Apollo 16 Shape-from-Shading Indicates that Small Craters are Shallow

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The Volatiles Investigating Polar Exploration Rover (VIPER) mission will conduct exploration science by mapping and measuring volatiles near the Lunar South Pole [1, 2] and characteristics of meter-scale craters are relevant for traverse planning. At VIPER’s polar site with its very low solar elevation, most of the meter-scale craters have unilluminated floors in the high-resolution Lunar Reconnaissance Orbiter Camera (LROC) images that blanket the area. The terrain of these unlit floors cannot be determined from stereo or shape-from-shading (SfS) techniques, which require illuminated terrain.

The Apollo 16 site is the only highland Apollo landing site and shares some characteristics with VIPER’s landing site. The Apollo 16 site is equatorial with enough LROC coverage to ensure no unlit crater floors.

In order to characterize meter-scale craters, we have created a 1 m/pixel SfS terrain model of the area around the Apollo 16 landing site, and have begun marking craters. We can compute the depth-to-diameter (d/D) ratio for this population of craters and compare these statistics to those of earlier characterizations for craters of 30 m in diameter and larger.

SfS Terrain: We began with the SLDEM2015 data set [3] and used GDAL [4] to interpolate the gridded terrain data to 1 m/pixel. The Integrated Software for Imagers and Spectrometers (ISIS, v 6.0.0) [5] was used for initial processing of the LROC images. The NASA Ames Stereo Pipeline (ASP, v 3.0.0-2021-07-27) [6], specifically the techniques for creation of the SfS terrain model [7], was used to generate the terrain data and other derived products.

There were \(\sim\)80 images that intersected the Apollo 16 area, and those with shadows and/or substantial jitter were removed resulting in 42 images that had good quality and spanned a variety of illumination and azimuth angles. These were bundle adjusted. Two stereo pairs and one stereo triplet were identified, and stereo models were built and aligned to the SLDEM terrain. These models did not completely cover the area. Additional rounds of bundle adjustment were applied to the images, and we built a 1 m/pixel SfS terrain model covering 11.8 km wide by 28.1 km long (Fig. 1).

Preliminary Crater Counting: Rather than perform crater counting on the LROC images themselves, we counted on hillshade maps generated from the terrain model. This allowed us to mark only those craters that we could identify in the 1 m/pixel SfS terrain.

The hillshade maps were created with the GDAL [4] gdaldem hillshade tool with low illumination from the east and the west which aided visual identification of craters in the SfS terrain. The LROC images were kept handy to reference and check features against, but the primary counting data were the SfS hillshade maps.

Preliminary counting was performed in QGIS [8] with the OpenCraterTool plug-in [9] by authors RB, JH, MH, HC, and VB. We note that the in-progress catalog

\[\text{Figure 1:} \quad \text{Upper Left:} \quad \text{Shaded-relief of SfS terrain for the entire Apollo 16 area;} \quad \text{Upper Right:} \quad \text{a mosaic of M135094104LE, M181058717RE, M181065865LE, and M181065865LE ortho-projected on to the SfS terrain with named craters marked and the Apollo 16 EVA traverses in red (courtesy LROC Team/ASU);} \quad \text{Lower Left:} \quad \text{Shaded-relief of SfS terrain around North Ray crater showing detail;} \quad \text{Lower Right:} \quad \text{Portion of M1182366809LE around North Ray crater.}\]
of approximately 4500 craters is currently spatially non-uniform and may contain an observational bias that will be mitigated once counting is complete.

**Automatic Counting:** An early version of an automatic crater detection algorithm (co-author Nefian, pers. comm.) was also applied to the images and terrain model which yielded approximately 193,000 craters to supplement the manually-marked craters.

**Preliminary Results:** The d/D results from the hand marking to-date and the early automatic counting are shown relative to a previous study of craters, including the Apollo 16 area, by Stopar et al. [10] in Fig. 2. These early automatic counts show their discrete nature at small diameters, and show a much larger spread in depths than the hand-marking. Depths less than 1 cm and d/D values less than 0.03 are likely the result of noise in the terrain data, and diameters less than 4 m are suspect (although the human-marked craters do fall off below that value).

Despite those shortcomings, the plot shows that there is good agreement with the larger diameter counts of previous work, and that the d/D trend continues to small crater diameters, as implied by Stopar et al. [10] and Mahanti et al. [11]. Small craters are not simply scaled-down versions of larger craters. Their d/D ratios are different and smaller craters are shallower (smaller d/D ratio) than larger craters. The VIPER mission anticipates collecting data to confirm this information about meter-scale craters, and should be able to determine if this trend continues to the smaller craters that VIPER will be able to resolve on the surface.

**References:**