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LAVA FLOW TOPOGRAPHIC MEASUREMENTS FOR RADAR DATA INTERPRETATION

Bruce A. Campbell

Center for Earth & Planetary Studies, National Air & Space Museum

James B. Garvin

NASA Goddard Space Flight Center

Abstract. Surface topography is of great importance in radar backscattering, but the quantitative interpretation of data collected in the field is still a difficult problem. We present topographic profiles at 25-cm and 5-cm horizontal resolution for three sites along a lava flow on Kilauea Volcano, and use these data to illustrate techniques for surface roughness analysis. Height and slope distributions and the height autocorrelation function are evaluated as a function of varying lowpass filter wavelength for the 25-cm data. Rms slopes are found to increase rapidly with decreasing topographic scale and are typically much higher than those found by modeling of Magellan altimeter data for Venus. A more robust description of the surface roughness appears to be the ratio of rms height to surface height correlation length. For all three sites this parameter falls within the range of values typically found from model fits to Magellan altimeter waveforms. The 5-cm profile data are used to estimate the effect of small-scale roughness on quasi-specular scattering.

INTRODUCTION

The topography of surfaces has a strong effect on many remote sensing observations. Radar measurements are generally made at wavelengths of 3-70 cm, where surface roughness on scales from several meters to less than a centimeter partially determines the amplitude and polarization of the backscattered wave. To date, there have been a number of efforts to quantify the roughness of terrestrial surfaces over the range from a few cm to tens of meters [McCollom and Jakosky, 1993; Farr, 1992; Gaddis et al., 1990; Schaber et al., 1979]. Techniques include template devices, stereo photography, simple surveying, laser altimetry, and radar interferometry. A primary issue in analyzing such data is how to quantify the surface roughness for comparison with radar observations and prediction of backscatter behavior at various incidence angles. Numerous conventions exist for this quantification, but the utility of the various methods is still an open question.

The issue of predicting radar backscatter properties for surfaces has gained new relevance with the acquisition of the Magellan dataset. Recent work has shown that airborne radar data can serve as a comparative base for Venus surface classification [Campbell and Campbell, 1992]. At the moment, however, there are no terrestrial radar systems which provide data similar to Magellan altimeter measurements, so topographic analysis must be used to estimate the near-nadir scattering properties of potential analog surfaces.

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In this paper, we present topographic data at 5 cm and 25 cm sampling intervals for three sites along a lava flow on Kilauea Volcano. The height and slope statistics of the surfaces are analyzed as a function of horizontal scale, and the utility of several roughness descriptors is evaluated. Special emphasis is placed on the quasi-specular scattering regime. Finally, we discuss the implications of our results for future topography data analysis and planetary remote sensing.

MEASUREMENT TECHNIQUES

We measured the surface topography of Hawaiian lava flows using two techniques. The 25-cm topography data were collected using a surveying transit and height rod, with a rope marked at intervals stretched taut along a horizontal profile line. Vertical accuracy was an estimated 1-2 cm. Accurate horizontal spacings became difficult to maintain on the rougher flows, but these errors are not expected to greatly bias the final results. Profile lengths collected by this technique are 100-120 m.

To collect topography data at smaller scales, we constructed a prototype laser profiling system using a Cubic Precision "Red Dot" laser rangefinder. In laboratory tests we found the root-mean-square (rms) error of this device to be ~7 mm. We mounted the laser on a wheeled trolley which was free to slide along a 3-m rigid aluminum channel. The channel was leveled for each profile, and longer transects were assembled by overlapping the first and last points of adjoining segments. Data were collected at 5-cm intervals, with profile lengths of 5.0-8.5 m.

Each profile was corrected for regional slope by fitting a linear least-squares function to the data and subtracting the best-fit line. The three sites are on the 1982 lava flow near the south rim of Kilauea caldera. Site 1 is a ponded surface consisting of smooth plates 1-3 m across tilted at small angles. Site 2 is a channelized pahoehoe flow, with alternating patches of smooth sheet-like texture and more ropy or slab-like rough areas. Site 3 is a moderately rough a'a, whose surface is comprised of broken plates and spiny rubble.

DESCRIPTION OF SURFACE ROUGHNESS

Topography at horizontal wavelengths of a meter or more is important in determining the near-nadir radar backscattering properties of a surface. At such small incidence angles the dominant form of scattering is expected to come from radar-facing smooth portions of the surface, which act as quasi-specular "facets" [Hagfors, 1964]. The scattering properties of gently undulating surfaces have been studied by a number of authors, and the Hagfors model is widely used in planetary radar analyses to quantify large-scale roughness. As noted above, there are no terrestrial data comparable to Magellan altimeter or Earth-based near-nadir planetary observations, so an understanding of the utility of these data and the applicability of the models must come from an evaluation of the roughness properties of reference surfaces.

Several statistical criteria for roughness characterization are discussed in the literature. The rms height h is the standard deviation of the distribution of profile point heights. The surface height correlation length l is defined as the "lag" value for which the normalized autocorrelation function of a profile first falls to ~0.37. The autocorrelation function is calculated by cross-multiplying the original profile and a shifted copy of itself, and summing these values at all overlap points. A surface may also be described by its power spectral density (PSD), which expresses the relative importance of each spatial harmonic component in constructing the measured surface.

The slope properties of a surface may be defined in two ways: (1) as the root mean square of the surface slopes ϕ over the length of the profile, or (2) as $\tan^{-1}(h/l)$. In each case, we define the profile slopes as the first difference in height between adjacent points. To avoid confusion, we will refer to the (h/l) parameter as an "effective slope", and leave "rms slope" to specify the standard deviation of the slope distribution. Defining a surface by these parameters implies certain assumptions about the distribution of roughness scales. If the surface is characterized by a narrow band of spatial harmonics, then the backscatter will depend upon the "significant slope" defined in Miller and Parsons [1990] as $(h/L)^2$, where h is the rms height and L is the dominant spatial wavelength (or correlation length). These authors further show that if the surface roughness spans a wide range of spatial wavelengths, then the backscattered power depends instead on the mean-square slope. Hagfors [1966] linked the two definitions for the case of a gently undulating (narrow-band) surface:

$$[\langle \tan^2\phi \rangle]^{0.5} = h / l \tag{1}$$

This equation shows that in Hagfors' approach the mathematical definition of "rms slope" is not critical, since the surface is assumed to have a narrow range of harmonic components.

In practice, we are unlikely to find natural surfaces that are so well behaved. Surfaces with roughness at the scale of the radar wavelength will exhibit strong wavelength dependence in backscatter [Tyler, 1976]. There are, however, two mechanisms which may act to band-limit the scattering surface we observe with the radar. First, lava flows exhibit preferential wavelengths of folding which are related to the thickness of the cooled surface layer [Fink and Fletcher, 1978]. Second, the more effective quasi-specular scatterers are those largest with respect to the radar wavelength, so slopes derived from physical optics ("facet") models in effect low-pass filter the true topography [Hagfors, 1966]. One might thus expect that the (h/l) parameter could be more appropriate for lava flow characterization in terms of radar-derived properties.

ANALYSIS OF 25-CM DATA

In this section, we analyze the 25-cm topographic data for our three lava flow sites and discuss the implications of these results for the physical optics scattering model. Figure 1 shows the measured profiles for our three sites. We calculated each of the parameters discussed above as a function of horizontal scale by applying low-pass filters to the original data (Table 1). The filter we used is a step function in the frequency domain. The "mean slope" is the arithmetic mean of the individual slope measurements, which can have positive or negative values.

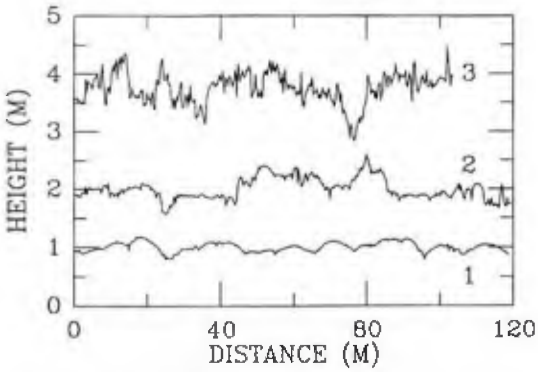

Fig. 1. Detrended profiles at 25-cm horizontal sampling for three study sites on the 1982 Kilauea lava flow. Profiles offset vertically for comparison. Site 1 is a smooth ponded flow surface, Site 2 is a ropy channelized pahoehoe, and Site 3 is a platy a'a.

McCollom and Jakosky [1993] present slope data for a range of terrestrial surfaces collected by measuring the local maximum ("adirectional") slope every 10 m along a transect line. Their results suggest that many surfaces have slope distributions which are not centered on zero. In contrast, all ten sites measured on Kilauea [Campbell, 1992] have mean and modal slope values close to zero (Table 1). The offset peaks in McCollom and Jakosky's data may be an artifact of their measurement method.

Figure 2 shows the calculated rms slopes as a function of low-pass filter cutoff wavelength. The shortest wavelength (50 cm) represents the original unfiltered data. Note that the rms slope for each surface increases rapidly as progressively smaller scales of roughness are included in the calculation. This is a reasonable result; very high slopes are rarely found over large distances, while the edges of a small rock may form right angles with the ground. From this parameter, however, no single value for the behavior of the surface can be defined; the roughness is very much scale dependent.

A different view of the surface is gained by using the (h/l) parameter. From Table 1 and Figure 3, we find that the two smoother test sites are characterized by relatively constant values of h and l over a wide range of spatial scales. Only the third site (the a'a) exhibits a large change in (h/l) as a function of cutoff wavelength. These results indicate that roughness on scales of several meters dominates the slope calculation for Sites 1 and 2, since we derive similar values whether or not the higher spatial frequencies are included. For Site 3, there is a continuum of roughness at all scales (at least down to 50-cm wavelengths), so the calculated slope rises with decreasing scale size. An interesting result of this analysis is the similar (h/l) ratios for Sites 1 and 2, which differ dramatically in their rms height. The similarity in (h/l) values occurs because the larger rms height of Site 2 is offset by a correspondingly large correlation length. Site 1 is thus characterized by low "hills"

TABLE 1

Cutoff (m)	RMS Height	Mean Slope	RMS Slope	Corr. length (m)	$\tan^{-1}(h/l)$
		Site 1 - 476 profile points			
0.5	0.077	0.04	3.92	3.50	1.27
1.0	0.077	0.02	2.72	3.50	1.26
5.0	0.076	0.00	1.73	3.50	1.24
10.0	0.070	0.00	1.23	4.25	0.95
		Site 2 - 479 profile points			
0.5	0.179	0.03	11.13	6.50	1.58
1.0	0.178	0.02	7.99	6.50	1.57
5.0	0.171	0.00	3.17	6.75	1.45
10.0	0.165	0.00	2.05	6.75	1.40
		Site 3 - 415 profile points			
0.5	0.269	0.29	24.91	2.75	5.58
1.0	0.262	0.13	19.24	2.75	5.44
5.0	0.236	0.00	6.54	3.00	4.51
10.0	0.206	0.00	3.34	4.75	2.48

Height (in meters) and slope (in degrees) statistics of 25-cm data for three lava flow sites as a function of low-pass filter cutoff wavelength.

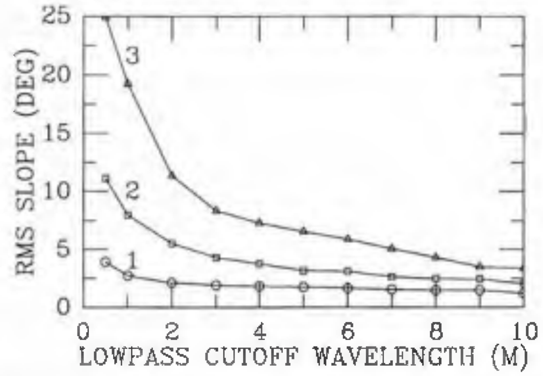

Fig. 2. RMS slope for the three study sites versus low-pass filter cutoff wavelength. Note the rapid increase in RMS slope as shorter topographic wavelengths are included in the calculation.

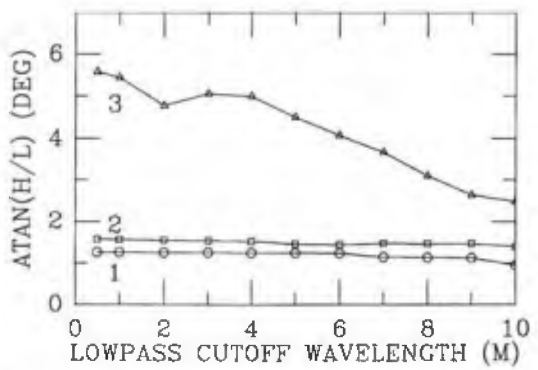

Fig. 3. Tan^{-1}(h/l) parameter for the three study sites. Note the relatively stable values for Sites 1 and 2, in contrast to the highly scale-dependent results for Site 3.

relatively close together, while Site 2 has larger hills spaced further apart.

From their 25-cm profiles we might expect Sites 1 and 2 to exhibit little wavelength dependence in their near-nadir backscatter, while Site 3 would exhibit strong wavelength dependence [Tyler, 1976]. The slopes measured here are "unidirectional", and if the surface roughness is azimuthally isotropic the calculated effective slope will be lower by a factor of ~1.4 than the "adirectional" slope to which the radar is sensitive. Sites 1 and 2 can be described by slope estimates ($1.4*\tan^{-1}(h/l)$) of 1.8° and 2.1° if we use the original raw profile data, while Site 3 varies from 2.5-5.5°.

ANALYSIS OF 5 CM DATA

The topography of surfaces on scales of less than ~1 m largely controls "diffuse" radar scattering. Figure 4 shows the profiles collected using the laser rangefinder system. Table 2 presents the rms heights for each site with no filter and for a high-pass filter with its cutoff at 1 m. The rms heights of the three sites after filtering are 1 cm, 4 cm, and 8 cm. It is interesting to note the large difference in raw and filtered rms height values for Site 2. This implies a surface with two or more independent scales of roughness, which corresponds to the actual terrain of broken glass chips on small pahoehoe ropes or billows.

In the discussion above we characterized our field sites at scales relevant to physical-optics scattering theory. These surfaces will not necessarily exhibit strong quasi-specular scattering, since we have not yet taken into account roughness on cm scales. The reflection coefficient at nadir of a rough facet will decline exponentially with rms height [Barrick and Peake, 1967]:

$$R = R_o \exp(-8\,\pi^2 h^2/\lambda^2) \qquad (2)$$

where R_o is the Fresnel reflection coefficient of a smooth facet, and λ is the radar wavelength (12.6 cm for Magellan). If we use the rms heights for our three surfaces (Table 2) in this

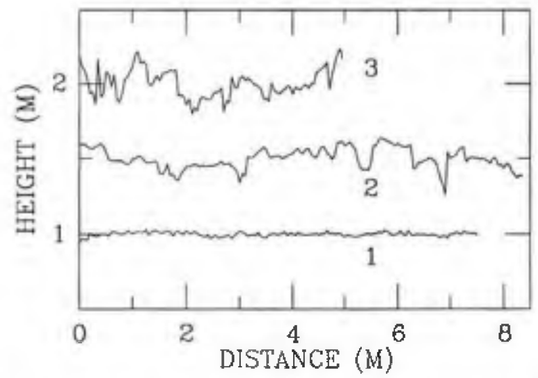

Fig. 4. Detrended profiles for the three study sites at 5-cm horizontal sampling. Profiles offset vertically for comparison.

TABLE 2

Cutoff (m)	RMS Height	Mean Slope	RMS Slope
	Site 1 - 151 profile points		
0.1	0.014	0.403	14.80
1.0	0.011	0.360	14.78
	Site 2 - 168 profile points		
0.1	0.069	-1.14	24.72
1.0	0.040	-1.08	24.87
	Site 3 - 100 profile points		
0.1	0.096	1.39	40.52
1.0	0.083	1.17	44.69

Height (in meters) and slope (in degrees) statistics for three lava flow sites for 5-cm raw profiles and for data high-pass filtered with a cutoff at 1 m.

equation, we find that Site 1 will display only ~60% of its smooth-surface return, while Sites 2 and 3 will have negligible quasi-specular echoes. This method likely overestimates the detrimental effect of the small-scale roughness at Site 2, since the scatterers are not uniformly distributed on all parts of the surface. There are broad patches of relatively smooth terrain, similar to Site 1, interspersed with much rougher areas. Since even small smooth facets are very effective scatterers, Site 2 may be expected to have a significant near-nadir backscatter peak. Only the a'a surface of Site 3 seems completely unsuitable for the quasi-specular model.

CONCLUSION

Our results show that the standard deviation of the slope distribution is very much scale-dependent, and is likely not appropriate for quantifying topography for comparison with radar altimeter echoes. The ratio (*h*/*l*) appears to be a more useful estimator of the large-scale roughness for radar studies. Terrestrial topography analysis for comparison to planetary radar observations must consider the scale-dependence of height and slope statistics.

The (*h*/*l*) values are strongly dependent upon the form of the autocorrelation function, and it is a simplification to characterize this shape by a single parameter. If the surface is comprised of two or more distinct (or narrow-band) scales of roughness, then the correlation length is not a unique descriptor of the topography. The *l* parameter is best suited to surfaces with either a single dominant structure or a smoothly varying continuum of harmonic components. With this caveat, the effective slopes for our three study sites do fall within the range typically derived from model fits to Magellan altimeter data [Tyler et al., 1992], so the (*h*/*l*) parameter may be useful in compiling Venus surface analogs.

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B.A. Campbell, Center for Earth and Planetary Studies, National Air & Space Museum, Washington, DC 20560.

J.B. Garvin, Code 622, Goddard Space Flight Center, Greenbelt, MD, 20771.

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