Improved LOLA Elevation Maps for South Pole Landing Sites: Error Estimates and Their Impact on Illumination Conditions

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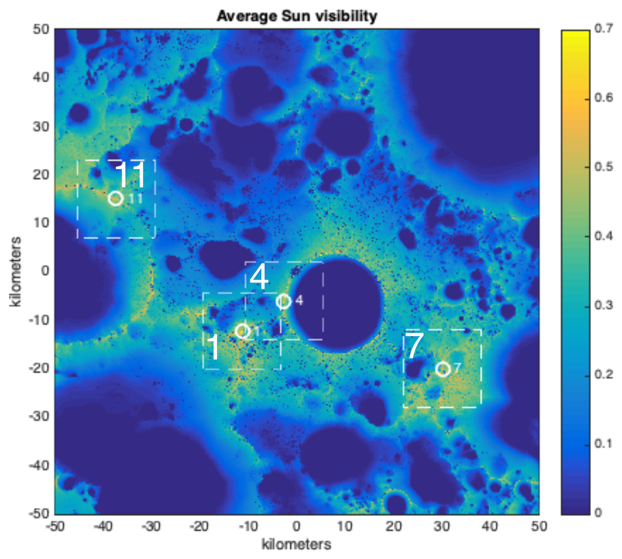
(1) Introduction

- Multiple national and international public- and private-sector organizations are actively planning to send robotic and human explorers to the south pole of the Moon.
- Mission design studies require accurate, precise, and high-resolution maps of surface height, slope, and roughness **both outside and within permanently shadowed regions** [1,2,3,4].
- To that end, we present new high-resolution (5 m/pix) topographic models of 4 high-priority lunar south pole landing sites based exclusively on laser altimetry data acquired by the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter.
- New track adjustment techniques, similar to those applied in [2,5], reduce the ground track geolocation uncertainty by over a factor of 10x, to ~10 – 20 cm horizontally and ~2 – 4 cm vertically.
- These new DEMs are substantially more realistic than the old versions and will be useful to constrain higher-resolution topographic models derived from imagery, which are not as well controlled geodetically and which can be hindered by shadows.

A major advantage of this process is that, for the first time, we can estimate realistic LOLA DEM height uncertainties and their effect on illumination conditions.

(2) Locations

- Presently focusing on the 4 highest-priority South Pole (SP) sites from [6]:
  Site 1, 4, 7, 11.
- We hope to extend the process to the entire region south of -84°.
- Here we focus mostly on Site 1, the "Connecting Ridge."
- Site 1 dataset consists of ~2500 tracks with ~1 million returns in 16x16 km region.
- Resolution: 5 m/pix, for which ~10% of pixels are filled, the rest interpolated.

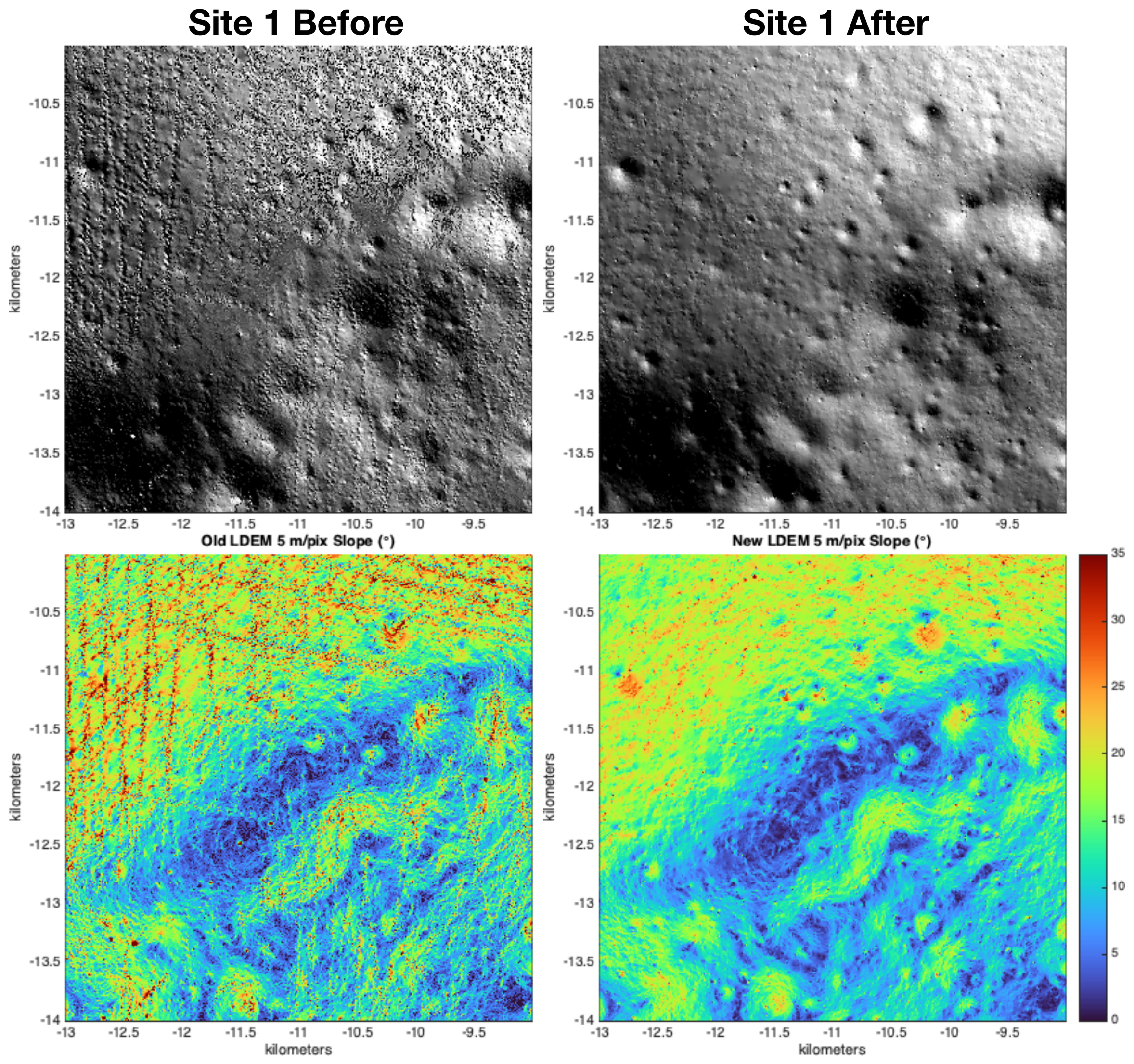


(3) Adjustment Method

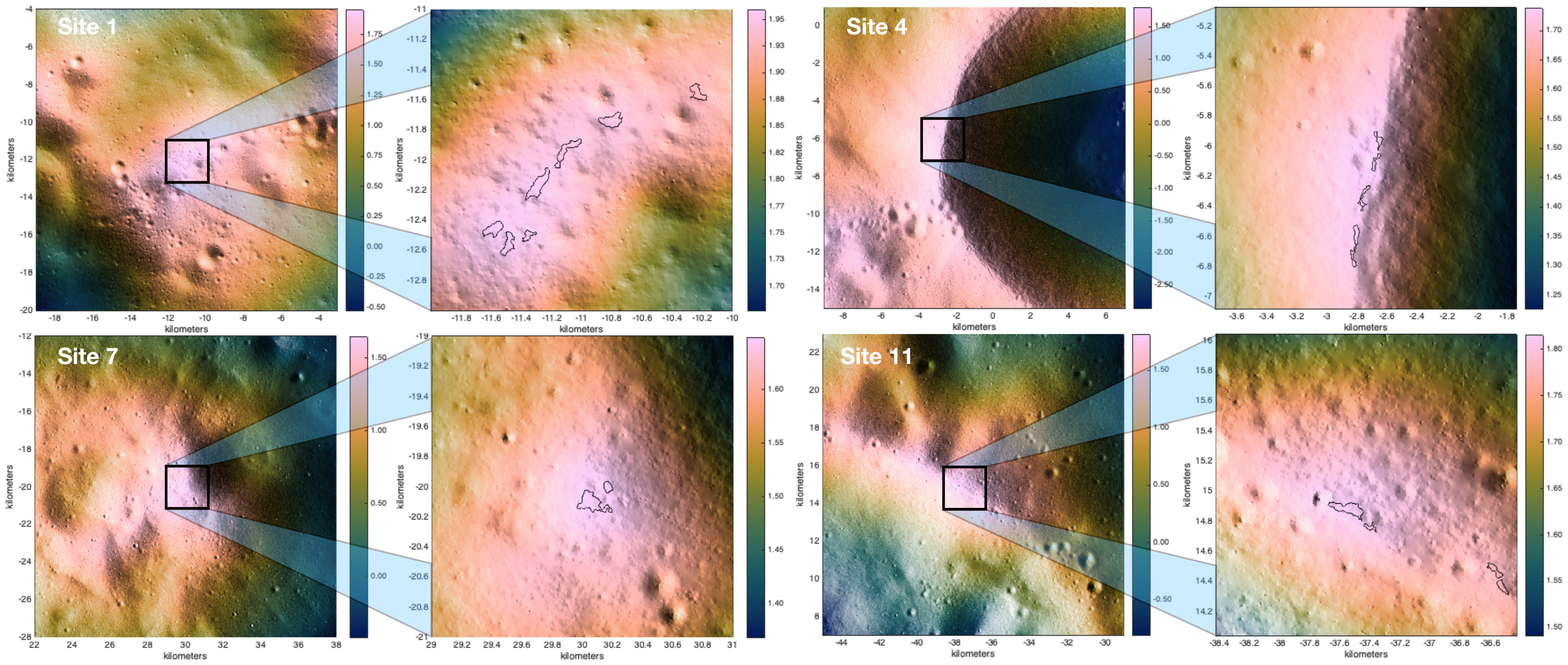
We randomly remove 2% of the tracks from the 5 m/pix LOLA DEM (LDEM) and adjust each of the missing tracks individually to the resulting "reduced" LDEM. 3-D offsets in the XYZ stereographic directions are applied to minimize the root-mean-squared (RMS) vertical (Z) residuals, repeating until all tracks have been adjusted. The whole process is repeated 5 times in total, each time starting from a new LDEM computed with the best-fit track adjustments from the previous iteration. Track adjustments converge towards zero and their dispersion decreases with each iteration. After 5 iterations, the median X/Y/Z offset is 0.00/0.01/-0.02 m and L1 scale is 0.14/0.12/0.02 m for Site 1 (and similar for the other sites). After the final iteration, we remove a small percentage (~0.1%) of outliers based on their abnormally high residuals and high slopes relative to local terrain.

The track adjustment and cleaning process remove the vast majority of artifacts visible in the hillshade and slope map.

Site 1 Before **Site 1 After**



(4) New 5 m/pix LDEMs



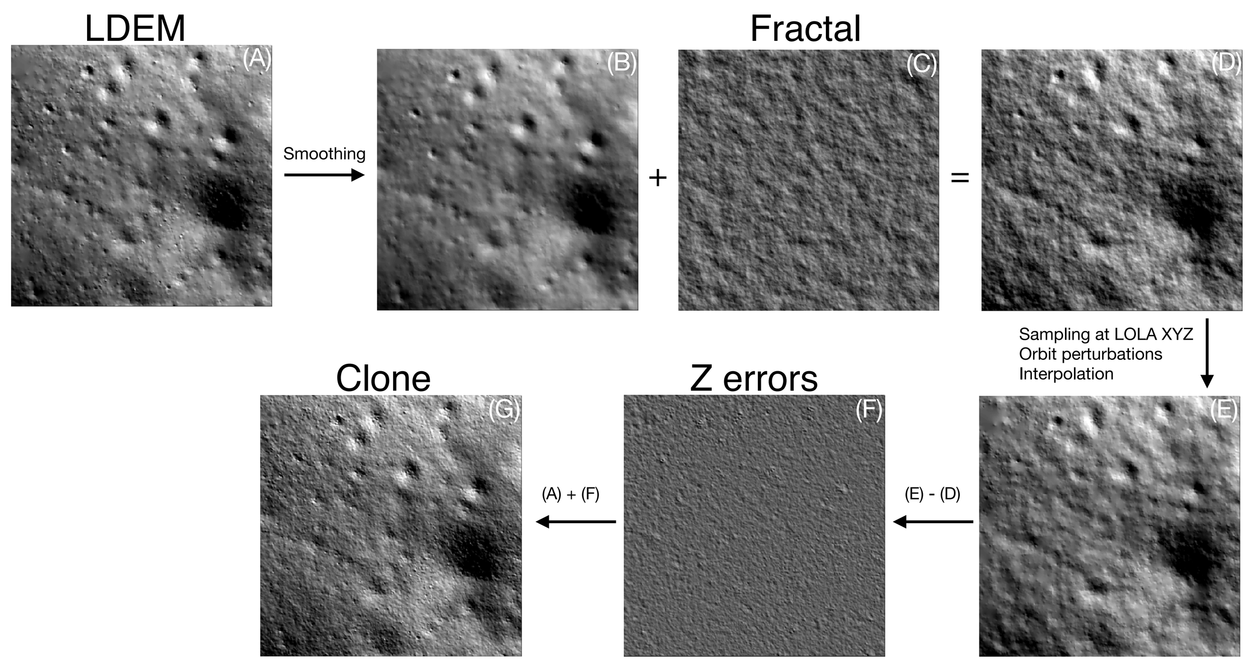
After the LOLA track adjustment process, the **track geolocation uncertainty is ~10 - 20 cm horizontally and ~2 - 4 cm vertically.**

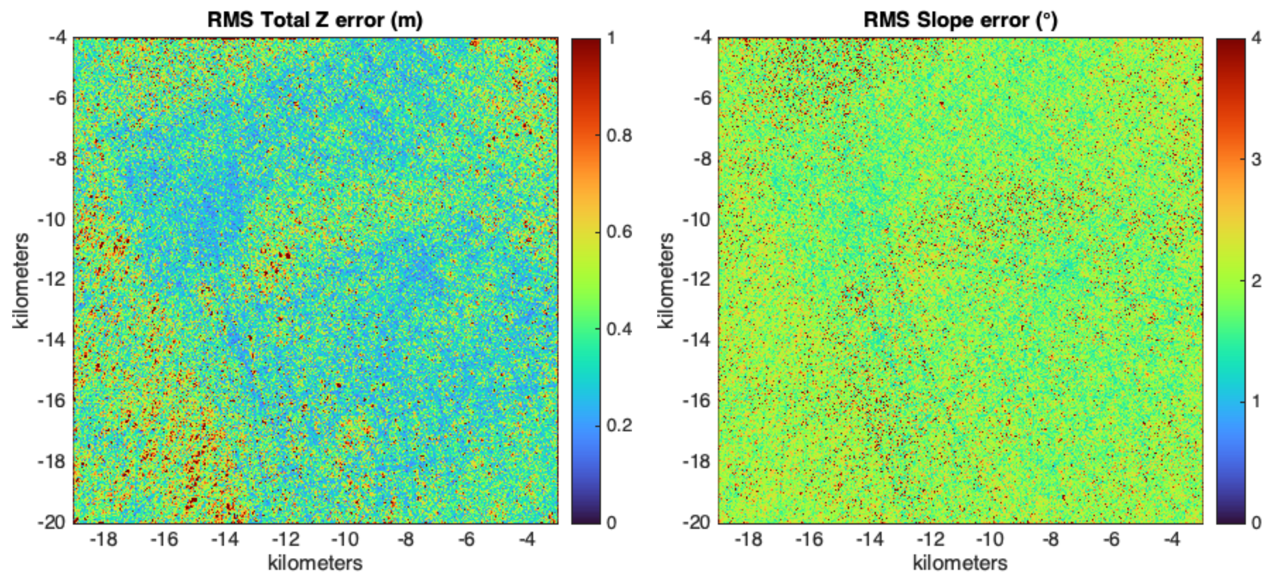
We compute predicted illumination conditions for the inset regions using the horizon method similar to [6] in which the horizon elevation viewed from every pixel is computed along 720 sight lines spaced 0.5° apart in azimuth, treating the Sun as a 2-D source with limb-darkening at 550 nm.

Black Contours: Regions-of-interest (RoIs) with average illumination > 70% in 2024 - 2025 at a height of 1 m above the surface and with area > 2500 m².

(5) Estimating Uncertainty

We developed a method to estimate surface height uncertainty in the new LDEMs that circumvents the infeasible computation of the full error-covariance matrix of the LDEM. Instead, we use the fractal nature of lunar topography to build a more computationally manageable **statistical ensemble of 100 "clones" with similar error properties as the data**. We use this ensemble to study height and slope uncertainty, as well as the uncertainty in illumination conditions. The LDEM height and slope uncertainties are similar across all the sites with a median RMS Z error ~ 0.30 – 0.50 m and a median RMS slope error ~ 1.5 – 2.5°.

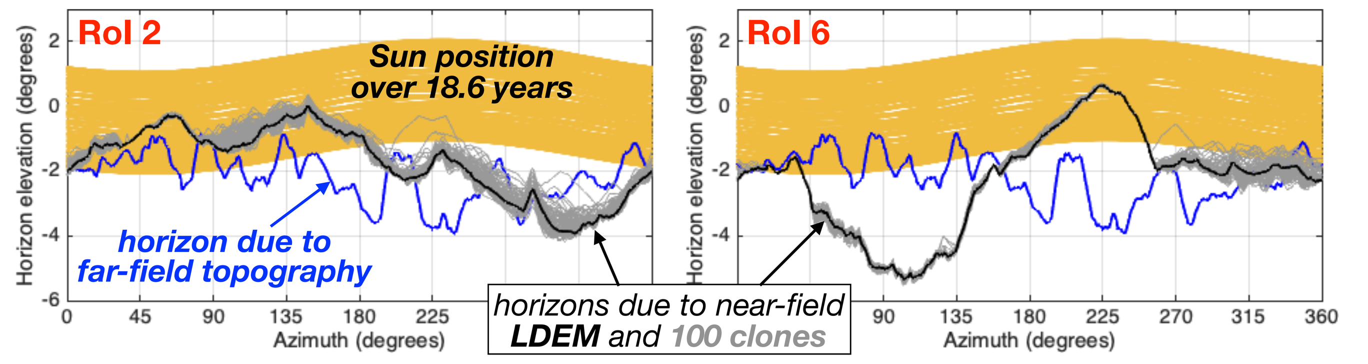


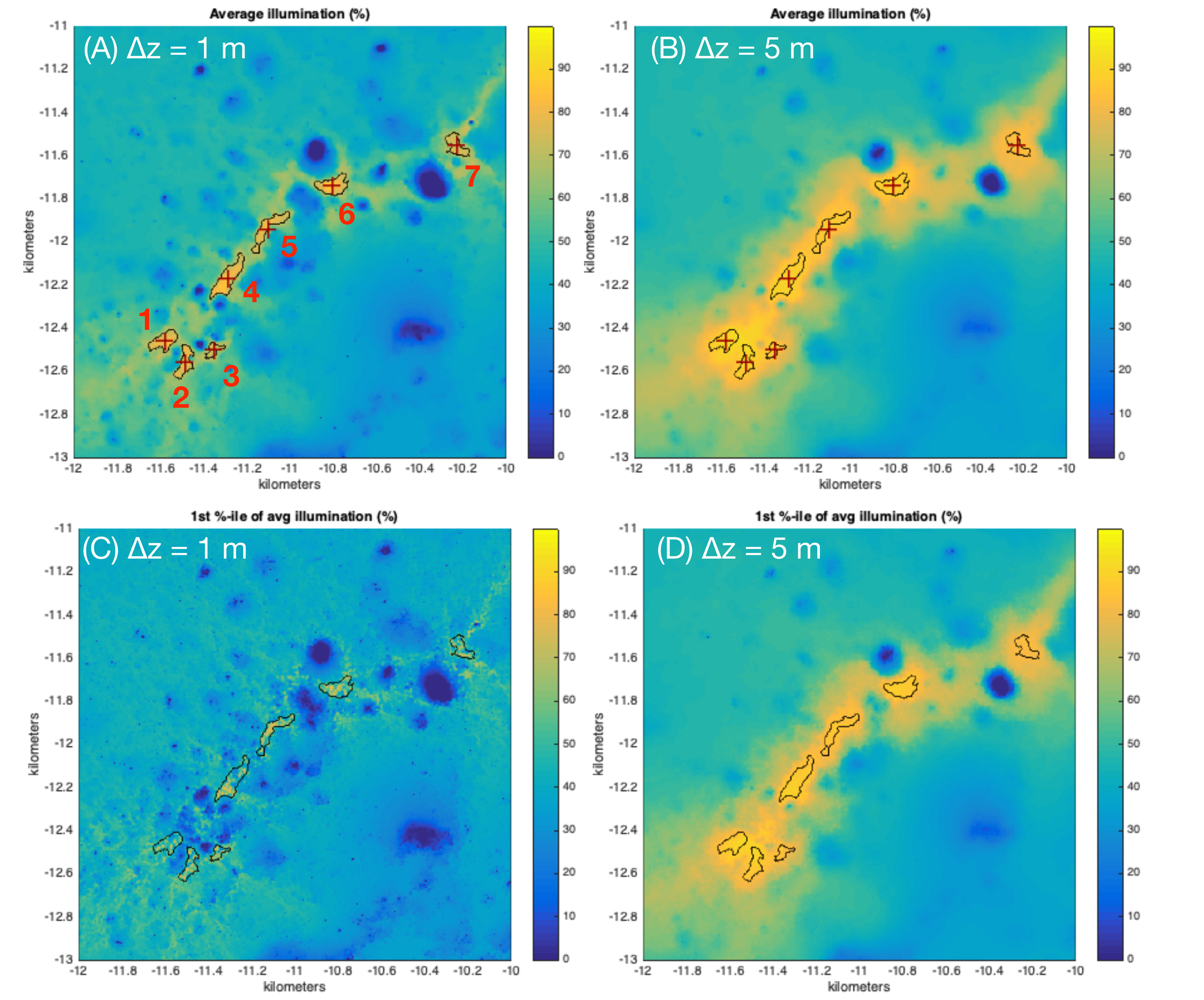


Left panel: RMS total Z error for all 100 clones of Site 1. This error includes interpolation, range, orbital, and sampling errors. Right panel: RMS slope error for all 100 clones. **Interpolation and slope error are spatially correlated with gap size (inverse of LOLA point density) and with slope.**

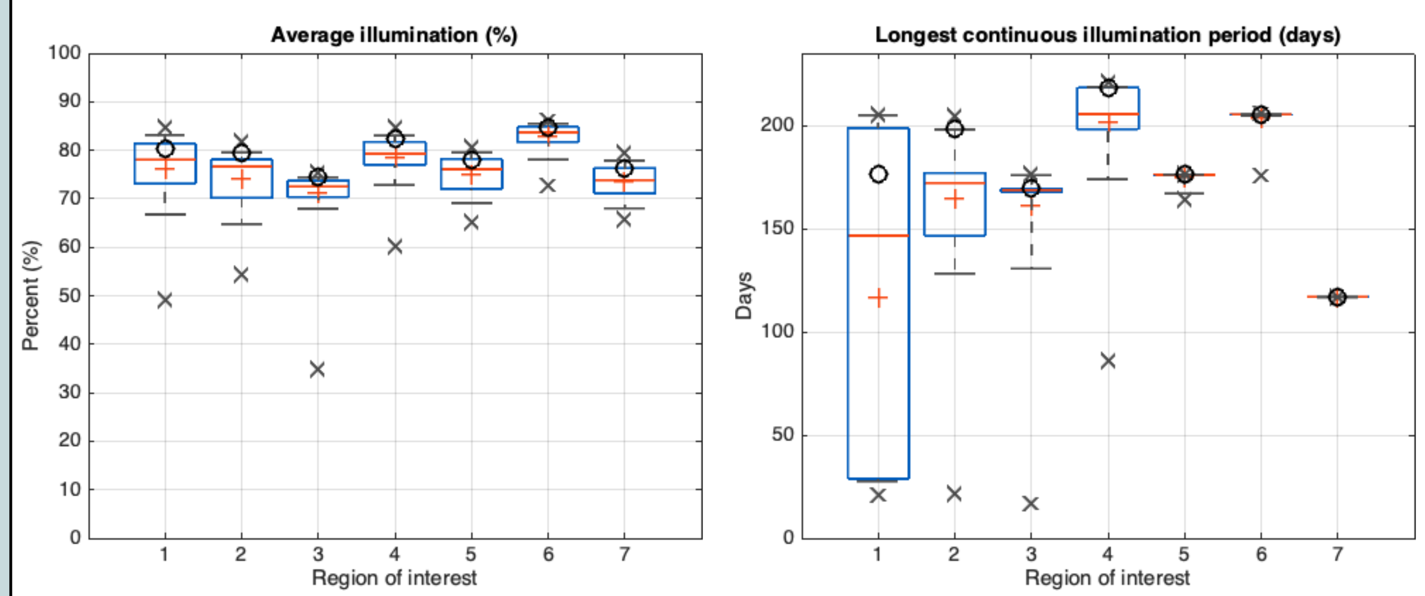
(6) Illumination conditions at Site 1 for 2024 - 2025

Surface height errors translate to near-field horizon elevation errors and variations in illumination conditions.





Average visible fraction of Sun's disk (A and B) at 1 m (left) and 5 m (right) above the surface. Minimum (1st percentile) of all 100 clones (C and D).



Box plots of illumination conditions at Site 1 during 2024 – 2025 at Δz = 1 m above each RoI's centroid pixel in the new LDEM (open circles) and 100 clones: mean (+), median (–) , inter-quartile range (box), 9th/91st percentiles (whiskers), and min/max (x). The width of each distribution reflects the overall uncertainty in illumination conditions at each location. RoI 6 tends to have the most favorable illumination conditions and smallest uncertainties out of all RoIs at all sites.

(7) Summary

- We present new and improved 5 m/pix LDEMs of 4 high priority south pole landing sites.
- Through an iterative process based solely on fitting geolocated LOLA profiles to the LDEM, we produce a **vastly cleaner LDEM** with fewer artifacts that will be more useful for landing site studies and as a constraint to higher-resolution DEMs from stereo imaging and shape-from-shading.
- We developed a method to produce a statistical ensemble with similar error properties as the data. We use this ensemble to study **height and slope uncertainty**, as well as the corresponding uncertainty in **illumination conditions**.

Such an approach can be useful in a range of other applications, not just pure illumination conditions, when examining the feasibility of potential landing sites.

- In 2024 – 2025, Site 1 has the most area with average illumination > 70% at 1 m above the surface and RoI 6 at this site generally has the least uncertain illumination conditions. At 5 m above the surface, the effect of LDEM uncertainties on illumination conditions are significantly reduced, and Site 1 has longer continuous illumination periods than the other sites.

References

[1] De Rosa, et al. (2012). *PSS*, 74, 224. [2] Gläser, P., et al. (2014). *Icarus*, 243, 78. [3] Gläser, P., et al. (2018). *PSS*, 162, 170. [4] Heldman, J. L., et al. (2016). *Acta Astronautica*, 127, 308. [5] Zuber, M. T., et al. (2012). *Nature*, 486, 378. [6] Mazarico, E., et al. (2011). *Icarus*, 211, 1066.