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The Polarization and Intensity of Thermal Radiation from a Planetary Surface

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The brightness temperature of an element of a planetary disk is dependent both on the direction of linear polarization to which the observing antenna is sensitive and the inclination of the element to the line-of-sight. Instruments of high resolution can be used to measure this dependence, providing values for the dielectric constant and emissivity of the planet's surface. The behavior of theoretical models, to which observations may be compared, is given.

Observations of the Moon and Venus are presented as examples of application of this theory. The dielectric constant of the Moon at 21 cm is found to be 2.1, in good agreement with the radar results. This implies the emissivity at the center of the disk is 0.97, yielding 241 ± 26°K as the actual surface temperature at the center of the disk. The radiometric data for Venus show the expected behavior but the dielectric constant obtained is inconsistent with the value obtained from radar experiments.

INTRODUCTION

Contemporary radiofrequency radiometry of planets provides only a mean brightness temperature for the entire disk of the planet. It would be valuable to measure, as well, the relevant physical properties of the surface, such as dielectric constant and surface roughness, allowing then, in principle, a calculation of the true surface temperature. In the case of the Moon, some of this information can be derived by an analysis of data concerning the variation of apparent temperature with phase; but application of the method to most planets is presently impossible because of poor observational sensitivity, and the highly uncertain influence of the planetary atmospheres. These difficulties may be circumvented partially through radar observations, which yield direct measurements, for the Moon and nearby planets, of the reflection coefficients for rays at normal incidence.

Radiometric observation of the polarization and apparent temperature across the disk of a planet with instruments of high resolution provides another technique for the measurement of the reflection coefficient, dielectric constant, and emissivity, and in turn the true surface temperature. This paper gives the theory applying to such observations, shows the expected results for various values of the dielectric constant, and gives two examples of application of the theory to actual observations.

THEORY

A Smooth, Homogeneous Spherical Planet

Consider a perfectly smooth homogeneous planet which is at a uniform temperature T, has a dielectric constant ϵ, a magnetic permeability of one, and is surrounded by free space ($\epsilon = 1$). The power reflection coefficient for a plane electromagnetic wave incident on a surface element of the planet is

$$R_{\parallel(\Theta)} = \left|\frac{\epsilon\cos\Theta - \sqrt{\epsilon - \sin^2\Theta}}{\epsilon\cos\Theta + \sqrt{\epsilon - \sin^2\Theta}}\right|^2 \quad (1a)$$

for linear polarization with the electric

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vector parallel to the plane of incidence, and

$$R_{\perp(\Theta)} = \left|\frac{\cos\Theta - \sqrt{\epsilon - \sin^2\Theta}}{\cos\Theta + \sqrt{\epsilon - \sin^2\Theta}}\right|^2 \quad (1b)$$

for the orthogonal linear polarization. Here Θ is the angle between the direction of propagation and a normal to the surface; ϵ is in general complex, but here we consider only real values, since the imaginary parts of most plausible values of ϵ are small compared to the real parts.

The emissivity $E_{(\Theta)}$ for thermal radiation leaving a surface at angle Θ is given by Kirchoff's Law,

$$E_{(\Theta)} = 1 - R_{(\Theta)}, \quad (2)$$

where $R_{(\Theta)}$ is the integral of the scattering coefficient over all angles of scattering for an angle of incidence equal to Θ. For the case of a smooth surface these integrals reduce to Eqs. (1), yielding

$$E_{\parallel(\Theta)} = 1 - R_{\parallel(\Theta)}$$

and (3)

$$E_{\perp(\Theta)} = 1 - R_{\perp(\Theta)}.$$

A radiotelescope capable of resolving the planet, and accepting only one linear polarization, will thus see a temperature distribution which is dependent on both the position on the disk and the direction of polarization. In particular, at the Brewster angle, Θ_B, defined by $\cos\Theta_B = [1/(\epsilon + 1)]^{1/2}$, $E_{\parallel} = 1$, while $E_{\perp} < 1$; so that areas of enhanced emission, "Brewster angle high lights," will be observed towards the ends of the planetary diameter parallel to the direction of received linear polarization.

We now compute the brightness distribution which would be observed. Assume the observing telescope accepts linear polarization, the direction of which is oriented on the planet's disk at angle D_0 with respect to the planet's equator. Then at any point on the disk situated on a line rotated an angle D from the equator, the brightness temperature measured (if the beamwidth is infinitely narrow) is

$$T_{D_0} = [E_{\parallel}\cos^2(D - D_0) + E_{\perp}\sin^2(D - D_0)] \cdot T \quad (4a)$$

and by rotating the feed horn 90°,

$$T_{(D_0+\pi/2)} = [E_{\parallel}\sin^2(D - D_0) + E_{\perp}\cos^2(D - D_0)] \cdot T. \quad (4b)$$

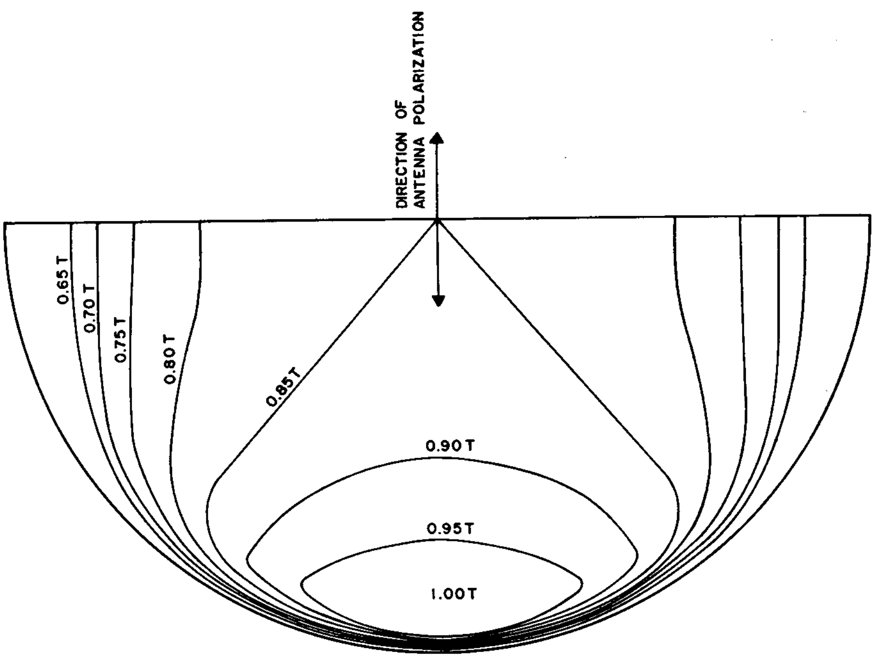

FIG. 1. Typical brightness temperature distribution on a planet's disk, as computed from Eq. (4). $\epsilon = 5$; T = actual surface temperature; the mean equivalent black body temperature = $0.85 \cdot T$.

Figure 1 shows the distribution of T_{D_0} on the planet's disk. The distribution of $T_{(D_0+\pi/2)}$ is that of T_{D_0} rotated $\pi/2$.

In practice, more precise results for the polarization can be obtained by measuring

$$\Delta T_p = T_{D_0} - T_{(D_0+\pi/2)},$$

since the differential measurement is easier to make than an absolute one. A typical contour plot of this quantity is shown in

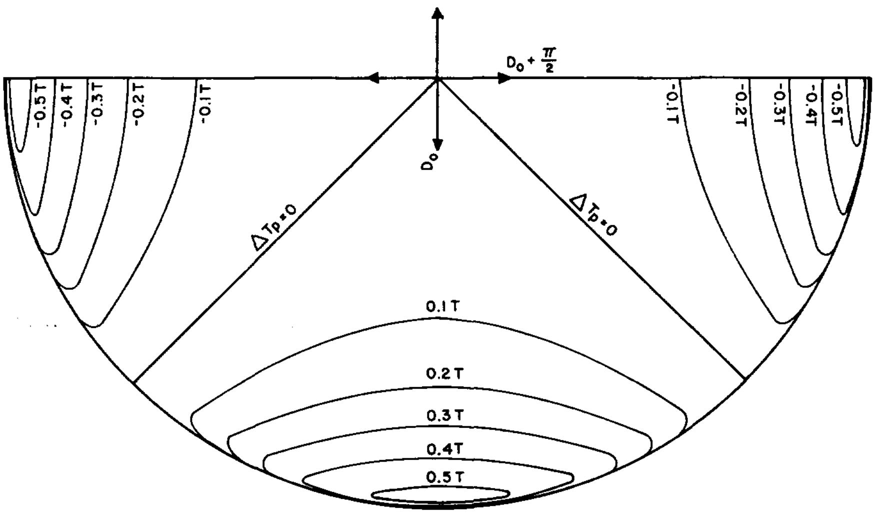

FIG. 2. Typical contour plot of $\Delta T_p = T_{D_0} - T_{(D_0+\pi/2)}$; $\epsilon = 5$.

Fig. 2. It is easily shown that ΔT_p at the Brewster angle is

$$\Delta T_{p\Theta_B} = (T_{D_0} - T_{(D_0+\pi/2)})_{\Theta_B} = \left|\frac{1-\epsilon}{1+\epsilon}\right|^2 T. \quad (5)$$

The maximum ΔT_p occurs at $\cos\Theta \approx \sqrt{\epsilon - 1}/4(\epsilon + 1)$, very near the edge of the disk for all dielectric constants. By smoothing such a contour plot with the antenna beam pattern, one obtains the polarized brightness distribution expected from measurements with a real antenna. The effects of beam smoothing are shown in Fig. 7, where a gaussian beam with a half-power beamwidth equal to one-third of the planetary diameter is assumed.

At present it is, of course, impossible to observe any celestial body but the Moon in such a detailed manner, because the resolution of all existing antennae is too small. However, resolution is obtainable indirectly by the use of interferometer techniques. Theoretical fringe amplitudes for a conventional two-element interferometer may be found from the expression:

Fringe visibility

$$= \frac{\left|\int_0^R T_B(x)\cos(2\pi ax/\lambda D)dx\right|}{\int_0^R T_B(x)\,dx} \quad (6)$$

where

R = radius of planet,
D = distance from Earth to planet,
λ = wavelength,
a = interferometer spacing,
x, y are rectangular coordinates centered on the planet's disk,
x is parallel to the interferometer base line,

$$T_B(x) = \int_0^{\sqrt{R^2-x^2}} T_B(x, y)\,dy,$$

$T_B(x, y)$ is the brightness temperature found from either Eq. 4a or 4b.

Fringe visibility functions so found are shown in Fig. 3. It is also enlightening to consider the equivalent one-dimensional source pictures of the planet, obtained by plotting $T_B(x)$ against x/R and shown in Fig. 4. The fringe visibility functions for a complex dielectric constant ($\epsilon_c = \epsilon + i\epsilon'$)

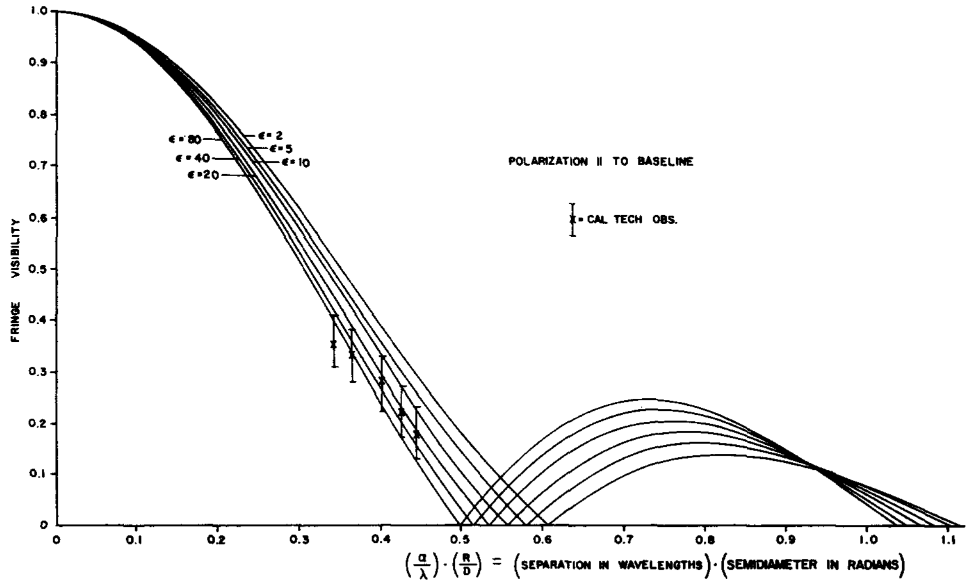

FIG. 3a.

FIG. 3. Fringe visibility function as calculated from Eq. 6. Barred points are observations of Venus by California Institute of Technology at 9.4 cm.

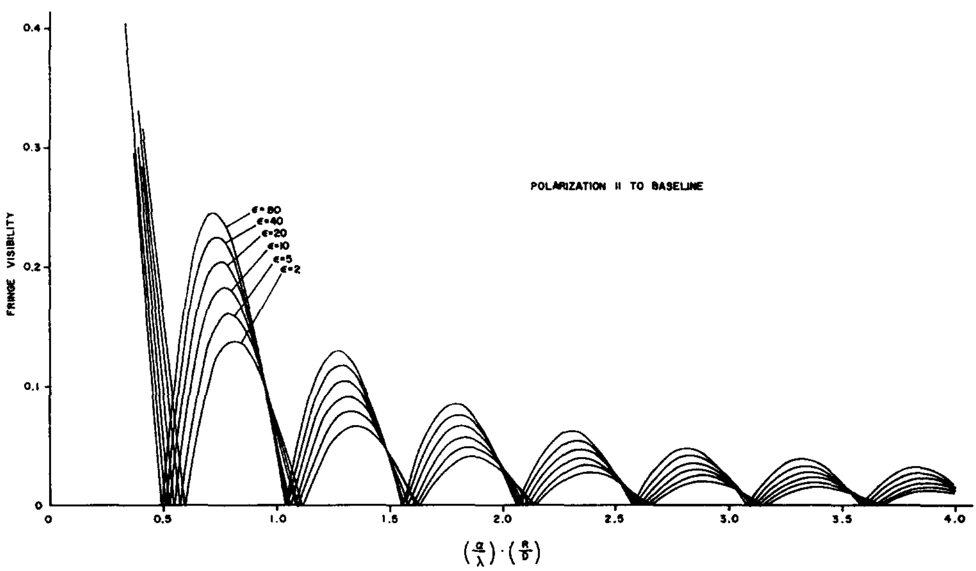

FIG. 3b.

can be roughly represented by using the plots for the real dielectric constant and setting $\epsilon = |\epsilon_c|$ in Figs. 3a–3d (see Fig. 3e).

As is well known, an effect of an increasing dielectric constant is to decrease the total power emitted by the planet from that emitted by a black body. To evaluate the equivalent black body disk temperature, we assume that the antenna response pattern is uniform over the disk of the planet (the planet ap-

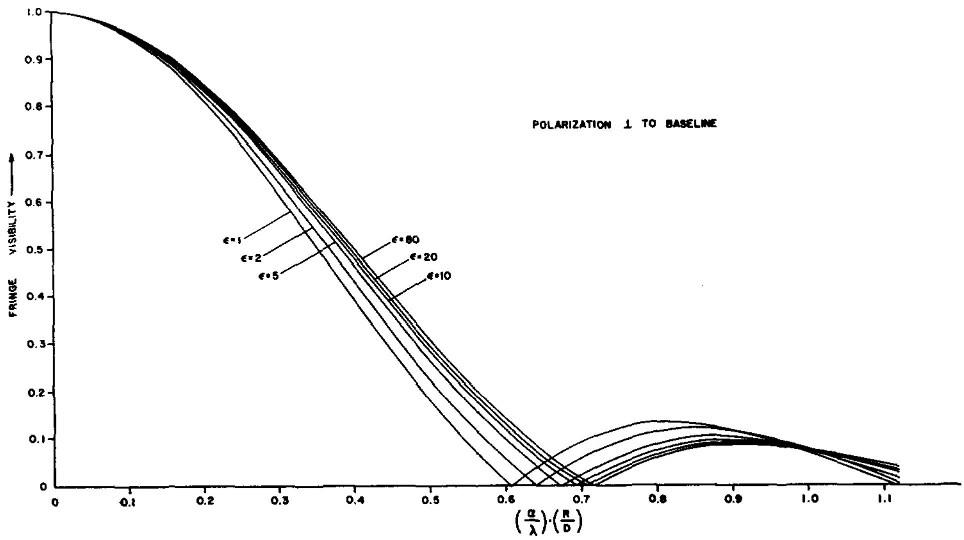

FIG. 3c.

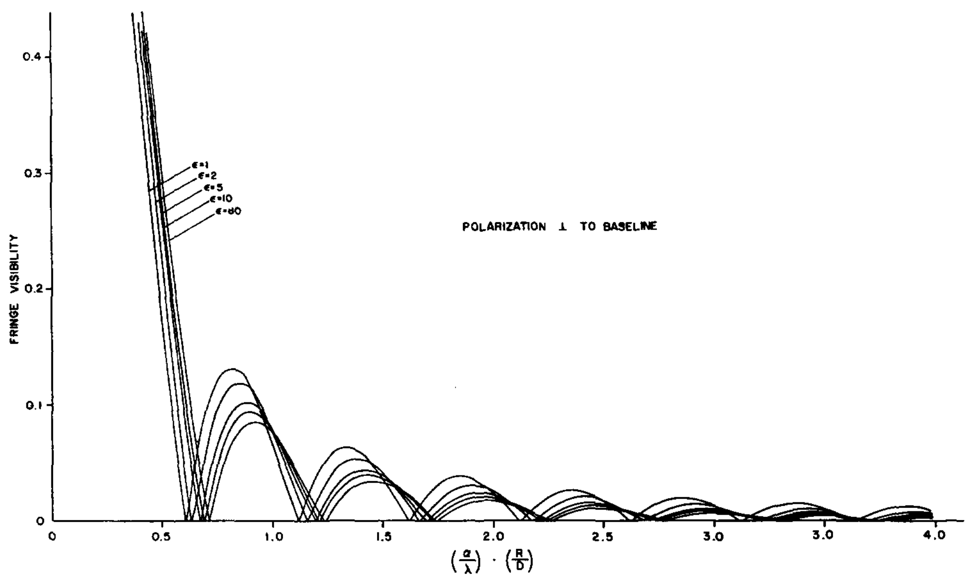

FIG. 3d.

pears a point source), and calculate the expression

$$\frac{T_{BB}}{T} = \frac{\int_0^R T_B(x)_{dx}}{\int_0^R T\,dx} = \frac{\int_0^R T_B(x)_{dx}}{T(\pi R^2/4)} \tag{7}$$

which is the ratio of the total power actually received by the antenna to that which would be received if the planet were a black body ($\epsilon = 1$). T_{BB} is the familiar mean equivalent black body disk temperature. In Fig. 5 are shown the results of this calculation; the calculated curve is very close to the one obtained by the use of the expression

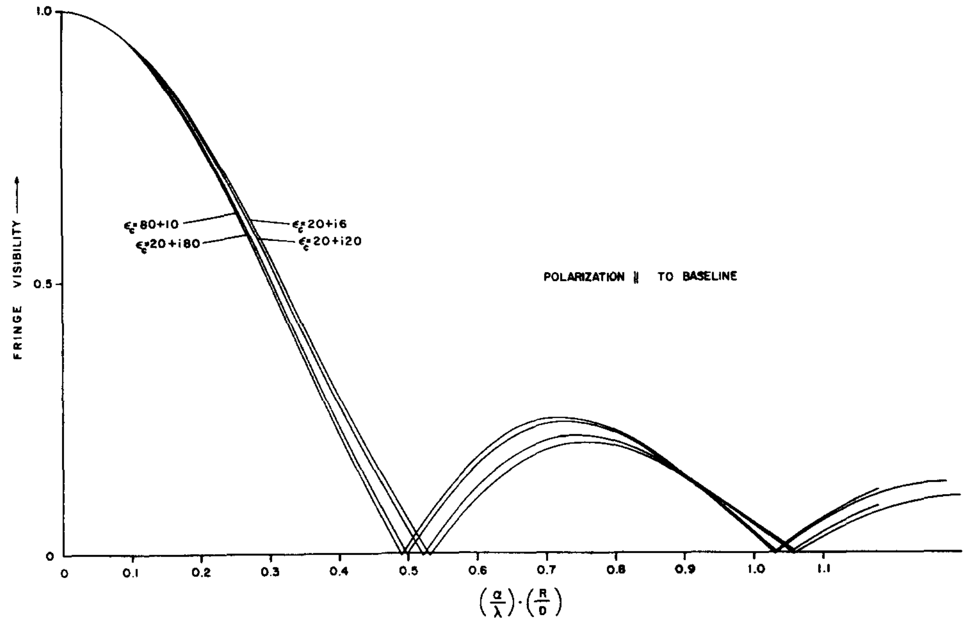

FIG. 3e.

$$\frac{T_{BB}}{T} = \left[1 - \left(\frac{\sqrt{\epsilon} - 1}{\sqrt{\epsilon} + 1}\right)^2\right] \tag{8}$$

i.e., by simply using the emissivity for $\Theta = 0$ in expressions (1) and (3).

Deviations from the Ideal Smooth Sphere

Deviations from the results obtained above can arise from at least four circumstances: one, the planet is not smooth; two, the surface is nonhomogeneous over the disk of the planet and/or vertically down to the effective depth from which a particular wavelength is emitted; three, the temperature is nonuniform; and four, the surface is not a good dielectric. The latter case is unlikely but is easily treated when necessary by the usual complex number mathematics and introduction of the magnetic permeability in Eqs. (1).

Consider now the effects of a rough surface. The polarization of thermal emission from any rough surface must be less than that from a similar surface which is smooth. If the surface is not too rough, models based on a superposition of two kinds of surface roughness can be used (Evans and Pettingill, 1963). The surface can consist of electrically smooth facets, large compared to a wavelength, having various orientations with respect to the mean surface; and the surface irregularities can be smaller, on the order of a wavelength in size, so that diffraction of the emitted wave must be taken into account. In the former case the depolarization produced is fairly easy to calculate theoretically (see Evans and Pettingill, 1963), but in the latter it can be estimated only with great difficulty. Unfortunately, in either case the adoption of undesirably *ad hoc* models for the spatial distribution and size distribution of the surface irregularities is necessary. Much work is called for on these problems. Empirical studies of typical rough surfaces would be perhaps a fruitful way to attack the problem.

In practice, a measured $\Delta T_{p\,max}$ enables one to calculate an effective dielectric constant for the rough surface, but this dielectric constant will not necessarily provide the correct value for the emissivity. Fortunately, for the two cases of the Moon and Venus, the surface appears relatively smooth at centimeter wavelengths (Evans and Pettingill, 1963; Pettingill *et al.*, 1962; Muhleman, 1962; Kotelnikov *et al.*, 1963), and the

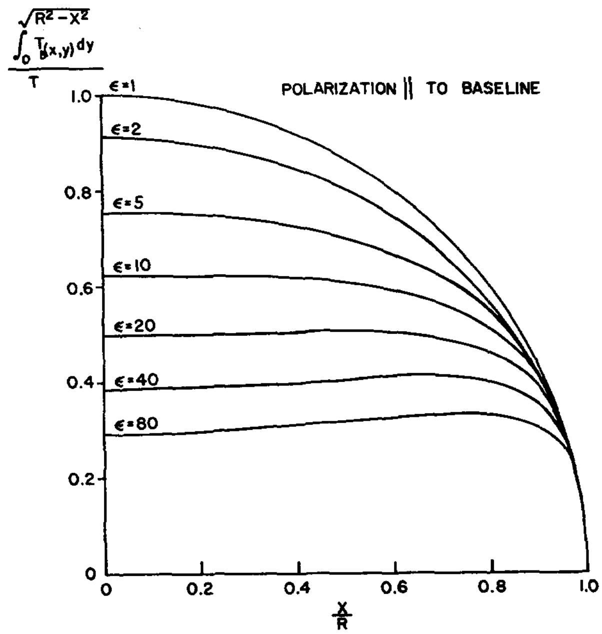

FIG. 4a.

FIG. 4. Brightness distribution across a smooth, homogeneous, spherical planet as would be observed by a conventional two-element interferometer.

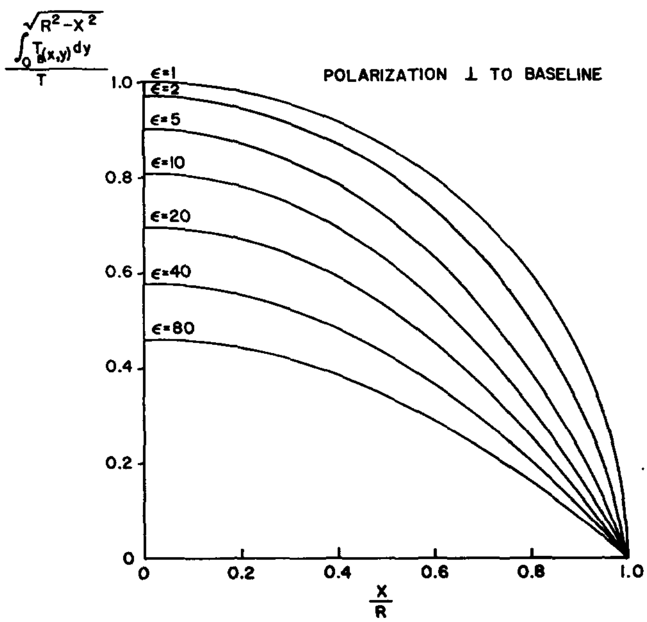

FIG. 4b.

theoretical relations for a smooth model may be applied with little error.

The remaining deviations from the ideal case can be dealt with straightforwardly. Changes in surface material chemical composition and/or physical structure, thus dielectric constant, across the disk will alter the pictures given in Figs. 1 or 2. The

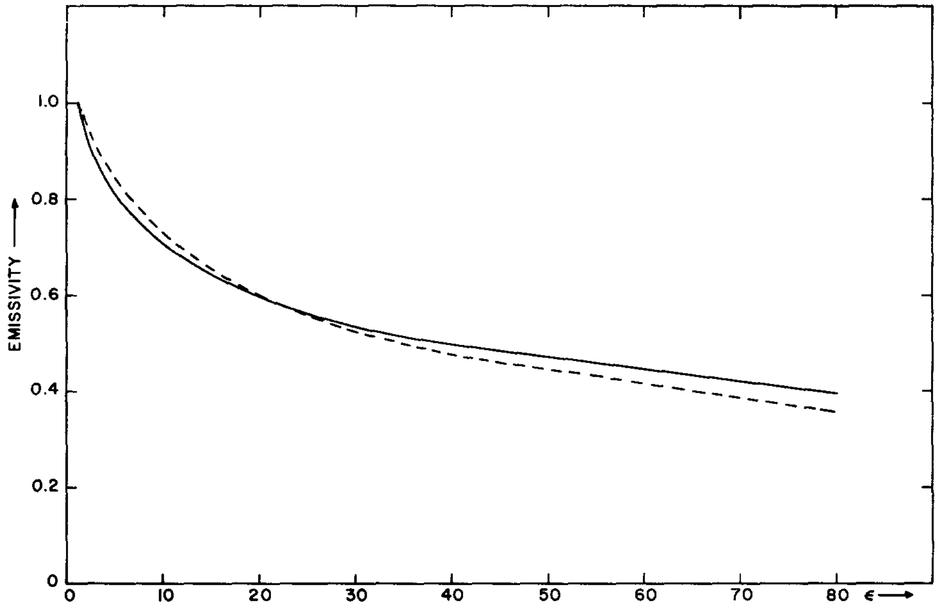

FIG. 5. Mean emissivity of a planetary disk as a function of dielectric constant (solid curve); emissivity at center of disk as a function of dielectric constant (dotted curve).

intensity at any point is simply calculated from the value of the dielectric constant of the surface material at that point. In viewing the Earth for example, one might see more than half the planet covered by sea water (having a dielectric constant of about 80) and the other half by continents (dielectric constant of about 5). Thus the Brewster angle high lights for the oceanic portions would be situated extremely near the limb and would be very striking in intensity and polarization; the high lights for the continents would be much lower in relative intensity and polarization, and would be located somewhat nearer the center of the planet.

One finds the changes of emissivity across a planetary disk caused by a vertically differentiated surface to be small, if the dielectric constant is larger than about two, even though the effective emitting layer is less deep near the edges of the disk than at the center. This fortunate circumstance arises from Snell's law; the direction of the wave emerging from inside the planet is always closer to the surface normal than that of the wave outside the surface. It is easy to show that, for a surface having properties which do not vary with depth, the minimum emission depth, occurring at the extreme edge of the disk, is given by

$$(d/d_0)_{min} = \sqrt{(\epsilon - 1)/\epsilon} \tag{9}$$

where d_0 is the effective emission depth at the center of the disk. For $\epsilon = 2$, for example, $(d/d_0)_{min} = 0.7$. The same qualitative behavior applies to the vertically differentiated surface. The effect is therefore usually negligible, unless the surface gradients are extremely steep or extreme accuracy of measurement is achieved.

The effects of temperature variations, both vertically in the surface and across the planet's disk, are obvious and require no elaboration.

Comparison with Radar Results

In passive radiometric measurements the emitting layer is located some distance d_0 beneath the actual surface of the planet. For the radar case, however, the mean reflecting layer is located roughly $d_0/2$ beneath the surface, since in each case the effective "layer" is located at the same optical depth, and the radar wave must both enter and leave the surface.

Thus we may expect that, when the passive measurements are inconsistent with radar measurements made at the same wavelength, better agreement may be obtained by repeating the radar observations at twice that wavelength. When this situation obtains, we may conclude that the surface is nonhomogeneous vertically.

Observational Examples

The Moon

The Moon was observed on the dates June 22, June 24, and June 28 of 1963 with the NRAO 300-ft telescope using simultaneously two crossed polarized feeds and two separate receivers which were constructed by the Naval Research Laboratory, and kindly made available by E. F. McClain, W. E. Rose, R. M. Sloanaker, and J. Bologna. The operating frequency was 1413 Mc and the beamwidth was ten minutes of arc, one-third the diameter of the Moon. The observational technique was that of "wobbling," i.e. scanning back and forth in declination across the Moon as it transited. In this manner 5 to 7 separate scans across the lunar disk were made per transit. The results are shown in Fig. 6 in the form of a map of the difference between the apparent black body lunar temperatures measured by the two feeds $\Delta T'_p$, where $\Delta T'_p$ is the observed brightness temperature difference between the two polarizations in the presence of beam smoothing. Figure 6a is the average of the contour maps obtained from the observations of June 22 and June 28, when the same feed orientation was employed; Fig. 6b gives the results from the June 24 observations. The probable error of a value of $\Delta T'_p$ in Fig. 6a is 6.5°K, and in Fig. 6b, 9.2°K. Polarization of lunar

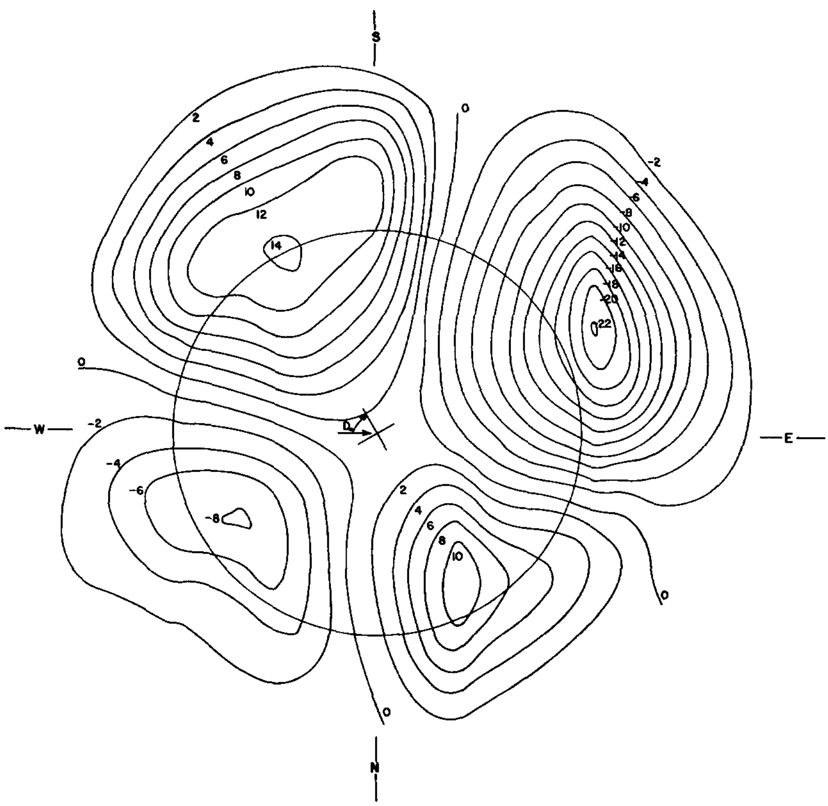

FIG. 6a. The Moon. Contours of $\Delta T'_p$ observed on June 22 and June 28.

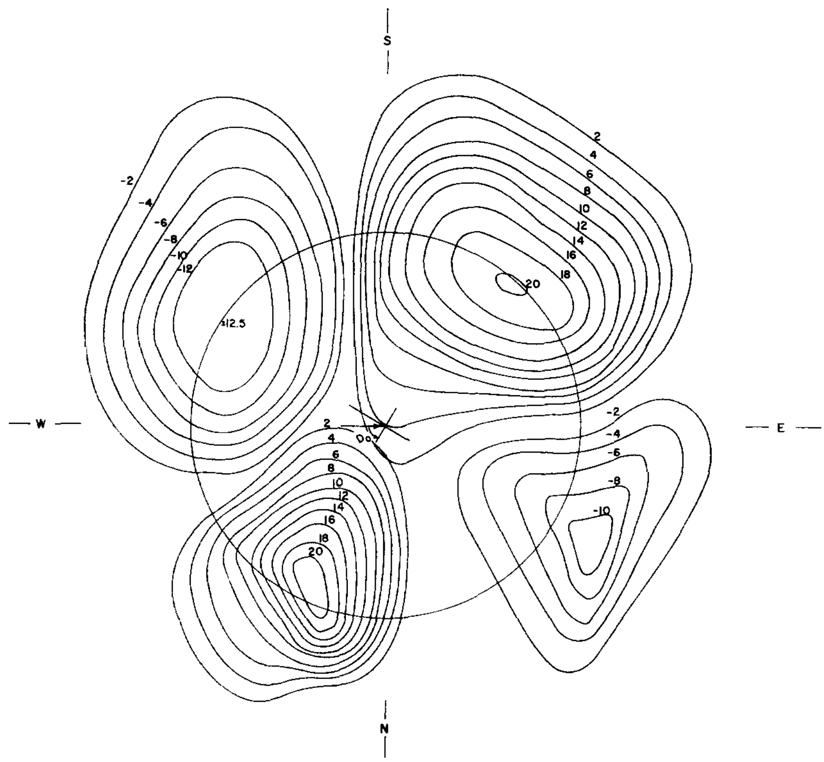

FIG. 6b. The Moon. Contours of $\Delta T'_p$ observed on June 24.

thermal emission has previously been observed by Sobolev (1962) and by the CSIRO group at 10 cm (unpublished).

Before reaching any conclusions, the effects of beam smoothing must be accounted for, as is obvious from the fact that the size of the theoretical Brewster angle high lights is actually comparable with the antenna beamwidth. One finds that the magnitude of the peaks and valleys in the observed polarization distribution is reduced by a factor of approximately five from the situation when resolution is perfect. This follows from calculating $\Delta T'_p$, given by:

$$\Delta T'_p(x_i, y_i) = \int_{-R}^{+R}\int_{-R}^{+R} \Delta T_p(x, y)\, A(x - x_i, y - y_i)\, dxdy, \quad (10)$$

where A is the antenna pattern.

A result applying to the data of Fig. 6 is given in Fig. 7, where the beam pattern $A(x, y)$ was approximated from beam pattern measurements by

$$A_{(x,\,y)} = (1/2\pi\sigma) \exp - [(x^2 + y^2)/2\sigma^2];$$
$$\sigma = 0.425 \cdot (2R/3);$$

ϵ was assumed to be 2, and T was assumed to be 230°K. It is seen that Figs. 6 and 7 are in good agreement both qualitatively and quantitatively.

The agreement between Figs. 6 and 7 indicates that the Moon appears almost entirely as a smooth sphere at 21-cm wavelength; this is in agreement with the well-known radar picture of the Moon. The asymmetry of the magnitudes of the polarization peaks appears statistically significant; if so, the differences are probably caused by surface inhomogeneities. The regions showing the lowest percentage polarization are dominated by maria, which is perhaps surprising. This could be a result of a relatively rough surface in the maria for 21-cm waves, or of a relatively lower dielectric constant in the maria. Either situation is of considerable interest; it would be desirable to extend and improve the accuracy of the observations.

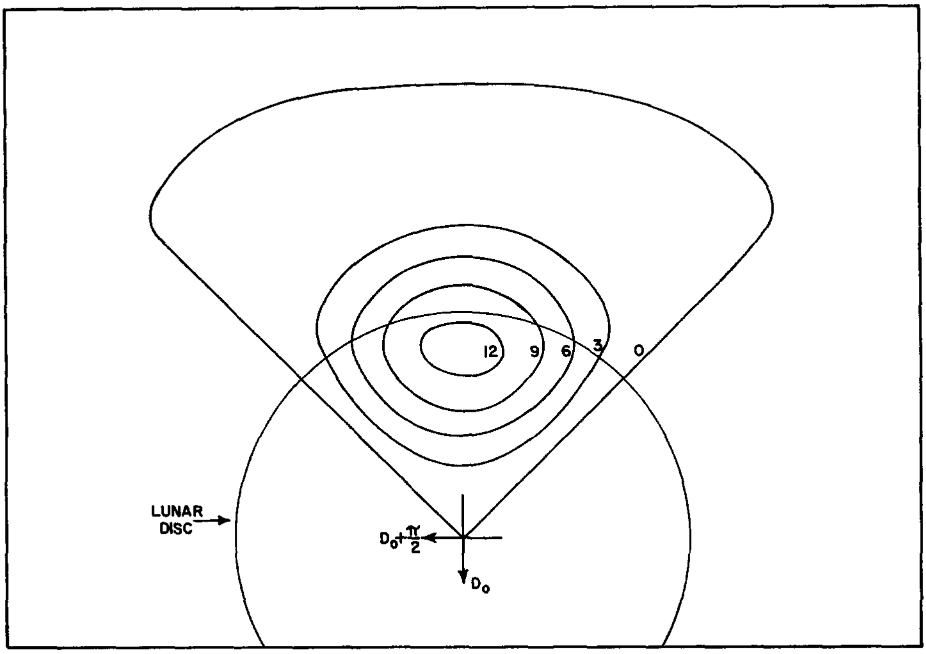

FIG. 7. Effect of beam smoothing on theoretical distribution of ΔT_p. Beamwidth $= \frac{1}{3}$ the apparent diameter of the Moon or planet observed. $T = 230$ °K. $\epsilon = 2.0$.

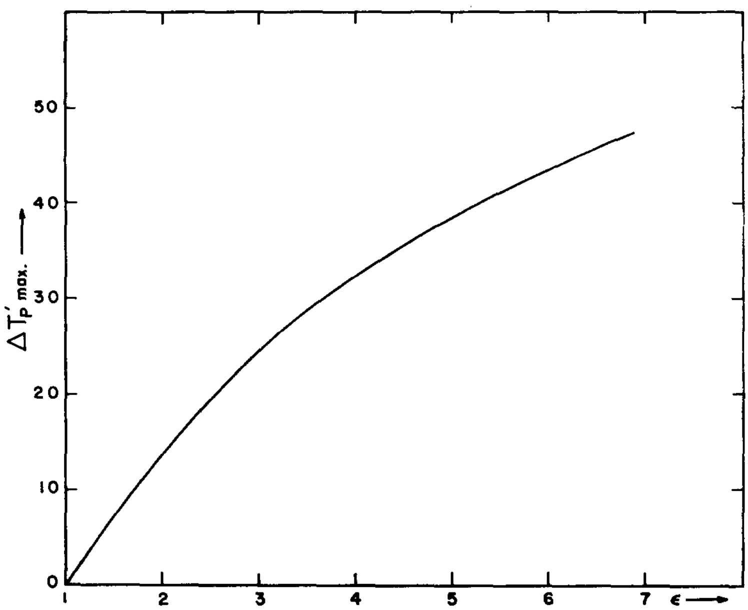

FIG. 8. $\Delta T'_{p\,max}$, observed with a beamwidth $= \frac{1}{3}$ the lunar or planetary diameter, as a function of dielectric constant ϵ.

The maximum values of $\Delta T'_p$, $\Delta T'_{p\ max}$, that would be observed from a smooth sphere in the presence of the actual beam smoothing have been computed. These are given in Fig. 8. A weighted mean of the actually observed maximum values of $\Delta T'_p$ is:

$$T'_{p\ max} = 14.5 \pm 3.5 \text{ (p.e.) °K},$$

corresponding to an observed percentage polarization of about 8.5%. The maximum observed polarization, which actually occurs at smaller values of $\Delta T'_p$, and smaller values of T'_B, was about 20%. From Fig. 8,

$$\epsilon = 2.1 \pm 0.3.$$

The summary of radar reflectivities of Pettingill and Evans (1963) shows that the best estimate for the normal incidence radar reflectivity at the relevant wavelength, 42 cm (see above), is 0.07. This gives a dielectric constant of about 3.0, in poor agreement with the above. However, measurements at shorter wavelengths by Sobolev (1962) at 3.2 cm give $\epsilon = 1.7$ and by Victor *et al.* (1961) at 12.5 cm give $\epsilon = 1.8$, indicating the presence of a vertically inhomogeneous structure which may explain this discrepancy.

The central brightness temperature was measured to be

$$T = 232 \pm 25°\text{K},$$

where the error quoted includes the estimated errors in the antenna beam efficiency of about 10%. This is in satisfactory agreement with the mean brightness temperature at the center of the disk, 211 ± 32°K, recently measured by Salomonovich and Losovsky (1962) at 8 mm wavelength, and 226 ± 9°K measured semiempirically by Krotikov and Troitsky (1962) at 3.2 cm wavelength. It does not lend support to the conclusion of Krotikov and Troitsky (1963) that the temperature of the Moon increases rapidly with depth.

From Eq. (8), with $\epsilon = 2.1$, the actual temperature at the center of the disk

$$T = 241 \pm 26°\text{K}$$

Venus

The California Institute of Technology group (Clark, private communication) made interferometer observations of Venus at 9.4-cm wavelength in December, 1962. The points with error bars in Fig. 3a give the results of these measurements. It is seen that the general trend of the observations is the expected one, and that the points fall roughly near the curve associated with $\epsilon = 40$. Such a high dielectric constant could occur if bodies of water were present, but this is ruled out by the high surface temperature. This ϵ is also approached by some iron oxides, which Martian observations suggest as a plausible surface constituent. However, $\epsilon = 40$ is in poor agreement with the values implied by the observed radar reflectivity (Pettingill *et al.*, 1962; Muhleman, 1962; Kotelnikov, 1963) which gives $\epsilon = 4$ to 6. This indicates either that a model consisting simply of a smooth spherical surface is incorrect for Venus at this wavelength, or that small observational errors exist. The Cal. Tech. results show that further interferometric or high resolution studies of the planet at several wavelengths would be very interesting.

Acknowledgment

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