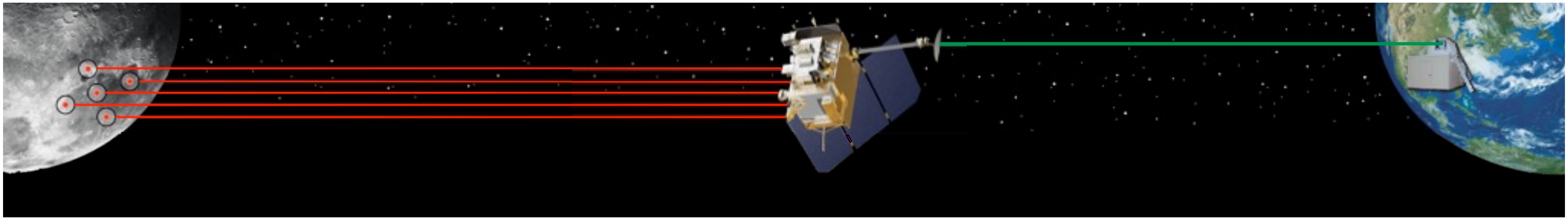


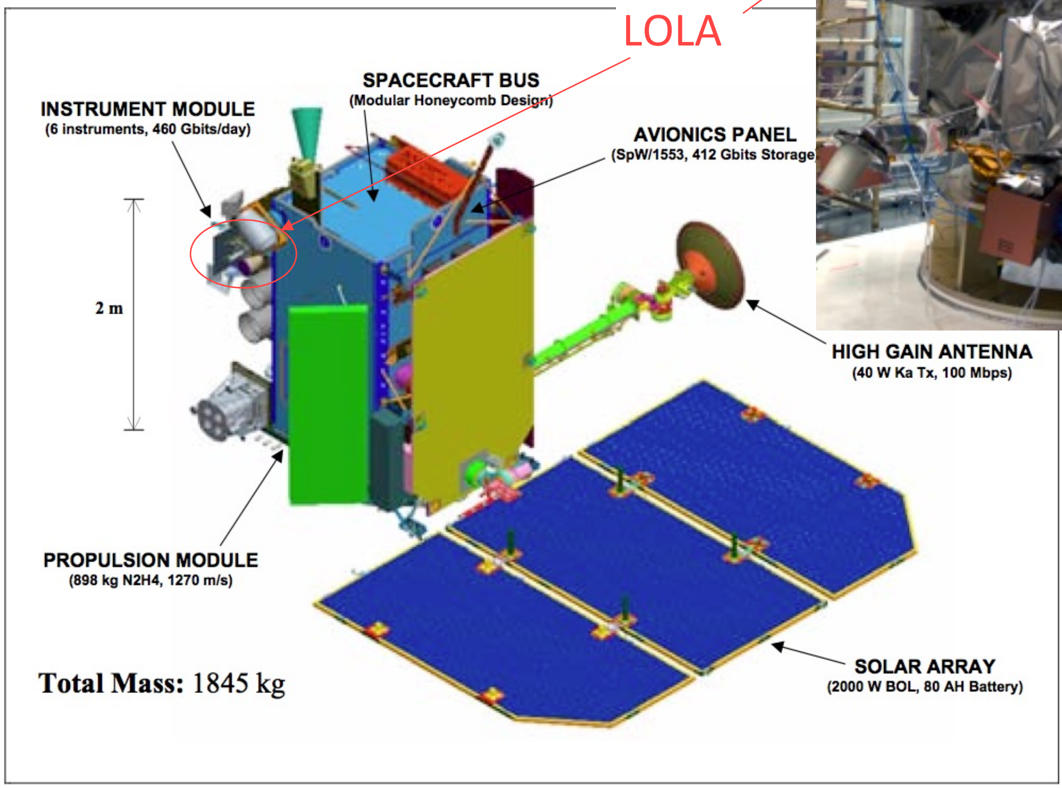
Topographic models from the Lunar Orbiter Laser Altimeter (LOLA) in support of terrain relative navigation at the moon

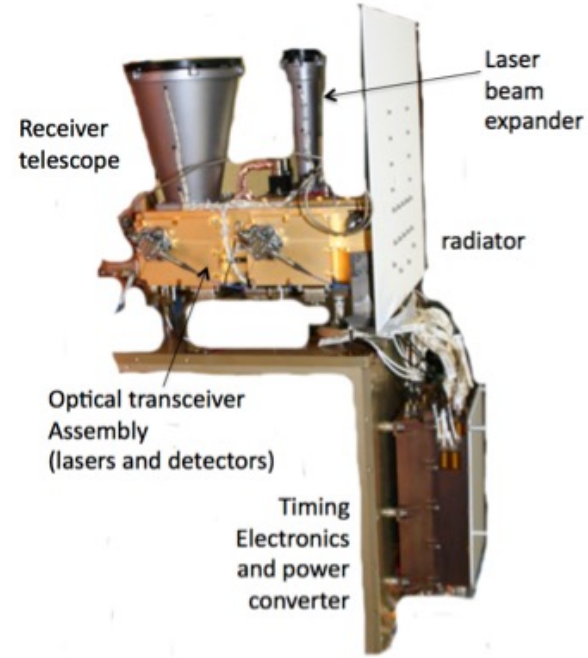
Mike Barker, Erwan Mazarico & LOLA Science Team

Lunar Reconnaissance Orbiter (LRO, 2009)
the Lunar Orbiter Laser Altimeter (LOLA) GSFC/ Lunar Orbit

GSFC

- **Launched June 18, 2009, still in orbit and collecting data**
- LOLA is one of the 7 payload instruments on LRO
- Objectives are to measure lunar surface topography and to establish a global lunar geodetic coordinate system.



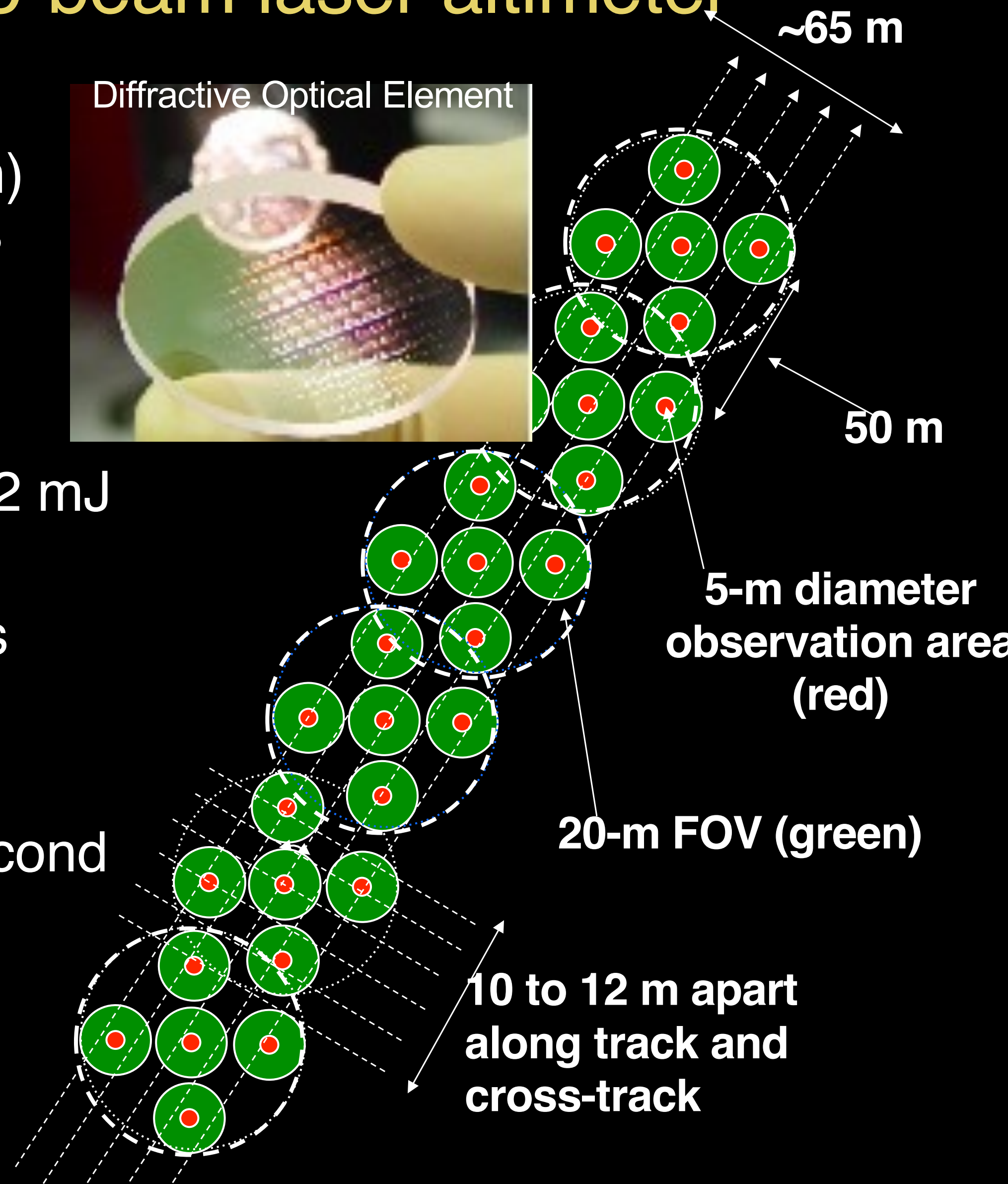


Parameter	Value
Laser Wavelength	1064.4 nm
Pulse Energy	2.7/3.2 mJ (laser1/laser2)
Pulse Width	~ 5 ns
Pulse Rate	28 ± 0.1 Hz
Beam Divergence	100 ± 10 µrad
Beam Separation	500 ± 20 µrad
Receiver Aperture Diameter	0.14 m
Receiver Field of View	400 ± 20 µrad
Receiver Bandpass Filter	0.8 nm
Detector responsivity	300 kV/W
Detector active area diameter	0.7 mm
Detector electrical bandwidth	46 ± 5 MHz
Timing Resolution	0.5 ns

Smith et al., *Space Science Reviews*, 2010

Lunar Altimeter: LOLA is a 5-beam laser altimeter

- Each 5-m spot provides:
  - range to surface (10 cm precision)
  - footprint-scale surface roughness
  - footprint-scale slope
  - 1064-nm reflectance of surface
- Transmitter energy (2 lasers): 2.7/3.2 mJ
- Diffractive Optical Element: 5 beams each 100-μrad divergence (red)
- 28 Hz laser, 140 measurements/second
- FOV: 400-μrad each spot (green)
- Detectors: 5 fiber optically-coupled avalanche photodiodes

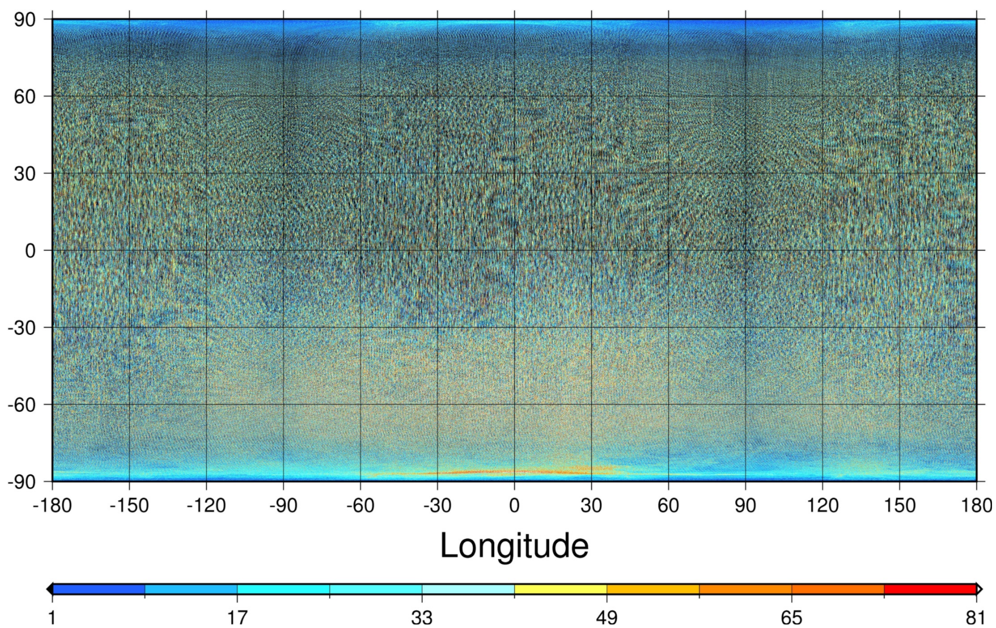


~7 billion surface height measurements

LOLA DEMs on the Planetary Data System

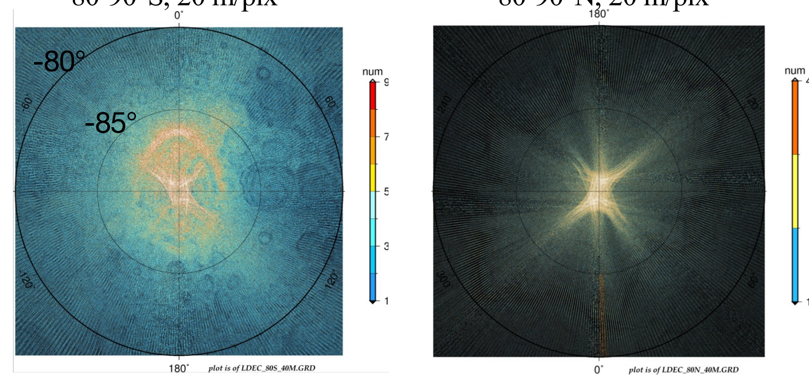
- Data gaps in the DEMs are interpolated, but associated count maps (LDECs) can be used to mask the interpolated values.

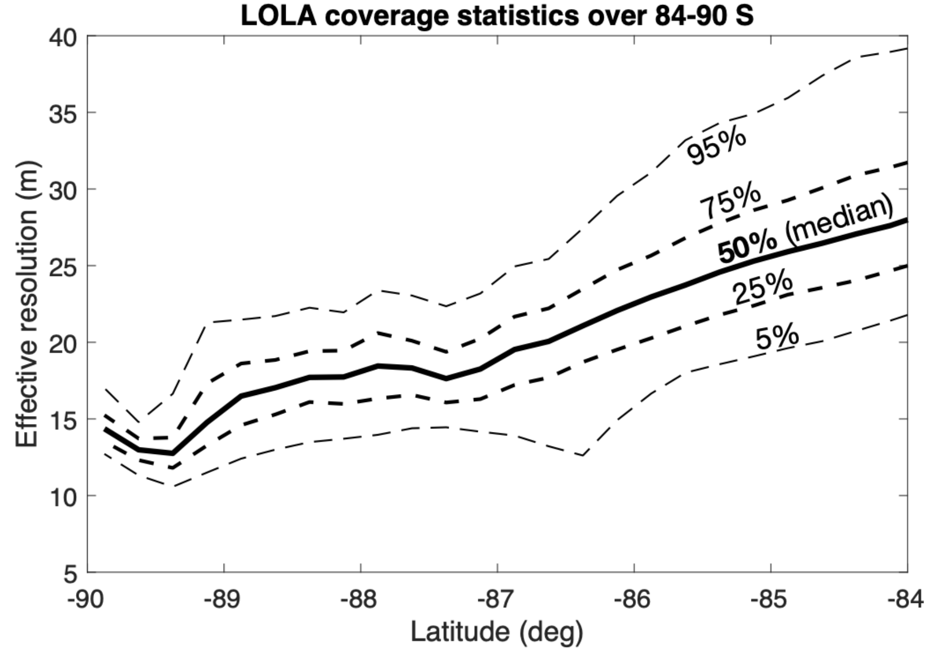
GLOBAL LDEC, 64 pix/°, ~500 m/pix at the equator



80-90°S, 20 m/pix

80-90°N, 20 m/pix

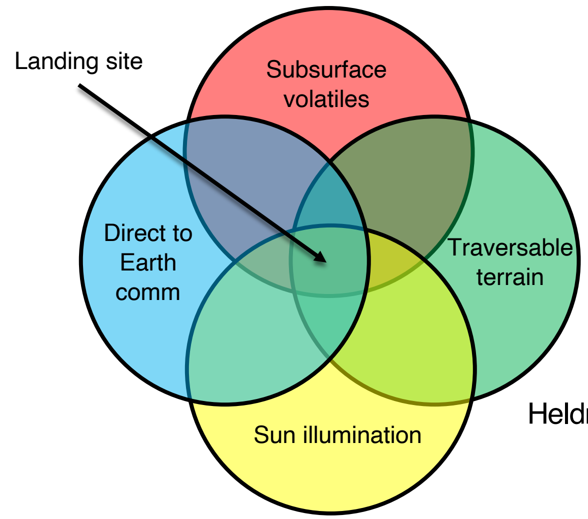




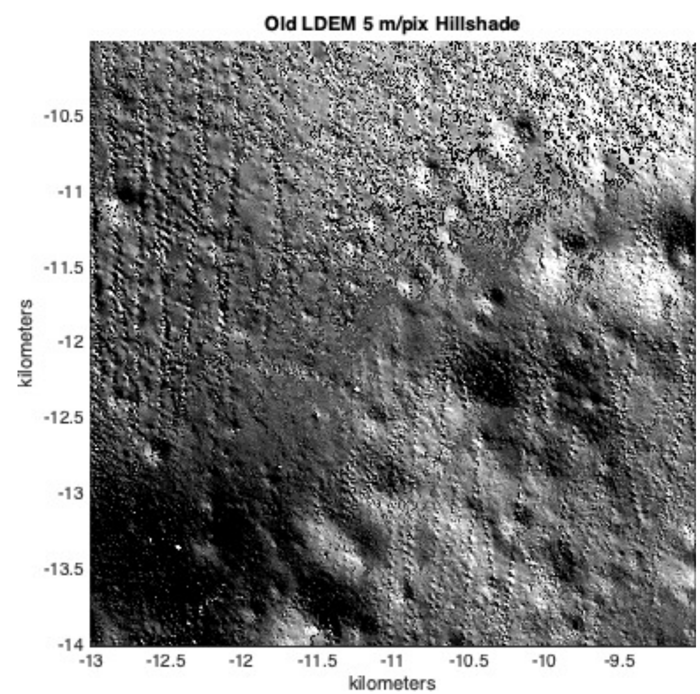
- The count maps can also be used to assess the "effective resolution" of LOLA locally.

Detailed and accurate topographic maps are critical inputs to mission & site planning.

- Subsurface volatiles, traversable terrain, sun illumination, direct-to-Earth comm.
- Need to know the topography both *outside* and *within* permanently shadowed regions on lander-relevant scales (~1-5 m).
- Imaging-based techniques face challenges in polar regions due to the extreme shadowing.
- LOLA not hindered by shadows, but by gaps between tracks and laser spots which require interpolation to fill in.
- Small errors in the LRO orbit reconstruction (~ few meters horizontally & ~0.5 m vertically) can cause streaky artifacts in a LOLA digital elevation model (DEM) at ~5 m/pix.
- Estimating and mitigating these issues are two of the primary goals of this work.



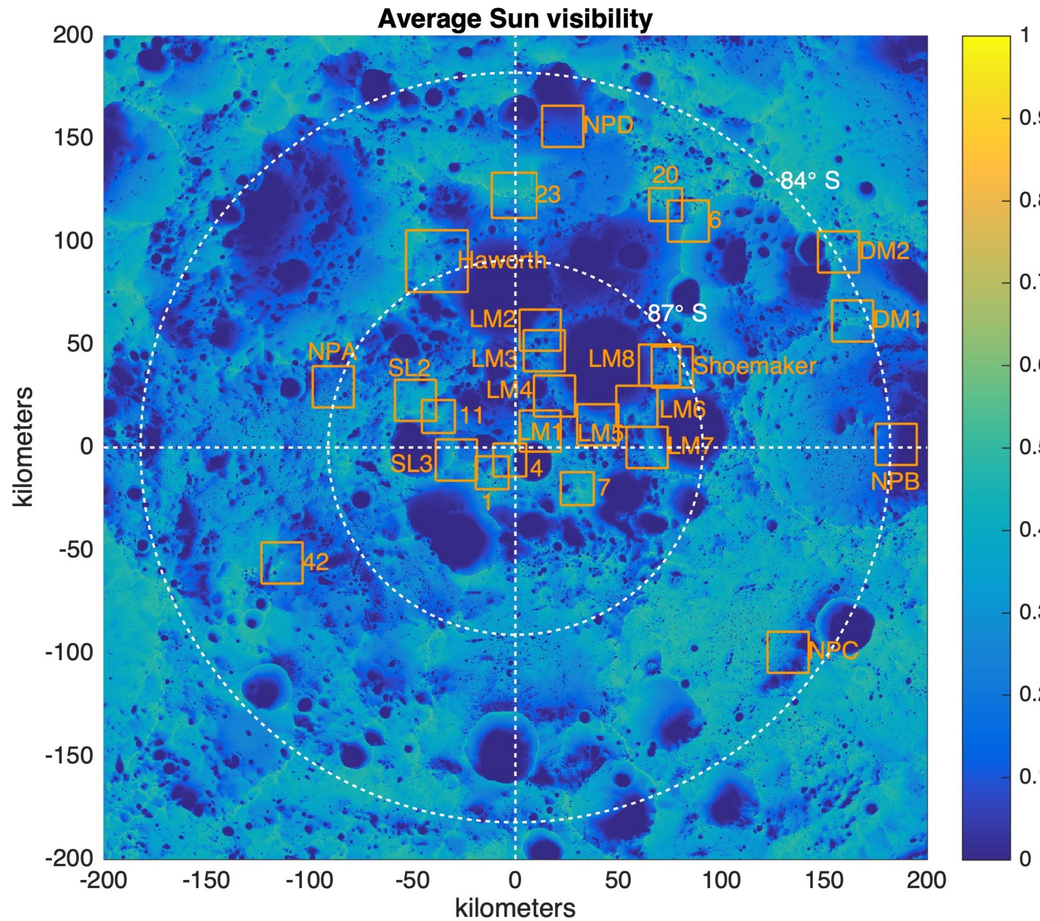
Heldmann et al. (2016)



Recent Efforts: Background

- To support Artemis and CLPS, we are updating the LOLA DEMs and quantifying their uncertainties.
- An updated 5 m/pix LOLA DEM, *with uncertainty estimates*, is more useful to landing site studies and as a constraint to higher-res models.
- Our methodology is applicable to both polar regions, but we currently focus on high-priority south pole sites
- Site 01: ~2500 tracks (~1 million spots), 5 m/pix fill ratio ~ 10%

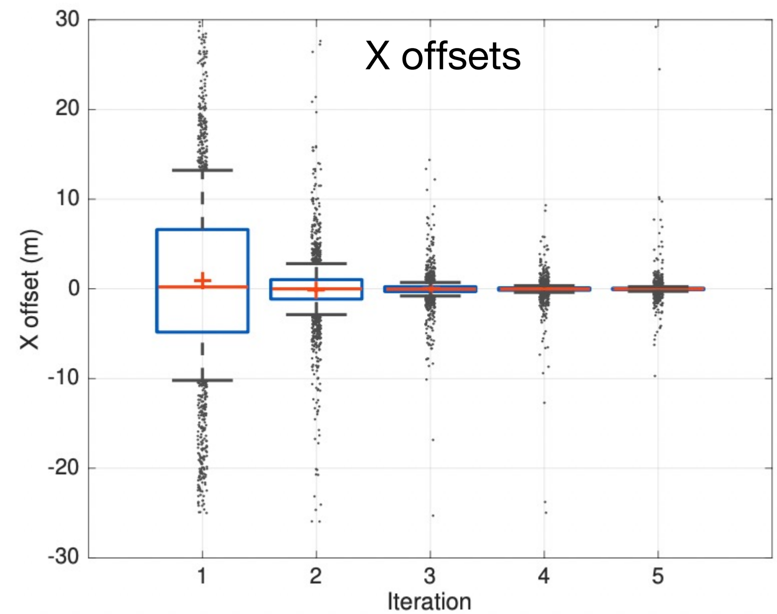
- **DOI: 10.1016/j.pss.2020.105119**
- **Data: https://pgda.gsfc.nasa.gov**

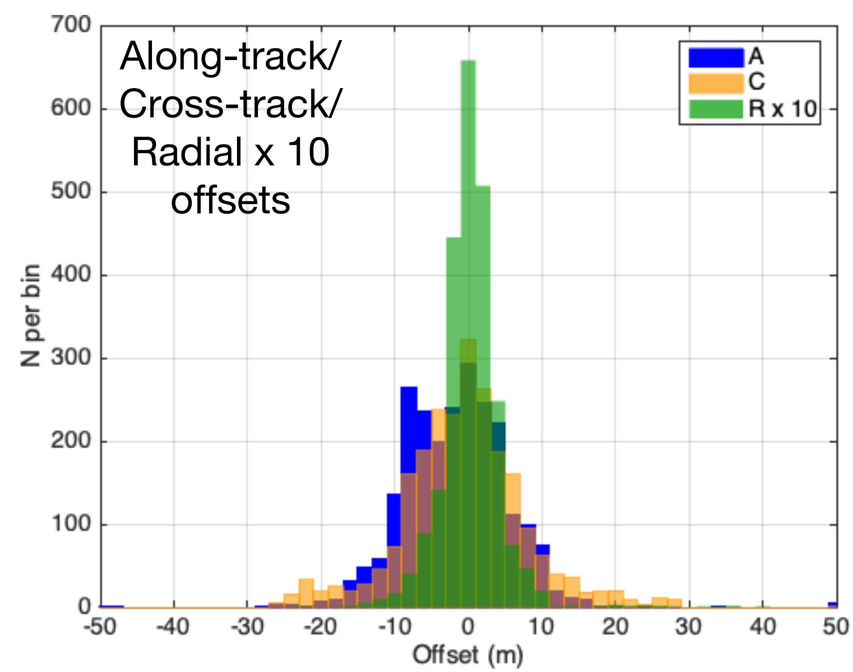


Iterative Adjustment Method

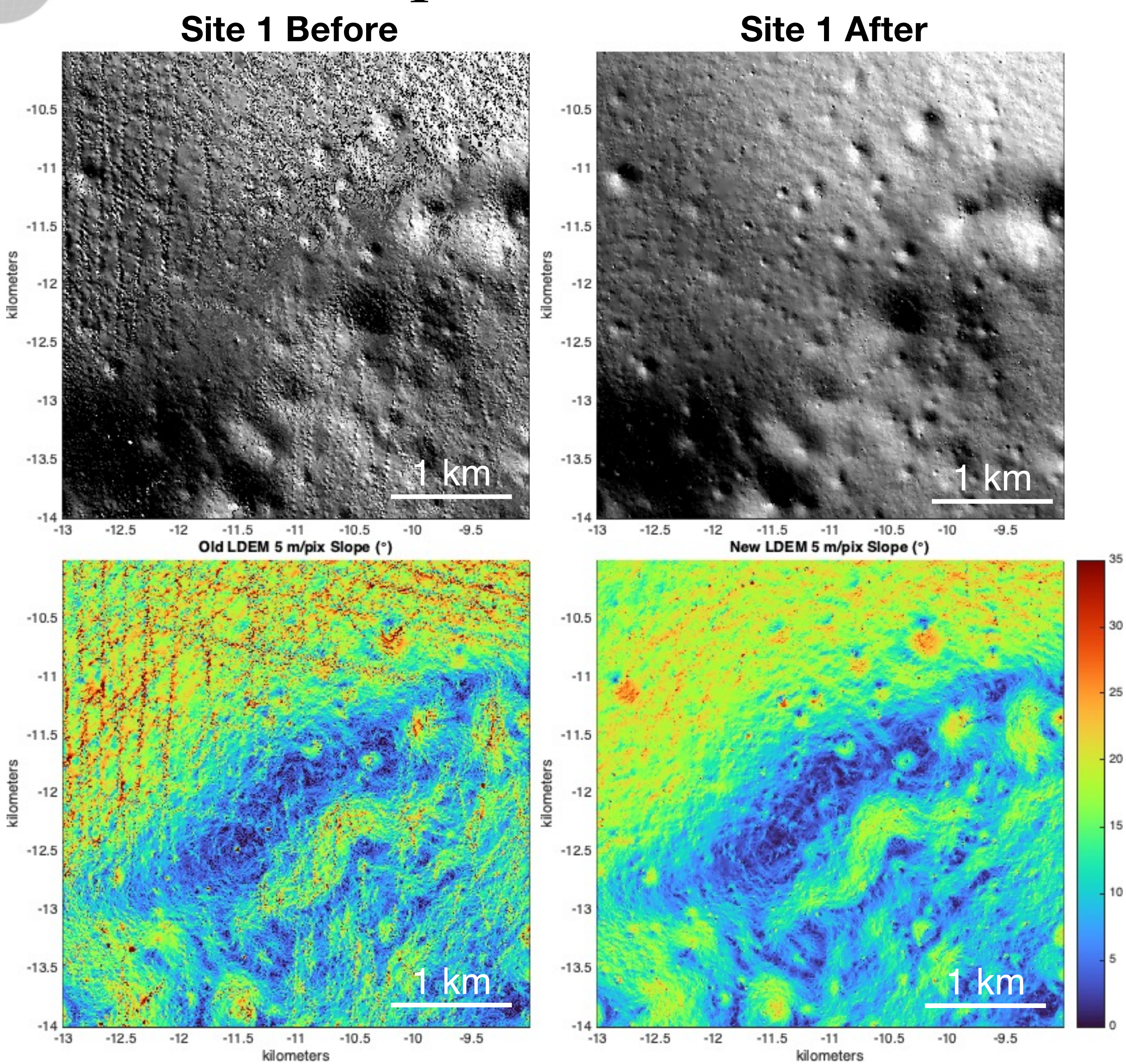
- Based on earlier work: Zuber+ 2012, Glaser+ 2018
- 3-D offsets are estimated for each track against an independent basemap made of 98% of the tracks; so work in 50 batches
  - Track adjustments converge towards zero and their dispersion decreases with each iteration.
  - After 5 iterations, spread of offsets reduced by >10x, to 0.14/0.12/0.02 m
  - Typical along-track/cross-track/radial (ACR) offsets 7.01/6.59/0.27 m, consistent with LRO orbit errors

- We also remove a small percentage (~0.1%) of outliers based on their abnormally high residuals and high slopes relative to local terrain.



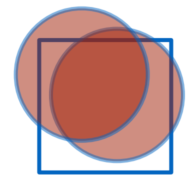


Improved DEM

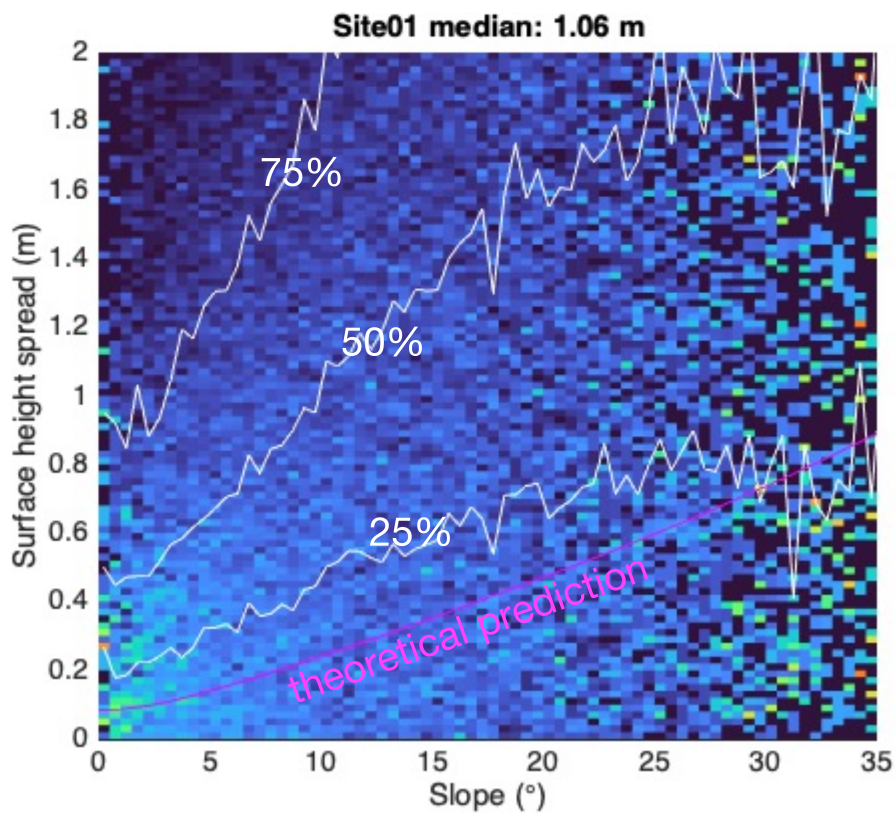


For any given LOLA *spot*, intrinsic range error (10 cm) is now the dominant source of uncertainty in surface height.

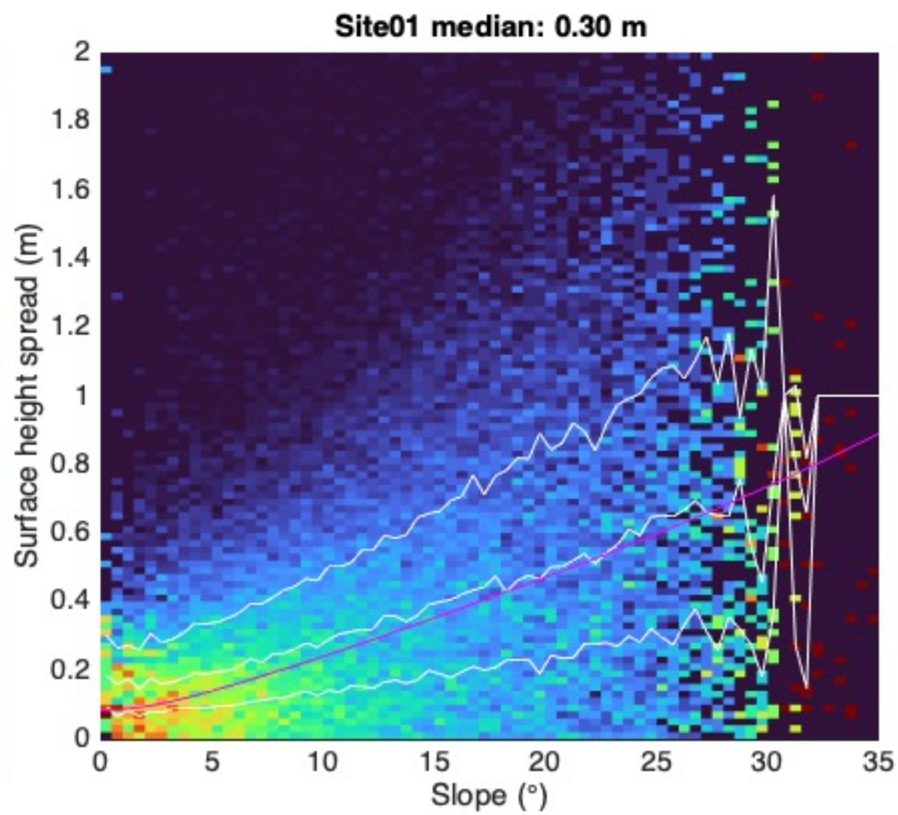
Thousands of "overfilled" (N spots > 1) pixels in the 5 m/pix LDEMs



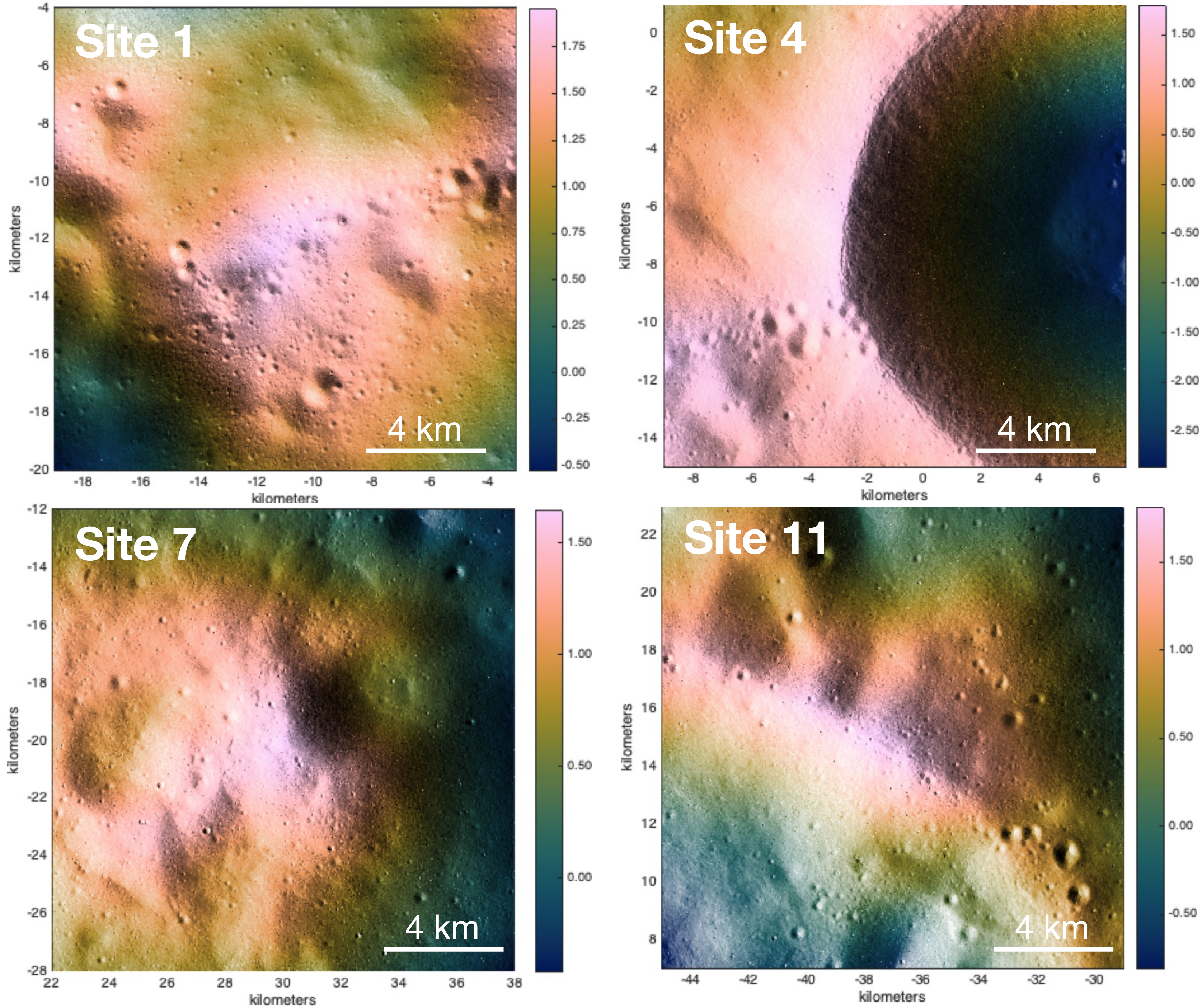
For any given *pixel*, dominant uncertainties: range, sub-pixel sampling (slope & roughness)

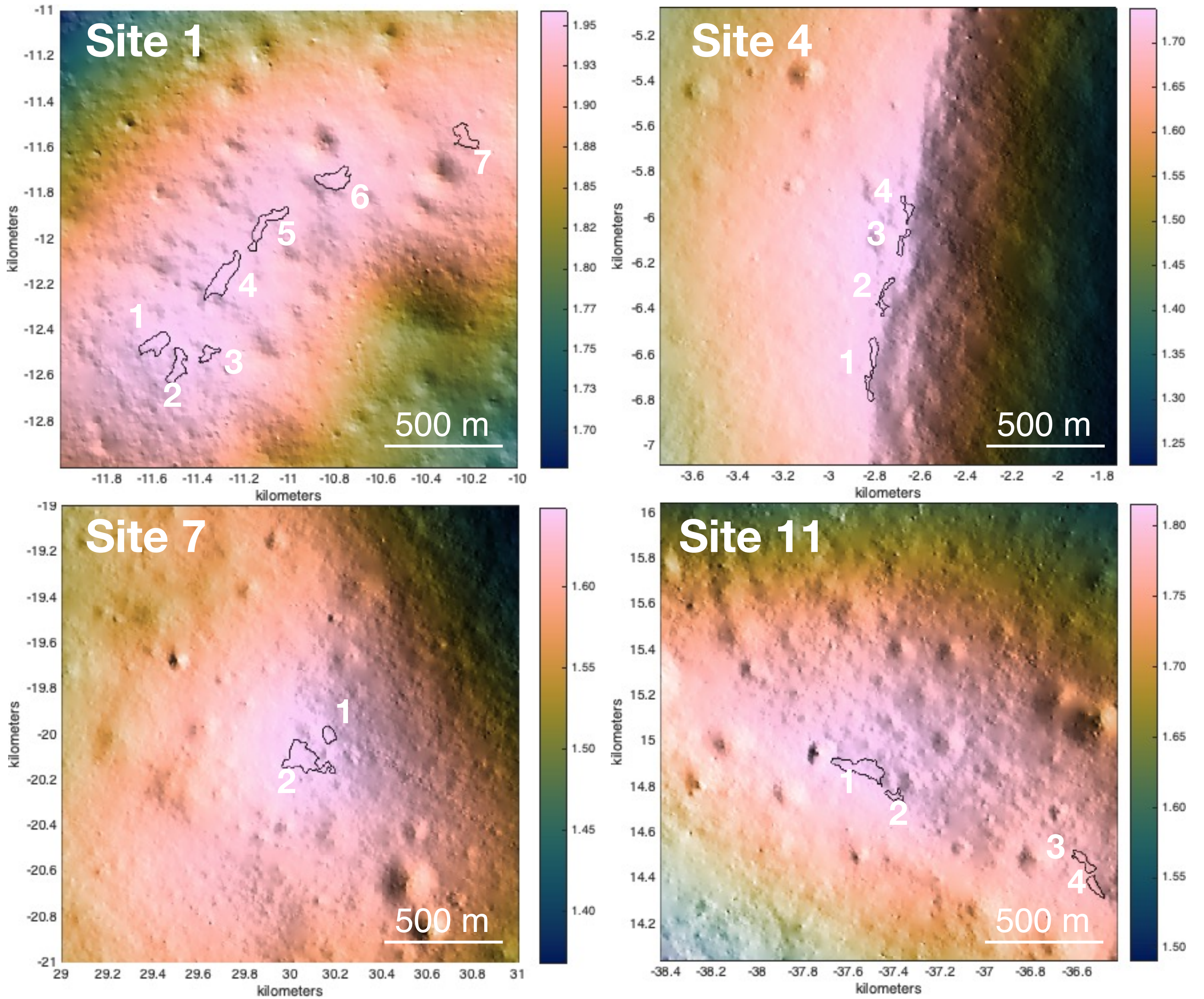


Original LDEM



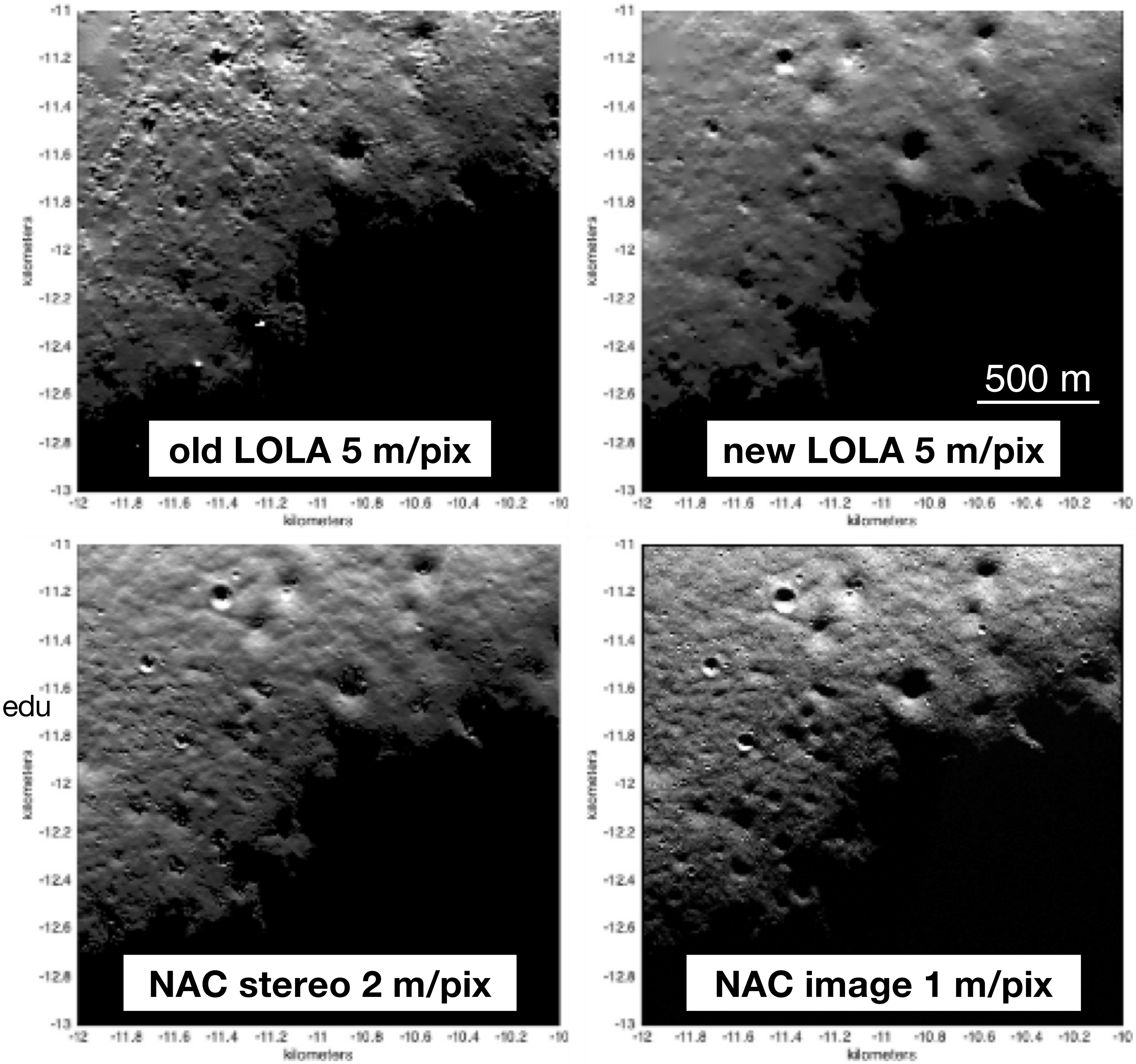
New LDEM


Site 1
Site 4
Site 7
Site 11
4 km
kilometers



black contours show >2500m^2 regions with > 70% average illumination in 2024 - 2025

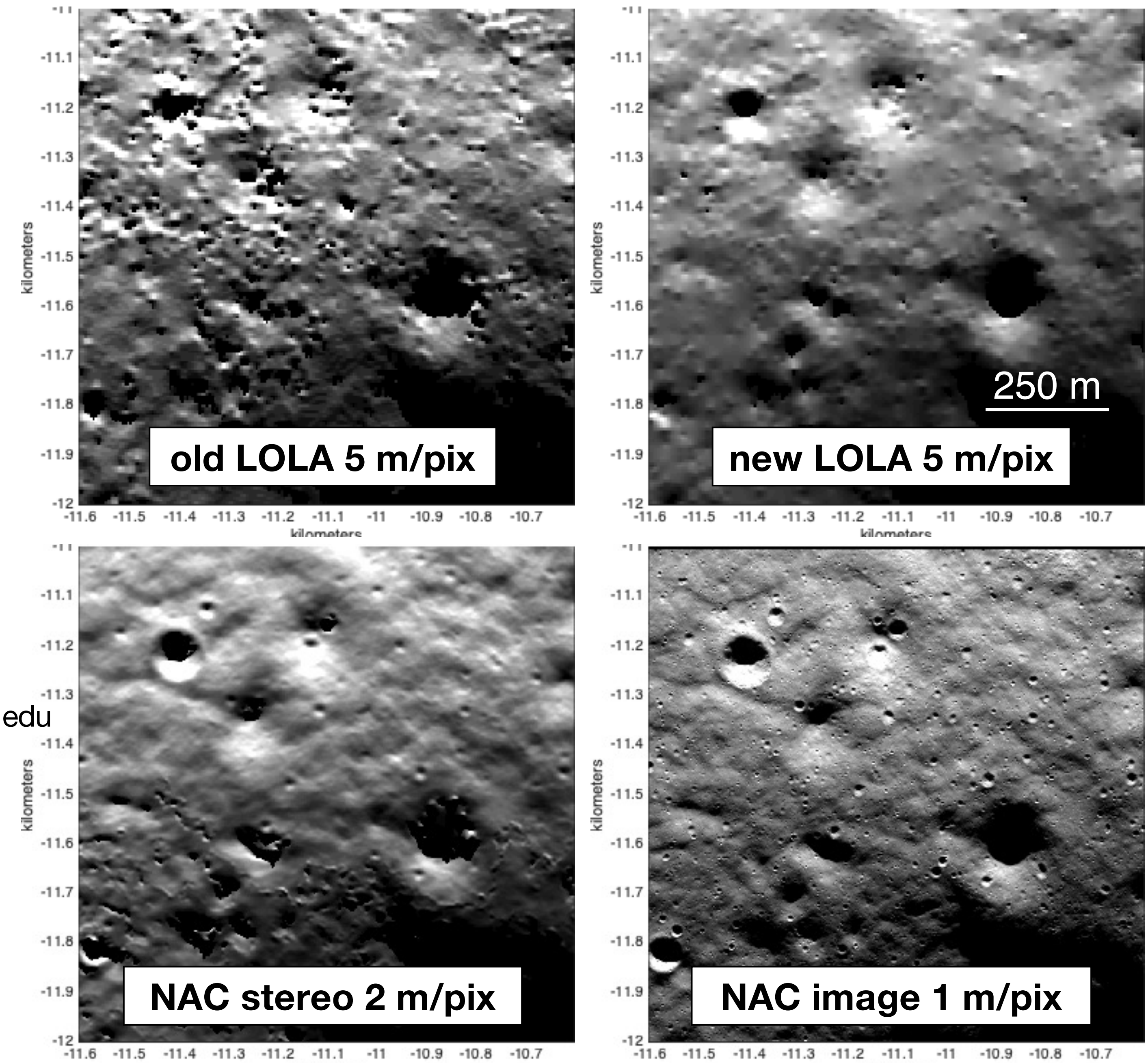
Image Simulation Comparison



Gläser+ 2014
www.lroc.asu.edu

LROC Narrow Angle Camera (NAC) image M139811097L/R

Image Simulation Comparison



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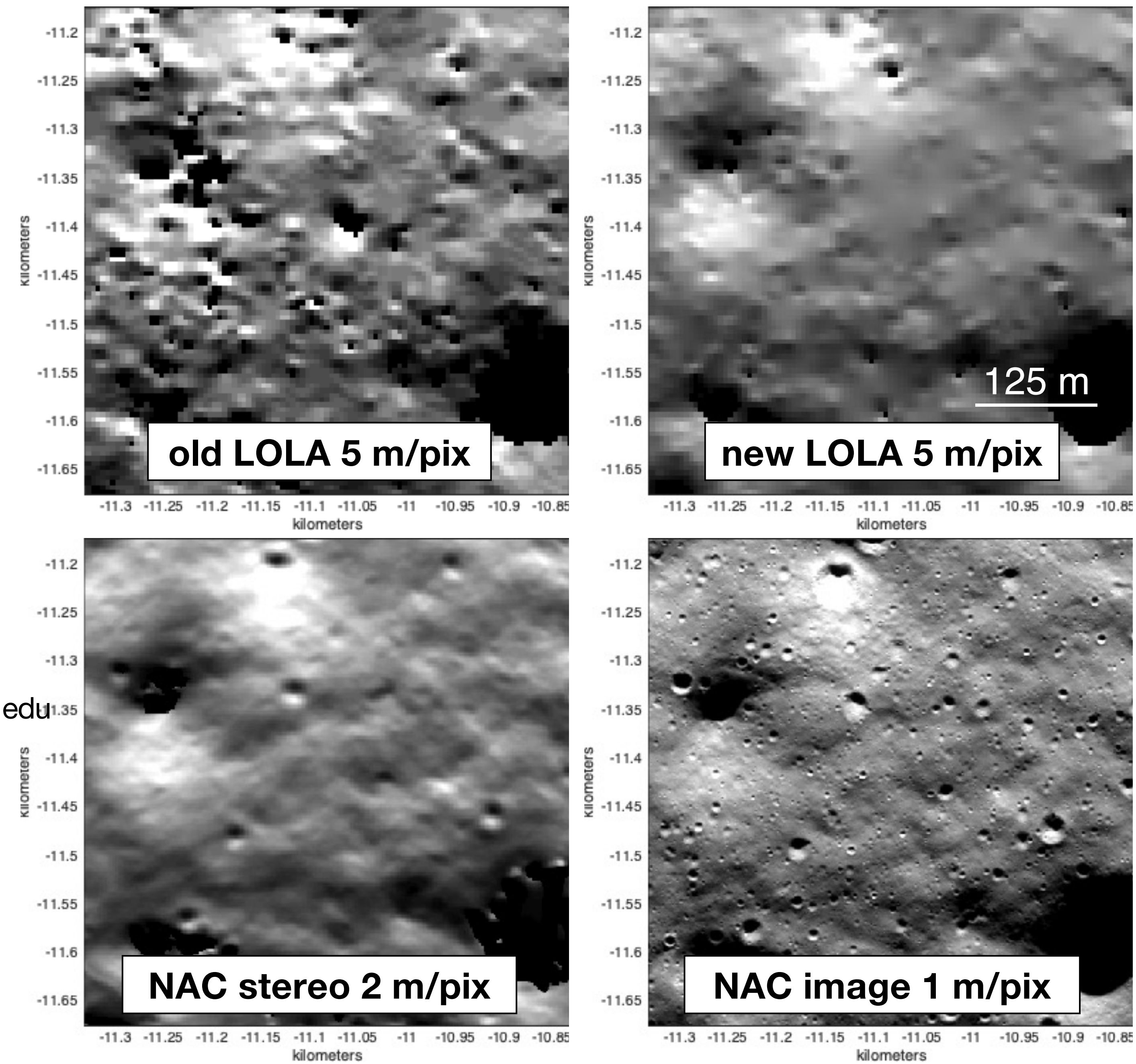

Gläser+ 2014
www.lroc.asu.edu

LROC Narrow
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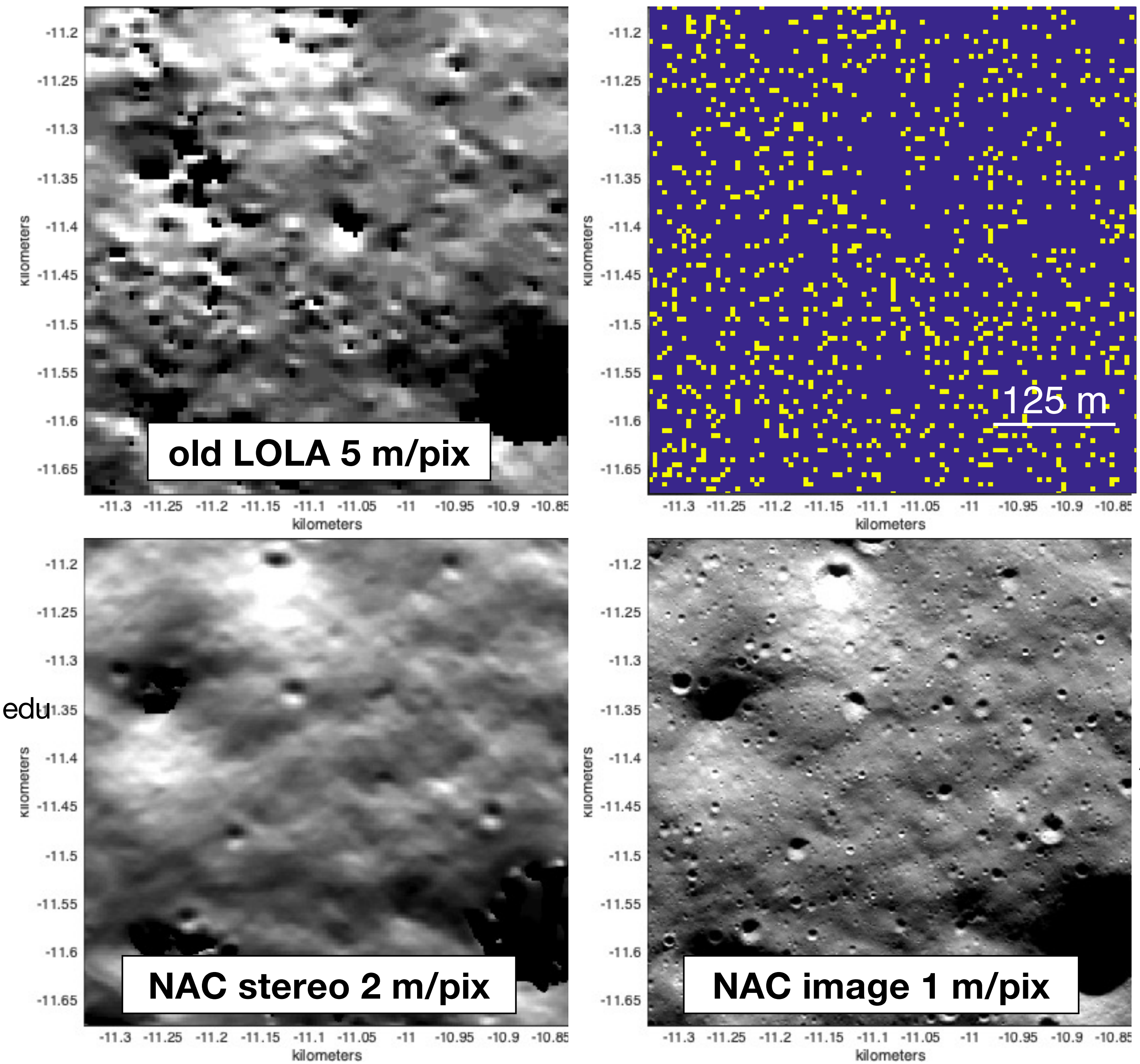

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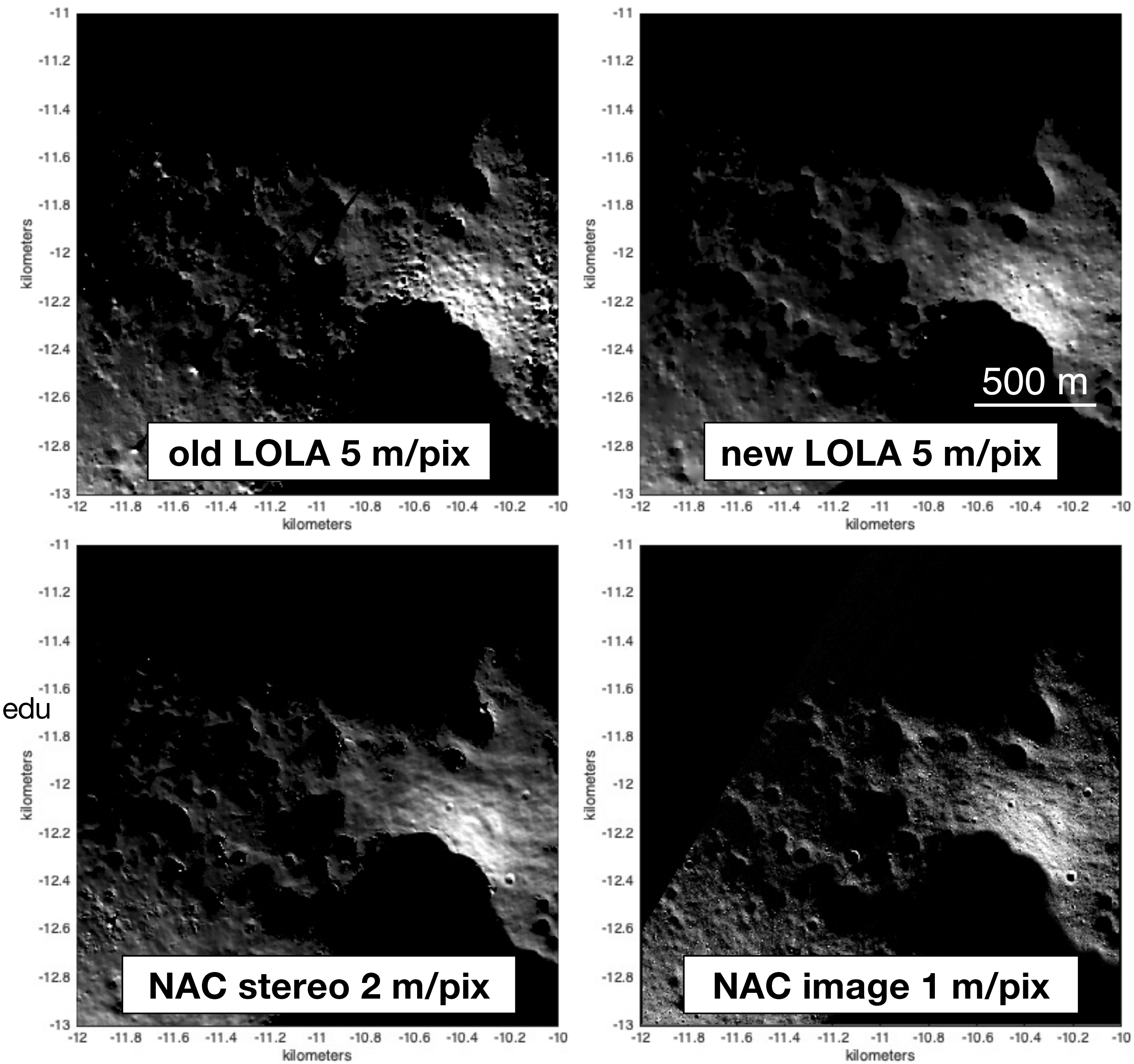
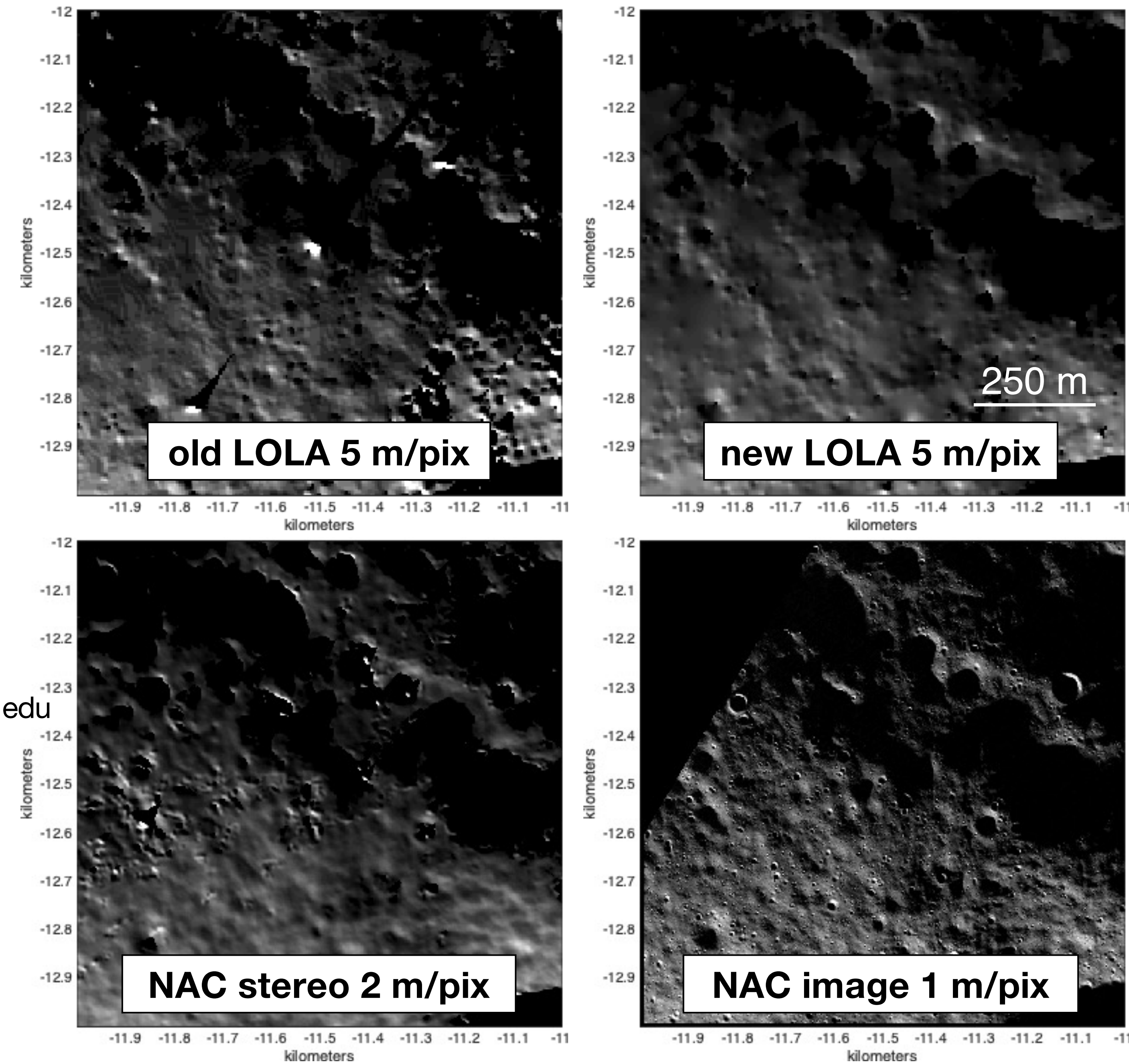


Gläser+ 2014
www.lroc.asu.edu

LROC Narrow Angle Camera (NAC) image M140883298L

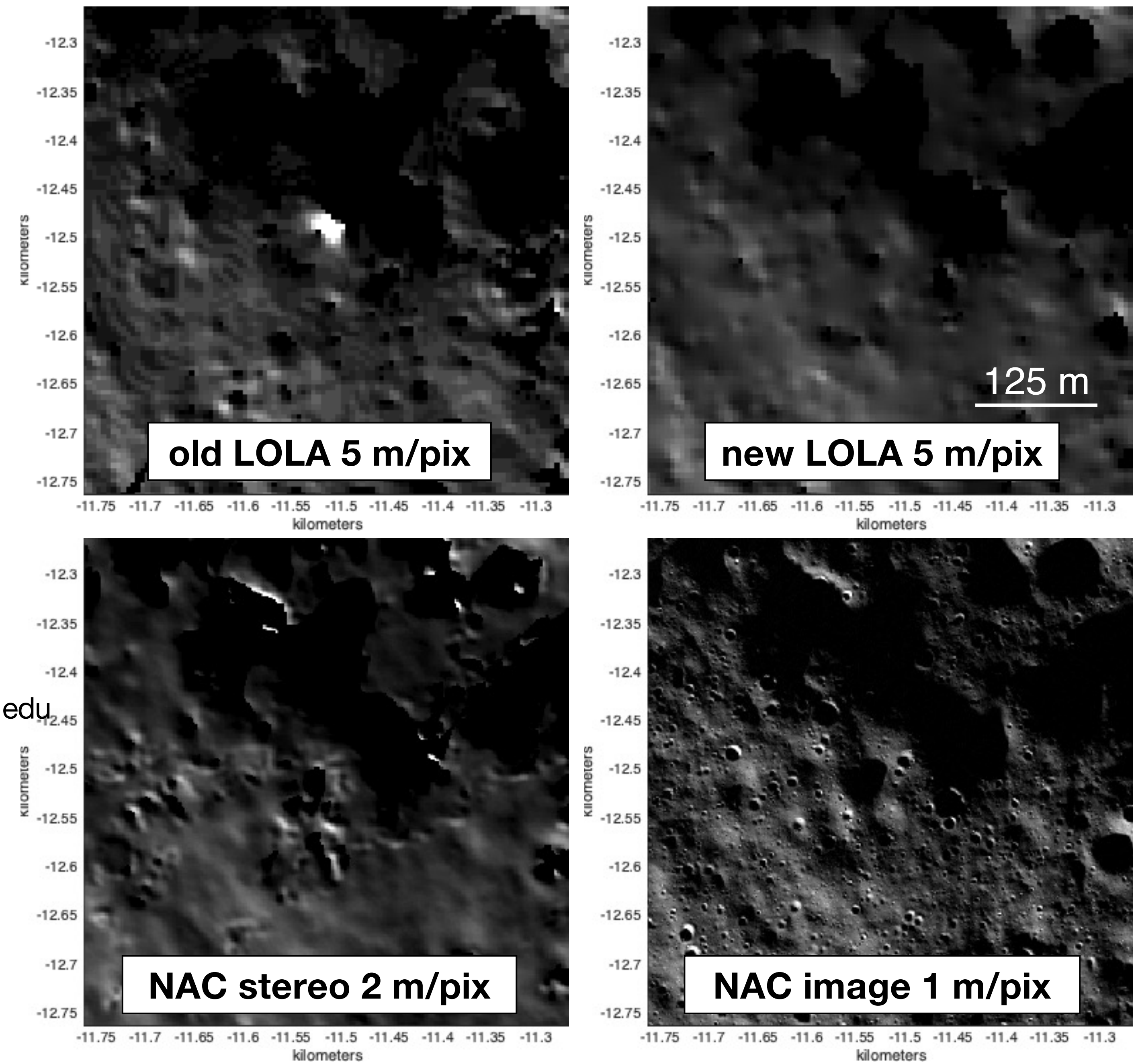
Image Simulation Comparison



Gläser+ 2014
www.lroc.asu.edu

LROC Narrow Angle Camera (NAC) image M140883298L

Image Simulation Comparison



Gläser+ 2014
www.lroc.asu.edu

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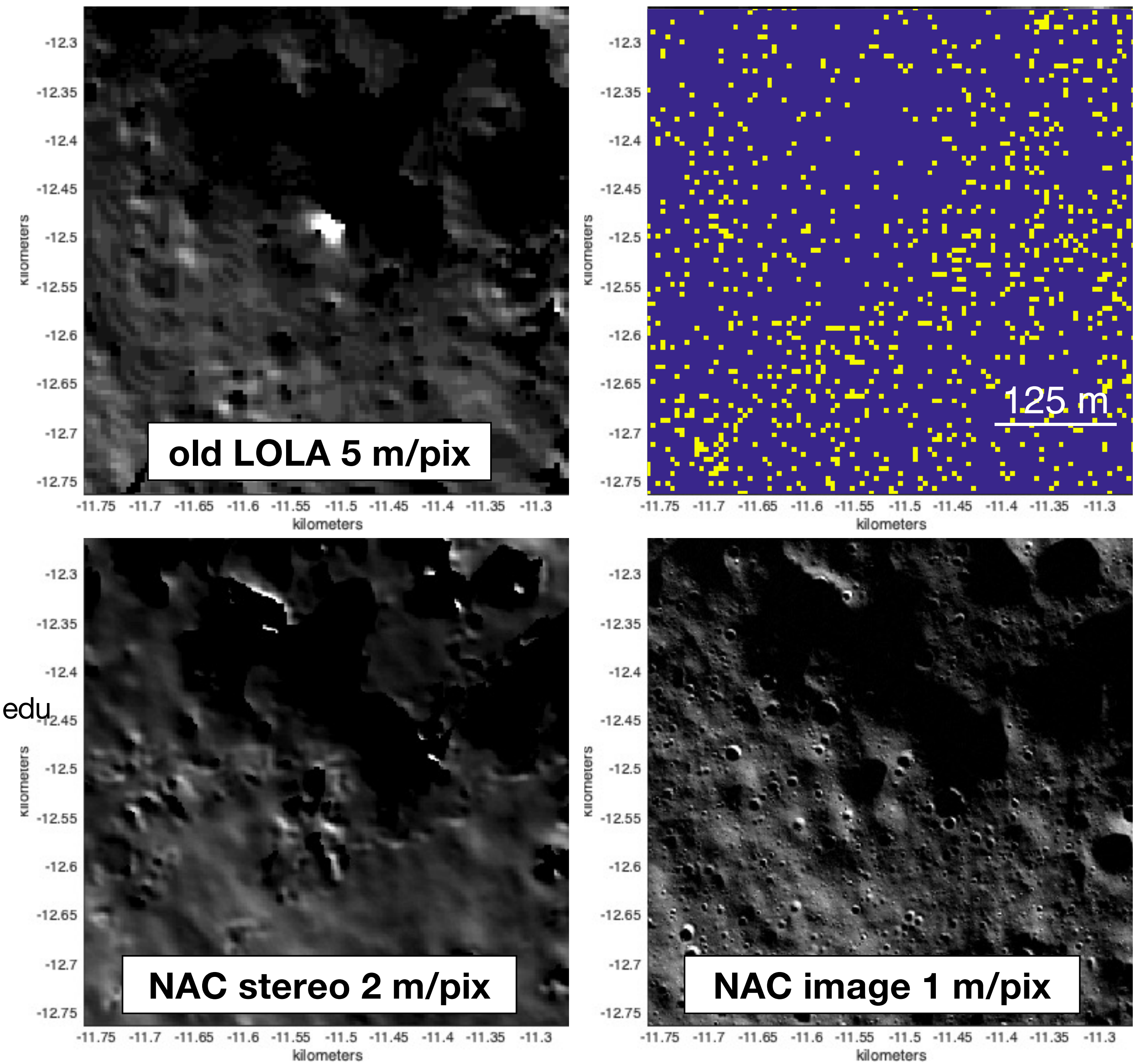
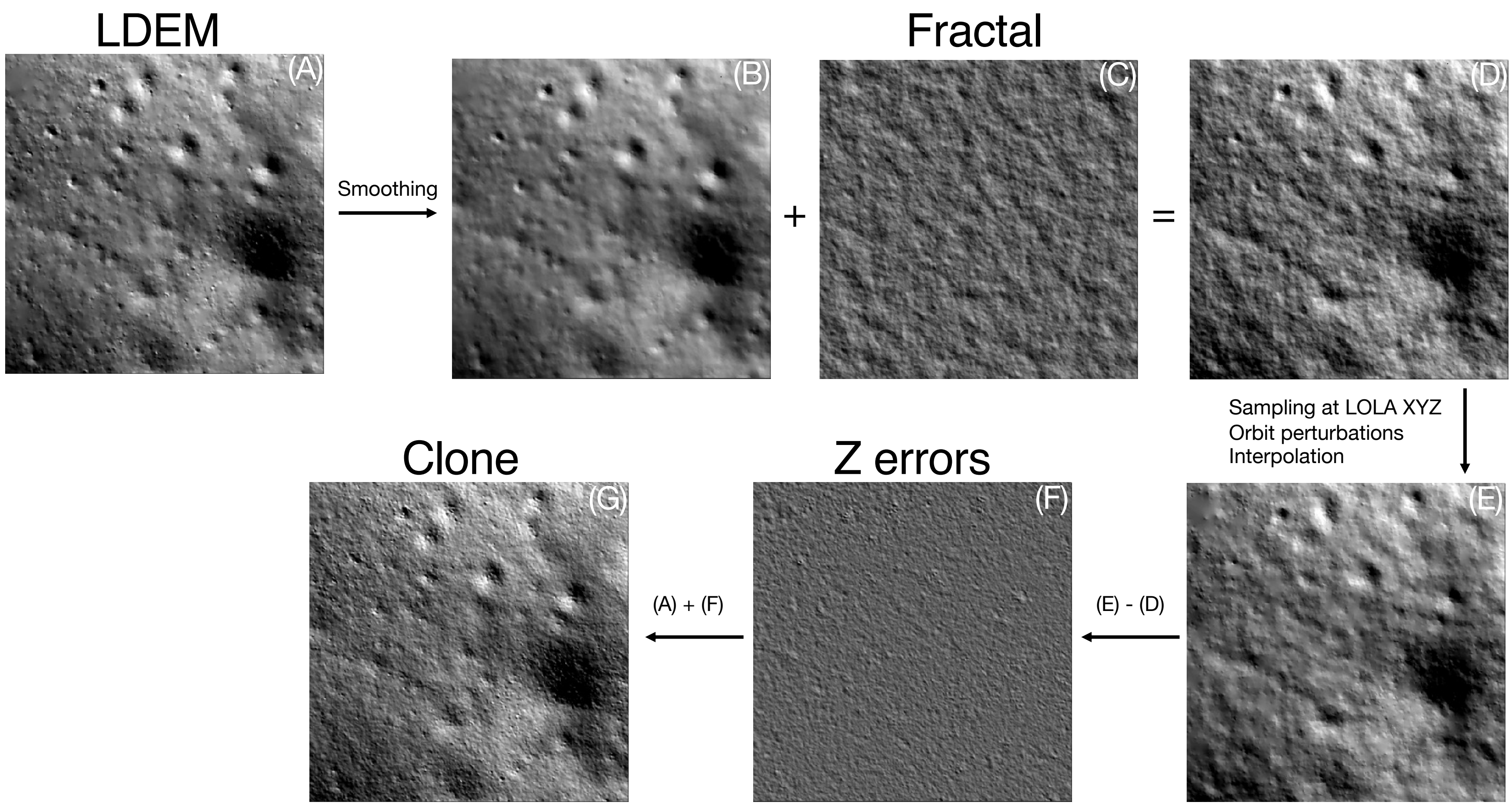


Gläser+ 2014
www.lroc.asu.edu

LROC Narrow Angle Camera (NAC) image M140883298L

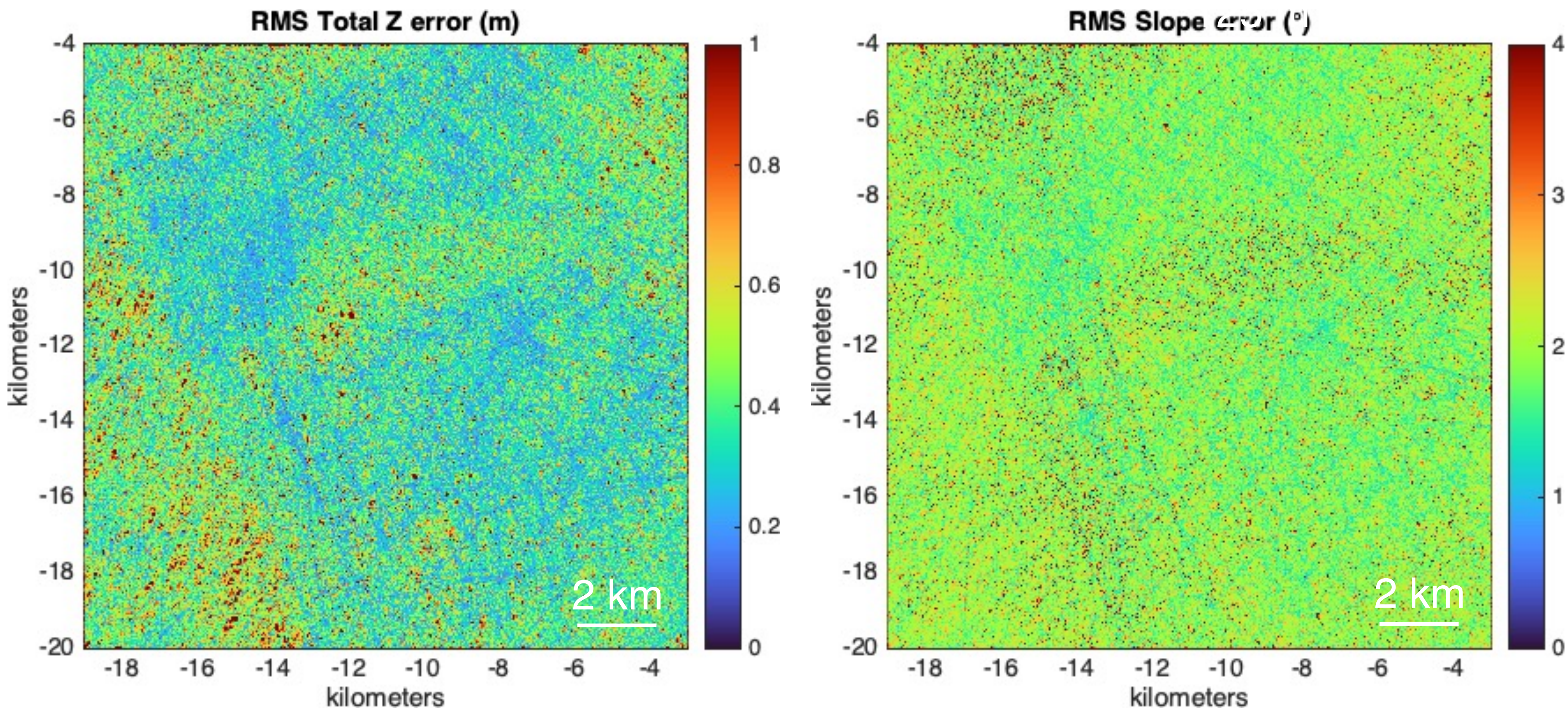
Assessing Uncertainty

- We circumvent the infeasible computation of the full error-covariance matrix of the DEM. Instead, we use the fractal nature of lunar topography to build a statistical ensemble
  - 100 “clones” with similar error properties as the data



Assessing Uncertainty

- Typical height / slope RMS uncertainties are 0.3-0.5 m / 1.5-2.5°
  - Interpolation and slope error are spatially correlated primarily with gap size (effective resolution).
  - Can be used as weight maps when constraining higher-resolution models, solar array height, traverse planning, etc.



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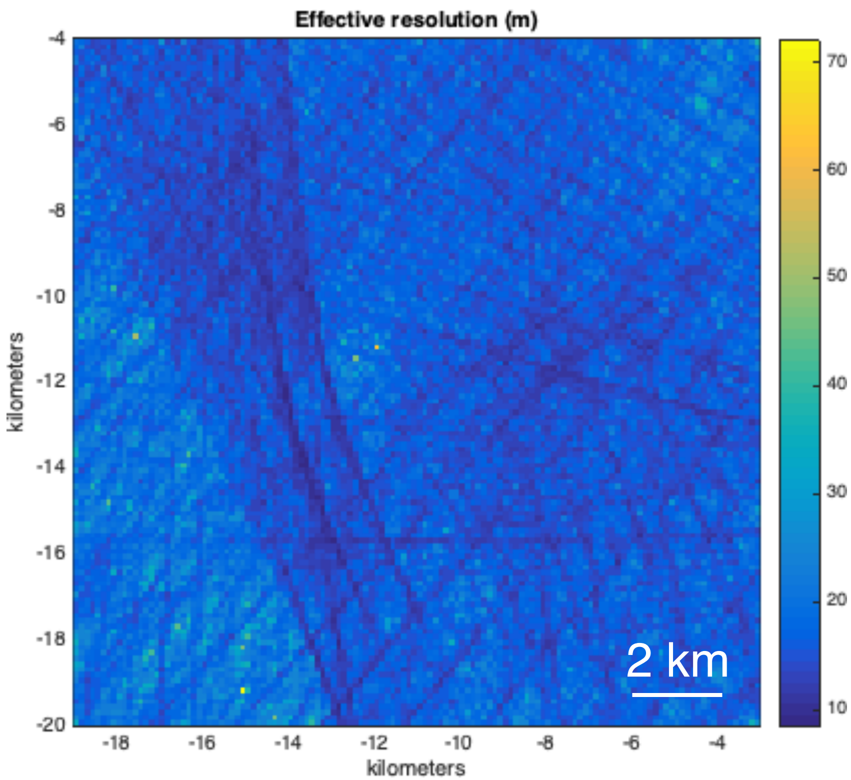
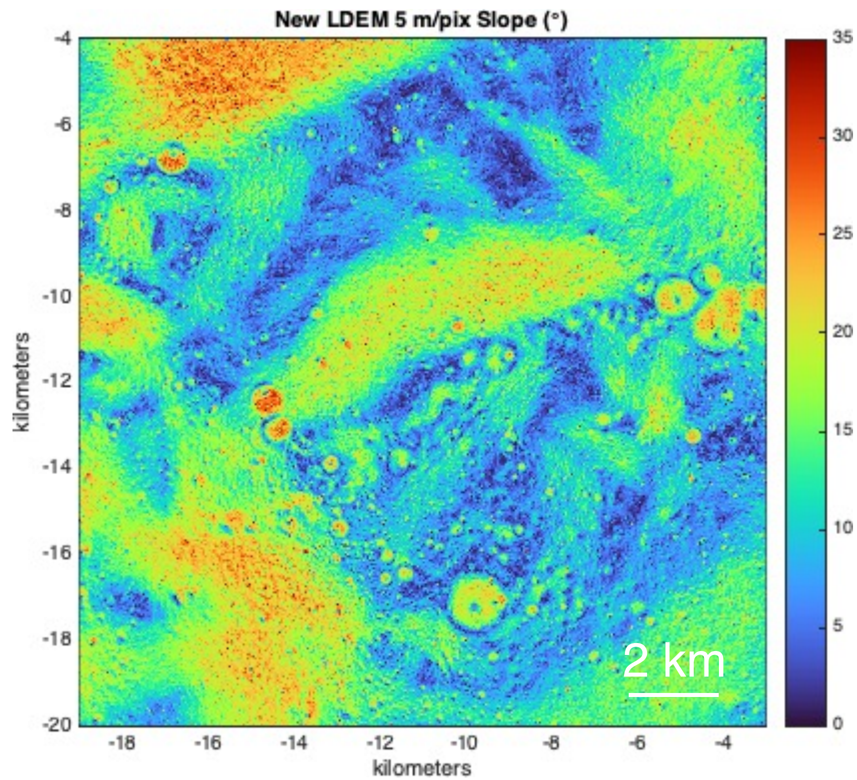
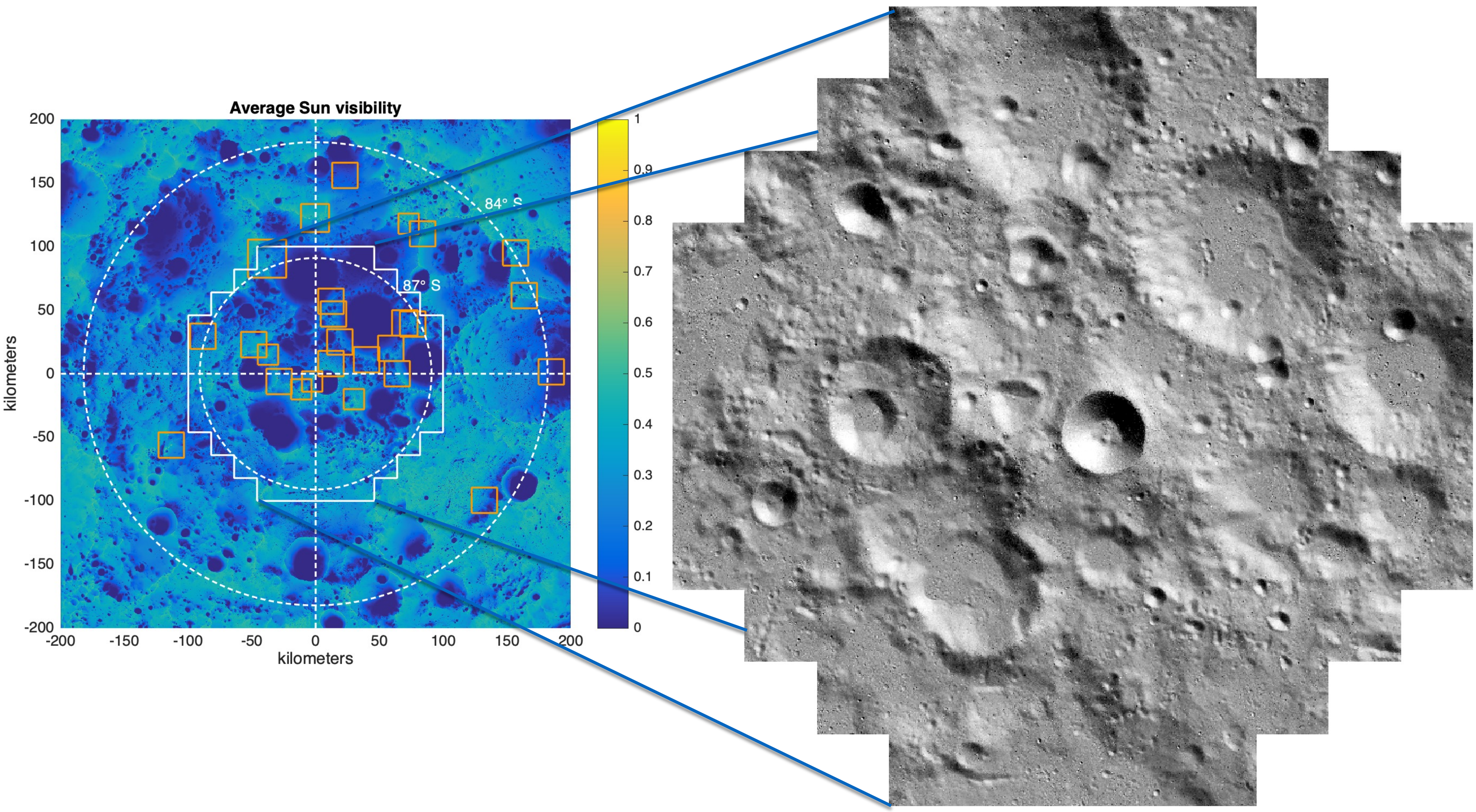




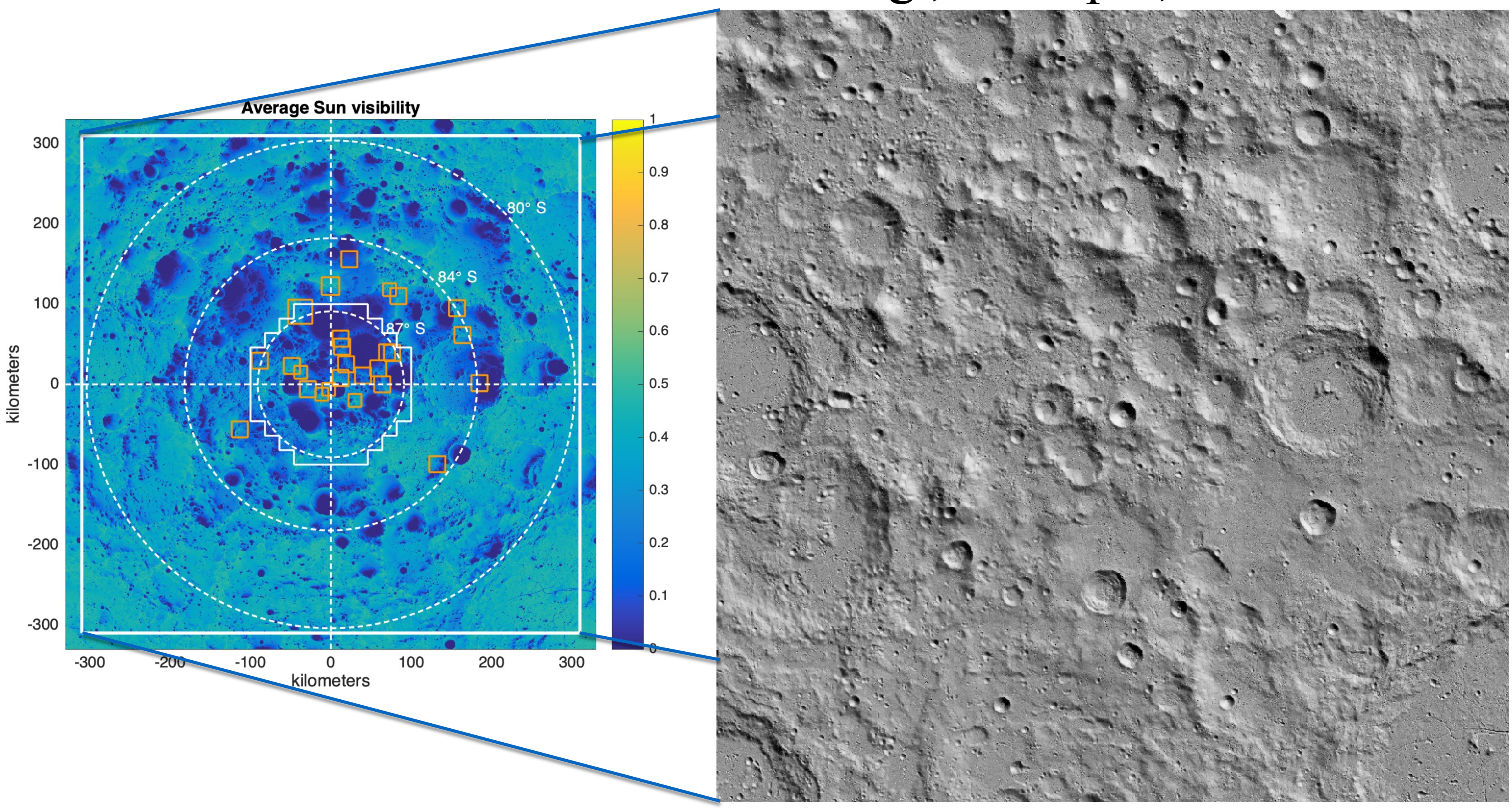
South Pole LOLA 5 m/pix DEM Mosaic



https://pgda.gsfc.nasa.gov/products/81

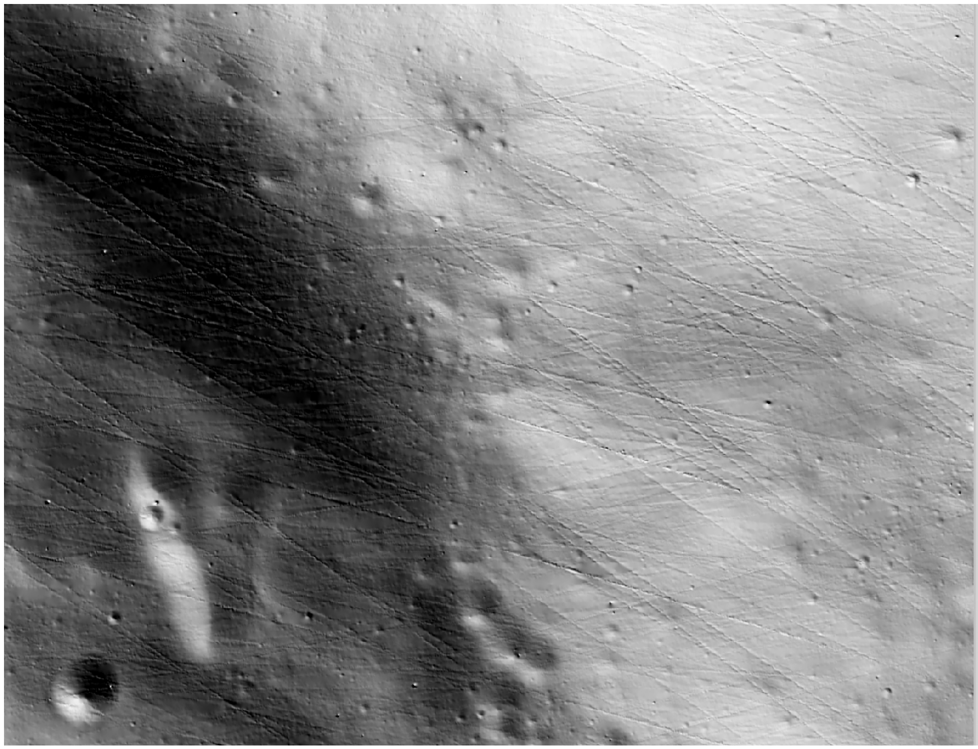
In progress: 10+ m/pix DEM Mosaics

E.g., 20 m/pix, 80-90° S

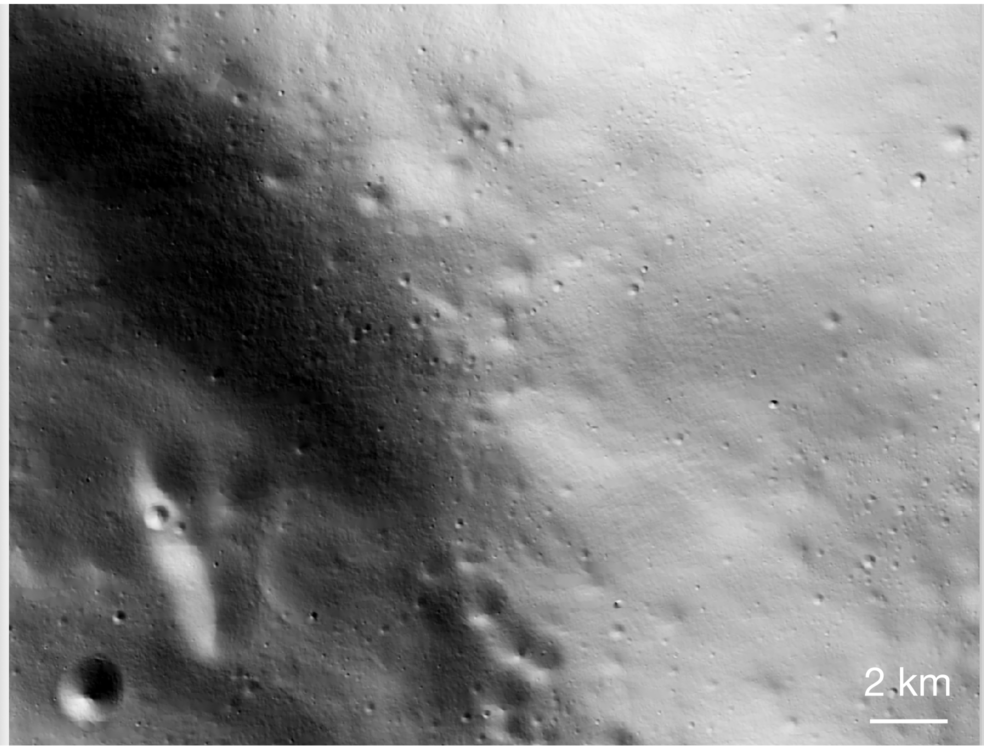


In progress: 10+ m/pix DEM Mosaics

Old

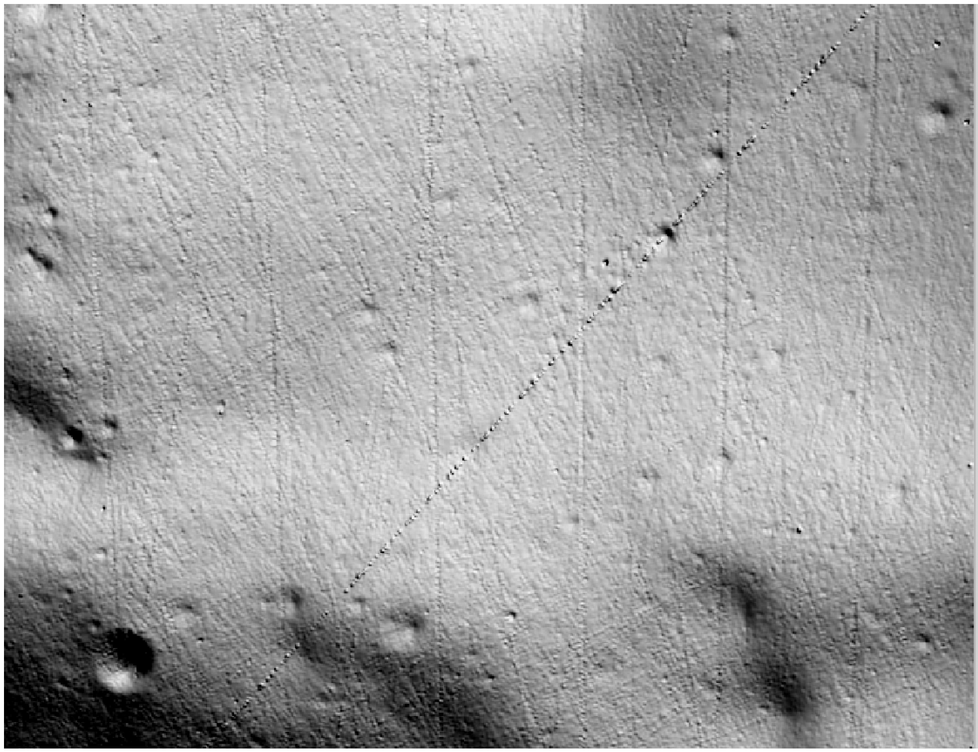


New

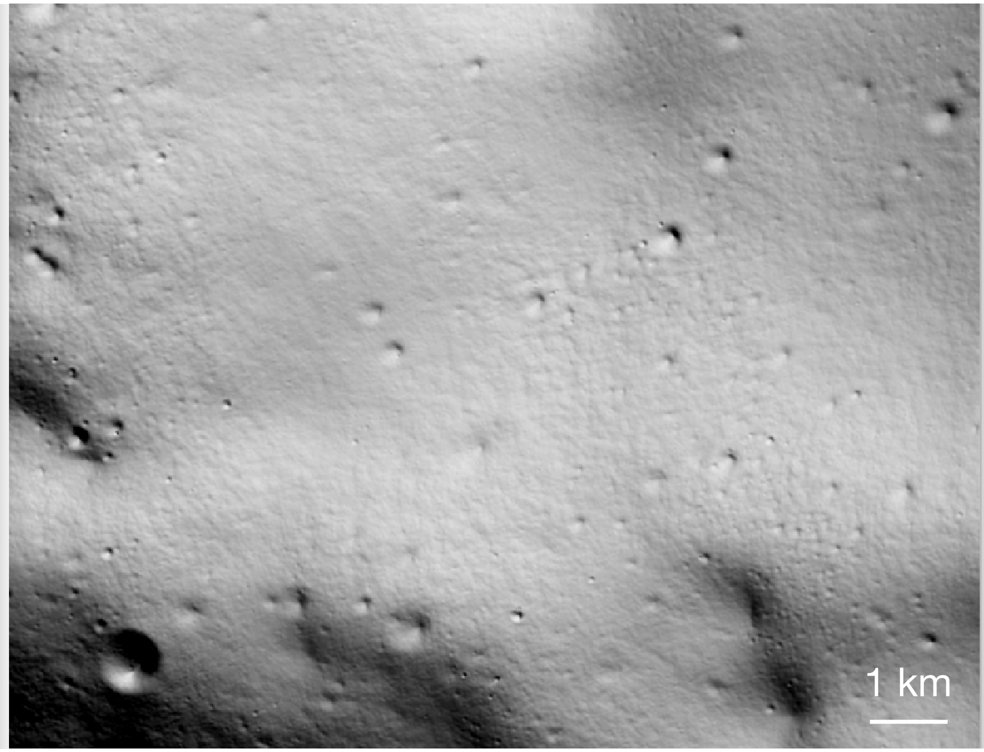


In progress: 10+ m/pix DEM Mosaics

Old



New



Summary

- LOLA provides the geodetic framework for the Moon.
- New high-resolution topographic maps of high-priority candidate lunar south pole landing sites based exclusively on LOLA data.
- These DEMs have accurate geodetic control and are unaffected by shadows. Most of the 5-m pixels are interpolated due to LOLA's cross-track and inter-spot spacing, but the interpolation errors are quantifiable.
- Height uncertainties propagate to variations in horizon elevation and thus the predicted illumination conditions.
- Error characterization can inform landing site studies and figures of merit.
- For small-scale detailed site studies, we recommend using all available datasets together (LOLA, images, image-based DEMs)

Paper: https://doi.org/10.1016/j.pss.2020.105119

Data: https://pgda.gsfc.nasa.gov

The End