THE SURFACE ROUGHNESS AND VOLATILE CONTENT OF THE MOON: A RADAR PERSPECTIVE. G. W. Patterson[1], L. M. Jozwiak[1], J. M. Leeburn[1,2], A. M. Stickle[1], J. T. S. Cahill[1], P. Prem[1] and the Mini-RF team. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD (Wes.Patterson@jhuapl.edu), [2]Dept. of Earth and Mineral Sciences, Pennsylvania State University.

Introduction: The Lunar Reconnaissance Orbiter (LRO) mission was launched in 2009 with a payload intended to characterize landing sites for the return of humans or future robotic missions to the Moon, as part of NASA's Exploration Systems Mission Directorate. The characterization of various potential landing sites, identified by the Constellation Program Office [1], illustrated the diversity of scientific and resource opportunities, and geographic terrains and locations, for future exploration, resource development, and mission operations. The role of Mini-RF was to measure wavelength-scale surface roughness of potential sites of interest and to search for water-ice. Here we review the results of Mini-RF data and their relevance for identifying potential landing hazards, impediments to trafficability, and/or volatile content. We also discuss useful ground truth measurements that could be obtained from landed platforms to inform the analysis of Mini-RF or Earth-based Synthetic Aperture Radar (SAR) data.

Mini-RF Operations: Mini-RF is a hybrid-polarized, dual-frequency SAR that operates at wavelengths of 12.6 cm (S band) and 4.2 cm (X/C band) [2]. The instrument was designed as a monostatic system – i.e., the antenna operated as a transmitter and receiver – that operated at a fixed incidence angle of 47°, with spatial resolutions of 30 m and 150 m. In this operational mode, it transmitted a left-circular polarized signal and received orthogonal linear polarizations. In December of 2010 the transmitter experienced a malfunction and ceased to operate, precluding further monostatic data collection. Prior to this malfunction, Mini-RF was able to collect S-band data that covered > 66% of the lunar surface and > 95% of the lunar poles. Controlled monostatic mosaics of these data for both poles have been produced by the USGS following the methodology outlined in [3]. These mosaics provide shadow-free access to polar crater floors at a resolution of 30 m/pixel (Fig 1.).

Shortly after the transmitter failed, Mini-RF began operating in concert with the Arecibo Observatory (AO) in Puerto Rico and then the Goldstone deep space communications complex 34 meter antenna DSS-13 to collect bistatic radar data of the Moon. In this architecture either AO (S-band) or DSS-13 (X-band) transmits a circularly-polarized signal to illuminate a portion of the lunar surface, and Mini-RF's receives the backscattered signal. In this architecture, the incidence angle varies as a function of the observation geometry and the data have a spatial resolution of ~100 m. Varying the incidence angle allows for wavelength-scale scattering properties of the surface and subsurface to be measured over a range of bistatic angles (i.e., equivalent to phase angle for optical instruments) [4]. This was not possible in Mini-RF's original monostatic configuration (phase angle = 0°).

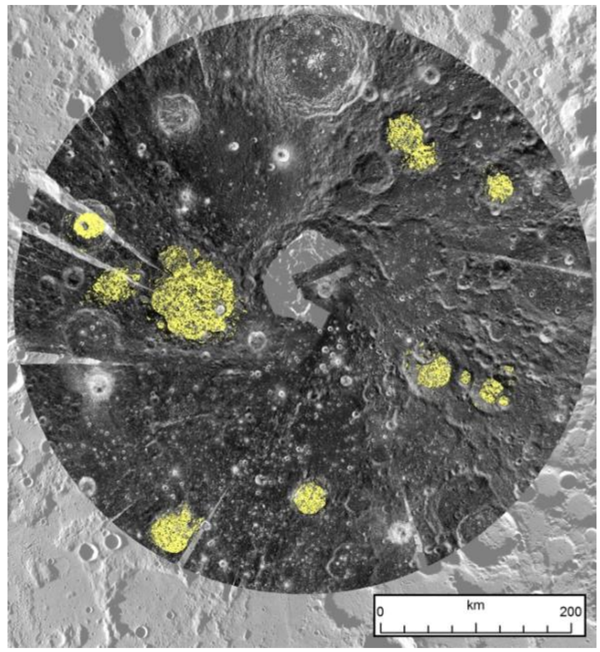

Fig. 1. Mini-RF controlled polar mosaic of the north polar regions (80°N to 90°N) overlain on WAC 100 m basemap. Yellow indicates permanently and non-permanently shadowed regions for the floors of craters with dia. > 15 km and slopes < 5° (for surface areas > 1 km^2).

Mini-RF Objectives: Over the 10 years LRO has operated, Mini-RF has addressed broad science objectives involving volatile, impact, and volcanic processes on the Moon [e.g., 4-9], as well as modeling of the radar response of materials at Mini-RF frequencies [10-14]. For the current spacecraft extended mission, Mini-RF continues to collect bistatic data that address LRO science objectives related to: the vertical distribution of water; the form and abundance of water ice; how impacts expose and break down rocks to produce regolith on the Moon and other airless bodies; the present rate of regolith gardening; and how lunar volcanism has evolved over time.

Mini-RF Capabilities: The Mini-RF architecture provides data of the backscattered return from the lunar surface in the form of the classical Stokes parameters (S_1, S_2, S_3, S_4). This information can be used to derive a variety of products that are useful for characterizing the surface. The circular polarization ratio is one such product and it is commonly used in analyses of planetary radar data.

The CPR of a surface provides an indication of roughness within the penetration depth of the radar, as determined by the distribution of surface and buried wavelength-scale scatterers (*e.g.*, boulders). While the spatial resolution of Mini-RF (and other radars operating at similar wavelengths) is not sufficient to identify hazards or trafficability at the scale of a lander or rover, the wavelength-scale sensitivity of the data are valuable for identifying regions where the relative roughness is more or less acceptable for EDL activities or rover operations (e.g., Fig. 1).

Water-ice can exhibit a strong response at radar wavelengths in the form of a Coherent Backscatter Opposition Effect (CBOE) and CPR can be a useful indicator of such a response—i.e., measured CPRs for icy materials typically exceed unity [15]. This effect has been used to explain observations of radar 'anomolous' craters on the Moon [7] but alternative interpretations are possible [16]. This effect has also been used to explain a unique bistatic radar response for the floor of the south polar crater Cabeus [4]. However, in this case, Mini-RF monostatic data (i.e., phase angle of 0°) of the crater floor at an incidence angle of 47° [17] and ground-based CPR measurements at a fixed bistatic (phase) angle (0.37°) and large (> 80°) incidence angles have been made [18] and don't agree. Given some of the inherent ambiguities in interpreting radar data of silicate-ice mixtures, our continued objective is to integrate multiple wavelength observations over a range of bistatic angles (and concomitant penetration depths) to help elucidate the structure of lunar polar regolith.

Ground Truth Considerations: Mini-RF data provide unique information regarding the presence of cm- to m-scale boulders, and volatiles of interest such as water-ice, at the surface and near sub-surface for a significant fraction of the lunar surface. However, the utility of those data are influenced by our current understanding of the physical properties of the regolith. Future landed missions (both human and robotic) that can directly sample the regolith in radar regions of interest and/or measure the characteristics of the subsurface (e.g, ground-penetrating radar) will provide important constraints on potential landing hazards, impediments to trafficability, and/or volatile content.

References: [1] Gruener J. E. and Joosten B. K. (2009) LRO Science Targeting Meeting, Tempe, Arizona, p. #6036; [2] Raney R. K. et al. (2011) *Proc. IEEE, 99*, 808–823. [3] Kirk R. L. et al. (2013) *LPSC XLIII*, Abstract #2920. [4] Patterson G. W. et al. (2017) *Icarus 283*, 2-19. [5] Cahill J. T. S. et al. (2014) *Icarus,* 243, 173-190; [6] Carter L. M. et al. (2012) *JGR* 117, E00H09; [7] Spudis P. D. et al. (2013) *JGR* 118, 1-14; [8] Stickle A. M. et al. (2016) *Icarus*, 273, 224-236; [9] Morgan et al. (2018), *49thLPSC* #1897; [10] Thompson T. W. et al. (2011) *JGR* 116, E01006; [11] Thomson B. J. et al. (2012) *GRL* 39, L14201; [12] Prem P. and Patterson G. W. (2018) *LPSC XLIX,* Abstract #2134 ; [13] Virkki A. K. and Bhiravarasu S. S. (2019) *JGR*, E006006; [14] Heggy E. et al, *EPSL*, in press; [15] Harmon J. K. et al., (1994) *Nature, 369*, 213–215; [16] Fa W. & Eke V.R. (2018) *JGR, 123*, 2119-2137; [17] Neish et al., 2011, JGR (Planets), 116, E01005; [18] Campbell et al., 2006, Nature 443, 835-837.