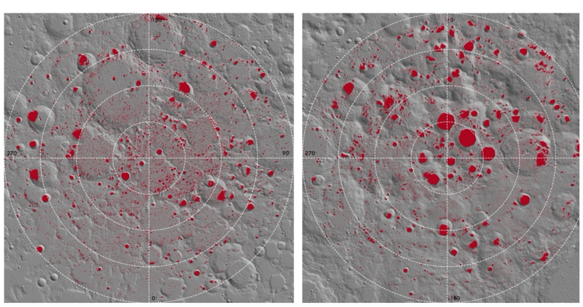
MAPPING LUNAR DOUBLE SHADOWS WITH DIGITAL TERRAIN MODELS. P. O'Brien[1] and S. Byrne[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 (pob@arizona.edu).

Introduction: Illumination conditions vary greatly at the poles of low-obliquity bodies like the Moon. High-standing topographic features can be perennially illuminated while nearby topographic depressions reside in constant darkness. In the absence of solar heating, permanently shadowed regions (PSRs) can reach temperatures of less than 100 K, cold enough to sequester water ice delivered to the poles [1].

Illumination (reflected from surrounding topography) and consequently temperature, varies between PSRs and within individual shadows. Topographic depressions within PSRs, e.g., small craters embedded on the floor of a large circumpolar crater, can be shielded not only from direct solar illumination but also from scattered sunlight and thermal emission from nearby sunlit surfaces. These double shadows (DPSRs) could approach temperatures as low as ~25 K [2] and could potentially harbor not only water but also CO_2, CO, N_2, Ar [3] and organic compounds found in comets and meteorites [4,5]. The manifest of volatile species sequestered in doubly shadowed regions therefore offers a direct test of volatile delivery mechanisms and a stratigraphic record of the most thermally unstable species.

Here we present new high-resolution PSR maps as well as the first map of double permanent shadows at the lunar poles and discuss future avenues of study regarding these ultra-cold regions.



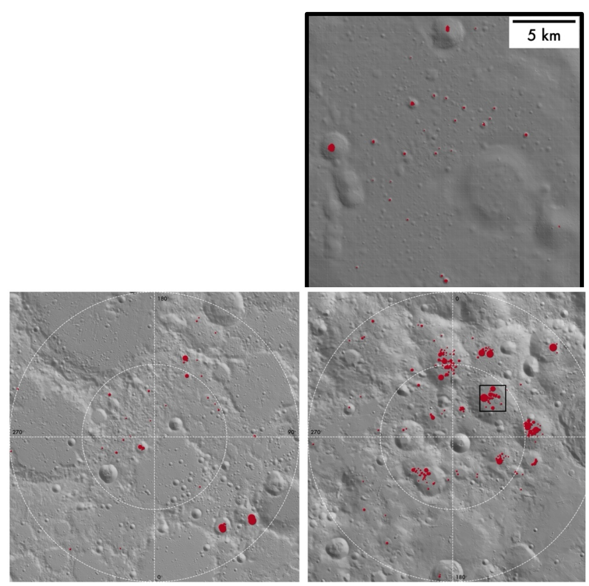
North Pole PSRs **South Pole PSRs**

Figure 1. Map of permanent shadowing at 30 m/pxl resolution, shown as shaded regions over LOLA topography. Dashed circles indicate spacing of 2.5° latitude.

Illumination modeling: We mapped regions of single and double permanent shadow using digital terrain models from the Lunar Orbiter Laser Altimeter [6]. High-resolution polar stereographic DTMs are available through the Planetary Data System at 30 m/pxl (>75° latitude) and 5 m/pxl (>87.5° latitude).

PSRs were identified using the horizon method pioneered by [7], wherein a point is permanently shadowed if the solar disc is never visible from that location on the lunar surface. For every pixel in the region of interest, we extract 720 line-of-sight profiles from a gnomonic projection centered on the pixel. The gnomonic coordinates are reprojected into polar stereographic and lunar radii interpolated from that LOLA DTM. The line-of-sight elevation profiles are corrected for planetary curvature and the elevation angle of the horizon is determined. Finally, the horizon elevation is compared to the maximum solar elevation in every direction. The resulting 30 m/pxl PSR map is shown in Figure 1.

Double shadows are points that are permanently shadowed and have no direct line of sight to any non-permanently shadowed surface facets. We apply a raycasting algorithm to every permanently shadowed pixel to identify all surface facets visible from that point. If every visible facet in every direction is permanently shadowed, that pixel is doubly shadowed. Figure 2 shows the location of double shadows larger than 5 contiguous 30 m pixels at both lunar poles.



North Pole DPSRs **South Pole DPSRs**

Figure 2. Map with locations of double shadows >85° latitude shown as dots (dot size exaggerated but reflects relative shadow area). Inset at upper right shows resolved double shadows within Shoemaker crater (DPSR area not exaggerated here).

Results: At 30 m/pxl resolution, we find that the total permanently shadowed area poleward of 80° latitude is 1.80×10^4 km^2 in the north and 2.09×10^4 km^2 in the south (6.23% and 7.25% of the total surface area in the region). Shadows smaller than 4500 m^2 are excluded to avoid spurious small shadows. These PSR areas are ~40%(pi* greater than [7] found over a similar latitude range, owing to the higher resolution DTM utilized in this work which allows us to resolve many small PSRs. The cumulative size-frequency distribution (SFD) of permanently shadowed regions is shown in Figure 3 and can be fit with a power law,

$$N(>A) = CA^{-b}$$

where A is shadow area. A power law fit to the PSR number densities yields a slope of b_n=0.74 for the north and b_s=0.78 for the south.

The total doubly shadowed area poleward of 85° latitude is 1.46 km^2 in the north and 5.34 km^2 in the south (0.02% and 0.07% of the PSR area in the region). The double shadow SFD is slightly steeper than that of single shadows, with a slope of b_n=0.77 in the north and b_s=1.06 in the south (Figure 3).

Mapping of double shadows poleward of 89° latitude in high resolution 5 m/pxl DTMs indicates that the power law trend of DPSR abundance is consistent from the largest double shadows, ~600 m across, down to the 5 m/pxl resolution limit at effective diameters of ~13 m (5 contiguous pixels). Extrapolating this trend to the centimeter scale, at which lateral heat conduction inhibits PSR cold trapping [8], predicts that double shadows >1 cm^2 occupy a total surface area of 1.55 km^2 in the north and 44.14 km^2 in the south.

Discussion: DPSRs are rare on the Moon, with ~0.05% of PSR area being doubly shadowed at the 30 m scale. As with single shadows, small DPSRs are more abundant than large ones and even at 5 m/pxl, many double shadows remain unresolved. Far-infrared emissivity features in Diviner bolometric temperature data have previously been attributed to sub-resolution "ultra-cold traps", i.e., double shadows [9]. Our results support this interpretation, demonstrating that many PSRs contain double shadows. Additionally, the spatial distribution of DPSRs (Figure 2) can be used to place a lower limit on the areal fraction of ultra-cold double shadows in Diviner observations (DPSRs unresolved at 30 m/pxl also contribute to anisothermality within the Diviner footprint).

Despite their relative rarity, the Moon's largest double shadows are potentially resolvable with existing orbital datasets. For example, the footprint of the Diviner instrument is 140 m x 400 m or ~0.056 km^2 [10]. We identified 23 DPSRs larger than a single Diviner pixel (7 in the north, 16 in the south). Correlating temperature and reflectance datasets with the locations of double shadows could reveal whether these regions are as cold as predicted by thermal modeling and whether they are important reservoirs for super-volatiles delivered to the lunar poles.

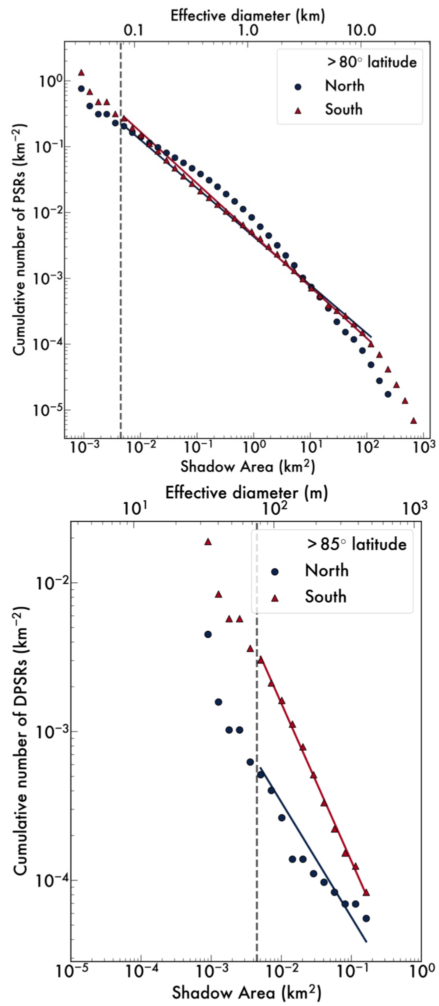


Figure 3. Cumulative size-frequency distribution of PSRs (top) and DPSRs (bottom). Dashed lines show the resolution limit at 5 contiguous 30 m pixels.

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