Reports

Tenuous Surface Layer on the Moon: Evidence Derived from Radar Observations

Abstract. *By radar backscattering, observations of the moon have been made which show a systematic difference between the backscattering coefficient of waves polarized in, and perpendicular to, the local plane of incidence. The results are in agreement with a model consisting of a tenuous top layer at least 10 centimeters thick, supported by a denser underlying layer.*

We here report a new type of polarization technique in radar astronomy and show how its use in the study of the moon indicates that the lunar surface is covered by a tenuous layer.

Radar measurements of the total backscattered power have previously been used to infer the reflectivity and hence the dielectric constant of the moon. For the frequency range of interest in the experiment reported here, the dielectric constant has been determined to be about 2.6 to 2.8 (*1, 2*). Studies of backscattered power as a function of range beyond the subterrestrial point on the moon have led to models of the lunar surface which can be described as gently undulating, with mean slopes on the order of 10° to 12° on the scale of about 1 m (*2*). Young craters or rayed craters on the moon have been shown to be anomalously strong scatterers, and it has been inferred that they are rougher and must have a higher intrinsic reflectivity than their surroundings (*3*). Depolarization studies have been carried out to the extent that the two orthogonal, circularly polarized waves have been observed when a circularly polarized wave was transmitted (*1*). These measurements have shown that a very appreciable amount of power is being returned in that circular component which should contain no power if the reflector were an ideal, properly oriented, large, surface facet. This has been interpreted to mean that the surface must contain small-scale structure which backscatters in a manner akin to that of a collection of randomly oriented dipoles. Randomly oriented, linear dipoles should, however, depolarize to the extent that the two circularly polarized, backscattered waves should have equal power when illuminated with a circularly polarized wave. If the same model were illuminated by a linearly polarized wave, it could be shown that three-fourths of the backscattered energy should be polarized in the same plane as the incident wave. In view of the results of Evans and Pettengill (*1*), we might therefore conclude that the lunar surface will largely scatter back in a polarization corresponding to that of the incident wave, when illuminated with linearly polarized waves. The general picture of the lunar surface emerging from these radar observations alone is therefore one of a sandy, desert-like surface (for quartz sand, $\epsilon \cong 2.6$) of fairly gentle undulations, with a few rocks strewn over it to act as discrete scatterers at very oblique incidence.

Radiometric studies of the thermal emission from the lunar surface have centered around the following types of observations. Measurements have been made of the emission temperature of the lunar surface throughout complete lunations, and the thermal cycle of the moon has been obtained at several different wavelengths. These measurements basically are sensitive to the ratio of the penetration depths of the thermal wave and the electromagnetic wave of observation. The results of these measurements show that the upper layers of the surface must have a very high thermal inertia, possibly corresponding to an extremely tenuous medium (*4*). Another type of observation consists in the measurement of temperature distribution across the lunar disk. The amount of limb darkening can be used to deduce an equivalent dielectric constant of the surface. The results of such observations have generally indicated a dielectric constant of $\epsilon = 1.1$ to 1.7 (*5*), corresponding to an extremely tenuous medium. The most direct method of obtaining data on the lunar surface material from radiometric observations appears to be the measurement of the polarization of the emission as a function of angle of incidence on the surface (*6*). These observations have been carried out by a number of observatories, and they nearly all seem to agree that the surface must be a material with a dielectric constant ϵ in the range 1.6 to 1.8 (*7*). Attempts to reconcile the radiometric and the radar data by carefully considering the effect of roughness on the thermal emission properties (*8*) has brought about somewhat closer agreement, but a very significant discrepancy still persists.

Inspection of the Ranger photographs seems to show that the surface of the moon is quite smooth even down to a scale of a meter or so. The surface irregularities, even on a small scale, can be described as gentle undulations. In particular, there seems to be practically a complete absence of visible protruding structures corresponding to rocks strewn over the surface, such as one might have expected from radar data alone.

In view of the discussion of different data presented above, it was felt that the backscattering at oblique incidence on the lunar surface might arise from some sort of irregular structure actually buried underneath a tenuous surface layer on the moon. If this layer were of sufficient thickness (that is, in excess of the wavelength of observation), it was argued that the strength of the backscattering should be systematically different for the two linearly polarized components in and across the local plane of incidence of the wave. This systematic effect was thought to arise from the difference in the transmission coefficients of the two linearly polarized waves penetrating the top layer. Such effects, obviously, can be studied only if it is possible to resolve fairly small areas on the moon.

The experiment to distinguish be-

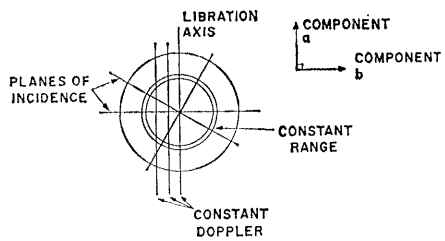

Fig. 1. Schematic view of the lunar disk with range-doppler coordinates and with the two received linearly polarized components *a* and *b*.

tween the two linearly polarized waves was done basically as follows. A circularly polarized wave illuminating the whole moon was transmitted. The radiation was pulsed so that various rings of constant range from the radar could be distinguished by range gating on the time base of the receiver. The additional coordinate necessary to resolve specific areas on the moon was provided by spectral analysis in each range ring. Owing to the apparent libration of the moon the approaching limb will scatter at a somewhat higher doppler frequency than the center of the moon, and the receding limb, at a somewhat lower frequency. Lines of constant doppler displacement correspond very closely to straight lines across the lunar disk parallel to the instantaneous apparent libration axis [for details, see Pettengill and Henry (*9*)].

The two orthogonal, linearly polarized components returned from the moon were studied separately but simultaneously. One of these was aligned (*E*-field) with the instantaneous libration axis of the moon (component *a*) and the other one was perpendicular to this axis (component *b*; see Fig. 1). A systematic difference in the backscattering of the two linearly polarized components should then show up as follows. For any given range ring, component *a* should be stronger (or weaker) than component *b* near the libration axis, that is, near zero frequency, and component *a* should be weaker (or stronger) than component *b* near the extreme frequencies of the range ring. The two linearly polarized components should be equally strong at 0.707 times the maximum frequency for any range ring, for reasons of symmetry (see Fig. 1).

The M.I.T. Lincoln Laboratory Millstone Radar used in the experiment operates at a 23-cm wavelength, with a 25-m parabolic antenna. In the experiment described here the pulselength was 200 μsec and the interpulse period 30 msec. The doppler frequency, the rate of change of doppler, and the direction of the instantaneous libration axis were predicted from the lunar ephemeris for every 5 minutes, and were set into the receiving equipment before every 5-minute run. The direction of the lunar polarization on reception was controlled by combining two orthogonally polarized received signals by means of a network consisting of two 3-db hybrids and two line stretchers. The two linearly polarized signals received were passed through separate receiver systems and the corresponding intermediate-frequency signals were detected in pairs of phase-detectors, so that both inphase and quadrature signals were available for both channels. The four outputs of the phase-detectors were sampled simultaneously and converted to six-bit numbers in sequence. An interval of 14.4 msec of the time base was sampled every 160 μsec, beginning 2.56 msec before the predicted leading edge of the echo in order to permit a noise base line to be established. The digital data were stored on magnetic tape, and a few of the range samples were analyzed on the Millstone CG 24 computer to provide the frequency spectra. The frequency analysis was carried out between -18 and $+18$ cy/sec, with a frequency resolution of 2 cy/sec. The power spectra corresponding to the two polarizations were normalized so that the areas under the curves were made the same. The noise base line was subtracted by

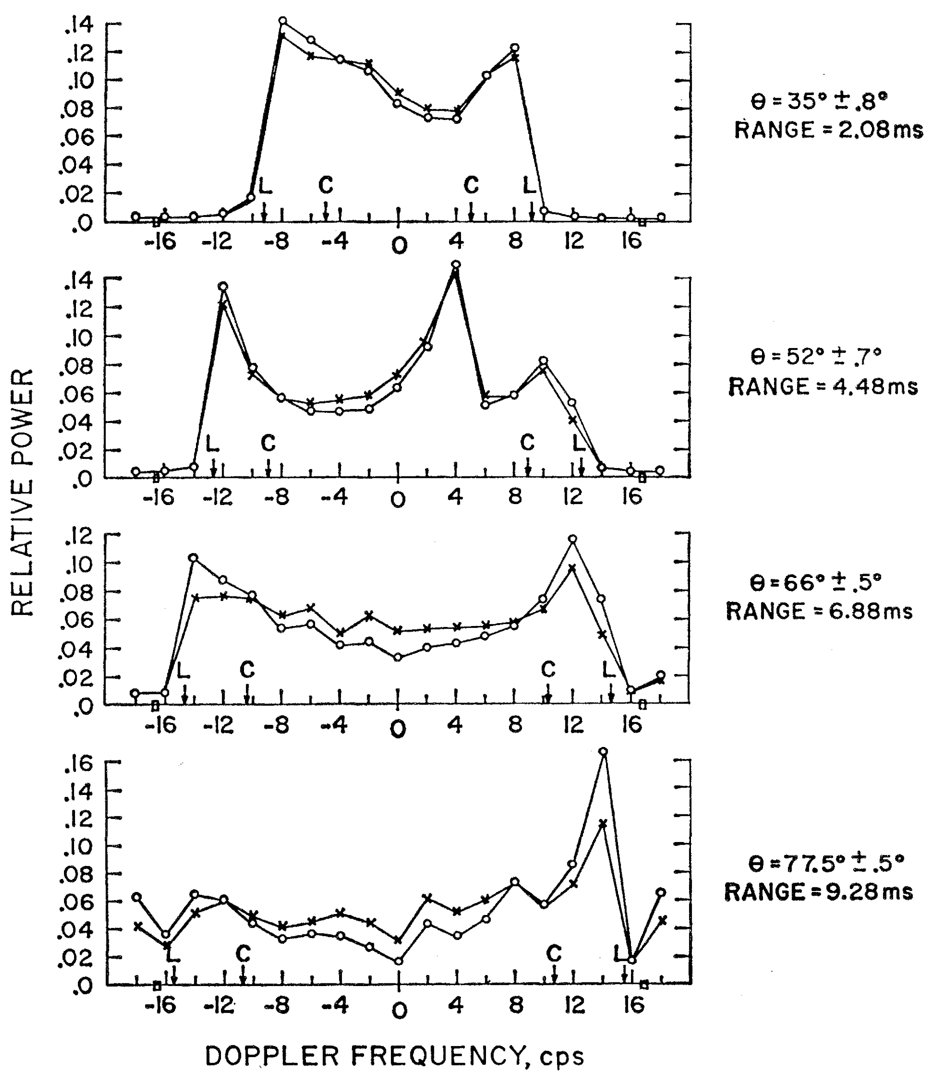

Fig. 2. Normalized frequency spectra of the moon, 18 June 1965, 0340 to 0435 E.S.T., for four range rings. Ranges in milliseconds (ms): λ, 23 cm; pulse length, 200 μsec; frequency box, 2 cy/sec. *L*, maximum frequency; *C*, crossover point. Curves: –x–, *E*-field aligned with libration axis; –o–, *E*-field normal to libration axis.

frequency-analyzing the noise immediately preceding the echo, in the same way as the signal. Twenty-five minutes of data were analyzed, and the various spectra were summed. This was justified in this particular case because the libration axis moved by only about 4° during the run, and the predicted doppler width did not change by more than 5 percent. The statistical uncertainty in the curves was equal to approximately 1/55 of the mean values of the power at any frequency offset.

The spectra for four different range rings are shown in Fig. 2; the effect predicted on the assumption of penetration through a top layer is clearly visible. The extreme frequencies are marked by L, and the predicted crossover points by C. The ratio of the two components decreases with increasing angle of incidence. The component with E-field along the plane of incidence is scattered more strongly than the orthogonal one, again as expected if a penetration mechanism is operating. There is a very sharp peak at a range of 4.48 msec, at a frequency offset of +4 cy/sec. At this peak the ratio of the two components is unexpectedly close to unity: compare the ratio at −4 cy/sec for the same range ring. At the time of observation the predicted range doppler coordinates of the crater Tycho were 4.30 msec and +2 cy/sec, and it therefore seems very plausible to ascribe the anomalous peak to the Tycho region which is known to be an outstanding scattering area (*9*). The Faraday rotation was estimated to be less than 10° and was therefore neglected.

In order to test the hypothesis of a penetration mechanism through a tenuous top layer on the lunar surface somewhat further, the ratio of the power in the two orthogonal, linearly polarized components was derived as a function of the angle of incidence on the mean lunar surface.

This information was most readily derived from the region near zero frequency. The same information could, in principle, be derived from the maximum frequency regions also, but in these latter regions the angles between the planes of polarization and the plane of incidence change much more rapidly with changes in frequency offset than they do near zero frequency, and for this reason the ratios were computed only on the basis of information derived from the power spectra near zero frequency offset.

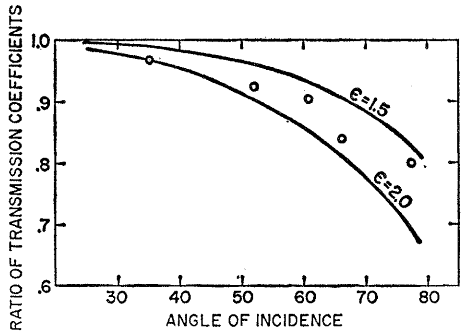

Fig. 3. Ratio of transmission coefficients derived from data as compared with theoretical predictions.

The scattering mechanism inside the top layer was assumed to scatter back principally in the same linear polarization as that of the incident wave. This appears to be justified in view of previous circular to circular depolarization studies (*1*), as discussed above. On this assumption, one would expect the ratio of the backscattering coefficients of the two linear polarizations to be equal to the square of the ratio of the corresponding transmission coefficients. In Fig. 3 the square root of the ratios derived from the ratio of the backscattering coefficients is plotted against the mean angle of incidence. In the same diagram is shown the ratio of the corresponding transmission coefficients for dielectric constants of 1.5 and 2.0. It is very tempting to ascribe to the postulated top layer a dielectric constant of about 1.7 to 1.8. It might be quite significant that this value corresponds very closely to the ones derived from radiometric observations of the polarization of the thermal emission from the lunar surface (*7*). The fact that no systematic difference in the backscattering coefficients of the two polarizations is seen in the Tycho region may be interpreted to mean that this region does not have a tenuous surface layer or that it is quite thin, probably less than a few centimeters. Elsewhere the top layer must be at least some tens of centimeters thick, since the depth of the surface layer must be greater than about a wavelength for the pronounced polarization effects observed to occur.

We have to reconcile our model with radar observations of cross section which, when interpreted on the basis of a single layer model, appears to give a dielectric constant of 2.6 to 2.8. On the assumption of a double layer model, the upper layer being of random thickness and having a dielectric constant of 1.8, it is possible to obtain the right amount of reflection with a base layer with $\epsilon = 4.5$ to 5. This model, incidentally, could also explain the increase in cross section observed by Davis and Rohlfs (*10*) at wavelengths between 10 and 20 m if the top layer were some 5 to 10 m deep. The radiometric determinations of the dielectric constant based on the polarization of the thermal emission might also be brought into line with our naive two-layer model. Calculations show that near grazing angles of incidence the polarization of the emission will be determined almost entirely by the top layer. A two-layer model of the lunar surface of the type suggested thus provides a rather self-consistent explanation of several different types of observations made of the moon by radio waves.

The double layer model of the lunar surface described appears to fit Gold's "dust" hypothesis (*11*), and it might also fit Kuiper's ideas about a rock froth layer of low density (*12*). The density of the surface layer cannot be derived unambiguously from the polarization data presented here. If the surface material in compacted form has a dielectric constant of 4.5 to 5, as we tend to see for the bottom layer, the porosity of the top layer can be estimated on the basis of either Odelevskii and Lenin's expression (see *5*) or on the basis of Twersky's formula (*13*), both of which can be derived from the Lorentz-Lorenz expression. The porosity turns out to be about 60 to 70 percent. If the dielectric constant of the material in bulk is much greater, the porosity comes out correspondingly higher.

It appears that the results presented above provide fairly direct evidence for the presence, nearly everywhere on the moon, of a tenuous surface layer in excess of some 20 cm in depth and having a dielectric constant of about 1.7 to 1.8. There is also good evidence that the young crater Tycho does not have such a surface layer in the same measure as the rest of the moon. The technique described could be exploited more extensively to explore several different features on the moon for possible classification in terms of the extent to which they possess such a layer. Much better bounds on layer depth could be obtained if other radar systems, working at different wavelengths, could be used in the same type of experiment. Similar observations could be made on some of the near planets in order to gain further insight into their surface characteristics or possibly their atmospheres.

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Mars: Compatible Determinations of Surface Pressure through Particle Scattering

Abstract. *The number of scattering particles required to bring the visual polarimetric and ultraviolet photometric estimates of the surface pressure of Mars into agreement are calculated. Concentrations of 10^8 to 10^9 ice particles, 0.2 micron in diameter, per square-centimeter column are obtained. Based on concentrations of Aitken nuclei in the atmosphere of Earth, a layer less than 100 meters thick would contain the required number of particles. The compatible pressures obtained in this manner for various N_2–CO_2 and Ar–CO_2 atmospheric models lie within the range of pressures determined spectroscopically.*

The interpretation of recent spectroscopic observations of the $5\nu_3$ band of CO_2 in the Martian atmosphere has suggested surface pressures far lower than the generally accepted value of 85 or 90 mb determined polarimetrically by Dollfus (*1*) and supported by the photometry of de Vaucouleurs (*2*). An upper limit for the surface pressure, based on ultraviolet photometry from the ground (*3*), lies between these values.

The discrepancies among these results and the design-data requirements for spacecraft entering the Martian atmosphere stimulated a great deal of new work on the problem of the surface pressure, including critical reviews by Chamberlain and Hunten (*4*) and by Cann, Davies, Greenspan, and Owen (*5*). The latter review considered the visual polarimetric measurements of Dollfus (*1*) and an ultraviolet photometric estimate by Musman (*3*), in addition to various pressure determinations from the spectroscopic observations by Kaplan, Münch, and Spinrad (*6*).

The polarimetric technique involves separation of the atmospheric brightness $B_a°$ and surface brightness $B_s°$ at the center of the disk on the basis of differences in polarizing characteristics. The absolute atmospheric brightness at 6100 Å is then determined from the ratio $B_a°/B_s°$ and from independent photometric observations of $B_s°$. The pressure is estimated from Rayleigh scattering theory; a pure molecular atmosphere with scattering and polarizing properties similar to those of air is assumed. Dollfus (*1*) obtained a brightness ratio ($B_a°/B_s°$) of 0.028 and a pressure of 90 mb. During the review of the polarimetric work (*5*) it was found that Dollfus (*1*) unnecessarily separated the phase and zenith-angle dependence of polarization. Reexamination of the data without separating variables yielded a revised value for the brightness ratio of 0.015 which, when coupled with more recent photometric results, gave a pressure estimate of 61 mb for a nitrogen atmosphere. Atmospheres consisting of two constituents were considered, and it was found that the visual pressure determination P_v could be expressed as:

$$P_v = \left(\frac{B_a°}{B_s°}\right)\left(\frac{B_s°}{B_s}\right)\frac{4\,\bar{p}_v g}{A_0 p\,(\cos 0)} \times \left[\frac{xM_1 + (1-x)M_2}{x\sigma_1^v + (1-x)\sigma_2^v}\right]$$

where ($B_a°/B_s°$) is the ratio of atmospheric to surface brightness at the center of the Martian disk at 6100 Å; ($B_s°/B_s$) is the ratio of the brightness of the center of the disk to the brightness of the entire disk; $\bar{p}_v = \pi B_s/E$ is the monochromatic geometric albedo at 6100 Å, where E is the monochromatic solar flux; g is the gravitational force per unit mass on Mars; $p(\cos 0)$ is the Rayleigh phase function for backscattering; A_0 is Avogadro's number; M_1 and M_2 are the gram molecular weights of the two constituents; σ_1^v and σ_2^v are the Rayleigh scattering cross sections per molecule for the two constituents at 6100 Å; and x is the fraction of molecules or atoms of constituent 1.

The estimate made by ultraviolet photometry (*3*) is based on the assumption that, because of the low surface albedo, the entire brightness of Mars at 3300 Å is due to atmospheric scattering. This estimate is necessarily an upper limit in the absence of absorption. This was pointed out by Musman (*3*), who matched the reflectivity of Mars at 3300 Å with model Rayleigh atmospheres and obtained an optical thickness of 0.058. This optical thickness corresponds to a surface pressure of 27 mb for a nitrogen atmosphere. For a two-constituent atmosphere, the ultraviolet pressure determination P_{uv} can be expressed as:

$$P_{uv} = \frac{\bar{p}_{uv} g}{0.794\,A_0}\left[\frac{xM_1 + (1-x)M_2}{x\sigma_1^{uv} + (1-x)\sigma_2^{uv}}\right]$$

where $\bar{p}_{uv} = \pi B_a/E$ is the monochromatic geometric albedo at 3300 Å; 0.794 is a factor containing the phase function and a correction for the sphericity of the atmosphere; and σ_1^{uv} and σ_2^{uv} are Rayleigh scattering cross sections per molecule for the two constituents at 3300 Å. The results obtained by this formulation are in agreement with Musman's determination (*3*).

In both of these techniques only molecular scattering is assumed for the