Lunar Orbiter Laser Altimeter (LOLA) Data Products and Contributions K. Jha[1,2] (kopal.jha@hexagonusfederal.com), G.A. Neumann[2], E. Mazarico[2], M.K. Barker[2], Sander Goosens[2], Dandan Mao[1], M.T. Zuber[3] and D.E. Smith[3]; [1]Sigma Space/Hexagon USF, 8800 Greenbelt Rd, Greenbelt, MD; [2]NASA Goddard Space Flight Center, Greenbelt, MD; Department of Earth, Atmospheric and Planetary Sciences, [3]Massachusetts Institute of Technology, Cambridge, MA.

Introduction: The Lunar Reconnaissance Orbiter (LRO) is a low-altitude mission in polar orbit around the Moon since 2009, allowing science teams to acquire datasets necessary to prepare for human return to the Moon, amongst other mission goals. The datasets and longevity (9 yrs and counting) of the mission make LRO data a keystone of lunar science.

The Lunar Orbiter Laser Altimeter (LOLA) [1,2] instrument greatly increased topographic knowledge of the lunar surface with its high sample rate (28 Hz) five-beam configuration and cm scale resolution. It has allowed other scientific measurements and results not originally planned for. Higher-level data derived from quantitative analysis have also been developed by the LOLA team, archived at the NASA Planetary Data System (PDS) Geosciences node in PDS3 structure and format. We review primary LOLA data products and present advances made by integrating LOLA data with other datasets (e.g. SELENE, GRAIL)[3].

Individual profiles: The data acquired by the instrument over each LRO orbit are recorded as individual products. These are calibrated and geolocated using reconstructed orbit and attitude information. These Reduced Data Records (RDR) give profiles of ground track position, range, lunar elevation, pulse return energy, but also contain key instrument settings such as detection thresholds and background noise counts, for each of the five channels.

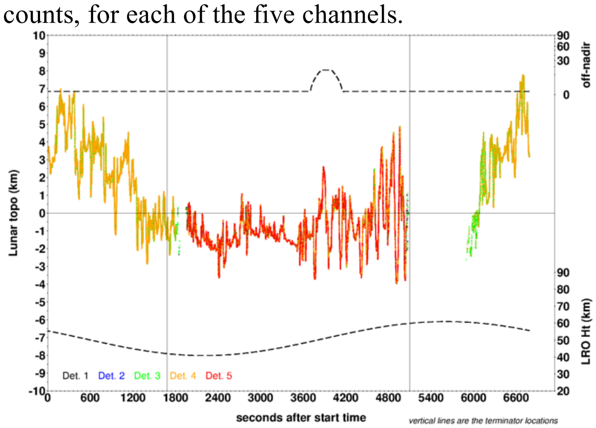

Figure 1. Altimetric profile of orbit 5709 (2010/09/20).

Topographic maps: The most scientifically used LOLA products are the LOLA Digital Elevation Models, or DEMs, constructed using individual profiles. These are archived in cylindrical and polar projections at a range of spatial resolutions and geographical extent. Strictly speaking, these products describe elevation, or shape, as no geoid correction is applied. Even with 44,000+ orbits, LOLA's narrow individual profiles do not sample the entire lunar surface. A slew campaign in 2010-2011 reduced the size of the coverage gaps between tracks, but interpolation is required for continuity at the highest resolutions. Count maps archived alongside DEMs can be used to consider the possible impacts of sampling and interpolation.

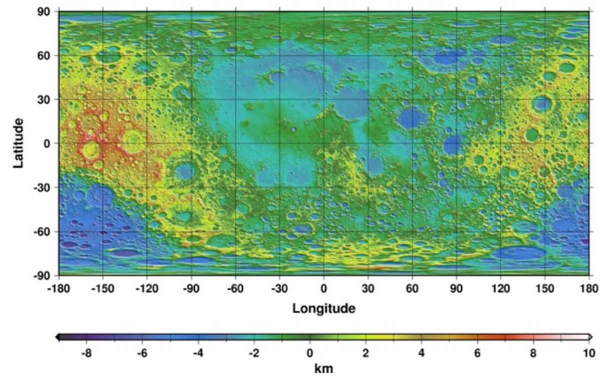

Figure 2. Global cylindrical map of lunar topography.

As LRO is in polar orbit, reduced spatial coverage at low latitudes is expected. The LOLA team combined geodetically-accurate LOLA data with Kaguya stereo camera data. The resulting SLDEM2015 topographic map [4], the best topographic product for the Moon as of today, is suited for most global studies.

Map area is distorted at higher latitudes. We will present projections addressing this issue.

GRAIL's gravity maps of the moon have been used to improve the location of LRO's orbit, further improving LOLA data quality. Other location-sensitive data aboard LRO have also benefitted from the precision orbits derived by the LOLA team.

Spherical Harmonics: The joint analysis of gravity and topography helps infer properties of the lunar interior, particularly its crust (thickness, density, porosity). Spherical harmonics expansion to degree and order 2050 were created from the global maps. A special version in the Principal Axes frame (the Mean Earth frame is typically used) is intended for use with the GRAIL gravity spherical harmonic coefficients [5] and as a special constraint to estimate density variations in the lunar crust [6].

Slope and Roughness: The expression of geologic features and processes in complex surface topography can be studied using their slope and roughness properties at various baselines. LOLA measures these in different ways and at different length scales. Long LOLA profiles of individual beams give one-dimensional slopes and roughness, while each five-beam LOLA footprint provides two-dimensional sub-50m slope and roughness information [7]. The return pulse shapes also relate to sub-footprint baseline roughness (~5-15m depending on LRO altitude). Finally, slope and slope azimuth at a given baseline are computed from a DEM at that scale.

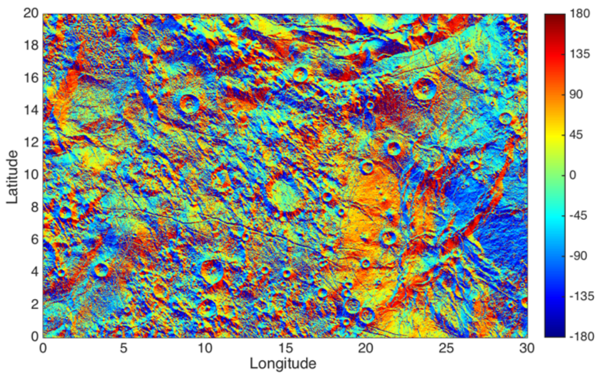

Figure 3. Slope azimuth at ~500-m baseline.

Active radiometry: The measurement of return pulse energy by the LOLA detector can be used to calculate surface reflectance at zero phase angle (normal albedo), after correction for surface range and calibration of detector response [8]. Calibration was especially difficult because of the 'LOLA thermal anomaly' near the poles and on the nightside. Individual profiles of calibration surface reflectance are combined into polar maps showing enhanced signal attributed to water frost [9,10].

Passive Radiometry: LOLA flight software allows automatic threshold adjustment to target a false-alarm rate, typically small (1-2%) in altimetric operations. In 2013, the thresholds were reconfigured to record 10,000's noise counts per second to allow passive radiometry measurement of the surface-reflected solar photons. This mode is used when LOLA is out of range, mostly in the northern hemisphere. Active measurements of normal albedo with passive data allow estimation of the lunar phase function at 1064 nm to better understand surface photometry and physical properties [11]. Calibrated passive radiometry is archived at PDS.

Illumination Conditions: LOLA topographic maps were used to survey the areas of permanent shadow in the lunar polar regions [11]. Maps of average solar illumination and average Earth visibility were similarly derived and archived. In addition, the solid angle of sky visible from the surface was computed, as it can be useful in studies dealing with external sources (starlight [12], solar wind, etc.)

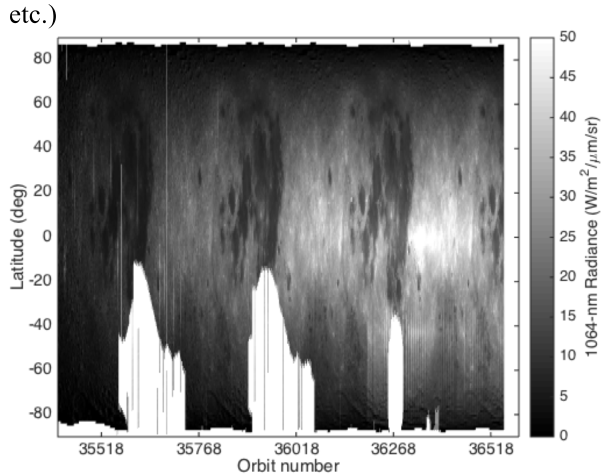

Figure 4. Three months of passive radiometry

Laser Ranging: The LOLA spot-1 detector is connected through fiber optics to the High-Gain Antenna to receive 532-nm laser pulses from ground stations and provide precise 1-way laser ranges for orbit determination [13,14] (from 2009 to 2014, now archived).

Other: Since the LRO 3rd Extended Science Mission (ESM3), the LR telescope has regularly observed geometrical configurations not possible from the nadir deck. A campaign of terminator observations close to the surface was performed to detect Apollo 15-like enhancements in dust forward-scattered light just before sunrise or after sunset [15]. The LRO spacecraft slewed on a few occasions to point LOLA towards a NIR telescope near GSFC and perform asynchronous two-way ranging, used for instrument pointing correction, pulse shape characterization and clock calibration.

References: [1] Smith D.E. et al. (2010) GRL, 37. [2] Smith D.E. et al. (2017), Icarus, 283. [3] Goossens et al. this mtg. [4] Barker M.K. et al. (2016) Icarus, 273. [5] Lemoine F.G. et al. (2014) GRL, 41. [6] Goossens et al. (2019) in prep. [7] Rosenburg M.A. et al. (2011) JGR, 116. [8] Lucey P.G. et al. (2014) JGR, 119. [9] Zuber M.T. et al. (2012) Nature, 486. [10] Fisher E.A. et al. (2017) Icarus, 292. [11] Barker M.K. et al. (2016b) Icarus, 273. [11] Mazarico E. et al. (2011) Icarus, 211. [12] Gladstone G.R. et al. (2012) JGR, 117. [13] Zuber M.T. et al. (2010) SSR, 150. [14] Mao D. et al. (2017) Icarus, 283. [15] Barker M.K. et al. (2018) Applied Optics. 27.