Effect of Venus surface illumination on photographic image texture

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Abstract. Radar images from Magellan have provided tremendous opportunities to study the geology and bulk dielectric properties of Venus, but many questions can only be addressed through direct photography or imaging spectroscopy of the surface. The thick atmosphere creates a situation of nearly isotropic illumination, so true shadows cannot exist for even very rough terrain. We carried out ray-tracing simulations for synthetic surfaces under both isotropic and directional illumination conditions. Relative to similar surfaces viewed under directional illumination, venusian terrain will exhibit an equal or greater range of mean brightness with changing roughness, but a concurrent reduction in the maximum possible standard deviation of brightness across any region of given roughness. The local variability of an image is often referred to as texture, and these results indicate that Venus geologic units will appear more homogeneous in brightness than the same surfaces viewed under favorable directional illumination. In addition, the lack of a preferred lighting direction makes identification of surface structural patterns difficult. A similar situation may occur on Titan.

Introduction

The thick atmosphere of Venus precludes direct visible or near-infrared observations of the surface from orbit. Earth-based observatories and a series of orbital probes have produced an extensive radar image database for the planet, culminating with high-resolution global mapping by Magellan [*Saunders et al.*, 1992]. Numerous geologic studies have been carried out using these data, but many questions remain that need to be addressed using direct observations of the surface. Four Venera lander missions acquired television images of the surface [*Garvin et al.*, 1984], but additional photography for a wider range of geologic units is of great importance, and balloon-borne camera systems have been proposed as the most practical way to acquire these data [*Cutts et al.*, 1995]. A major factor in the design of such systems is the effect of the atmosphere on the observable properties of the surface. The atmosphere of Titan may also produce nearly isotropic illumination, so these same issues may arise in the design of future missions to this satellite.

In general, the capability to discriminate between any two surface units under a given illumination depends upon: (1) their relative albedo, (2) their respective scattering properties, and (3) the surface roughness. The latter characteristic manifests itself as changes in the mean brightness (which tends to be lower for rougher surfaces due to self-shadowing) and in the variability of brightness within a unit (image texture). Rougher areas tend to have greater ranges of image pixel brightness because the viewer sees facets at a larger range of incidence and emission angles. Both relative brightness and differences in texture have been used widely to categorize surfaces from remote observations.

In this paper, we consider the effect of the dense Venus atmosphere on the illumination of the surface, the photographic contrast between units of different roughness, and the image texture within a given unit. We first examine the differences in scattering functions for a facet as the illumination changes from directional (terrestrial) to isotropic (venusian). The effects of differing illumination are then illustrated with ray-tracing simulations for synthetic surfaces. Finally, we assess the impact of these results on the likely appearance of the surface and the interpretation of Venus airborne photographs.

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Scattering functions for varying illumination

For scattering problems, natural surfaces are often modeled as a collection of small facets with varying orientation. Each facet has a characteristic pattern of scattered radiation for a given illumination geometry. This function is generally expressed in terms of an incidence angle i between the surface normal and the incoming beam, the emission angle e between the surface normal and the observer, and the phase angle g between the incidence and emission vectors. In planetary work, the most commonly used model of scattering is that proposed by *Hapke* [1981]. This model was derived for a particulate surface illuminated from a specific direction, and contains five or more independent parameters.

In our analysis, we wish to simplify the scattering function as much as possible while still retaining realistic behavior. We therefore examine two commonly assumed scattering functions: Lambert and Lommel-Seeliger (L-S):

$$B_L = \cos i \tag{1}$$

$$B_{LS} = \frac{\cos i}{\cos i + \cos e} \tag{2}$$

where we have normalized the maximum brightness of each model to unity. The Lommel-Seeliger function can be theoretically derived assuming a particulate surface of isotropically-scattering particles. This function is a special case of the Hapke model in which the opposition surge brightening is nonexistent and the surface is assumed to be perfectly smooth. Because multiple scattering is neglected, this model is usually valid only for darker surfaces. The Lambert function is an empirical model, but has been found to closely approximate the behavior of many brighter "matte" and particulate surfaces [*Kortum*, 1969; *Shepard et al.*, 1993]. We will also address a possible specular scattering component for those cases where macroscopic roughness allows it.

For the terrestrial situation, the illumination comes from a small area on the sky, so we can calculate the brightness of a facet from (1) or (2). For incidence or emission angles greater than 90°, the facet is in shadow or hidden from view, and there may be further cast shadows from other portions of the surface. To a first approximation, the Venus sky is equally bright in all directions, and we will use isotropic illumination as an end-member scenario. We also neglect any thermal component to the energy emitted by the surface. As the sun drops to very low angles on the horizon, thermal emission may well compete with reflected solar energy, so our analysis assumes that the local time is between late morning and early evening [*D. Crisp*, pers. comm., 1996]. Finally, we do not consider differences in path length through the Venus atmosphere, which will create large differences in brightness due to scattering. For a balloon-mounted camera, the likely observation direction will be toward the nadir, so path length differences within a scene will be minimal.

Under isotropic illumination, an isolated facet absorbs radiation from a section of the hemisphere above it dictated by its tilt angle γ. The brightness function is thus an integral over the visible portion of the sky, which for the Lambert case leads to a scattering function of:

$$B_L^V = \frac{(1+\cos\gamma)}{2} \tag{3}$$

We cannot solve the brightness function for a Lommel-Seeliger facet in closed form, but numerical results show that the observed brightness is nearly uniform until $\gamma=60^\circ$, beyond which there is a sharp upturn. Since facets with slope greater than 60° are likely to be rather rare, a L-S surface has effectively no dependence of brightness on facet tilt distribution. Local changes in brightness due to roughness, which define the image texture, will thus be muted on Venus. On a real surface, however, the tilt angle alone does not define the brightness of an area, because nearby facets can affect the fraction of the sky visible from any given point. There are no completely shadowed areas on Venus, but other higher-standing parts of the surface can reduce the local brightness by narrowing the visible portion of the sky.

Ray-tracing of synthetic surfaces

In theory, one could combine a facet scattering function with a probability density function for surface tilts to estimate the brightness mean and standard deviation. However, this also requires analysis of the effects of nearby facets on the energy reaching a given point on the ground, and such treatments are lengthy and do not specify the brightness of a given surface point (only the statistics of image values) [*Smith*, 1967; *Wagner*, 1967; *Hapke*, 1984]. A second method for approaching the problem is to produce a simulated landscape of facets and use a ray-tracing algorithm to determine the brightness of each point.

Natural surfaces can often be described by fractal models, in which the vertical topographic variations scale as a power-law function of the horizontal measurement length. A fractal dimension of D=2.5 corresponds to a Brownian or random-walk process, and topographic profiles of Hawaiian lava flows tend to cluster about this value [*Campbell and Shepard*, 1996]. We used a synthetic Brownian surface, 256x256 elements, for our tests. The height fluctuations on this surface follow a Gaussian distribution, and the rms slope s can be varied by multiplying each height value by a scaling factor.

The ray-tracing algorithm divides the sky into small regions, then attempts to trace a line from each surface element to a given sky point. If the ray intersects another facet, then this portion of the sky is blocked. If not, we calculate the observed flux based on the local incidence and emission angles and the effective area of the observable portion of the sky. For the Venus simulations, the hemisphere above the surface was represented by 3,600 elements. A buffer of 32 pixels was used at the edges of the fractal surface to provide adequate neighboring topography for potential shadowing, and the mean and standard deviation of image values were calculated for the remaining region. In order to compare the relative properties of surfaces on Venus and the Earth, we normalized the Lambert and Lommel-Seeliger results to their respective maximum values. In reality, any given unit will have a characteristic reflectance or single-scattering albedo which determines the absolute value of the observed radiance, but for this investigation we are concerned only with the statistical properties of the illuminated surfaces.

Under the terrestrial situation of directional illumination, we calculated the mean and standard deviation of image brightness as a function of solar zenith angle θ for rms slope values of $s=5^\circ$ to $s=60^\circ$ (Figures 1 and 2). The observer is assumed to be directly above the surface. The jagged behavior of these graphs at high roughness and low zenith angles is an artifact of representing the surface by discrete elements with uniform spacing. It is important to note that the mean and standard deviation of image brightness are not ideal descriptive parameters, since in many cases the distribution of pixel values within a scene is not Gaussian. Because the brightness of a facet can only range from zero to unity, one side of the distribution may be truncated. In the most extreme case, the distribution may have a Rayleigh-like behavior. The actual shape of the pixel brightness distribution might eventually be used to infer the nature of the surface scattering

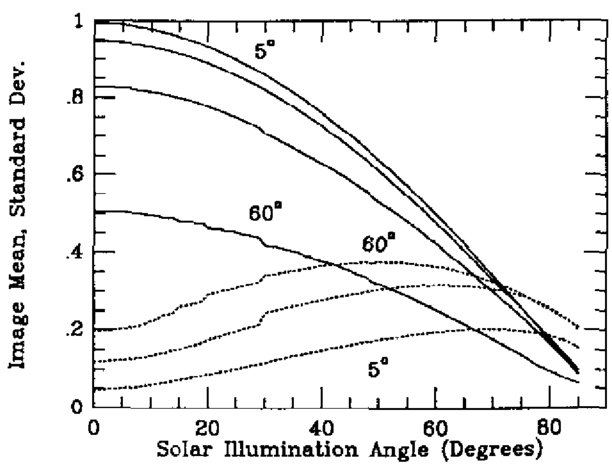

Figure 1. Mean brightness (solid) and standard deviation (dotted) of image pixels as a function of solar zenith angle for rms slope values of 5°, 15°, 30°, and 60°. The Lambert scattering function was assumed for each facet. The observer is directly above the surface.

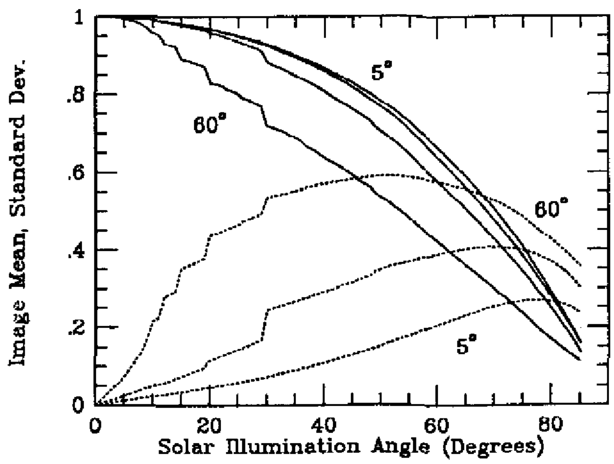

Figure 2. Mean brightness (solid) and standard deviation (dotted) of image pixels as a function of solar zenith angle for rms slope values of 5°, 15°, 30°, and 60°. The Lommel-Seeliger scattering function was assumed for each facet. The observer is directly above the surface.

function and the roughness, but for this paper we use the simple mean and standard deviation as general guides to image properties.

For the Lambert surface, the observed brightness decreases with greater roughness, and this effect is most pronounced at very low phase angles. The standard deviation of brightness increases with roughness and with zenith angle out to a rollover point. The maximum contrast occurs for zenith angles of 50-60°. At smaller angles the surface is comprised of more homogeneous bright pixels, while at higher angles the dark shadowed pixels predominate. A Lommel-Seeliger surface has no variation in brightness with roughness under normal (zero-phase) illumination, and the mean value is most sensitive to roughness near $\theta=50^{\circ}$. The L-S standard deviation follows a similar trend to that of the Lambert surface, but has proportionally greater variability with roughness.

Lambert surfaces of differing roughness will thus have the greatest image contrast when viewed from above under near-normal illumination. Image texture, as represented by the brightness standard deviation, is significant at this geometry but well short of its maximum possible value. Lommel-Seeliger surfaces will appear homogenous and of uniform brightness regardless of roughness under these conditions. As is well-known from many photogeologic studies, oblique illumination of 40-60° offers the best opportunity to discriminate roughness changes based on image texture over a planetary surface.

We calculated the same statistics for this synthetic surface under isotropic illumination as a function of rms slope (Figure 3). The two scattering functions have similar normalized values for mean brightness until s becomes very large. The total range in mean brightness for the Lambert case is similar to that for the same surfaces viewed under normal (zero-phase) directional illumination. The standard deviation of image brightness is also similar to that observed for zero-phase conditions. A Lommel-Seeliger behavior actually leads to larger shifts in mean brightness for isotropic illumination than would be observed under favorable directional illumination (0-50°). The range in standard deviation is considerably lower than the best possible case for directional illumination, though obviously better than the completely homogenous behavior observed for zero-phase conditions.

Some surfaces on Earth and Mars have scattering functions which exhibit preferential forward scattering in the form of a specular glint [*Shepard et al.*, 1993], with brightness dependent upon the tilt angle and the refractive index. We considered the effect of such a model on the brightness distribution for a Venus surface viewed from directly overhead. Since only a small area on the sky can contribute to the specular glint, shadowing by neighboring facets leads to a bimodal distribution of bright and dark image points. Likewise, any facet tilted more than 45° to the horizontal has no specular component, since the required sky point is below the visible horizon. For the remaining tilted facets, however, the range of brightness is rather small, since the specular model has little variation for small values of γ. The strongest glints come from facets with tilts of 45°, and there is no azimuthal variability. Most observations of specular scattering on natural surfaces are made at very high incidence and emission angles, which will not be possible for an airborne camera system.

In summary, the rough Lambert surface under Venus conditions behaves almost identically to a similar surface viewed under normal illumination, such that roughness changes lead to strong mean brightness contrasts and limited textural shifts. The Lommel-Seeliger surface has a wider range of mean brightness than might be obtained with ideal directional illumination, but a narrower range in image texture. Relative to a flat plate of each scattering behavior, the Lambert and L-S models lead to very similar textural changes with roughness. The addition of a specular component to either of these models may increase the standard deviation of brightness to some degree at higher roughnesses, but should not greatly affect the image mean.

Implications for image interpretation

The illumination provided by the Venus atmosphere limits the range of image textural variability with surface roughness, but such changes will likely be detectable and useful for characterizing geologic units. A second concern is the impact of this lighting on the inference of large-scale surface morphology (i.e., the presence of ridges, crater rims, or lava flow structures). Views of a Lambert surface with $s=15^{\circ}$ under

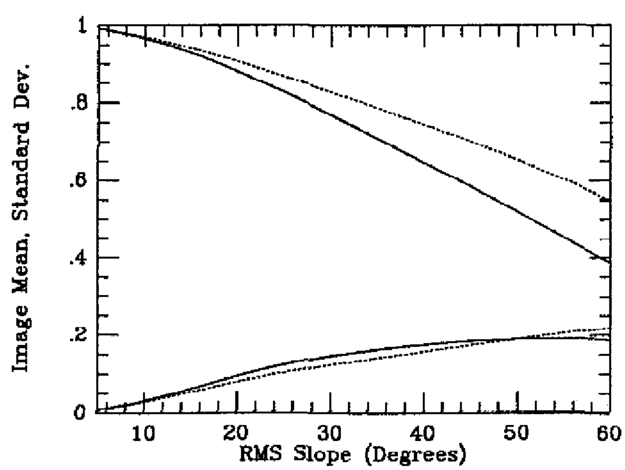

Figure 3. Mean brightness and standard deviation of image pixels as a function of rms slope for isotropic illumination (Venus conditions). Results for the Lambert (solid) and Lommel-Seeliger (dotted) scattering functions are shown. The observer is directly above the surface.

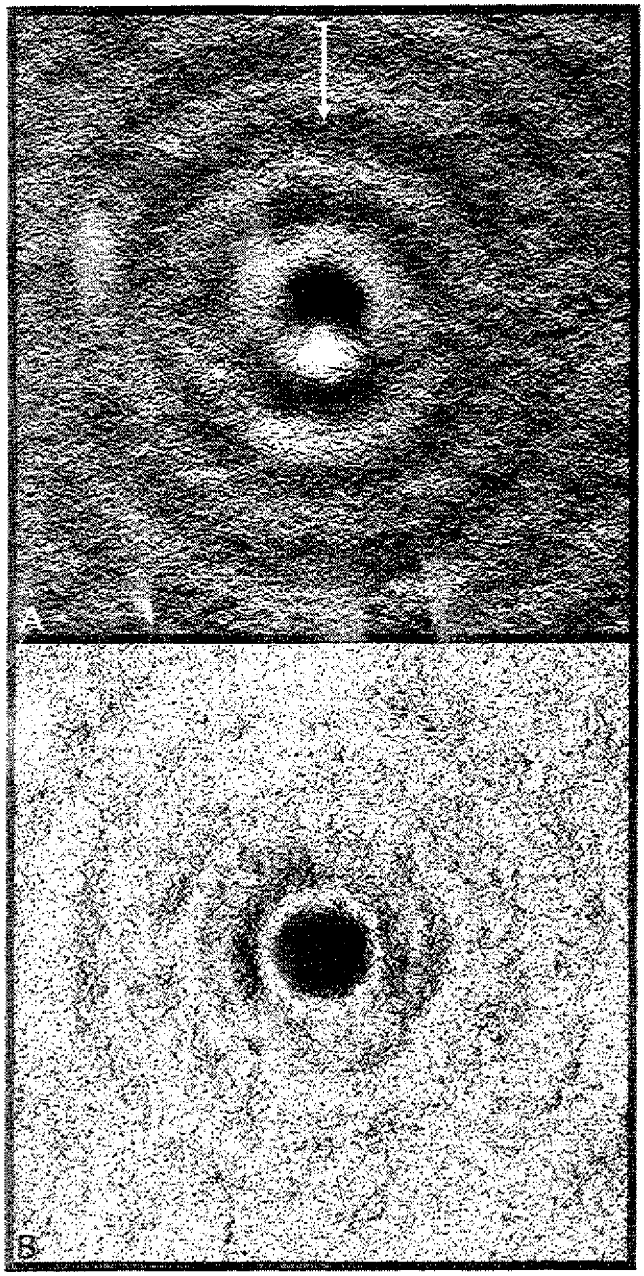

Figure 4. Images of a synthetic Lambert-scattering surface under varying illumination geometry. The observer is directly above the surface. Rms slope of the fractal roughness is 15°, and we have added a sinc-function topography to simulate a central crater and concentric rings. (a) Directional illumination at a solar zenith angle of 45°. The light is incident from the top of the image. Image stretch 0.4-1.0. (b) Isotropic illumination. Image stretch 0.8-1.0.

favorable directional ($\theta=45^{\circ}$) and isotropic illumination are shown in Figure 4. We have added to the fractal roughness map an azimuthally symmetric (sinc-function) topography, which simulates a central depression and annular rings which decrease in magnitude with distance from the crater. The directional illumination highlights sun-facing slopes, delineating structural patterns which trend perpendicular to the incident ray. Isotropic illumination leads to a very different view of the surface. The brightest facets are those which are exposed to the largest amount of sky (e.g., the tops of ridges), while the floor of the crater is very dark. The observed brightness of a pixel is thus as much a function of its absolute height as of its tilt with respect to the horizon. Identification of structural patterns is still possible from this image, but requires careful interpretation.

Conclusions

This work shows that for Lambert and Lommel-Seeliger scattering behaviors, we can expect to observe on Venus significant changes in mean brightness as a function of roughness, such that moderate-resolution images will be capable of discriminating the boundaries of lava flows, crater ejecta blankets, and surface soil deposits, even if their intrinsic albedo contrasts are small. Image textural variations, which can provide geologic information on surface roughness, will be muted by the lack of true shadows, but will still be significant relative to the changes in mean brightness across various terrains. Of greater concern is the partial loss of visual cues to the presence and orientation of larger-scale structural features such as ridges. Magellan radar images, with their directional illumination, will be valuable in identifying such structures, so the accurate geolocation of surface photography becomes an imperative for any future mission.

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