REGIONAL LIDAR TOPOGRAPHY AND REFLECTANCE ENABLE THE SCIENTIFIC EXPLORATION OF THE LUNAR SOUTH POLE: STATUS AND PERSPECTIVES. E. Mazarico[1], M. K. Barker[1], G. A. Neumann[1], D. E. Smith[2], M. T. Zuber[2], X. Sun[1], G. Yang[1], J. Chen[1], D. Harding[1], D. R. Cremons[1], J. W. Head[3], P. G. Lucey[4] ; [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; [2]Massachusetts Institute of Technology, Cambridge, MD 02139, USA; [3]Brown University, Providence, RI, USA; [4]University of Hawaii, Honolulu, HI, USA.

Introduction: The return of humans to the South Pole of the Moon with the Artemis program holds great promise for the scientific exploration of the Moon. Our knowledge of the Moon has greatly benefited from the recent wave of observation that started with the launch in September 2007 of the JAXA SELENE mission [1]. The NASA Lunar Reconnaissance Orbiter (LRO) spacecraft continues to collect large amounts of data from lunar orbit [2]. Among its instruments, the Lunar Orbiter Laser Altimeter (LOLA) collected billions of lidar observations [3], which enabled accurate topographic mapping, polar illumination modeling, and reflectance measurements within permanently shadowed regions (PSRs). We present the LOLA polar topography and reflectance, and discuss the potential of future lidar instrumentation to support Artemis [4].

Current Knowledge from LOLA: LOLA is the first multi-beam space laser altimeter [5]. Its 28-Hz firing rate and 5-m footprint size were chosen to allow measurements of surface topography and slope at scales relevant to landing systems envisioned for the Constellation program. Far surpassing the original 1-year mission duration, its inclusion in the LRO payload helped define a geodetically-accurate topographic reference for the Moon. Nearly seven billion altimetric measurements have been collected, primarily early in the LRO mission. The convergence of the groundtracks at the poles provides significantly higher density of measurements, while 100m-scale gaps remain at low latitudes. The northern latitudes are easily accessible since the change to LRO's elliptic near-frozen orbit in late 2011.

Figure 1 shows the intrinsic resolution of the LOLA dataset over the South Pole region (84-90°S). Nearest the poles (89-90°S), where several landing regions of interest lie (Shackleton Rim, Connecting Ridge), the LOLA spot density is highest, and the effective resolution is 10-15 meters per pixel. It slowly increases with latitude (like each latitude bin's surface area) up to 25-30 meters per pixel at 84°S. Percentiles are also shown, highlighting variations in spatial density.

In addition to altimetry, which is obtained from the laser pulse time-of-flight measurement, LOLA collects information on the return pulse energy, related to the surface reflectance [6]. Because of the lidar geometry, such reflectance measurements are always at zero phase, which obviates the need for (empirical) photometric corrections to relate observations Moonwide. These active reflectance measurements also occur over unilluminated surfaces (the lidar provides the light), including the PSRs. The LOLA measurements have been important to the study of the distribution and origin of the polar volatiles, observed by many instruments operating in different wavelengths and regimes, but still not well understood [7-9].

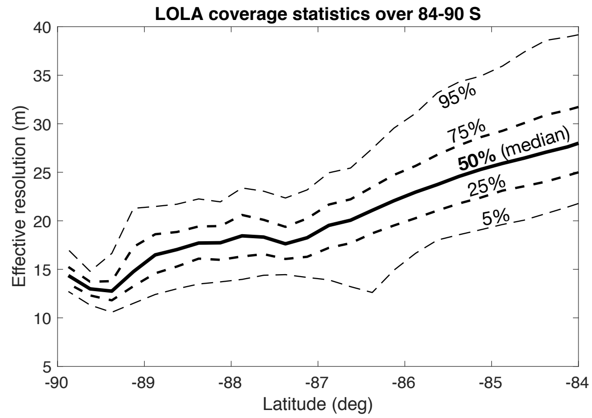

Figure 1: Effective resolution of the LOLA maps near the south pole (84-90°S), computed from the LDEC data count maps on the Planetary Data System. Before statistics were computed with 0.25° latitude resolution, the map resolution was 640 m/pixel.

Limitations: LOLA continues to collect limited amounts of altimetry when the LRO altitude is sufficiently low, but the LRO orbit inclination has continuously increased since 2009, to 86±0.6° now, so no new altimetric data are forthcoming for many polar sites. A study of elevation uncertainties is currently underway [10] in part to quantitatively assess their impact on illumination modeling [11], with implications for mission planning (Figure 2). Indeed, illumination conditions are particularly challenging for operations near the poles [12] given the Sun always stays low in the sky near the horizon. Thus, errors in topographic heights around landing sites (due to LOLA groundtrack position errors and/or surface interpolation in areas with no LOLA data) should be considered in mission design.

While the active radiometry collected by LOLA is free of some issues affecting passive imagers, LOLA reflectance data ideal in terms of spatial coverage and precision. The 'thermal blanket' anomaly pulled the laser beams out of alignment with the receiver fields of view at night and near the poles, except during short time periods. The measurement precision was thus limited to ~10%, and the spatial resolution was ~1 km near the poles. Finally, the LOLA reflectance measurements, considered alone, are ambiguous when it comes to interpretation of volatile distribution because they are taken at a single wavelength (1064 ± 0.2 nm). Nevertheless, when interpreted within the context of the entire suite of LRO multi-wavelength datasets, they have revealed new characteristics of the nature and distribution of polar volatiles [8,13].

Outlook for Artemis: The advances in our understanding of lunar topography and reflectance enabled by LOLA can be further augmented to benefit the Artemis missions, thanks to recent lidar technological developments. We will present technological solutions to support Artemis science and exploration, using orbital lidar instruments being developed at the Goddard Space Flight Center.

Multispectral reflectance. While LOLA was built firstly to obtain elevation data, lidar systems can be designed to focus on the reflectance measurement, and have been [14-15]. The Spectral Infra-Red Reflectance LIDAR (SpIRRL) instrument in particular benefits from MLA and LOLA heritage and would obtain precise (SNR>100) sub-km-resolution global maps of reflectance, at seven wavelengths specifically chosen to inform the OH/H_2O static and diurnal/seasonal distribution [15]. As this would allow mapping of OH/H_20 and surface water ice within PSRs, it would be invaluable to provide more *context* for Artemis mission planning [4].

Topographic mapping. The LOLA maps of surface elevation enabled accurate surveys of the PSRs and of the high-illumination sites particularly attractive to long-lasting surface operations [16]. However, the resolution is not sufficient to retire all hazard and illumination-related risks associated with human landing. Swath-mapping lidars currently under development would allow meter-scale topographic (and single-wavelength reflectance) mapping of large portions of the polar regions, again providing refined *context* for detailed mission planning [4]. This can be achieved with a single arrayed detector and a single tunable fiber laser [17], making this concept compatible with any orbital platform (*e.g.*, SmallSat). A grating is used to allow selectable cross-track pointing, and multiple laser shots are averaged to achieve LOLA-quality vertical accuracy. The laser can be fired at MHz frequency to allow complete mapping of swaths as wide as 200m per passage. Full coverage of sizeable polar sites can be achieved in short durations as a result of polar orbit convergence and day/night operations. More details on the technology and instrument concept will be presented at the meeting.

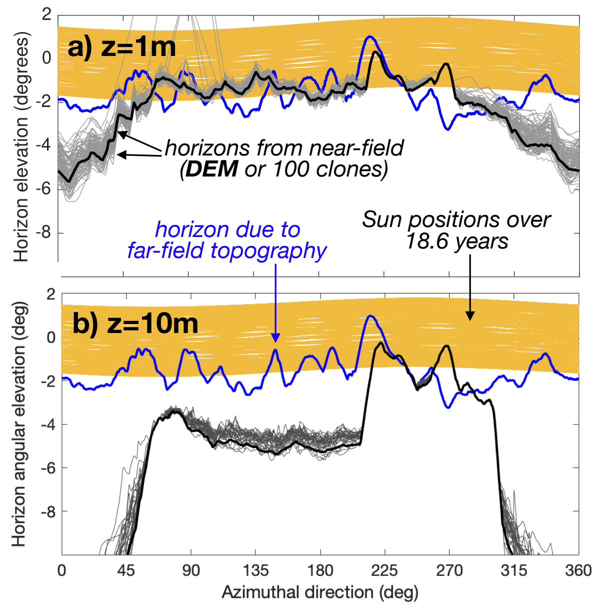

Figure 2: Examples of solar occultation at altitudes of 1 (a) and 10 (b) meters above the surface show the increasing importance of topographic knowledge of near-field obstacles as the size of surface stations or vehicles are reduced. Sun position over a full lunar cycle are shown in orange. The near-field horizon computed from the high-resolution 5 m/px DEM of the Shackleton rim is shown in black, as well as 100 horizons in gray from 'clones' that account for groundtrack position and surface interpolation uncertainties. The horizon from far-field topography is shown in blue.

References: [1] Kato M. et al. (2010), *Space Science Reviews*, 154, 3-19. [2] Vondrak R.R. et al. (2010), *Space Science Reviews*, 150, 1-4. [3] Smith D.E. et al. (2010), *Space Science Reviews*, 150, 209-241. [4] Head J.W. et al. (2020), *this meeting*. [5] Smith D.E. et al. (2017), *Icarus*, 283, 70-91. [6] Lucey P.G. et al. (2014), *JGR Planets*, 119, 1665-1679. [7] Lemelin M. et al. (2016), *Icarus*, 273, 315-328. [8] Fisher E.A. et al. (2017), *Icarus*, 292, 74-85. [9] Qiao L. et al. (2019), *Earth and Space Science*, 6, 467-488. [10] Barker M.K. et al. (2020), *LPSC*. [11] Mazarico E. et al. (2020), *LPSC*. [12] Petro N.E. et al. (2020), *this meeting*. [13] Deutsch A.N. et al. (2020), Icarus, 336, 113455. [14] Cohen B.A. et al. (2017), *LPSC*, 1709. [15] Lucey P.G. et al. (2017), *Lunar Exploration Analysis Group*, 5048. [16] Mazarico E. et al. (2011), *Icarus*, 211, 1066. [17] Jiang Y. et al. (2020), *Nature Photonics*, 14, 14-18.