SUPPORTING LUNAR LANDERS WITH LROC NAC PRODUCTS. M. R. Manheim[1], M. R. Henriksen[1], R. V. Wagner[1], M. S. Robinson[1], and the LROC Team[1], [1]Lunar Reconnaissance Orbiter Camera Science Operations Center, Arizona State University, Tempe, AZ 85287 (mmanheim@ser.asu.edu).

Introduction: The Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Cameras (NACs) provide some of the highest-resolution images available for the lunar surface, with pixel scales of 0.5 to 2.0 m. These images and their derived products, such as feature mosaics (FMs), digital terrain models (DTMs), and photometric series, are fundamental data sources for planning and supporting landed lunar missions. NAC images and data products have been used to identify areas of high scientific value and safe landing sites.

The LROC team created NAC data products to support recent and upcoming lunar lander missions (i.e. SpaceIL Beresheet, ISRO Vikram, and JAXA SLIM [**1**]). Many data products have also been created covering regions identified as key science sites [**1,2**]. LROC continues to actively acquire images and create products to support future landed exploration.

Landing Site Selection and Mission Planning: High-resolution NAC imagery and data products can be used to address engineering questions and help to choose safe and scientifically valuable landing sites and exploration areas. Targets for traverses can be identified by examining morphologic features at a variety of illumination geometries [**2**]. Consistent lighting geometry and resolution over a site tens of km across, as is provided by FMs, can be beneficial when interpreting landforms and geology [**3**].

Hazards can be assessed for planning both landing ellipses and safe traverses between target locations over a variety of terrains using high-resolution imagery and topography. Slope maps and DTMs provide data for traversability studies and for planning landing ellipses, while low-Sun NAC FMs and other imagery can provide even higher pixel scale information for assessing hazards from small features, such as boulders [**4**]. Other NAC imagery, such as photometric series, can provide more detailed information for classifying terrain types and identifying areas of scientific interest [**3**].

Illumination geometry for solar arrays is a concern on longer-duration landed missions, especially near the poles where the low Sun elevation makes local horizon topography critical. DTMs can be used to simulate how local topography may affect available solar power [**5**], and NAC images acquired over the last 10 years give insight into seasonal and monthly variations. Similar simulations can be used to calculate line-of-sight for communications, either to Earth or to a fixed communication relay on the surface [**6**].

We can also learn necessary lessons for future missions by revisiting previous landing sites. Images and data taken on the ground by Apollo astronauts and landed missions such as Lunokhod 1 and 2 provide the highest-resolution lunar data available; NAC data products covering these sites allow us to compare them to potential future landing sites. NAC images at varying lighting angles allow us to retrace the rovers' tracks; DTM-derived slope maps let us compare the traversed slopes to the historical rover performance, and make extrapolations for future rover engineering and route planning (**Fig. 1**) [**7,8,9**].

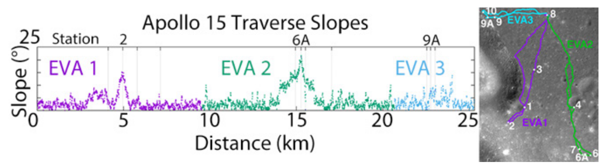

Fig. 1: Slopes at the Apollo 15 site from a NAC DTM.

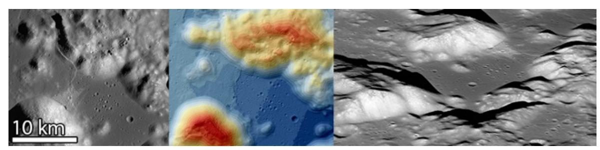

Fig. 2: *Left-to-right:* FM, DTM mosaic color-shaded relief, and oblique NAC of the Apollo 17 landing site.

NAC Data Products: During its more than ten years in orbit, LROC has collected over a million NAC observations at a wide range of imaging geometries and illumination conditions. The LROC team processes NAC images into several data products useful for landing site analysis and support. These include DTMs, FMs, photometric series, and obliques (**Fig. 2**).

DTMs. Geometric stereo images are acquired by slewing the spacecraft off-nadir on successive orbits, ensuring similar lighting between images. DTMs require a parallax angle of 15° to 40° and incidence angles >35° [**10**]. DTMs with incidence angles >65° are possible, but have null data where there is shadowed terrain. LROC has acquired 4410 stereo pairs to date. LROC DTMs are made at 2, 3, or 5 m/px, and have vertical precisions better than their pixel scales. They are tied to overlapping LOLA tracks, and have accuracies of <1 m vertically and <10 m horizontally. To date, the LROC team has processed and archived 477 DTMs, including 45 DTM mosaics [**10**].

At the north and south poles, pitched slews are required to take stereo images; however, with LROC's current orbit these images can no longer be acquired close to the poles (>86.9° N and <86.3°S). Polar stereo is also limited by the extreme lighting conditions in these regions; many stereo pairs taken at different times are required to build up stereo coverage.

FMs. FMs consist of multiple NAC images targeted to overlap on successive orbits, building up accurate (±20 m) high-resolution coverage with minimal variation in lighting conditions and pixel scales [**11**]. This requires the spacecraft to slew (up to 25°) on the outermost images and are therefore most often targeted with incidence angles >65° and <35° to avoid conflicts with targeting geometric stereo [**12**]. FMs of regions of interest are often acquired under both high and low-sun conditions; the high-sun mosaics highlight albedo variations, while boulders and other topographic features are more apparent in low-sun mosaics.

To date, 309 FMs have been processed and archived by the LROC team. These include 15 FMs made from long exposure observations of polar permanently shadowed regions [**13**].

Photometric Series. These consist of up to 100 NAC images of a feature acquired across a wide range of incidence, emission, and phase angles. Once controlled to a NAC DTM, accurate photometric information can be extracted, offering unique information about planetary surface properties [**3**]. The LROC team has published 4 photometric series.

Obliques and Nadirs. In addition to the products described above, LROC also acquires targeted NAC oblique and nadir images to support landed missions. Oblique images are slewed >30° (generally 50°-70°); these cover more area than a nadir image and provide new perspectives on lunar terrain (**Fig. 2**).

Ongoing/Active Mission Support: LROC has acquired and processed FMs, stereo pairs, nadirs, and oblique images to support several recent and upcoming missions by ISRO, ESA, JAXA, Roscosmos, and Google X-Prize teams, for a total of 1080 observations [**1**]. For the SpaceIL Beresheet and ISRO Vikram landing attempts, LROC also acquired post-impact observations and created FMs and DTMs to investigate changes to the surface as a result of the loss of the two spacecraft.

In addition, LROC observations can be requested through the Lunar Reconnaissance Orbiter project to support mission proposals and missions in development.

High-Priority Landing Sites: The 2018 Lunar Science for Landed Missions Workshop at NASA Ames produced a report identifying potential landing sites for investigating key science goals [**2**]. It describes 13 specific sites or categorical targets [**2**], which range in size from tens to thousands of km in diameter. Table 1 describes LROC coverage for these sites (excluding 4 basin targets, which each cover areas >300 km in diameter), as well as coverage for the SLIM landing site [**1**], for a proposed Chang'e 5 landing site [**14**], and for the polar regions (**Table 1**).

Future Support: LROC will continue to target NAC observations to support upcoming missions, including commercial landers, and for areas of interest to the lunar science community [**15**].

Site (Center coordinates, if applicable)	**# DTMs**	**# Stereo Pairs**	**# FMs**
Aristarchus plateau* (50°W, 25°N)	8	26	6
Compton-Belkovich* (99.5°E, 61.1°N)	3	15	4
Gruithuisen domes* (40.2°W, 36.5°N)	13	15	1
IMPs: all (70 known)*	18	~26	10
Marius Hills* (53°W, 13°N)	6	20	5
Mare pits (16 known)*	5	~11	5
P60 basalt unit* (53.8°W, 22.5°N)	4	11	2
Reiner Gamma*† (59°W, 7.5°N)	5	10	6
Rima Bode* (3.5°W, 12°N)	0	3	0
Rumker Hills area (Chang'e 5) (59°W, 42.5°N) [**14**]	13	15	3
Theophilus ejecta (SLIM) (25.2°E, 13.3°S)	5	6	2
North Pole (>80°)*	0	3	8
South Pole (<-80°)*	0	51	10

Table 1: LROC NAC data product coverage for high-priority sites. *Site from Ames report [**1,2**]. †Reiner Gamma represents the general 'swirls' target. LROC has also published a photometric series for this site.

References: [1] Manheim, M. R. et al. (2019) *4th Planet. Data Wkshp.,* #7069. [2] Jawin, E. R. et al. (2019) *Earth Space Sci., 6(1)*, 2-40. [3] Martin, A. C. et al. (2018) *LPS XLIX*, #1621. [4] Golombek, M. et al. (2012) *Space Sci. Rev., 170(1-4)*, 641-737. [5] Speyerer, E. J. et al. (2016) *Icarus, 273,* 337-345. [6] Menon, M. S. et al. (2018) *SpaceOps Conf.,* AIAA 2018-2494. [7] Watkins, R. N. et al. (2019) *JGR Planets, 124(11)*: 2754-2771. [8] Manheim, M. R. et al. (2019). *GSA*, *51(5)*, ISSN 0016-7592. [9] Basilevsky, A. T. et al. (2019) *Solar Sys. Re., 53(5),* 383-398. [10] Henriksen, M. R. et al. (2017) *Icarus, 283*, 122-137. [11] Martin, A. C. et al. (2019) *4th Planet. Data Wkshp.,* #7077. [12] Klem, S. M. et al. (2014) *LPS XLV*, #2885. [13] Cisneros, E. et al. (2017) *LPSC XLVIII,* #2469. [14] Wu, B. et al. (2018) *J. of Geophys. Res.: Planets, 123(12)*, 3256-3272. [15] NASA (2019) https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190001685.pdf.