COOLER THAN COOL: DOUBLY SHADOWED REGIONS AT THE LUNAR POLES. P. O'Brien[1] and S. Byrne[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 (pob@lpl.arizona.edu)

Introduction: Permanently shadowed regions (PSRs) at the poles of low obliquity planetary bodies like the Moon are some of the coldest locations in the solar system [1]. Shielded from solar illumination for billions of years, lunar PSRs reach temperatures of less than 100 K, cold enough to trap water ice delivered to the poles by comets, asteroids, and volcanic outgassing, or produced *in situ* by solar wind-regolith interactions [2,3]. Illumination modeling has revealed the locations of PSRs resolvable with current orbital datasets [4,5], but recent modeling efforts suggest a significant fraction of the Moon's permanently shadowed area could be contained in micro-cold traps as small as 1 cm in size [6]. These permanently shadowed regions are a crucial record of volatiles in the inner solar system as well as a valuable resource for future human exploration. However, there exist even colder areas on the Moon.

PSRs are heated by solar radiation reflected off nearby illuminated areas as well as thermal radiation emitted from those warm surfaces. Topographic depressions within PSRs can be shielded not only from direct solar illumination but also from these secondary heating sources and can be as cold as ~25 K [3,7]. These *double shadows* could trap not only water ice but also more volatile compounds such as CO_2, CO, N_2, and Ar. Here we present a survey of doubly shadowed regions within large PSRs at the lunar poles.

Identifying double shadows: Illumination modeling by [4] produced stereographic maps of PSRs at the lunar poles for spatial resolutions ranging from 240 m/pxl (poleward of 65° latitude) to 60 m/pxl (poleward of 85° latitude). Using these shadow maps, as well as Lunar Orbiter Laser Altimeter (LOLA) elevation maps at the same resolutions, we determine the size and location of doubly shadowed regions within PSRs previously identified as likely harboring volatile deposits in some form [8].

For a given site, we reproject elevation and shadow maps in a region surrounding the site to a gnomonic projection, in which great circles plot as straight lines. The size of the region of interest is determined by the most distant horizon point visible from that location on the lunar surface. For each permanently shadowed pixel within the region of interest, we extract line of sight topography in every direction at 0.5° intervals and correct for the curvature of the Moon. If every point visible from a pixel in every direction is permanently shadowed, the pixel is considered doubly shadowed since it "sees" no illuminated surface facets.

Results: Double shadow locations are computed in PSRs deemed high priority targets for the study of lunar polar volatiles [8]. These include the three large south polar PSR craters, Haworth, Shoemaker, and Faustini, as well as Cabeus (site of the LCROSS impact), de Gerlache, and PSR 51 (or "Region 5"), a shadowed region between Haworth and Shoemaker with especially low temperatures as measured by the Diviner radiometer [9]. The total double shadowed area within each PSR is shown in Table 1.

Site	240 m/pxl	120 m/pxl	60 m/pxl
Haworth	0.35 km^2	0.56 km^2	0.87 km^2
Shoemaker	0.35 km^2	0.62 km^2	0.77 km^2
Faustini	0.29 km^2	0.59 km^2	0.90 km^2
Cabeus	0 km^2	0.058 km^2	N/A
de Gerlache	0 km^2	0 km^2	0.018 km^2
PSR 51/ Region 5	0.35 km^2	0.50 km^2	0.66 km^2

Table 1. Double shadow area as a function of spatial resolution in six south polar PSRs.

The fraction of PSR area that is doubly shadowed increases at smaller spatial scales (Figure 1) as higher resolution topography data can resolve smaller shadows. PSR 51 has the highest fraction of double shadowing, reaching 0.3% of the total PSR area at 60 m/pxl, while the three largest south polar PSRs, Haworth, Shoemaker and Faustini, follow the same general trend in double shadow area fraction with increasing resolution.

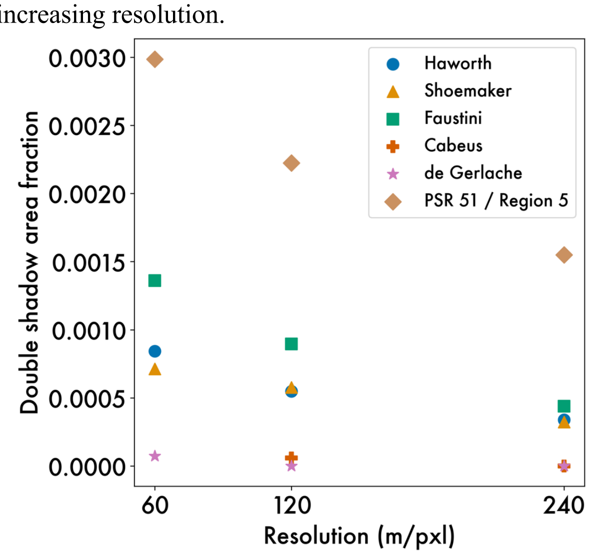

Figure 1. Fraction of permanently shadowed area that is doubly shadowed at each site. Newly reprocessed LOLA elevation data [10] could extend this progression down to 5 m/pxl.

Figure 2 shows doubly shadowed regions within the Faustini PSR at 60 m/pxl resolution. This map reveals numerous small craters on the flat floor which are shielded from the partially illuminated walls of the larger crater. The largest of these resolvable double shadows are ~240 m across.

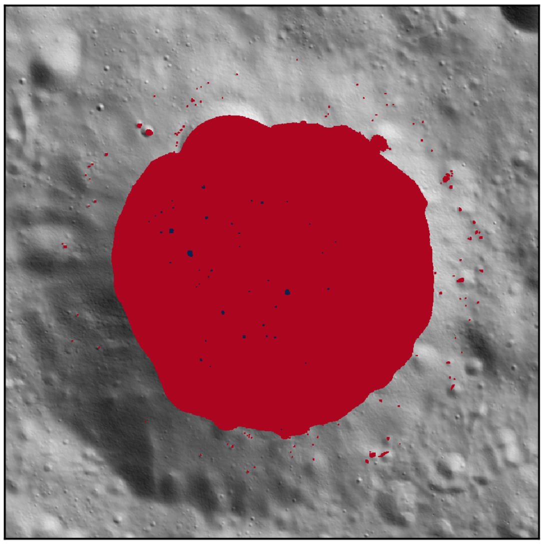

Figure 2. Permanently shadowed region (large red area) and double shadows (small blue areas) within the 39 km-diameter Faustini crater at 60 m baselines.

Discussion: Small double shadowed regions make up approximately 0.1% of the singly shadowed area within large PSRs at the lunar poles (at 60 m/pxl scale). Based on the topography shielding these areas from scattered and thermal radiation, it is expected that these double PSRs (DPSRs) will be colder than the surrounding PSR. However, the radiation budget, and therefore temperature, within a shadow is strongly dependent on solar declination, even in doubly shadowed areas [9,11]. Additional data is needed to conclusively state whether a DPSR is a suitable cold trap for species more volatile than water.

Nearly all the DPSRs identified here are smaller than the Diviner radiometer footprint (~140 m cross-track width and ~400 m along-track length [9]), making it difficult to directly measure the temperature of any individual double shadow. Far-IR emissivity features in Amundsen crater are consistent with anisothermality due to so called "ultra-cold traps" at the sub-Diviner field of view scale (presumed to be doubly shadowed surfaces on rough terrain) [12]. Our results support this conclusion and suggest that DPSRs can approach the scale of the Diviner FOV in some locations. Upcoming missions like the VIPER rover [13] might encounter small doubly shadowed regions on rough terrain, but the size of the largest DPSRs identified here indicate it might be possible to target an ultra-cold trap that meets mission requirements on terrain grade and accessibility.

Recent work by [6] demonstrated that unmapped PSRs exist at scales down to 1 cm and micro cold traps between 1 cm and 1 km in size could constitute up to 20% of the total water ice cold trap area on the Moon. A similar paradigm exists for DPSRs, with small double shadows being more numerous than large ones and a significant fraction of the cold trap area for super-volatiles like CO_2, CO, N_2, and Ar is likely unresolvable with current orbital datasets. Landscape evolution models, e.g. [14], can simulate realistic topography at any scale and can be used to estimate the abundance of small-scale lunar DPSRs.

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LDEM_60S_240M
LDEM_75S_120M
LDEM_75S_60M
LPSR_65S_240M_201608
LPSR_75S_120M_201608
LPSR_85S_060M_201608

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