GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 17, PAGES 1803-1806, AUGUST 15, 1994

Evaluation of an empirical radar backscatter model for predicting backscatter characteristics of geologic units at Pisgah volcanic field, California

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Abstract. Comparison of radar backscatter coefficients ($\sigma°$, in dB), calculated by using the empirical model of Oh et al. [1992], to $\sigma°$ extracted from AIRSAR data of four geologic units at Pisgah shows that the model predicts measured $\sigma°_{vv}$ and $\sigma°_{hv}$ to within ±3 dB. The model predicts higher $\sigma°_{hh}$ than those observed. For smooth surfaces (rms height=s, s<8 cm), model results depend strongly on the accuracy of the surface measurements (s and dielectric constant, ϵ_r). For rougher surfaces, the model is less dependent on the accuracy of surface characterizations. The model may be inverted to estimate s from measured $\sigma°$ for surfaces with ks<3 (k=wavenumber, or $2\pi/\lambda$, where λ=radar wavelength). Model inversion for a pahoehoe unit at 30° to 50° incidence angles (θ) resulted in an estimate of s to within <1 cm of the measured 3 cm. The inability of the model to estimate accurately $\sigma°_{hh}$ and the anomalously high nadir Fresnel reflection coefficients (Γ_0) and ϵ_r required in the model inversion may both be due to ~equal co-polarized ratios ($\sigma°_{hh}/\sigma°_{vv}$=**p**~1) of the soils used to derive the model. For effective application to many geologic surfaces, for which **p**<1 is often observed at θ>30°, the model will require modification to include surfaces with non-unity $\sigma°_{hh}/\sigma°_{vv}$.

Introduction

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 natural surfaces. Natural surfaces may have both large- and small-scale roughness or a continuous distribution of roughnesses with respect to a given radar wavelength (λ). For many natural surfaces, none of the commonly used theoretical models is appropriate, such as the small perturbation model [e.g., *Ulaby et al.,* 1982; *van Zyl et al.,* 1991; *Campbell et al.,* 1993], the physical optics model [Beckmann and Spizzichino, 1963], and their modified or combined versions [e.g., *Fung and Eom,* 1981]. An empirical model relating measured surface characteristics to radar backscatter may provide the best means of extracting physical parameters such as roughness from calibrated radar data of geologic surfaces. The recent and planned acquisition of calibrated, multi-polarization, and/or multi-wavelength radar data for remote geologic surfaces on Earth (by systems such as AIRSAR and SIR-C) and on planets such as Venus (by Magellan) has emphasized the need for understanding the relations between radar backscatter and surface physical parameters such as large- and small-scale roughness for interpreting the origin and geologic history of natural surfaces.

This study evaluates the empirical backscatter model of Oh et al. [1992] for predicting backscatter and/or surface roughness of geologic units at Pisgah volcanic field, California (35°45' N, 116°23' W). Calibrated data from the NASA/JPL Airborne Synthetic Aperture Radar (AIRSAR) for four units with a range of roughnesses (Table 1) were compared with empirical values. The geologic units were a playa and three types of lava flow: "platform" pahoehoe, hummocky pahoehoe, and aa. AIRSAR data have been used previously to characterize geologic units at Pisgah [e.g., *Gaddis,* 1992; *Arvidson et al.,* 1993].

Pisgah volcanic field consists of Quaternary basaltic lava flows and a cinder cone superimposed on alluvial deposits and the lacustrine sediments of Lavic Lake playa [*Dibblee,* 1966]. Lava erupted in three phases: Phase I produced pahoehoe; Phase II, aa and pahoehoe; and Phase III, pahoehoe. Phase I pahoehoe is ≤1m thick, with smooth surfaces marked by ~5-cm-high ridges and shallow (≤20 cm), commonly sand-filled depressions. Near the vent, Phase II aa lavas are ≤5 m thick with up to 4 m of vertical relief, and their surfaces are covered with abundant clinker (up to 20 cm across) and collapse depressions. Phase III lavas are ~3-5 m thick, with hummocky surfaces characterized by pressure ridges and tumuli ≤3 m high.

Radar data used here were acquired in June 1988 by AIRSAR [*Wall et al.,* 1988]. These data were processed to a 10 x 10 m pixel size and were acquired simultaneously at three wavelengths (P-band: 68 cm; L-band: 24 cm; C-band: 5.6 cm). AIRSAR images of Pisgah were calibrated to within an estimated accuracy of ±1-3 dB ($\sigma°$ in dB, or radar cross-section per unit area) [*van Zyl,* 1990]. For the four geologic units, $\sigma°$ were extracted at P-, L-, and C-band wavelengths and at hh, hv, and vv polarizations. Local variability in $\sigma°$ (probably the largest source of error) is represented by one standard deviation of pixel values averaged for each unit; note that all values are less than ±3.5 dB. Interference from local ground signals compromised the P-band data and thus they were not used [*van Zyl et al.,* 1991].

The Empirical Model

The empirical radar backscatter model to be tested was developed by Oh et al. [1992], who used polarimetric radar measurements of bare soil surfaces under a variety of roughness and moisture conditions at L- (24 cm), C- (6.3 cm), and X- (3.16 cm) bands and at θ=10° to 70°. Backscatter data were collected with a truck-mounted scatterometer (LCX POLARSCAT) and were recorded for distributed soil targets in a fully polarimetric format [*Tassoudji et al.,* 1989]. Average dielectric constants (ϵ_r) of the soils at 0 to 4-cm depths were measured by using a C-band portable dielectric probe [*Brunfeldt,* 1987]. Radar measurements

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Paper number 94GL01253

Table 1. Surface Characteristics

unit	s (cm)	ks (C)	ks (L)	ϵ_r
playa**	0.83	0.93	0.22	2.36+i0.2
pahoehoe (platform)**	2.9±1.2	3.36	0.78	4.5+i0.0
pahoehoe (hummocky)	6.0***	6.72	1.56	4(ave. 3-5)*
aa	20***	22.4	5.2	4(ave. 3-5)*

*Arvidson et al., 1993.
**van Zyl et al., 1991.
*** R. Greeley et al., unpublished data, 1994.

were made for dry and wet surfaces under four surface-roughness conditions ranging from s=0.32 to 3.02 cm (measured with a laser profiler for 1-m profiles with 0.25-cm horizontal spacing); only the dry-surface empirical model will be considered here. A practical measure of roughness in this context is the "electromagnetic roughness" (roughness with respect to the wavelength), ks, where k is the wavenumber ($k=2\pi/\lambda$). For the soil surfaces, ks =0.1 to 6.01. Surface-height distributions for all four soil surfaces were approximately Gaussian, with measured autocorrelation functions of exponential form for the three smoothest surfaces and of Gaussian form for the roughest. These data were used to examine the dependence of $\sigma°$ on soil roughness and moisture content for a range of λ.

In the case of vv polarization and θ=30° to 70°, a sensitivity to surface roughness was observed [*Oh et al.,* 1992]; $\sigma°_{vv}$ for s =0.3 to 3.0 cm increased in strength and decreased in slope, indicating a decreasing dependence on θ for increasing s. At X-band, $\sigma°_{vv}$ was observed to vary little with increasing s, indicating an insensitivity of $\sigma°_{vv}$ to s for ks>2.0. Similarity in angular behavior and backscatter strength was observed by Oh et al. [1992] between $\sigma°_{hh}$ and $\sigma°_{vv}$, and the ratio of these values (the co-polarized ratio, $\mathbf{p}=\sigma°_{hh}/\sigma°_{vv}$) is ≤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≥3), **p**~1 and is independent of θ. For co-polarized ratio data (**p**), these observations indicate a strong dependence on ks, an implicit dependence on ϵ_r, and (at larger θ) a weak dependence on θ. Although the behavior of $\sigma°_{hv}$ and $\sigma°_{vv}$ with respect to θ is 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 so the cross-polarized ratio ($\mathbf{q}=\sigma°_{hv}/\sigma°_{vv}$) increases with increasing ks. For dry surfaces, these observations of cross-polarized ratio data (**q**) reflect a strong dependence on ks, an implicit dependence on ϵ_r and a lack of dependence on θ.

Oh et al. [1992] used co- and cross-polarized ratio data (**p** and **q**) as functions of ks for a range of s at θ=30°to 50° (Figure 1) to derive empirical functions. For the simpler cross-polarized case, they observed that **q** increases rapidly from -20 dB at ks=0.1 to -10 dB at ks≥3, and maintains that level for ks>3. The empirical function describing this behavior is given as

$$\mathbf{q} = \frac{\sigma°_{hv}}{\sigma°_{vv}} = 0.23\sqrt{\Gamma_o}\,[1-\exp(-ks)], \qquad (1)$$

where Γ_o is the Fresnel reflectivity of the surface at nadir ($\Gamma_o = |(1-(\epsilon_r)^{-2}) / (1+(\epsilon_r)^{-2})|^2$). For the co-polarized case and ks<1, **p**~-6 dB and increases to ~0 dB for ks≥3. The empirical function describing this behavior is given as

$$\mathbf{p} = \frac{\sigma°_{hh}}{\sigma°_{vv}} = [1-(2\theta/\pi)^{[1/3\Gamma_o]} \bullet \exp(-ks)]^2 \qquad (2)$$

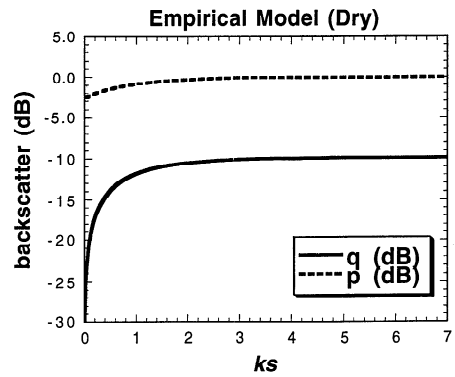

Figure 1. Empirical relationships of backscatter ($\sigma°$) versus ks as observed for cross- (**q**) and co-polarized (**p**) ratios of scatterometer data for dry soil surfaces [after Oh et al., 1992].

where θ is incidence angle in radians. The magnitudes for the three linearly polarized backscattering coefficients, as related to surface parameters ks and ϵ_r, are given by the empirical relations

$$\sigma°_{vv}(\theta, \epsilon_r, ks) = (g\cos^3\theta/\sqrt{\mathbf{p}}) \bullet [\Gamma_h(\theta)+\Gamma_v(\theta)] \qquad (3)$$

where

$$g = 0.7[1-\exp(-0.65(ks)^{1.8})] \qquad (4)$$

and Γ_h and Γ_v are the horizontal and vertical components of the Fresnel reflectivities (respectively) for the surface at θ. Further,

$$\sigma°_{hh}(\theta, \epsilon_r, ks) = g\sqrt{\mathbf{p}}\cos^3\theta\bullet[\Gamma_h(\theta)+\Gamma_v(\theta)], \qquad (5)$$

and

$$\sigma°_{hv}(\theta, \epsilon_r, ks) = q\,\sigma°_{vv}(\theta, \epsilon_r, ks). \qquad (6)$$

Note that (as supported by the observation of similar values of $\sigma°_{hh}$ and $\sigma°_{vv}$ for rougher surfaces), **p** is very sensitive to both ks and ϵ_r; for dry, smooth surfaces with low dielectric constants and small ks, **p** approaches 1 (0 dB) very rapidly. Thus, this empirical model does not predict significant differences between $\sigma°_{hh}$ and $\sigma°_{vv}$ for most surfaces; for ks≤2, the factor **p** accounts for the small differences between $\sigma°_{hh}$ and $\sigma°_{vv}$ and includes a dependence on ϵ_r. 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° to 70°.

Model Application

Surface characteristics (s, ϵ_r) measured for four geologic units at Pisgah [Table 1; *van Zyl et al.,* 1991; *Arvidson et al.,* 1993; *R. Greeley et al., unpublished data,* 1994] were used with the empirical model of Oh et al. [1992] to predict $\sigma°$ at C- and L-bands. Predicted $\sigma°$ values were compared with calibrated $\sigma°$ values from AIRSAR data for the same sites. For application of the model, it is assumed that surface-height distributions are Gaussian and that the surface autocorrelation functions are either exponential or Gaussian in form [after *Oh et al.,* 1992].

Agreement between measured and model data is quite good (Figures 2 and 3) for $\sigma°_{hv}$ and $\sigma°_{vv}$; the empirical model predicted $\sigma°$ to within ±3 dB of the measured values (i.e., within the ±3.5 dB local variability of $\sigma°$). Agreement is poorer for $\sigma°_{hh}$ for

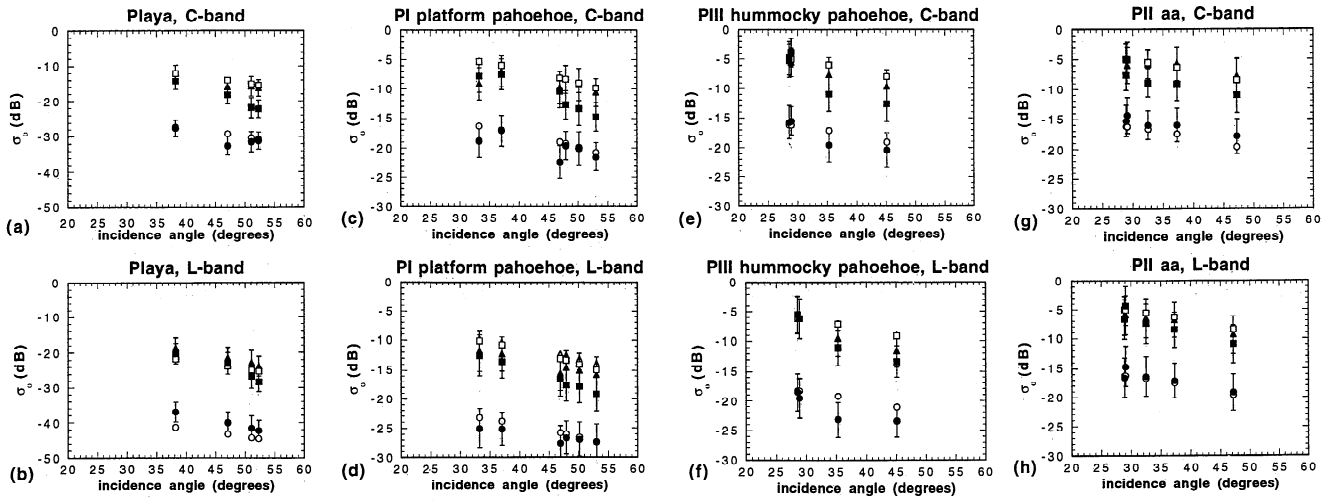

Figure 2. A comparison of model versus measured σ° for four geologic units at Pisgah. Open symbols are model data, filled symbols are measured data; triangles are vv, squares are hh, and circles are hv data.

which measured data are as much as 7 dB lower than the predicted values. The empirical model predicts little difference (<3 dB) between σ°_{hh} and σ°_{vv} for all surface roughnesses, reflecting the lack of strong differences between σ°_{hh} and σ°_{vv} for the scatterometer data used to derive the model (i.e., **p**~1). This ~equal vv and hh scattering behavior suggests that the soil surfaces exhibited uniform scattering geometry in the horizontal and vertical directions as viewed by the scatterometer. Although Campbell et al. [1993] observed that $\sigma^\circ_{hh}/\sigma^\circ_{vv}$ ~1 for lava flows at Kilauea, Hawaii, such behavior is in contrast to the general backscatter of many natural, slightly rough surfaces at θ~30° to 60°, which show σ°_{hh} to be lower than σ°_{vv} [e.g., *Ulaby et al.*, 1982; *van Zyl et al.*, 1987; *Evans et al.*, 1988; *Gaddis*, 1992; *Arvidson et al.*, 1993]. These differences in apparent hh vs. vv scattering behavior between soils and other common geologic surfaces suggest that the model of Oh et al. [1992], developed for surfaces with **p**~1, cannot be applied with confidence to derive σ°_{hh} for the many natural surfaces for which **p** is non-unity.

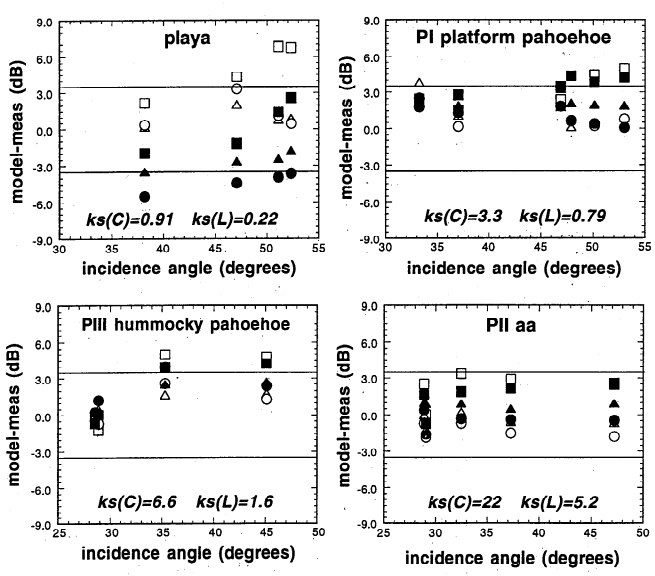

Figure 3. A summary of the differences in backscatter coefficients (model minus measured) for four units at Pisgah. Horizontal bars mark the full ±3.5 dB range of local variability for all measured σ° (local variability for each measured σ° is represented by one standard deviation of the pixel values averaged). Open symbols are C-band data, filled symbols are L-band data; triangles are vv, squares are hh, and circles are hv data.

Agreement between model and measured σ° is influenced by the values of s and ϵ_r used (Figure 3). If s=0.5 cm is used in the L-band model for the playa rather than the measured value of s=0.83 cm (θ=50°, ϵ_r=2.36), the discrepancies shown in Figure 3 increase: Δ_{vv} changes from -2.4 dB to -6.3 dB, Δ_{hv} from -3.9 to -9.9 dB. Only Δ_{hh} remains within the AIRSAR error limits, changing from 1.4 dB to -2.5 dB. A similar calculation with s=1.1 cm shows better agreement for σ°_{vv} and σ°_{hv}, with Δ_{vv}=-0.3 dB, Δ_{hh}=3.6 dB, and Δ_{hv}=-0.7 dB. Decreasing only ϵ_r from 2.36 to 2.0 yields Δ_{vv} = -3.4 dB, Δ_{hh}=0.6 dB, and Δ_{hv}=-5.8 dB. Increasing ϵ_r to 2.7 yields Δ_{vv} = -1.7 dB, Δ_{hh}=1.9 dB, and Δ_{hv}=-2.6 dB. The closest agreement between model and measured σ° for the playa at θ=50° is obtained for s=1.1 cm and ϵ_r=2.0-2.7 (e.g., for ϵ_r=2.0, Δ_{vv}=-1.2 dB, Δ_{hh}=2.7 dB, and Δ_{hv}=-2.6 dB), indicating that the model is more sensitive to variation in s than in ϵ_r for smooth surfaces.

In the case of the aa unit (Table 1), variations in s and ϵ_r produce less dramatic differences in the model and measured σ°. Tests with measured data for the aa at L-band and θ=30° resulted in close agreement: Δ_{vv}=1.0 dB, Δ_{hh}=1.7 dB, and Δ_{hv}=0.4 dB. Variation in s only (from 17 to 23 cm) produced negligible changes in these differences; changing ϵ_r from 3.0 to 5.0 [the full range determined for most geologic units at Pisgah by *Arvidson et al.*, 1993] produced variations of <±1 dB from the original difference values. For rougher surfaces 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. For the aa unit, the closest agreement between model and measured σ° was obtained for the measured values of s and ϵ_r (Table 1).

The empirical model of Oh et al. [1992] may be inverted to extract s from measured σ° for surfaces with ks<3.0. Such an inversion was conducted for the platform pahoehoe unit by using the L-band AIRSAR data. By starting with measured σ°_{hh}, σ°_{vv}, and σ°_{hv}, **p** and **q** are first calculated. Removing ks from (1) and (2) results in the following nonlinear equation for Γ_o:

$$(2\theta/\pi)^{[1/3\Gamma_o]} \bullet [1-(\mathbf{q}/0.23\sqrt{\Gamma_o})] + \sqrt{\mathbf{p}} - 1 = 0 \qquad (7)$$

(where θ is in radians). Solving iteratively for Γ_o we calculate ϵ_r, ks [from (2)], and, finally, s. Figure 2 shows the results of the forward application of the empirical model to the platform

Table 2. Model Inversion: Platform Pahoehoe (L-band, *ks*=0.78)

θ	Γ_o	ϵ_r	*ks*	*s* (cm)
53°	0.38	17.8	0.67	2.6
50°	0.33	13.7	0.71	2.7
48°	0.35	15.2	0.61	2.3
37°	0.22	7.7	0.68	2.6
33°	0.18	6.1	0.66	2.5

pahoehoe; Table 2 shows results of the model inversion for the same unit. First, note that all calculated *s* values are within <1.0 cm (0.3 to 0.7 cm) of the measured *s* of 3.0 cm. Also, note that a different Γ_o is required for each θ. The relatively high Γ_o values required at high θ (~50°) produce anomalously high ϵ_r (>10) for this unit. These inversion results suggest model inaccuracies possibly related to its dependence on **p** (**p** is often <1 for geologic units at θ>30°).

Conclusions

Comparison of $\sigma°$ calculated by using the empirical model of Oh et al. [1992] to $\sigma°$ extracted from AIRSAR data of four geologic units at Pisgah has shown that the model is able to estimate $\sigma°_{vv}$ and $\sigma°_{hv}$ to within ±3 dB (i.e., within the ±3.5 dB local variability of s°). Agreement between measured and model data is poorer for $\sigma°_{hh}$, largely because the scatterometer data of soil surfaces upon which the model was based showed ~equal $\sigma°_{hh}$ and $\sigma°_{vv}$ (**p**~1), in contrast to the $\sigma°_{hh}/\sigma°_{vv}$<1 behavior observed in the AIRSAR data. Possible differences in hh scattering behavior between soils and many common geologic surfaces suggest that the empirical model, developed for surfaces with **p**~1, cannot be applied with confidence to derive $\sigma°_{hh}$ for natural surfaces for which **p** is non-unity.

For smooth surfaces (*s*~<8 cm), test results depend on the accuracy of the *s* and ϵ_r values used. For rougher surfaces, model results are less dependent on the accuracy of surface characterizations. The empirical model may be inverted to predict *s* from measured $\sigma°$ for surfaces with *ks*<3. Model inversion for the platform pahoehoe unit enabled the estimation of measured *s* to within <1 cm of the measured 3 cm. Model inversions at larger θ produced anomalously high Γo and ϵ_r, possibly due to the dependence of the inversion on **p**. Future work with this model for application to geologic surfaces will require modifications to include surfaces for which **p** is non-unity.

Acknowledgments. This work was performed under NASA Grant W-18,396 (Venus Data Analysis Project). Thanks to Randy Kirk, Ray Arvidson, Bruce Campbell, Tom Farr, and Gerry Schaber for their careful and thoughtful reviews.

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(Received: February 28, 1994; Accepted: March 25, 1994.)