SURFACE ROUGHNESS AND RADAR SCATTERING PROPERTIES OF VOLCANIC TERRAIN: GEOLOGIC APPLICATION OF KINEMATIC MOBILE LiDAR SCANNING

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Introduction: This study seeks to better understand the surface scattering properties of multi-frequency synthetic aperture radar (SAR) data of planetary surfaces. Using quad-polarimetric SAR data from spaceborne (RADARSAT-2 (C-band, 5.6 cm λ) (Fig. 1a)) and airborne (AIRSAR (L-Band, 24 cm λ)) platforms, as well as field measurements of surface topography from a cutting-edge backpack-mounted kinematic mobile LiDAR scanning (KLS) system, we investigate the surface roughness and radar backscatter properties of volcanic terrains (various lava flows, spattercones, etc.) in and around the Craters of the Moon National Monument and Preserve (CRMO) in the Snake River Plain, Idaho, USA. This project was done in collaboration with the NASA Solar System Exploration Research Virtual Institute (SSERVI) Field Investigations to Enable Solar System Science and Exploration (FINESSE) project, and seeks to understand lava flow roughness as a planetary analog for lunar impact melt flows and Martian lava flows [e.g. 1]. By quantifying the surface roughness over large areas, we can better understand the radar scattering properties, which are measured at lower spatial resolution than the KLS (Radar: 5-40 m/pixel vs. KLS: 2.5 cm/pixel). In this study we report on how surface roughness parameters (e.g. RMS height, RMS gradient, and others) correlate with the circular polarization ratio (CPR) of the radar data (CPR; the ratio of the same-as-transmitted vs opposite-as-transmitted polarization signal).

Datasets and Methods: Eighteen scenes of Fine-Quad fully polarimetric RADARSAT-2 SAR data (~35 m/pixel after processing) were acquired in 2015 and 2016 and cover the entirety of the 2,900 km^3 National Monument. Four strips of quad-polarimetric data from JPL's AIRSAR (acquired March 2003; ~12 m/pixel) cover ~80% of the monument. Both RADARSAT-2 and AIRSAR quad-pol data were calibrated, multi-looked, speckle-filtered, and terrain corrected using a combination of ESA's SNAP, PolSAR-Pro, and ASF MapReady processing software. Additional processing was done to calculate the circular polarization ratio and derive the Freeman-Durden and Pauli Decomposition maps.

Kinematic Mobile Lidar Scanning (KLS) System: Ultra-high resolution topography measurements were made using the AKHKA-R3 backpack-mounted KLS system developed by A. Kukko and H. Kaartinen at the National Land Survey of Finland [2].The KLS instrument (consisting of a Reigl VUX-1-HA laser line scanner coupled to a tactical grade inertial measurement unit (IMU) and a GPS/GNSS receiver antenna) allows for measurement of the topography and surface roughness at ultra-high resolution (cm scale), over large areas of the ground (>2,500 m^2) with vertical accuracy ~5 mm. As the operator traverses the ground, the surface is scanned by the laser at 1 million points and 120 lines/sec, and ground range to the scanner is measured. Absolute global position is determined by GPS/GNSS. Post-processing solving for operator and laser trajectories results in an ultra-dense point cloud representation of the surface in 3D. Further processing converts the point cloud to a raster digital elevation model (DEM). Point cloud spatial resolution within 20 m of the scanner is on the order of 5 mm (depending on distance from the scanner), with vertical accuracy <2cm and absolute global position <<10 cm. Data collection time for a 50 m grid with 2.5cm/pixel resolution is ~10-15 min.

Grid Locations: LiDAR topographic maps from 11 different lava flow textures located within the Green Dragon Flow, Indian Tunnel region, and the Kings Bowl region were made. From these large area maps, topographic and surface roughness data was extracted for 33 square grids, each ~ 50 m x 50 m (2,500 m^2). On average, grids contained more than 200 million LiDAR point measurements, resulting in Digital Elevation Models (DEMs) with 1 – 2.5 cm/pixel resolution (Fig. 1d). LiDAR grids were geolocated within an ESRI ArcGIS map package containing the SAR data (calculated CPR, σ^0 for HH, HV, VH, VV channels) and zonal statistics [3] were extracted for both C- and L-band data from the 50 m measurement area, and a larger 200 m (0.04 km^2) surrounding region (for increased radar sampling statistics). For brevity, here we only report results of CPR extracted from the 50 m grids (Fig 1a).

Determining Surface Roughness Properties: Describing the roughness properties of a surface is non-trivial, and quantification of roughness parameters is often scale-dependent [4]. Drawing from Metrology Science standards for evaluating surface roughness in 2D and 3D, we calculate our surface roughness parameters using International Standards Organization (ISO) 25178 (for 3D area parameters [5]) and ISO-4287 [6] (2D roughness and waviness parameters) using industry standard Digital Surf MountainsMap 7, and SPIP Image Metrology software. As per the metrology standard parameters, (e.g. *q* (RMS height), *dq* (RMS gradient), *fd* (fractal dimension)) are calculated over a defined sampling length (aka cut-off or evaluation length).

Results and Discussion: We find that RMS height as a measure of surface roughness is correlated with block sizes proportional to the radar wavelength, and that the roughness profile is very sensitive to the defined sample length. Figure 1a compares the RMS height (R*q*) calculated at a sample length of 30 cm for the 33 grid locations (labeled in Fig. 1a) for C-band (blue dots) and L-band (orange dots). Overall, C-band CPR does not indicate the presence of dihedral reflectors (i.e. "double-bounce" reflections where the polarity sense of the signal sent is the same as the signal returned). The surface roughness therefore appears "smooth" to the radar signal at C-Band, despite incredibly rough surfaces observed in the field. The "smoothness" of the C-band CPR suggests that short (5.6 cm) wavelength specularly reflects off the large blocks, giving little information about the block sizes in the observed area. The C-band behavior is expected for flat pahoehoe flows, but the lack of sensitivity to rough, slabby, or blocky flows is surprising (as observed by [1]).

Conversely, L-band CPR at the same locations often displays dihedral scattering, particularly in areas of blocky or slabby flows. In these regions, the L-band CPR data is providing useful information about the morphometry of ground features (block- and fracture-sizes on the order of 24 cm), which is supported by ground-truth measurements of these features. Interestingly, there are occasional outliers of high L-Band CPR with low RMS height roughness in the pahoehoe flows (e.g. LF1, red oval Fig 1a). LF1 is characterized by an impressive lava cascade (Fig 1d) containing numerous pressure ridges and flow lobes that are ~25 cm high that increase the dihedral scattering response.

Surface roughness vs CPR results observed in these volcanic terrains are in stark contrast to those measured with the same technique and radar wavelengths in the Canadian High Arctic [7]. There, the opposite behavior between C- and L- band is observed (with L-Band appearing smooth, despite rough terrain). The difference between Arctic periglacial terrain and volcanic terrains demonstrate that radar data must be used in context with other remote-sensing and ground-truth data, and multiple radar wavelengths are necessary to provide unambiguous descriptions of planetary surfaces.

Acknowledgements: RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates, Ltd. (2015) – All Rights Reserved. RADARSAT is an official trademark of the Canadian Space Agency.

References: [1] Neish, C. D., et al. (2017). *Icarus*, *281*(C), 73–89. [2] Kukko, A. (2013) Kirkkonummi, PhD thesis, 247p. [3] ESRI ArcGIS Help – How Zonal Statistics Works [4] Shepard, M. K. et al., (2001) JGR 106 E12 [5] ISO25178-2:2012 Surface texture: Areal [6] ISO4287:1997 Surface texture: Profile [7] Zanetti et al., (2017). LPSC Abs #2775.

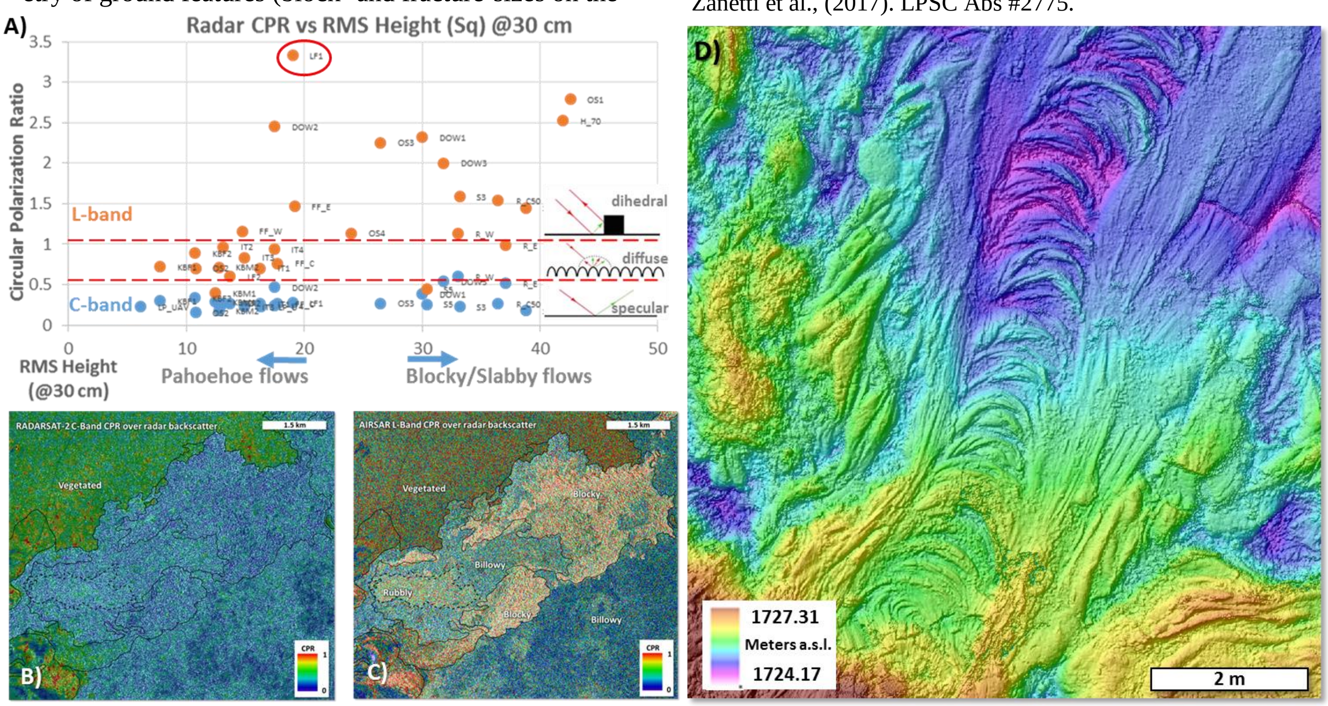

Figure 1: Results of C- and L-band Circular Polarization Ratio vs Surface Roughness study at Craters of the Moon National Monument. A) Graph of CPR vs RMS height derived from KLS LiDAR data and sourced from 33 sites around the park. C-band (5.6 cm λ) in blue, L-Band (24 cm λ) in orange. Red dashed lines denote different scattering properties (low to high: specular, diffuse, and dihedral). Smooth pahoehoe flows are clusters to the left, blocky slabby flows to the right. Note that sites vary considerably in RMS height, but in C-band, nearly all scattering is specular. B) Radarsat-2 C-band CPR data over the Green Dragon flows of CRMO. C) AIRSAR L-Band data over same region. Note the preponderance of dihedral reflections (red/orange regions) in blocky and slabby areas of the flows. D) Example of the KLS mobile LiDAR data from a pahoehoe lava flow (site LF1, red oval Fig 1a). Pressure ridges and flow direction are easily discernable and likely contribute to the anomalously high L-Band CPR at this site. DEM resolution is ~1 cm/pixel.