LROC NAC DTM PRODUCTION. M. R. Henriksen[1], M. R. Manheim[1], E. J. Speyerer[1], A.K. Boyd[1], and M. S. Robinson[1], [1]School of Earth and Space Exploration, Arizona State University, 1100 S. Cady, Tempe, AZ 85287 – (mhenriksen@ser.asu.edu)

Introduction: Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) stereo observations combined with Lunar Orbiter Laser Altimeter (LOLA) profiles are used to create dense and accurate DTMs of the lunar surface. The NACs consist of two linear pushbroom cameras designed to provide 0.5 meter pixel scale panchromatic images for a combined swath of 5 km at an altitude of 50 km [1]. Although the NACs were not designed as a stereo imaging system, it is possible to acquire stereo pairs by collecting images on two separate orbits, where the spacecraft is slewed off-nadir for at least one orbit. The convergence angle between the two images has a range of 10° to 40°. The amount of overlap and actual image footprints are affected by topography and acquisition parameters including center latitude, center longitude, and slew angle. LOLA is a pulse detection time-of-flight altimeter that was designed to measure the shape of the Moon by using precision orbit determination of LRO to precisely measuring the range from the spacecraft to the lunar surface [2]. By registering NAC DTMs to LOLA profiles, the absolute accuracy can be improved and evaluated. LOLA profiles with crossover correction and GRAIL gravity model improvement are accurate to within 10 meters horizontally and 1 m radially [3].

Methodology: DTM processing at ASU is completed using a combination of the Integrated Software for Imagers and Spectrometers and SOCET SET from BAE Systems [4].

Pre-processing. Image pre-processing is accomplished using ISIS to ingest, radiometrically calibrate, and remove echo effects [5] for all the images in a stereo pair or stereo mosaic. Orientation parameters stored in a series of binary and text based Spacecraft, Planet, Instrument, C-Matrix and Events (SPICE) kernels are applied to the images, which are then formatted for compatibility and imported into SOCET SET [6].

Relative Orientation. In order to register the images to the geodetically accurate LOLA grid [3], each image is first be corrected for relative orientation to the other images in the stereo model [7]. First, a set of “tie” points is inserted by matching pixels between images. A bundle adjustment is then performed to align the images using a multi-sensor triangulation (MST) algorithm [8,9]. Once an acceptable RMS error (< 0.5 pixels) is reached for the stereo model, a first-iteration DTM is extracted for absolute registration.

Absolute Orientation. Before April 2013, the standard registration technique (NAC DTM to LOLA profiles) was a manual optimization requiring the analyst to iteratively refine parameters to match two LOLA profiles to the DTM. The LROC team has since developed an automated tool using the Optimization Toolbox within MATLAB [10]. This program eliminates the need for manual parameter adjustments and can register multiple LOLA profiles simultaneously. Coordinates acquired by the MATLAB routines are exported back in to SOCET SET as control points, and a final bundle adjustment is performed to improve the absolute positioning of the NAC images. In addition to assessing overall RMS error and point residuals, the solution is evaluated on the latitude, longitude, and elevation RMS error values associated with the control points, which are considered acceptable within the known accuracies of the LOLA tracks.

Terrain Extraction. The Next Generation Automatic Terrain Extraction (NGATE) program in SOCET SET is used to extract DTMs from the epipolar rectified images [7,9]. NGATE uses image correlation and edge matching algorithms on each image pixel with a window size that adjusts with elevation differences to improve image correlation in a total of seven passes to create a dense model [10,11]. The DTM is then resampled to at least three times the ground sampling distance (GSD) of the images in order to reduce noise, typically at 2 or 5 m/px. Next, the DTM is run through a single pass of the Adaptive Automatic Terrain Extraction (ATE) SOCET SET application, smoothing elevation data by performing image correlation in a single pass on individual posts rather than at each image pixel, increasing the signal to noise ratio [12].

Orthophoto Generation. Once the DTM is processed, it is used to create orthophotos, or orthorectified maps of the parent NAC stereo images. The orthorectification process removes distortion due to camera obliquity and terrain relief, allowing accurate distance measurements to be made from the images maps [13]. Orthophotos are generated at both the native image resolution and at the resolution of the DTM for each image in the stereo pair.

Post-processing. For each set of stereo images, SOCET SET outputs the final DTM and Figure of Merit (FOM), or confidence map, as raw image files, and the orthorectified images as 16-bit GeoTIFFs (eight per stereo pair). These are imported into ISIS, mosaicked together, and converted to the standard PDS format for release. In addition, the Geospatial

Data Abstraction Library (GDAL) is used to derive a terrain-shaded relief map, a color-shaded relief map, and a color slope map from the DTM as 8-bit GeoTIFFs [14].

Error Analysis: Qualitative and quantitative error analysis is performed for every NAC DTM and both the relative and absolute accuracies are reported.

Relative. The relative linear error as calculated by SOCET SET is recorded for each DTM as a measure of precision. This value measures the one-dimensional error for elevation of one point with respect to another point, defined by the normal distribution function at 90% probability [9,11]. Precision is expected to be less than the DTM's GSD. The DTM horizontal precision is the same as the spatial sampling of the DTM [9].

Absolute. Every completed NAC DTM is compared to LOLA tracks, and the root mean square error (RMSE) for the offset is recorded. In addition, the final DTM is re-registered to the LOLA tracks and the offsets for latitude, longitude, and elevation recorded. To be considered accurate, the RMSE must be less than the pixel scale of the DTM and the offsets in latitude, longitude, and elevation need to be within the uncertainties attributed to the LOLA data, allowing for the precision of the DTM (for DTMs registered after April 2013, offsets should be < 10 m in latitude/longitude and 1 m in elevation). DTMs created prior to 2013 use an alternative registration technique, which was not as accurate; as a result, these DTMs may have systematic errors affecting the accuracy that are larger than LOLA uncertainties.

Jitter. Small spacecraft motions, or jitter, can emerge in the DTM as undulating geometric noise parallel to the image line. Extensive analysis of NAC images was conducted in an effort to pinpoint unknown sources of jitter and to identify affected images, but small levels of jitter may still be present in some NAC DTMs [15].

Scientific Applications: As the highest resolution topographic resource of the lunar surface available, the NAC DTMs serve as a valuable tool for the scientific and space exploration communities. Recent applications of NAC DTMs include the optimization of traverse planning using slope maps derived from DTMs [16], the calculation of melt volume estimates [17], and using Chebyshev polynomial fitting to characterize the morphology and age of small craters [18].

Production and Future Work: To date, ASU has processed 293 individual stereo pairs covering144 regions of scientific interest, covering a total area of ~97,138 km^2. The absolute accuracy has improved significantly. Changes to production, especially to registration, have reduced the overall time and expertise required to process a single stereo pair, allowing the ASU DTM production team to produce a higher volume of stereo mosaics and to reprocess many older DTMs to improve absolute accuracy. ASU DTMs and all associated products are released through the PDS and are available at http://wms.lroc.asu.edu/lroc/rdr_product_select.

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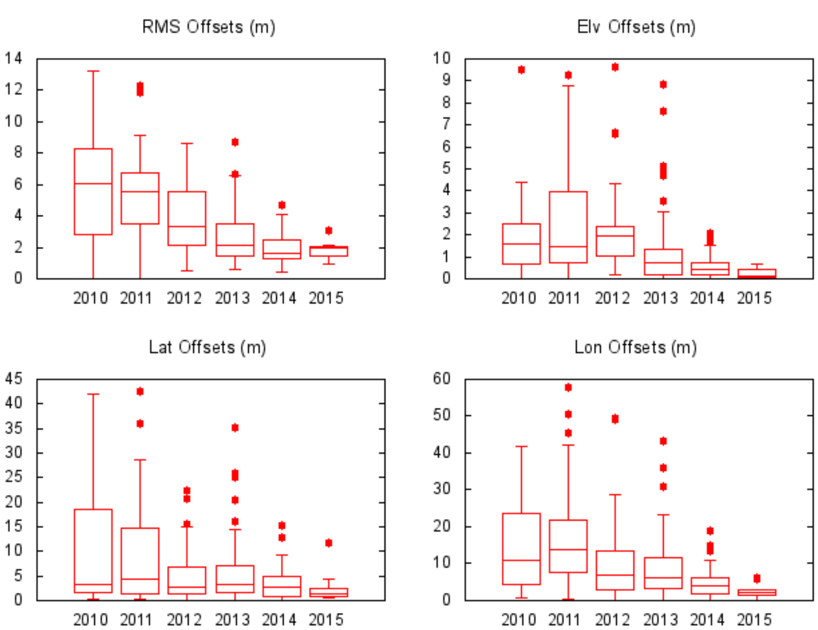

Figure 1: **Offsets between NAC DTMs and LOLA profiles (in meters) by year.** Errors are shown compared to most recent LOLA data (accuracy <10 m horizontally and < 1 m vertically). NAC DTMs are made at either a 2m or a 5m resolution. RMS errors are expected to be less than the resolution and Offsets are expected to be less than the accuracy of the available LOLA data, allowing for vertical and horizontal precision.