SURFACE SCATTERING AND DIELECTRIC PROPERTIES

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Radio and radar observations of Venus, made over several decades, have determined that the typical surface at elevations below about 6054-km radius has a bulk dielectric constant lying between 4.0 and 4.5. This value is consistent with dry compacted rocks of various compositions, presumably similar to those found on Earth and seen on the other terrestrial planets. Occasional lower values probably arise from an overlying layer of dusty or granular material. The typical surface is quite smooth at radio wavelengths, exhibiting 10 to 20% depolarization in its total scattered energy, and a root-mean-square average surface slope of 2° to 4° on scales of decimeters to meters. Regions of much higher roughness are found, however. Terrain lying above a planetary radius of about 6054 km often displays surface electrical properties vastly different from those found at lower elevations. A recent bistatic radar observation over the Maxwell Montes region finds a complex dielectric constant of \(-i100\), that can be interpreted as a surface conductivity of 13 mhos m\(^{-1}\). Candidates for surface materials include ferro-electrics, a plating of magnetite or a thin layer of tellurium frost.

I. INTRODUCTION

The massive, visually opaque, Venus atmosphere limits global remote sensing of a planet's surface to radio wavelengths that can penetrate the atmosphere with acceptable transmission loss (wavelengths of about 3 cm or longer). Both "active" (radar) observations and "passive" (thermal radioemission) measurements yield the discontinuity in index of refraction at the surface-atmosphere interface, a discontinuity which is primarily controlled by the bulk dielectric permittivity of the surface. While admittedly not the optimum way to discriminate among different types of minerals, measurements of the electro-
magnetic properties of the Venus surface nevertheless place useful constraints on the types and density of surface constituents. They presently represent the only surface properties accessible to direct measurement from above the thick Venus atmosphere, and join a small number of in-situ lander results.

There are several ways that radio waves can give information on the electromagnetic properties of a surface: (1) through the intensity of radar echoes; (2) through the polarization changes introduced by the scattering; (3) through the thermal emission intensity from a surface at a known physical temperature; and (4) through the polarization of that emission. The first, second and fourth of these methods require a surface having sufficient coherence (smoothness) for the Fresnel formulas for reflection and emission to hold, although corrections can often be made if the surface is not entirely rough. The third method is the least sensitive to surface roughness, requiring corrections for roughness only in second order, if averaged over polarization. Because each of the methods has a different dependence on surface structure, and generally suffers from very different systematic errors, more credible results are usually obtained when two or more of the methods are applied to the same terrain, and the results compared.

The first measurements of the radar reflectivity of the (unresolved) disk of Venus took place in 1961, from Earth (Victor and Stevens 1961; Pettengill et al. 1962). Since then, mostly at times of inferior conjunction when the planet is closest to Earth and most easily observed, measurements have been made at wavelengths covering the interval from 7.84 m to 3 cm (see Pettengill [1978] for a summary). Because of limitations imposed on the Earth-based observing geometry by the small obliquity of Venus, echoes at normal incidence could be obtained only near the Venus equator. At wavelengths longer than 15 cm, a value of about 0.15 for the disk-averaged reflectivity was obtained. Beginning in 1978, and extending to March, 1981, the high-inclination Pioneer Venus Orbiter's radar altimeter carried out vertical incidence measurements of the planet's surface reflectivity (Pettengill et al. 1982, 1988), yielding a near global distribution of results that were free of the geometric limitations imposed on Earth-based data.

Most observations of the brightness temperature of Venus prior to the arrival of Pioneer Venus were limited to whole-disk averages and were made near inferior conjunction, where the angular size of the disk is largest (see Pettengill et al. [1988] for a summary); the most accurate disk-averaged result for surface brightness temperature emerging from these observations was 636±25 K. Assuming a surface physical temperature of 735±5 K (Marov 1978) leads to a corresponding disk-averaged emissivity of 0.87±0.04, a value in excellent agreement with a mean observed disk-averaged radar reflection coefficient of 0.13±0.03 (Pettengill 1978).

Pettengill et al. (1982) were the first to report (based on Pioneer Venus data) the existence of regions on the surface of Venus that exhibited unexpectedly high values of radar reflectivity (up to 0.4). Most of these regions were located at relatively high altitudes. Shortly afterwards, Ford and Pettengill
(1983) reported low values of surface emissivity (as low as 0.54), also obtained from the Pioneer Venus radar instrument, which were associated with the same regions that exhibited the anomalously enhanced radar reflectivities reported earlier. Additional observations of Venus, in which the distribution of brightness temperature could be resolved over surface areas as small as 200 km, were made in 1983 from Earth, using the Very Large Array (VLA) in New Mexico (Pettengill et al. 1988). The latter data confirmed the existence of regions having radio emissivities as low as 0.58; it was the discovery and confirmation of the unusual behavior of these regions that largely justified the incorporation of a radiometer in the Magellan radar mission sent to Venus in 1989.

The Magellan mission carried a very competent radar system (Pettengill et al. 1991) that allowed detailed, near-global measurements of both the radar reflectivity and radiothermal emission of the surface. It is these measurements that provide our best current knowledge of the electrical properties of Venus, and that form the bulk of the data discussed in this review. The major shortcoming of the Magellan radar system was its inability to determine the full polarization state of the received radar echo or radiothermal emission; Earth-based observations have been used where available to supply this (and other) useful additional information.

II. RADIO WAVES AND SURFACES

Backscattering from a single interface is often modeled as a combination of quasi-specular reflection, involving coherent processes on an undulating surface (Hagfors 1970) that may be described by the Fresnel equations (Stratton 1941), and a diffusely scattering component arising from rough surface structure of the order of a wavelength in size (Pettengill and Thompson 1968). The quasi-specular component is frequently approximated by the Hagfors scattering function, given by

$$\sigma_a^{QS}(\theta) = \frac{R_o C}{2(\cos^4 \theta + C \sin^2 \theta)^{3/2}}$$  \hspace{1cm} (1a)

where $\sigma_a(\theta)$ is the specific (dimensionless) radar cross section observed at incidence angle, $\theta$, $C = \alpha^{-2}$, $\alpha$ is the root mean square (rms) average value of the undulating surface slope, in radians, and $R_o$ is the Fresnel power reflection coefficient at normal incidence. The diffuse component is often modeled as

$$\sigma_a^D(\theta) = B \cos^n \theta$$  \hspace{1cm} (1b)

where $B$ is a constant chosen to fit data at large incidence angles (where the diffuse component predominates), and $n$ is usually a small number in the range: $1 \leq n \leq 3$. The combination of undulating surface and wavelength-sized roughness enables this parameterized model to be fitted to almost any observed angular behavior when the echo polarization has the expected sense.
for a quasi-specular surface. However, neither the Hagfors nor any other quasi-specular, model can account for depolarized scattered power. Viewed in emission, this type of surface will emit preferentially in the vertical linearly polarized mode, as shown by Eq. (3).

The Fresnel equations (Stratton 1941) controlling the power reflectivity, \( R = |\rho|^2 \), of a smooth surface yield the complex reflection coefficient \( \rho \) as

\[
\rho_h = \frac{a - b}{a + b} \quad \text{and} \quad \rho_v = \frac{\varepsilon a - b}{\varepsilon a + b}
\]  

(2)

where \( a = \cos \theta \), and \( b = \sqrt{\varepsilon - \sin^2 \theta} \).

The corresponding radiothermal emission efficiency, usually called the emissivity, \( e = 1 - R \) (for a smooth surface), may be written as

\[
e_h = \frac{4a\Re(b)}{|a + b|^2} \quad \text{and} \quad e_v = \left| \frac{4\varepsilon a\Re(b)}{(\varepsilon a + b)^2} \right|
\]

(3)

where \( \Re(b) \) is the real part of \( b \).

In these equations, \( \theta \) is the angle of incidence or emergence and \( \varepsilon \) is the complex ratio of the relative dielectric permittivities (often called dielectric constants) characterizing the two sides of the interface. Contributions from a discontinuity in the magnetic permeability at the interface are assumed to be negligible. The subscripts \( h \) and \( v \) refer to radiation polarized perpendicularly ("horizontal" to the surface) or parallel ("vertical" to the surface), respectively, to the plane of scattering or emission. For reference, the relative dielectric permittivity of the carbon dioxide atmosphere just above the planet's surface (\( P = 92 \) atm; \( T = 735 \) K) is 1.034.

According to the quasi-specular model, radar backscatter is dominated by reflection from locally smooth facets, oriented at normal incidence to the illuminating radar beam (at any particular angle to the mean surface, of course, these facets normally comprise only a small fraction of the total illuminated area). For normal incidence

\[
R_h = R_v = \left| \frac{1 - \sqrt{\varepsilon}}{1 + \sqrt{\varepsilon}} \right|^2
\]

(4)

and the polarization of the specularly reflected component is preserved (for incident elliptically polarized radiation, the rotational sense is reversed by inversion of the direction of propagation).

The situation for emissivity is more complicated, because we are usually viewing at oblique angles to the surface. In general, emissivity depends on the angle of emission, as shown by Eq. (3), although for the range of values of \( \varepsilon \) encountered here that dependence is not significant at angles below 45°, when averaged over polarization (Fig. 1a). The emissivity of a rough surface is harder to calculate, although measurements reported by Ulaby et
Figure 1. (a). Variation of emissivity with emission angle, for a smooth (Fresnel) interface having a dielectric discontinuity ratio of 30. The term "in-plane" refers to the linearly polarized (vertical) component lying in the scattering plane, normal to the interface; "out-of-plane" refers to the linearly polarized (horizontal) component normal to that plane. Note how little variation with angle is displayed by the average of these two components, at least below 70°. (b) Variation of emissivity for a partially roughened interface, which is otherwise similar to that shown in (a).
al. (1982) suggest that, for a given value of surface dielectric constant, the total polarization-averaged emissivity increases slowly as the surface becomes rough at scales smaller than the wavelength, still tending to remain constant over angles of emission less than about 45°. The degree of linear polarization is reduced by the roughening, of course, as the coherence of the surface is destroyed (Fig. 1b).

Detailed thermodynamic balance requires that, at a given wavelength and angle of emergence, a surface's emissivity be equal to its absorptivity for radiation incident at that angle. The absorptivity, in turn, must be the unit complement of the reflectivity (summed over all scattering directions) for power incident at that angle, in order to conserve energy. The observed emissivity can therefore be considered the complement of the reflectivity measured in a totally uncollimated outgoing geometry. This implies that the observed brightness temperature for Venus is lower than the physical surface temperature, because of a contribution from reflected cold sky integrated over the upper hemisphere and weighted by the appropriate bistatic surface scattering function. For a smooth, or smoothly undulating (quasi-specular) surface, most of the contribution will come from the direction corresponding to specular reflection. For a highly diffuse Lambert-law surface, the sky's contribution will derive from the entire upper hemisphere, weighted only by the cosine of the zenith angle.

Volume scattering results from successive interactions with one or more interfaces or inhomogeneities internal to the planetary surface, and is known to play an important role in radar scattering from the icy surfaces of the Galilean satellites, as well as from the ice deposits at the poles of Mars and Mercury. It is not thought to play a significant role on Venus, where ice is absent.

III. OBSERVATIONS

A. Monostatic Intensity Observations

The Magellan radar system provided three single-antenna (monostatic) data sets that can be used to extract information on surface roughness and dielectric constant; these were obtained by the synthetic aperture radar (SAR), the radar altimeter, and the microwave emission radiometer (Pettengill et al. 1991). All three were taken at 12.6-cm wavelength, with the SAR and radiometer looking to one side in a common polarization and viewing geometry. The altimeter collected vertical-incidence measurements of backscatter near the spacecraft's nadir. Each data set has particular sensitivities to roughness and dielectric properties, which can be exploited to create a more complete picture of the Venus surface.

The backscattered radar intensity and state of polarization vary with both the dielectric properties of the surface-atmosphere interface and the detailed structure of the surface. At the angles viewed by Magellan (20° to 45°), the SAR echoes depend primarily on diffuse scattering, typically associated with surface structure on the scale of the radar wavelength, but are also affected
strongly by surface tilts on the scale of the image resolution. The Magellan
SAR data are augmented for portions of the surface by Earth-based radar
images collected at the Goldstone and Arecibo Observatories; these images
contain data for both rotational senses of circular echo polarization and cover a
range of incidence angles that nicely complement the Magellan observations.

The radar altimeter system has a much poorer linear spatial resolution
(about 10 km) than that achieved either with the Magellan SAR (typically
120 m) or at Arecibo (1 to 2 km), but can collect measurements of the radar
cross section within about $15^\circ$ of normal incidence. As discussed above,
we expect that large quasi-specular facets will dominate the radar return at
such low angles of incidence. The scattered energy is modeled assuming the
Hagfors behavior given in Eq. (1a) (Ford and Pettengill 1992). For gently
undulating terrain, the Hagfors model also provides a useful estimate of the
rms surface slope at scales of decimeters to meters (but see Sec. IV.A). This
model also estimates the normal-incidence power reflection coefficient of the
surface, as shown in Fig. 2, but only to the extent that the area within the
footprint satisfies the quasi-specular assumptions. Diffuse roughness will
tend to spread the incident energy over a wide range of scattering angles and
thus reduce the inferred reflectivity. A correction for this "lost" power is
included in altimeter processing algorithms, using the SAR data to estimate
the amount of roughness, but its reliability in areas of very high roughness is
uncertain (Pettengill et al. 1988).

In contrast to the strong correlation between radar backscatter and wave-
length-scale roughness, when viewed at oblique angles, microwave thermal
emission is primarily controlled by changes in the bulk dielectric constant of
the surface. As noted earlier, surface roughness has a significant effect on
the polarization state of the emitted energy (Fig. 1b). For those limited areas
on the surface where dual-polarization SAR and emission data have been
collected, the polarization-averaged emissivity can provide a robust estimate
of the dielectric constant largely independent of roughness. In most areas,
however, we must estimate the roughness and dielectric constant using only
the horizontally polarized components of radar backscatter cross section $\sigma_r$,
and emissivity $e$. For regions below 6054 km in altitude, the two parameters
tend to be highly anticorrelated, suggesting a relatively narrow variation in
dielectric constant over the plains. A model has been presented by Campbell
(1994), which attempts to use values of $\sigma_r$ and $e$ to estimate both a diffusely
scattering surface fraction and the dielectric constant.

For any given location on Venus, we usually have only a single observa-
tion of radar backscatter at an incidence angle defined by a latitude-dependent
viewing geometry profile (Saunders et al. 1992). In its initial observations,
Magellan viewed the surface at incidence angles between $25^\circ$ and $45^\circ$. How-
ever, later surveys covered most of the surface at a different angle. Further-
more, Arecibo data are available that augment our knowledge of the angular
scattering behavior, especially for areas seen from Earth at high incidence
angles, e.g., Maxwell Montes, Beta Regio and Mylitta Fluctus.
Figure 2. Mercator and polar stereographic projections of the distribution of power reflection coefficient over the Venus surface, as determined by the Magellan radar altimeter. Values are rendered by a gray scale, shown in the inset. Black areas represent missing data. Data south of approximately 60° S are noisy, because of lower system sensitivity at the high spacecraft altitudes in this portion of the elliptical orbit.

The low-emissivity highlands have backscatter cross sections much larger than those of any dry, rough terrestrial surface. Examination of Arecibo data shows that these areas are characterized by high circular polarization ratios (see Sec. III.B) and unusual angular backscattering functions. Backscatter from Maxwell Montes, the Beta Regio mountains, and Ovda Regio tends not only to be very strong, but also varies only slowly with incidence angle over the range 0° to 25°; however, it drops sharply as the angle increases toward 45° and beyond (Fig. 3). This behavior is not seen in scattering from rocky terrains on Earth.

B. Monostatic Polarization Observations

Single-antenna, i.e., monostatic, measurements of the polarization state of the backscattered radar return have been used to estimate the degree of wavelength-scale surface roughness (Pettengill and Thompson 1968). How-
Figure 3. Specific radar cross section (in decibels) of the quasi-specular component of scattering for planetary surfaces as a function of the angle of incidence. Open circles detail the behavior of areas within Maxwell Montes, drawing on both Magellan and Arecibo data taken at 13-cm wavelength; filled symbols refer to terrestrial data for Hawaiian lava flows of varying surface roughness. The dotted curve represents the Venus mean scattering function (Muhleman law), as adopted by the Magellan Project.

However, if subsurface or volume scattering contributes significantly to the echo, the polarization state may be affected by the polarization-dependent transmission of the wave both into and out of the surface. Hagfors et al. (1965) suggested that scattering from low-porosity powdered surfaces like the upper lunar regolith represents an example of this process, and used such a model to estimate the dielectric constant of the lunar surface, on the assumption that the backscattered echo at high incidence angles originated entirely from diffuse subsurface scatter. Hagfors and Campbell (1974), using a circularly polarized transmitted signal, failed to find any corresponding linearly polarized component in Arecibo 70-cm wavelength radar returns from areas on Venus viewed at high incidence angles. This result suggests that, for Venus, the majority of the radar echo comes from scattering at the atmosphere-surface boundary, with little or no subsurface contribution.
While the electromagnetic properties of the Venus surface cannot be directly deduced from the polarization state of the backscattered radar return, the polarization can be used to help discriminate among the various models invoked to explain the low radiothermal emission observed above 6054 km. The most extensive studies of the polarization properties of the backscattered Venus radar echo have been made at Arecibo, using its 13-cm wavelength radar system (the same wavelength used by Magellan). The Arecibo system normally transmits left circularly polarized radiation, and receives both the left (LL) and right (LR) circularly polarized echo components. The LL (depolarized sense) and LR (expected sense) cross sections are used to calculate the LL/LR polarization ratio (Campbell and Campbell 1992). Tryka and Muhleman (1992) mapped the RR cross section of Alpha Regio at 3.5-cm wavelength, using the 70-m Goldstone Deep Space Network antenna for transmission, and the VLA antenna array to synthesize an angularly resolved image of the depolarized echoes. In this experiment, the RL polarized echoes were sufficiently strong to saturate the receiving system, and were lost. The large, two-way atmospheric absorption for Venus at a wavelength of 3.5 cm forced this system to limit its RR imaging to those regions which could be viewed at relatively low angles of incidence, principally Alpha Regio. The depolarized observations of Alpha Regio, a region that does not exhibit unusual values of emissivity, showed several small areas of localized RR enhancement.

Typical values for the LL/LR polarization ratio of echoes from the Venus lowlands and rolling plains, viewed at incidence angles above 40° from Arecibo, fall near 0.2; in contrast, the high-altitude, high-reflectivity (and low-emissivity) regions show ratios that often exceed unity. In the Maxwell Montes, the polarization ratio is everywhere close to unity, with maximum values rising to 1.25 along its northern and southern edges (Fig. 4). For Beta Regio, values of the ratio slightly lower than unity are found near the summit of Theia Mons, although there are a few areas where the ratio is close to one. High ratios correlate well with areas of large LR cross section, but the correlation is not perfect. We note also, that regions with a large polarization ratio tend to correspond to regions having very low values of emissivity in the Magellan data, although the latter have a poorer spatial resolution than do the corresponding radar images. Figure 5 shows an LL (depolarized) image of Maxwell Montes obtained at Arecibo, indicating the track along which the ratios given in Fig. 3 were obtained. (This track is also the path of the bistatic observations discussed in Sec. III.C).

C. Bistatic Observations

Bistatic radar experiments, where the reflecting surface element is illuminated and viewed from different directions, allow a wider variety of useful measurements, particularly of the polarization dependence, of the scattering process than is available in the more usual monostatic geometry, where the two directions are retro-aligned (Simpson 1993). The Magellan spacecraft has been used in this mode to study Venus by illuminating the planet's surface with its
13-cm-wavelength telemetry transmitter, in a geometry chosen to satisfy the requirements for specular reflection as viewed from Earth (Pettengill et al. 1996). The echo signals were received using dual phase-coherent, orthogonal, circularly polarized receiving channels, which enabled recovery of a full Stokes-vector description of the received energy.

The 13-cm-wavelength continuous wave (CW) downlink radiation was linearly polarized at transmission. By adjusting the orientation of the spacecraft, the polarization angle of the incident polarization was maintained at 45° to the scattering plane. Thus, the power striking the surface in both the in-plane (vertical) and out-of-plane (horizontal) linearly polarized components was equal and in-phase. The polarization angle of the reflected signal was, therefore, determined simply by the inverse tangent of the ratio of the amplitude reflection coefficients given in Eqs. (2). For rough surfaces, we expect weak echoes, since the scattered energy is diffused over a wide range of emerging solid angle. Where the surface is reasonably smooth, the signal is concentrated in the specular direction and remains highly polarized. An important advantage of this observing technique is that the ratio of the in-plane and out-of-plane reflected components depends only on the dielectric constant of the surface, thus eliminating the need for accurate calibration of the received power. Equally useful is that only a small portion of the scattering
Figure 5. Arecibo radar image of Maxwell Montes, using the depolarized (LL) sense of received circular polarization. The data for this image, which has a resolution of approximately 1.5 km, were obtained during the June 1988, inferior conjunction of Venus. The track starting northeast of the 100-km diameter crater Cleopatra, and extending to the south-southwest is the track of the specular reflection point for the 5 June 1994, Magellan bistatic experiment described in the text.

surface need be smooth to yield a measurement of the rotation angle of the incoming polarization, and thus the ratio of components described above. In this way, even an extremely rough surface can yield credible estimates of its dielectric properties, as long as a few smooth horizontal facets are present.

In bistatic measurements carried out 5 June 1994 (Pettengill et al. 1996),
Figure 6. The polarization position angle observed during the bistatic experiment carried out by the Magellan spacecraft on 5 June 1994, as it flew over the Maxwell Montes. A polarization angle of zero degrees corresponds to reflection at the Brewster angle, resulting in a polarization direction parallel to the Venus surface. The dashed line shows the theoretical behavior (varying with incidence angle) expected for a smooth surface having a dielectric constant of 4.0.

the observing geometry permitted the Magellan spacecraft to illuminate a surface swath that traversed much lowland terrain, but also passed over the high-altitude low-emissivity regions in the southeast of Maxwell Mons (Fig. 5). Near Maxwell Mons, because of its high latitude, the angle of incidence (67°) was close to the Brewster angle (64°) for material having a dielectric constant of about 4.5; thus, where the illuminated footprint comprised "typical" surface material, very little in-plane echo was generated and the polarization angle of the reflected ray was nearly perpendicular to the scattering plane. In fact, for typical lowlands regions, the observed polarization angle rotation was consistent with a dielectric constant of 4.0±0.5. As the footprint moved into the low-emissivity regions in Maxwell, however, the plane of received polarization suddenly rotated through nearly 45° (Fig. 6). Analysis shows a polarization angle of 36.9°±2° in the Maxwell Montes region at the edge of the crater Cleopatra, implying a surface dielectric constant there of order 100. A particularly surprising result was the appearance over Maxwell of a component of right circularly polarized power corresponding to about 10% of the total reflected signal. The amount of this component (presumably arising from a finite phase difference between the complex amplitudes given in Eqs. (2), as a result of electrical loss in the surface), the observed polarization angle, and the previously measured emissivity of about 0.33 place constraints
on the electrical properties of the reflecting surface of the Maxwell Montes. The effects seen may conceivably result from a lossy dielectric, but a more likely assumption of a semiconducting layer having an imaginary dielectric constant of $-i100 \pm i50$ appears to work quite well (Pettengill et al. 1996). The consequences of this unusual finding are explored in the next section.

IV. SURFACE STRUCTURE AND COMPOSITION

A. The Typical Surface

Venus backscatter values have been interpreted by a number of workers through comparison with similar radar measurements of putative terrestrial analogs (Gaddis 1992; Arvidson et al. 1992; Campbell and Campbell 1992; Plaut 1991). With the exception of some crater-related deposits, variations in the surface dielectric constant for most areas on Venus below 6054 km radius are small enough to be neglected in a broad-brush survey.

The plains that make up more than half the planet’s surface area vary widely in their backscatter characteristics, depending on the density of superposed tectonic ridges and fractures, but the underlying material was clearly very smooth when emplaced, a property that is consistent with its assumed origin as fluid lava erupting from linear vents or fissures. The inference of smoothness is based on the relatively low backscatter coefficient of the Venus plains relative to terrestrial lava flows, and on the rapid decrease in backscattered power as the incidence angle increases. A survey of volcanic edifices on Venus suggests that, in general, the magma issuing from many of the large shield volcanoes appears similar to smooth terrestrial basaltic flows (Campbell and Campbell 1992). The rough textures often seen in terrestrial flows emplaced at high eruption rates, or resulting from lavas with high silica content, are rare on Venus (Moore et al. 1992). Some radar-dark flows, typically those appearing stratigraphically recent, are smooth down to the centimeter level.

Dielectric constants vary only slightly (from 3 to 6) over the plains and edifice lava flows; the changes seen probably arise from relatively small differences in mineral content or magma density. At altitudes below a planetary radius of about 6054 km, the mean surface has a bulk dielectric constant of between 4.0 and 4.5 (Pettengill et al. 1992, 1996). This value is consistent with dry compacted rocks of a variety of compositions, as seen on Earth and other planets (Campbell and Ulrichs 1969); the occasional surface areas having lower values are consistent with layers of overlying, less compact, dusty or granular material (Gold et al. 1970; Carrier et al. 1991).

The dielectric values derived from the altimeter and the emissivity data, respectively, agree well for these surfaces, presumably because corrections for small-scale roughness are small. Areas possessing a higher dielectric constant (up to 8), usually associated with parabolic crater ejecta deposits and radar-bright crater floors, have been identified in the plains (Campbell et al. 1992; Plaut and Arvidson 1992). The crater parabolas probably result
from mantling by fine material produced in relatively recent impact events; if not recent, they would likely have been dispersed by the wind over a few tens of Myr (Izenberg et al. 1994; Arvidson et al. 1992; Greeley et al. 1992). The emissivity data suggest a dielectric enhancement in the fine-grained material, that may be related to the impact melting process. In any event, the enhancement evidently survives in the lowland environment for a significant period of time. Low-dielectric areas around impact craters and some volcanoes are attributed to fine-grained material which mantles the underlying rocky surface, but which lacks enhancement in its constituent dielectric constant. Based on the reflectivity and emission data, the amount of porous material on the surface seems relatively low, and is consistent with slow erosional mechanisms and limited aeolian transport (Greeley et al. 1992).

The coherent radar echoing properties of most of the Venus surface appear to be well represented by models assuming quasi-specular scattering from a single interface. Because the probability density function for surface slopes is proportional to the specific radar cross section under certain conditions (Barrick 1968), probability functions $p(\beta)$ (where $\beta$ is the tilt of a reflecting element with respect to the normal to the mean spherical surface) can be extracted from the Magellan altimeter echoes and used to characterize surface morphology in a statistical sense over areas as small as a few thousand square km. Tyler et al. (1992) have shown that the Hagfors function given in Eq. (1a) provides good agreement with the data, but that an exponential form for $\sigma_\nu(\theta)$ yields lower residuals in most areas. The typical surface is quite smooth at radio wavelengths, undulating with values of rms slope between 2° and 4° (Ford and Pettengill 1992; Tyler et al. 1992), and exhibiting only 10 to 20% depolarization in its scattered energy (Carpenter 1966).

Hagfors (1970) assumed that the quasi-specular scattering surface had a Gaussian height distribution and an exponential lateral autocorrelation function, but argued that high frequencies in the surface structure are effectively filtered out by the choice of radar wavelength. Surfaces with “sawtooth” profiles are thus permissible as long as we allow the sharp corners to be rounded during the scattering process. The corners themselves may contribute to the diffuse component of the echo, which is distributed widely in angle compared with the quasi-specular component. The fact that the Magellan data often match an exponential better than the Hagfors scattering function suggests that not only can much of the Venus surface be modeled as a set of flat, tilted plates, but that there are more plates with zero tilt than we would expect if the tilts were randomly distributed. At least in selected locations on the broad Venus plains, Venera lander images confirm that the surface is composed of larger and flatter facets than we see on Mars and the Moon, and that there are fewer discrete, rounded rocks exposed (Garvin et al. 1981, 1984).

The average tilt of reflecting facets may not, in fact, always be zero. A surprising result of the analysis carried out by Tyler et al. (1992) showed that Magellan altimetry echoes are often asymmetrically distributed in frequency. In some regions, echoes seem to arise from surface elements that are pref-
erentially inclined for backscatter ahead of the spacecraft (positive Doppler shifts), while in others the echoes seem to come preferentially from behind (negative Doppler shifts). Although large-scale topographic tilt can account for some of this offset, in many areas, the observed effects are an order of magnitude larger than could be explained by large-scale topography. One possibility is that the reflecting facets are oriented to have long, gradual rises in one direction, followed by sharp drops. In this way more of the surface could tilt toward the north (for example) while the net topographic change along the track would be zero. Similar Doppler offsets have since been found in Venera altimetry data (A. Zakharov, personal communication; Maurer et al. 1993). East-west asymmetries in the distribution of backscattered energy have been reported from analysis of Magellan SAR data for a few areas linked to aeolian features on the surface (Plaut et al. 1992; Weitz et al. 1994).

In mountainous areas on Venus, as compared with the lowlands, the surface roughness inferred from nadir radar sounding is generally higher, and the specific radar cross section tends to be better represented by an expression using a lateral auto-correlation of Gaussian form, rather than either the truncated exponential function used in the Hagfors formulation (Eq. 1a) or a simple exponential (Tyler et al. 1992). In most such areas, the primary scattering still appears to be quasi-specular, suggesting that the surface is likely to be more angular, and have fewer flat, plate-like components, than in the lowlands. The panoramic view from Venera 9 (Garvin et al. 1984) is consistent with such a more angular surface at higher elevations. For a small region in Alpha Regio, Tryka and Muhleman (1992) suggest that the polarization properties are consistent with volume scattering. Volume scattering of any type implies very low loss tangents (negligible amounts of absorbing material, such as iron-bearing minerals), which would likely require a nonbasaltic composition (Ulaby et al. 1982; Carrier et al. 1991; Wilt 1992). The emission associated with the Alpha Regio areas, although locally low, is still much greater than that seen in most highland regions, where values of horizontally polarized emissivity (at 45° viewing angles) below 0.33 are sometimes found.

B. The Low-Emissivity Surface

In contrast to data for the lowlands, observations of the Venus highlands often yield dielectric constants of 50 or more (Pettengill et al. 1992). In general, dielectric values extracted from emissivity observations tend to be significantly larger than those obtained from altimeter data; however, the accuracy of the latter may suffer from the large diffuse scattering corrections needed for the rough highland surfaces. The transition from “normal” dielectric values typical of the lowlands to the large values found at high altitudes occurs rapidly above a critical elevation; the altitude of the onset appears to vary slightly with location on the planet (Arvidson et al. 1992, 1994; Klose et al. 1992; Wilt 1992), moving from just below 6054 km planetary radius near the equator, to just above 6055 at high northern latitudes. While roughness
in areas above these levels tends to be high, this roughness appears to stem from the formational history of the terrain, i.e., producing a preponderance of tesserae, rather than from a weathering of the high-dielectric material (Arvidson et al. 1994; Campbell 1994). There is relatively little correlation between the visible structure of any given terrain and its dielectric enhancement.

Several possible explanations for the low emissivity of the Venus highlands have been proposed since the discovery of the phenomenon. The first of these, postulating a surface loaded electrically with small conductors (iron sulfides of various forms) was put forward by Pettengill et al. (1982), Ford and Pettengill (1983), and Pettengill et al. (1988). As the required value of surface dielectric permittivity has been pushed higher and higher by the observations (currently it is around 100), materials with ferroelectric properties have been proposed (Shepard et al. 1994), which also allow for a rapid variation in electromagnetic reactivity with small changes in ambient temperature. But the ferroelectric mineral with the precise properties required by the observations has yet to be identified. With the recent results obtained from the bistatic experiment described in Sec. III.C, however, it is clear that a semiconducting surface layer will also suffice to meet the electrical requirements of the observations. Pettengill et al. (1996) derive a value for the surface electrical conductivity of 13 mhos m$^{-1}$. Of the chemical elements, only germanium and tellurium have values of conductivity that might accommodate this value; tellurium appears particularly intriguing, because it has a freezing point temperature of 723 K, almost precisely that of the limiting highlands elevation above which the anomalous effect is seen. In fact, the small (1 km) variation in onset altitude may reflect corresponding differences in atmospheric temperature (8 K) with latitude. Brackett et al. (1995) have investigated the problem of volatile transport from the lowlands to higher and cooler locations on Venus, although specific calculations for tellurium (or tellurides) have not yet been carried out. It is interesting to note that, if the semiconducting material is tellurium, a thin layer (less than 3 mm, and perhaps only several $\mu$m thick) may be able to support the results seen; it is estimated that only between $10^{-3}$ to $10^{-5}$ of the tellurium contained in the crust and mantle of Venus need be outgassed to support this hypothesis (Pettengill et al. 1996). Another possibility involves the slow deposition of magnetite above the critical altitudes (see the chapter by Wood).

In addition to understanding the dielectric properties of the low emissivity surface, it is necessary to explain the large depolarization ratios seen in these areas (Fig. 4). An intriguing possibility, enhanced by the efficient reflectivity of a semiconducting surface, is that whiskers or other highly inclined dendritic structures on the surface might allow the multiple (primarily dual) reflections needed to give rise to the the coherent backscatter opposition effect (Hapke 1990).
V. CONCLUSIONS

The surface of Venus is dominated by plains comprised largely of flat plates of basaltic material. These plates exhibit complex regional tilt patterns, which have not as yet been plausibly explained. The typical plains region has a surface with an rms slope between 2° and 4° at lateral scales greater than a few meters; a 5 to 10% component of small-scale (several cm) roughness; and a nominal dielectric constant falling between 4.0 and 4.5. Variations in the dielectric constant across the plains likely arise from minor changes in chemical composition, density, or post-emplacement soil formation. The large volcanic edifices are often characterized by relatively smooth-surface lava flows, suggesting low magma viscosity or slow effusion rates. Occasional high surface roughness in these areas probably results from a viscous magma or large eruption rates.

Fine-grained material is found mostly surrounding impact craters, and has widely varying dielectric properties. Some low-dielectric deposits mantle the underlying terrain to depths of 10 to 50 cm, attenuating the backscattered echo. Parabolic crater deposits often have low-intensity backscatter signatures, as a result of their relative smoothness, but their relatively low values of emissivity imply a moderately high dielectric constant (about 8). Porous layers should have lower dielectric constants than their parent rock, so a moderately higher intrinsic dielectric constant is implied for these deposits. Because similar emissivity values are found in some crater floors, the enhancement may arise from impact melt processes.

The radar-bright highlands appear to be underlain by normal volcanic or tectonically deformed terrain, covered by a lossy conducting material yielding an imaginary dielectric permittivity of about 100. A possible candidate for this layer is a composite of basaltic rock and magnetite, or a frost of tellurium. It is likely that a full understanding of the low-emissivity surface composition and structure must await in-situ studies. The highland regions of Venus obviously form high-priority targets for future Venus landers.

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