HIGH-PRECISION DIGITAL TERRAIN MODEL OF A CANDIDATE LANDING SITE NEAR LUNAR SOUTH POLE USING MULTI-IMAGE SHAPE-FROM-SHADING.

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Introduction: A planned JAXA/ISRO collaborative mission aims to send a lander with a rover to the surface of the lunar polar region (±85° to 90°) to investigate the possible abundance of water in the mid-2020s [1,2]. High-accuracy and high-resolution digital terrain models (DTMs) of landing candidate sites are necessary for the assessments of both meter-scale landing and roving safeties (e.g., accurate ground coordinates of the landing site, the local slope within the landing ellipse, the surface roughness along the rover path, and the illumination condition). Since June 2009, Lunar Reconnaissance Orbiter (LRO) has obtained high spatial resolution (0.5 to 2.0 m/pixel) images taken by the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC, which consists of two CCDs, NAC-L and NAC-R, without a stereo optics) [3], and high-accuracy elevation data measured by Lunar Orbiter Laser Altimeter (LOLA) with <1-m radial accuracy and <50-m horizontal accuracy. To date, there are two different NAC stereo-derived DTMs of the lunar south polar region, such as U.S. Geological Survey's (USGS) DTM (4 m/pixel; SOCET SET-based stereo-photogrammetry) [5] and German Aerospace Center's (DLR) DTM (2 m/pixel; VICAR-based stereo-photogrammetry) [6]. Despite their high spatial resolution, they still exhibit 10's-m scale artifacts (e.g., linear discontinuities caused by the boundaries of misaligned NAC-L and NAC-R images), and they do not fully reconstruct small-scale (from tens of meters to a few meters) topographic features (Figure 1). To minimize these problems, we invoke two additional procedures, such as (i) correction of the misalignment of NAC-R to NAC-L, and (ii) shape-from-shading (SfS). Although SfS can improve a DTM resolution up to about the ground pixel scale of an input image, applications of the SfS to the multiple images having extremely high incidence angles (around 89°) and a range of solar azimuths may be challenging. In this paper, we show our new data processing schemes and experimental results, with comparison to the previous DTMs.

Study site. Several candidate landing sites near the lunar south pole had been proposed by the European Space Agency (ESA) Lunar Lander mission project. We selected the ridge connecting de Gerlache and Shackleton craters, previously referred to as "Connecting Ridge" (CR1; roughly centered at 89.47°S, 222.1°E) [7], as the test site for the extraction of our DTM and its comparison to the DLR DTM.

Methods: *Data sets.* We used the NAC image pairs at 1 m/pixel, which are also used to produce the DLR DTM of CR1. In terms of their spatial extents of illuminated areas, they are classified into five stereo pairs: (1) two overlapping stereo pairs covering the eastern part of CR1 (M139797542, M139811097, and M139817894), (2) one stereo pair of the southwestern part of CR1 (M140869717 and M140876512), and (3) two overlapping stereo pairs of the northwestern part of CR1 (M141412504, M141432879, and M141439653). The DLR DTM with its ortho-mosaic image and all the LOLA footprints covering the CR1 area (197 to 243°E, 89.0 to 89.9°S) are used as the reference ground coordinates.

Image processing. Starting from a total of sixteen Experimental Data Records (EDR) of LROC NAC images, we performed radiometric calibrations, removals of NAC echo effects, collections of ground control points (GCPs) of each stereo pair, bundle adjustments of each stereo pair with GCPs, and a bundle adjustment of all the sixteen images without GCPs, using USGS's Integrated Software for Imagers and Spectrometers v3 (ISIS3). After that, for each NAC-L/R pair, we co-registered a NAC-R image to NAC-L image by taking several tens of tie points by means of ISIS3's coreg with manual corrections of all the poor co-registrations. To create a seamless NAC-L/R mosaic, we also normalized a NAC-R image by multiplying it by the median of the ratios (NAC-L/NAC-R) of all the overlapping pixels before mosaicking. Finally, we created eight non map-projected mosaics of NAC-L and NAC-R images, which we call "NAC mosaics."

Stereo processing. We extracted five stereo DTMs (12 m/pixel) from eight NAC mosaics through NASA's Ames Stereo Pipeline (ASP) v2.6.2 [8]. Using a mosaic of the five NAC DTMs, the five NAC mosaics were map-projected to improve ASP's stereo correlation. The resulted mosaics were used to derive five DTMs again. A mosaic of these DTMs was converted to a point cloud data of 41,966,218 points, and then translated to best fit LOLA shots of 418,314 points by Iterative Closest Point (ICP) method [8,9], which is similar to the method of Gläser et al. [6].

Shape from Shading (SfS). The 10 m/pixel mosaicked DTM was trimmed to a ~4×4 km zone, smoothed by a Gaussian filter to reduce artifacts (Fig. 1), and resampled to 1 m/pixel. Using this DTM as the initial elevation model, the SfS (ASP's parallel_sfs [10]) was applied to the seven NAC mosaics (one NAC mosaic was not used because it has similar observation geometry to another mosaic). The ASP's sfs parameters, such as smoothness-weight (μ) and initial-dem-constraint-weight (λ), were set to 0.12 and 10^{-12}, respectively. The terrain, camera poses, and image exposures were varied, and the lunar-Lambertian reflectance model and shadow thresholds (pixels covered by shadows were not used) were applied as well. The SfS DTM, represented by a point cloud of 16,008,001 points, was translated to appropriately align to LOLA footprint data of 139,375 points using ICP. Consequently, the SfS DTM and its corresponding mosaic of three ortho-rectified NAC mosaics were produced at a spatial resolution of 1 m/pixel (Fig. 1).

Results and Discussions: Figure 1 shows the newly-developed stereo and SfS DTMs, which are compared to the existing DTMs. Along-track artifacts of the existing DTMs are not noticeable in our DTMs. The 'zig-zag' seams and artificial pits in the DLR DTM, probably originated from mosaicking of misaligned DTMs, are less obvious in our DTM. The difference in overall shape between previous and current DTMs suggests that the degree of misalignment of NAC-L/R images could affect the accuracy of bundle adjustments and DTMs. Also, in contrast to the stereo DTMs, the SfS DTM represents meter-scale topographic reliefs including impact craters and "tree bark" texture. Future studies are needed to improve the SfS DTM quality and the application of SfS to the NAC images of other candidate landing sites to properly support future landing missions.

References: [1] Inoue H. et al. (2018) *LPS XLIX,* Abstract #1738. [2] Inoue H. et al. (2019) *LPS L,* Abstract #2155. [3] Robinson M. S. et al. (2010) *Space Sci. Rev., 150,* 81–124. [4] Smith D. E. et al. (2010) *Space Sci. Rev., 150,* 209–241. [5] Rosiek et al. (2013) *LPS XLIV,* Abstract #2583. [6] Gläser P. et al. (2013) *Planet. Space Sci., 89,* 111–117. [7] De Rosa D. et al. (2012) *Planet. Space Sci., 74,* 224–246. [8] Beyer R.A. et al. (2018) *Earth Space Sci., 5,* 537–548. [9] Beyer R.A. et al. (2014) *LPS XLV,* Abstract #2902. [10] Alexandrov O. and Beyer R.A. (2018) *Earth Space Sci., 5,* 652–666.

Additional information: We used the USGS DTM available at https://astrogeology.usgs.gov/search/map/Moon/LRO/MOON_LRO_NAC_DEM_89S210E_4mp and the DLR DTM available at http://wms.lroc.asu.edu/lroc/view_rdr/NAC_DTM_ESALL_CR1.

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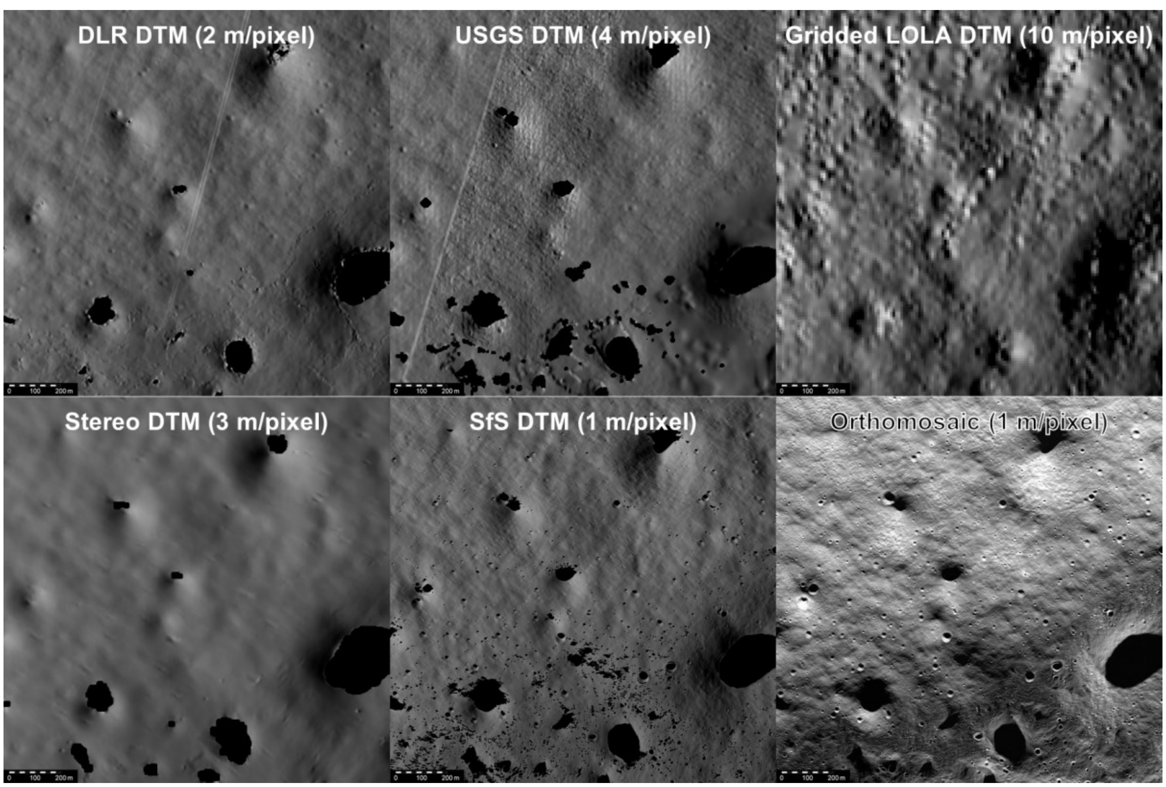

Figure 1. Close-up views (~1.5×1.5 km-area) of CR1. Three previous DTMs (top) are in comparison to our experimental results (bottom). DTMs are displayed as shaded-relief images (shadowed areas are colored in black).