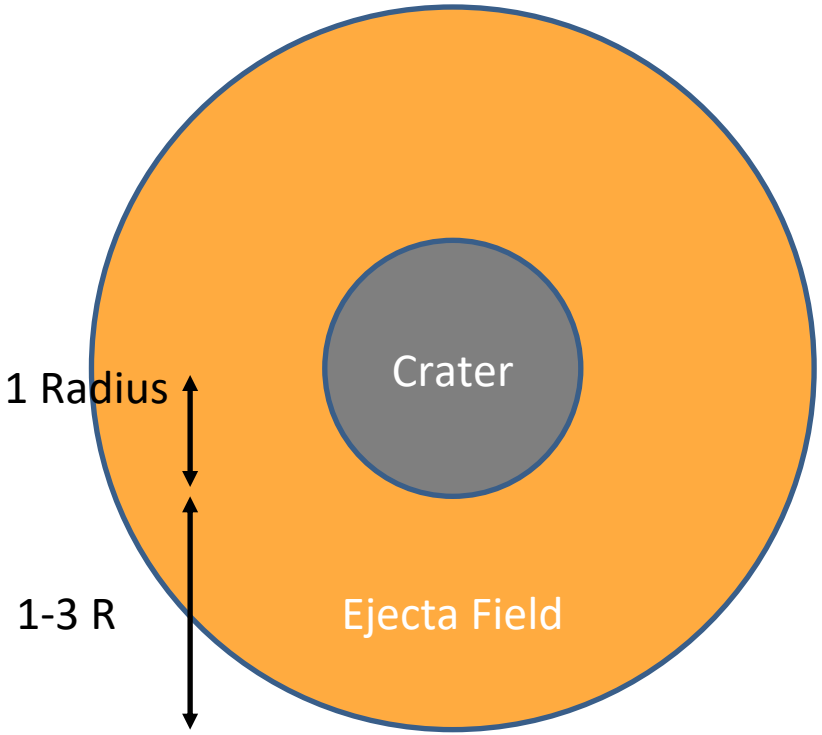
Chang-e descent image

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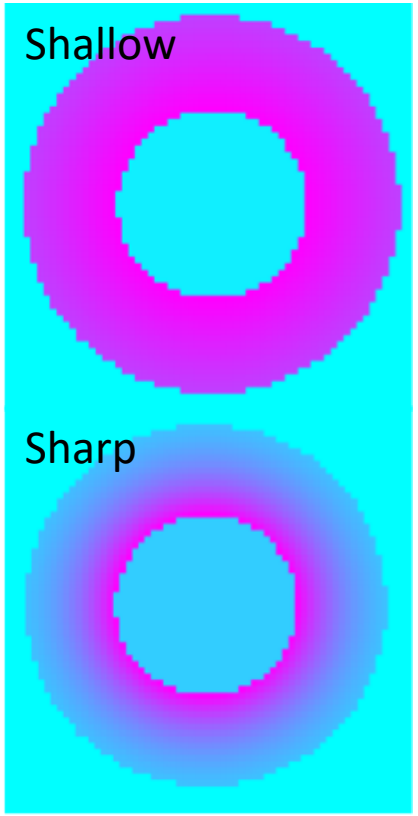
Rocks - Ejecta

- Older craters have less rocks than newer craters
- Number of “visible” rocks decays as a power of age





Parameters control the spatial size of ejecta field.

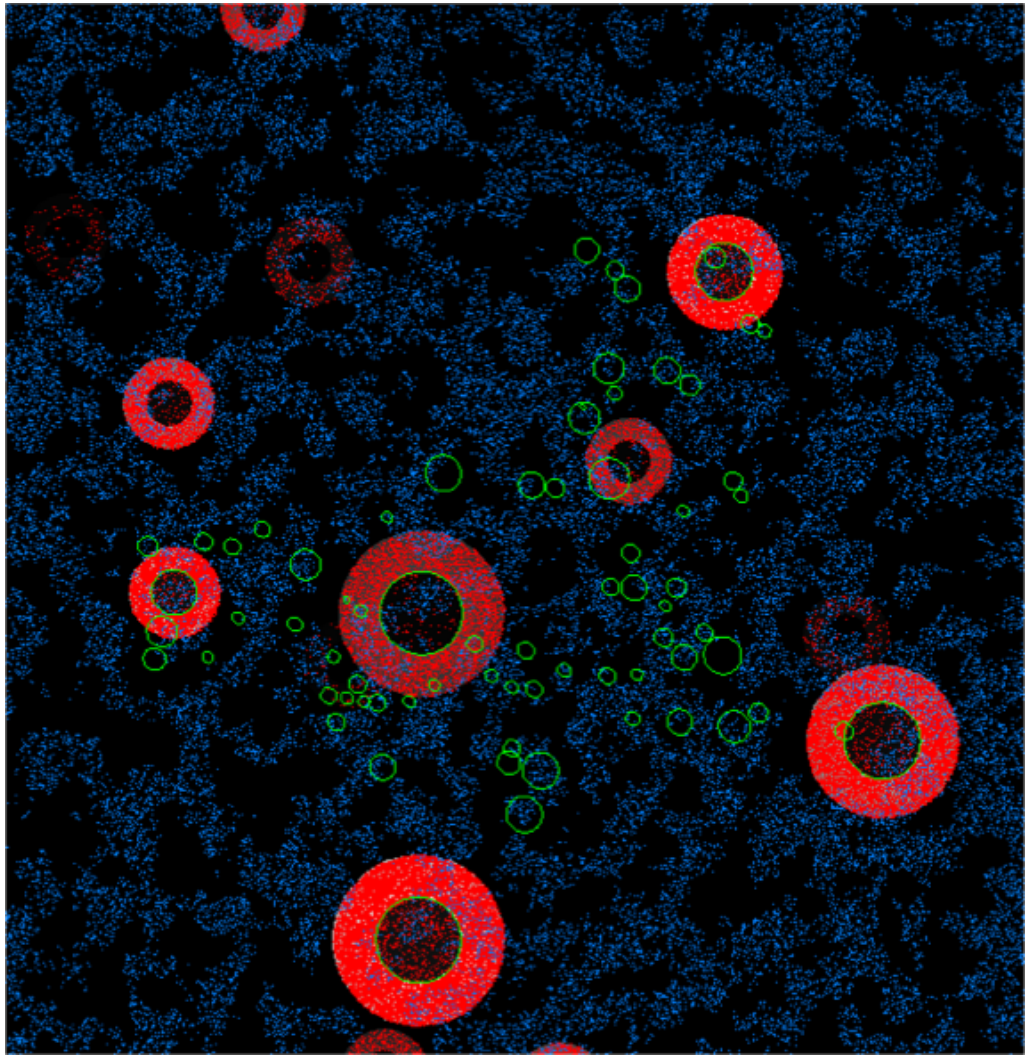


Falloff parameters control if rock distribution within the ejecta field is uniform vs center-weighted.

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Rocks - Distribution

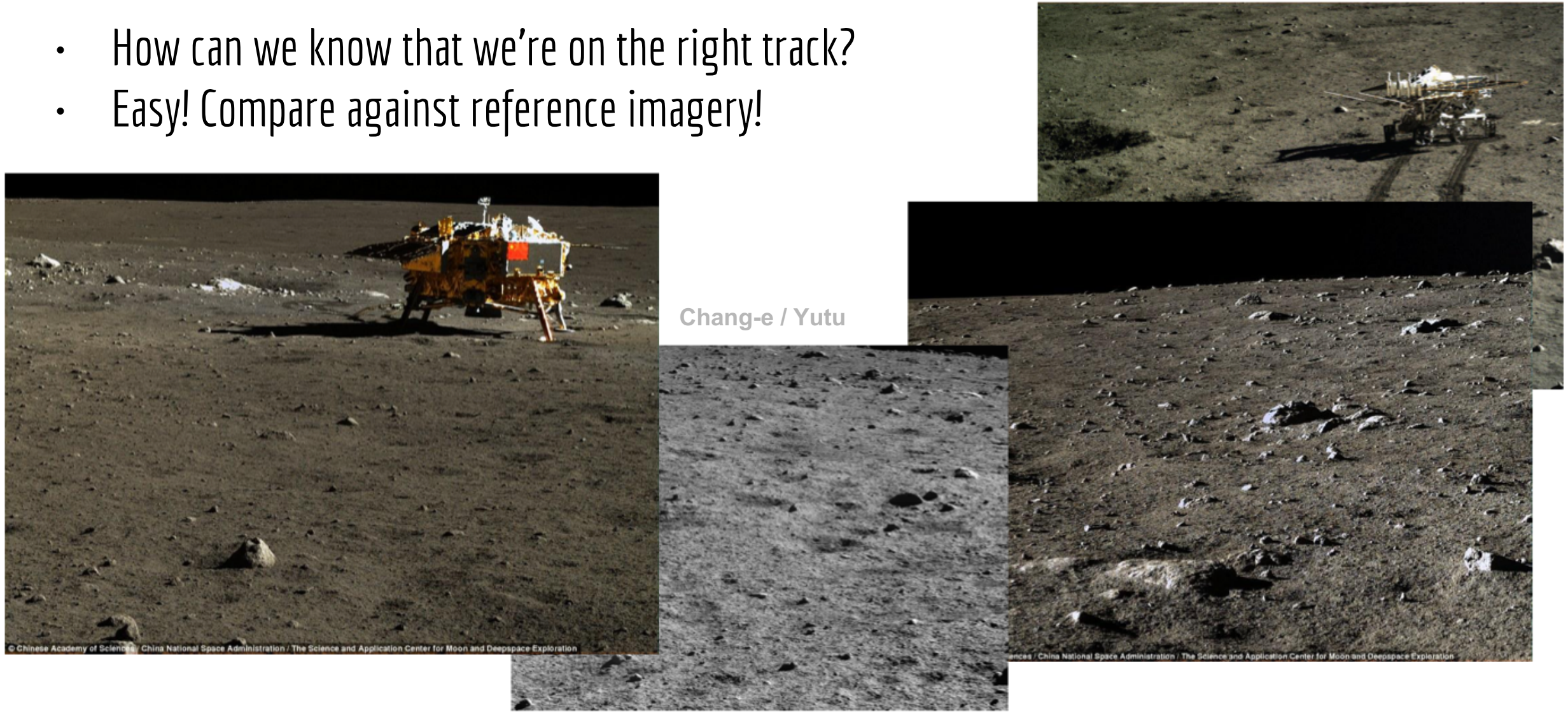
- Per Environmental Spec, **5%** of the total land area is high-density ejecta fields
  - Start with the largest craters and create ejecta fields for each one, until total ejecta surface area is › 5%
  - In a typical scene, a ~50m crater will generate ejecta
  - There is a parameter that controls the min crater diameter that can spawn an ejecta field
- According to the size-frequency distributions in the Environmental Spec, the RP rover is not likely to encounter many hazardous rocks



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Reality Check

- How can we know that we're on the right track?
- Easy! Compare against reference imagery!



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Reality Check

Sorry, no.

- Chang-e landed in a mare region
- We received specific guidance not to use images from mare regions as a reference
  - Regolith is
    - Darker
    - Shallow
  - More rocks
  - Fewer craters

The Moon's Surface

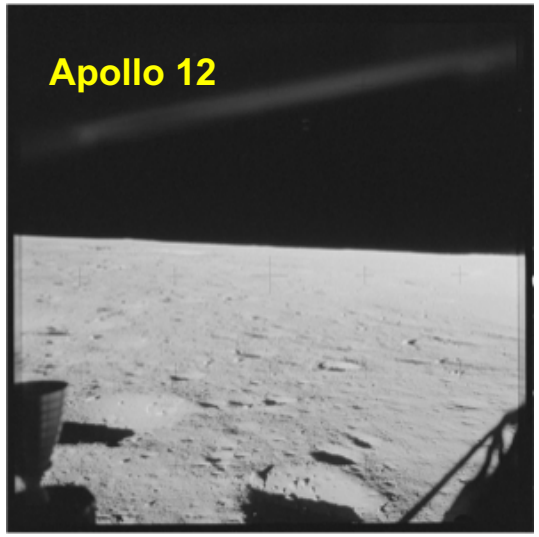
- **Lunar highlands** are heavily cratered regions of the Moon that are light in color and mountainous.
- **Maria** are dark, smooth plains where the craters have been filled with lava from when the moon was tectonically active

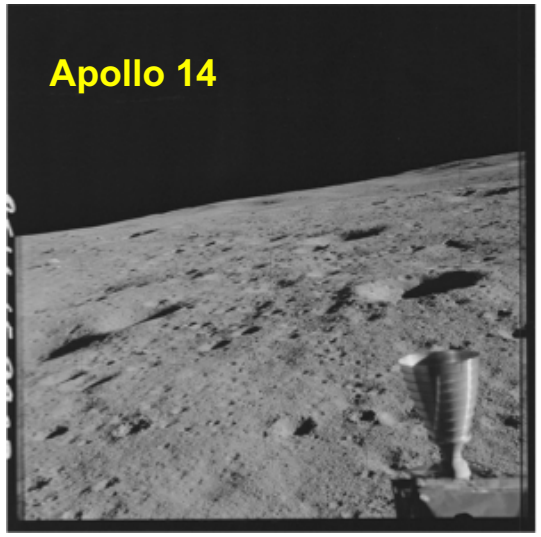


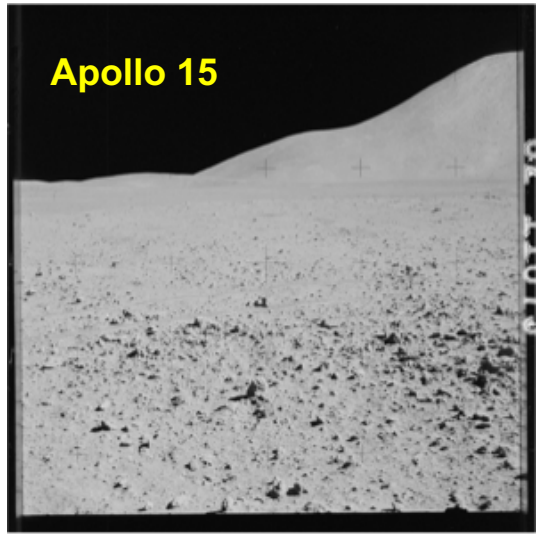
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Reality Check - What about Apollo surface imagery?













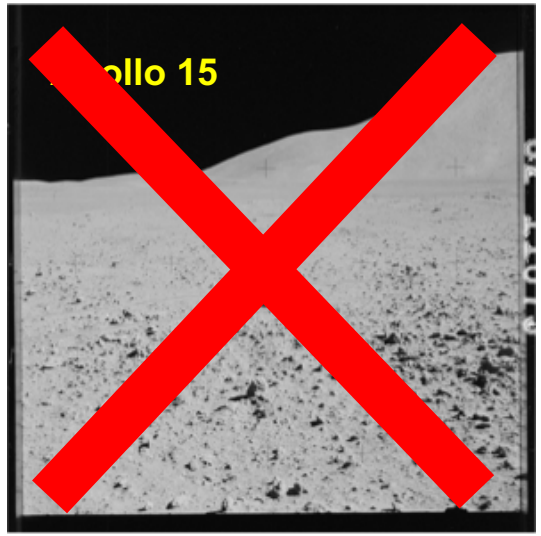
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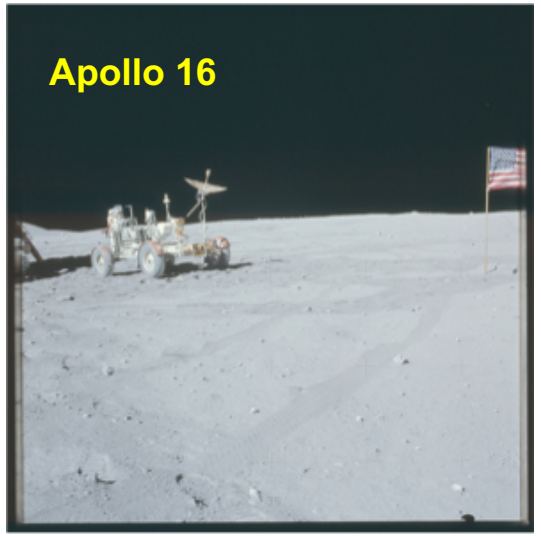
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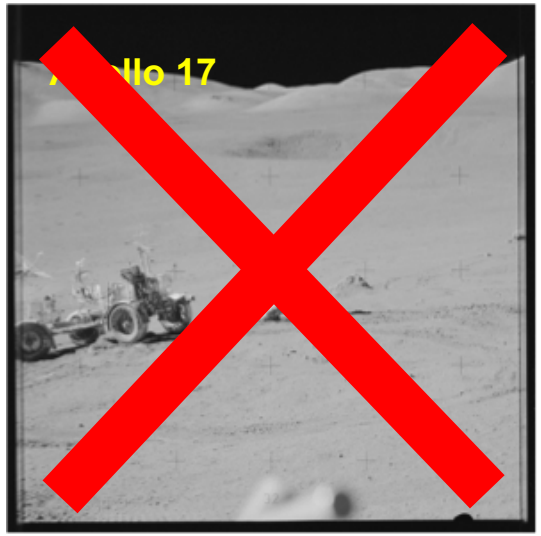












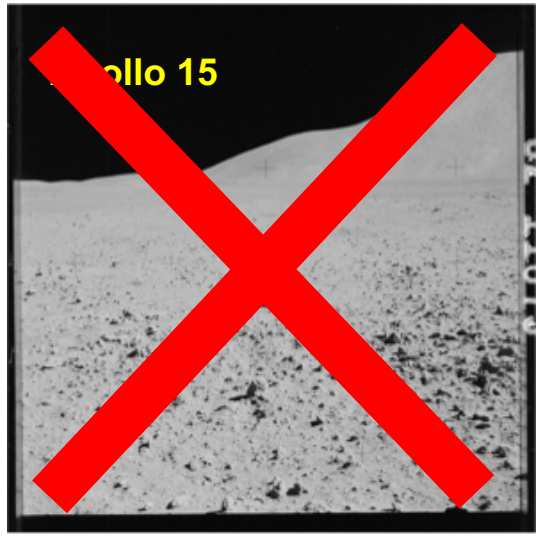
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Reality Check - What about Apollo surface imagery?

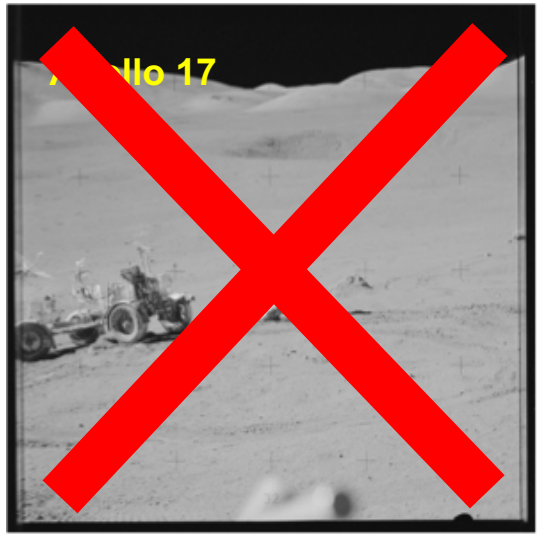












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Reality Check - Orbital Images

- Compare synthetic terrain against LRO NAC Images
  - Use SPICE to get sun angle at time reference image was taken
  - Use sun angle to generate
    - DEM hillshade
      - (simple shading model)
    - DEM shadow map
      - (simple raytracing)

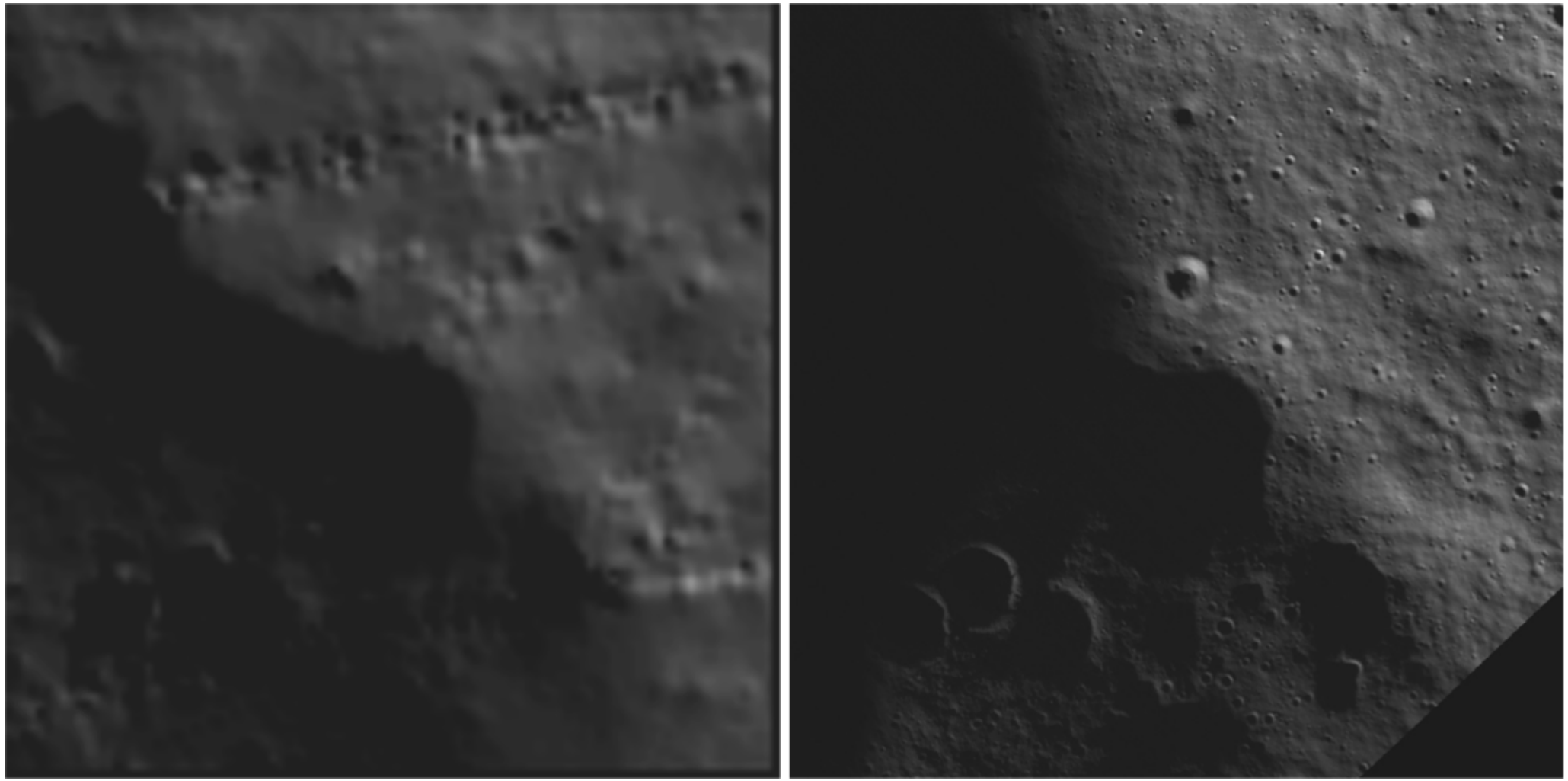


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2010-04-02T20:32:03
http://wms.lroc.asu.edu/lroc/view_lroc/LRO-L-LROC-2-EDR-V1.0/M124879589RE

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Reality Check - Orbital Images

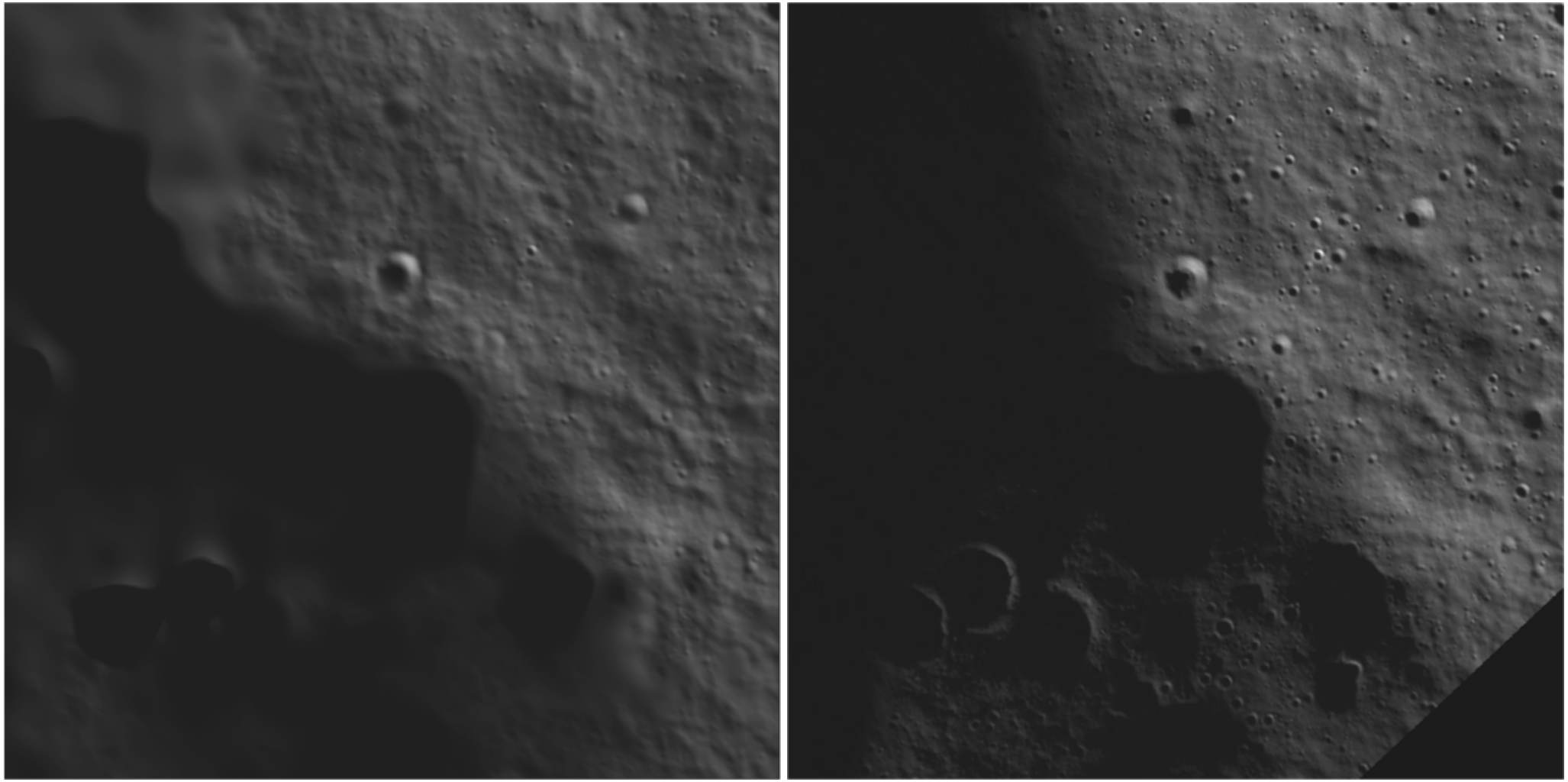
LOLA (10M)



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Reality Check - Orbital Images

SfS DEM (1m)

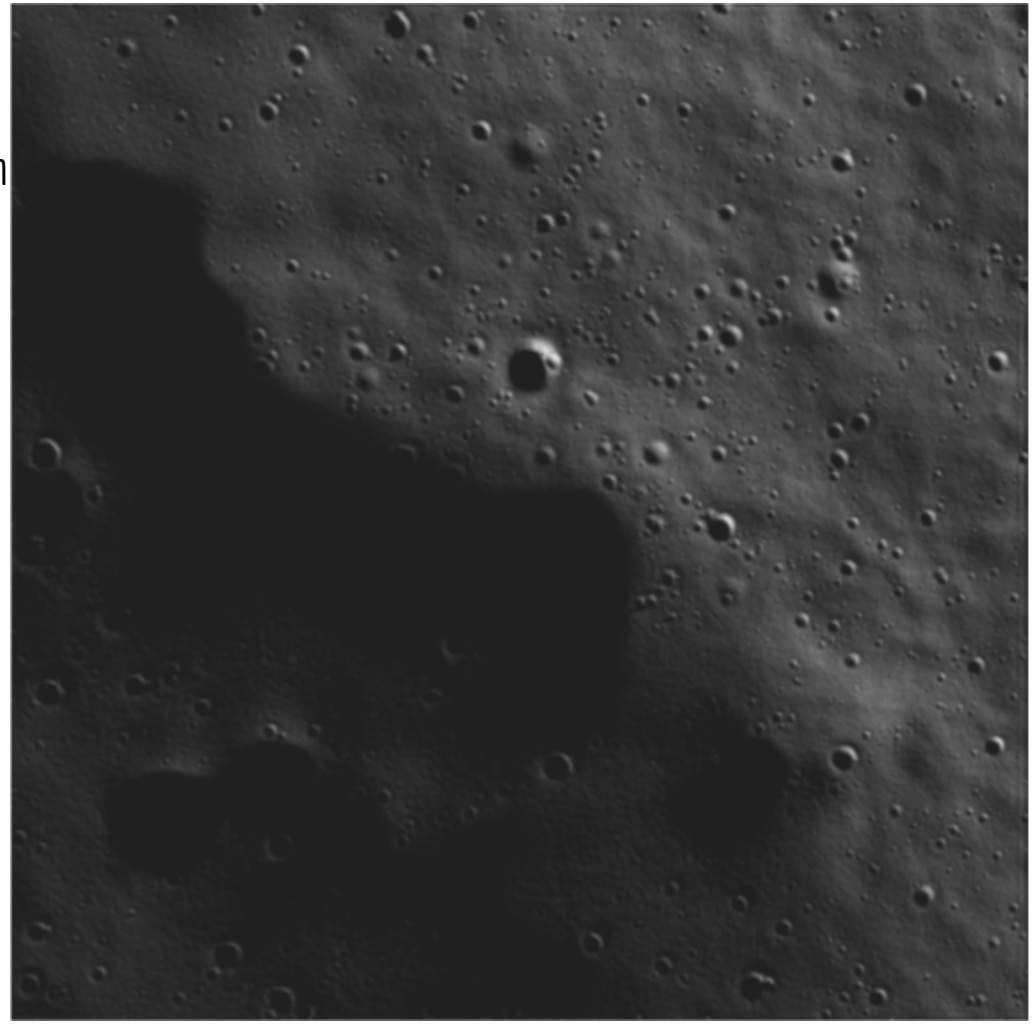


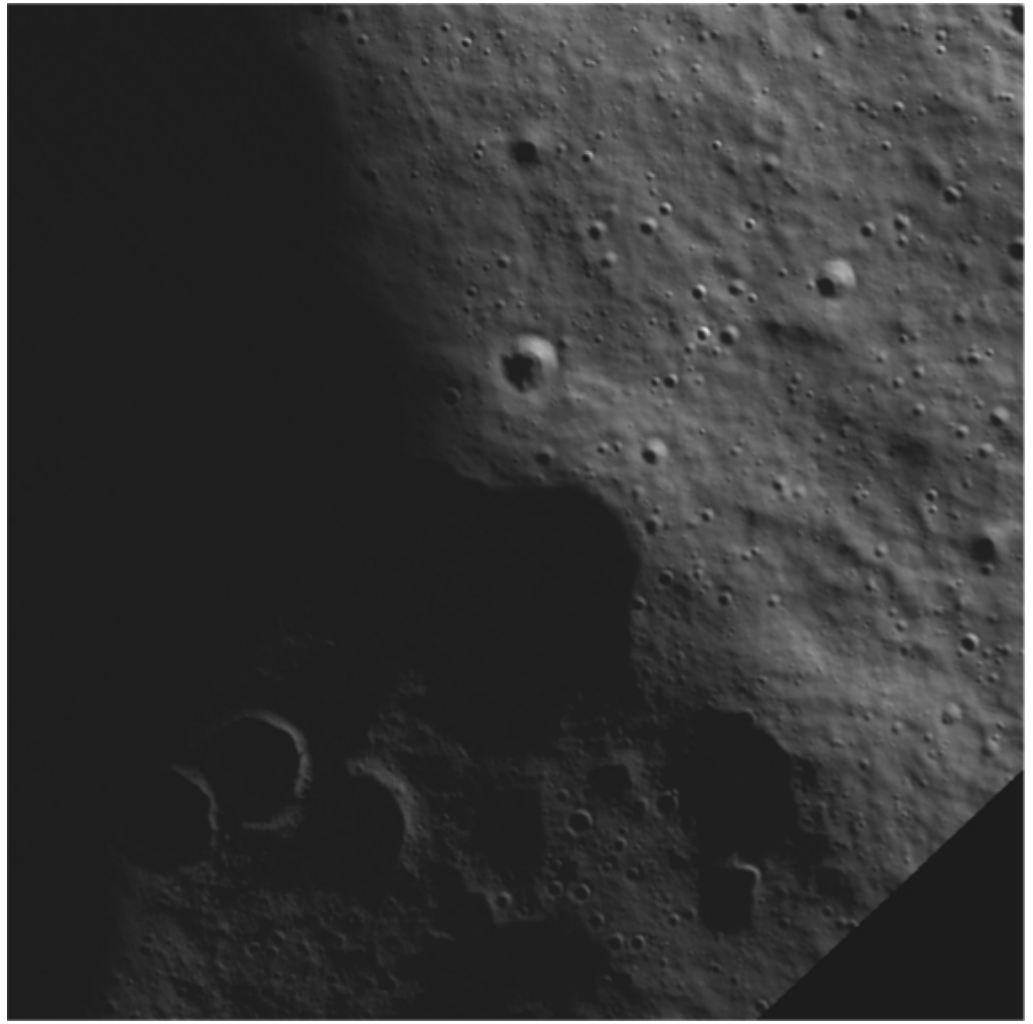
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Reality Check - Orbital Images

Synthetic (1m)

*4cm downsampled to 1m

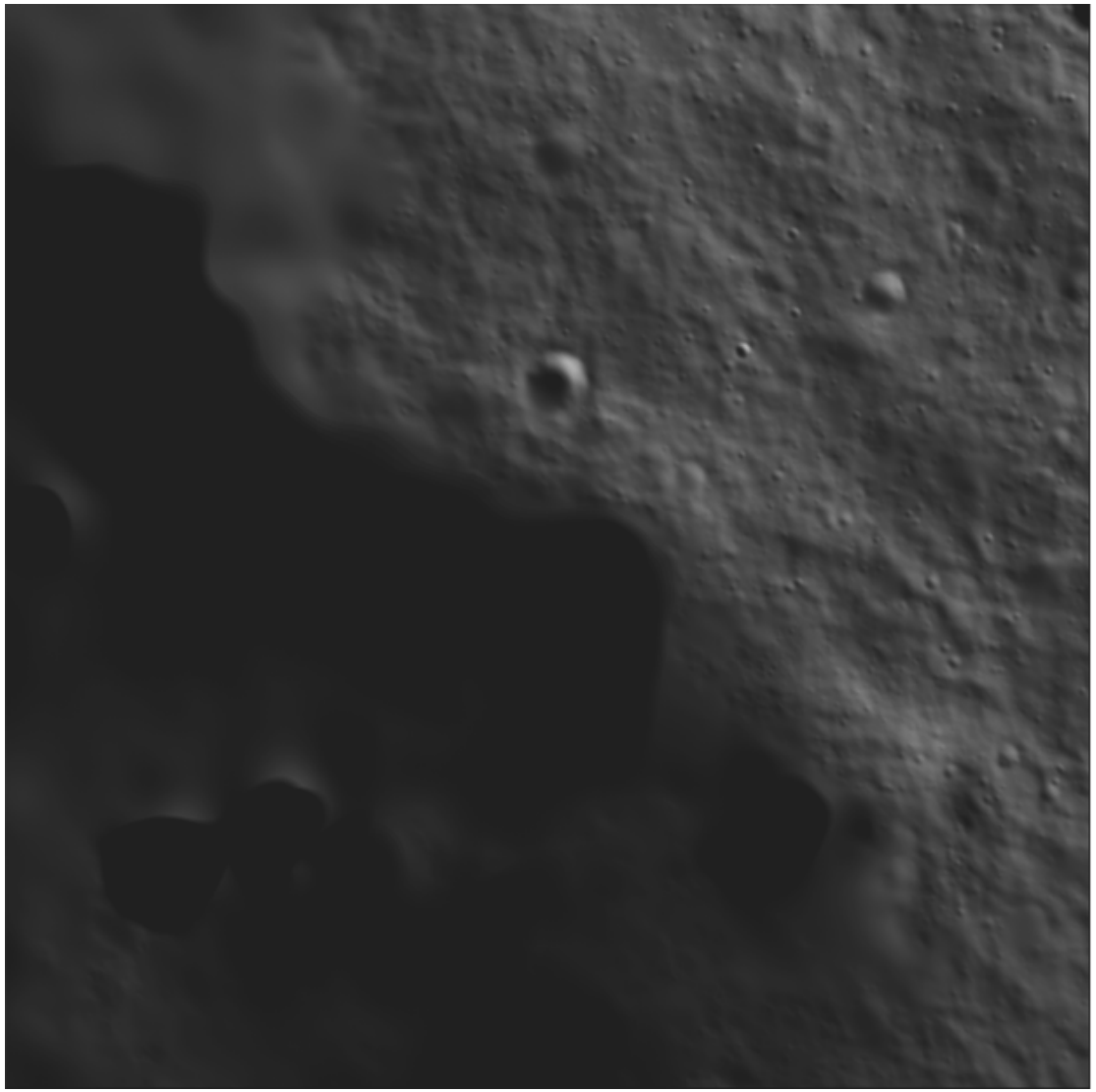




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Reality Check - Orbital Images

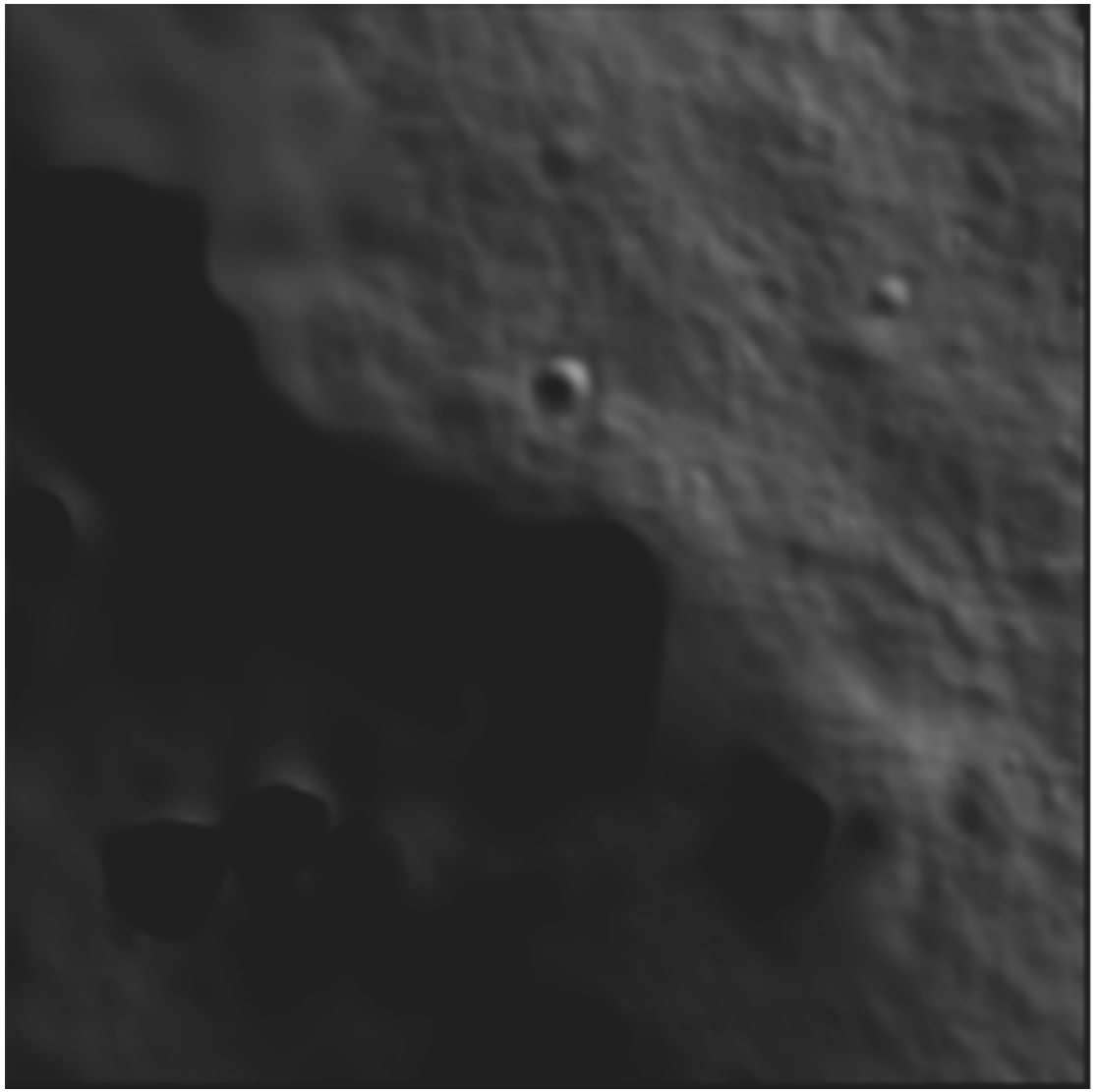
- Start with 1m SfS DEM



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Reality Check - Orbital Images

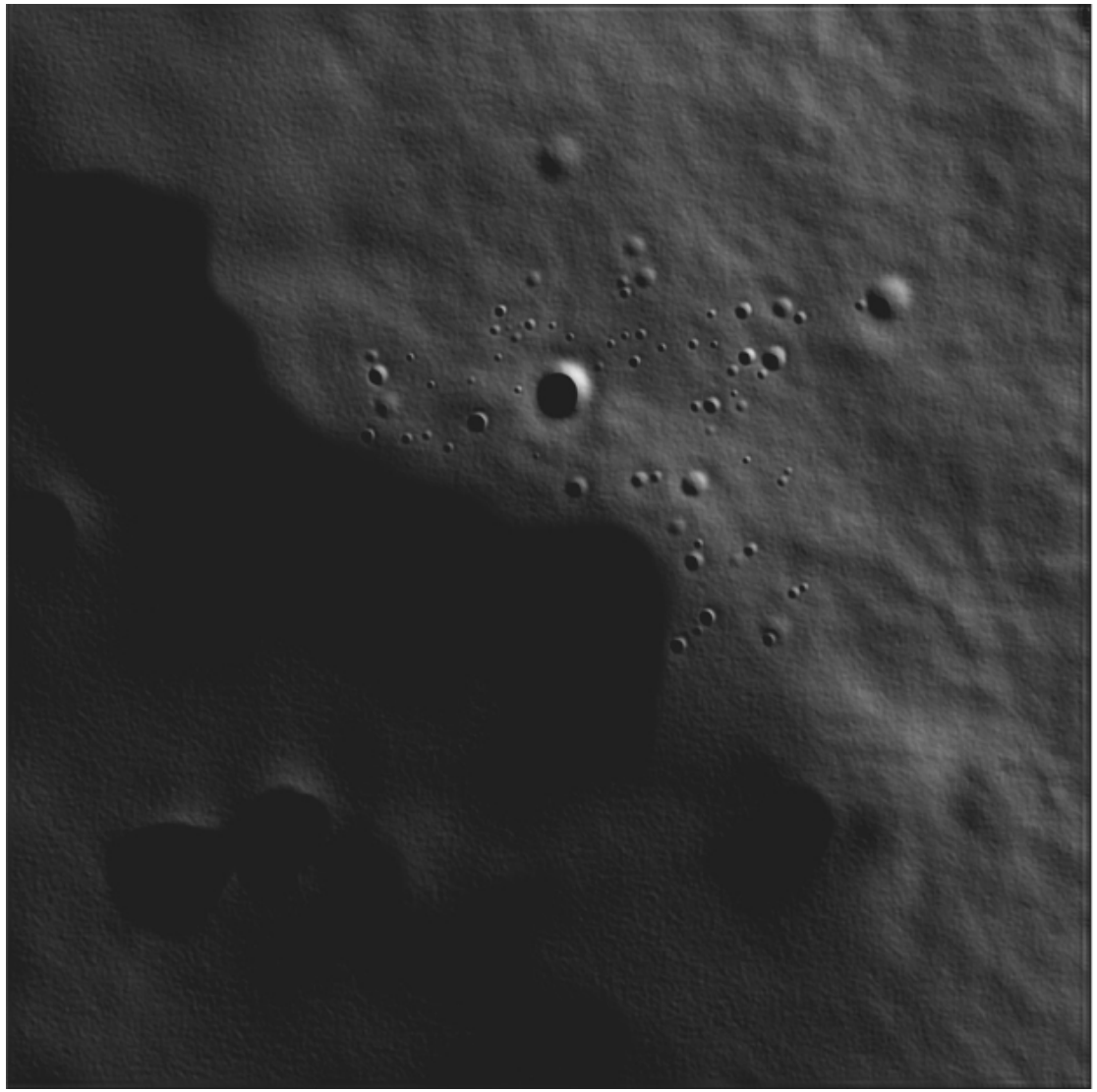
- Downsample SfS DEM to 5m
  - In retrospect, this was not the best idea



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Reality Check - Orbital Images

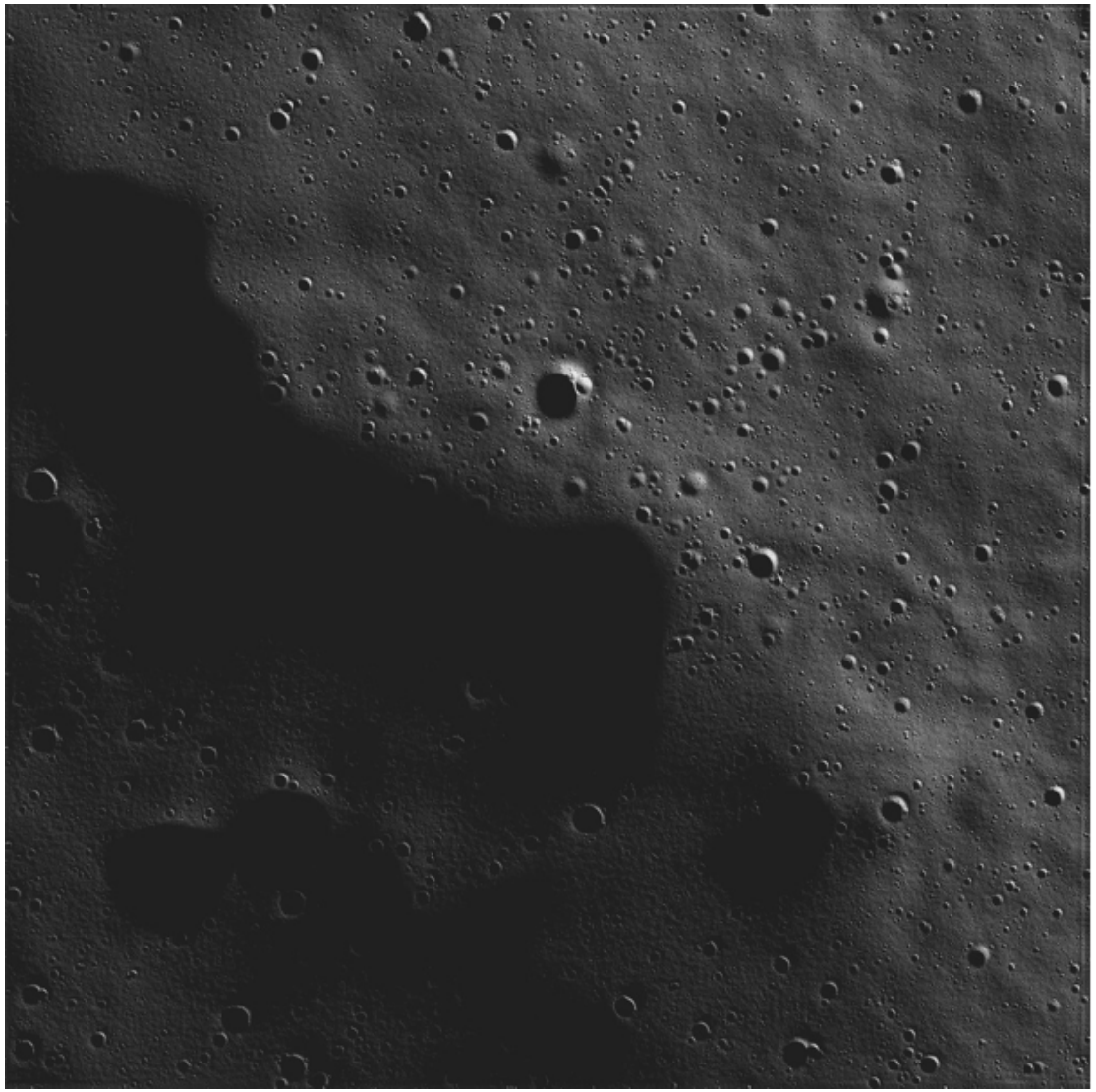
- Manually add craters



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Reality Check - Orbital Images

- Add random craters and rocks

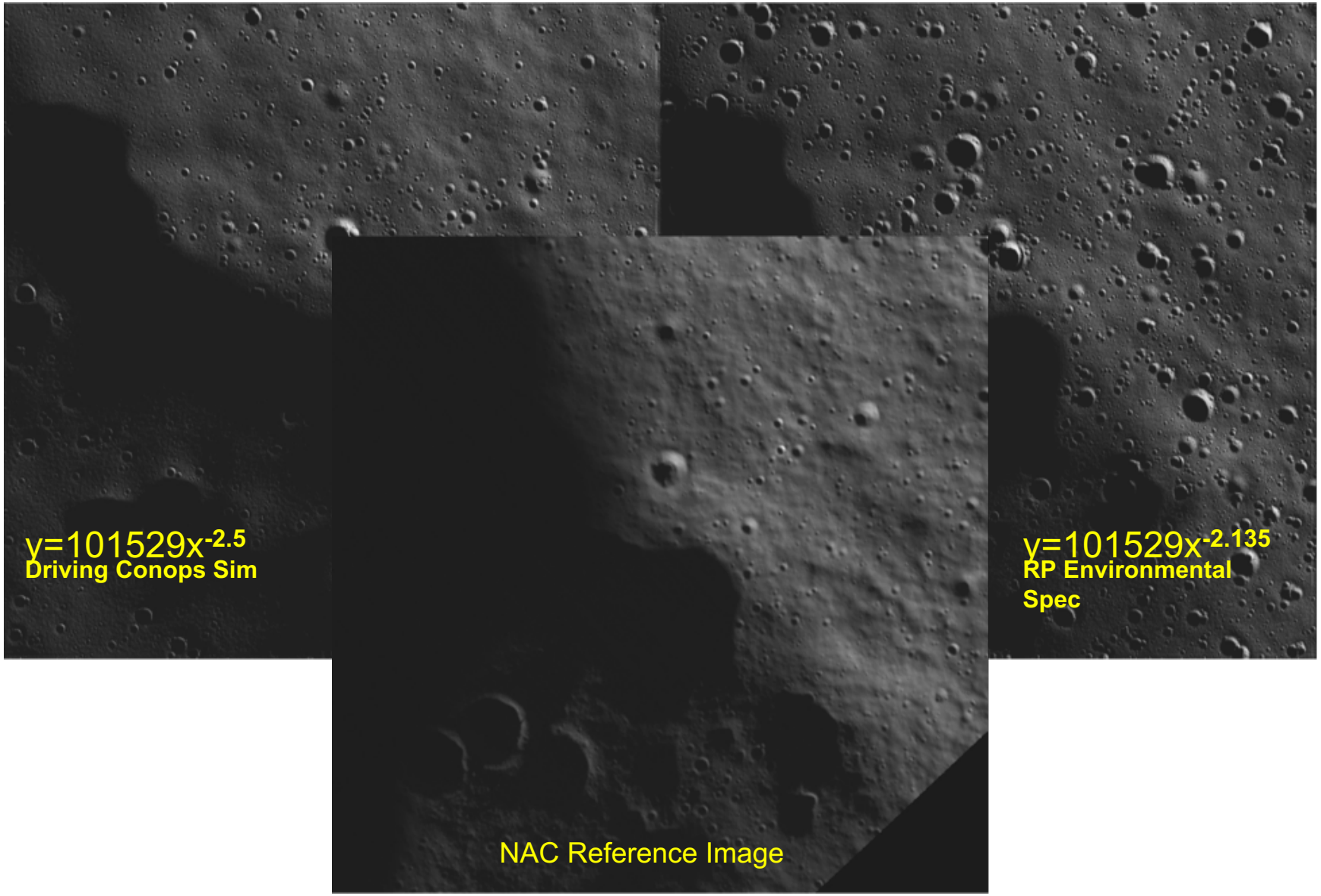


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TODO: Crater Size-Frequency Distribution

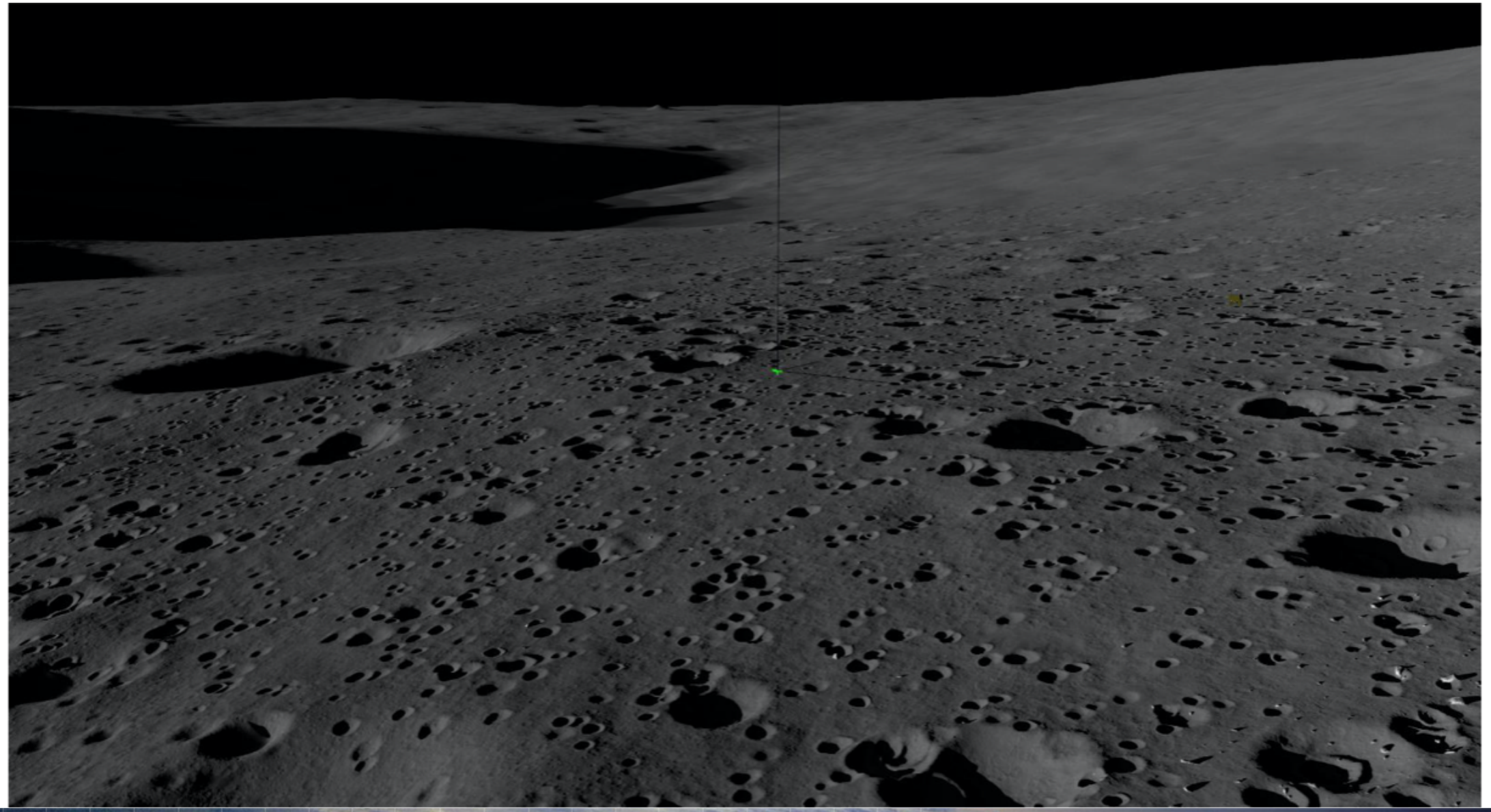
Size-Frequency distribution from the Environmental Spec produces too many craters compared to reference image

...still iterating on this with science team



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Simulator Images



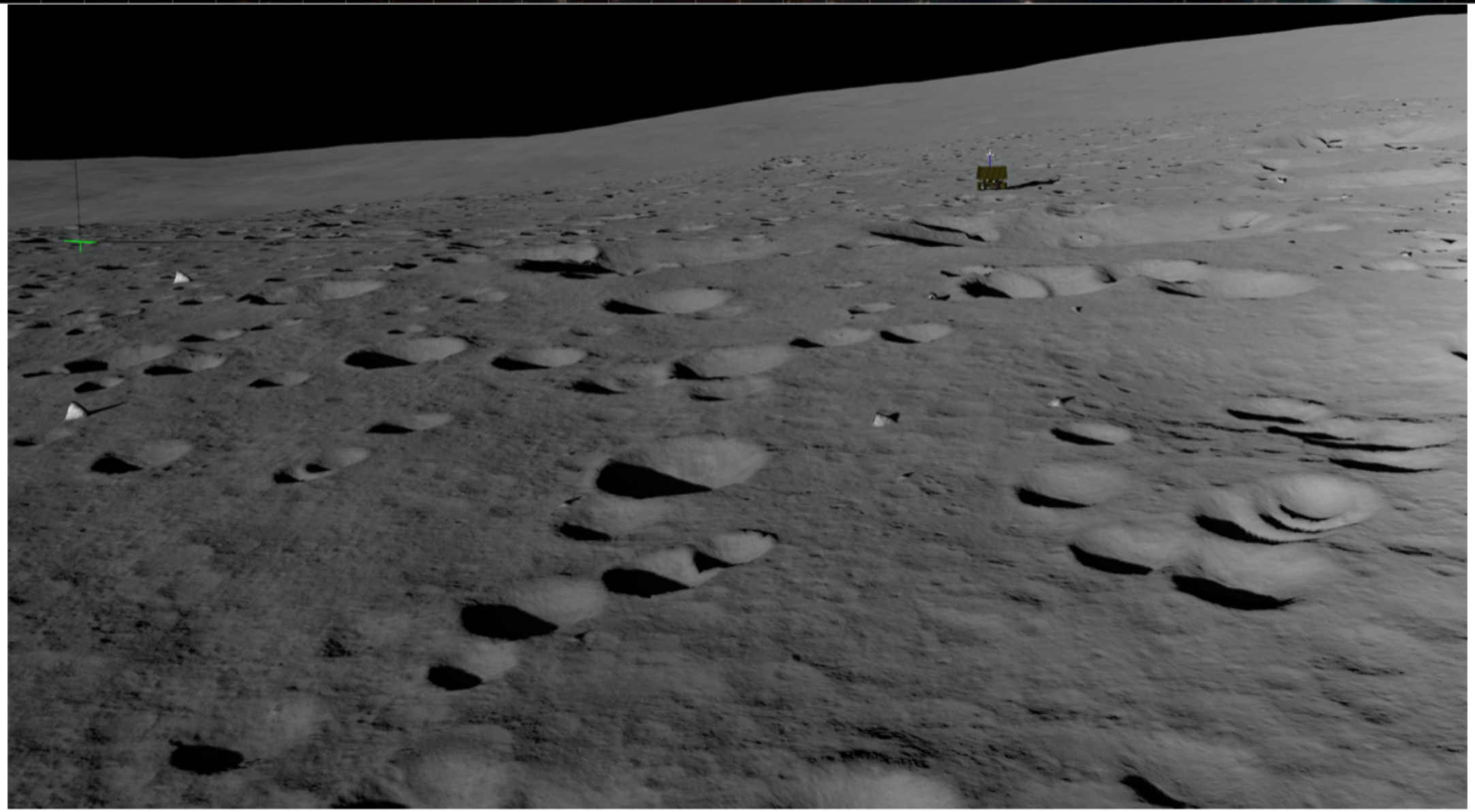
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Simulator Images



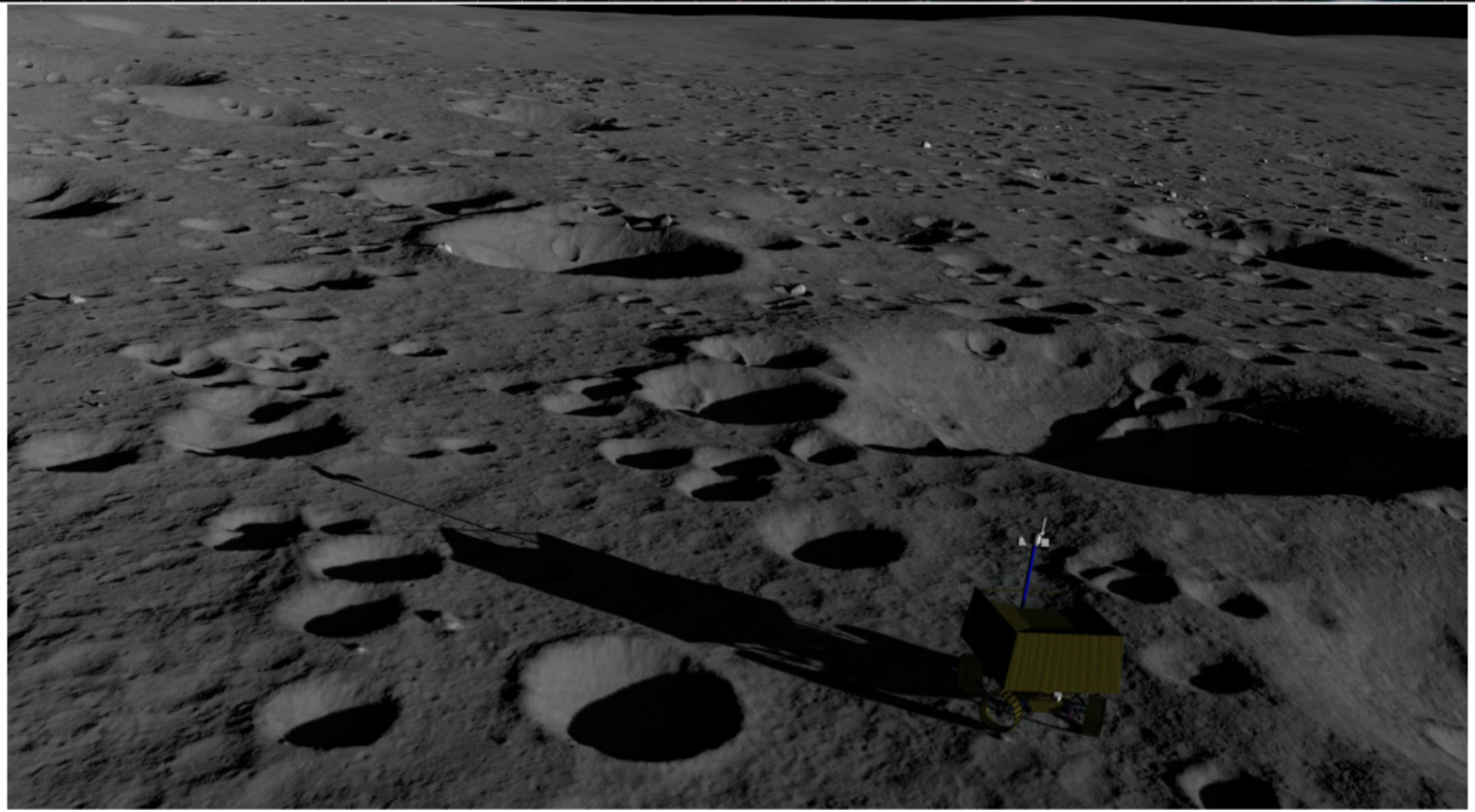
Information contained in this presentation is not subject to Export Controls (ITAR/EAR)

Simulator Images



Information contained in this presentation is not subject to Export Controls (ITAR/EAR)

Simulator Images



Information contained in this presentation is not subject to Export Controls (ITAR/EAR)

Video



Information contained in this presentation is not subject to Export Controls (ITAR/EAR)

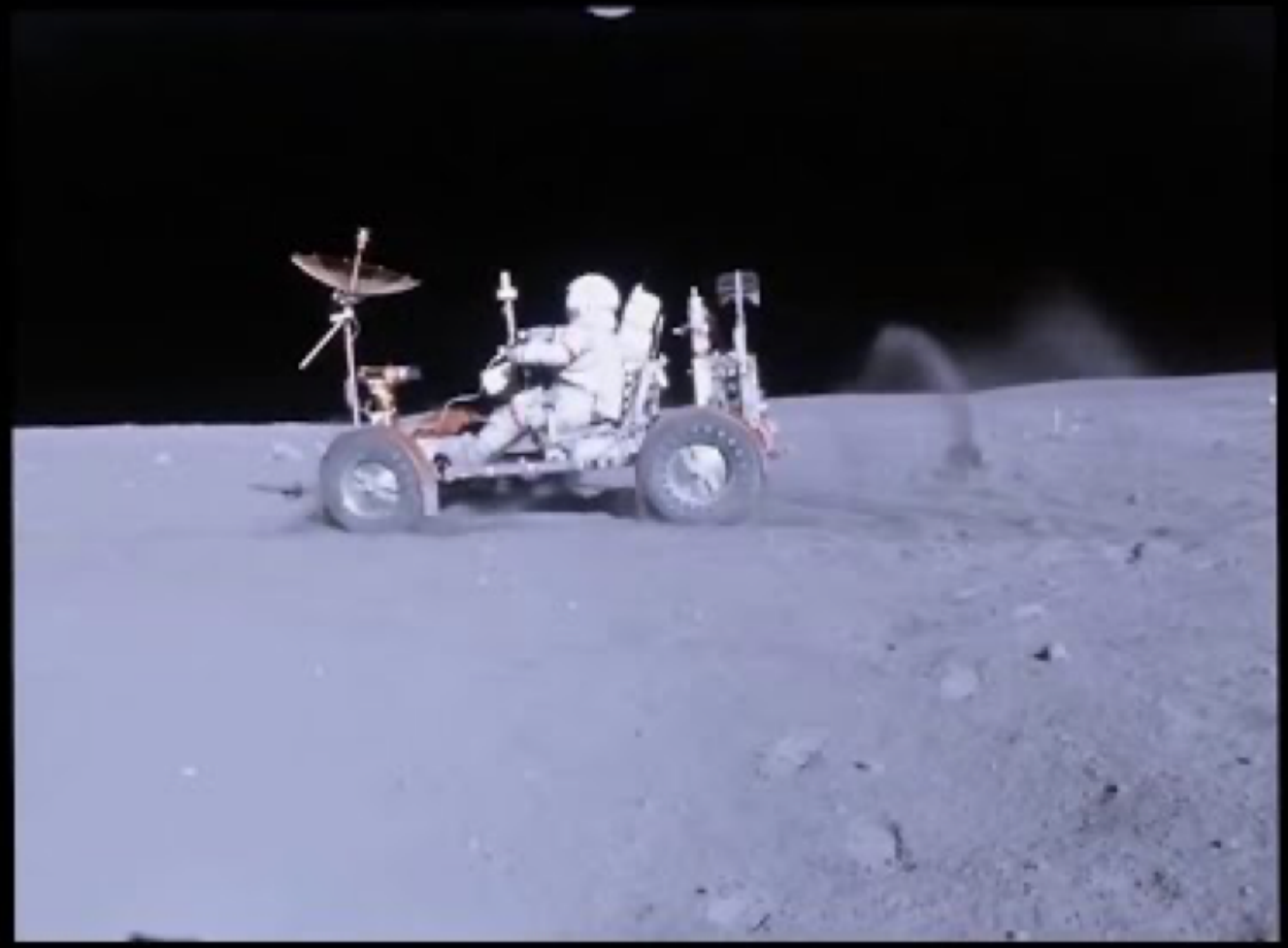
Questions?

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Backup Slides

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Apollo 16 Lunar Rover



Information contained in this

Crater Insertion

1. Fit plane to crater area
2. Scoop out crater bowl
3. Blend ejecta blanket into surrounding terrain

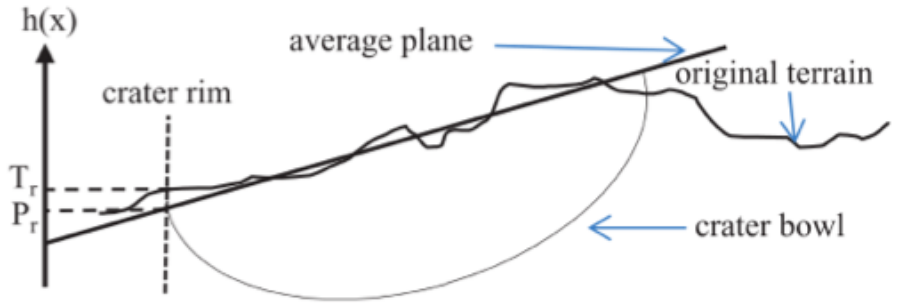


Fig. 1. Definition of plane to represent obliterated crater interior.

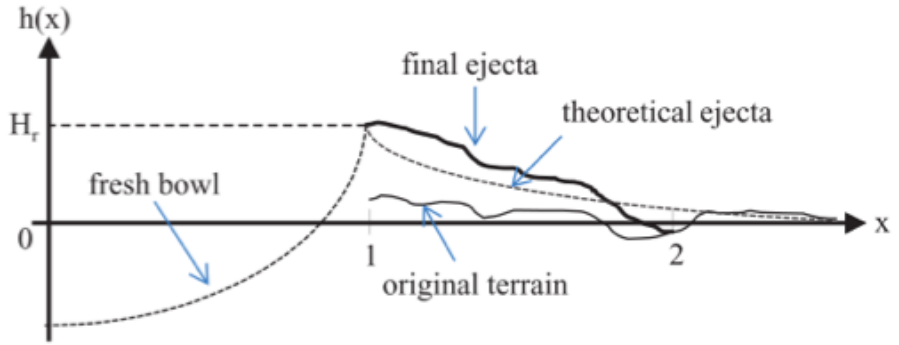
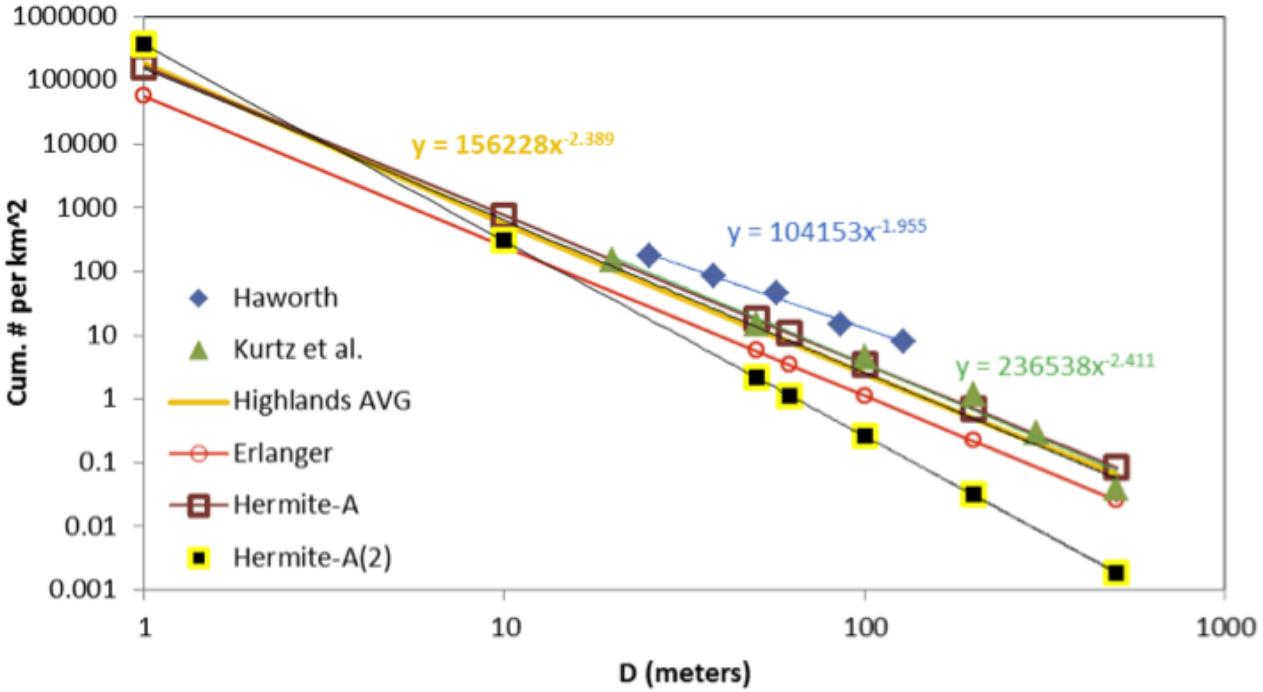
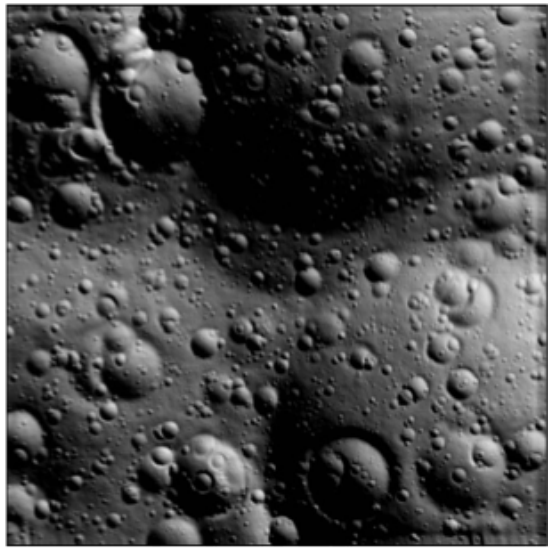


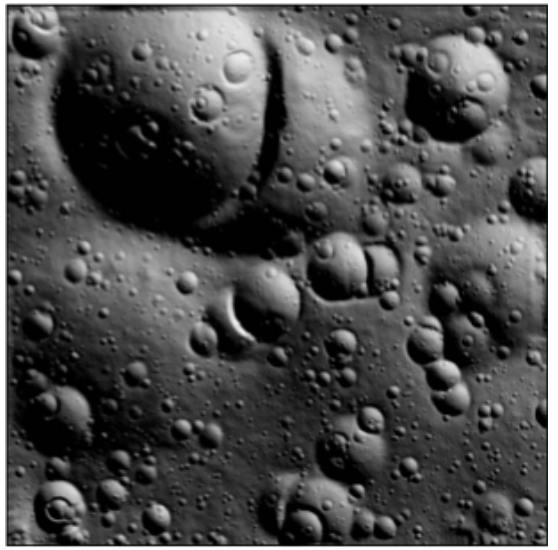
Fig. 2. Crater model profile showing blending of idealized ejecta with surrounding terrain.

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Craters -







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