Status of Geodetically Controlled High-Resolution LROC Polar Mosaics

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Introduction

Our goal is to create geodetically controlled high-resolution (1 m/pixel) Lunar Reconnaissance Orbiter (LRO) [1] narrow angle camera (NAC) [2] polar mosaics of the lunar north and south polar caps (Figures 1 and 2), from ±85° to ±90° latitude. See Figure 3 for a local size comparison. The final products will include controlled mosaics of all useful images and "illumination" controlled mosaics made at every 10° of solar longitude.

Similar mosaics were previously made under the Lunar Mapping and Modeling Project (LMMP) [3]. However, they [4] were only from 85.5° poleward, using a much smaller number of images. They were also not optimized to allow the creation of the "illumination" mosaics. We have corrected some problems in the control network used for the previous mosaics and have improved our image tie-pointing methods and network solution parameterization.

Illumination Mosaics: There will be 36 mosaics for the north and south poles, at every 10° of solar longitude (e.g. Figures 4 and 5). We are evaluating whether to make one or two types of mosaics, including averaged mosaics and mosaics with the best illuminated images shown in front of other images. Note that doing such averaged mosaics (Figures 6 to 8) is only possible when the images are controlled to the sub-pixel level, thus allowing images to be co-added, increasing the SNR in low light conditions and showing all areas ever illuminated (at least while the images were collected).

These mosaics will provide many benefits for science, engineering, exploration, and for supporting future mapping and global lunar reference frame improvement efforts. The high resolution and accurate registration properties will be useful for identifying small scale permanently shadowed regions (lunar cold traps) or areas of lengthy solar illumination (ideal sites for future exploration [5]), targeting observations by future missions (e.g. [6]), detailed surface characterization and landing site assessment [7], geological and resource mapping, and change detection.

Other Benefits: This work also provides information on what critical tools will need to be developed in advance of future such work [8]. These products can also be used to characterize the precision and accuracy of a priori LRO SPICE data and possibly to provide further geometric calibration of the LROC and LOLA instruments (Figure 9). The updated LRO orientation data could also be used to improve the LRO Lunar Orbiter Laser Altimeter (LOLA) [9] results. For example, improved orientation data would allow for a new type of "crossover" adjustment of LOLA data with controlled simultaneous NAC images.

Current Solution Statistics: Control solutions are being performed with the USGS ISIS software package [10] and in particular the jigsaw application [11]. We have mostly completed preliminary control network solutions for both poles, but are doing final checks of the solutions and test mosaics. These networks have not yet been (well) constrained (controlled to ground in absolute coordinates). Network statistics are in Table 1.

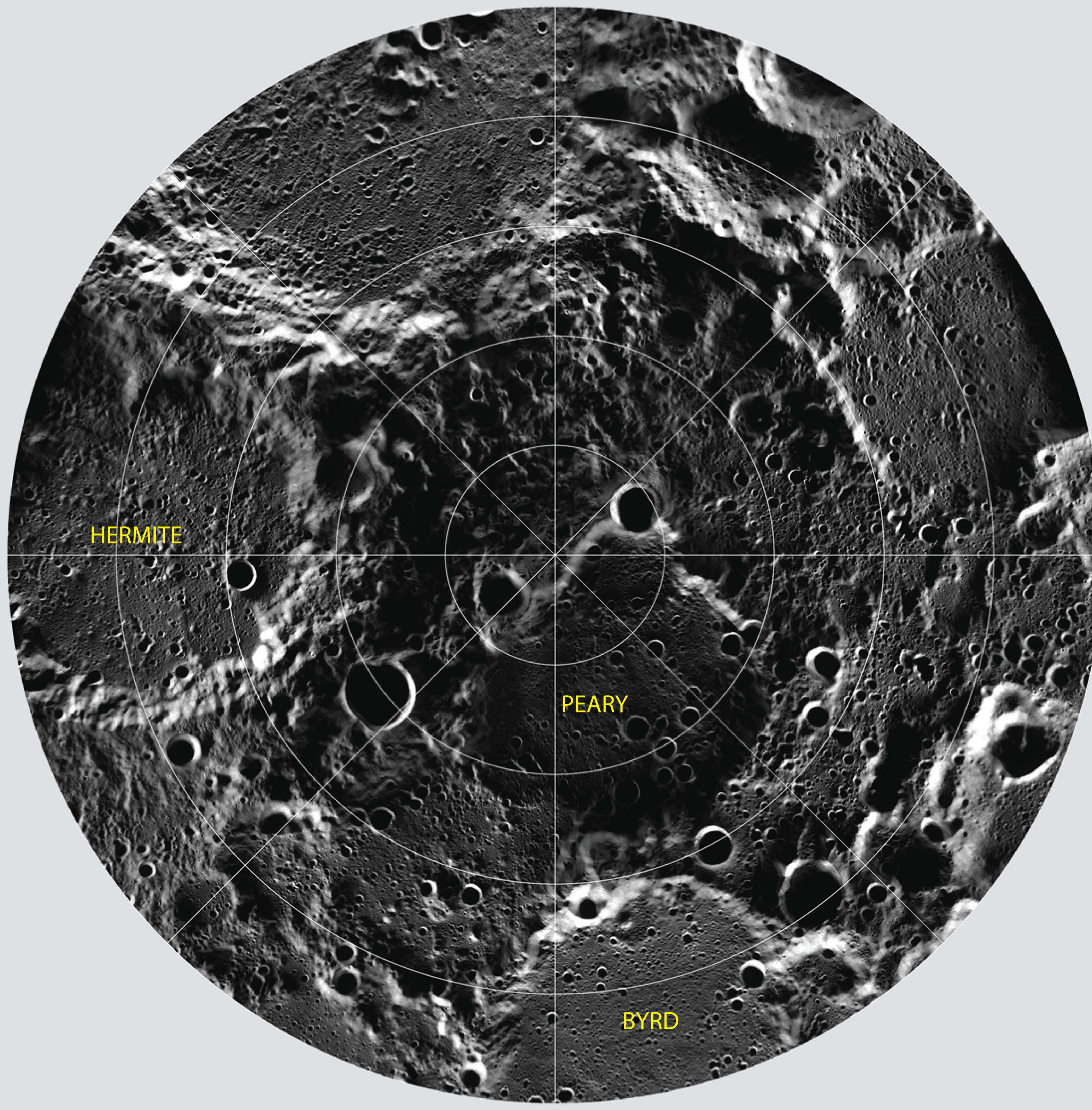
Technical Problems: Include: a) manual checking of high residual tie points; b) manual measures needed to be added for some (26 in the north) "island" images (i.e. with few areas of illuminated overlap with other images); and c) some images (532 in the north) have not been successfully controlled because they are blank, or they are part of an island and the images do not overlap. We are also still assessing the best way to winnow out bad/no data near the edges of images and in shadows when the mosaics are generated (e.g. Figure 10).

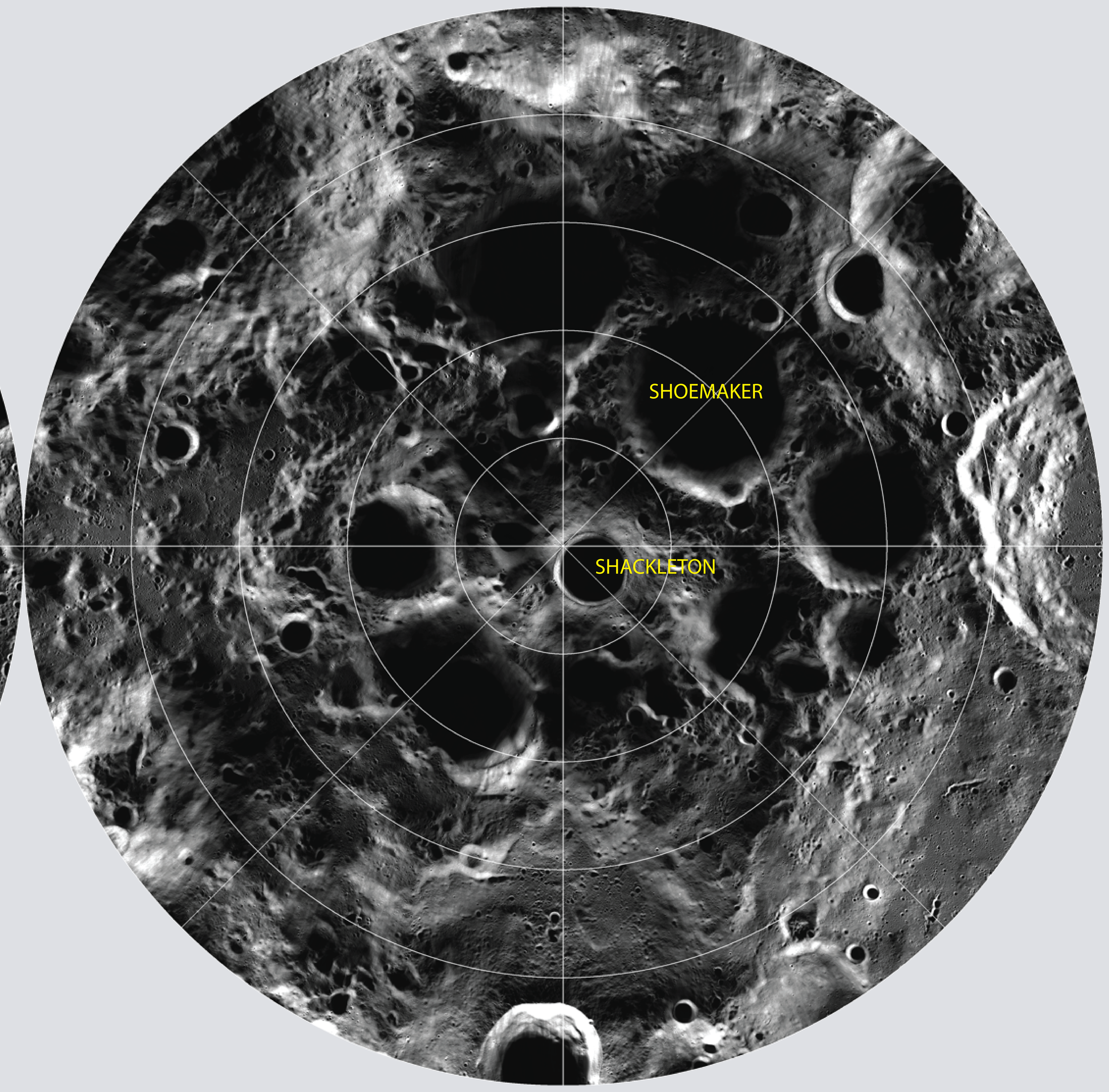
Comparison to Other Networks: Due to the significant increase in the number of images used, these networks are substantially larger than the original LMMP networks, and in terms of the total number of control points and measures (Table 2), comprise the largest solar system control networks ever done, possibly including terrestrial networks.

Ground Control: We are considering several possibilities for providing absolute horizontal and vertical control of these networks. We now plan to use NASA Ames Stereo Pipeline [12] routines that are to be available soon. Algorithms have been successfully developed for matching between LOLA track data and Apollo Metric camera images and are being adapted to do matching to NAC images.

Plans: This year we will finish the initial full solutions, create preliminary averaged mosaics and test 10° illumination mosaics, and derive LOLA-based control points for comparison. In 2016, we will complete final solutions tied to LOLA points, make final mosaics, archive products to the PDS, and document the work with a journal article.

Future Needs: This work serves as a reminder of the need for developing cartographic processing tools for even larger mosaics. The likely global coverage of the Moon at 2 m/pixel with LROC images – will likely *require the control of well over 1 million NAC images* – as opposed to the ~28,000 images being worked here. Previous recommendations [9] regarding the need for doing NASA cartography planning and developing such tools still stand.





Figures 1 and 2: North (left) and south (right) polar mosaics. Shown at 280 m/pixel resolution. Derived from 3 m/pixel resolution. Final version will be at 1 m/pixel. Polar stereographic projection. Grid shows 10° of latitude and 45° of longitude. Following cartographic convention, for the north pole, 0° longitude is at the bottom (toward Earth) and for the south pole, 0° longitude is at the top. Together *these are possibly the largest controlled planetary mosaics ever made,* in both number of original image pixels and numbers of tie points and measurements. These mosaics, covering out to 85° latitude, are 23% larger than the previous LMMP mosaics which only had coverage out to 85.5°. The area covered is 72,172 km² each, or 144,344 km² for both. However this total is still only 0.38% of the total surface of the Moon (~37,932,000 km²).

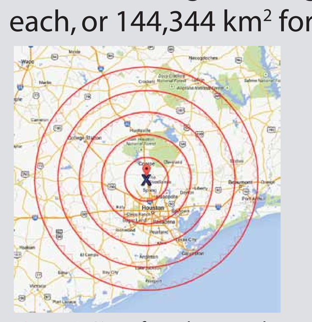


Figure 3: Size of north or south polar mosaic in comparison to the Houston, Texas area. Rings show every 1° of latitude (1° latitude on the Moon = 30.3 km).

Solution Statistics	North pole	South pole
Images:	9,688	18,963
Points:	386,873	1,638,727
Measures:	3,064,199	13,745,057
Constrained points (so far):	16	0
Residual information (pixels)		
Mean:	0.46	1.08
Std Deviation:	0.31	0.65
Median:	0.39	0.97
Mode:	0.25	0.79
Skew:	0.70	0.50
Maximum:	7.27	4.99
Note: 1 pixel ~= 1 meter		

Table 1: Solution Statistics

Body	Network/Mosaic Name	# images	# points	# measures	Reference(s)
Moon	ULCN 2005	43,866	272,931	546,126	Archinal et al., 2006. (OFR)
Moon	LMMP North Pole (USGS)	3,682	340,142	2,102,373	Lee et al., 2012. Pole to 85.5°d, LROC NAC.
Moon	LMMP South Pole (USGS)	3,827	527,756	3,363,623	Lee et al., 2012. Pole to 85.5°d, LROC NAC.
Mercury	(USGS MESSENGER)	60,281	555,120	6,599,703	Personal communication, L. Weller.
Mars	(USGS THEMIS IR)	13,496	1,578,113	6,069,647	12 of 28 tiles, test merge. Pers. Comm., L. Weller.
Moon	North Pole	9,688	386,873	3,064,199	This work
Moon	South Pole	18,693	1,638,727	13,745,057	This work
Moon	Both poles	28,381	2,025,600	16,809,256	This work

Table 2: Solar System Control Network Statistics

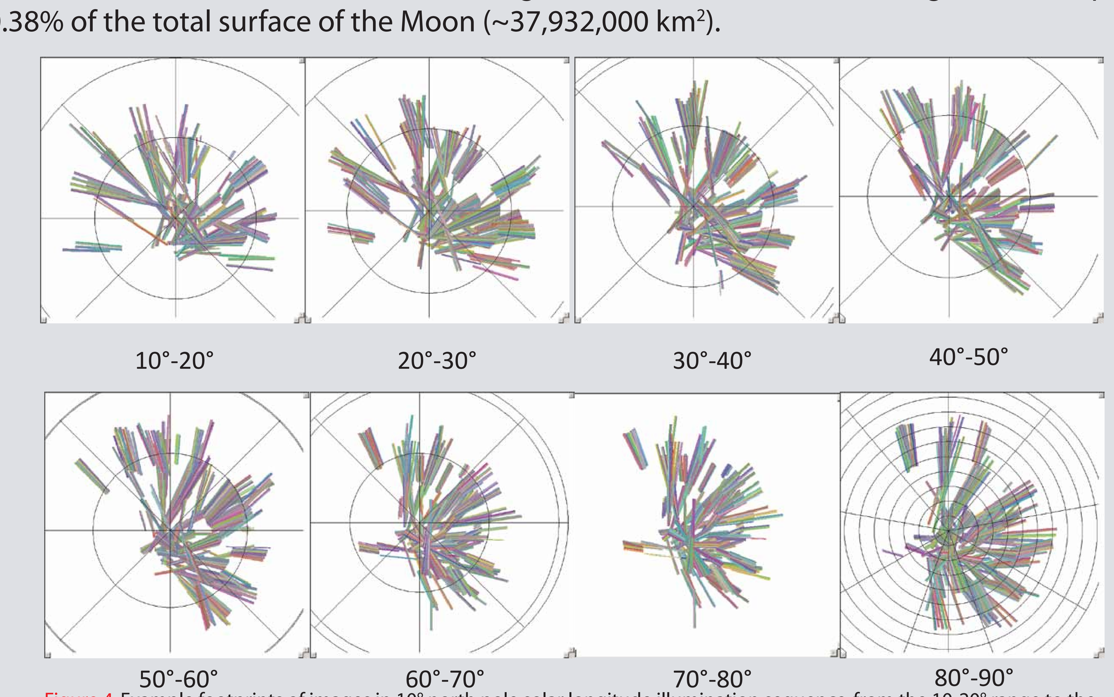


Figure 4: Example footprints of images in 10° north pole solar longitude illumination sequence, from the 10-20° range to the 80-90° range.

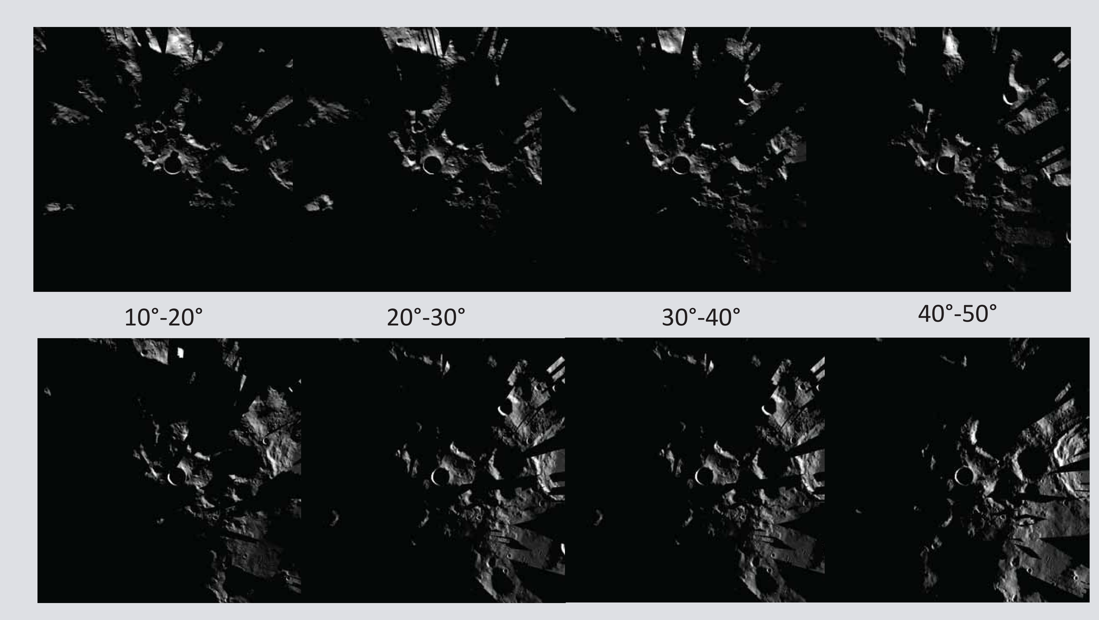


Figure 5: Example mosaics in 10° north pole solar longitude illumination sequence, from the 10-20° range to the 80-90° range. The images were initially controlled by tiepointing such common illumination images, and then once the image positions were improved were tiepointed further to images with different illumination.

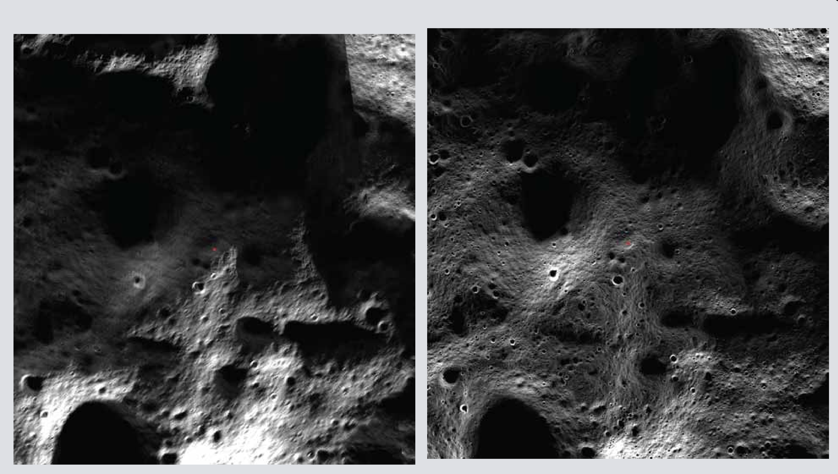


Figure 6: Detail: The *north pole* (red dot) area before and after (left and right) control of images. Shown at 10 m/pixel (3.6 x 3.9 km area). This clearly shows that in general all images are misregistered at this scale, and that averaging of images to increase SNR and to demonstrate areas of illumination is only possible when the images are registered (controlled) as in the image on the right.

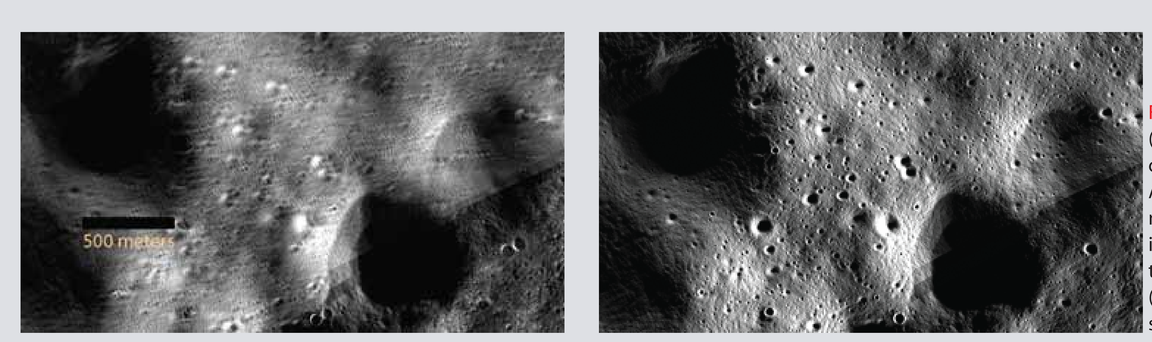


Figure 7: Detail: An area in the north pole mosaic (latitude 85.6°) before and after (left and right) control of 7 images, and shown at a resolution of 7.5 m/pixel. Again, in the uncontrolled version all the images are misregistered at this scale, and averaging of images to increase SNR and to demonstrate areas of illumination is only possible when the images are registered (controlled) as in the image on the right. The largest shifts here are up to 165 m.

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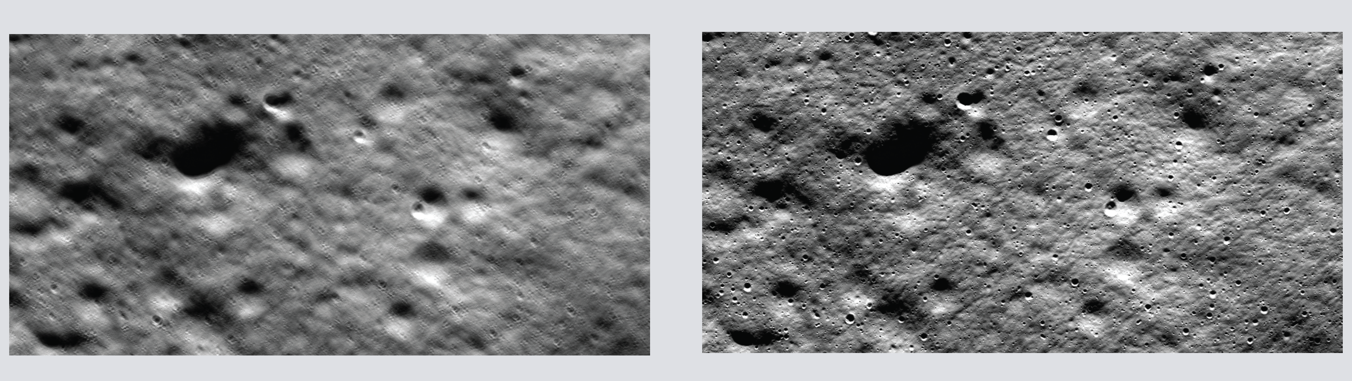

Figure 8: Detail: Similar figures showing improvements in the area of the south pole, from 9 images total. Again, the resolution is 7.5 m/pixel. The area covered is 3.4 x 1.7 km.

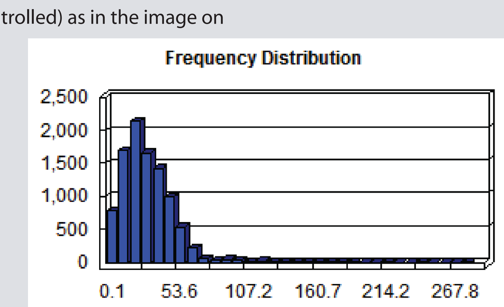

Figure 9: Histogram of image movement (m) between uncontrolled and controlled position. Shown for all (9,688) north pole images (including the left and right images, which of course tend to move about the same amount). The mean total movement is 32 m ±21 m, with a maximum outlier of 281 m. This mosaic has been tied to LOLA ground points in 16 locations. Therefore these movements reflect: a) the errors in the a priori SPICE (CK and SPK) data; b) possibly an insufficient number of ground points; c) and errors in the positioning of the LOLA track data used.

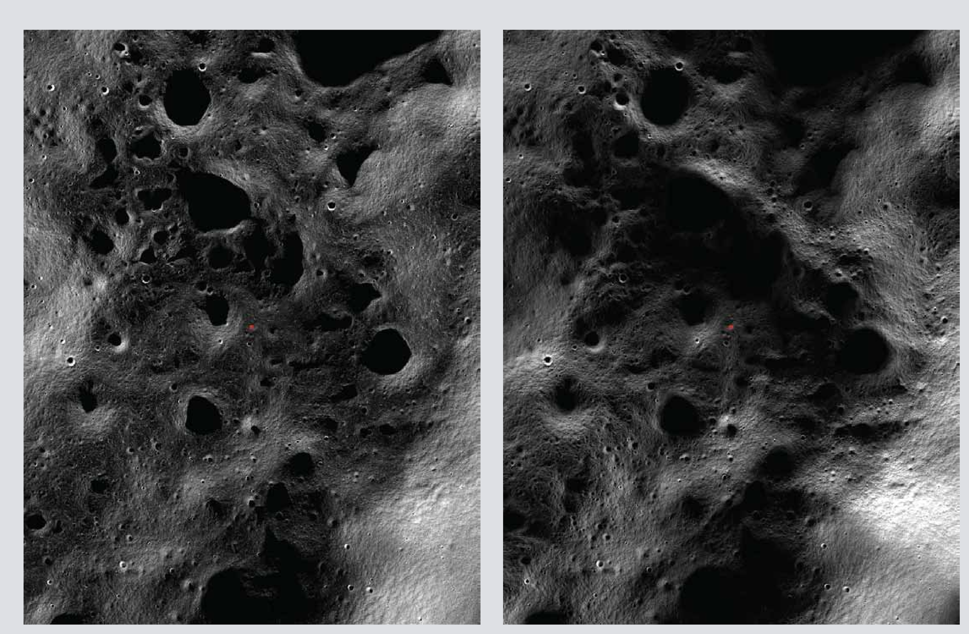

Figure 10: Detail: Comparison of LMMP mosaic (left image) to current mosaic (right image), at 11 m/pixel, covering 11.4 x 5.7 km. The red dot is the north pole of the Moon. The central region here is also shown in Figure 6. The oddly sharp edges to features in the left image are due to automatic removal of low SNR portions of images in the averaged LMMP mosaic. The darker areas in the right image are due to the lack of such editing and the averaging of many dark images in the current mosaic. Which is best?

References: [1] Vondrak et al. (2010) Space Sci. Rev. 150, 7. [2] Robinson et al. (2010) Space Sci. Rev. 150, 81. [3] Noble et al. (2009) LEAG, #2014. [4] Lee et al. (2012) LPS XLIII, #2507. [5] Speyerer and Robinson (2012) Icarus, 222, 122. [6] Jolliff et al. (2009) LPS XL, #2343. [7] Archinal et al. (2011) LPS XLII, #2316. [8] Archinal et al. (2012) LPS XLIII, #2394; http://astrogeology.usgs.gov/groups/nasa-planetary-cartography-planning. [9] Archinal et al. (2010) LPS XLI, #2609. [10] Keszthelyi et al. (2014) LPS XL, #1686. [11] Edmundson et al. (2012) Int. Ann. Photog., Rem. Sens. & Spatial Inf. Sci., I-4, 203. [12] Moratto et al. (2010) LPS XLI, #2364.