RESULTS FROM THE LUNAR ORBITER LASER ALTIMETER (LOLA): GLOBAL, HIGH-RESOLUTION TOPOGRAPHIC MAPPING OF THE MOON. David E. Smith[1], Maria T. Zuber[1], Gregory A. Neumann[2], Erwan Mazarico[1], James Head 111[3], Mark H. Torrence[4] and the LOLA Science Team, [1]MIT, Cambridge, MA 02139 (smithde@mit.edu); [2]NASA Goddard Space Flight Center, Greenbelt, MD 20771; [3]Brown University, RI 02912; [4]SGT, Inc., 7701 Greenbelt Rd., Greenbelt, MD 20770.

Introduction: The Lunar Orbiter Laser Altimeter (LOLA) [1], a payload element on NASA's Lunar Reconnaissance Orbiter mission [2] has been operating nearly continuously in lunar orbit since July 13, 2009. The objective of the LOLA investigation is to characterize potential future robotic or human landing sites and to provide a precise global geodetic grid of the Moon. LOLA's primary measurement is surface topography, but the instrument also provides ancillary measurements of surface slope, root mean square (rms) roughness and 1064-nm reflectance. LOLA has so far collected over 3.1 billion precise measurements of lunar elevation and continues to operate in nominal fashion during the LRO science mission.

LOLA Description: LOLA [1] is a multi-beam laser altimeter that operates at a wavelength of 1064.4 nm with a 28-Hz pulse repetition rate. A single laser beam is split by a diffractive optical element into five output beams, each of which has a 100-μrad divergence and illuminates a 5-m-diameter spot from LRO's mapping orbit, resulting in a total sampling rate of the lunar surface of 140 measurements/sec.

LOLA's sampling strategy produces 5 parallel profiles along LRO's sub-spacecraft ground track. Profiles are 10-12-m apart with observations within each profile separated by ~56 m, determined by the laser pulse repetition rate and spacecraft velocity. The laser spots form a cross pattern on the lunar surface, with each beam separated by an angle of 500 μrad and rotated 26^{o} about the nadir axis with respect to the spacecraft forward velocity vector. The sampling pattern permits calculation of surface slopes along a range of azimuths.

LOLA has two laser transmitters with pulse energies of 2.5 and 2.7 mJ, respectively. The lasers are operated one at a time, alternated on an approximately monthly basis in order to monitor instrument performance. Since initial turn on, neither laser has shown a decrease in output energy.

LOLA Operation in Lunar Orbit: A brief instrument checkout was followed by a 3-month calbration period while LRO was in its commissioning orbit, a near-polar eccentric orbit with height varying between ~30 km and 200 km. The commissioning orbit is frozen with the periapse over the south pole, and it was followed by 1 year of continuous operation in the mapping orbit, at 50-km average altitude to support identification and characterization of potential future landing sites, areas of permanent shadow and locations of near permanent sunlight. In September 2010 LRO transitioned to its science mission and is expected to remain in the same mapping orbit until August 2011, at which time the spacecraft will trnsition to another, slightly higher polar orbit for continued science operations.

By March 2011, LRO will have been operating for approximately 21 months and the laser altimeter will have been operating almost continuously and is expected to have acquired over 3.5 billion altimeter obervations with a nominal ranging precision of 10 cm. The LRO spacecraft is routinely tracked by Doppler and range tracking from the Universal Space Network (USN), but LRO also has a high-precision laser tracking system [3] that employs laser stations on Earth that make one-way laser range (LR) measurements to a small optical receiver on the LRO High Gain Antenna and into a fiber-bundle that carries the incident photons to one of the LOLA detectors [1]. The Earth laser stations operate at 28 Hz, or some fraction, and the data are returned to Earth via the LOLA data stream. These observations, accurate to a few cm averaged over 5 seconds, enable precise positioning of LRO.

Precision orbit determination via a combination of Dopper and range tracking, laser ranging and altimetric crossovers has led to a striking improvement in lunar geodetic positioning; the current radial accuracy of the LOLA global topographic model is <1 m and the spatial accuracy of the lunar geodetic grid is ~30 m [5]. Comparsison to locations of Apollo retroreflectors measured by Earth-based Lunar Laser Ranging [6] yields agreement in elevation of 0.8 ± 1.5 m [5].

LRO's laser ranging capability also helps LRO to maintain <1 msec timing accuracy with respect to UTC for LOLA and the other LRO instruments [4], which facilitates cross-registration of observations from LRO and other lunar missions.

Global Data Sets: Maps of LOLA data sets are shown in Figure 1. LOLA altimetry has been used to assemble a precise global model of lunar topography. The global grid current in the NASA Planetary Data System (PDS) is LDEM_512, and is 16x2 GB with a pixel size in latitude of 59.225 m. A spherical harmonic expansion of the gridded data to degree and order 720 (spatial block size 7.5 km) has permitted refinement of fundamental parameters of the lunar shape [3].

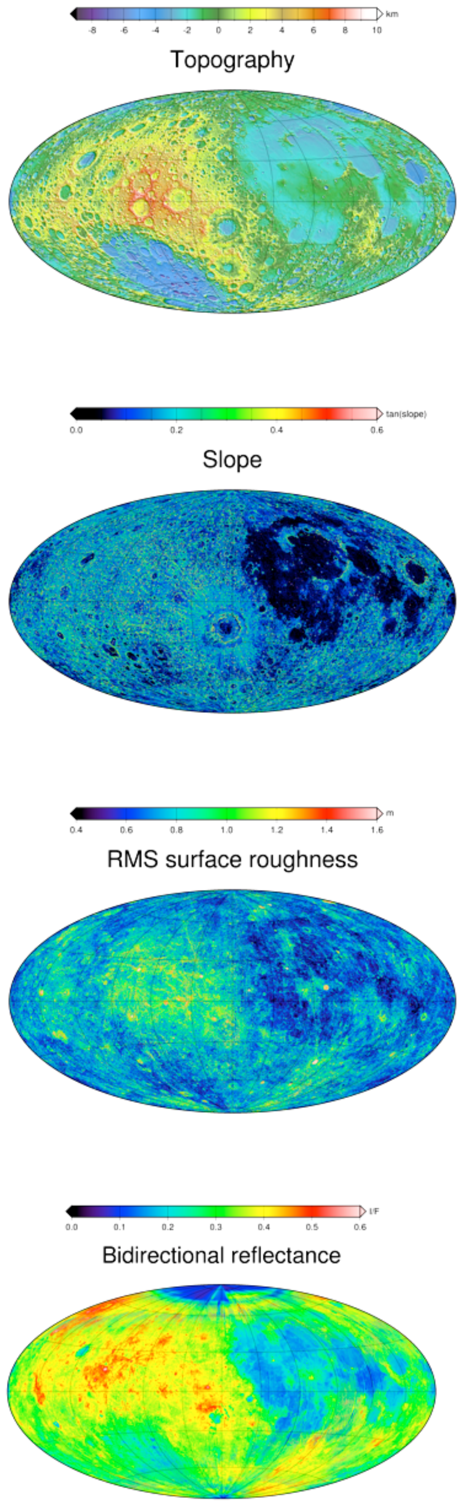

Figure 1. Hammer equal-area projections of topography, 56-m-baseline slopes, 5-m-scale rms roughness, and bidirectional reflectance of the Moon as measured by the Lunar Orbiter Laser Alimeter (from [3]).

The degree-2 shape is dominated by the flattening ($c_{2,0}$) and the nearside southern highland/farside highland relief. The nearside northern maria and farside equatorial highlands give rise to a large equatorial ellipticity ($c_{2,2}$) in the global shape, as well as to a significant $c_{4,0}$ term.

Analysis of rms roughness at various spatial scales shows that, as for Earth and Mars, distinctive geologic units have differing slope properties. For 56-m slopes a region of representative maria topography (-75 to 30 E, 30 to 60 N) exhibits a median slope of ~3.8^o, while a region representative of highlands (180 to 240 E, 5 to 60 N) has a steeper median slope of ~9.8^o. Fully 95% of slopes are shallower than ~17.5^o in the maria, and than ~25.2^o in rougher highlands [3].

Surface roughness at the LOLA footprint scale of 5 m shows that pulse widths are visibly widened on crater rims, basin rings, central peaks, the aprons of some impact structures and by South Pole-Aitken massifs, among other structures [3].

LOLA's pulse energy measurement provides a unique new view of the lunar reflectance. In Figure 1 the brighter anorthositic highlands and darker basaltic maria are apparent as they are in other near-IR spectral maps. But unlike previous imaging measurements that must contend with highly variable lighting and lunar bidirectional reflectance variations from terrain to terrain, LOLA observes the entire lunar surface at zero phase. This uniform illumination allows the reflectance of different lunar terrains to be compared precisely with none of the potential systematic errors due to uncertainty in lunar photometric properties that plague passive imaging sensors.

Ongoing analysis [7, 8] of LOLA topography, slope, roughness and reflectivity properties is addressing regional problems relevant to the Moon's tectonic, volcanic, impact and volatile evolution.

References: [1] Smith D. E. et al. (2010) *Space Sci. Rev*., 150, 209-241. [2] Chin G. et al. (2007) Space Sci. Rev. *129,* doi:10.1007/s11214-007-9153-y. [3] Zuber M.T. et al. (2010) *Space Sci. Rev., 150,* 63-80. [4] Smith D.E. et al. (2010) *Geophs. Res. Lett., 37,* doi:10.1029/2010GL043751. [5] Neumann G.A. et al. (2010) *Amer. Geophys. Un. Fall Meeting.* [6] Murphy T. et al. (2000) *Proc. 12th Int. Workshop on Laser Ranging,* Matera, Italy. [7] Neumann G.A. et al. (2011) this meeting. [8] Zuber M.T. et al. (2011) manuscript in preparation.