LROC NAC DIGITAL TERRAIN MODELS: PRODUCTION AND AVAILABILITY

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Introduction. High-resolution and accurate topographic data is essential for planning and executing safe lunar landings and surface activities. The Lunar Reconnaissance Orbiter Camera (LROC) Science Operations Center (SOC) team produces accurate and precise digital terrain models (DTMs) from sets of geometric stereo Narrow Angle Camera (NAC) images tied to Lunar Orbiter Laser Altimeter (LOLA) cartographic grid.

To date, LROC has acquired >4000 sets of geometric stereo observations useful for geologic studies, landed mission planning and outreach materials. The SOC team has produced 474 DTMs, including 45 DTM mosaics, with pixel scales of 2-5 m, and archived them in NASA's Planetary Data System (PDS) [1]. Here we describe the methodology for producing and evaluating NAC DTMs, as well as the variety of tools for finding and using available topographic data.

NAC Geometric Stereo. LROC NACs have pixel scales between 0.5 m and 2 m and cover a region of about 5-20 km across-track by 26-104 km down-track (resolution and area vary with orbital altitude: apoapsis of ~114 km near the north pole, periapsis of ~74 km near the south pole), providing some of the highest-resolution imagery of the lunar surface [2]. Images are acquired on subsequent orbits to ensure near identical illumination geometry and pixel scales. LROC NAC stereo images are also specifically targeted to have parallax angles between 17° and 45° and, for most observations, to have incidence angles between 35° and 65°. These constraints minimize noise and data loss to shadows while maximizing vertical precision. Topography can be derived for illuminated terrain from images with higher incidence angles (>65°), such as those near the lunar poles, although such DTMs have gaps where terrain is in shadow.

An accurate geodetic reference for absolute orientation is provided by LOLA profiles converged with the GRAIL gravity model GRM900C [3], which have uncertainties of <10 m horizontally and <1 m vertically [4]. Profiles acquired after 2014, during slews, and during nightside operations are excluded to maximize accuracy [1].

Methodology. The LROC SOC uses a combination of the Integrated Software for Imagers and Spectrometers (ISIS3) and SOCET SET, a commercial software from BAE Systems, to produce NAC DTMs.

Preprocessing. Once a site has been chosen from the available stereo, the images are ingested into ISIS3, radiometrically calibrated and echo corrected [5]. Orientation and position information from SPICE kernels is gathered and converted to SOCET SET compatible keywords. The images and orientation data are then imported into SOCET SET.

Relative and Absolute Orientation. Images are first aligned relative to each other using SOCET SET's multi-sensor triangulation algorithm. When a stereo model with an overall RMS error <0.5 pixels and individual residuals <1.0 pixels has been reached, a DTM is extracted for use in determining absolute orientation.

For absolute orientation, preliminary DTMs are registered to LOLA profiles using an automated MATLAB tool developed by the LROC SOC team [1]. Chosen control points are transferred to SOCET SET, and the images are re-triangulated. This process is repeated until the overall triangulation RMSE is <0.5 pixels, control point uncertainties are better than LOLA profiles' uncertainties, and the DTM's offsets from LOLA when compared in the MATLAB tool both are better than the LOLA profiles' uncertainties and have no systematic offsets.

DTM Extraction. To reduce noise, final DTMs are extracted in SOCET SET at post spacings of at least 3x the pixel scales of the input images. Any blunders in the resulting DTMs are corrected using SOCET SET editing tools [1]. Where sufficient image data does not exist to accurately extract terrain, as in the case of deep shadows, the blunders are simply removed and replaced with null data to prohibit possible misinterpretation.

Post-Processing. When the DTM is complete, orthophotos are derived for each image in the stereo set at both the native pixel scale and the post spacing of the DTM. The DTM, orthophotos, and a confidence map for interpreting DTM values are then exported from SOCET SET and converted to PDS format. Additional products are created in GeoTIFF format using the Geospatial Data Abstraction Library (GDAL): a color-shaded relief, a terrain-shaded relief, and a color slope map, as well as legends for colorized products. A readme containing uncertainty analysis information on interpreting the products is generated as well.

Mosaics. Regions of interest often cover areas larger than one set of stereo images. In these cases, multiple stereo sets are controlled together in SOCET SET to create large-area stereo mosaics [1]. Because the lighting can vary greatly between sets of stereo observations, the DTMs for each set are extracted separately and then mosaicked together. Special care is taken to ensure that the vertical offsets in the seam between the data sets are less than the post-spacing of the DTM. Each component DTM and its associated sub-products are also individually released at the best available post-spacing. To date, we have archived 45 DTM mosaics.

DTM Uncertainty. The LROC SOC team performs both qualitative and quantitative uncertainty analysis on the DTMs. While in SOCET SET, DTMs are reviewed in stereo as contour lines overlaid onto the NAC images to check for blunders. DTMs released by LROC since 2013 have relative linear errors (a measure of vertical precision at a 90% confidence level) and relative circular errors (a measure of horizontal precision at a 90% confidence level) less than their post spacings [1,6]. As a measure of absolute accuracy, the RMSE of the vertical offsets between the DTMs and the LOLA profiles is less than the DTM post spacing, and the DTMs, if re-registered to LOLA, are not offset horizontally or vertically by more than the LOLA profiles' uncertainties [1]. Plots of the vertical offsets are also examined to check for trends in the offset data. Some DTMs produced prior to 2013 may have higher offsets; these are being reprocessed and re-released [1]. For DTMs produced in 2013 or later, the mean RMSE is 2.18 m, and the mean latitude, longitude, and elevation offsets from LOLA are 3.0 m, 3.8 m, and 0.5 m, respectively.

Available DTMs and Geometric Stereo. DTMs are archived in the LROC PDS node every three months along with their orthophotos, derived products, and readmes. There are a variety of resources to discover and access both the DTMs and stereo images, all available from the Archive section of the LROC website [7].

The LROC PDS data node allows searches for individual images and RDR products [8]. Under the RDR tab, the user can search by geographic bounding box, type of product, and name. All DTMs and their associated derived products can be located by selecting 'NAC_DTM' under the RDR Prefix list.

ESRI shapefiles of both DTM and stereo observation footprints are also available (and updated quarterly) (Fig. 1). They can be found by selecting 'SHAPEFILE' under the RDR Prefix list. Sets of stereo images with known issues, such as jitter or active spacecraft slewing, have been removed [1]. The DTM shapefile attribute table contains expanded uncertainty analysis information, as well as 'tags' of 30 common geologic features and other characteristics, such as 'Volcanism', 'Rille', or 'Anthropogenic'. These shapefiles are also available through Quickmap [9] and Lunaserv [10].

ACT-REACT Quickmap is a web interface for map-related products that offers a large number of lunar datasets as interactive layers, including NAC DTM related data: shaded reliefs, color-shaded reliefs, and vector layers for stereo observations and DTMs. These layers help users identify DTMs or stereo for their area of interest, determine data extents, and visualize available data. The vector layers can also be used to locate the DTMs and stereo observations in the archive. The NAC DTM elevation data is also available when profiling along a path and visualizing the Moon in 3D.

Lunaserv is a Web Map Service (WMS) implementation developed by the LROC team at Arizona State University (ASU) to work with planetary datasets [11]. LROC hosts an instance of Lunaserv with layers for many planetary bodies, including all of the LROC PDS data. Users can access Lunaserv with any WMS-capable GIS software, such as ArcGIS and QGIS. These map layers can also be accessed online with Lunaserv Global Explorer (LGE) [10]. LROC RDR NAC DTM Footprints can be turned on by selecting the relevant checkbox under Layers: Regional Products. Using the LGE interactive tools on an area will open a list of overlapping DTMs, associated derived products, and links to the LROC PDS node for download.

Current Production and Future Work. Numerous DTMs have been created that cover sites deemed high-priority exploration targets by the lunar science community, and more DTMs can be made on request from new and existing stereo [12,13]. Until April 2018, LROC was limited to a maximum of four slews per day; due to an instrumental anomaly, slewing has since been further curtailed [14]. In the 10 years since the launch of LRO, a total of 4410 stereo pairs covering 4% of the lunar surface have been acquired, and ~10% of these have been processed into DTMs by the LROC team. We continue to refine our process for producing NAC DTMs, while generating precise, accurate and documented products to support lunar science and exploration.

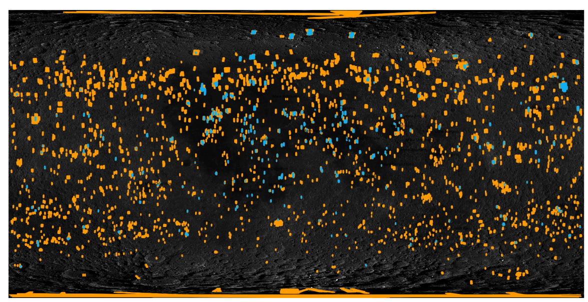

Figure 1. NAC DTM shapefile (teal) and stereo observations shapefile (orange as of January 2020). Shapes are exaggerated here for visibility.

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