MULTI-SCALE ROUGHNESS SPECTRA OF VOLCANIC DEBRIS FLOWS; R. T. Austin and A. W. England, Radiation Laboratory, University of Michigan, Ann Arbor, Michigan, USA.

ABSTRACT. The topographies of several debris flow units near the Mount St. Helens Volcano were measured at lateral scales of millimeters to meters in support of studies of electromagnetic scattering by volcanic terrains. We used a laser profiling system and surveying instruments to obtain elevation data for square areas that varied from 10 cm to 32 m on a side. These data were converted to estimates of the power spectrum of surface roughness. The conversions were based upon modified spectral estimation techniques designed to compensate for errors present in the profilometer data. The resultant spectral estimates suggest a power-law spectrum for the primary debris flow surfaces and a mixed spectrum for the surfaces modified by sedimentation.

MOTIVATION. Although radar is an increasingly common tool in planetary science, much remains to be done in extracting all useful information from planetary radar measurements. For example, Earth-based, time-domain radar surveys of Mars consist of a well-understood specular return from the sub-Earth region and delayed diffuse returns (from concentric rings centered on the sub-Earth point) which are less well understood. An interpretation of the diffuse backscatter beyond inferences based upon the Rayleigh roughness criterion requires some assumption about the roughness statistics of the Martian surface and a scattering theory that permits roughness at all scales. (Several investigators (1,2) have argued that natural surfaces are scaling and therefore have a multi-scale roughness.) We are investigating such a scattering theory by examining the roughness statistics and scattering of an Earth analog of a Mars volcanic region. Scattering from such volcanic terrains is also of interest in terrestrial remote sensing.

DEBRIS FLOW MEASUREMENTS. Surface roughness measurements were performed on several debris flows near the Mount St. Helens Volcano during September 1990. The examined surfaces were located in the debris avalanche WNW of the volcano, along the North Fork Toutle River Valley. Most of the debris was deposited during and immediately after the eruption of Mount St. Helens on 18 May 1980. Since then, the deposits have undergone significant erosion by wind and water. A geologic description of the debris avalanche is given by Glicken (3).

Our objective was to characterize the surface roughness of the debris flows at scales smaller than, similar to, and larger than the wavelength of common remote sensing radars. Two techniques were used. A computer-driven, 2D laser profilometer recorded surface height profiles of square grids with sides between 10 cm and 1 m in length. The grids were sampled at intervals between 2 mm and 2 cm. We used surveying instruments to measure elevation data over larger square areas (32 × 32 m).

The 2D laser profilometer system is based on a surveying electronic distancemeter (EDM), which uses an infrared laser to measure the distance from a reference plane to a target surface. The EDM laser has a spot diameter of $\sim$1.5 mm; the standard deviation of the measured surface height is 3 mm. Profilometer measurements require 2–3 seconds per surface point; a typical scan measuring 10 cm × 10 cm with $\Delta = 2$ mm (2601 points) takes $\sim$1.8 hours.

Larger-scale topographies were surveyed. Square grids with sides of 32 m were delineated by cables, and a self-leveling surveying level and stadia rod were used to measure the surface height at intervals of 1–4 m, depending on the surface roughness. Surveying was slow: each data point required 20–40 seconds to measure and record.

SPECTRAL ESTIMATION TECHNIQUES. Profilometer data suffered from errors which precluded the use of standard spectral estimation techniques. Since the measurements could not be repeated, we modified our estimation algorithm to minimize the effects of the errors. The data errors were of two types: (i) incorrect heights due to overheating of the EDM, and (ii) intermittent level shifts due to instability in the EDM.

Errors due to overheating resulted in negative "spikes" in the surface elevation. These errors were easily distinguishable in plots of the surface height profile. Bad pixels were removed from the data sets by a combination of median and quartile difference filtering.

The second source of error in the profilometer scans was an occasional level shift due to an instability in the EDM. The EDM would function normally for 20–30 minutes, suddenly shift its reference plane by 2–7 mm, and then become stable again. This resulted in horizontal bands across the profilometer scans. Although the level shifts were small compared to the topographical variations, we felt that they would corrupt the spectral estimates enough to make their elimination worthwhile. We first discard scan rows with visible level shifts (the reference level was stable within most rows). We perform spectral estimation by linear sampling, in which we compute a spectral estimate for each row and average the resultant spectra. By averaging a number of estimators, we reduce the effect of any remaining errors as well as the variance inherent to the surface random process.

The assumption that the surface statistics of the debris flows are isotropic is reasonable due to the structure and origin of the surfaces. The flow units examined were formed in a debris avalanche when the north side of the volcano collapsed. The avalanche was composed of a loose mixture of rock and ash which showed no directional structure, unlike a viscous lava flow which has a definite flow direction.

The algorithm for obtaining a spectral estimate from a linear sample is described in Kay (4) and summarized here: let the along-row surface height $Z[n]$ be a wide-sense stationary random process. The covariance matrix $\mathbf{R}_{zz}$ is defined as

$$[\mathbf{R}_{zz}]_{ij} = \langle Z^{*}[n]Z[n+i-j]\rangle \tag{1}$$

where $\langle\cdot\rangle$ indicates an ensemble average. $Z[n]$ is assumed ergodic, and an estimate $\hat{\mathbf{R}}_{zz}$ of the covariance matrix is obtained using a modified algorithm. We then obtain an estimate of the surface spectrum using the Capon or minimum variance spectral estimator:

$$\hat{P}_{MV}(f) = \frac{p\Delta}{\mathbf{e}^{H}\hat{\mathbf{R}}_{zz}^{-1}\mathbf{e}} \tag{2}$$

where $\mathbf{e} = [\ 1 \quad e^{j2\pi f} \quad e^{j4\pi f} \quad \dots \quad e^{j2\pi(p-1)f}\ ]^{T}$, p is the dimension of the covariance matrix, and ^{H} indicates the hermitian transpose. $\hat{P}_{MV}(f)$ results in a one-dimensional estimate of the power spectral density of a single row. The estimates obtained from all rows are then averaged to reduce the variance. The same algorithm was used on the survey data.

Averaged spectral estimates from different scales are then fit with a function to approximate a composite spatial frequency spectrum. The two-dimensional spectra are then obtained using the assumption of isotropic surface statistics.

RESULTS. The resultant spectral estimates suggest a power-law spectrum for the primary debris flow surfaces and a mixed spectrum for the surfaces modified by sedimentation. An overview of the surface profile measurements and the final spectral estimates will be shown in the presentation of this work.

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