AN IMPROVED METHODOLOGY FOR THE 3-DIMENSIONAL CHARACTERIZATION OF SURFACE ROUGHNESS AS APPLIED TO LAVA FLOWS. K. A. Fan[1], C. D. Neish,[2] M. Zanetti[2], A. Kukko[3], [1]The University of British Columbia, Vancouver, BC, Canada (kevin.fan@alumni.ubc.ca), [2]Western University, London, ON, Canada, [3]Finnish Geospatial Research Institute, Helsinki, Finland.

Introduction: Topographic roughness analysis is often employed in order to quantitatively classify and differentiate a variety of surfaces in earth and planetary science [1,2,3,4]. Such analysis has the potential to provide insight into emplacement mechanisms, formation processes, and geochemistry on worlds where limited 'ground truth' is available.

However, the problem of optimal methodology for the quantitative measurement of surface roughness is longstanding in a myriad of fields, ranging from engineering texture analysis [5] to earth sciences [6]. The earth sciences in particular have only very recently adopted 3D roughness methods, despite the ubiquity of 3D DEMs (Digital Elevation Models), and the fact that 2D methods often neglect to account for anisotropy [4]. Even amongst such examples of 3D surface roughness characterization in the earth sciences (e.g., [3,4]), fundamental issues pertaining to roughness persist, such as the ambiguity of the scale (or range of such) at which roughness parameters are measured. Furthermore, there is inconsistency in the type of initial detrending applied amongst different workers prior to roughness parameter calculation, in order to separate large-scale topography from small-scale roughness – or in whether it is applied at all (e.g., [1,2,3,4]).

Topographic roughness analysis can contribute to studies in volcanic geomorphology by quantifying the substantial textural variation observed amongst lava flow deposits. Our new topographic analysis technique facilitates 3-dimensional estimation of roughness parameters as applied to lava flows in Craters of The Moon National Monument and Preserve in Idaho. We envisage future applications to planetary analogue studies, in order to assess geomorphic variation amongst different lava flows on planetary bodies for which DEMs of high resolution and large areal extent are available, such as the Moon and Mars.

LiDAR DEM Data: We sought to determine the surface roughness of lava flows at Craters of The Moon National Monument and Preserve. To do this, we obtained high-resolution DEMs of several lava flow surfaces using a kinematic, backpack-mounted AkhkaR3 LiDAR system [8,9,10] with ultra-high horizontal spatial resolution of 1-2.5 cm and vertical resolution of <<5 cm. DEMs are produced upon processing of point-clouds for a variety of lava flow textures around the study area. Below, we show one DEM as an example, representative of the 'rubbly flow' texture observed at North Crater Flow (Fig. 1a; further description given in [2]).

Methodology: For a given rectangular DEM input (denoted the "primary surface"), composed of a grid of regularly spaced square pixels of known separation distance and resolution (Fig. 1b) , a 3D Gaussian Filter is applied to the original DEM. The cut-off wavelength, at which 50% of the spatial frequency content of the topography is transmitted and 50% is attenuated, is 5 m, which is 5 times the maximum lag scale of interest. The result of the low-pass filter is a 3D "waviness surface" (Fig. 1c), and the result of the high-pass filter is a 3D "roughness surface" (Fig. 1d), where the latter consists primarily of the spatial frequencies below the cut-off wavelength, with some leakage from higher spatial frequencies. In essence, the "roughness surface" respresents the small scale roughness of the lava flow, while the "waviness surface" represents the large scale topographic variation.

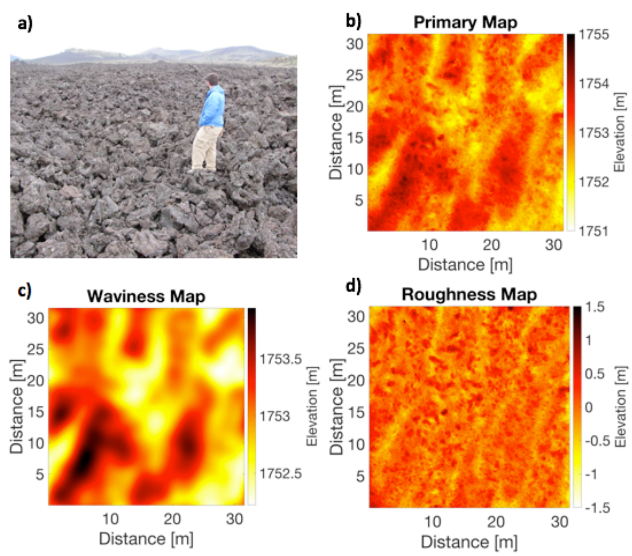

Figure 1: *a) Picture of rubbly lava at North Crater Flow, with accompanying DEMs of b) primary, c) waviness (low-pass), and d) roughness (high-pass) surfaces.*

We then calculate the RMS Slope for the roughness surface. The RMS Slope provides a statistical measure of the deviation of the heights within an area at a particular scale, i.e., the 'average' slope at a particular scale. The Hurst Exponent is directly related to fractal dimension and arises from mathematical considerations of a surface's degree of self-affinity over a specified range of scales, i.e., how the roughness of a surface changes over a specified range of scales [7]. For each and every pixel (excepting those at the edges), a 2D, 4x4 m square "evaluation cell" is partitioned out of the larger DEM.

Within this evaluation cell, the root mean square amongst the height differences between all possible point pairs is determined for each lag vector ***r***=<±*q*,+*p*>, where *q* is the lag component in the x direction, and *p* is the lag component in the y-direction. The minimum absolute value for both components is the pixel resolution (i.e., (q,p) ≥ 2.5 cm), while the maximum absolute value is five times smaller than the Gaussian filter cutoff wavelength (i.e., (q,p) ≤ 1 m = 40 pixels). The RMS Deviation *v(q,p)* (the RMS Slope scaled by the lag vector magnitude) is then:

$$v(q,p) = \sqrt{\frac{1}{N}\sum_{i=1}^{c-q}\sum_{j=1}^{c-p}[z(x_i,y_j) - z(x_{i+q},y_{j+p})]^2} \quad (1)$$

where *z* is the height associated with a particular pixel of the DEM, *i* is the row index, *j* is the column index, and *N* is the number of sample points separated by ***r***. The RMS Deviation and associated lag vector magnitude is then iteratively calculated for every lag vector (both magnitude and direction), resulting in a variogram surface that depicts RMS Deviation as a function of lag vector magnitude and distance. A weighted linear least-squares regression is then applied, giving the Hurst exponent as the slope of the line and the RMS Slope as the intercept of the line in log space. The entire algorithm is then iterated for all DEM pixels, resulting in 3D RMS Slope and Hurst Exponent maps for the entire area (Figure 2).

Results: We applied the 3D roughness methodology to the DEM of the Gaussian-filtered roughness surface (Fig. 1d). We calculated the RMS Slope and Hurst Exponent maps over the range of 0.025-1 m. For the rubbly lava flow shown in Figure 1a, the RMS Slope (Fig. 2a) ranges from 0-25° and the Hurst Exponent (Fig. 2b) ranges from 0.2-0.6, which is comparable to the typical value of ~0.5 about which natural surfaces tend to cluster [1]. High values of RMS Slope tend to be visually correlated with locations on the roughness surface with rapid changes in topography, capturing quantitatively this intuitive notion of roughness. Hurst Exponent does not however show any apparent visual correlation with the roughness surface.

More generally, we visualized the 3D variogram surface as a contour plot (Fig. 2c). This effectively involves the application of Eq. (1), using the entire roughness DEM as the evalatuion cell. The plot indicates three roughness regimes. Circular contours from the minimum scale of 0.025-1 m imply an isotropic roughness regime, followed by ellipsoidal contours from 1-6 m. This implies an anisotropic roughness regime with principal axes of N20°E (minimum roughness) and E20°S (maximum roughness), and therefore flow emplacement direction along the N20°E axis. Above this 1-6 m 'non-correlation threshold', there is an absence of discernable contour shape, implying a final transition above which all point pair heights are spatially uncorrelated. RMS Deviations above this scale attain a maximum value of ~0.4 irrespective of increasing lag magnitude, implying that roughness attains a maximum above this final transition.

Discussion: Our proposed topographic analysis workflow can provide high-resolution 3D, direction-dependent characterization of the roughness of geologic surfaces. This is done via the determination and comparison of their scale-dependent isotropic, anisotropic, and non-correlation regimes. It can be applied to any 3D DEM for applications in remote sensing, geomorphology, and planetary analogue studies. This technique is especially useful in locations where it may be infeasible to directly ascertain ground truth about emplacement processes.

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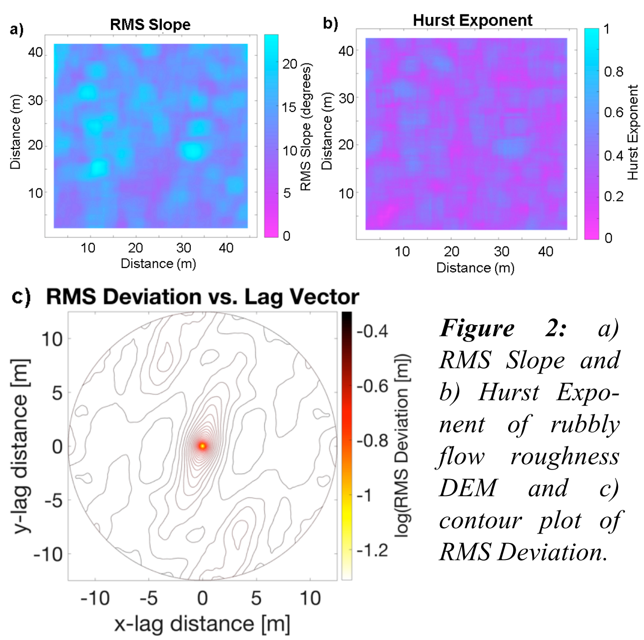

Figure 2: *a) RMS Slope and b) Hurst Exponent of rubbly flow roughness DEM and c) contour plot of RMS Deviation.*