ESTIMATING SURFACE ROUGHNESS: EVALUATION OF AN EMPIRICAL BACKSCATTER MODEL Lisa Gaddis, USGS, 2255 N. Gemini Dr., Flagstaff, AZ 86001

Overview: Comparison of radar backscatter coefficients ($\sigma°$, in dB), calculated using the empirical model of Oh et al. [1], to $\sigma°$ extracted from AIRSAR data of four geologic units at Pisgah volcanic field shows that the model is able to predict measured $\sigma°$ to within ±3 dB. The empirical model may be inverted to estimate rms height (*s*, in cm) from measured $\sigma°$ for surfaces with $ks<3$ [*ks*, or "electromagnetic roughness," is the wavenumber ($k=2\pi/\lambda$, λ=radar wavelength) times *s*]. For example, model inversion for a platform pahoehoe unit at 30°-50° incidence angles (θ) was able to estimate *s* to within ±1 cm of the measured value of 3 cm. Work is underway to extend the applicability of this model to rougher natural surfaces and to apply these results to estimation of surface roughness on Venus through analyses of Magellan radar data.

The radar backscatter response of surfaces is a complex function of radar instrument parameters and surface characteristics. Theoretical radar backscatter models seek to characterize this response for cases that may have little or no applicability to most natural surfaces. For many natural surfaces, none of the commonly used theoretical models (small perturbation model [2], physical optics model [3], and their modified or combined versions [4,5]) is appropriate; natural surfaces are complex and may have both large- and small-scale roughness or a continuous distribution of roughnesses with respect to a given λ. Until appropriate theoretical backscatter models are available for natural surfaces, an empirical model relating measured surface characteristics to radar backscatter may provide a useful means of extracting physical parameters such as surface roughness from calibrated radar images of geologic surfaces.

I have compared calculated empirical backscatter values with calibrated data from the NASA/JPL Airborne Imaging Radar (AIRSAR) for four geologic units with a range of roughnesses. The four units occur at Pisgah volcanic field, California. They are playa material (s=0.83 cm, dielectric constant ϵ_r=2.36) [6,7]; "platform" pahoehoe (s=3.0 cm, ϵ_r=4.5) [7]; hummocky pahoehoe (s=6.0 cm, ϵ_r=4.0) [8,9]; and clinkery aa lava flows (s=20.0 cm, ϵ_r=4.0) [8,9]. Pisgah AIRSAR images were calibrated to accuracy of ±3 dB [10]. Backscatter coefficients were extracted at L- and C-band wavelengths (24 and 5.6 cm, respectively) and at HH, HV, and VV polarizations.

The Model: The empirical radar backscatter model was developed by Oh et al. [1], who used polarimetric radar measurements collected with a scatterometer for bare soil surfaces under a variety of roughness conditions at L- (24 cm), C- (6.3 cm), and X-bands (3.16 cm) and at θ=10°-70°. Ground truth data (*s*, correlation length, and ϵ_r) were collected for each surface by using a laser profiler and dielectric probes. Radar measurements were made for dry and wet surfaces for surface roughnesses of s=0.32-3.02 cm; only the dry-surface data (moisture content~0.15 wt.%) are considered here. Surface-height distributions for the four model surfaces were ~Gaussian, with measured autocorrelation functions of exponential form for the three smoothest surfaces and of Gaussian form for the roughest surface. For the model surfaces *s* ranged from s=0.32 to 3.02 cm, and the "electromagnetic roughness" ranged from ks=0.1 to 6.01.

For development of the model, the angular (θ~10°-70°) backscattering behavior of the model surfaces was observed at VV, HV, and HH polarizations and at L-, C-, and X-bands [1]. For $\sigma°_{VV}$ and q=30°-70°, a sensitivity to surface roughness was observed; backscatter for s=0.3-3.0 cm increased in strength and decreased in slope, indicating a decreasing dependence on θ for increasing *s*. Also in this wavelength range, $\sigma°_{VV}$ at X-band was observed to vary little with increasing *s*, indicating an insensitivity of $\sigma°_{VV}$ to *s* for $ks>2.0$. A strong similarity in angular behavior and backscatter strength was observed [1] between $\sigma°_{hh}$ and $\sigma°_{VV}$, and the ratio of these values (the co-polarized ratio, $\mathbf{p}=\sigma°_{hh}/\sigma°_{VV}$) is always ≤1, approaching 1 as *ks* increases. For smoother surfaces, **p** is a function of θ, decreasing as θ increases. For rougher surfaces (e.g., $ks\geq3$), **p**~1 and is independent of θ. For co-polarized ratio data, these observations indicate a strong dependence on *ks*, an implicit dependence on ϵ_r, and (at higher θ) a weak dependence on θ. Although the behavior of $\sigma°_{hv}$ and $\sigma°_{VV}$ with respect to θ is very similar for a given λ and *s*, $\sigma°_{hv}$ is always less than $\sigma°_{VV}$; for increasing *ks* the separation between $\sigma°_{hv}$ and $\sigma°_{VV}$ decreases, and the cross-polarized ratio ($\mathbf{q}=\sigma°_{hv}/\sigma°_{VV}$) increases with increasing ks. For dry surfaces, these observations of cross-polarized ratio data reflect a strong dependence on ks, an implicit dependence on ϵ_r, and a lack of dependence on θ.

Co- and cross-polarized ratio data (**p** and **q**) as functions of ks for a range of s and at θ=30°-50° were used [1] to derive empirical functions: **q** is a function of nadir Fresnel reflectivity (Γ_0, and thus ϵ_r) and ks; **p** is a function of **q**, Γ_0, θ, and ks. The magnitudes of the backscattering coefficients are given by additional empirical relations: σ°_{vv} is a function of ks, **p**, and the horizontal and vertical components of the Fresnel reflectivities (Γ_h, Γ_v) of the surface at θ; σ°_{hh} is a function of ks, **p**, Γ_h, and Γ_v; and σ°_{hv} is a function of **q** and σ°_{vv}. Note that **p** is very sensitive to both ks and ϵ_r; for dry, smooth surfaces with low ϵ_r and small ks, **p** approaches 0 very rapidly. Thus, the empirical model does not predict significant differences between σ°_{hh} and σ°_{vv} for most dry surfaces; for $ks \leq 2$, the factor **p** accounts for the small differences between σ°_{hh} and σ°_{vv} and includes a dependence on ϵ_r. Also, no attempt was made to include a coherent component in the empirical model, so its range of applicability does not extend to θ<20° for smooth surfaces. For rougher surfaces, a coherent component is expected to be negligible and so the model may be used at θ=10°-70°.

Application: Surface characteristics (s, ϵ_r) for four units at Pisgah were used in conjunction with the empirical backscatter model [1] to predict σ° at C- and L-bands. Predicted values were compared with σ° for the same sites. Agreement between the model and the measured values is influenced by the exact values of ϵ_r and s used in the model calculations. Tests indicate that the model is more sensitive to variation in s than in ϵ_r for smooth surfaces. For rougher surfaces (e.g., aa, ks=22), the model is less sensitive to changes in either s or ϵ_r, with only slightly more sensitivity to variation in ϵ_r than in s. Agreement between measured and model data is quite good for σ°_{hv} and σ°_{vv}, for which the empirical model predicted σ° to within ±3 dB of the measured values (the estimated range of calibration accuracy of the AIRSAR data). However, the agreement between measured and model data is poorer for σ°_{hh}, for which the measured data are as much as 7 dB lower than the predicted values. As described above, the empirical backscatter model predicts little or no difference in σ°_{hh} and σ°_{vv}; apparently the scatterometer data from which the empirical model was derived exhibited comparable σ°_{hh} and σ°_{vv}. As indicated by [2] for the general theoretical behavior of σ° at θ~30°-60° for slightly rough surfaces, σ°_{hh} is expected to be lower than σ°_{vv}, suggesting that the AIRSAR data show more realistic backscattering differences at horizontal and vertical polarizations. This discrepancy between the scatterometer data and the AIRSAR data is under investigation.

The empirical model [1] may be inverted to estimate s from measured backscatter data for surfaces with ks<3.0. Such an inversion was conducted for the platform pahoehoe by using L-band AIRSAR data (ks=0.6). All calculated s values are within ±1 cm of the measured value of 3.0 cm. However, a different Γ_0 is required for each θ, confirming the complexity of modeling backscatter from natural surfaces (radar energy no doubt "sees" a single surface roughness differently at each θ for a given λ).

These promising results suggest that Magellan data can be used to infer surface roughnesses on Venus. Such roughness data can serve as a basis for comparison of the terrestrial and Venusian lava flow textures that are indicative of flow eruption and emplacement processes. Quantitative morphologic and surface textural analyses of lava flows can then be complemented by correlation of backscatter data with physical properties and/or composition as constrained by Magellan altimetry and emissivity data. Future work with this empirical backscatter model will involve modifications of the model to reflect accurate differences in HH and VV, as well as extension of the model to rougher surfaces (ks>6).

References: [1] Oh, Y. et al., IEEE Trans. Geocsci. Rem. Sens., GE-30, 370-381, 1992; [2] Ulaby, F.T. et al., Microwave Remote Sensing, Active and Passive, II, 1982; [3] Beckmann, P. and A. Spizzichino, The Scattering of Electromagnetic Waves from Rough Surfaces, 1987; [4] Brown, G.S., IEEE Trans. Ant. Prop., AP-26, 472-482, 1978; [5] Fung, A.K. and H.J. Eom, IEEE Trans. Ant. Prop., AP-29, 463-471, 1981; [6] Gaddis, L.R., GSA Bull., 104, 695-703, 1992; [7] van Zyl, J.J. et al., GRL, 18, 1787-1790, 1991; [8] Greeley, R. et al., submitted to Desert Aeolian Processes (Tchakerian, ed.); [9] Arvidson, R.E. et al., GSAB, 105, 175-188, 1993; [10] van Zyl, J.J., IEEE Trans. Geosci. Rem. Sens., 28, 337-348, 1990.