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Extracting accurate and precise topography from LROC narrow angle camera stereo observations

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ABSTRACT

The Lunar Reconnaissance Orbiter Camera (LROC) includes two identical Narrow Angle Cameras (NAC) that each provide 0.5 to 2.0 m scale images of the lunar surface. Although not designed as a stereo system, LROC can acquire NAC stereo observations over two or more orbits using at least one off-nadir slew. Digital terrain models (DTMs) are generated from sets of stereo images and registered to profiles from the Lunar Orbiter Laser Altimeter (LOLA) to improve absolute accuracy. With current processing methods, DTMs have absolute accuracies better than the uncertainties of the LOLA profiles and relative vertical and horizontal precisions less than the pixel scale of the DTMs (2–5 m).

We computed slope statistics from 81 highland and 31 mare DTMs across a range of baselines. For a baseline of 15 m the highland mean slope parameters are: median = 9.1°, mean = 11.0°, standard deviation = 7.0°. For the mare the mean slope parameters are: median = 3.5°, mean = 4.9°, standard deviation = 4.5°. The slope values for the highland terrain are steeper than previously reported, likely due to a bias in targeting of the NAC DTMs toward higher relief features in the highland terrain.

Overlapping DTMs of single stereo sets were also combined to form larger area DTM mosaics that enable detailed characterization of large geomorphic features. From one DTM mosaic we mapped a large viscous flow related to the Orientale basin ejecta and estimated its thickness and volume to exceed 300 m and 500 km^3, respectively. Despite its ~3.8 billion year age the flow still exhibits unconfined margin slopes above 30°, in some cases exceeding the angle of repose, consistent with deposition of material rich in impact melt.

We show that the NAC stereo pairs and derived DTMs represent an invaluable tool for science and exploration purposes. At this date about 2% of the lunar surface is imaged in high-resolution stereo, and continued acquisition of stereo observations will serve to strengthen our knowledge of the Moon and geologic processes that occur across all of the terrestrial planets.

1. Introduction

The Lunar Reconnaissance Orbiter (LRO) was launched on 18 June 2009 and is in a lunar polar orbit. Its seven science instruments collect comprehensive remote-sensing measurements of the surface and its environment. These observations are paving the way towards future robotic and crewed missions to the surface (Chin et al. 2007). Among the instruments are the Lunar Reconnaissance Orbiter Camera (LROC) and the Lunar Orbiter Laser Altimeter (LOLA). The LROC instrument itself consists of three cameras: two identical Narrow Angle Cameras (NACs) and a Wide Angle Camera (WAC) (Robinson et al. 2010) that respectively provide panchromatic, high-resolution (pixel scale of 0.5 to 2.0 m) views and seven-band color observations (pixel scale of 100 m). Using the stereo observations acquired by the NACs, together with the ranging observations from LOLA, research groups are able to produce detailed and accurate digital terrain models (DTMs) of the lunar surface.

NAC DTMs are a high-resolution topographic dataset that addresses both engineering and scientific needs. Speyerer et al. (2015) developed a path-planning algorithm that uses NAC DTMs to identify the least energy traverses allowing determination of capabilities that are required to reach specific targets, such as rolling resistance, turning capability, and maximum slopes.

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Gläser et al. (2013) enabled a comparison of surface morphology and surface roughness at both the laser footprint and DTM scales by co-registering NAC DTMs and LOLA profiles. The NAC DTMs enable investigations of elevation, slope, volume, roughness, and other parameters to place constraints on complex geologic processes (impact cratering, volcanism, tectonism) over time that have shaped the lunar surface (Ashley et al. 2012; Jolliff et al. 2011; Watters et al. 2012; Lawrence et al. 2013; Braden et al. 2014; Stopar et al. 2014; Mahanti et al. 2014; French et al. 2015).

Four LROC affiliated research groups produce NAC DTMs using stereo methods: Arizona State University (ASU), Astrogeology Science Center of the U.S. Geological Survey (USGS), University of Arizona (UA), and the German Aerospace Center (DLR) (Tran et al. 2010; Rosiek et al. 2012; Mattson et al. 2012; Oberst et al. 2010). ASU, USGS, and UA all use SOCET SET from BAE Systems in combination with the Integrated Software for Imagers and Spectrometers (ISIS) (Anderson et al. 2004; Keszthelyi et al. 2013) from the USGS to produce controlled stereo products (DeVenecia et al. 2007; Mattson et al. 2012; Rosiek, et al. 2012). Finally, the group at DLR utilizes custom, VICAR-based proprietary photogrammetry software to create terrain models using both NAC and WAC images (Oberst et al. 2010; Scholten et al. 2012). In addition to these affiliated groups, NASA Ames Research Center also uses their own automated Ames Stereo Pipeline to create 3D surface reconstructions from NAC stereo pairs (Moratto et al. 2010; Moratto et al. 2014; McMichael et al. 2015). Here we describe the techniques and workflow used at the LROC Science Operations Center (SOC) on the ASU campus to produce accurate and precise NAC DTMs. We also present a method for evaluating the resulting DTMs in terms of their precision and accuracy.

2. Data sources

2.1. Narrow angle cameras

The NAC consists of two linear pushbroom cameras each with a focal length near 700 mm. The NACs are mounted on LRO with the linear arrays perpendicular to the flight direction of the spacecraft. The field of view (FOV) of each camera is approximately 2.86°, and the 1 × 5064 pixel NAC arrays are positioned such that the imaging area overlaps by ~135 pixels cross-track (Robinson et al. 2010). In doing so, the NAC-Left (NAC-L) and NAC-Right (NAC-R) cameras essentially double the observed swath width during each observation. The resulting observations, whose image names are denoted by an 'L' and an 'R', respectively, cover a combined area 5 km wide and over 26 km long from an altitude of 50 km. Robinson et al. (2010), Speyerer et al. (2014), and Humm et al. (2015) provide comprehensive details of the cameras, their geometry, and their optical and radiometric performance.

While the NACs were not designed as a stereo imaging system, it is possible to acquire stereo observations by collecting co-located images from two or more orbits, where the spacecraft is slewed off-nadir for at least one orbit (Fig. 1). To ensure that the lighting conditions are similar, these images are usually obtained on consecutive orbits. Slew angles vary from 0° to 30° to obtain a convergence angle, or the angle of separation between images forming a stereo pair, ranging from 10° to 45° (the mean convergence angle for completed DTMs is 28°). Depending on the overlapping regions between the NAC-L and NAC-R images in the two stereo observations, three or four stereo models are necessarily created from which to collect elevation data. The number of stereo models is determined by the orientation of the images and how they intersect (Fig. 2). The amount of overlap and image footprints are affected by the topography and acquisition parameters, including image pixel scale and slew angle.

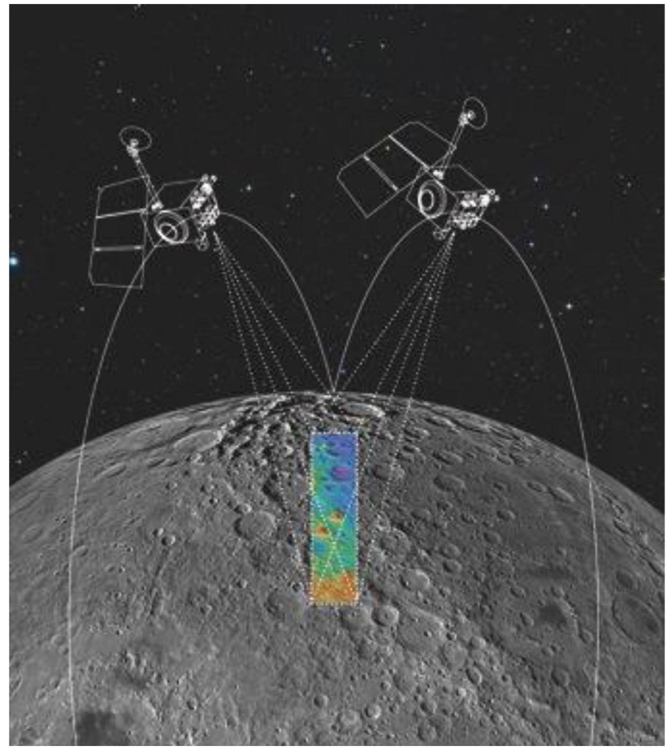

Fig. 1. NAC stereo acquisition over two orbits, not to scale.

2.2. LOLA topographic profiles

LOLA is a time-of-flight altimeter that uses a single laser pulse to simultaneously illuminate a five-spot pattern on the surface; the spots are detected with a series of five detectors. Using the time between the sent and received pulse, the range from the spacecraft to the surface is derived with a nominal precision of 10 cm at 28 Hz (LOLA's nominal pulse rate, with an uncertainty of ±0.1 Hz) (Zuber et al. 2010; Smith et al. 2010). By incorporating precision orbit determination of LRO, the shape of the Moon was derived along with an accurate global geodetic grid for the Moon to which all other observations are precisely referenced (Zuber et al. 2010; Smith et al. 2010; Mazarico et al. 2012; Mazarico et al. 2013). By registering the NAC DTMs to LOLA profiles, we can increase the absolute accuracy of the NAC DTMs.

The laser altimeter fixed 28 Hz rate places shots approximately every 57 m on the surface when the spacecraft is traveling at its nominal velocity of 1.6 km/s. At an altitude of 50 km, each spot within the five-spot pattern has a diameter of 5 m while each detector field of view has a diameter of 20 m. The spots are 25 m apart and form a cross pattern canted by 26° counter-clockwise to provide five adjacent profiles (Smith et al. 2010; Zuber et al. 2010). The LOLA instrument boresight is aligned with the LROC NAC cameras to enable altimetry collection in the overlap region between the NAC-L and NAC-R.

LOLA altimeter profiles are used to align the NAC stereo models with the LOLA geodetic grid and thus improve the accuracy of the final DTM product. We currently use profiles from the LOLA Reduced Data Record (RDR) products, which were released to the NASA Planetary Data Service (PDS) on 21 July 2014 (Version ID: v1.04). LRO radiometric tracking data were combined with the GRAIL gravity model to significantly improve the spacecraft ephemeris and subsequently the geodetic accuracy (Lemoine et al. 2014; Mazarico et al. 2012; Mazarico et al. 2013). These refinements reduce the positional uncertainty of each LOLA spot to less than 10 m horizontally and 1 m vertically