SHAPE-FROM-SHADING REFINEMENT OF LOLA AND LROC DIGITAL ELEVATION MODELS: APPLICATIONS TO UPCOMING HUMAN AND ROBOTIC EXPLORATION OF THE MOON.

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**Introduction:** One of the most critical aspects of landing site selection and traverse planning for past missions to the Moon has been the assessment of surface topography, slopes, access and trafficability, and linking these to regional geology and the scientific goals and objectives of the mission. Major technological improvements have provided a new set of tools for assessing and presenting these data. We outline a processing pipeline in development over the last year that leverages automated image alignment and parallelized batch processing to significantly reduce the computation time and human intervention required to generate high-resolution digital elevation models (DEMs) of the Moon. We refine pre-existing LOLA LDEM [1] and LROC NAC DTM [2] products using the Ames Stereo Pipeline shape-from-shading (SfS) algorithm [3-4] with individual NAC image frames. Most higher-level topographic data product generation for the Moon to date has focused on upcoming human landing sites in the lunar south polar region (SPR) as part of ongoing NASA Artemis internal science team activities [5-8]. Here, we demonstrate how SfS-refined DEMs can be used in mission planning and landing site characterization in a broader context for upcoming human and robotic exploration of the Moon, both at the poles and at lower equatorial latitudes.

**Methods:** Our processing pipeline combines the generation of SfS topography solutions with automated image alignment and packaging in a Linux environment that leverages the SLURM workload management tool [9] for faster parallel processing; we outline both of these approaches below.

**Automated image alignment.** After radiometric calibration and an initial bundle adjustment and map projection step, the NAC EDR products to be used for SfS undergo further alignment using the ASP image_align tool to match individual NAC frames to an associated DEM orthoimage via x-y translation. The tool outputs alignment transforms in an Earth-centered, Earth-fixed (ECEF) reference frame (“Earth” refers to the reference body, i.e. the Moon) that can be fed into further bundle adjustment steps. Due to varying illumination conditions, frames with bad data, and other factors, the alignment transform occasionally outputs spurious results. To correct for this, we implement a second filtering step using a structural similarity index (SSIM) [10] to determine which aligned images match the orthoimage within a given threshold.

**Parallel processing.** The ASP SfS algorithm is capable of parallel processing by splitting large DEMs into tiles. We choose instead to manually parallelize our processing to have greater control over the exact size and extent of tiles, typically 600x600 pixels with a 100-pixel overlap, which are later mosaicked together into a single DEM using dem_mosaic in ASP. In addition to aiding in parallel processing, we found that image_align performs much better with individual tiles than across whole images, where in the former case the required adjustments are relatively small.

**Sample datasets and applications to upcoming missions:** Meter-scale SfS topography products (effective horizontal resolution better than 1 meter per pixel, mpp) will have broad applicability to landing site characterization and mission planning for upcoming human and robotic exploration of the Moon. For the Artemis campaign, SfS-refined LOLA LDEM products of candidate landing regions near the lunar south pole will be crucial where extreme illumination conditions make stereo photogrammetry impractical. Analysis of planned landing sites for CLPS deliveries anticipated later in 2024, e.g. Intuitive Machines Nova-C (Malapert A) [11] and Astrobotic Griffin/VIPER (Nobile) [12-13], would benefit from these same data products. SfS will also be useful for refining LROC NAC DTM products [4], which cover a much wider range of sites for potential future exploration beyond the SPR [e.g. 14].

Fig. 1 shows sample output products from our SfS pipeline for two sites of interest, one each for a LOLA LDEM of the SPR (Malapert Massif, Artemis candidate landing region; Fig. 1A–B) and a NAC DTM of an equatorial site (Ina pit crater, PRISM DIPLE payload; Fig. 1C–D). Improvements in effective horizontal resolution range from ~3–5x. There are significant enhancements to short-baseline slope features and small craters, both of which will be critical to mission planning and the selection of safe landing sites. The SfS solution also removes noise and artifacts that are present in the reference DEMs.

The Malapert Massif candidate landing region is an ideal location for understanding the earliest geologic history of the Moon and likely samples ancient uplifted crustal material from the SPA impact [15-17]. The nominal landing site is on a ridge near the summit of Mons Malapert (Fig. 1A–B). Ina is one of the largest irregular mare patches (IMPs) on the Moon, appearing to indicate extremely young mare volcanism in the form of collapsed summit calderas (pit craters) and solidified
mounds of late-stage lava extrusions that would significantly extend the known lifetime of volcanic activity on the Moon [18-20]. As a selection for PRISM, the DIMPLE payload [21] will ride onboard a future CLPS lander to investigate the age and origin of these materials at Mons Agnes, a large mound located near the eastern edge of Ina (Fig. 1C–D). Mons Agnes will allow access to both mound and floor material for a small rover that will return samples to the lander for radiometric analysis.


Fig. 1. Results of SfS processing for two sites of potential future exploration on the Moon at Malapert Massif (A–B) and Mons Agnes, Ina (C–D). Reference DEM products (A. LOLA LDEM; C. NAC DTM) are compared to the resulting SfS-refined products (B, D). Improvements in effective horizontal resolution are ~5x for the LOLA LDEM (5 mpp vs. 1 mpp) and ~3x for the NAC DTM (2 mpp vs. 0.6 mpp). SfS performed with LROC NAC images will routinely result in refined DEMs with better than 1 mpp horizontal resolution.